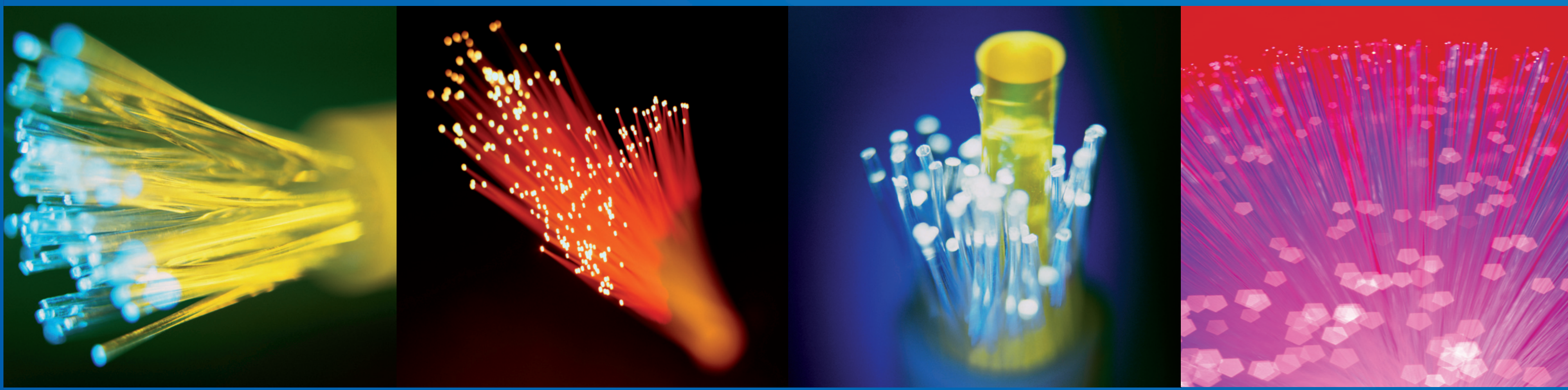
International Telecommunication Union



Optical fibres, cables and systems

ITU-T Manual

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Foreword

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As we approach the half century mark for the dawn of the era of optical communications, it is appropriate to take stock of the journey of discovery and application of this empowering technology. As with most new technologies, the engineering challenges associated with its assimilation into the existing infrastructure have been as significant as the scientific advances within the invention of the laser itself. ITU-T has been active in the standardization of optical communications technology and the techniques for its optimal application within networks from the infancy of this industry. However, it is not always easy to find out what has been covered, and where it can be found. This manual attempts to aggregate all of the available information on ITU-T's work.

The manual is intended as a guide for technologists, middle-level management, as well as regulators, to assist in the practical installation of optical fibre-based systems. Throughout the discussions on the practical issues associated with the application of this technology, the explanations focus on how ITU-T Recommendations address them. It provides the organized insights of those who have created and lived with the evolution of the technology for several decades.

The first ITU-T Handbook related to optical fibres, *Optical Fibres for Telecommunications*, was published in 1984, and several others have been produced over the years. It is an honour to present you with the latest version, which is another example of how ITU-T is bridging the standardization gap between developed and developing nations. I trust that this manual will be a useful guide for those looking to take advantage of optical cables and systems and I welcome feedback from readers for future editions.

The success of efforts such as this, and the underlying standardization upon which it is based, depends on attracting and involving the pioneers of new technologies in a spirit of collaborative competition to establish the best practices for the common good. Participation is open to all.

I would like to express my appreciation to the experts from the ITU membership, who have provided us with valuable proposals and to those who have contributed to the new version. My particular appreciation goes to Mr. Gastone Bonaventura, former Vice-Chairman of ITU-T Study Group 15, the leading Study Group on Optical Networks, and his team of collaborators.

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PREFACE

The invention of the laser and its demonstration is dated 1960. It was suggested in 1966 that optical fibres might be the best choice for using laser light for optical communications, as they are capable of guiding the light in a manner similar to the guiding of electrons in copper wires. The main problem was the high losses of optical fibres: fibres available during the 1960s had losses in excess of 1 000 dB/km. A breakthrough occurred in 1970 when the losses could be reduced to below 20 dB/km in the wavelength region near 1 000 nm. At about the same time, GaAs semiconductor lasers, operating continuously at room temperature, were demonstrated. The simultaneous availability of compact sources and of low-loss optical fibres led to a worldwide effort for developing optical fibre communication systems.

The real research phase of fibre-optic communication systems started around 1975. The enormous progress realized over the 30-year period extending from 1975 can be grouped in several distinct phases. Over this time period the BL product [B is the bit rate and L is the repeater spacing, where the repeaters perform optical to electrical to optical conversion] doubled every year. In every phase BL increased initially but began to saturate as the technology matured. Each new phase brought a fundamental change.

The first phase

The first phase of lightwave systems operated **near 850 nm** and used GaAs semiconductor lasers with *multimode fibres*. After several field trials during the period 1977-79, such systems became available commercially in 1980. They operated at a bit rate of 34-45 Mbit/s and allowed repeater spacings of up to 10 km. The larger repeater spacing compared with 1-km spacing of coaxial systems was an important motivation for system designers because it decreased the installation and maintenance costs associated with each repeater.

This phase of lightwave systems was specified in two Recommendations. The first one is ITU-T G.651, where the characteristics of a multimode optical fibre operating at 850 nm are specified. The second one is ITU-T G.956 (now ITU-T G.955) where are specified the characteristics of the optical systems operating at 850 nm and suitable for the bit rates of the plesiochronous digital hierarchy (PDH).

The second phase

It was clear during the 1970s that the repeater spacing could be increased considerably by operating the lightwave systems in the wavelength region near 1 300 nm, where fibre loss is below 1 dB/km. Furthermore, optical fibres exhibit minimum dispersion in this wavelength region. This realization led to a worldwide effort for the development of InGaAsP semiconductor lasers and detectors operating **near 1 300 nm**.

The second phase of fibre-optic communication systems, based on InGaAsP semiconductor lasers and detectors operating near 1 300 nm became available in the early 1980s, but the bit rate of early systems was limited to below 100 Mbit/s because of dispersion in multimode fibres. This limitation was overcome by the use of *single-mode fibres*. A laboratory experiment in 1981 demonstrated transmission of 2 Gbit/s over 44 km of single-mode fibre. The introduction of commercial systems followed. By 1988, second-generation lightwave systems, operating at bit rates of up to 1.7 Gbit/s with a repeater spacing of about 50 km, were commercially available.

This second phase of lightwave systems was also specified in some Recommendations. In particular, Recommendation ITU-T G.652 specifies the characteristics of a single-mode optical fibre operating at 1 300 nm. Recommendation ITU-T G. 957 specifies the characteristics of optical systems operating at 1 300 nm and suitable for transmitting the bit rates of the synchronous digital hierarchy (SDH) up to STM-16. Moreover the text of Recommendation ITU-T G.956 (now Recommendation ITU-T G.955) was extended to include also PDH systems operating at 1 300 nm.

The third phase

The repeater spacing of the second phase lightwave systems was limited by the fibre losses at the operating wavelength of 1 300 nm (typically 0.5 dB/km). Losses of silica fibres become minimum near 1 550 nm. Indeed, a 0.2 dB/km loss was realized in 1979 in this spectral region.

However the introduction of third phase lightwave systems operating **at 1 550 nm over single-mode fibre** was considerably delayed by the large fibre dispersion near 1 550 nm. Conventional InGaAsP semiconductor lasers could not be used because of pulse spreading occurring as a result of simultaneous oscillation of several longitudinal modes. The dispersion problem can be overcome either by using *dispersion-shifted fibres* designed to have minimum dispersion near 1 550 nm or by limiting the laser spectrum to a single longitudinal mode. Both approaches were followed during the 1980s. By 1985, laboratory experiments indicated the possibility of transmitting information at bit rates of up to 4 Gbit/s over distances in excess of 100 km. Third generation lightwave systems operating at 2.5 Gbit/s became available commercially in 1992. Such systems were capable of operating at a bit rate of up to 10 Gbit/s. The best performance is achieved using dispersion-shifted fibres in combination with lasers oscillating in a single longitudinal mode.

Also, this phase of lightwave systems was specified in some Recommendations. Recommendation ITU-T G.653 specifies the characteristics of a dispersion-shifted single-mode optical fibre. Recommendations ITU-T G.652, ITU-T G.955 (ex-G.956) and ITU-T G.957 were revised / extended in order to include optical systems operating at 1 550 nm. Recommendation ITU-T G.974 specified the characteristics of the optical systems to be used for the submarine applications.

The fourth phase

A drawback of third phase 1 550 nm systems is that the signal must be regenerated periodically by using electronic repeaters spaced apart typically by 70-80 km. This situation changed with the advent of fibre amplifiers in 1989.

The fourth phase of lightwave systems makes use of **optical amplification** for increasing the repeater spacing **and** of wavelength division multiplexing (**WDM**) for increasing the aggregate bit rate. The advent of the WDM technique started a revolution that resulted in doubling the system capacity every 6 months. In most WDM systems fibre losses are compensated periodically using erbium-doped fibre amplifiers typically spaced 70-80 km apart. Such amplifiers, **operating in C-band (1 530-1 565 nm)**, were developed after 1985 and became available commercially by 1990. A 1991 experiment showed the possibility of data transmission over 21 000 km at 2.5 Gbit/s and over 14 300 km at 5 Gbit/s, using a recirculating-loop configuration. This performance indicated that an amplifier-based, all-optical, submarine transmission system was feasible for intercontinental communication. By 1996, not only transmission over 11 600 km at a bit rate of 5 Gbit/s had been demonstrated by using actual submarine cables, but commercial transatlantic and transpacific cable systems also became available. Since then, a large number of submarine lightwave systems have been deployed worldwide.

In order to specify the characteristics of optical fibres and systems operating with optical amplifiers and the WDM technique, many new Recommendations were developed in ITU-T. Recommendation ITU-T G.655 specifies a non-zero dispersion-shifted single-mode optical fibre. Recommendations ITU-T G.694.1 and ITU-T G.694.2 specify the spectral grids for DWDM and CWDM applications. Some Recommendations specify the characteristics of optical systems devoted to particular DWDM applications: Recommendations ITU-T G.959.1 (inter-domain applications without line OA), G.698.1 (metro access applications without line OA), ITU-T G.698.2 (metro core / regional applications with line OA), ITU-T G.696.1 (backbone applications with line OA), ITU-T G.973 (submarine applications without line OA), and ITU-T G.977 (submarine applications with line OA). Recommendation ITU-T G.695 specifies CWDM systems for access / metro access applications.

The fifth phase

In the current development of lightwave systems, which is considered as the fifth phase, there are several directions of evolution.

The first one, **mainly related to the long-haul systems**, is towards increasing the capacity transmitted on an optical fibre:

i) by transmitting more and more channels through the WDM technique in the C-band (1 530-1 565 nm), by reducing the channel spacing. Commercial terrestrial systems with the capacity of 1.6 Tbit/s (160 optical channels at 10 Gbit/s) are now available with a channel spacing of 25 GHz;

ii) by deploying the optical channels not only in the C-band, but also in the short wavelength S-band (1 460-1 530 nm) and in the long wavelength L-band (1 565-1 625 nm). The Raman amplification technique could be used for signals in all three wavelength bands. Moreover a new type of fibre, known as the dry or low water peak fibre has been developed with the property that fibre losses are small over the entire wavelength region extending from 1.3 to 1.65 μm. Availability of such fibres and new amplification schemes may lead to lightwave systems with a larger number of WDM channels on a single optical fibre;

iii) by increasing the bit rate of each channel within the WDM signal. Starting in 2000, many experiments used channels operating at 40 Gbit/s. Moreover starting from 2006 some experiments demonstrated the feasibility of systems operating up to 110-130 Gbit/s per channel. Most of these new systems require an extremely careful management of their dispersion and new techniques to deal with polarization time variant effects (1^{st} and 2^{nd} order PMD, PDL, etc).

The second direction of evolution is the **reduction of the number of expensive optical/electrical/optical (O/E/O) conversions** within the optical transport networks (OTN). The two main reasons for the reduction in the number of O/E/O conversions are that DWDM systems are becoming capable of carrying light signals for thousands of kilometres without electrical regeneration and that photonic cross-connect (PXCs) and optical add-dDrop multiplexers (OADMs) are becoming available with the capacity, space requirements, power consumption, reliability and cost, suitable for their use in the telecommunication networks. With this evolution it is possible to foresee that all optical networks (AONs) could extend to all potential routes of the backbone network of a medium size country with optical paths up to around 2 000 km.

The third direction (an alternative to the second one) is the implementation of multiple O/E/O regenerators at a cost comparable to that of an optical amplifier. This is today a realistic objective, thanks to recent advances in photonic integrated circuits and silicon photonics. 40 WDM channels, 40 Gbit/s each channel, have been recently demonstrated on the same chip. Following this way of evolution, the O/E/O regenerators could be put practically in all the nodes of the network. The additional cost could compensate the technical problems related to the implementation of an AON (impairments accumulation, network planning rules, optical monitoring, etc.).

In the framework of these evolutions several Recommendations have already been prepared and the preparation of others is under way. Among those completed it is possible to quote Recommendation ITU-T G.656 for a fibre with non-zero dispersion for wideband optical transport, the extension of Recommendation ITU-T G.959.1 to include also 40 Gbit/s systems, and Recommendation ITU-T G.680, which allows operators to take OADMs and PXCs from different vendors and integrate them into an AON without having to add expensive O/E/O conversions.

In parallel with the above stated developments of the DWDM systems for the backbone network, passive optical networks (PON) have been developing. A PON is an optical access network that extends from an operator central office into individual homes, apartment houses and business offices. A PON can be deployed in a FTTH (fibre to the home) architecture or in a FTTB (fibre to the building), a FTTC (fibre to the curb) or a FTTCab (fibre to the cabinet) architecture, depending on local demands. In order to reduce the need for separate fibres for the two direction of transmission, the PON systems can take advantage of WDM signal multiplexing technique, where downstream and upstream channels are transmitted at different wavelengths.

Optical fibres for the access network are specified in Recommendations ITU-T G.657 and ITU-T G.651.1. PON systems specifications are included in the ITU-T G.983 x-series of Recommendations and in the ITU-T G.984 x–series of Recommendations.

Applications of optical technology in the telecommunication networks

Given that the first-generation systems had a capacity of 34-45 Mbit/s per fibre in 1980, the capacity of optical systems has jumped by a factor of more than 10 000 over a period of 20 years. In the same time period, the applications of optical technology progressively moved from short distance links (a few tens of km) to the very long distance links of the backbone networks, completely substituting the traditional copper conductors. In the last few years the optical technology also started to be deployed in the access networks.

This wide range of applications is not only based on the above-quoted development of optical fibres and systems. It has been also necessary to develop and to specify many other aspects related to the practical implementation of the optical plant.

Optical fibres must be inserted in cables, which are laid in different ways: buried, in ducts, aerial, in sewers, submarine, etc. For each of these ways of laying, it is necessary to properly design the cable in order to respect well-defined mechanical (bending, tensile strength, crush, impact, torsion, etc.) and environmental conditions (moisture permeation, water penetration, vibration, temperature variations, fire safety, etc.).

In the same way, it is necessary to define the installation techniques to maintain the dynamic strain below the specified maximum allowable fibre strain, in order not to reduce the predictable lifetime of the fibres.

Moreover, the optical plant needs a lot of complementary hardware (passive nodes, optical distribution frames, joint closure, cabinets, etc.), which needs a detailed development and specification both for technical and economical reasons.

The ITU-T has published a complete set of Recommendations dealing with the above subjects: Recommendations of the ITU-T G-series on optical fibres and systems and Recommendations of the ITU-T L-series on construction, installation, jointing and termination of the optical cables.

The content of this ITU-T Handbook is mainly based on the content of those ITU-T Recommendations.

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CHAPTER 1

OPTICAL FIBRES CHARACTERISTICS

Introduction

This Chapter is devoted to the description of the main characteristics of the optical fibres. In clause 1 the difference between multimode and single-mode is outlined. Fibre design issues and fibre manufacturing methods are shortly dealt with in clauses 2 and 3. Clauses 4, 5, 6 and 7 are dedicated to the criteria adopted for the specification of the optical fibres in ITU-T (fibre attributes, cable attributes, link attributes). Clause 8 gives a glance to the test methods. Clause 9 describes the characteristics of the optical fibres specified in ITU-T and their possible applications. For a more detailed description of these applications see Chapter 8.

For further information on the content of this Chapter see Recommendations ITU-T G.650.1, ITU-T G.650.2, ITU-T G.650.3, ITU-T G.652, ITU-T G.653, ITU-T G.654, ITU-T G.655, ITU-T G.656, ITU-T G.657 and ITU-T G.651.1.

1 Single-mode and multimode optical fibres

Multimode optical fibres are dielectric waveguides which can have many propagation modes. Light in these modes follows paths that can be represented by rays as shown in Figure 1-1a and 1-1b, where regions 1, 2 and 3 are the core, cladding and coating, respectively. The cladding glass has a refractive index, a parameter related to the dielectric constant, which is slightly lower than the refractive index of the core glass.

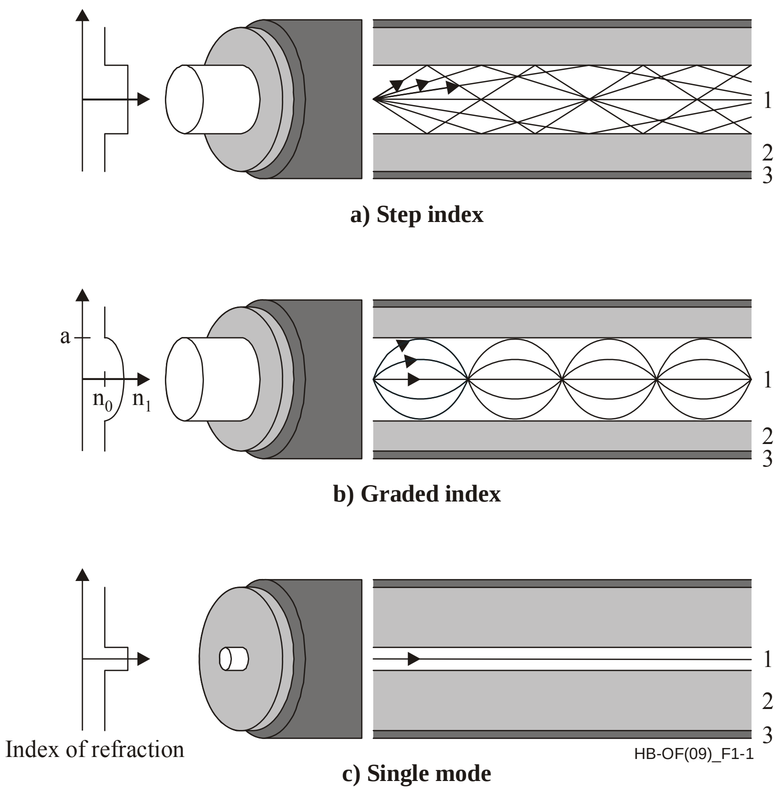


Figure 1-1 – The three principal types of fibres

The fibre in Figure 1-1a is called “step index” because the refractive index changes abruptly from cladding to core. As a result, all rays within a certain angle will be totally reflected at the core-cladding boundary. Rays striking the boundary at angles greater than this critical angle will be partially reflected and partially transmitted out through the boundary towards the cladding and coating. After many such reflections, the energy in these rays will eventually be lost from the fibre. Region 3, the coating, is a plastic which protects the glass from abrasion.

The paths along which the rays (modes) of this step-index fibre travel differ depending on their angle relative to the axis. As a result, the different modes in a pulse arrive at the far end of the fibre at different times, resulting in pulse spreading, which limits the bit rate of a digital signal that can be transmitted.

The different mode velocities can be nearly equalized by using a “graded-index” fibre as shown in Figure 1-1b. Here the refractive index changes smoothly from the centre out in a way that causes the end-to-end travel time of the different rays to be nearly equal, even though they traverse different paths. This velocity equalization can reduce pulse spreading by a factor of 100 or more. By reducing the core diameter and the refractive index difference between the core and the cladding only one mode (the fundamental one) will propagate and the fibre is then “single-mode” (Figure 1-1c). In this case there is no pulse spreading at all due to the different propagation time of the various modes.

The cladding diameter is 125 µm for all the telecommunication types of fibres. The core diameter of the multimode fibres is 50 µm, whereas that of the single-mode fibres is 8 to 10 µm.

2 Fibre design issues

As said above, in its simplest form a step-index fibre consists of a cylindrical core surrounded by a cladding layer whose index is slightly lower than that of the core. Both core and cladding use silica as the basic material, the difference in the refractive indexes is realized by doping the core or the cladding or both. Dopants such as GeO_2 and P_2O_5 increase the refractive index of silica and are suitable for the core. On the other hand, dopants such as B_2O_3 and fluorine decrease the refractive index of silica and are suitable for the cladding. The major design issues for the optical fibres are related to the refractive-index profile, to the amount of dopants, and the core and cladding dimensions.

Figure 1-2 shows typical index profiles that have been used for different types of fibres.

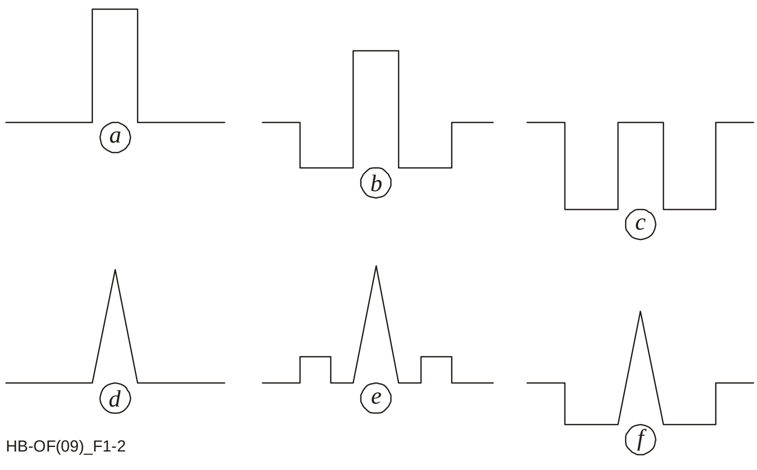


Figure 1-2 – Examples of index profiles of single-mode fibres

The top row corresponds to standard fibres which are designed for having minimum dispersion near 1 300 nm with a cut-off wavelength in the range 1 100-1 200 nm. The simplest design (Figure 1-2a) consists of a pure silica cladding and a core doped with GeO_2. A commonly used variation (Figure 1-2b) has a reduced cladding index over a region adjacent to the core by fluorine doping. It is also possible to have an undoped core using a design shown in Figure 1-2c. The fibres of these last two types are referred to as depressed cladding fibres. They are also called W fibres reflecting the shape of the index profile. The bottom row of Figure 1-2 shows three index profiles used for the dispersion-shifted fibres which have the zero-dispersion wavelength in the range 1 450-1 600 µm. A step or triangular index profile with a depressed or raised cladding is often used for this purpose. The refractive indexes and the thicknesses of the different layers are optimized to design a fibre with the desirable dispersion characteristics.

3 Fibre manufacturing methods

Preparation of silica fibres consists of two major processes: preform making and drawing. The attenuation and the dispersion characteristics of optical fibres largely depend on the preform making process, while glass geometry characteristics and strength depend on the drawing process. These two processes are shortly described in the following.

Several methods can be used to make the preforms. The four commonly used methods are modified chemical-vapour deposition (MCVD), plasma-activated chemical-vapour deposition (PCVD), outside-vapour deposition (OVD) and vapour-axial deposition (VAD).

The second process (drawing) of the preparation of a fibre is essentially the same, irrespective of the process used to make the preform.

Figure 1-3 shows the drawing apparatus schematically.

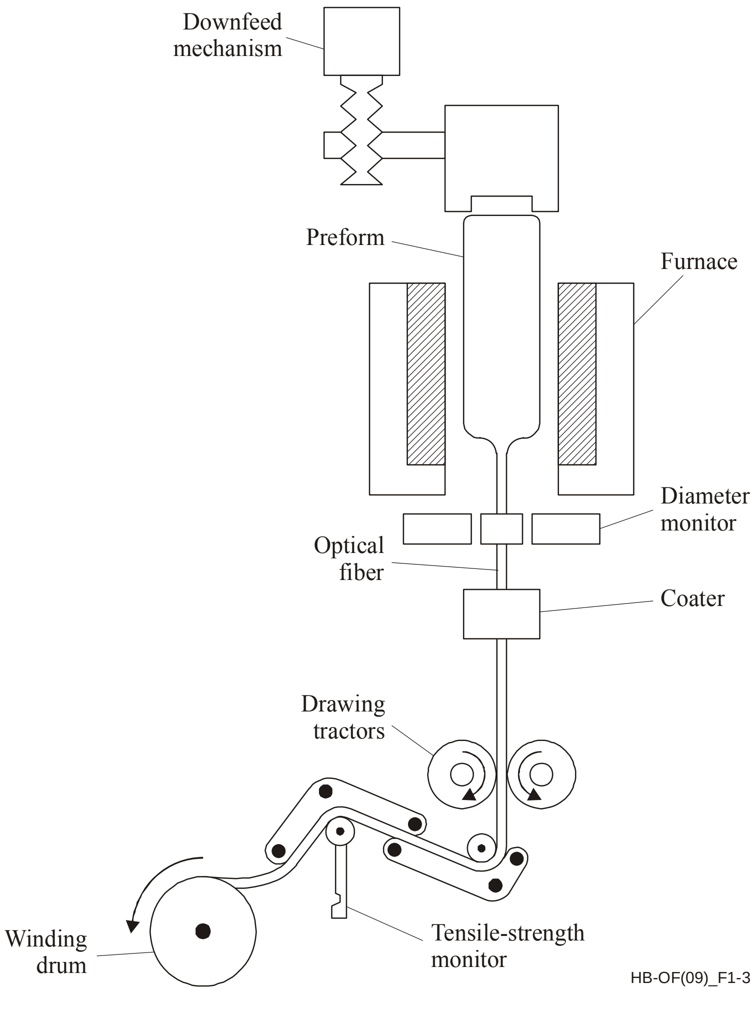


Figure 1-3 – Apparatus for fibre drawing

The preform is fed into a furnace in a controlled manner where it is heated to a temperature of about 2 000° C. The melted preform is drawn into a fibre by using a precision-feed mechanism. The fibre diameter is monitored optically by dedicated measurement equipment. The fibre diameter can be kept constant to within 0.1%. A polymer coating is applied to the fibre during the drawing step. It serves a dual purpose, as it provides mechanical protection and preserves the transmission properties of the fibre. The diameter of the coated fibre is typically 245 μm, although it can be as large as 900 μm when multiple coatings are applied.

A proof-stress which breaks weak spots is applied while the fibre is winding on the drum. This proof-stress can be applied either on-line during the drawing process, or off-line as a separate process step. The proof-test is a main reliability tool.

4 Specification of the optical fibres characteristics

The optical fibres are specified in ITU-T with reference to the geometrical, optical, transmission and mechanical attributes listed in Table 1-1. However, as shown in the same table, for some attributes there is not the specification of a value or limit.

Fibre attributes are those that are retained throughout cabling and installation. Among the fibre attributes only those providing a minimum essential design framework for fibre manufacture are recommended (e.g. mode field diameter, cladding diameter, cut-off wavelength, macrobending loss). Chromatic dispersion coefficient is also included in these attributes.

Cable attributes are recommended for cables in factory lengths as they are delivered. The attenuation coefficient and the polarization mode dispersion (PMD) coefficient are included among the cable attributes since they can be affected by the cabling process.

Link attributes are characteristic of concatenated cables. A concatenated link usually includes a number of spliced factory lengths of optical fibre cable. The transmission parameters for concatenated links must take into account not only the performance of the individual cable factory lengths, but also the statistics of concatenation. The transmission characteristics of the factory length optical fibre cables will have a certain probability distribution which often needs to be taken into account if the most economic designs are to be obtained. Link attributes are affected by factors other than optical fibre cables by such things as splices, connectors and installation.

The definitions and the characteristics of all these attributes are given in the following clauses.

5 Fibre attributes

Fibre attributes are those characteristics that are retained throughout cabling and installation processes. The values specified for each type of fibre can be found in the appropriate ITU-T Recommendation for multimode fibre (Recommendation ITU-T G.651.1) or single-mode fibre Recommendations ITU-T G.652, …, G.657.

5.1 Core characteristics

A value for the *core diameter* and for *core non-circularity* is specified for multimode fibres.

The *core centre* is the centre of a circle which best fits the points at a constant level in the near-field intensity pattern emitted from the central region of the fibre, using wavelengths above and/or below the fibre's cut-off wavelength. Usually the core centre represents a good approximation of the mode field centre (see § 5.2). The *cladding centre* is the centre of a circle which best fits the cladding boundary. The *core concentricity error* is the distance between the core centre and the cladding centre.

Table 1-1 – Fibre, cable and link attributes

	Unit	Relevant for single-mode fibres	Value specified by ITU-T	Relevant for multimode fibre	Value specified by ITU-T
Fibre attributes					
Core diameter	µm	–	–	Yes	Yes
Core non-circularity	%	–	–	Yes	Yes
Mode field diameter	µm	Yes	Yes	–	–
Effective area	μm^2	Yes	No	–	–
Core concentricity error	µm	Yes	Yes	Yes	Yes
Cladding diameter	µm	Yes	Yes	Yes	Yes
Cladding non-circularity	%	Yes	Yes	Yes	Yes
Cut-off wavelength	nm	Yes	Yes	–	–
Numerical aperture		–	–	Yes	Yes
Macrobending loss	dB/turn or dB	Yes	Yes	Yes	Yes
Microbending loss	dB/km	Yes	No	Yes	No
Fibre and protective materials		Yes	No	Yes	No
Protective materials		Yes	No	Yes	No
Proof-stress level	GPa	Yes	Yes	Yes	Yes
Refractive index profile		Yes	No	Yes	No
Modal bandwidth	MHz • km	–	–	Yes	Yes
Longitudinal uniformity of chromatic dispersion		Yes	No	–	–
Chromatic dispersion coefficient	ps/(nm • km)	Yes	Yes	Yes	Yes
Cable attributes					
Attenuation coefficient	dB/km	Yes	Yes	Yes	Yes
Polarization mode dispersion coefficient	ps/√km	Yes	Yes	–	–
Modal bandwidth	MHz • km	–	–	Yes	No
Link attributes					
Attenuation	dB	Yes	Yes	–	–
Chromatic dispersion	ps/nm	Yes	Yes	–	–
Differential group delay	Ps	Yes	Yes	–	–
Non-linear coefficient	W^{-1}	Yes	No	–	–

The tolerances on the physical dimensions of an optical fibre (core, mode field, cladding) are the primary contributors to splice loss and splice yield in the field. The maximum value for these tolerances (concentricity errors, non-circularities, etc.) specified in ITU-T Recommendations help to reduce systems costs and support a low maximum splice-loss requirement typically around 0.1 dB. Fibres with tightly controlled geometry tolerances will not only be easier and faster to splice, but will also reduce the need for testing in order to ensure high-quality splice performance. This is particularly true when fibres are spliced by passive, mechanical or fusion techniques for both single fibres and fibre ribbons (see Chapter 2).

5.2 Mode field characteristics

The *mode field* is the single-mode field distribution of the fundamental mode (LP_{01}) giving rise to a spatial intensity distribution in the fibre. For step-index fibres, the mode field can be well represented as a two-dimensional Gaussian form. The *mode field diameter* (MFD) represents a measure of the transverse extent of the electromagnetic field intensity of the mode in a single-mode fibre cross-section. Mode field diameter describes the size of the light carrying portion of the fibre. For single-mode fibre this portion includes the fibre core as well as a small portion of the surrounding cladding glass. MFD is an important parameter for determining the fibre resistance to bend induced loss and can affect splice loss as well. MFD, rather than the core diameter, is the functional parameter that determines optical performance when a fibre is coupled to a light source. It is a function of wavelength, core diameter and the refractive index difference between the core and the cladding.

5.3 Effective area (A_{eff})

Effective area (A_{eff}) is a parameter that is closely related to optical fibre non-linearities that will affect the transmission quality of the optical fibre systems, especially in long-haul, optically amplified systems. For Gaussian-shaped fields, A_{eff} is very close to $\pi MFD^2/4$.

5.4 Cladding characteristics

The *cladding* is the outermost region of glass in the fibre cross-section. The *cladding centre* is the centre of a circle which best fits the cladding boundary. The *cladding diameter* is the diameter of the circle defining the cladding centre. The *cladding non-circularity* is the difference between the maximum and minimum radii divided by the radius of the best fit circle, expressed as a percent.

As above said, the nominal value of the cladding diameter is 125 µm for all the types of optical fibres specified in ITU-T. A tolerance is also specified and the cladding deviation from nominal shall not exceed the specified tolerance.

5.5 Cut-off wavelength

Theoretical cut-off wavelength is the shortest wavelength at which only the fundamental (LP_{01}) mode can propagate in a single-mode fibre. At wavelengths below the theoretical cut-off wavelength, several modes propagate and the fibre is no longer single-mode, but multimode. This parameter can be computed from the refractive index profile of the fibre.

In optical fibres, the change from multimode to single-mode behaviour does not occur at an isolated wavelength, but rather smoothly over a range of wavelengths. Consequently, for determining fibre performance in a telecommunication network, theoretical cut-off wavelength is less useful than the actual threshold wavelength for single-mode performance when the fibre is in operation. Thus, a more effective parameter, called cut-off wavelength, has been introduced for single-mode fibre specifications.

Cut-off wavelength is defined as the wavelength greater than which the ratio between the total power, including launched higher order modes and the fundamental mode power has decreased to less than 0.1 dB. According to this definition, the second order (LP_{11} or LP_{02} for some profiles) mode undergoes 19.3 dB more attenuation than the fundamental (LP_{01}) mode when the modes are equally excited.

Because cut-off wavelength depends on the length and bends of the fibre, as well as its strain condition, the resulting value of cut-off wavelength depends on whether the measured fibre is configured in a deployed cabled condition, or whether the fibre is short and uncabled. Consequently, there are three types of cut-off wavelength defined: cable cut-off wavelength, fibre cut-off wavelength and jumper cable cut-off wavelength.

Jumper cable cut-off wavelength λ_{cj} is measured on jumper cables in the following configuration: 2 metres, with one loop of × mm radius, often specified as 76 mm, with the rest of the jumper cable kept essentially straight.

Fibre cut-off wavelength λ_c is measured on uncabled primary-coated fibre in the following configuration: 2 metres, with one loop of 140 mm radius (or an equivalent, e.g. split mandrel) loosely constrained with the rest of the fibre kept essentially straight.

Fibre cut-off wavelength and mode field diameter can be combined to estimate a fibre's bend sensitivity. High fibre cut-off and a small mode field diameter result in a more bend resistant fibre. However all practical installation techniques and cable designs should ensure a cable cut-off wavelength below the operating wavelength.

Cable cut-off wavelength λ_{cc} is measured prior to installation on a substantially straight 22 m cable length prepared by exposing 1 m of primary-coated fibre at either end, the exposed ends each incorporating a 40 mm radius loop. Alternatively, this parameter may be measured on 22 m of primary-coated uncabled fibre loosely constrained in loops > 140 mm radius, incorporating a 40 mm radius loop at either end.

Alternative configurations may be used if the empirical results are demonstrated to be equivalent within 10 nm. For example, two 40 mm radius loops in a two-meter length of uncabled fibre meets this equivalent criterion for some fibre and cable designs.

To avoid modal noise and dispersion penalties, the cut-off wavelength λ_{cc} of the shortest cable length (including repair lengths when present) should be less than the lowest anticipated system wavelength, λ_s:

$$\lambda_{cc} < \lambda_s$$

This ensures that each individual cable section is sufficiently single mode. Any joint that is not perfect will create some higher order (LP_{11}) mode power and single-mode fibres typically support this mode for a short distance (on the order of metres, depending on the deployment conditions). A minimum distance must be specified therefore between joints, in order to give the fibre sufficient distance to attenuate the LP_{11} mode before it reaches the next joint. If the above inequality is satisfied in the shortest cable section, it will be satisfied automatically in all longer cable sections, and single-mode system operation will occur regardless of the elementary section length.

Since specification of cable cut-off wavelength, λ_{cc}, is a more direct way of ensuring single-mode cable operation, specifying this is preferred to specifying fibre cut-off wavelength (λ_c) in Recommendations ITU-T G.652 through ITU-T G.657.

5.6 Numerical aperture

The numerical aperture (*NA*) is the sine of the vertex half-angle of the largest cone of rays that can enter or leave the core of an optical fibre, multiplied by the refractive index of the medium in which the vertex of the cone is located. All values are measured at 850 nm. The value of the numerical aperture is about 5% lower than the value of the maximum theoretical numerical aperture NA_{tmax} which is derived from a refractive index measurements trace of the core and cladding:

$$NA_{tmax} = \left(n_1^2 - n_2^2\right)^{1/2}$$

in which n_1 is the maximum refractive index of the core and n_2 is the refractive index of the innermost homogeneous cladding.

5.7 Macrobending loss

For *single-mode fibres* macrobending loss varies with wavelength, bend radius and number of turns about a mandrel with a specified radius. Therefore, the limit for the macrobending loss is specified in ITU-T Recommendations for defined wavelength(s), bend radius, and number of turns.

The recommended number of turns corresponds to the approximate number of turns deployed in all splice cases of a typical repeater span. The recommended radius is equivalent to the minimum bend-radius widely accepted for long-term deployment of fibres in practical systems installations to avoid static-fatigue failure.

For *multimode fibres* the launch condition is of paramount importance for macrobending loss, in particular the presence of higher order modes which are the most sensitive being stripped off due to bending. The mode distribution encountered at a specific macrobend may depend on how many macrobends precede it. For example, the first bend might influence the launch condition at the second bend, and the second bend might influence the launch condition at the third bend, etc. Consequently, the macrobending added loss at a given bend might be different than the macrobending added loss at another bend. In particular, the first bend may have the largest influence on following bends. Consequently, the macrobending added loss produced by multiple bends should not be expressed in the units of “dB/bend” by dividing the total added loss by the number of bends, but in dB for the specified number of bends.

5.8 Fibre and protective materials

The substances of which the fibres are made should be known because care may be needed in fusion splicing fibres of different substances. However adequate splice loss and strength can be achieved when splicing different high-silica fibres.

The physical and chemical properties of the material used for the fibre primary coating and the best way of removing it (if necessary for the splicing of the fibres) should be indicated.

The primary coating is made by the layer(s) of protective coating material applied to the fibre cladding during or after the drawing process to preserve the integrity of the cladding surface and to give a minimum amount of required protection (e.g. a 250 µm protective coating).

A secondary coating made by layer(s) of coating material can be applied over one or more primary coated fibres in order to give additional required protection or to arrange fibres together in a particular structure, e.g. a 900 µm “buffer” coating, “tight jacket”, or a ribbon coating (see Chapter 2).

5.9 Proof-stress level

The fibre mechanical performance is largely dependent on the application of a proof-stress to the whole length of fibre. The optical fibre proof-test is characterized by the load applied to the fibre or the fibre elongation. The proof-stress level is the value of tensile stress or strain to which a full length of fibre is subjected for a specified short time period. This is usually done sequentially along the fibre length. The level of the proof-stress is determined as a function of the cable structure.

5.10 Refractive index profile

The refractive index profile is the refractive index across a diameter of the fibre. The refractive index profile of the fibre does not generally need to be known and therefore it is not specified in the ITU-T Recommendations.

5.11 Modal bandwidth

The different velocities of the various modes propagating in a graded-index multimode fibre can be nearly equalized by using a refractive index profile that changes smoothly from the centre to the cladding in a way that causes the end-to-end travel time of the different rays to be nearly equal, even though they travel different paths (see § 5.1.1). This is shown by the following approximated relation between the refractive index "*n*" and the radial co-ordinate "*r*":

$$n\,(r) \approx n_1\,[\,1 - \Delta\,(r/a)^g\,]$$

where:

a: core radius,

g: index profile shape parameter and

Δ: $(n_1 - n_0)/n_1$

where:

$n_1 = n_{(0)}$ and

$n_0 = n_{2(a)}$.

A more correct version is given as follows.

Following the notation of Snyder & Love, the quadratic index profile is given by:

$$n^2(r) = n_{co}^2(1 - 2\Delta R^g)$$

where:

$$\Delta = \frac{n_{co}^2 - n_{cl}^2}{2n_{co}^2} \qquad R = \frac{r}{a}$$

n_{co}: refractive index at the core centre

n_{cl}: refractive index of the cladding

a: core edge (µm)

r: radius within the core.

The profile shape parameter "*g*" has an optimal value around 2 (parabolic profile) that most nearly equalizes the group velocities of the propagating modes.

However, in practice, small perturbations from the ideal profile are generally present and this leads to differences among the group velocities of the various modes higher values than the theoretical ones (Figure 1-4). The result of this modal dispersion is a limitation of the available bandwidth.

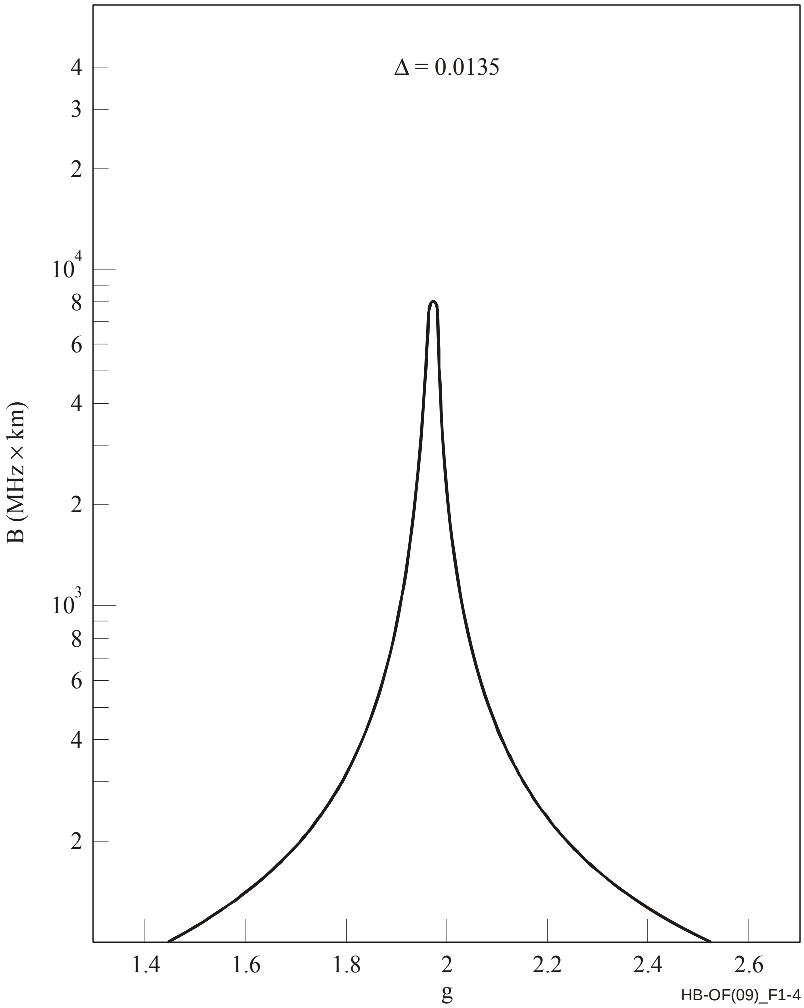
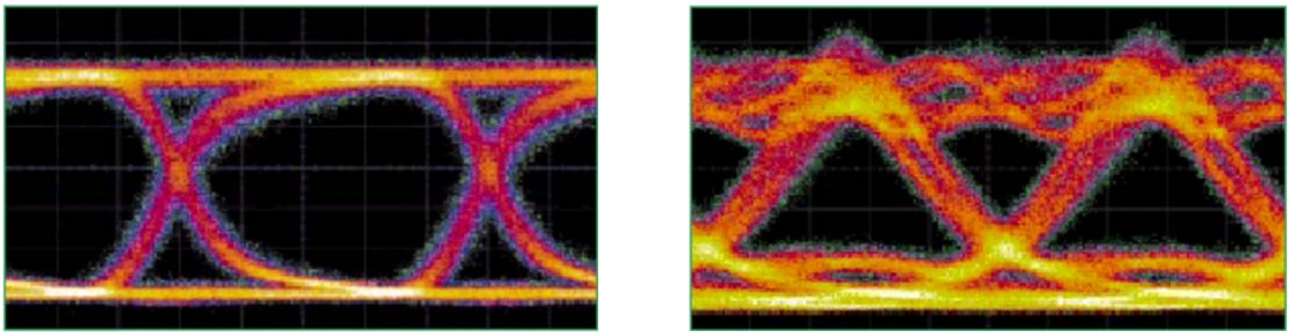


Figure 1-4 – Modal dispersion: Theoretical dependence of bandwidth on profile parameter "g"

The modal bandwidth is specified with a minimum value at one or more wavelengths in both the 850 nm and 1 300 nm regions. The optical fibre modal bandwidth shall not be lower than the recommended values. By convention, the modal bandwidth is linearly normalized to 1 km.

5.12 Chromatic dispersion

Chromatic dispersion is caused by delay differences among the group velocities of the different wavelengths composing the source spectrum. The consequence of the chromatic dispersion is a broadening of the transmitted impulses (Figure 1-5).



Pulse stream without chromatic dispersion **Pulse stream with chromatic dispersion**

Figure 1-5 – The effect of the chromatic dispersion: pulse broadening and eye closing

The chromatic dispersion is essentially due to two contributions: material dispersion and waveguide dispersion. The *material dispersion* occurs because the refractive index of silica (and hence the group velocities) changes with the optical frequency (wavelength). It is generally the dominant contribution, except in the wavelength region in which it vanishes (for silica based material this happens around 1 300 nm).

The *waveguide dispersion* depends on the dispersive properties of the waveguide itself (e.g. the core radius and the index difference). An example of the interplay between these two contributions in the total dispersion is given in Figure 1-6. From a practical point of view, a significant property is that the waveguide dispersion has opposite signs with respect to the material dispersion in the wavelength range above 1 300 nm.

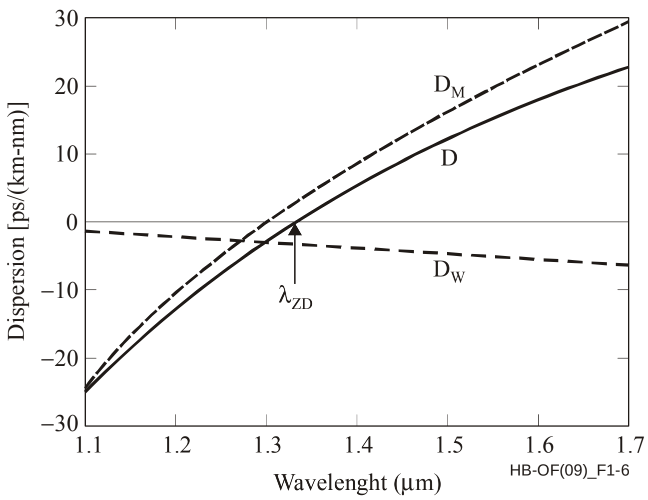


Figure 1-6 – Total dispersion D and relative contribution of material dispersion DM and waveguide dispersion DG for a conventional single-mode fibre

This property can be used to develop dispersion shifted fibres choosing suitable values for the core radius and for the index difference. The wavelength of the zero dispersion is moved from the region of 1 300 nm versus the region around 1 550 nm to coincide with the minimum loss region.

5.12.1 Chromatic dispersion definitions

Chromatic dispersion is the spreading of a light pulse in an optical fibre caused by the different group velocities of the different wavelengths composing the source spectrum. *Group delay* is the time required for a light pulse to travel a unit length of fibre. The group delay as a function of wavelength is denoted by $\tau(\lambda)$.

It is usually expressed in ps/km. *Chromatic dispersion coefficient* is the change of the group delay of a light pulse for a unit fibre length caused by a unit wavelength change. Thus, the chromatic dispersion coefficient is $D(\lambda) = d\tau / d\lambda$. It is usually expressed in ps/nm • km. *Chromatic dispersion slope* is the slope of the chromatic dispersion coefficient versus wavelength curve. The dispersion slope is defined as $S(\lambda) = dD / d\lambda$. *Zero-dispersion wavelength* is the wavelength at which the chromatic dispersion vanishes. *Zero-dispersion slope* is the chromatic dispersion slope at the zero-dispersion wavelength.

5.12.2 Chromatic dispersion coefficient

The chromatic dispersion coefficient, D, is specified within a wavelength range. There are two methods for specifying the limits, the original method, which is a box-like specification, and a newer method, in which the dispersion coefficient values are bound by a pair of curves.

In the *original specification form* the chromatic dispersion coefficient, D, is specified within a wavelength range, by stating a range of allowed absolute values of the chromatic dispersion coefficient. Particular types of fibre – the so-called non-zero dispersion-shifted single-mode fibres (e.g. those described in Recommendations ITU-T G.655 and ITU-T G.656) have an additional requirement that the chromatic dispersion coefficient shall not cross zero within the specified wavelength range. The sign of the chromatic dispersion is also specified. The form of such a specification is:

$$D_{min} \le |D(\lambda)| \le D_{max} \qquad \text{for} \quad \lambda_{min} \le \lambda \le \lambda_{max}$$

Values for D_{min}, D_{max}, λ_{min}, λ_{max} and sign are specified for each type of optical fibre.

In the *specification based on a pair of limiting curves* for each wavelength, λ, the chromatic dispersion coefficient, $D(\lambda)$, shall be restricted to a range of values associated with two limiting curves, $D_{min}(\lambda)$ and $D_{max}(\lambda)$, for one or more specified wavelength ranges defined in terms of λ_{min} and λ_{max}. The bounding curves may vary from one wavelength range to another; see for example the solid lines in Figure 1-7, representing the specification for ITU-T G.655.D fibres. The dotted lines show some individual distributions of commercial fibres.

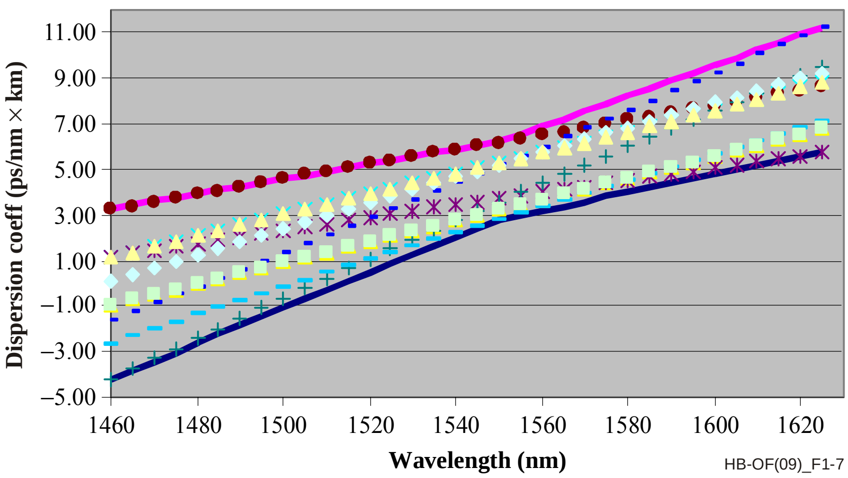


Figure 1-7 – Specification of the chromatic dispersion coefficient based on a pair of limiting curves

The requirements on chromatic dispersion follow from wavelength-division-multiplexing (WDM) system design, which must balance first order chromatic dispersion with various non-linear effects, such as four-wave mixing, cross-phase modulation, modulation instability and stimulated Brillouin scattering (see Chapter 7).

5.12.3 Longitudinal uniformity of chromatic dispersion

At a particular wavelength, the local absolute value of chromatic dispersion coefficient can vary away from the value measured on a long length. If the value decreases to a small value at a wavelength that is close to an operating wavelength in a WDM system, four-wave mixing can induce the propagation of power at other wavelengths, including other operating wavelengths. The magnitude of the four-wave mixing power is a function of the absolute value of chromatic dispersion coefficient, the chromatic dispersion slope, the operating wavelengths, the optical power, and the distance over which four-wave mixing occurs (see Chapter 7).

6 Cables attributes

Cable attributes are those recommended for cables as they are delivered.

6.1 Attenuation

The *attenuation* $A(\lambda)$ *at wavelength* λ of a fibre between two cross-sections, 1 and 2, separated by distance L is defined, as:

$$A(\lambda) = 10 \log \frac{P_1(\lambda)}{P_2(\lambda)} \quad (\text{dB})$$

where:

$P_1(\lambda)$: optical power traversing the cross-section 1, and

$P_2(\lambda)$: optical power traversing the cross-section 2 at the wavelength λ.

For a uniform fibre, it is possible to define attenuation per unit length, or an *attenuation coefficient* which is independent of the length of the fibre:

$$a(\lambda) = \frac{A(\lambda)}{L} \quad (\text{dB/unit length})$$

The attenuation coefficient depends on the wavelength of transmitted light. Figure 1-8 shows the attenuation spectrum of a conventional and of a low water peak fibre.

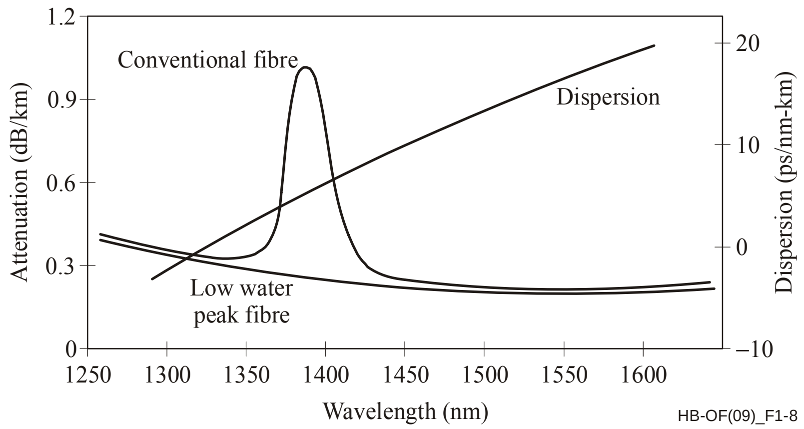


Figure 1-8 – Attenuation of an optical fibre

The conventional fibre exhibits a secondary minimum around 1 310 nm and an absolute minimum near 1 550 nm. In older fibre (e.g. ITU-T G.652.B) a strong peak of attenuation was present around 1 383 nm due to the presence of the residual water vapour in silica (OH ion). In modern low water peak fibre (e.g. ITU-T G.652.D) the concentration of the OH ion is drastically reduced and the attenuation peak around 1 383 nm has practically disappeared. The low water peak fibre allow the possibility of using a larger wavelength range in respect of older fibres, in particular for WDM system applications.

The attenuation coefficient is specified with a maximum value at one or more wavelengths in both the 1 310 nm and 1 550 nm regions. The attenuation coefficient may be calculated across a spectrum of wavelengths, based on measurements at a few (3 to 4) predictor wavelengths. This procedure is described in Recommendation ITU-T G.650.1 and an example is given in Recommendation ITU-T G.650.1.

6.2 Polarization mode dispersion

Polarization mode dispersion (PMD) is related to the differential group delay (DGD), the time difference in the group delays between two orthogonal polarized modes, which causes pulse spreading in digital systems and distortions in analogue systems.

In ideal circular symmetric fibres, the two polarization modes propagate with the same velocity. However, real fibres cannot be perfectly circular and can undergo local stresses; consequently, the propagating light is split into two polarization modes (Figure 1-9).

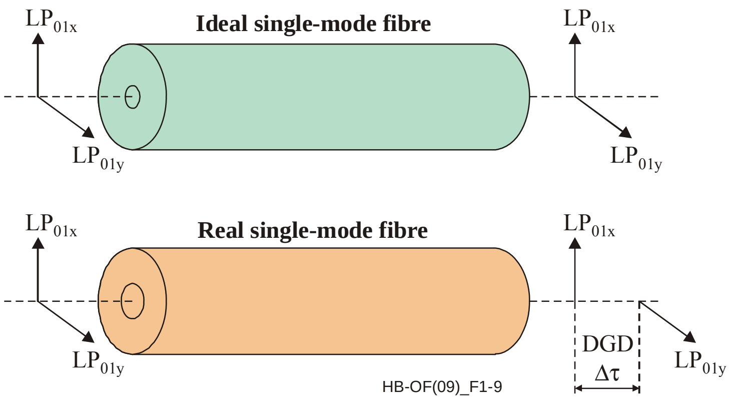


Figure 1-9 – DGD due to the two polarization modes propagating at different velocities

These two local polarization modes travel at different velocities causing a pulse spreading in digital systems (Figure 1-10). The so induced DGDs vary randomly along the fibre and in time, leading to a statistical behaviour of PMD, both in time and wavelength. At a given time, the DGD values vary randomly with wavelength. The PMD value is the average of the DGD values. While the individual values can shift from one time to another the overall distribution, hence the average is assumed to be fixed.

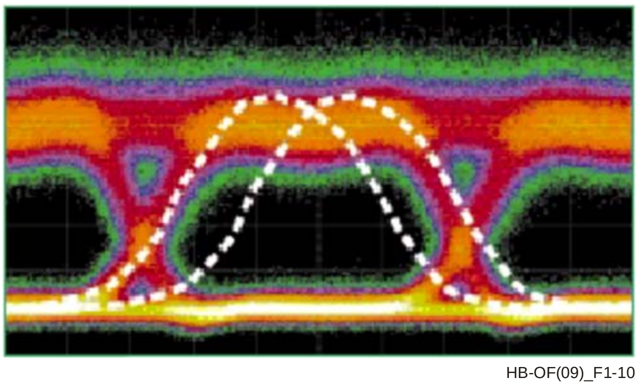


Figure 1-10 – Eye diagram of a 10 Gbit/s signal transmitted on a fibre with PMD

The *PMD coefficient* is the PMD value normalized to the measurement length. For random mode coupling, the PMD coefficient is the PMD value divided by the square root of the length ($L^{1/2}$) and is usually reported in units of ps/km$^{1/2}$.

For normal random-mode coupled fibre, the PMD distribution is ergodic, which means that the statistical distribution remains the same over time and wavelength, for a sufficiently long period or wide range.

As a consequence the mean value of all the distributions (over a long period of time, over large range of wavelengths, over a great number of concatenate sections of cable) is the same.

This also allows the assumption that measurements over a finite wavelength range are representative of other wavelength ranges or of the same wavelength range at different times over a long period of time.

For mode coupled fibres, the ergodic distribution is normally Maxwellian (see Recommendation ITU-T G.650.2) with a single parameter, which is the product of the PMD coefficient of the link and the square root of the link length (Figure 1-11).

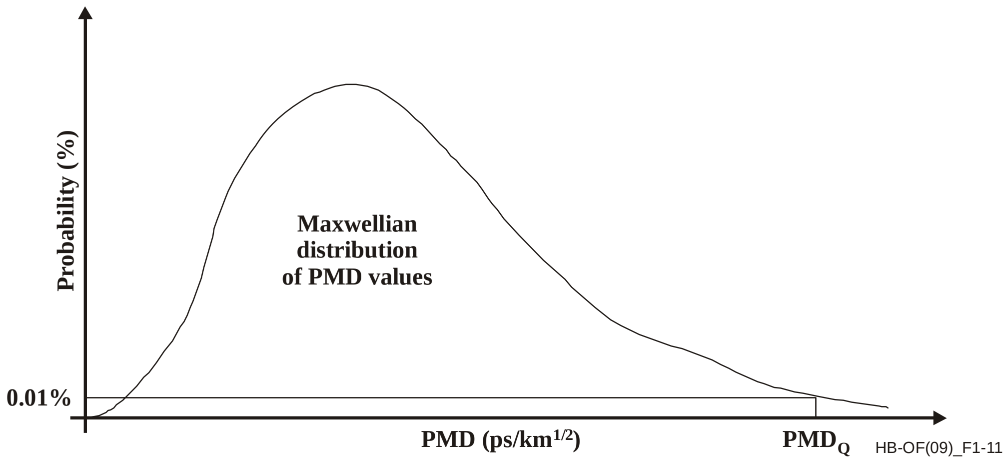


Figure 1-11 – The meaning of PMD_Q

A Maxwellian distribution may not be the case if there are point sources of elevated birefringence (relative to the rest of the fibre), such as a tight bend, or other phenomena that reduce the mode coupling, such as a continual reduced bend radius with fibre in tension.

Cabled fibre polarization mode dispersion is specified, therefore, on a statistical basis and not on an individual fibre basis. Moreover, the requirements pertain only to the aspect of the link calculated from cable information.

The manufacturer shall supply a PMD link design value, PMD_Q, that serves as a statistical upper bound for the PMD coefficient of the concatenated optical fibre cables within a defined possible link of M (generally M = 20) cable sections. The upper bound is defined in terms of a small probability level (generally 0.01%), Q, which is the probability that a concatenated PMD coefficient value exceeds PMD_Q.

A PMD_Q specification is required only where cables are employed for systems that have the specification of the max DGD.

As said before, a probability value of 0.01% not to be exceeded is specified for the PMD, partially on the basis of obtaining equivalence with the probability that DGD exceeds a bound. As a matter of fact, the probability limit to exceed the maximum DGD value is set at $6.5 \cdot 10^{-8}$ (2 sec/year), based on various system considerations including the presence of other PMD-generating components that may be in the links.

The presence of two statistical limits, one for the PMD and another one for the DGD makes possible two approaches to the design of a transmission system:

– to take as basis the PMD_Q of the cabled fibre (e.g. when an already laid cabled fibre is used) and to choose the main system characteristics (channel bit rate, modulation format, etc.) in such a way that the DGD limit is respected;

– to take as a basis the characteristics of the system to be deployed (and therefore the DGD limit to respect) and to choose a cabled fibre which has the necessary PMD_Q .

7 Link attributes

A concatenated link usually includes a number of spliced factory lengths of optical fibre cable. The characteristics of factory lengths are given in § 6. The transmission parameters for concatenated links must take into account not only the performance of the individual cable lengths but also the statistics of concatenation.

The transmission characteristics of the factory length optical fibre cables will have a certain probability distribution which often needs to be taken into account if the most economic designs for the link are to be obtained (see Chapter 7).

Link attributes are affected by factors other than optical fibre cables, by such things as splices, connectors, and installation.

7.1 Attenuation

7.1.1 Attenuation of a link

The attenuation *A* of a link is given by:

$$A = \alpha L + \alpha_S x + \alpha_C y$$

where:

α: typical attenuation coefficient of the fibre cables in a link

α_S: mean splice loss

x: number of splices in a link

α_C: mean loss of line connectors

y: number of line connectors in a link (if provided)

L: link length.

A suitable margin should be allocated for future modifications of cable configurations (additional splices, extra cable lengths, ageing effects, temperature variations, etc.). The above equation does not include the signal loss of equipment connectors. The attenuation budget used in designing an actual system should account also for the statistical variations in these parameters.

7.1.2 Wavelength dependence of attenuation

The attenuation coefficient of an installed optical fibre cable is wavelength-dependent (see § 6).

Table 1-2 contains the assumed minimum and maximum attenuation coefficient values for some wavelengths used in Coarse-WDM (CWDM) systems (see Chapter 6). They are also depicted graphically in Figure 1-12 and in Figure 1-13. These values were obtained by combining measurements of the attenuation coefficient of underground and buried optical fibre cables at 1 550 nm and 1 625 nm with full spectrum measurements of uncabled fibres and with the limits specified in Recommendation ITU-T G.652 for the A-B-C-D types (see § 9.2.1).

Table 1-2 – Assumed attenuation coefficient values

Nominal central wavelength (nm)	ITU-T G.652.A&B cable		ITU-T G.652.C&D cable	
	Minimum attenuation coefficient (dB/km)	Maximum attenuation coefficient (dB/km)	Minimum attenuation coefficient (dB/km)	Maximum attenuation coefficient (dB/km)
1 271	0.392	0.473	0.385	0.470
1 291	0.370	0.447	0.365	0.441
1 311	0.348	0.423	0.352	0.423
1 331	0.331	0.425	0.340	0.411
1 351	0.320	0.476	0.329	0.399
1 371			0.316	0.386
1 391			0.301	0.372
1 411			0.285	0.357
1 431	0.263	0.438	0.269	0.341
1 451	0.250	0.368	0.254	0.326
1 471	0.238	0.327	0.240	0.312
1 491	0.229	0.303	0.229	0.300
1 511	0.221	0.290	0.220	0.290
1 531	0.215	0.283	0.213	0.283
1 551	0.211	0.278	0.209	0.277
1 571	0.208	0.276	0.208	0.273
1 591	0.208	0.278	0.208	0.275
1 611	0.208	0.289	0.212	0.283

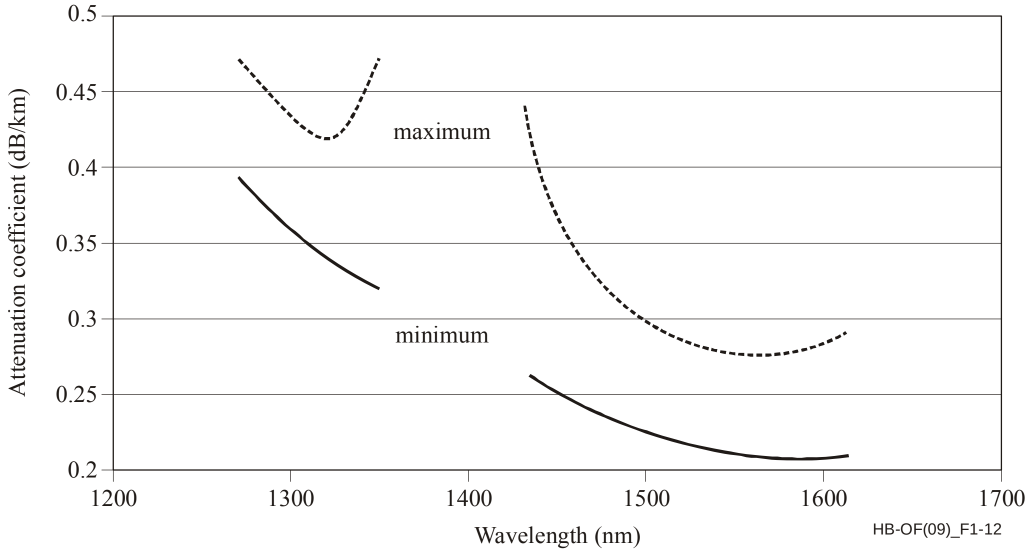


Figure 1-12 – Assumed attenuation coefficient values for G.652.A&B cable

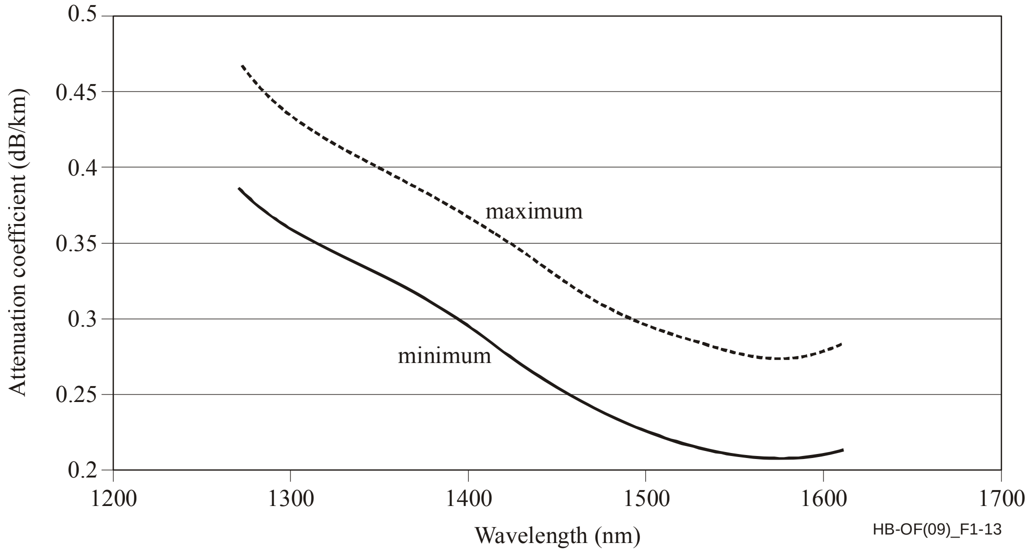


Figure 1-13 – Assumed attenuation coefficient values for ITU-T G.652.C&D cable

These attenuation coefficient values are based on the spectral results of a limited number of fibres, together with an assumption of 0.275 dB/km at 1 550 nm for the maximum attenuation coefficients and 0.210 dB/km at 1 550 nm for the minimum attenuation coefficients. Actual installed cable attenuation is statistical in nature, and these values should not be taken as specification limits on individual fibres, cable sections, or splices.

7.2 Chromatic dispersion

7.2.1 Chromatic dispersion of a link

The chromatic dispersion of a link (in ps/nm) can be calculated from the chromatic dispersion coefficients of the factory lengths, assuming a linear dependence on length, and with due regard for the signs of the coefficients.

7.2.2 Wavelength dependence of chromatic dispersion

The chromatic dispersion coefficient is wavelength dependent. Table 1-3 contains the assumed maximum chromatic dispersion coefficient values at the central wavelength (plus the maximum allowed central wavelength deviation) for some channels used in CWDM systems.

Table 1-3 – Assumed chromatic dispersion coefficient values for ITU-T G.652, ITU-T G.653 and ITU-T G.655 fibres

Channel wavelength (nm)	Maximum dispersion coefficient (ps / nm / km)					
	ITU-T G.652 fibres		ITU-T G.653 fibres		ITU-T G.655 fibres	
	Negative	Positive	Negative	Positive	Negative	Positive
1 291	–3.85	–	–	–	–	–
1 311	–1.85	1.60	–	–	–	–
1 331	–	3.34	–	–	–	–
1 351	–	5.02	–	–	–	–
1 371	–	6.62	–	–	–	–
1 391	–	7.97	–	–	–	–
1 411	–	9.14	–	–	–	–
1 431	–	10.31	–	–	–	–
1 451	–	11.49	–	–	–	–
1 471	–	12.68	–8.64	–	–2.99	4.78
1 491	–	13.86	–6.94	–	–1.45	5.79
1 511	–	15.06	–5.24	0.82	–	6.80
1 531	–	16.25	–3.54	1.75	–	7.82
1 551	–	17.46	–2.59	2.68	–	8.85
1 571	–	18.66	–1.66	3.71	–	9.90
1 591	–	19.87	–0.72	5.41	–	10.96
1 611	–	21.09	–	7.11	–	12.01

7.3 Differential group delay

For a link with a specific PMD coefficient, the system impairment at a specific time and wavelength depends on the DGD at that time and wavelength.

7.4 Non-linear coefficient

The effect of chromatic dispersion is interactive with the non-linear coefficient, n_2 / A_{eff}, as regards system impairments induced by non-linear optical effects. Typical values vary with the implementation (see Chapter 7).

8 Test methods of single-mode optical fibres and cables

The specification of the test methods for the fibres / cables attributes is very important, because it is not possible to specify the values of the various attributes that characterize an optical fibre without having previously specified the definitions of the attributes and the test methods for measuring their values.

Test methods are classified in two categories: Reference Test Methods (RTM) and Alternative Test Methods (ATM).

A *Reference Test Method* is a test method in which a characteristic of a specified class of optical fibres or optical fibre cables is measured strictly according to the definition of this characteristic and which gives results which are accurate, reproducible and relatable to practical use.

An *Alternative Test Method* is a test method in which a given characteristic of a specified class of optical fibres or optical fibre cables is measured in a manner consistent with the definition of this characteristic and gives results which are reproducible and relatable to the reference test method and to practical use.

Both Reference Test Method and Alternative Test Methods are usually specified in Recommendation ITU-T G.650.1, and in Recommendation ITU-T G.650.2 for some parameters, and it is the intention that both the RTM and the ATMs may be suitable for normal product acceptance purposes. However, when using an ATM, should any discrepancy arise, it is recommended that the RTM be employed as the technique for providing the definitive measurement results.

Recommendations ITU-T G.650.1 and ITU-T G.650.2 contain definition and test methods suitable mainly for factory measurements, while Recommendation ITU-T G.650.3 outlines the tests normally done on installed optical cable sections.

Definitions and test methods contained in these three Recommendations are generally not appropriate for multimode fibre, such as that described in Recommendation ITU-T G.651.1. Here reference is made to appropriate IEC standards. Some of the test methods, when so indicated, may also be used to characterize discrete optical components, such as those described in Recommendation ITU-T G.671.

A description of the test methods is outside the scope of this Handbook; however, some general information is given in the following of this clause.

Definitions and test methods suitable mainly for factory measurements of the linear, deterministic attributes of the single-mode optical fibres and cables described in Recommendations ITU-T G.652 through ITU-TG.657 are specified in Recommendation ITU-T G.650.1.

Recommendation ITU-T G.650.1 contains RTM and ATMs for the following parameters of the optical fibres: mode field diameter, cladding diameter, core concentricity error, cladding non-circularity, cut-off wavelength, attenuation, chromatic dispersion and proof-testing.

A schematic diagram of the test apparatus is given for each test method together with the description of the main conditions for carrying out the tests. The measurement procedure and the presentation of the results are also described.

Definitions and test methods suitable mainly for factory measurements of the statistical and non-linear attributes of the single-mode optical fibres and cables described in Recommendations ITU-T G.652 through ITU-T G.657 are specified in Recommendation ITU-T G.650.2.

Recommendation ITU-T G.650.2 contains RTM and ATMs for the PMD. Test methods for non-linear attributes are still under study. However, Appendix II of Rec. ITU-T G.650.2 gives some information on effective area (A_{eff}), non-linear coefficient (n_2/A_{eff}) and stimulated brillouin scattering.

A schematic diagram of the test apparatus is given for each test method together with the description of the main conditions for carrying out the tests. The measurement procedure and the presentation of the results are also described.

The tests normally done on installed optical fibre cable links are specified in Recommendation ITU-T G.650.3, which includes a collection of references to the main measurement methods and gives an indication of which are most suitable for installed cable sections, depending on the required inspection level needed.

Recommendation ITU-T G.650.3 contains test methods that are suited particularly to the characterization of single-mode optical fibre cable links. The methods are not intended for application to links that contain optical network elements, such as amplifiers, dispersion compensators, or passive splitters/combiners.

Recommendation ITU-T G.650.3 uses a tiered approach. The first level indicates measurements that may normally be done as part of installation. The second level indicates measurements that are normally done on exception, such as to satisfy Service Level Agreements or to verify attributes of older links that may be used at high bit rates.

Test methods for characteristics of optical fibre cable links specified in Recommendation ITU-T G.650.3 include attenuation, splice loss, fibre uniformity, PMD and chromatic dispersion.

9 Optical fibre types specified by ITU-T

9.1 Multimode optical fibres

9.1.1 A 50/125 µm multimode graded index optical fibre cable

The characteristics of a multimode graded index optical fibre cable were specified in Recommendation ITU-T G.651, originally published in 1984 and deleted in 2008. Recommendation ITU-T G.651 covered the geometrical and transmissive properties of multimode fibres having a 50 µm nominal core diameter and a 125 µm nominal cladding diameter.

That Recommendation was developed during the infancy of optical fibre solutions for publicly switched networks. At that time (pre-1984), these multimode fibres were considered as the only practical solution for transmission distances in the tens of kilometres and bit rates of up to 40 Mbit/s. Single-mode fibres, which became available shortly after the publication of ITU-T G.651, have almost completely replaced multimode fibres in the publicly switched networks.

Today, multimode fibres continue to be widely used in premises cabling applications such as Ethernet in lengths from 300 to 2 000 m, depending on bit rate. With a change in the applications, the multimode fibre definitions, requirements, and measurements evolved away from the original ITU-T G.651 and were moved to the modern ITU equivalent, Recommendation ITU-T G.651.1.

Recommendation ITU-T G.651.1, *Characteristics of a 50/125 µm multimode graded index optical fibre cable for the optical access network*, provides specifications for a 50/125 µm multimode graded index optical fibre cable suitable to be used in the 850 nm region or in the 1 300 nm region or alternatively may be used in both wavelength regions simultaneously. This Recommendation contains the recommended values for both the fibre and cable attributes.

The applications of this fibre are in specific environments of the optical access network. These environments are multi-tenant building sub-networks in which broadband services have to be delivered to individual apartments. This multimode fibre supports the cost-effective use of 1 Gbit/s Ethernet systems over link lengths up to 550 m, usually based upon the use of 850 nm transceivers.

Quite a large percentage of all customers in the world are living in these buildings. Due to the high connection density and the short distribution cable lengths, cost-effective high capacity optical networks can be designed and installed by making use of 50/125 µm graded-index multimode fibres.

The effective use of this network type has been shown by its extended and experienced use for datacom systems in enterprise buildings with system bit-rates ranging from 10 Mbit/s up to 10 Gbit/s. This use is supported by a large series of IEEE system standards and IEC fibre and cable standards, which are used as the main references in Recommendation ITU-T G.651.1.

9.2 Single-mode optical fibres

9.2.1 The ITU-T first single-mode optical fibre and cable

The first single-mode optical fibre was specified in Recommendation ITU-T G.652, *Characteristics of a single-mode optical fibre and cable*, and for this reason, the ITU-T G.652 fibres are often called, "standard single-mode fibres". These fibres were the first to be widely deployed in the public network and they represent a large majority of fibres that have been installed. The agreements that led to the first publication of Recommendation ITU-T G.652 formed a key foundation to the modern optical networks that are the basis of all modern telecommunications.

Recommendation ITU-T G.652 describes the geometrical, mechanical, and transmission attributes of a single-mode optical fibre and cable which has zero-dispersion wavelength around 1 310 nm. This fibre was originally optimized for use in the 1 310 nm wavelength region, but can also be used in the 1 550 nm region. Recommendation ITU-T G.652 was first created in 1984; several revisions have been intended to maintain the continuing commercial success of this fibre in the evolving world of high-performance optical transmission systems.

Over the years, parameters have been added to Recommendation ITU-T G.652 and the requirements have been made more stringent to meet the changes in market and technological demands, and in manufacturing capability. An example is the addition of a requirement for attenuation at 1 550 nm in 1988. In that year, the chromatic dispersion parameters and requirements were also defined.

Some other examples include the addition of low water peak fibres (LWP) with negligible sensitivity to hydrogen exposure and the addition of requirements for PMD. However at the advent of these new capabilities and perceived needs, there was a consensus that some applications would need these attributes for advanced technologies, bit rates, and transmission distances; however, there were also applications that would not need these capabilities. Therefore, some options had to be maintained.

For this reason, it was agreed to create different categories of ITU-T G.652 fibres. At the present time there are four categories, A, B, C, and D, which are distinguished on the PMD_Q link design value specification and whether the fibre is LWP or not, i.e. water peak is specified (LWP) or it is not specified (WPNS), as shown in Table 1-4.

Table 1-4 – ITU-T G.652 fibre categories

Category	Maximum PMD_Q ($ps/km^{1/2}$)	Water Peak
A	0.5	WPNS
B	0.2	WPNS
C	0.5	LWP
D	0.2	LWP

A non-normative Appendix in Rec. ITU-T G.652 gives representative values of attenuation and chromatic dispersion, which can be taken as the basis for the design of concatenated optical fibre links in accordance with the guidelines outlined in Supplement 39 to the ITU-T G-series Recommendations. The same Appendix gives an indication of the maximum link length at various channel bit rates allowed by different values of Polarization Mode Dispersion (PMD_Q).

Category A of ITU-T G.657 (see § 9.2.6) is aligned with all the ITU-T G.652.D values, but has more stringent bend loss requirements.

9.2.2 A dispersion-shifted single-mode optical fibre and cable

The characteristics of a dispersion-shifted single-mode optical fibre and cable are described in Recommendation ITU-T G.653. This fibre has a nominal zero-dispersion wavelength close to 1 550 nm and a dispersion coefficient that is monotonically increasing with wavelength. This fibre was initially developed for use in single-channel high bit rate and long distance transmission in the 1 550 nm region (where the attenuation coefficient is smallest) by shifting the zero-dispersion wavelength of the ITU-T G.652 fibre to around 1 550 nm. This fibre is optimized for use in the 1 550 nm region, but may also be used at around 1 310 nm subject to the constraints outlined in the Recommendation. Some provisions are made to support transmission at higher wavelengths up to 1 625 nm and lower wavelengths down to 1 460 nm.

This was the second Recommendation for single-mode fibre and cable, and it was first created in 1988. The current version contains two categories, A and B, that are distinguished on the PMD_Q link design value specification, the description of the chromatic dispersion coefficient, the geometrical parameters and the macrobending loss specifications.

ITU-T G.653.A fibre is the base category for a dispersion-shifted single-mode optical fibre and cable, and retains the original "box-type" specification for the dispersion coefficient. The zero-dispersion wavelength is within the operating wavelength range from 1 525 nm to 1 575 nm, so that it performs very well for single-channel systems (e.g. ITU-T G.957, ITU-T G.691 and ITU-T G.693 systems), but non-linear effects are deleterious in dense wavelength division multiplexing (DWDM) systems with an equal channel spacing in the 1 550 nm wavelength region. However, this category is also suitable for multichannel systems (e.g. ITU-T G.692 and ITU-T G.977 systems) with unequal channel spacing in the 1 550 nm wavelength region (for more detail on unequal channel spacing see Recommendation ITU-T G.692). The ITU-T G.653.A fibre is used for multichannel systems with equal channel spacing within the operating wavelength range from 1 565 nm to 1 625 nm where the chromatic dispersion has non-zero values (e.g. ITU-T G.698.1 and ITU-T G.698.2 systems).

Many submarine applications can utilize this category. For some submarine applications, the full optimization can lead to choosing different limits than are found here. One example could be to allow cable cut-off wavelength to values as high as 1 500 nm.

ITU-T G.653.B fibre attributes are similar to those of ITU-T G.653.A fibre, but the more stringent PMD requirement allows STM-64 systems to lengths longer than 400 km and ITU-T G.959.1 NRZ 40G applications. This category defines the chromatic dispersion coefficient requirements as a pair of bounding curves vs. wavelength for wavelengths from 1 460 nm to 1 625 nm. This category may support coarse wavelength division multiplexing applications which do not have significant non-linear impairments.

9.2.3 A cut-off shifted single-mode optical fibre and cable

The characteristics of a cut-off shifted single-mode optical fibre and cable are specified in Recommendation ITU-T G.654, which describes the geometrical, mechanical and transmission attributes of a single mode optical fibre and cable which has its zero-dispersion wavelength around 1 300 nm and which is loss-minimized and cut-off wavelength shifted to the 1 550 nm wavelength region.

At first, this Recommendation was created as “Characteristics of a 1 550 nm wavelength loss-minimized single-mode optical fibre cable” in 1988, for the purpose of submarine cable system use. In 1997, the name of this Recommendation was changed to “Characteristics of a cut-off shifted single-mode optical fibre and cable”, in order to make clearer the features of this fibre.

The main features of the fibre described by Recommendation ITU-T G.654 are its longer cut-off wavelength and lower attenuation coefficient at 1 550 nm compared to other single-mode optical fibres. The longer cut-off wavelength can allow lower macrobending loss fibre design; hence, it is advantageous to submarine cables, which require lower attenuation. The lowest values of attenuation coefficient depend on fabrication process, fibre composition and design, and cable design. Values of 0.15 to 0.19 dB/km in the 1 550 nm region have been achieved. These features are suitable for long-haul transmission in the 1 530-1 625 nm region.

The current version of this Recommendation contains three categories: A, B and C.

Category A is the base category that, considering its very low attenuation, can be used for long-distance digital transmission applications such as long-haul terrestrial line systems and submarine cable systems using optical amplifiers. This category is suitable for the systems specified in Recommendations ITU-T G.691, ITU-T G.692, ITU-T G.957 and ITU-T G.977 in the 1 550 nm wavelength region.

Category B has a larger upper limit of MFD than Category A and reduced PMD requirement. This category is suitable for the systems described in the above-quoted Recommendations and for the ITU-T G.959.1 long-haul applications in the 1 550 nm wavelength region. This category B can also be applied to longer distance and larger capacity WDM repeaterless submarine systems with remotely pumped optical amplifier, as discussed in Recommendation ITU-T G.973 and submarine systems with optical amplifiers, as discussed in Recommendation ITU-T G.977.

Category C is similar to Category A, but the reduced PMD requirement also supports the highest bit-rate and long-haul applications among those described in ITU-T G.959.1.

9.2.4 A non-zero dispersion-shifted single-mode optical fibre and cable

The characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable are described in Recommendation ITU-T G.655. This Recommendation specifies the geometrical, mechanical, and transmission attributes of a single-mode optical fibre which has the absolute value of the chromatic dispersion coefficient greater than some non-zero value throughout the wavelength range from 1 530 nm to 1 565 nm. This dispersion reduces the growth of non-linear effects which are particularly deleterious in dense wavelength division multiplexing systems.

This Recommendation was first created in 1996 and was initially developed following the creation of the dispersion-shifted fibres (see Recommendation ITU-T G.653) and the advent of dense wavelength division multiplexing (DWDM) in long distance, optically amplified and dispersion compensated networks. As indicated above, allowance for zero or low values of dispersion in the operating window of these systems allows the growth of non-linear effects, such as four-wave mixing. For this reason, the zero-dispersion wavelength had to be moved out of the operating window.

In the initial version of this Recommendation, the dispersion requirements were expressed as a "box specification", in which the absolute value of the dispersion coefficient had to be restricted to a range starting with a positive value and bound by another larger value over a wavelength range believed to encompass the operating window of the DWDM systems. Many possible technical tradeoffs and developments were anticipated, so the initial ranges were allowed to be large enough to allow evolution. Examples of such tradeoffs include:

i) degree of dispersion compensation, amplification, and consequent optical noise;

ii) DWDM channel density and range;

iii) channel power levels;

iv) the possibility of Raman amplification;

v) the possibility of dispersion management.

Despite the looseness of the primary chromatic dispersion coefficient requirement and the mix of system strategies, large volumes of ITU-T G.655 fibres were deployed in the longer distance networks that emerged in the late 1990's and early 2000's. These fibres had, depending on the fibre manufacturer, differently detailed, but more restrictive, limits on the chromatic dispersion coefficient, depending on the relevant technical strategy of their customers. As an example, in 2000, the second edition adapted a new Table B for which the maximum absolute value of dispersion was allowed to reach 10 ps/(nm.km) over the 1 530-1 565 nm band (vs. 6 ps/(nm.km) in Table A), introducing the medium-dispersion type ITU-T G.655 fibre.

In 2005, following the bursting of the "telecommunications bubble", two main aspects emerged, which changed the standardization strategy for ITU-T G.655 fibres:

i) the customers and network providers demanded more specific values for the chromatic dispersion coefficient vs. wavelength. The "box specification" was not sufficiently useful;

ii) two main varieties of these fibres were seen in the market: one with lower dispersion coefficient and another with medium dispersion coefficient, but much lower than ITU-T G.652 fibres.

To address these aspects, surveys of all the participating fibre manufacturers were conducted. The results of these surveys were used to define the chromatic dispersion coefficient limits vs. wavelength for two new categories that are defined in Tables D and E of Recommendation ITU-T G.655, which have been included in the present version of Recommendation ITU-T G.655. They distinguish the two main families of ITU-T G.655 fibres that are supported by multiple vendors. Both of these categories limit the chromatic dispersion coefficient by a pair of bounding curves vs. wavelength for the range of 1 460 nm to 1 625 nm. Although the dispersion can change sign at wavelengths less than 1 530 nm, the inclusion of these lower wavelengths is intended to provide information to support CWDM applications which do not have significant non-linear impairments, at channels from 1 471 nm and higher.

Tables A, B, and C have not been changed. Tables A and B are not included in the 2006 version of this Recommendation, but are in the 2003 edition. Table C, based on a box specification that allows positive and negative dispersion coefficients for possible use in dispersion managed systems, was retained.

9.2.5 A fibre and cable with non-zero dispersion for wideband optical transport

The characteristics of a fibre and cable with non-zero dispersion for wideband optical transport are specified in Recommendation ITU-T G.656. The specification is for a single-mode fibre and cable with chromatic dispersion that is greater than some non-zero value throughout the wavelength range of 1 460-1 625 nm.

In the current development of lightwave systems, one direction of evolution is towards increasing the capacity transmitted on an optical fibre. One of the solutions is by deploying the optical channels not only in the C-band, but also in the short wavelength S-band (1460-1530 nm) and in the long wavelength L-band (1 565-1 625 nm). This type of fibre can be utilized for both CWDM and DWDM systems throughout the wide wavelength region between 1 460 and 1 625 nm.

Recommendation ITU-T G.656 describes the geometrical, mechanical, and transmission attributes of the fibre and cable. The chromatic dispersion of the fibre reduces the growth of non-linear effects which are particularly deleterious in DWDM systems over a wider wavelength range than the fibre described in Recommendation ITU-T G.655.

Recommendation ITU-T G.656 has a single category of the fibre and cable. The category limits the chromatic dispersion coefficient by a pair of bounding curves vs. wavelength for the range of 1 460 nm to 1 625 nm, which provides information to support CWDM applications such as those described in Recommendation ITU-T G.695 and DWDM applications such as those described in Recommendations ITU-T G.692, ITU-T G.696.1, ITU-T G.698.1, ITU-T G.698.2 and ITU-T G.959.1. The PMD requirement of the fibre and cable allows operation of STM-64 systems to lengths of up to 2 000 km, depending on other system elements.

9.2.6 A bending loss insensitive single mode optical fibre and cable for the access network

The characteristics of a bending loss insensitive single mode optical fibre and cable for the access network are specified in Recommendation ITU-T G.657.

Worldwide, technologies for broadband access networks are advancing rapidly. Among these, the technology applying single mode fibre provides for a high-capacity transmission medium that can answer the growing demand for broadband services.

The experience with the installation and operation of single mode fibre and cable based networks is extensive and ITU-T G.652 fibre characteristics have been adapted to this experience. Nevertheless, the specific use in an optical access network puts different demands on the fibre and cable. Due to the dense distribution and drop-cable network, the limited space and the many manipulations in this part of the network, fibre and cable requirements may be optimized for lower bending sensitivity compared to that of cabled fibre used in a general transport network.

It is the aim of Recommendation ITU-T G.657 to support this bending optimization by recommending different attribute values and by recommending other classes of single mode fibre types.

Recommendation ITU-T G.657 describes two categories (A and B) of single-mode optical fibre cable that are suitable for use in the access networks, including inside buildings at the end of these networks.

Category A fibres are suitable to be used in the O, E, S, C and L-band, i.e. throughout the 1 260 to 1 625 nm range (See Chapter 6). Fibres and requirements in this category are a subset of ITU-T G.652.D fibres and have the same transmission and interconnection properties. The main improvements are lower bending loss and tighter dimensional specifications, both for improved connectivity.

Category B fibres are suitable for transmission at 1 310, 1 550 and 1 625 nm for restricted distances that are associated with in-building transport of signals. These fibres may have different splicing and connection properties than ITU-T G.652 fibres, but can be used at very low bend radii because of further improved bending loss.

The improved macrobending behaviour of ITU-T G.657 fibres for use in broadband optical access networks, supports small volume fibre management systems and low radius mounting in telecom offices and customer premises in apartment buildings and single dwelling houses.

CHAPTER 2

GENERAL CHARACTERISTICS OF OPTICAL CABLES

Introduction

This Chapter is devoted to the description of the general characteristics of the optical cables. The basic purpose of optical fibre cable construction is to keep transmission and mechanical strength properties of the optical fibres stable in the course of the cable manufacturing, installation, and operation process.

The aim of clause 1 is to outline the external factors impacting optical cables. Clause 2 deals with the mechanical and environmental effects that the external factors can have on the optical fibres contained in a cable. In clause 3 a description is given of the general structure of the optical cables, while clause 4 describes the structure of the optical cables for specific applications.

The dimensional and transmission characteristics of the optical fibres put in the optical cables used for telecommunication should be in accordance with Recommendations ITU-T G.651.1, ITU-T G.652, ITU-T G.653, ITU-T G.654, ITU-T G.655, ITU-T G.656 and ITU-T G.657, which are described in Chapter 1.

1 External factors impacting optical cables

Optical cables are installed in various environments (aerial, buried, duct, tunnel, underwater, etc.) and are therefore exposed to different environmental conditions. The range of environmental conditions must be considered with great care in order to determine the cable construction that will continuously maintain the desired characteristics. The external factors relating to the various environmental conditions can be divided into two categories:

i) natural external factors (temperature, wind, water, earthquakes, etc.), which are listed in Table 2-1;

ii) man-made factors (smoke, air pollution, fire, etc.), which are listed in Table 2-2.

For both categories of factors the tables show the *effects on the optical cables* laid in different environments.

Table 2-1 – External factors related to environmental conditions – Natural external factors

Natural external factors		External cables					Internal cables	
		Trunk, junction and distribution					Customer premises	Central office
		Aerial	Buried	Duct	Tunnel	Underwater	Building	
Temperature change	B	Cable sheath contraction with core thrusting out					–	–
	A	Increase of optical loss due to high and low temperature						
Very low temperature	B	Embrittlement of cable sheath under low temperature			–	–	–	–
	A	Crushing due to ice formation						
Wind	A	Excess strain due to wind pressure	–	–	–	–	–	–
	B	Periodical excess strain due to cable dancing	–	–	–	–	–	–
Salt water	B	Corrosion of metal catenary	Corrosion of armour	–	–	Corrosion of armour	–	–
Rain and hot spring	B	Corrosion of metal catenary	Corrosion due to hot springs		–	–	–	–
Snow and ice	A	Sheath degradation, crushing and excess strain due to snow and ice	–	–	–	Sheath degradation and crushing due to ice	–	–
Water and moisture	A	Increase in optical loss due to water penetration. Decrease of strength of fibre					–	–
Sunshine	B	Degradation of sheath by UV rays	–	–	–	–	–	–
Lightning	B	Crushing damage due to lightning and hazards to personnel			–	–	–	–
Earthquakes and slip, ground subsidence and falling stones	B	Sheath degradation and impulsive excess strain due to falling stones	Cutting of cables due to ground movements		–	–	–	–
Condition of soil	B	–	Corrosion of armour	–	–	–	–	–
Rodents, birds and insects	B	Sheath damage due to birds, rodents and insects		–	–	–	–	–
Hydrogen	A	Increase in optical loss due to hydrogen					–	–
Water flow	B	–	–	–	–	Cable damage	–	–
Mould growth	B	–	–	Sheath damage	–	–	Sheath damage	–

A. Particular consideration for optical fibre cables.
B. Intrinsic consideration for outside plant.

Table 2-2 – External factors related to environmental conditions – Man-made factors

Man-made factors		External cables					Internal cables	
		Trunk, junction and distribution					Customer premises	Central office
		Aerial	Buried	Duct	Tunnel	Underwater	Building	
Factory smoke and air pollution	B	Corrosion of metal	–	–	–	–	–	–
	B	Chemical attack on sheath	–	–	–	–	–	–
Traffic (cars, trucks)	B	–	Damage to cable sheath and joints due to creep. Transient optical loss due to vibration of fibres		–	–	–	–
Induced voltage (AC traction systems, power lines)	B	Damage to cable and hazards to personnel			–	–	–	–
DC current	B	–	Electrolytic corrosion	–	–	–	–	–
Petroleum gas leakage	B	–	Sheath degradation due to chemical attack	–	–	–	–	–
Fire	B	Sheath (and cable core) burning	–	–	Sheath (and cable core) burning	–	Sheath (and cable core) burning	
Nuclear radiation	B	Under consideration					–	–
Hydrogen	A	Increase in optical loss due to hydrogen					–	–
Installation practices	B	Cutting or breaking of the cables						
	A/B	B – Strain due pulling-in for installation			A - Strain due pulling-in for installation		–	–
	A/B	B – Bending at pulley for installation	B – Bending and squeezing due to burying machine		A – Bending at pulley for installation			
					A – Bending at curve in duct	–	–	–

A. Particular consideration for optical fibre cables.

B. Intrinsic consideration for outside plant.

2 Mechanical and environmental effects on the optical fibres

As shown in Table 2-3, the external factors have a direct impact also on the performance of the optical fibres contained in a cable.

The main objective in the design of an optical cable is to ensure that the protection technique used will maintain the good properties of the optical fibres, under all the kinds of conditions to which the cables may be exposed during manufacture, installation, and operation.

This clause lists the main mechanical and environmental effects on the optical fibres contained in a cable, giving the cause, the effect and the constructional measures to be taken to counteract these effects.

2.1 Residual fibre strain

2.1.1 Causes

Residual fibre strain may be caused by tension, torsion and bending occurring in connection with cable manufacture, installation and operational environment.

2.1.2 Effects

Residual fibre strain may shorten the lifetime of the fibre due to increased crack growth in the presence of environmental contaminants. Also, the level of residual strain will affect the level of dynamic strain which the fibre can withstand before breaking.

2.1.3 Constructional considerations

Optical fibres differ mechanically from copper and steel wires, mainly as regards elastic properties and failure mechanisms. Glass used for optical fibre behaves elastically up to a few percent and then it fails in brittle tension. The strength of fibres is mainly governed by the size of flaws, which are always present, under the influence of stress which causes the glass fibre to weaken. This weakening is accelerated if the stress is combined with moisture. When designing optical fibre cable, it is important to know the minimum strength of the fibres. For this reason, optical fibres are proof-tested to a certain stress level during manufacture. Studies of flaw growth mechanisms and accelerated aging experiments have shown that in order to achieve fibre lifetime of 20-40 years, the residual fibre stresses should not exceed 20-30% of the proof-test stress. In special circumstances where the cable is to be used in a high moisture environment or for aerial cable applications taking into account large thermal changes and strong winds, it should be noted that a larger proof-test strain may be necessary or the installation must compensate for the conditions. For example, a heavier support strand may be used for aerial applications to limit strains.

A good cable design will limit the long-term strain to the safe levels above to prevent the growth of surface flaws, which could eventually lead to fracture of the fibres. The proof-test strain may therefore be specified by the permissible strain and the required life time. Usually the fibre is proof-tested with a load applied to the fibre. The value of the load is specified for each type of fibre in the ITU-T G.65 x-series of Recommendations. The long term strain level is a small fraction of the maximum proof-test. When a whole cable structure is subject to residual longitudinal tensile strain, some strain may remain in the optical fibres of the cable.

2.2 Impulsive fibre strain

2.2.1 Causes

Impulsive fibre strains may be imposed by impact and snatch during installation and the operational life of the cable.

Table 2-3 – Relationship between external factors to be considered for optical fibre cables and mechanical / environmental effects on optical fibres

External factors			Mechanical and environmental effects on optical cables							
			Residual fibre strain	Impulsive fibre strain	Fibre macro-bending	Fibre micro-bending	Physical or chemical reaction			
							Water and moisture	Hydrogen	Lightning	Nuclear radiation
Natural factors	Temperature	High and low	–	–	–	Loss increase	–	–	–	–
		Ice formation	Strength degradation	–	–	Loss increase	–	–	–	–
	Wind	Pressure	Strength degradation	Fibre breakage	Loss increase	Loss increase	–	–	–	–
	Snow and ice	Ice loading	Strength degradation	–	–	–	–	–	–	–
	Water and moisture	Penetration	Strength degradation	–	Loss increase, strength degradation				–	–
	Water flow		Strength degradation	Fibre breakage	–	–	–	–	–	–
	Lightning		Strength degradation	Fibre breakage	–	–	–	–	Loss increase	–
Man-made factors	Hydrogen gas	Diffusion	–	–	–	–	–	Loss increase	–	–
	Nuclear radiation		–	–	–	–	–	–	–	Loss increase
	Impact		–	Fibre breakage	–	–	–	–	–	–
	Installation practices		Strength degradation	Fibre breakage	Loss increase	Loss increase	–	–	–	–
Manufacture			Strength degradation	Fibre breakage	Loss increase	Loss increase	–	–	–	–

2.2.2 Effects

When the impulsive strain exceeds a certain limit, breakage of the optical fibre will occur. The number and magnitude of these strains can allow a crack to reach a critical size, causing breakage of the optical fibre.

2.2.3 Constructional considerations

For the protection of optical fibres from the lateral force caused by impact, a buffer coating layer may be used. Further protective layers in stranding and sheath construction may also be considered. Armouring is considered to be one of them.

Under dynamic stress conditions encountered during installation, the fibre is subjected to strain from both cable tension and bending. The strength elements in the cable and the cable bending radius must be selected to limit this combined dynamic strain.

2.3 Fibre macrobending

2.3.1 Causes

Macrobending of an optical fibre may be caused through bending of the fibre by the stranding of optical fibres in cable manufacture as well as bending the cable into its final installed position.

2.3.2 Effects

The fibre may be bent to such a small radius to cause an increase in optical loss. In single-mode optical fibres, the further the operational wavelength is from the cut-off wavelength, the less well-guided the mode will be, resulting in greater loss for the same fibre bend radius.

2.3.3 Constructional considerations

The cable construction and the bends set into the installed cable must be selected to ensure that the fibre is not subjected to a bend radius that could cause an increase in optical loss due to macrobending.

2.4 Fibre microbending

2.4.1 Causes

Microbending of the fibre is caused by localized lateral forces along its length. These may be caused by manufacturing and installation strains, as well as dimensional variations in the cable materials due to temperature changes. Sensitivity to microbending is a function of the difference of refractive index of the core and the cladding, as well as of the diameters of the core and cladding.

2.4.2 Effects

The effect of microbending is increased optical loss.

2.4.3 Constructional considerations

To reduce microbending losses the cable structure must protect the optical fibres from lateral forces. The cable construction should be selected to prevent buckling of the fibre during temperature changes leading to microbending loss.

Cable components such as the cable sheath and the strength member are important because they also help to reduce the microbending caused by the external mechanical forces on the cable and by temperature changes.

Microbending losses may also be introduced in aerial cables subjected to excessive elongation (e.g. heavy ice loading).

2.5 Water and moisture

2.5.1 Causes

Moisture may permeate into optical fibre cables through diffusion and, in the case of inadequate cable construction or sheath damage, water may penetrate longitudinally within the cable core or between sheath layers.

2.5.2 Effects

The tensile strength of fibres in the presence of water or moisture is reduced and the time to static fatigue failure is also reduced. Optical loss may increase with some cable constructions incorporating metallic elements due to the generation of hydrogen when water is present in the cable structure.

2.5.3 Constructional considerations

Optical fibres should be isolated from water and moisture particularly in the presence of excessive fibre strain.

a) Moisture permeation

Because filling compounds and plastic sheaths are not impervious to moisture, in time the moisture content in the cable may rise. Permeation is minimized by longitudinal overlapped and bonded metallic foil and the use of water-blocking material. Alternatively, a seamless metallic barrier can be completely effective in preventing permeation, but this barrier is recommended only for unfilled cables due to problems associated with trapped hydrogen.

b) Water penetration

In order to prevent or minimize longitudinal penetration of water in an optical cable core, either water-blocking materials (continuous, as filling compound or discrete water-blocking) or dry-air pressurization may be used.

When dry-air pressurized cable maintenance method are used for optical fibre cables, the cables do not need any water-blocking materials but require low pneumatic resistance.

2.6 Hydrogen

2.6.1 Causes

Hydrogen gas concentrations may build up within a cable from:

i) hydrogen released from the cable components;

ii) electrolytic effects between two different metallic elements in the presence of moisture;

iii) hydrogen contained in pressurized air pumped into the cable;

iv) corrosive reaction of the metallic elements in presence of moisture.

2.6.2 Effects

Hydrogen in the fibre core will increase the optical loss at wavelengths of 1.24 μm or 1.38 μm or both. Part of the loss is a reversible interstitial effect as a function of the relative pressure of hydrogen due to molecular hydrogen, and the rest is a permanent chemical change caused by the formation of OH bonds in the glass and a wavelength dependent loss.

2.6.3 Constructional considerations

Materials to be used in the cable construction should be selected so that the concentration of hydrogen within the cable is low enough to ensure that the long-term increase of optical loss is acceptable. Alternatively, hydrogen absorbing materials or dynamic gas pressurization can be used to eliminate or reduce the added loss due to hydrogen within the cable core. In the event of an external concentration of hydrogen greater than that within the cable core, a reduced influence on optical loss can be obtained by the use of hermetically coated fibres or by the use of a hermetic sheath around the cable core mainly.

The concentration of hydrogen within the cable core could be estimated from knowledge of the hydrogen released from the components of the cable. Some test methods are described in Recommendation ITU-T L.27.

2.7 Lightning

2.7.1 Causes

Optical fibre cables containing metallic elements have a greater susceptibility to be struck by lightning than cables without metallic elements.

2.7.2 Effects

When buried or aerial (and sometimes duct) optical cables contain metallic elements, such as conventional copper pairs, a metallic sheath, or a metallic strength member, and are struck by lightning, a current will flow in the cables. The mechanical impact and energy dissipated from the lightning strike may damage the sheath and the fibres in the cables.

2.7.3 Constructional considerations

To prevent or minimize lightning damage, consideration may be given to the use of non-metallic cables, high current carrying sheath layers or, alternatively, methods proposed in Recommendation ITU-T K.25.

When a non-metallic cable is used, it should be protected against mechanical damage.

2.8 Nuclear radiation

2.8.1 Causes

Optical fibre cables may be exposed to nuclear radiation.

2.8.2 Effects

Under exposure to nuclear radiation, the optical loss may increase to an unacceptable level.

2.8.3 Constructional considerations

Under study.

2.9 Induced voltage

2.9.1 Causes

Under fault conditions of electricity lines, optical fibre cables containing metallic elements are susceptible to induced voltages.

2.9.2 Effects

Induced voltages on the metallic elements of cables can reach magnitudes which may cause damage to the cable and/or be a safety hazard to personnel in contact with the cable.

2.9.3 Constructional considerations

To prevent or minimize the effects due to induced voltages the ITU-T *Directives concerning the protection of telecommunication lines against harmful effects from electricity lines* shall be taken into account.

2.10 Biological attack

(For further information, see Recommendation ITU-T L.46.)

The outside cables can be damaged from biological attack which can be caused by:

i) mammals, squirrels, mice, rats, moles, gophers and other rodents;

ii) birds like woodpeckers and cockatoos;

iii) insects such as termites, ants, beetles, wasps and caterpillars;

iv) microorganisms like bacteria, fungus and/or moulds.

Where it is not possible to re-site the plant, one possible action could be to eliminate the pests, such as insects and rodents, using chemicals or poisons. However, it should be noted that, while some chemicals and poisons are useful as a countermeasure for biological attacks, they sometimes can also be a danger to humans and cause environmental pollution.

Some chemicals are useful as a deterrent. These chemicals do not work as poisons but they repel the attacker. For example, some chemicals are sprayed on the cable surface and leave a special smell as a deterrent.

Another option for protection of the plant is to shield it by the use of protective materials around the plant in order to prevent access. Cables with sheaths of lead, polyethylene, polyvinylchloride, neoprene and other polymers are all susceptible to attacks. Cables with steel armouring, dielectrical armouring such as fibreglass, or both do not suffer any damage of this type as long as the armour is intact.

3 General structure of optical fibre cables

The external factors (natural and man-made) listed in § 2 as well as the type of installation of the cable in the telecommunication network are the basic requirements for determining the structure, the dimensions and the materials of an optical fibre cable.

From a general point of view, the main components of an optical cable may be divided into the following five groups:

i) optical fibre coatings;

ii) cable core;

iii) strength members;

iv) water-blocking materials (if necessary);

v) sheath materials (with armour if necessary).

The relation between the mechanical and environmental factors and the main components of an optical cable is given in Table 2-4.

Table 2-4 – Mechanical and environmental factors affecting the choice of cable components

Mechanical and environmental factors	Coated optical fibres	Cable core	Strength member	Water-blocking materials	Sheath materials
Residual fibre strain	A	A	A	–	B
Impulsive fibre strain	A	A	–	–	A
Fibre macrobending	A	A	B	–	A
Fibre microbending	A	A	B	B	B
Water	A	A	–	A	A
Moisture	B	–	–	–	A
Hydrogen	B	B	B	B	B
Lightning	–	–	A	B	A
Nuclear radiation	under consideration				
A. Primary factor to be considered. B. Secondary factor to be considered.					

The cable core should be covered with a sheath suitable for the relevant environmental and mechanical conditions associated with installation and operation. The sheath may be of a composite construction and may include strength members of protective armour to meet particular environmental conditions.

The general structure of the optical fibre cables is described in this clause, while the specific characteristics of the structure related to some types of installation are described in § 4.

3.1 Coated optical fibres

Silica fibre has an intrinsically high strength but in actual practice its strength may be reduced by surface flaws. To protect the fibre surface a composite primary coating is applied at the fibre drawing stage. The term “primary coating” means the primary protection of a fibre. A secondary protection of primary coated fibres may be also applied by using several protection methods.

3.1.1 Primary coating of fibres

The primary coating of a fibre must withstand handling of the fibre during cable manufacture and installation. In addition, the primary coated fibre should be proof-tested, in order to be able to predict the fibre life for the installation and the expected environmental conditions.

The primary coating materials must be selected to ensure stability over the range of temperature to be considered and in the presence of moisture.

The primary coating should consist of an inert material that can be readily removed for splicing purposes without damage to the fibre. It is desirable that the material should have a slightly higher refractive index than the fibre cladding and an absorption loss to prevent the propagation of undesirable modes. Acrylate or silicon rubber is typically used for the primary coating.

If the primary coating needs to be coloured to aid fibre identification, the colouring should be stable in the presence of other materials and compatible with them during the lifetime of the cable, and the application technique should not affect any transmission characteristic. The colouring may be in the coating or applied to the surface of the coating.

Primary coated fibres must comply with the relevant ITU-T G.65x series.

3.1.2 Secondary protection of fibres

The primary coated fibre may be protected by:

- i) loose packaging within a tube or groove;
- ii) micromodule construction;
- iii) tight polymer coating;
- iv) ribbon construction.

The protection method should be selected, taking into account the optical fibre unit structure.

3.1.2.1 Loose packaging within a tube

Several methods for loose packaging of primary coated fibres within a tube are used. One typical method is shown in Figure 2-1.

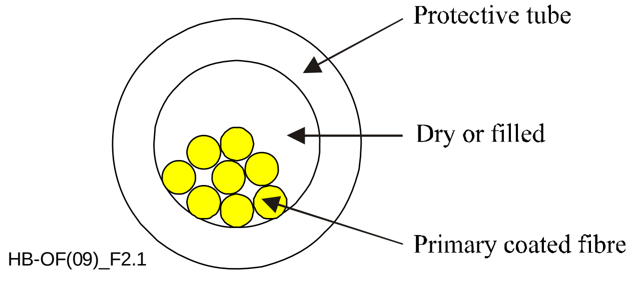


Figure 2-1 – Example of primary coated fibres protected by loose packaging within a tube

The protective tube may be reinforced with a composite wall. Special filling compounds are used within the protective tube to prevent longitudinal migration of water. They should be chosen so that the fibres are free to move throughout the filling compound when the cable is strained at any temperature within the operational range of the cable.

3.1.2.2 Loose packaging within a grooved cylindrical unit

The cabling element consists of a V-grooved core, in which one or more fibres are laid in each groove without tension and with a slight excess length. The slots are helical, or reverse-lay, and a central strength member reinforces the cylindrical rod (Figure 2-2). This provides the unit with enhanced mechanical and thermal qualities. The optical unit can be laid up with other elements as required.

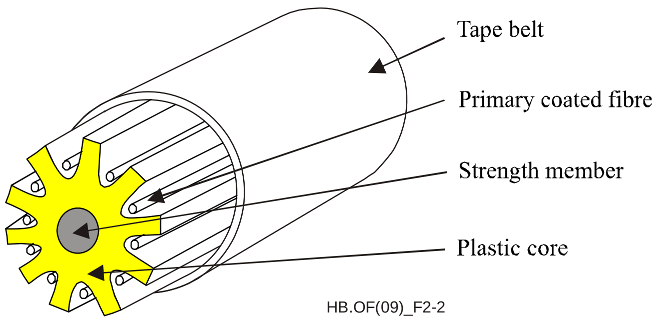


Figure 2-2 – Example of primary coated fibres protected by loose packaging within grooves

3.1.2.3 Micromodule construction

A micromodule is made with thin wall tubing, filled with a suitable compound, housing a bundle of optical fibres. In modified "micromodule cable" designs, replacing the central strength member with radial strength members (see examples in Figures 2-3 and 2-4), the compression of the micromodules against the central strength member is eliminated and easy access is enabled to both the micromodule tubes and the fibres. Such a cable design results in one of the smallest cable cross sections in the industry, offering increased protecting during sheath entry, and is resistant to crush and impact forces.

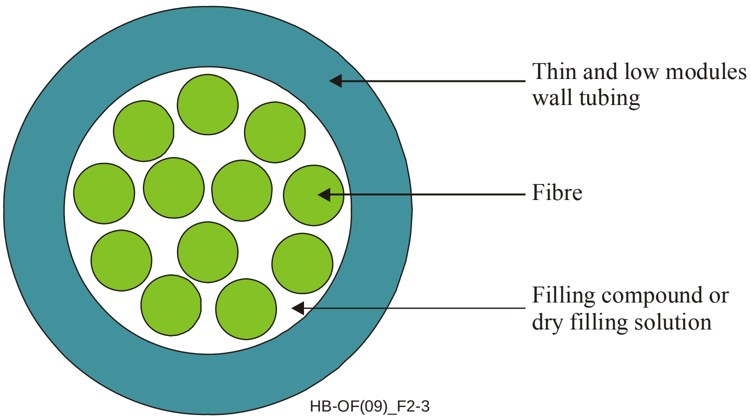
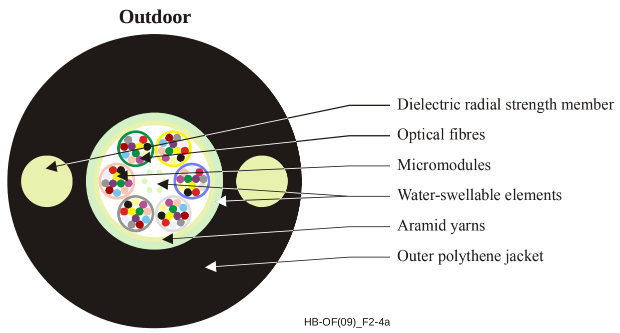
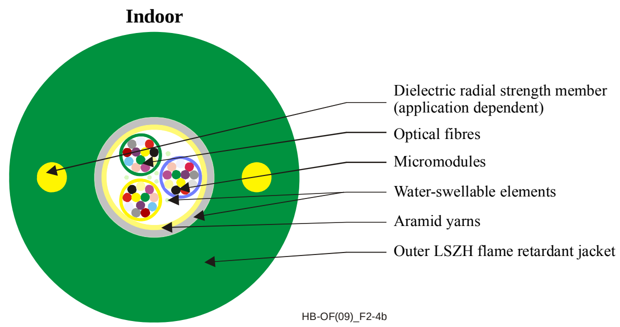


Figure 2-3 – Example of primary coated fibres protected by a micromodule

The small diameter micromodule is made of a very soft and flexible material which is easily strippable without dedicated tool. Furthermore this leads to easy micromodules storage in splicing boxes and trays.

Suitable for various applications, micromodule cables offer significant improvement in installation and deployment time over other cable type. Thanks to its attributes, "micromodule cables" is a suitable design for FTTH applications (see Chapter 9 dealing with the optical access network).





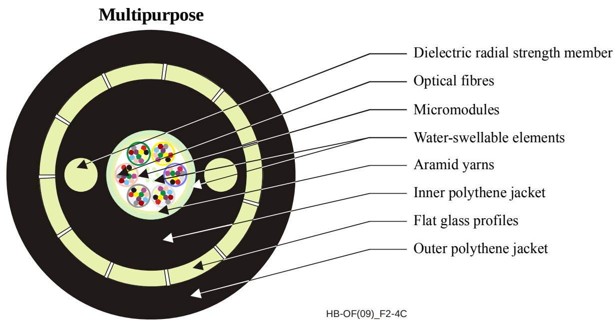


Figure 2-4 – Example of cable construction made with micromodule (outdoor, indoor or multipurpose application)

3.1.2.4 Tight secondary coating

A multiple layer tight coating consists of a composite primary layer, an optional buffer layer, and a polymer secondary coating. A buffer layer improves the stability of the optical loss when the fibre is subjected to radial pressure (Figure 2-5). A secondary coating of polymer improves the compressive load characteristic of the fibre. It improves the handling properties of the fibre and makes it particularly suitable as an equipment tail cable when it is encapsulated in a sheath reinforced with aramid yarn strength members.

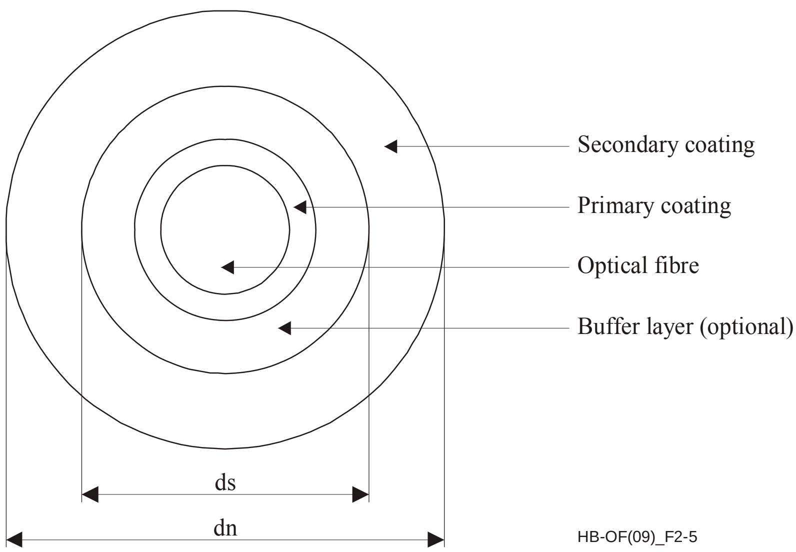


Figure 2-5 – Example of multilayer tight coated fibre

The dimensions of the multiple layers are determined from radial pressure and low temperature characteristic considerations. Example dimensions are shown in Table 2-5.

Table 2-5 – Example of dimensions on multilayer tight-coated fibre

Layer	Diameter (mm)
Primary coating	0.25
Buffer layer, ds	0.25-0.4
Secondary coating, dn	0.7-1.0

To improve the stability of optical loss during dimensional changes associated with temperature variations, a layer of secondary coated optical fibres is tightly stranded around a central steel wire to form an optical fibre unit (Figure 2-6). The laid up fibres are cushioned using a buffer layer which is held in position by an overall application of tape.

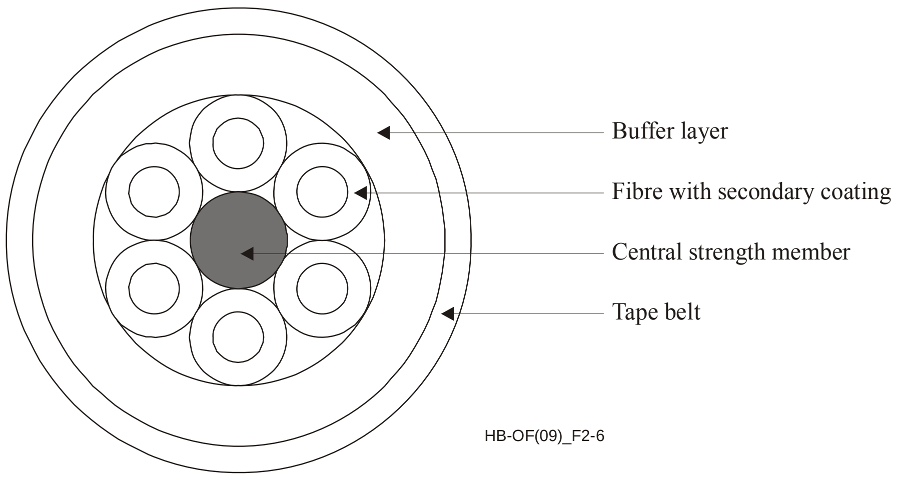
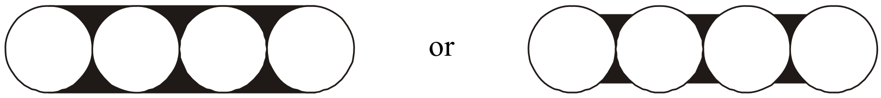


Figure 2-6 – Example of secondary coated fibre stranded around a central strength member

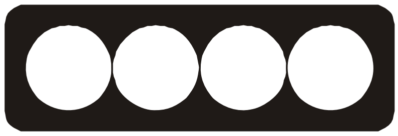
3.1.2.5 Ribbon construction

A ribbon construction is a linear array of fibres which may be assembled in a number of ways, examples of which are shown in Figure 2-7. A ribbon construction is advantageous for splicing multiple fibres, and allows greater fibre density within a cable.

Optical fibre ribbons consist of optical fibres aligned in a row. Optical fibre ribbons are divided into two types, based on the method used to bind optical fibres. One is the edge-bonded type; the other is the encapsulated type, shown in Figures 2-7(a) and 2-7(b) respectively. In case of the edge-bonded type, optical fibres are bound by adhesive material located between optical fibres. When the encapsulated type is adopted, optical fibres are bound by coating material. In ribbons, optical fibres shall remain parallel, and do not cross. Each ribbon in a cable is identified by a printed legend or unique colour.



(a) Cross-section of a typical edge-bonded ribbon



(b) Cross-section of a typical encapsulated ribbon

Figure 2-7 – Examples of ribbon construction

3.1.3 Fibre identification

Fibre should be easily identified by colour or position within the cable core. If a colouring method is used, the colours should be clearly distinguishable and the colouring should be stable in the presence of other materials used in cable construction during the lifetime of the cable. If the primary coating is coloured, it may be required that the coloured coating should also be compatible with local light injection into the fibre core and detection from it during core alignment when jointing the fibre.

3.1.4 Optical fibre unit

An optical fibre unit is defined as the basic unit for constituting the core of an optical fibre cable. The structure of an optical fibre unit usually depends on the type of the secondary protection of the primary coated fibres.

For ribbon construction, the optical fibre unit is usually formed by laying fibre ribbons with other elements, as required. In one of the optical fibre unit structures, multiple fibre ribbons are tightly stranded around a slotted rod which has several slots. In another structure, multiple fibre ribbons are stacked and helically twisted within a single tube.

A general relationship between types of secondary protection and structures of the optical fibre units is shown in Table 2-6. A combination of the types of the secondary protection may be assembled together to form an optical fibre unit. The unit so formed can be laid up with other elements as required.

3.2 Optical cable core structures

The core of optical fibre cable is usually formed by using one or more optical fibre units. The required number of fibres in the cable and the type of application of the cable will determine what kind of optical fibre unit structure is selected. In order to determine the cable core structure or to select the optical fibre unit structure, it is also important to take the cable installation and the fibre jointing into consideration.

In this section, the cable construction of optical fibre cables will be classified into the following two types:

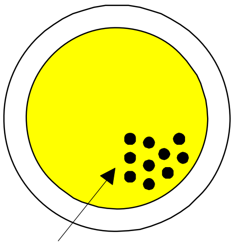
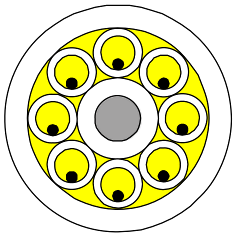
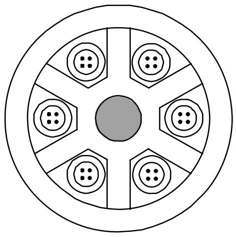
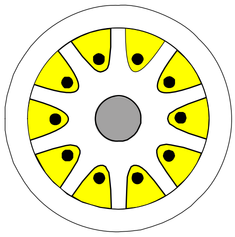
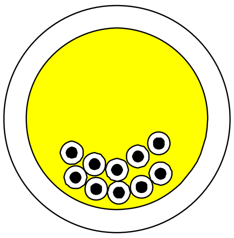
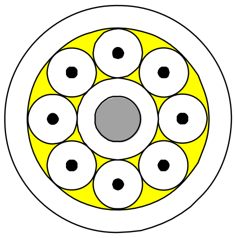
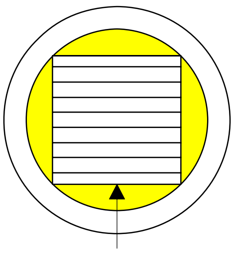
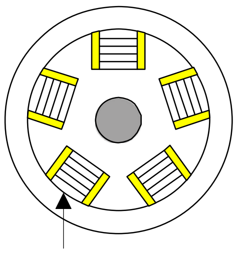
i) single unit cables, which consist of a single optical fibre unit;

ii) multiple unit cables, which consist of multiple optical fibre units.

3.2.1 Single unit cables

Cable core constructions of single unit cables correspond to the optical fibre units shown in Table 2-6.

Table 2-6 – Examples of optical fibre unit structure

Protection		Structures of optical fibre units		
		Single tube structure	**Layer structure**	**Slotted rod structure**
Loose packaging	Within a tube			
	Within a groove			
Tight secondary coating				
Ribbon construction				

● : Primary coated fibre(s) [one or more]

: Tight secondary protected fibre

: Strength member

: Water-blocking material

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Examples of medium to high fibre count cable constructions among various single unit cables are given in Figure 2-8.

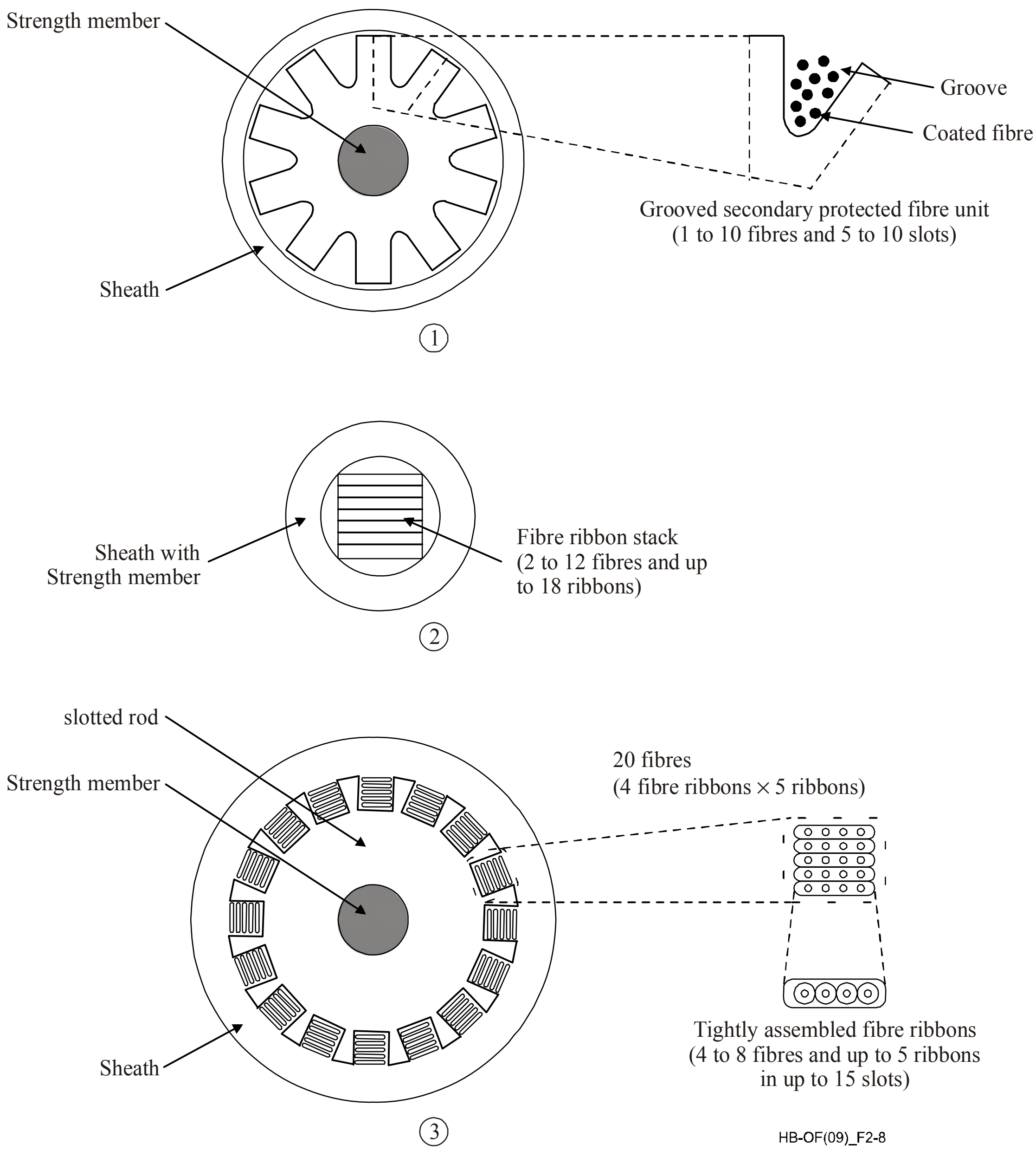

Figure 2-8 – Examples of single unit cable construction

Laying up small diameter optical fibre units can result in high pneumatic resistance from the small interstitial gaps within the cable core. In such cases, if gas pressurization is required, special low pneumatic resistance fillers must be introduced. As an alternative to gas pressurization, water-blocking materials may be introduced.

3.2.2 Multiple unit cables

Multiple unit cables are constructed by:

i) stranding multiple optical fibre units together around a central strength member;

ii) placing multiple, bound, optical fibre units loosely into a single tube within a sheath containing strength members.

If the size of the central strength member, to accommodate a single layer of the desired number of optical units does not provide sufficient design strength, then additional strength members may be stranded over the cable core. The stranding should be preferably in two directions to prevent torque when the cable is loaded.

Examples of multiple unit cable constructions are given in Figures 2-9a, 2-9b and 2-9c.

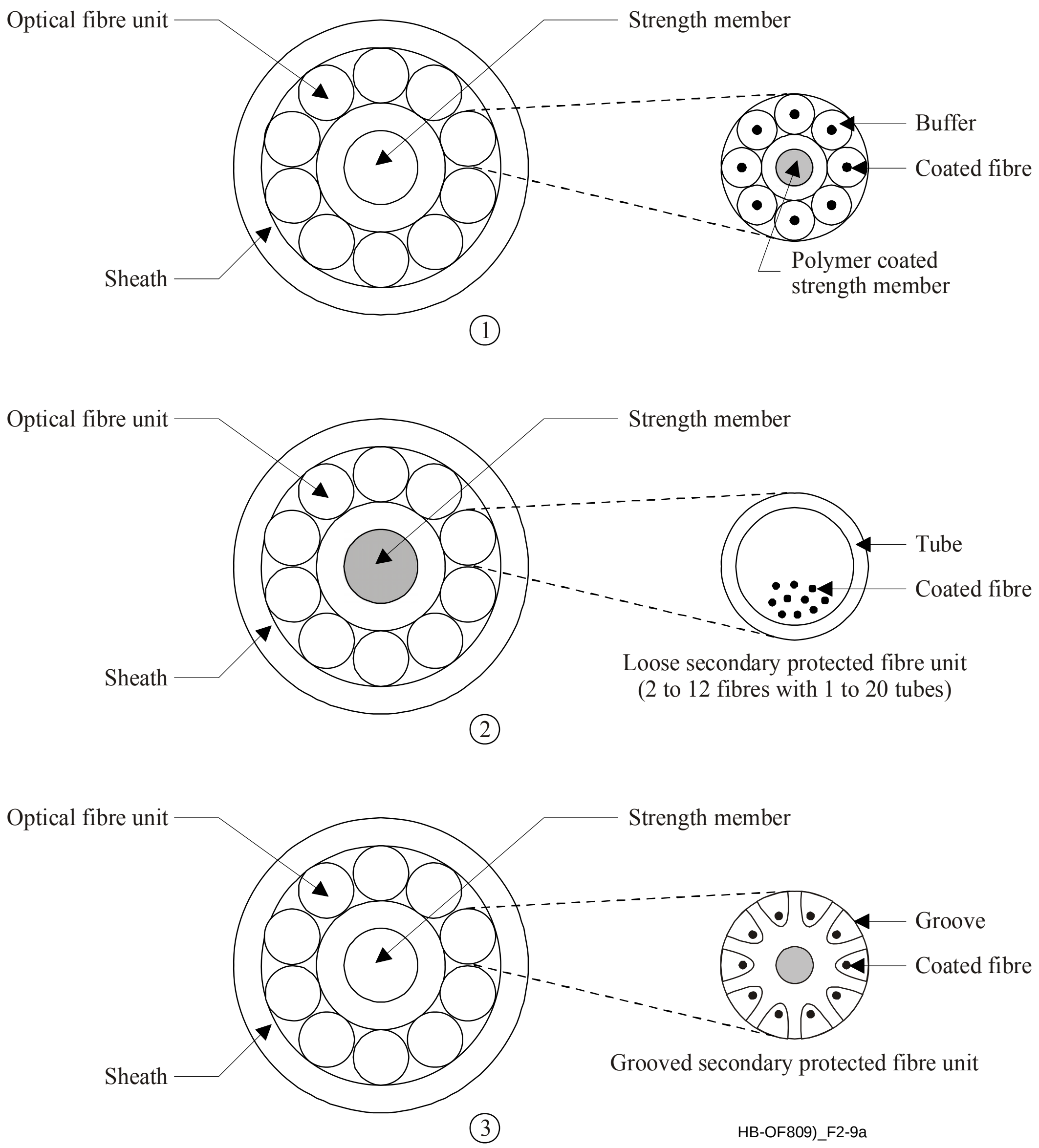

Figure 2-9a – Examples of multiple unit cable construction

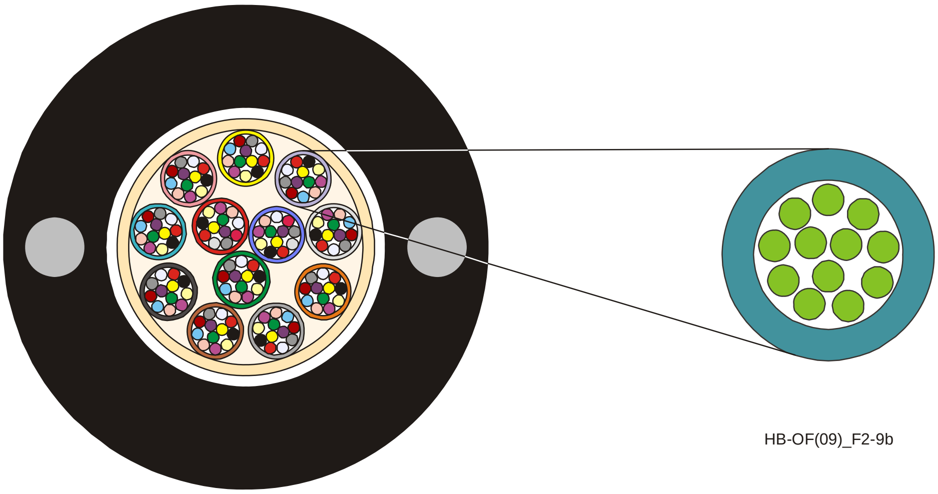

Figure 2-9b – Example of multiple unit cable construction

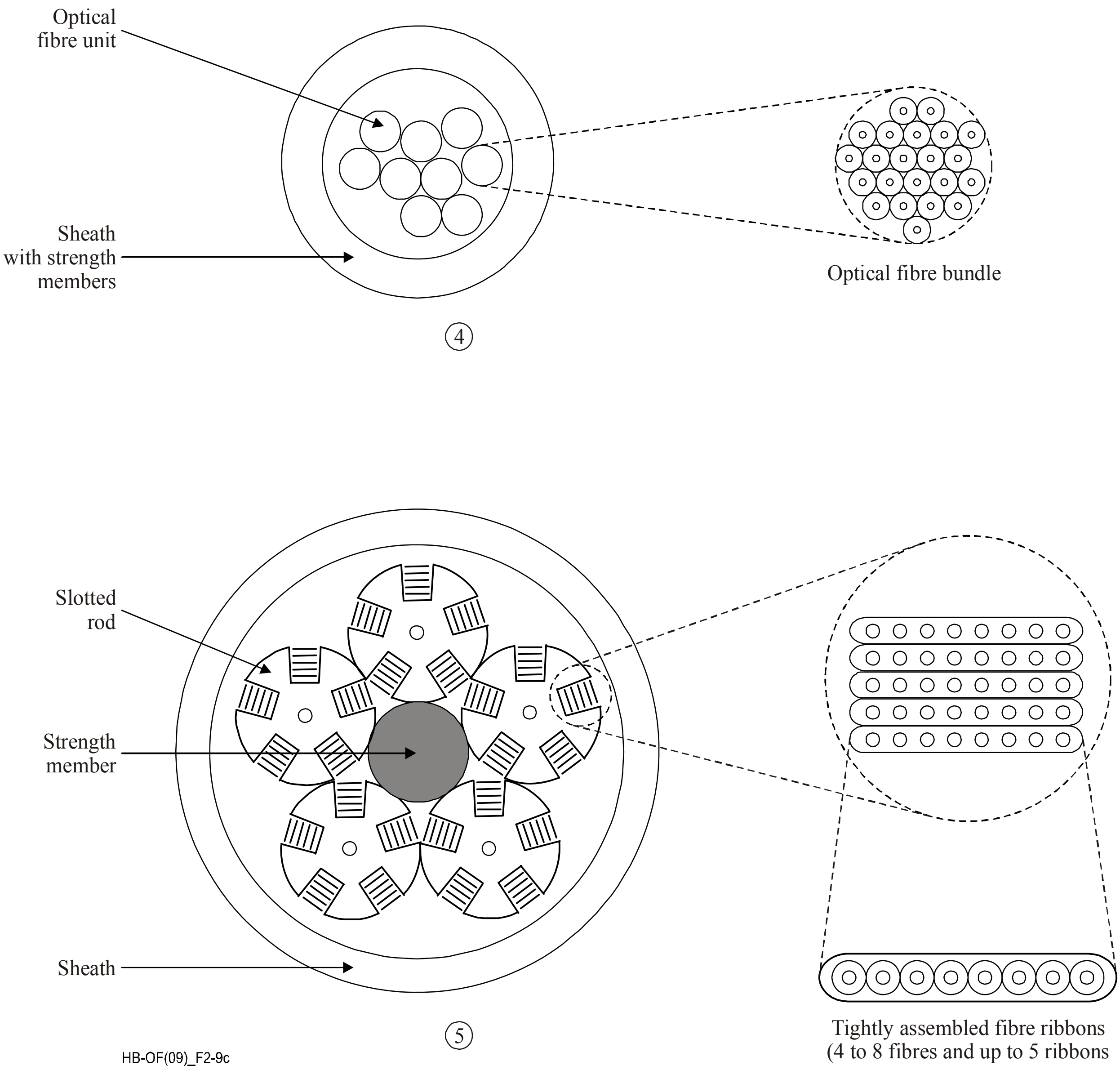

Figure 2-9c – Examples of multiple unit cable construction

3.2.3 Protection against moisture

The cable core is protected against water ingress by the cable sheath. Cable installed in the ground, ducts, or underwater environment should be particularly designed so that the cable core is protected against the ingress of water or moisture in the longitudinal direction if the sheath is perforated. The protection method should be selected from the following two methods when determining the cable core make-up:

i) protecting a cable with water-blocking material;

ii) pressurization.

3.2.3.1 Water-blocking materials

Water-blocking material is one means of protecting the fibres from the ingress of water or moisture. A filling compound, swelling tape, swelling powder or a combination of materials may be used. The filling compound or swelling powder is distributed into interstices of the optical fibre unit (Table 2-6) and the cable core. The filling compound can be also used as a filler of a tube or groove. Swelling tape is usually wrapped around the optical fibre units or the cable core.

The following points are important for the filling compound, swelling tape or power in optical fibre cables:

i) fibre movement should not be constrained by stickiness;

ii) compatibility with primary coating or colouring materials;

iii) no change in the optical performance with activation of the water-blocking material;

iv) no change in optical performance with temperature variations;

v) easy removal of water-blocking materials for splicing.

When longitudinal water tightness of the optical fibre cable including the cable joints is required, the following options are commonly used:

i) continuous blocking,

ii) discrete blocking.

In cable designs with a central strength member and filling compound, the filling material must be selected to minimize the slip between the strength member and the sheath. It should be noted that precaution needs to be taken for potential water migration within stranded elements should these be used as strength members.

In the case of discrete blocking it is desirable that water detectors be included within the cable (network) construction.

Hydrogen absorbing chemicals may be introduced into the filling compound applied to the interstices of the cable core should unacceptably high concentrations of hydrogen be predicted within the cable during its lifetime. Alternatively, the cable construction can be such as to minimize generation of hydrogen.

3.2.3.2 Pressurization

When dry-air pressurization is used for cable maintenance the optical fibre unit structure is selected taking into account the pneumatic resistance and the cable diameter which will satisfy the installation environment.

Such small diameter cables as single unit cables or multiple unit cables laying up small diameter optical fibre units may have high pneumatic resistance from the small interstitial gaps within the cable core. In such cases, if gas pressurization is required, special low pneumatic resistance fillers may be introduced.

3.3 Strength members

In order to select the strength members the required tensile load should first be estimated taking into account the cable weight, the cable design, the range of environmental temperatures and the conditions of installation (whether the cable is installed in ducts, is buried, is subject to bends, etc). The strength members must provide sufficient strength to the cable to ensure the fibres are not strained beyond their permissible limit taking into account the dynamic strain introduced during handling of the cable. Under maximum loading the strength members should remain elastic to ensure that when the cable is relaxed the fibres are maintained below their permissible long term residual strain.

Certain installation requirements may dictate where the strength members are located within the cable, for example:

- i) cable preparation and fibre splicing;
- ii) sheath jointing;
- iii) cable pulling devices;
- iv) cable size.

Any type of strength member can be employed as long as the fibre strain is held within permissible values. As the rigidity of a solid wire is proportional to the 4th power of its diameter, stranded wires should be used for the larger diameters. Non-metallic strength members, for example glass fibre reinforced plastic, fibre glass yarns, oriented polymers, or aramid yarn, may be used for strength elements.

When armour wires are used as the strength members, care should be taken to ensure that the torque introduced under maximum loading does not stress the fibres beyond their permissible long term strain limit.

3.4 Cable sheath and armour

The cable sheath protects the cable core from mechanical and environmental damage. The following characteristics should be considered when choosing a sheath:

- i) hydrogen generation;
- ii) climatic performance;
- iii) air tightness;
- iv) moisture penetration resistance;
- v) mechanical stability (bending, torsion, radial pressure, tension, abrasion, etc.);
- vi) chemical resistance;
- vii) diameter;
- viii) weight;
- ix) fire resistance;
- x) rodent resistance.

3.4.1 Cable sheath types

Various kinds of cable sheath have been introduced for optical fibre cables applied to both external and internal installations. These are classified into the following five types:

- i) metal/plastic sheath with metallic tapes or metallic layer;
- ii) plastic sheath only;
- iii) plastic sheath with strength members;
- iv) plastic sheath with embedded strength members with a metallic tape;
- v) cable sheath with armour.

Typical application of them in various environmental conditions is shown in Table 2-7.

Table 2-7 – Typical application of cable sheath types in various environmental conditions

Cable sheath types	External cables					Internal cables
	Aerial	Buried	Duct	Tunnel	Underwater	Building
Metal/plastic sheath with metallic tapes or metallic layer	A	A	A	A	B	B
Plastic sheath only	A	B	A	A	B	A
Plastic sheath with strength members	A	A	A	A	B	A
Plastic sheath with embedded strength members with metallic tape	A	A	A	A	B	B
Cable sheath with armour	A	A	B	B	A	B
A. Typically applied type. B. Rarely applied type.						

3.4.2 Metal/plastic sheath with metallic tapes or metallic layer

This type of cable sheath has a metallic moisture barrier tape and, in some of these constructions, an impervious barrier is achieved. The metallic tape may be corrugated to improve the flexibility and crushing strength of the cable.

3.4.2.1 Metal/plastic bonded sheath with coated aluminium tape

This type of sheath incorporates a tape of aluminium which is usually coated on one side with a thin film of polyolefin or copolymer. The coated aluminium tape is laid longitudinally over the cable core with the coated side outwards so as to form a tube with an overlap. A polyolefin sheath is then extruded over the tape and the coating fuses to the extruded sheath to provide a firm bond between it and the aluminium tape. Aluminium tape coated on both sides may be used when it is necessary to seal the overlap to improve the moisture barrier or to avoid sheath circulating current.

3.4.2.2 Metal/plastic bonded sheath with coated steel tape

This type of sheath incorporates a tape of steel coated on both sides with a thin film of copolymer. This tape is corrugated and laid longitudinally over the cable core as to form a tube with an overlap, along which the copolymer is fused to ensure a firm bond. A plastic sheath such as polyethylene is then extruded over the tape.

3.4.2.3 Metal/plastic sheath with aluminium tape and soldered tinned-steel tape

This type of sheath includes a longitudinally applied aluminium tape formed into a tube over which is a similar tube of tinned-steel in contact with it. The edges of the tinned-steel tape are overlapped and soldered. For large cables both tapes are corrugated to improve flexibility. A layer of compound is applied over the tinned-steel tube before a plastic sheath is extruded over it for corrosion protection. This sheath forms an impervious moisture barrier.

3.4.2.4 Metal/plastic sheath with a welded-steel tape

This type of sheath includes a longitudinally applied steel tape formed into a tube with its edges continuously welded together. The tube is then corrugated down onto the cable core. A layer of compound is applied over the steel before a plastic sheath is extruded over it for corrosion protection. This sheath forms an impervious moisture barrier.

3.4.2.5 Metal/plastic sheath with an extruded lead sheath

This type of sheath includes as the impervious layer an extruded lead sheath. To protect the cable core from the lead extrusion temperature, a suitable heat barrier layer between core and lead sheath is necessary.

3.4.3 Plastic sheath only

This type of sheath is extruded from plastic material (PE or PVC etc.) and is not moisture resistant.

3.4.4 Plastic sheath with strength members

This sheath design contains longitudinal or cross-ply strength members which may be metallic or non-metallic.

3.4.4.1 Plastic sheath with cross-ply strength members

This type of sheath has helically wound strength members in two torsionally balanced layers in opposite directions, with a plastic sheath extruded over them. The strength members can be made of either steel of fibreglass reinforced plastic (FRP).

3.4.4.2 Plastic sheath with bonded strength members

This type of sheath has generally aramid strength members and may also include glass fibre strength members bonded to the cable sheath. With aramid strength members in the sheath construction it may be necessary to introduce an antibuckling central strength member. The sheath may contain a moisture barrier.

3.4.5 Plastic sheath with embedded strength members with a metallic tape

This type of cable sheath has two parallel, steel strength members embedded in the plastic sheath, which is extruded over a corrugated steel tape. The steel tape is placed over the core and provides a moisture barrier.

3.4.6 Cable sheath with armour

A number of armour oversheaths are used for added protection to the optical cable to meet particular environmental conditions. An example of where additional protection is applied to the cable sheath is for lake and river crossings to resist water current and snagging. One or more helically applied layers of zinc coated steel or stainless steel wires may be applied to the sheath and protected with layers of compound, twine bedding and wrapping, or layers of compound and an extruded plastic sheath. Generation of hydrogen due to corrosion must be considered when selecting the armour wires. A copper tape may be applied as anti-teredo protection.

A lead oversheath may be applied over the plastic sheath in areas of severe or extensive exposure to petrochemicals.

As a protection against rodents, a metal/plastic bonded sheath with a corrugated steel, or stainless steel, tape that is coated on both sides may be applied over the sheath.

3.4.7 Sheath with identification

If visual identification is required to distinguish an optical fibre cable from a metallic cable, this can be done by visibly marking the sheath of the optical fibre cable. For identifying cables, embossing, sintering, imprinting, hot foil and surface printing can be used by agreement between user and manufacturer.

4 Structure of optical fibre cables for specific installations

The general structure of the optical fibre cables described in § 3 well applies to optical cables to be installed in ducts, tunnels and bridges, as described in Recommendation ITU-T Rec. L.10, or to be directly buried in the ground, as discussed in Recommendation ITU-T Rec. L.43. On the contrary other types of installation (aerial, marinized, submarine and sewer duct) need specific structures, even if always based on the general ones described in § 3. These specific structures are described in this clause.

4.1 Optical fibre cables for aerial applications

(For further information, see Recommendation ITU-T L.26.)

4.1.1 Environmental conditions

In aerial applications *water* in the cable may be frozen under some conditions and can cause fibre crushing with a resultant increase in optical loss and possible fibre breakage.

Overhead cable *vibrations* are produced either by laminar wind streams, causing curls at the lee side of the cable (aeolian vibration) or by variations in wind direction relative to the cable axis (galloping effect). A well-established surveillance routine will identify the activity in order to make a careful choice of the route and to decide upon the installation techniques, or the use of vibration control devices, or both to minimize this type of problem. In these situations, cables should be designed and installed to provide stability of the transmission characteristics and mechanical performance. To reduce any fibre strain induced by wind pressure, the strength member should be selected to limit this strain to safe levels, and the cable construction may mechanically decouple the fibre from the sheath to minimize the strain. Alternatively, to reduce fibre strain, the cable may be lashed to a high-strength support strand.

Generally, aerial cables are more exposed to significant *temperature* variation than underground cables. Therefore, this issue is very important. Expansion of the cable due to a variation in temperature to a high level may cause a significant reduction of the safe clearance to ground. Shrinkage of the cable due to a variation in temperature to a low level may cause the maximum working tension to be reached. Under these conditions, the variation of attenuation of the fibres shall be reversible and shall not exceed the specified limits.

Fibre strain may be caused by tension occurring in connection with *snow loading* and/or *ice* formation around the cable. Induced fibre strain may cause excess optical loss and may cause fibre breakage if the specified long-term strain limit of the fibre is exceeded. Dynamic strain in the fibre may be induced by vibration caused by the action of snow or ice falling from the cable. This may cause fibre breakage. Under the load of snow or ice, excessive fibre strain may easily be induced by wind pressure. To suppress the fibre strain by snow loading or ice formation or both, the strength member should be selected to limit this strain to safe levels, and the cable profile may be selected to minimize snow loading. Alternatively, to suppress fibre strain, the cable may be lashed to a high-strength support strand. Cable should be designed and installed to provide stability of the transmission characteristics, cable sag/tension, fatigue of the strength member and tower/pole loading.

Metal-free aerial cables installed in the high-voltage environment of power lines are susceptible to the influence of the *electric field* of these power lines, which may lead to phenomena such as corona, arcing and tracking of the cable sheath. To prevent damage, the cable should be installed on the power transmission lines in a position of minimum field strength, or special cable sheath materials may be used, or both approaches may be followed depending on the level of the electric field. Also, the effect of sheath marking should not cause any deterioration of the sheath in these circumstances.

4.1.2 Cable construction

For aerial application, the following special cable structures may be adopted:

– *All-Dielectric Self-Supporting* (ADSS): the tensile element is provided by a non-metallic reinforcement (e.g. aramid yarns, glass-fibre-reinforced materials or equivalent dielectric strength members) placed under or within the plastic sheath; the outer shape is circular (Figure 2-10a);

– *Self-Supporting (SS) cable*: the sheath includes a metallic or non-metallic bearing element, to form a figure "8" (Figure 2-10b);

– *Lashed cable*: non-metallic cables installed on a separate suspension catenary and held in position with a binder cord or special preformed spiral clips.

A knowledge of span, sag, wind and ice-loading is necessary to design a cable for use in aerial applications.

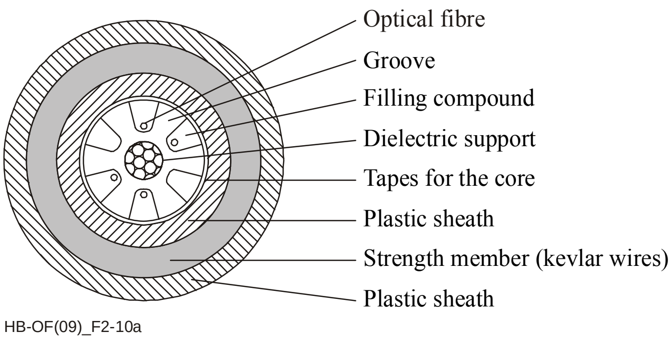

Figure 2-10a –
All-dielectric self-supporting cable

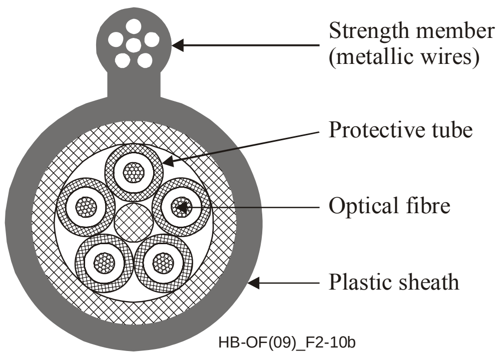

Figure 2-10b –
Self-supporting cable (figure 8 cable)

4.2 Marinized terrestrial cables

(For further information, see ITU-T Handbook, *Marinized Terrestrial Cables*.)

A marinized terrestrial cable (TMC) is an underwater optical fibre cable construction based on a *conventional multiple fibre terrestrial cable core*, protected to withstand the marine environment. MTC is designed for unrepeatered applications, hence without the need to carry electrical power and is tested for use in non-aggressive shallow waters. The main applications are for crossing rivers, lakes, fjords, etc.

4.2.1 Mechanical and environmental characteristics

Marinized terrestrial cables must be able to withstand during their life time the water pressures that act upon them, in accordance with the depth of the water (up to about 100 m) in which they are used.

Depending on the marine installation and maintenance operation adopted, the cable can be subjected to lateral pressure from the sheaves of a cable-laying vessel. Similarly, lateral pressure can be created on a laying vessel using a drum engine or a powered reel. All these lateral pressures increase with increased cable tension and depth of water. Moreover, the storage of cables in layers of coils produces lateral pressure proportional to the height of the accumulated layers in the cable span. The cable should be designed with sufficient strength to withstand the pressures it is intended to encounter.

The minimum bending radius should be as small as possible in order to minimize the space necessary for transportation and to maximize the cable length available for installation in one trip. Small vessels, unless specially designed for cable laying operations, may have relatively small size sheaves.

Laying and recovery operations induce also longitudinal tensile forces on marinized terrestrial cables, such as:

i) static tension which is related to the unit weight of the cable in water and the depth of the water;

ii) dynamic tension which is caused by the pitching of the cable laying vessel.

In recovery operations, the cable forms a catenary and is acted upon by static tension in accordance with the amount of slack in it and by the resistance of the water. In the case of buried cables, a further tensile force is involved in the earth moving operation of dragging the cable out of the sea beds.

4.2.2 Cable structure

The typical cable design is made by a terrestrial cable core, contained in an impervious sheath protected with armour to withstand local seabed environment.

The cable core should be preferably the same as the terrestrial cable to which it is to be joined. It should have preferably the same number of fibres as the terrestrial cable.

An impervious sheath of copper, lead or steel may be applied over the cable core. This may be protected with an extruded plastic sheath or a layer of servings to provide bedding for armour.

Usually the armouring consists of a single or double layer of steel wires. The wires may be individually coated with plastic. A layer of servings[1] may be applied between two layers of armour wires to act as bedding.

An outer covering of serving or a plastic sheath is usually applied as protection against wear and corrosion. Servings made of polypropylene, nylon or jute yarns usually include an application of bituminous compound.

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[1] "Serving" is a traditional nautical term that refers to a tight **wind**ing of **spun yarn**, or the like, **around** a **rope** or **cable**, so as to **protect** it **from chafing** or **from** the **weather**.

A marinized terrestrial cable core may consist of a single optical unit or multiple optical units, which are similar to those used for terrestrial cables. As for the outer structures, which are specifically designed for this type of application, two alternatives generally are adopted (Figure 2-11):

i) Reinforced core structures, which is based on the winding of armours around a reinforced cable core. The reinforced cable core consists of a central optical unit protected by strength members (metallic or non-metallic), a metallic sheath and a polyethylene sheath. The strength members provide tensile strength and limit cable an fibre elongation. The metallic sheath is typically a continuous welded copper pipe. The welded copper pipe forms a seal against hydrogen diffusion.

ii) Standard core structure, which is specifically designed for shallow water applications. The cable usually consists of a central optical unit packed by a plastic sheath and armour winding. The armour is steel wire which can serve as both protection for the cable against abrasion and as a strength member.

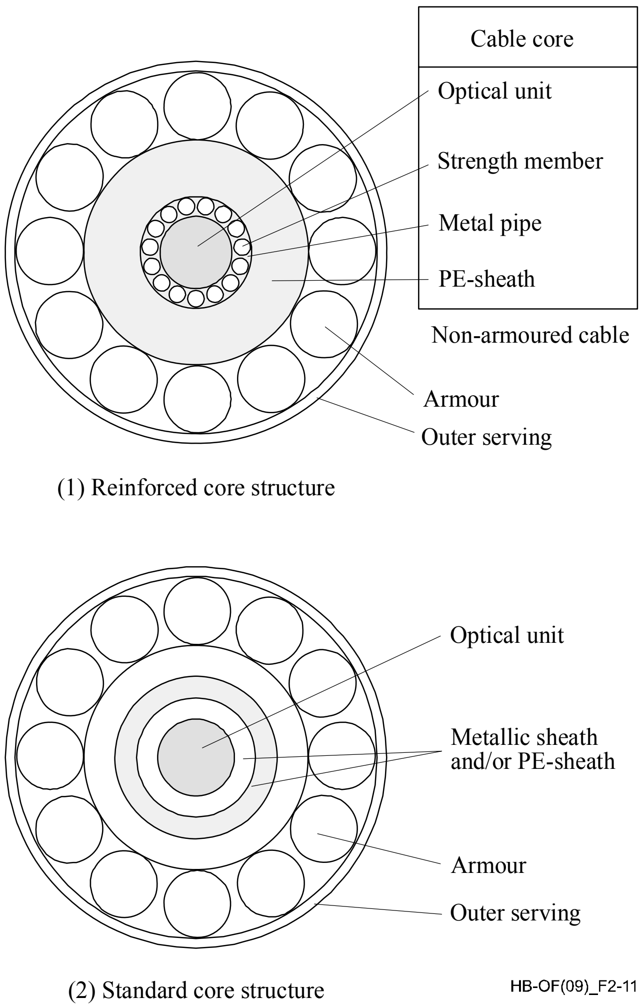


Figure 2-11 – Typical armour structures of marinized terrestrial cables

4.3 Submarine cables

(For further information, see Recommendation ITU-T G.978.)

The optical submarine cable is an underwater optical fibre cable designed to be suitable for shallow and deep water use, which is required to ensure protection of optical fibres against water pressure, longitudinal water propagation, chemical aggression and the effect of hydrogen contamination throughout the cable design life. The submarine cable is extensively tested to show it can be installed and repaired *in situ*, even in worst weather conditions, without any impairment of optical, electrical or mechanical performance or reliability. This means that the submarine cable is conceptually different from a marinized terrestrial cable defined in § 4.2.

Based on application, the optical fibre submarine cable can be a repeatered submarine cable or a repeaterless submarine cable. A repeatered submarine cable must contain a low resistance electrical conductor to provide power to the optical repeaters. A repeaterless submarine cable doesn't need to have the electrical conductor for repeaters. In general, while the typical maximum number of fibres within repeatered submarine cable is fewer than 16, repeaterless submarine cable contains much larger quantity of fibres (up to several hundreds of fibres).

4.3.1 Mechanical and environmental characteristics

The cable, with the cable jointing boxes, the cable couplers, and the cable transitions, should be handled with safety by cable ships during laying and repair operation (depth up to about 8 000 m); it should withstand multiple passages over the bow of a cable ship.

The cable should be repairable and the time to make a cable joint on board during a repair in good working conditions should be reasonably short.

Should the cable be hooked by a grapnel, an anchor or a fishing tool, it usually breaks for a load approximately equal to a fraction (depending on the cable type and the grapnel characteristics) of the breaking load in straight line conditions; there is then a risk of reduction of the fibre and cable lifetime and reliability in the vicinity of the breaking point, due in particular to the stress applied to the fibre or to water penetration. The damaged portion of cable should be replaced and its length should stay within a specified value.

Should a cable break on the sea bottom, water should not propagate in the cable for a given cable length (around 1 km).

Several parameters are defined in Recommendation ITU-T G.972 to characterize the cable mechanical characteristics and the ability of the cable to be installed, recovered and repaired; these can be used as guidance for cable handling:

i) the cable breaking load (CBL), measured during qualification test;

ii) the nominal transient tensile strength (NTTS), which could be accidentally encountered, particularly during recovery operations;

iii) the nominal operating tensile strength (NOTS), which could be encountered during repairs;

iv) the nominal permanent tensile strength (NPTS), which characterizes the status of the cable after laying;

v) the minimum cable bending radius, which is a guidance for cable handling.

4.3.2 Cable structure

The submarine cable should be designed so as to guarantee the system design life, taking into account the cumulative effect of load applied to the cable during laying, recovery and repair, as well as any permanent load or residual elongation applied to the installed cable. Two generic types of fibre containment structure are commonly used to protect the optical fibres:

i) the tight cable structure, where the fibres are strongly maintained in the cable, so that the fibre elongation is essentially equal to that of the cable;

ii) the loose cable structure, where the fibres are free to move inside the cable, so that the fibre elongation is lower than that of the cable, staying zero until the cable elongation reaches a given values.

The central optical unit is usually reinforced by closely packed high strength wires to withstand the weight of the cable during deployment and hydrostatic pressure of the sea bottom. They are formed into a locked vault structure around the central optical unit and wrapped by an external, welded copper tube. The copper tube provides strength, a powering path and hydrogen resistance (Figure 2-12).

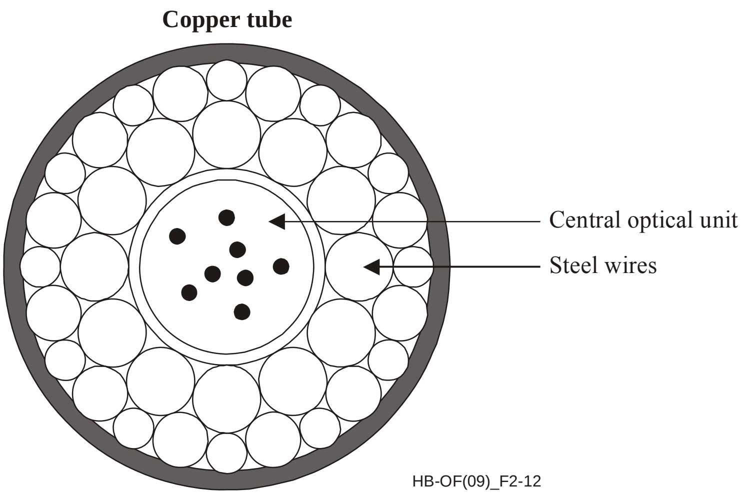


Figure 2-12 – Typical wire vault structure of submarine cables

The optical fibre submarine cable should also provide protection against the environmental hazards at its depth of utilization (up to ~8 000 m): protection against marine life, fish-bite and abrasion, and armours against aggression and ship activities. Different types of protected cable are defined in Recommendation ITU-T G.972, in particular:

i) the lightweight cable (LW cable) which is suitable for laying, recovery and operation, where no special protection is required;

ii) the lightweight protected cable (LWP cable) which is suitable for laying, recovery and operation, where special protection is required (Figure 2-13a);

iii) the single armoured cable (SA cable) which is suitable for laying, burial, recovery and operation and is suitably protected for specific area in shallow water;

iv) the double armoured cable (DA cable) which is suitable for laying, burial, recovery and operation and is suitably protected for specific area in shallow water (Figure 2-13b);

v) the rock armoured cable (RA cable) which is suitable for laying, recovery and operation and is suitably protected for specific area in shallow water.

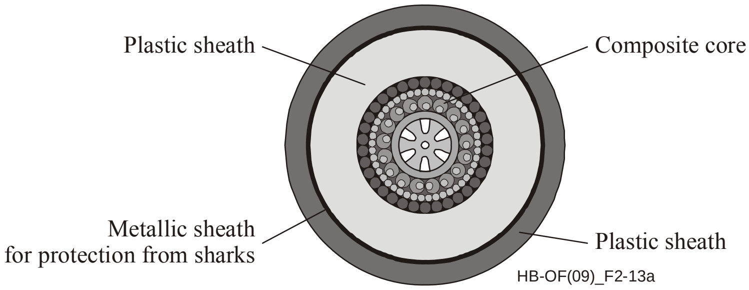


Figure 2-13a – Lightweight-protected cable

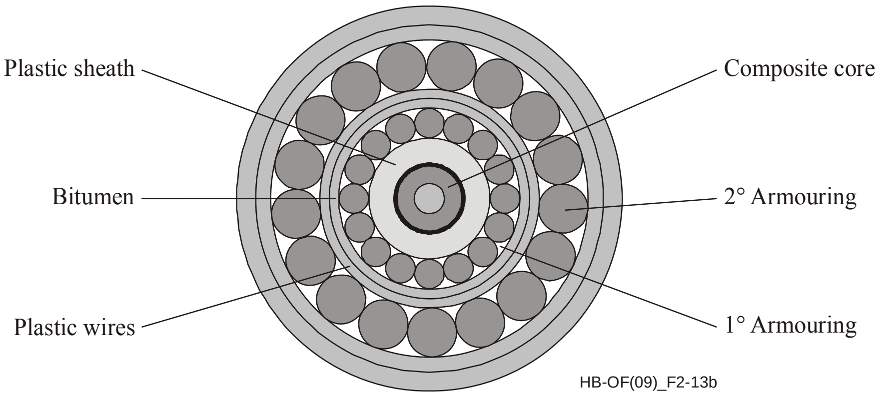


Figure 2-13b – Double-armoured cable

Table 2-8 indicates the typical application depth of each cable.

Table 2-8 – Typical application depth of optical fibre submarine cables

	LW/LWP cable	SA cable	DA cable	RA cable
Depth (m)	> 1 000	> 20 –1 500	0 – 20	0 – 20

Optical fibre land cable should protect the system and personnel against electrical discharges, industrial interference and lightning. Two types of protected land cable are commonly used:

i) armoured land cable, with an armour to be maintained at earth potential, and which is suitable to be buried directly;

ii) duct shielded cable, with a circumferential safety shield (which may be the fish-bite protection shield), and which is suitable to be pulled into ducts.

4.4 Optical fibre cables for sewer duct applications

(For further information, see Recommendation ITU-T L.78.)

4.4.1 Environmental conditions

The environmental conditions in a sewer pipe may be harsh compared with those experienced by conventional underground cables.

Temperature variation strongly depends on climatic conditions and the temperature of liquid passing through a sewer pipe. Therefore, it is important to examine the expected temperature range during their operational lifetime. It is recommended that the optical fibre cable structure be designed so that no increase in fibre attenuation exceeds the specified limits under those conditions.

Rodents may be found in sewer pipes. Where those rodents cannot be excluded, a suitable and effective protection should be provided. Further information is in Recommendation ITU-T L.46. Effective protection can be provided by metallic (steel tape or wire armouring) or non-metallic (e.g. fibreglass rods, glass yarns/tapes) barriers.

Although it is undesirable, there is a possibility that certain kinds of chemical agent will flow through a sewer pipe. After installation, contact with several chemical material agents may degrade the cable sheath characteristics, leading to the weakening of the cable core protection. To avoid this problem, cable sheath materials should be selected carefully, based on their robustness with regard to chemical agents. First of all, it is important to assess what kind of chemical agents may exist in the area where the cable is to be laid. Then, sheath material durability with respect to these chemical agents should be examined.

A highly humid environment may result in moisture permeation depending on the cable sheath structure. When moisture permeates the cable sheath and is present in the cable core, the tensile strength of the fibre deteriorates and the time-to-static failure will be reduced. To ensure a satisfactory cable lifetime, the long-term strain level of the fibre must be limited. Various materials can be used as barriers to reduce the rate of moisture permeation. Alternatively, filled metal-free cable construction can be used.

When an optical fibre cable is soaked in water, moisture permeation and water penetration may be caused depending on the cable structure. When there is a crack in the cable sheath, water may soak into the cable core. Water causes fibre strength degradation more rapidly than high humidity. If there is a possibility that the cable will be soaked in water, it is recommended that water-blocking materials be used to prevent the cable core from being immersed in water.

4.4.2 Cable structure

For sewer application, the following special cable structures may be adopted:

i) Single-armoured cable (SA cable), which is suitable for laying, recovery and operation and is suitably protected for specific area in sewer pipe (Figure 2-14a);

ii) Self-supporting (SS) cable, which is suitable for hungering, recovery and operation and is suitably protected for the specific conditions in sewer pipe. If using this type of a cable, knowledge of span and sag is necessary to design a cable (Figure 2-14b).

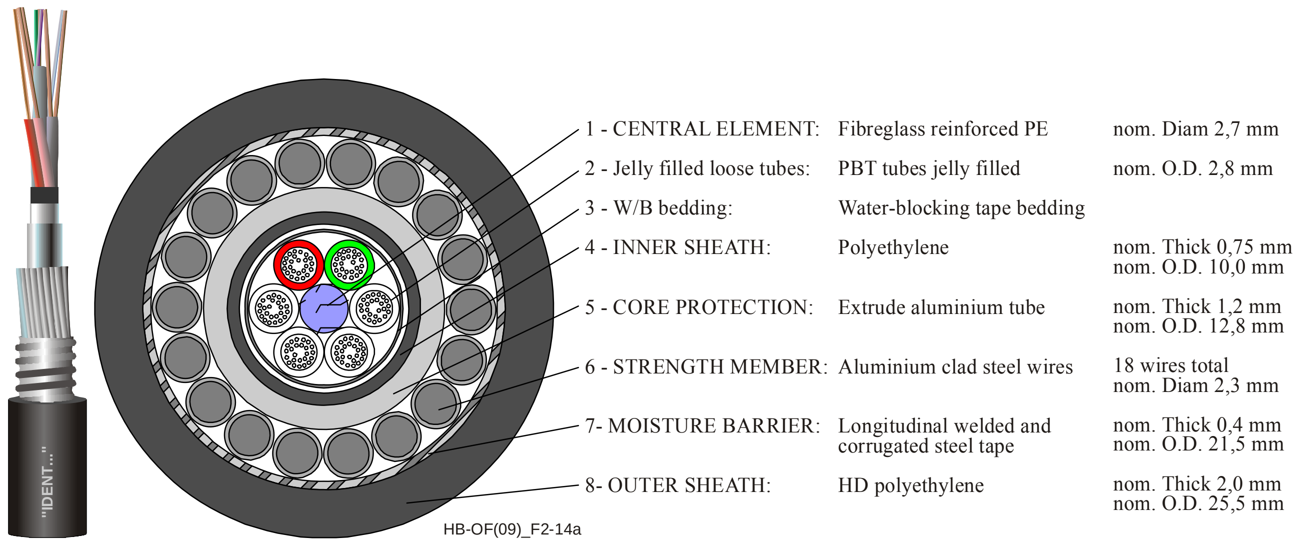
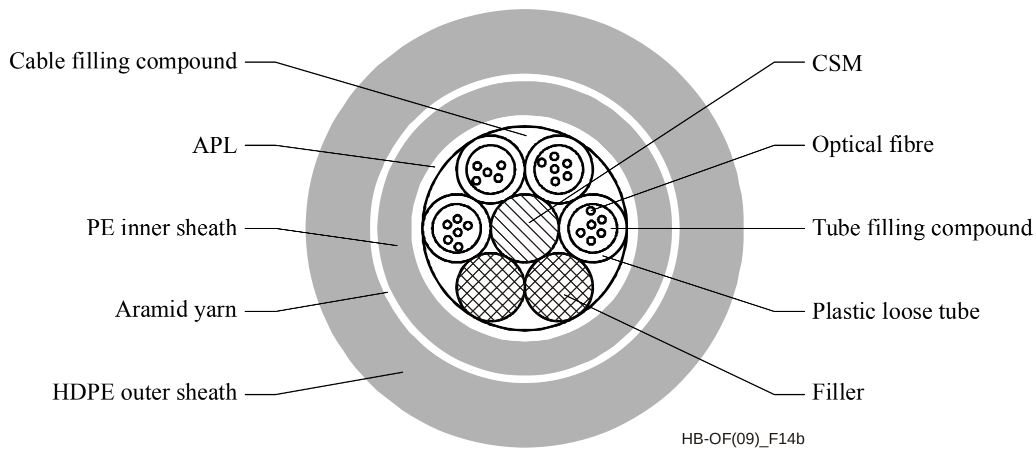


Figure 2-14a – Single-armoured cable with stranded plastic loose tube structure for sewer application



APL =	Aluminium polyethylene laminated	HDPE =	High-density PE
PE =	PolyEthylene	CSM =	Central support member

Figure 2-14b – Self-supporting cable with stranded plastic loose tube structure for sewer application

4.5 Optical fibre cables for multidwelling FTTH indoor applications: riser cable

4.5.1 Environmental conditions

Optical fibre communications networks have entered in a new phase with the ongoing demand for FTTH networks (fibre to the home). It is necessary to bring fibre(s) up to the customer premises following different scenarios (residential, aerial, multidwelling units, etc.). For more information on this issue, see Chapter 9 dealing with the optical access networks.

Indoor cables can be used from the building entry and may be for short runs within a house or long runs through a building. Since products are used in customer premises, they all offer some form of flame retardancy. This includes the use of a low smoke, zero halogen sheath, while the cable is constructed in such a way as to afford some degree of protection from flame propagation and smoke emission. The materials are characterized for halogen content and for corrosivity risks.

Focusing on multidwelling units, the vertical access to buildings with several floors requires a new types of cable, so-called "Riser".

For vertical cabling, a mid-span access allows one to extract a fibre or bundle of fibres on each floor, depending on the building configuration or on the number of customer to be connected.

There are two types of mid-span access:

i) full mid-span access: all fibres, or bundles of fibre, are extracted at each distribution point, by removing the entire riser sheath over few tens of centimetres;

ii) tapping access, or easy mid-span access: extraction of necessary fibre(s) or bundle(s) of fibre is made at the distribution point, creating windows into the cable sheath with a dedicated tool, in order to access the cable core content. The other fibre(s) or fibre bundle(s) remain in the cable core, without the need for dedicated management at the distribution point. This procedure is depicted in Figure 2-15. First, create two windows, one at the distribution point, and another somewhere further along its length. Cut the designated fibre(s) or fibre bundle(s) on the upper part and extract it (them) at the lower distribution point.

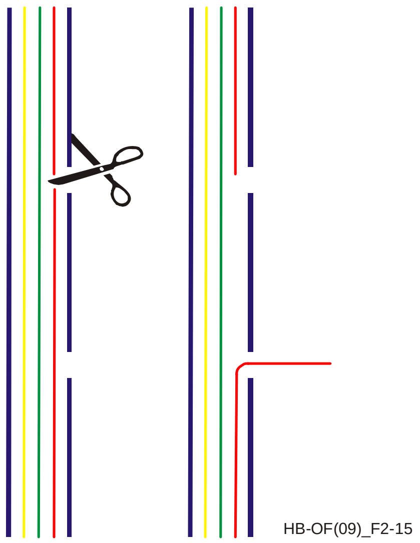


Figure 2-15 – Example of a tapping, mid-span access

4.5.2 Cable structure

Several riser cable designs have been developed and installed worldwide.

Strength members, such as glass fibre reinforced plastic material in the sheath or peripheral strength elements aramid yarns, can be used to provide the enough tensile strength to the cable, since the cable will be installed inside the buildings, sometimes in fully occupied ducts.

Below are described some of the designs available:

i) micromodule riser cable design, based on micromodules containing optical fibres (Figure 2-16);

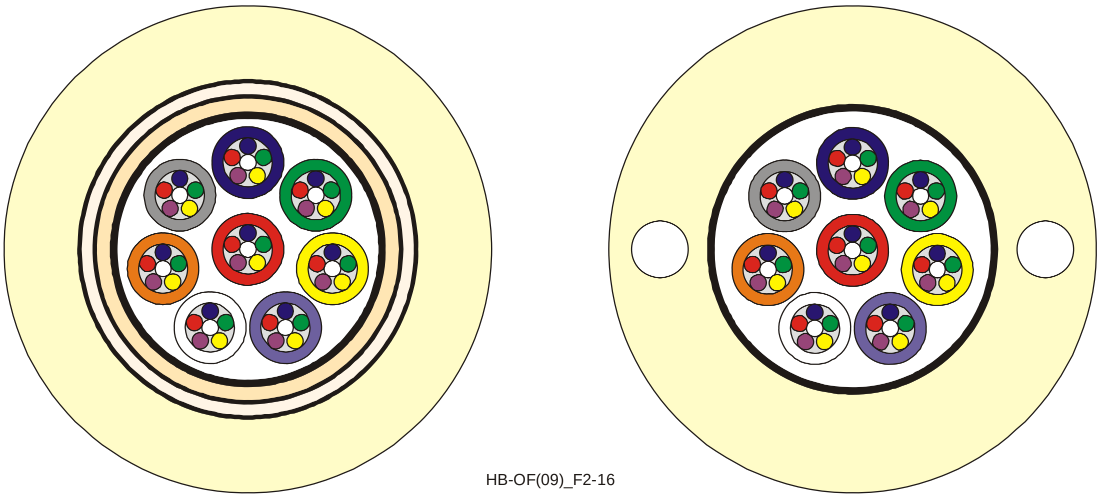


Figure 2-16 – Example of micromodule riser cable

ii) individual fibre protected by buffer, based on ITU-T G.657B optical fibres also complaint to ITU-T G.652D individually protected with a buffer, stranded to form the optical core (Figure 2-17).

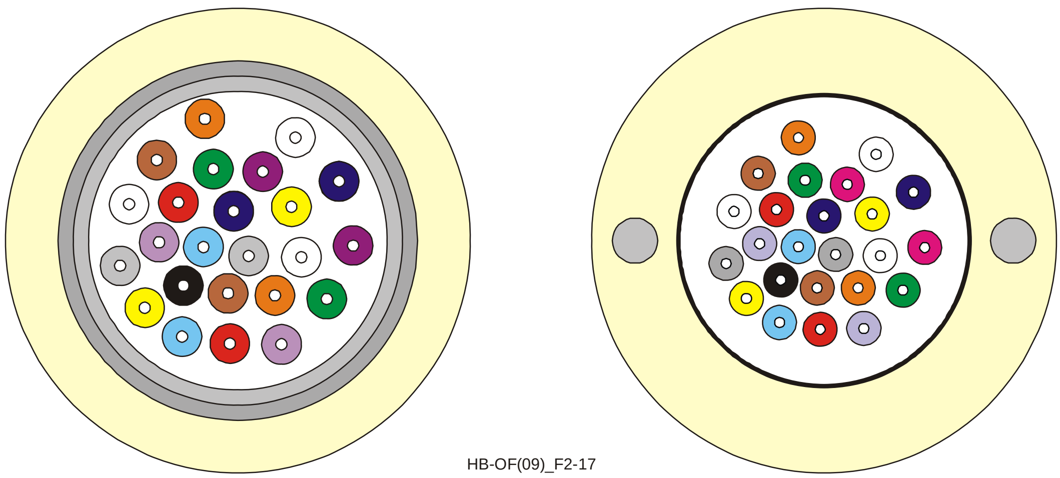


Figure 2-17 – Example of individual fibre buffer riser cable

5 Cable tests

The description of the cable tests is outside the scope of this Handbook. Information on cable tests can be found in Supplement 40 to the ITU-T G-series Recommendations and in the relevant ITU-T L-series Recommendations.

CHAPTER 3

OPTICAL CABLE INSTALLATION

Introduction

This Chapter is devoted to the description of the optical cable installation methods. Each type of optical fibre cable has a specific strain limit and special care and arrangements may be needed to ensure successful installation without exceeding it. Damage caused by overloading during installation may not be immediately apparent, but can lead to failure later in its service life. Also aspects related to bending during the installation may require special consideration.

In Section 1, many types of cable installation (underground duct, trenchless, mini-trench, aerial, submarine, etc.) are described. Clause 2 deals with additional safety precautions when installing optical cables.

1 Cable installation methods

Optical fibre must be protected from excessive strains, produced axially or in bending, during installation and various methods are available to do this. The aim of all optical fibre cable installation methods and systems should be to install the cable with the fibre in, as near as possible, a strain free condition, ready for splicing.

Methods and practices used in the handling of optical fibre cables during installation can, without producing any immediately evident physical damage or transmission loss, affect their long term transmission characteristics.

Technicians involved in installation procedures should be made fully aware of the correct methods to employ, the possible consequences of employing incorrect methods, and have sufficient information and training to enable cables to be installed without damage to fibres. In particular, installation crews should be made aware of minimum bending criteria, how easy it is to contravene these when installing by hand, and the difficulty of making consequential additional splices.

Ambient conditions may affect installation procedures, and it is good practice to install optical fibre cables, particularly in long lengths, only when the temperature is within the limits set specifically for the particular product.

1.1 Installation of cables in underground ducts

1.1.1 Route considerations

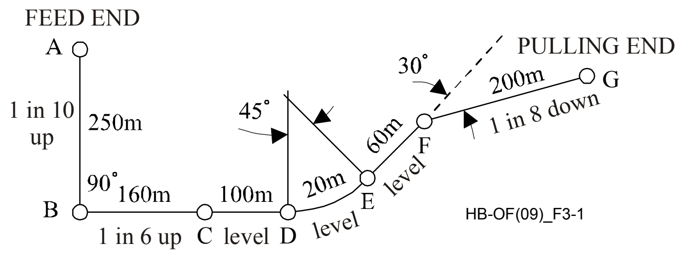
Some of the most difficult situations for the installation of optical fibre cables are in underground ducts. The condition and geometry of duct routes is of great importance. Where the infrastructure includes ducts in poor condition, contains excessive curvature, includes ducts already containing cables or access points with abrupt changes of direction, the maximum pull distance will be reduced accordingly.

Provision of long cable lengths in underground duct situations may involve installation methods that require access to the cable at intermediate points for the application of additional winching force or figure-of-eight techniques, and these sites should be chosen with care. Consideration should also be given to factors of time and disturbance. Installation equipment may be required to run for long periods of time and the time of day, noise levels, and traffic disruption should be taken into account.

Because the condition of underground ducts intended for optical fibre cable is of particular importance, care should always be taken to ensure that ducts are in sound condition and as clean and clear as possible (see Chapter 10). Consideration can also be given to the provision of a subduct system, either in single or multiple form, to provide a good environment for installation, segregation of cables, extra mechanical protection and improved maintenance procedures. Subducts can be more difficult to rope and cabled than normal size duct, particularly over long lengths, and the diameter ratio between the cable and subduct should be considered. Methods have been developed that install cables into small size ducts by blowing, which leaves the cable essentially stress free (see § 1.1.8).

1.1.2 Cable installation tension prediction for cables pulled into ducts

The potential for providing very long lengths of optical fibre cable can lead to the need for confidence that a particular installation operation will be successfully achieved, particularly in underground ducts, and a good indication can be provided, in some cases, by calculating the maximum cable tension. This maximum tension can be compared with the stated mechanical performance of the cable, and where these values are close, consideration can be given to methods for providing a greater safety margin such as an alternative cable design, shortening the route, changing the route or direction of cabling, provision of intermediate winches, or by taking special precautions at particular locations. Calculation considerations are indicated in Figure 3-1. Here the cable is approximated as flexible, and the route between deviations and inclinations is considered straight. When taking into account cable stiffness and undulations in the trajectory, the results may differ.



T = Tension at end of section (kN)
Ti = Tension at beginning of section (kN)
μ = Coefficient of friction (between cable and duct or guide)
l = Length of section (m)

w = Cable specific mass (kg/m)
θ = Inclination (radius, + = up and – = down)
β = Deviation (horizontal plane, radians)
g = Acceleration due to gravity (9.81 m/s²)

Figure 3-1 – Cable tension calculation

The following main contributory functions need to be considered when calculating cabling tensions.

i) the mass per unit length of cable;

ii) the coefficient of friction between cable sheath and surfaces with which it will come in contact;

iii) deviations and inclinations.

Examples:

Straight sections $T = T_i + \mu lwg \times 10^{-3}$

Inclined sections $T = T_i + lwg(\mu \cos\theta + \sin\theta) \times 10^{-3}$

Curved sections $T = T_i\, e^{\mu\beta}$

Using the route and common tension formulae in Figure 3-1 as an example, total tension can be calculated on a cumulative basis working through each section from one end of the route to the other as indicated in Table 3-1. (For example, $\mu = 0.55$ and $w = 0.92$ kg/m.)

Table 3-1 – Example of cable tension calculation

Section	Length (m)	Tension Eqn 1 (kN)	Incl. (radians)	Tension Eqn 2 (kN)	Deviation (radians)	Tension Eqn 3 (kN)	Cum. Tension (kN)
A-B	250	–	0.10	1.47	–	–	1.47
at B	–	–	–	–	1.57	3.49	3.49
B-C	160	–	0.17	4.51	–	–	4.51
C-D	100	5.01	–	–	–	–	5.01
D-E	20	5.11	–	–	–	–	5.11
at E	–	–	–	–	0.79	7.87	7.87
E-F	60	8.16	–	–	–	–	8.16
at F	–	–	–	–	0.52	10.88	10.88
F-G	200	–	0.13	11.65	–	–	11.65

NOTE – Where more than one cable per duct is installed, tension can be greatly raised and it is necessary to take account of this by applying a factor before the deviation calculation. Factors vary with the number of cables, sheath/cable materials, cable/duct sizes, cable flexibility, etc. Values can be in the order of 1.5-2 for two cables, 2-4 for three cables, and 4-9 for four cables.
Factors also depend on relative size; e.g. for 2 equal cables the jamming factor f_{jam} follows:

$$f_{jam} = \frac{D_d - D_c}{\sqrt{D_d (D_d - 2D_c)}}$$

Here D_d is the inner diameter of the duct and D_c the diameter of the cables.

1.1.3 Cable overload protection methods

Where all actions and precautions have been taken to protect the cable and its fibres from excessive load as far as suitability of route, guiding, etc. is concerned, then there still remains the possibility, in the dynamics of an installation operation for high loads to be applied to the cable and it is therefore necessary to provide a cable overload prevention mechanism. There are two classes of device to provide this protection: those situated at the primary or intermediate winch and those at the cable/rope interface. Those at the winch include (depending on winch type) mechanical clutches, stalling motors and hydraulic bypass valves which can be set to a predetermined load and the dynamometer/cable tension monitoring type systems to provide feedback for winch control. Those at the cable/rope interface include mechanical fuses (tensile or shear) and sensing devices to provide winch control information. All these systems have a common aim of limiting or stopping the winching operation when loads applied on the cable approach a damaging level (Figure 3-2).

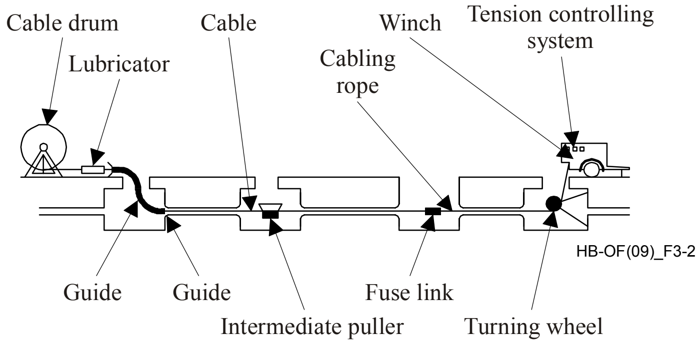


Figure 3-2 – Optical fibre cabling in underground duct

1.1.4 Winching equipment and ropes

Provided the need for overload protection is borne in mind, most normal speed controlled cable winching equipment and systems are suitable for installing optical fibre cables in ducts. These include end-pull winches, with various types of primary mover, intermediate winches for longer length schemes and where necessary, powered cable feeding equipment.

Where intermediate winches (capstan or caterpillar) and/or powered cable feeding equipment are used, a method of synchronization, to prevent excessive fibre strain, should be employed; it should be borne in mind that some intermediate capstan type winches can introduce a twist into the cable. Ropes or lines of low specific weight and a high modulus of elasticity are necessary for optical fibre cabling. Placing long lines or ropes can be difficult, but can usually be accomplished by using normal installation methods successively. Lines or ropes must be placed using care, where there are already optical fibre cables in a duct; knots in the lines or ropes must be avoided.

1.1.5 Guiding systems and cable bending

Bending optical fibre cable under tension during installation should be undertaken with care. Guiding systems and equipment should be examined for their suitability for purpose and take into account cable manufacturers' stated bending criteria. In general, a minimum bending radius of around twelve times the cable diameter is considered appropriate, but when being installed under tension, it is suggested that this ratio should be doubled. Most guiding equipment can be used for both optical fibre and metallic cables, but the laying of long cable lengths may require many guiding elements and they should all have the properties of lightness and low friction.

1.1.6 Cable friction and lubrication

Special attention should be paid to friction and lubrication when installing optical fibre cables. The friction forces which must be overcome are related to several factors, primarily the materials and finishes of the cable sheath.

1.1.7 Cable handling methods to maximize installed lengths by pulling

Where it is not possible, because of load limitations, to install long length optical fibre cables using a single end-pull, it may be necessary to employ a method of dividing the load along the cable length and this can be done, depending on circumstances, by either static or dynamic methods.

The most common static method is known as the "figure-of-eight system". This procedure requires the cable drum to be placed at an intermediate point and cable drawn in one direction of the route by normal end-pull techniques. The remaining cable is then removed from the drum and laid out on the ground in a figure-of-eight pattern. The winch is then moved to the other end of the section and the laid out cable is drawn in using the same end-pull method. This method requires appropriate space at the figure-of-eight point.

Dynamic load sharing is more complicated and requires more equipment and setting up; however, it has the advantage of allowing installation in one direction straight from the drum. In this process special cable winches are employed at intermediate points and the maximum load on the cable is related to the distance between these intermediate points. It should be borne in mind that with intermediate winching all the installing forces are transmitted through the cable sheath and the design of a particular cable being placed by this method should take this into account. Intermediate or distributed winching systems require good coordination, synchronization and communication between the intermediate points. Capstan type intermediate winches may introduce additional cable twisting.

Hand-pulling methods can be employed at intermediate points on long length optical fibre cable installation, but great care must be taken to ensure that minimum bending and other mechanical criteria are not contravened.

1.1.8 Air-assisted cable installation

Air-assisted installation is based on forcing a continuous high-speed airflow along the cable with an air source. Moving air force pushes the cable and makes it advance forward at a typical speed supported by the equipment.

Generally, the load on the cable is an order of magnitude lower than the typical force involved with other installation methods, like pulling techniques, reducing installation hazards. Additionally, with this technique, bends in duct run are not as important a matter of concern as they are in pulling techniques, so that installation speed increases and longer lengths of cable can be installed. Cables are installed without virtual stress, leaving the cable relaxed in the duct upon completion of the installation.

Different systems using blowing techniques have been developed to install bundles, cables or fibre into tubes or ducts.

The first of these consists of a two-pass process, where the tube is installed prior to the installation of the fibre. In this method, initially a bundle of tubes (micro-ducts), either loose or constructed as a cable, is installed using normal or blowing techniques. Jointing and branching of tubes within the fibre route can be easily done using simple push-fit connections. As fibres are required, either sheathed bundles of fibre (4 or 8 fibres), typically < 2 mm in diameter, or larger micro-duct cables (e.g. 96 fibre cables, typically < 7 mm in diameter) are blown by compressed air into the pre-installed tubes with an insertion speed of about 2 km/h. By this method of installation, the fibres experience little or no strain. Cable routes of up to 10 km without the need for intermediate splices can be achieved.

A second system has been developed and used in which normal, rather stiff, optical fibre cables are blown by compressed air into small pipes or ducts. Depending upon the cable characteristics (diameter, weight, flexibility), the duct diameter, the friction between the cable and the duct and the number of curves in the overall duct run, installation units may be placed every 500, 750 or 1 000 metres. No matter how many installation units are used in tandem, there is never a synchronization problem. The cable is installed at about 2 km/h. Pre-lubrication of the ducts will increase the distance over which one unit can install a cable. The cable itself can also be lubricated, with the help of an in-line cable lubricator with air-bypass.

(For further information, see Recommendation ITU-T L.57.)

1.1.9 Water pumping system

The water pumping system (floating technique) is based on forcing along the cable route, by means of a pump, a suitable water flow (Figure 3-3). The water thrust minimizes the friction effect generated between the cable and the duct during the installation process. The water pumping system can be used with or without a parachute (piston) attached to the cable end. In the first situation the water pressure exerts a pulling force on the cable end. In the latter situation this is not the case. But, here the moving water (faster than the cable) exerts a distributed action on the cable that pushes it forward at a speed in the range 30-40 m/min.

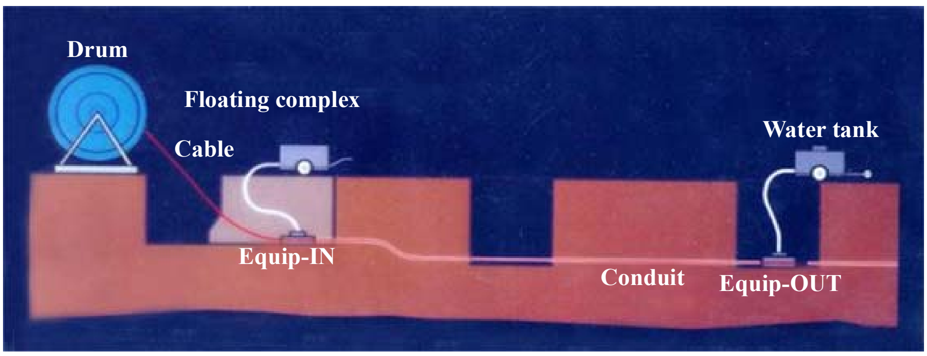


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Figure 3-3 – Schematic layout of water pumping

With this technique, the applied forces on the cable are lower than those applied in the case of the use of pulling techniques, thus reducing the installation hazards. Additionally, the presence of bends along the cable route becomes a less significant factor compared with the pulling technique. Fluid speeds of 1 m/s are advisable for heavy optical cables (around 300 kg/km).

Cables are installed without virtual stress, leaving the cable relaxed in the duct upon completion of the installation. Finally, water floating does not cause a significant increase of the duct temperature, providing another advantage over those systems that use gas as a laying element.

In the situation with parachute (piston) attached to the cable end, a piston that seals to the duct is connected to the pulling eye of the cable. The piston and the end of the cable are passed through a water injection device, which is attached to the duct. Water is than pumped into the duct through the water injection device, and pushes the piston through the duct. The cable is pulled along by the piston. The flow of the water hydraulically assists the passage of the cable through the duct and provides some lubrication. A relatively small, gasoline powered pump can install a kilometre of cable in a few minutes. Cable lengths of several kilometres have been installed using this method (Figure 3-4).

(For further information, see Recommendation ITU-T L.61.)

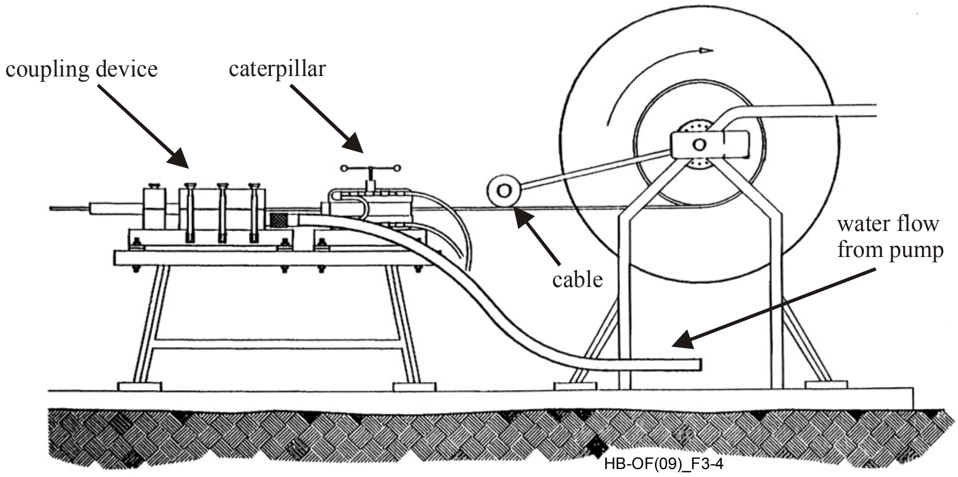


Figure 3-4 – General assembly of the floating machine

1.1.10 Jointing length allowance

It is important when installing optical fibre cable lengths in underground ducts to make proper arrangements for an adequate extra length of cable at the access point for testing and jointing. This additional length, at each end of the cable, is normally greater than that allowed for metallic cables and should not include that part of the cable used for the rope attachment, which is not suitable for jointing.

1.2 Installation of optical cables with the trenchless technique

The trenchless techniques (or no-dig techniques) allow installation of underground optical cables minimizing or eliminating the need for excavation. These techniques create a horizontal bore below the ground in which the underground infrastructure (ducts, pipes or direct buried cables) can be placed. Trenchless techniques can reduce environmental damage and social costs and, at the same time, provide an economic alternative to open-trench methods of installation.

(For further information on these installation techniques, see Recommendation ITU-T L.38).

1.2.1 Trenchless techniques and their applications

There are several different trenchless techniques. Their classification and detailed description are in Recommendation ITU-T L.38. The scheme of one of these methods is shown in Figure 3-5.

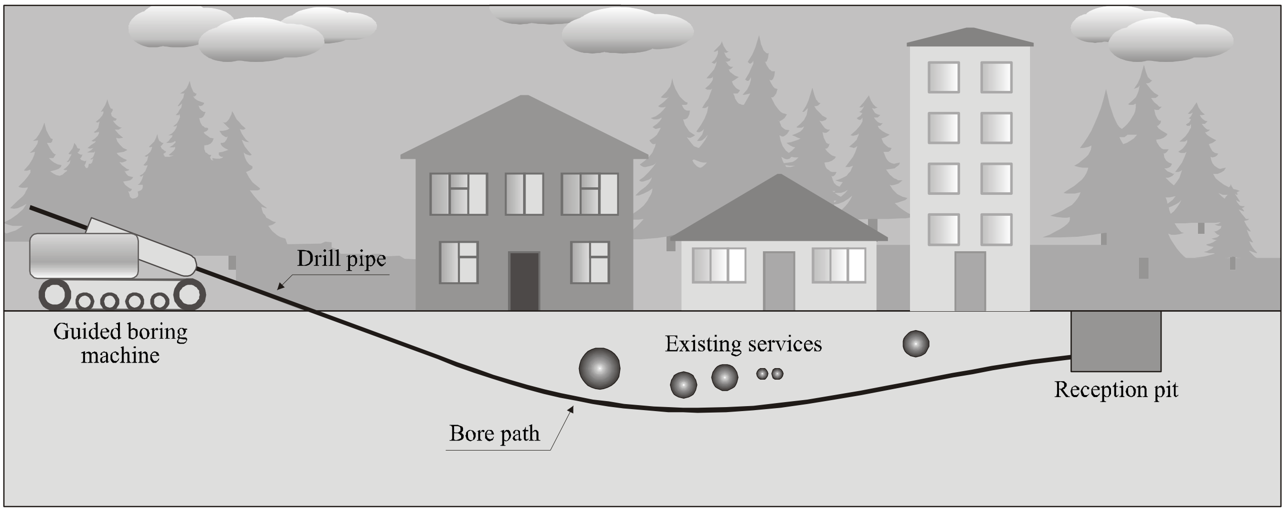


Figure 3-5 – General scheme of the directional drilling technique: drilling the pilot hole

From a general point of view, the trenchless techniques are very useful in the following situations:

i) where road surface excavation is restricted or prohibited by administrative agencies, etc. (newly constructed roads, emergency vehicle entrances/exits, etc.);

ii) where the open-cut method cannot assure safety or would cause risks to traffic and pedestrians;

iii) where noise, vibration, dust and other pollution are caused by open-cut method;

iv) where the open-cut method may impede road traffic and thus hinder the business of nearby stores;

v) where congested sections where open-cut method may damage the buried facilities of other companies or sections where the presence of buried objects causes significant lack of work efficiency;

vi) where conduits should be buried at deep locations and open-cut construction would greatly increase the amount of excavated soil;

vii) where road surfaces use high-grade material which would increase the cost of reinstatement after excavation;

viii) where road sections with high traffic volumes limit the work to the night-time hours (lower work efficiency, higher labour costs);

ix) where open-cut construction would involve extra costs to move historic remains or other items.

The choice of the most suitable technique to be adopted is related to each type of application, as outlined in the following.

Long installation lengths can be achieved (several km) by dividing the work length into shorter sections (100-200 m as an average). The length of each section will depend on the characteristics of the machines and the design requirements. Boring/directional drilling (both fluid-assisted and dry boring) machines should be used for this particular application.

River and railway crossings were the first applications of trenchless technology due to the fact that traditional digging techniques were not suitable. Surface-launched machines are often the best solution because obstacles can be crossed with a curved drilling path, thus avoiding the need to excavate deep launch and reception pits (especially in river crossings). It is possible to consider two different kinds of crossing with respect to the length and to the depth of the installed duct:

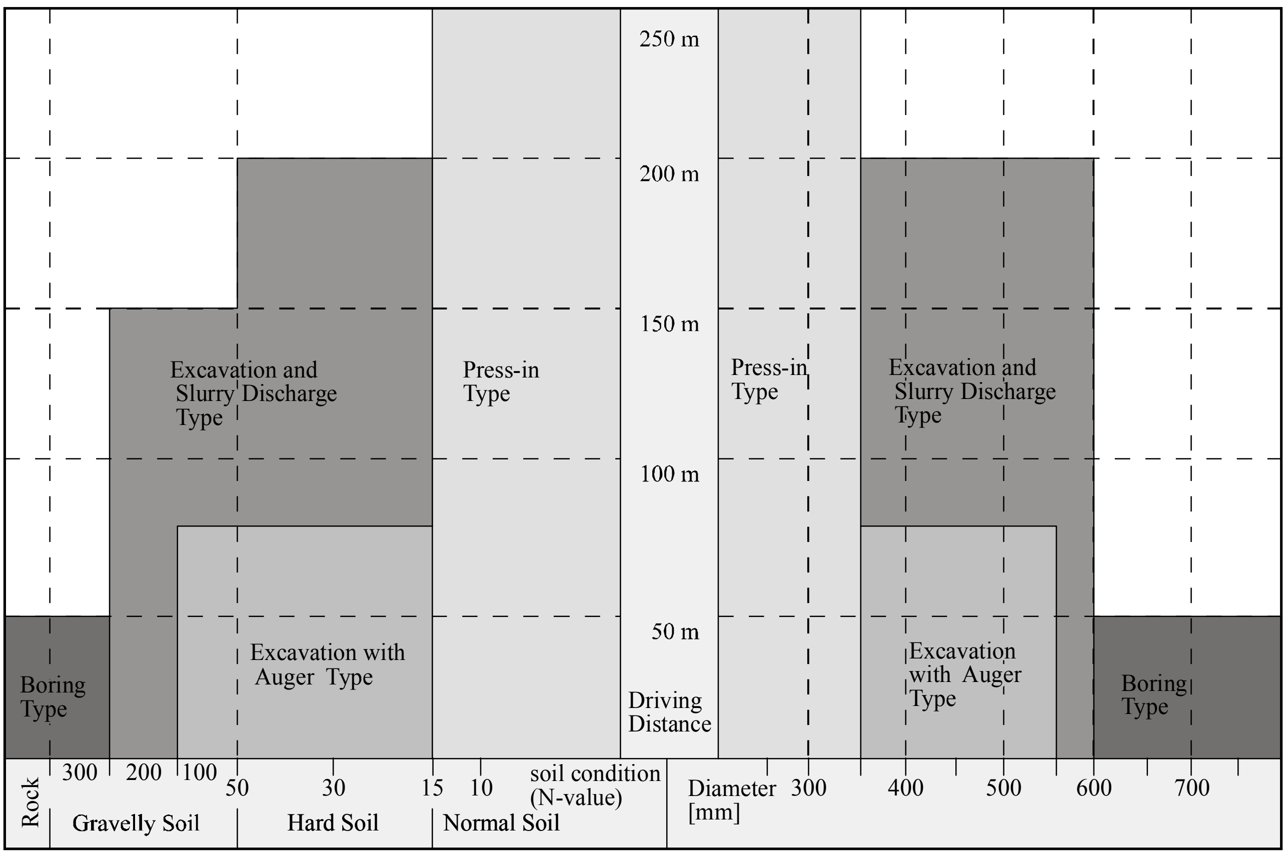
i) road and railway crossings. For both, the length of the drilling is normally not very long, so that both fluid-assisted and dry directional drilling machines can be used, or the use of micro-tunnelling systems depending on the duct diameter;

ii) river crossings. The length and the depth of the bore normally required are very long and deep, and it is important to avoid the excavation of big launch and reception pits on the opposite sides of the river. For these situations the drilling is started directly from the surface using a fluid-assisted directional drilling system.

<u>*Urban environments*</u> are also very attractive for the application of trenchless technology because it could avoid, or drastically reduce, the troublesome drawbacks normally created by digging work in urban areas. Due to the small diameters of the ducts and the short distance of each drilling section (manholes or chambers are normally very close together), a small and dry directional rig is used, in order to reduce the overall dimension of the working site, and to avoid flooding of the drilling fluid along the drilling path and the use of microtunnelling systems, depending on the duct diameter.

Moreover the choice of the trenchless technique to be adopted depends upon other elements such as the soil conditions. A general view of the impact of the soil conditions is given in Table 3-2.

Table 3-2 – Fields of application of different microtunnelling excavation techniques as a function of driving distance, tunnel diameter and soil conditions



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The four above-quoted microtunnelling excavation techniques are described in Recommendation ITU-T L.38.

Therefore, an investigation of the soil in order to get information, not only about the position of buried objects, but also on the nature of the ground is very important. There are several techniques for the investigation of the soil, which are detailed described in Recommendation ITU-T L.39. The data obtained by this investigation are necessary to plan the execution of work using trenchless techniques and to optimize the drilling path thus avoiding the risk of damage to both the existing infrastructures and the drilling equipment.

1.3 Installation of optical cables with the mini-trench technique

(For further information on this installation technique, see Recommendation ITU-T L.48).

The so-called mini-trenching technique allows the installation (in small trenches) of underground optical cables in ducts. The advantages of this technique over conventional cable laying technologies lie essentially in its speed of execution, lower cost, significantly lower environmental impact and limited disruption to road traffic and, as a consequence of the previous items, easiness in obtaining permits for the taking over of public area.

The mini-trenching technique can be applied on routes that generally involve asphalted surfaces such as roads and sidewalks with a compact soil subgrade.

It is not recommended that the technique be used on routes where the soil subgrade is sandy, gravelly or contains medium-sized cobbles (i.e., measuring 10 to 20 cm in diameter). If other underground utilities crossing a planned route already exist at a depth interfering with the depth of the mini-trench, this technology is not appropriate.

1.3.1 Traditional mini-trench (10 × 30 cm)

Mini-trenching is normally carried out by simultaneously cutting through the paving and digging a trench whose depth and cross-section vary in accordance with the number of ducts to be laid: depth is normally between 30 and 40 cm, while cross-section can vary between 7 and 15 cm. In order to guarantee a protection against impact resulting from road-repairing, the depth of the laid infrastructure shall be maintained constant at a known level that must be 5 cm deeper than the foreseen asphalt cutting depth normally specified for road surface repair works.

Figure 3-6 shows one of the possible installation configurations that can be used. Which configuration is selected will depend on the type of machinery employed and the number of ducts or cables envisaged in the project.

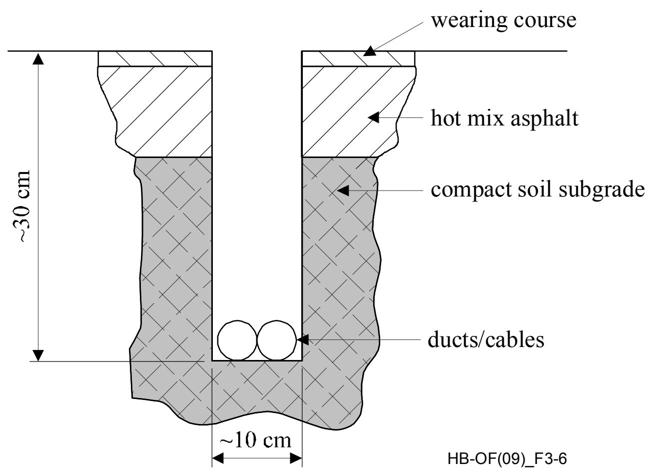

Figure 3-6 – Example of mini-trenching installation configuration

In cases where the mini-trench is dug along a road with no curb or sidewalk, the excavation shall normally be located at distance of around one metre from the edge of the road (or, if possible, just on the external side of the lateral line). In special circumstances where this is not possible, the mini-trench may be dug in the shoulder at the edge of the asphalt. Any crossings through unpaved sections (which must in any case have a compact subgrade) should be carried out using the same technique.

1.3.1.1 Traditional mini-trench preparation and duct/cable laying

The mini-trench is excavated using appropriate disc-type cutting machines.

The designed route shall be free from sharp changes in direction. Where such changes are unavoidable, they shall be made by means of cuts angled so as to comply with the minimum bend radius specified for the ducts and cables.

The location of all underground utilities must be determined in order to establish the correct route for the trench. This is normally accomplished by means of cartographic documentation provided by the administrations that own the road or by the utility company, and/or through instrumented field surveys. Where other means of determining the location of underground utilities are not available, ground penetrating radar shall be used at detection depths up to 1 metre.

The infrastructure or cables can be installed in two ways:

i) simultaneous excavation and ducts or cables laying. Reels can be mounted on board the cutting machine so that the duct or cable can be automatically fed into the trench, via a suitably shaped guide integrated into the ploughshare, as excavation proceeds. If obstacles or situations are encountered which make it impossible to proceed with the mini-trench, the reel (and thus the ducts or the cable) can be removed from the cutting machine without having to cut the ducts, thus ensuring that cable deployment can be continued using conventional methods without performing splices that are unnecessary from the technical standpoint.

ii) non-simultaneous excavation and duct- or cable-laying. After completing the excavation, ducts or cables are installed using the conventional method and in accordance with the requirements specified in the installation standard. Ducts and cables installed in trenches shall maintain their initial configuration and position in the excavation, unless special circumstances dictate otherwise.

After the ducts or cables are installed, the mini-trench is backfilled by pouring concrete (e.g. 200 kg/m^3 cement) with suitable foaming additives to ensure that a large amount of air is entrained, thus making the resulting structure mechanically as similar as possible to the soil subgrade surrounding the trench. In addition to securing the infrastructure in position at the bottom of the mini-trench, backfilling materials provide ducts and cables with mechanical protection.

Where interference with other utilities can occur and it is not possible to comply with the spacing requirements envisaged by current regulations, ducts shall be provided with mechanical protection in accordance with applicable standards and regulatory requirements.

Where the infrastructure is installed near trees whose roots could cause damage, it shall be protected by means of U-shaped galvanized steel raceways of suitable dimensions, equipped with covers and embedded in the same type of concrete backfill envisaged for the excavation.

Resurfacing should be delayed until at least 24 hours have passed from the time the mini-trench was backfilled.

1.3.2 The enhanced mini-trench

Further mini-trench technique development has resulted in a new solution in which all phases of duct/cable laying are simultaneous.

In details, the enhanced mini-trench is characterized by reduced dimensions of 5 cm wide and 30 cm deep (mini-trench 5 × 30), In the enhanced mini-trench 5 × 30 it is possible to lay one Ø 50 mm duct or two (one laid upon the other) (Figure 3-7).

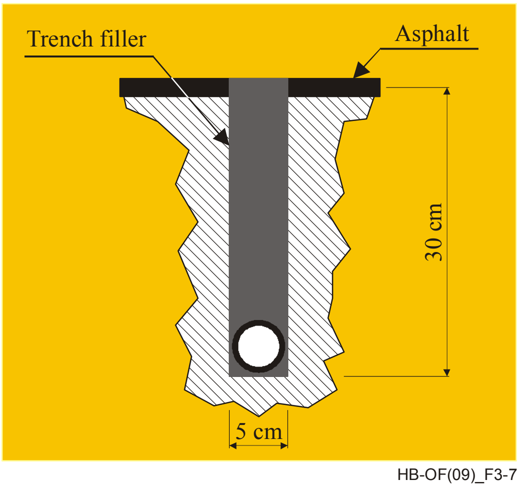

Figure 3-7 – Example of mini-trench 5 × 30 cm configuration

The enhanced mini-trench allows one to operate with smaller machinery on narrow roads, producing a lower quantity of waste material and thereby reducing operating expense. In order to execute the mini-trench 5 × 30 technique, a new digging technology can be used, characterized by the simultaneous use of a trench saw and a suction pump, by rapid excavation, and by the use of a very fast hardening material to fill-in the trench (Figure 3-8).

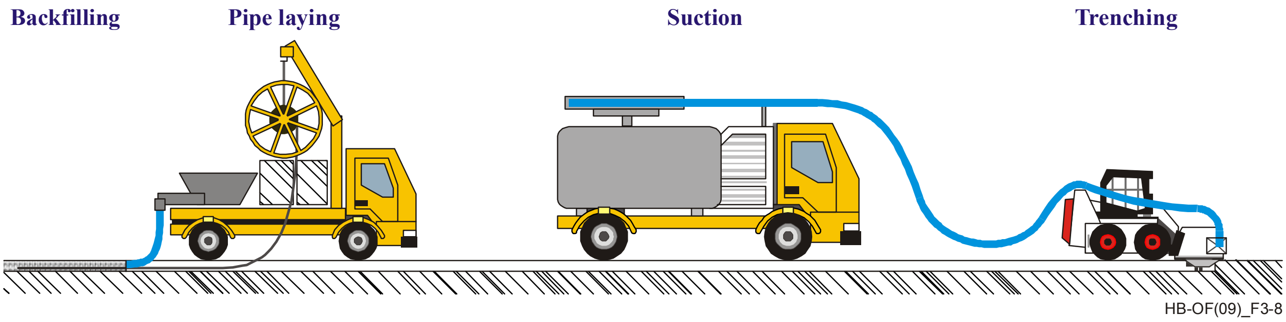

Figure 3-8 – Schematic layout of enhanced mini-trench 5 × 30 cm technology

This advanced solution allows both flexible use of smaller machines and reduction of time and space occupancy (Figure 3-9).

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Figure 3-9 – Example of application of enhanced mini-trench 5 × 30 cm technology

So, this solution can operate both in urban and in non-urban environments. All the construction activities are split into separate operational steps involving subsequent phases:

i) trenching dig phase, characterized by small size saw disks, allowing utilization of small operating machines;

ii) material debris suction phase, characterized by innovative operation(sawing and debris suction/ removal carried out at the same time), sharp and clean trench, debris suction and immediate loading on a debris removal truck;

iii) backfilling phase (after cable/duct laying), characterized by use of highly resistant and fast hardening material, no waste of back filling material, lack of bitumen materials, vehicle traffic restoration within 1 to 2 hours, high compatibility with mechanical and visual characteristics of existing pavement surface.

1.4 Installation of optical cables with the micro-trench technique

(For further information on the installation with the micro-trench techniques, see Recommendation ITU-T L.49.)

The micro-trenching technology can be applied on routes that involve asphalted surfaces, such as roads or sidewalks with a base of compact material (asphalt or concrete).

Its advantages over conventional cable-laying technologies lie essentially in its speed of execution, major reduction in infrastructure deployment costs, and significantly lower impact on the environment and on road traffic.

Protection against breakage from road reparation is not possible due to the shallow depths used in micro-trenching techniques. It is therefore essential to carefully plan the routes on which these techniques are to be used, in order to provide long-term stability of the routes.

Micro-trenching is normally carried out by cutting a shallow groove in the asphalt (better if not less than 7 cm), but without penetrating past the asphalt layer. Care must be taken to avoid cutting entirely through the asphalt, as this could cause the pavement along the sides of the groove to crack or split.

This precaution must be borne in mind in all cases where there is no lateral protection on one or both sides of the groove, which can prevent the asphalt layer from shifting, and particularly in cases where micro-trenching is performed along the edge of a road with no curb or sidewalk. In such cases, the groove shall normally be located at a suitable distance (e.g. at least one metre) from the edge of the road.

Groove width may vary (e.g. 10-15 mm) in accordance with the diameter of the cable laid.

The cable should meet exacting demands as to crush resistance and, in particular, temperature resistance, which is needed when sealing the cable in the groove with hot bitumen. The bitumen temperature during the sealing operation can reasonably vary between 100° C and 170° C.

The optical fibres are preferably enclosed in a metallic (e.g. copper) tube filled with a suitable filling compound and surrounded by a polyethylene jacket. There are currently in use different cable types, containing varying numbers of fibres and with different outside diameters.

The cable can be manufactured and supplied in long lengths; in city networks it is, however, often convenient to use short or matching lengths, particularly for crossing under road or rail.

1.4.1 Micro-trench preparation and duct/cable laying

As is customary, a detailed survey of the route must be carried out, the purpose of which is to identify the work required to be done before starting cable installation operations. Such work could include, for instance, the preparation at bridges, or at road or rail crossings. Furthermore, it is necessary to determine closure locations and section ends.

The route subsoil, i.e., asphalt thickness, road or sidewalk composition may have to be investigated by test drillings.

Micro-trenching is performed using an asphalt cutting machine. Cutting speed will depend on the type of machine used. The route shall be free from sharp changes in direction. Where such changes are unavoidable, they shall be made by means of cuts angled as illustrated in Figure 3-10.

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Figure 3-10 – Sharp change in route direction

The cable can be installed manually in the micro-trench, laying it gradually off the reel and into the bottom of the groove with the aid of a reel trolley.

While changes in direction are permissible, care must be taken not to exceed the minimum cable bend radius.

A retaining strip (e.g. an expanded polyethylene strip) shall be run into the groove, above the cable, to fix it in place inside the groove. The retaining strip shall then be covered by a highly water-repellent filling material (e.g. a rubber strip), whose dimension shall be slightly greater than the groove cross-section. Each strip shall be fixed in place using a suitable roller.

In addition to securing the cable to the bottom of the groove, the primary function of these filler materials is to provide mechanical protection for the cable. The rubber strip also provides thermal protection.

After the cable and protective strips have been installed, the groove shall be closed with hot liquid bitumen. To ensure that the bitumen adheres to the side walls of the groove and creates an effective seal, a liquid bonding agent (primer) shall be first applied to the entire length of the groove and the groove edges. Liquid bitumen shall be applied using an appropriately sized nozzle. This operation shall be performed in a way (e.g. two consecutive passes) to ensure that the groove is filled uniformly up to road level. To ensure that the groove is correctly filled and sealed, the primer and bitumen shall be compatible.

At the end of the operations described above, measurement shall be carried out (e.g. by means of a wheel track) in order to ensure that there are no uneven edges, steps or irregularities along the cable groove as a result of overfilling with liquid bitumen. These conditions must be maintained over a long period of time.

The micro-trenching cable laying technique is typically used for customer drop connection to the distribution network (connections to existing networks).

These connections shall normally be routed along two physically separate paths.

In addition to the information which is normally required (cable route, type of installation, installation in road, sidewalk, etc.), cartographic documentation for cables installed using the micro-trenching technique shall also indicate reference depth relative to known datum points.

1.5 Installation of aerial cables

1.5.1 Installation methods

Installation methods of optical aerial cable include the normal practices for both self supporting cables (all-dielectric or including a metallic element) and lashed cables (e.g. attached to a pre-installed tension strand).

The mechanical stresses and, therefore, strain experienced during aerial cabling are generally less than those induced during underground placing and in a mixed underground/overhead route underground cable may, with care, be used for overhead sections.

1.5.2 Cable protection methods

In general, where end-pull or distributed pull methods are used, the various types of systems indicated in the above clauses to protect the cable from excessive strain during installation may be employed for aerial cable and it is good practice also to ensure that cable back-tension is always carefully controlled.

Where lashing to pre-tensioned support wire or existing metallic cable is employed, the optical fibre aerial cable must be constructed to withstand lashing. The lashing-wire tension must also be carefully controlled. Great care must be exercised when handling cable in aerial route installations.

1.5.3 Winching and guiding systems

Provided the need to protect from overload and over-bending is borne in mind, most normal aerial cable installation winching equipment including end-pull winches, intermediate winches, controlled cable feeding devices, etc., can be used (Figure 3-11). For long length installations, where end-pull or distributed-pull systems are used, it is very important that proper guiding equipment is provided at positions where sharp changes of direction occur, and every effort should be made to ensure pulling-in at an even speed.

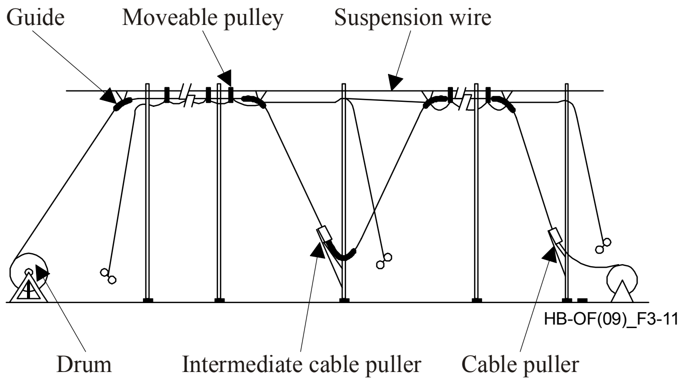

Figure 3-11 – Aerial cable pulling through system

1.5.4 Methods to maximize lengths

Where relatively unrestricted access to the route is possible, it is feasible in many cases to install, using a variety of normal methods, very long lengths of aerial optical fibre cable with the main limitation being only the capacity of the cable drum. However, where road or other crossings are involved and extra splices are not acceptable a system of pulling through this section must be devised. Also, where winching methods are used, cumulative friction effects limit the installation length and as with underground systems, intermediate winching systems may be employed. A way of reducing or limiting the strain in the cable during installation is to use the moving reel method, i.e. the cable is attached to the strand as the cable reel is moved along the pole line.

1.5.5 Jointing length allowance

It is important when installing aerial optical fibre cable lengths to make proper arrangement for an adequate extra length of cable at a pole position for testing and jointing. This length at each end of the cable must be sufficient to enable construction of joints and sheath closures at a convenient work position and it may be necessary to allow extra length for ground level operations.

1.5.6 In-service considerations

Great care should be taken during cable installation to minimize fibre strain, and with aerial routes in particular, steps to ensure that strain levels remain within manufacturer's recommendations during service. All types of movement, whether produced by cable weight, thermal changes, ice loading, or wind dancing, produce strain that must be taken into account and minimized where possible.

Where wind and/or ice and snow loading is anticipated or for long spans it may be necessary to use a higher strength strand than normal to prevent excessive strains due to sagging. Furthermore, the possibility of excess induced strain must be considered if an optical fibre cable is lashed to an existing cable. Cable dancing due to wind can cause excessive fibre strain in an aerial optic cable. Methods should be employed, such as dampers and springs, to reduce cable dancing.

Although optical fibre cables are generally light in weight, their addition to an existing suspension member can take the optical fibre beyond its recommended strain limit and the added dip and extension should be calculated before installation.

1.6 Installation of buried cables

1.6.1 Installation methods

Normal buried cable installation methods, including ploughing (direct, vibratory or winched), trenching and moling, can, in general, be used for direct burial of optical fibre cable, provided the cable is specifically designed for this type of application (Figure 3-12). The same depth of cover as for metallic cables is usually adequate, but traffic capacity or other considerations of security may indicate a requirement for greater depth. Where a trench method is used, back filling materials and practices may require particular consideration so that fibre strain limits are not reached during this operation.

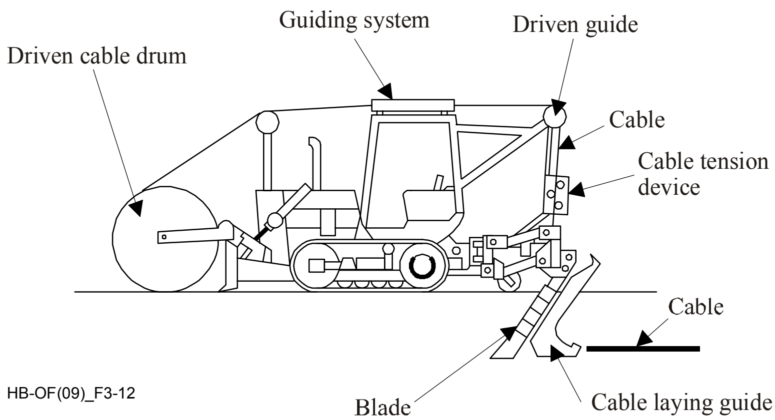

Figure 3-12 – Installation by cable ploughing

1.6.2 Cable guiding and protection

When ploughing methods are used the design of the guiding equipment between the cable reel and the cable laying guide must take careful account of specified cable bending criteria and have a low friction value to prevent fibre overstrain. Cable overload protection systems are not normally necessary but, where a large ploughing machine is used and there are driven cable reels and guide wheels, a tension device can be incorporated. In-service mechanical protection at road or service crossings, or in situations of high vulnerability, may be felt to be necessary.

1.6.3 Methods to maximize lengths

Provided proper preparations are made, direct buried installation of optical fibre cable is normally only limited by obstructions and, to a lesser extent, the reel capacity. However, where some parts of a long length, ploughed installation involve difficult ploughing through stony or rocky sections, preparation by slitting or trenching can be beneficial. A moving reel technique may also be used to maximize lengths installed.

1.6.4 Jointing length allowance

It is important where installing directly buried optical fibre cable to make proper arrangement for an adequate extra length of cable at both ends of a section for testing and jointing. This length must be sufficient to enable construction of joints and sheath closures at a convenient work position.

1.7 Installation of cables in tunnels and on bridges

Winching optical fibre by end-pull or distributed methods in tunnels can be considered a special case of cabling in ducts, and those methods and considerations indicated above for ducts apply. However, where cable is laid out and manually inserted onto trays or bearers, care must be taken to ensure that support geometry and handling operations do not contravene the specified bending criteria. Cleating and fixing systems must be suitable for use with optical fibre cables.

The normal considerations for placing metallic cable also apply to optical fibre cable to be laid on bridges, but with additional care required to counter cable movement in steep approach sections or vertical sections. This type of movement, which can be produced by traffic vibrations, could lead to excessive fibre strain and suitable cable restraints should be used.

1.8 Installation of optical fibre ground wire (OPGW) cable

(For further information on this type of installation, see Recommendation ITU-T L.34.)

Optical fibres are particularly suitable for use on the aerial power lines in high-voltage networks, because they are immune by electromagnetic influences. There are several types of cable and installation technology.

Among them, Optical Fibre Ground Wire (OPGW) cable technology is specifically designed for high-voltage power line installations. OPGW has the advantage of using the ground wire of a power line also for communications. However, users of OPGW need to be aware that if the cable fails it may not be repaired quickly. Therefore, an alternative routing for the optical circuits needs to be considered.

These cables consist of a nucleus containing optical fibres and an armour, generally composed of one or more layers of aluminium wire, steel wire or aluminium-coated steel wire. The additional features of these cables compared to others types of cable are basically as follows:

- i) greater tensile strength;
- ii) protection of fibres against excessively high temperatures when high current densities occur in the cable.

The following factors should be considered in determining the type of cable, maximum tension and the installation plan:

- i) maximum short-circuit current through the cable;
- ii) disconnection time of a short-circuit to earth;
- iii) sag of the phase conductors;
- iv) spans;
- v) positions in relation to poles;
- vi) maximum wind speed;
- vii) maximum ice load;
- viii) other aspects such as: risk of atmospheric discharge, fire, discharge of bird-shot, saline fog, aggressive chemical agents in the atmosphere.

The following installation materials and equipment should be used:

i) anchoring units. Used to lash the cable to the poles where necessary, they should be able to withstand installation tensions even under the worst working conditions envisaged (wind, ice), without damaging the cables or affecting their useful life;

ii) suspension units. Placed on poles that do not have a cable anchorage to support them. Their characteristics should be the same as those of the anchoring units;

iii) vibration suppressors. Used to absorb vibrations produced by the wind;

iv) pole clamp element. Used to fasten the cables and splice cases to the poles;

v) payoff reel with a brake in the spin axis. Used to maintain a certain tension in the cable to be installed;

vi) cable grips with anti-rotational device. Used to attach the OPGW cable to the pulling rope;

vii) sheaves. Located at the poles and used to guide the pulling rope and the cable during the installation procedure. To prevent damage to cable during installation, a minimum sheave diameter is needed. That diameter depends on the type of cable, the tension applied to it and the degree of deflection (typically 25 times the diameter of the cable or as recommended by the cable manufacturer);

viii) capstan. Used to pull the draw rope;

ix) splice cases. Used to house the fibre splices.

Recommendation ITU-T L.34 outlines the precautions that should be taken when handling the reels, all the steps necessary to string the cable, and what should be borne in mind for splicing.

1.9 Installation of optical cables along railways

(For further information on this type of installation, see Recommendation ITU-T L.56.)

Railway companies have become interested in laying optical cables along their own infrastructures. These installations could be used for internal communications of the railway companies, or be offered to other customers for public telecommunications.

Moreover, telecommunication companies could use the railway facilities to provide telecommunication services to their clients.

Types of cable and infrastructures used in these installations can be very different.

The cable core may have different configurations: tight tube, loose fibre in tube, loose fibre in groove and ribbon. Usually, the most common configuration is loose fibre in tube.

The type of sheath and armouring of the cables depends on several factors: design of the cable, method of installation and kinds of infrastructures to be used. Generally, totally dielectric cables or armoured cables with corrugates steel tapes, can be used in direct burying and in ducts installations. In aerial applications, totally dielectric cables are recommended. Another alternative to these aerial cables are Optical Fibre Ground Wire (OPGW) cables (see § 1.8). In this case, caution must be taken in order to avoid problems in the signalling system or traction line of the railway.

Several types of installations can be used: ducts, directly buried or aerial. In case of metallic armouring, periodic ground feed-through should be implemented. Recommendations ITU-T K.33 and ITU-T K.53 give guidance of this issue.

The choice of one among various types of infrastructures depends on the environment (urban area or rural area). Existing infrastructures should be used wherever possible. A study of environmental impact, regulations in each region and economic factors should be carried out in order to decide on the type of installation.

1.9.1 Duct installation

In duct installations, different cable designs can be used: totally dielectric cable, or metallic armoured cable.

Depending on the cable design, they should be installed in the duct by any of the traditional or blowing methods. In any case, all the precautions about handling cable, splice boxes, storage of excess length of cable and personal security should be taken into account.

In the case where the cable is laid into a concrete trench, which is then covered with plates, armoured cable is recommended.

1.9.2 Directly buried cable installation

In directly buried cable installation, it is recommended that a cable designed to protect optical fibres from external shocks, attacks from rodents, or any other harsh environmental conditions, should be chosen. Armouring with corrugated steel tape or any other type should be considered.

Any of the traditional methods of installation should be used, depending on the cable design.

1.9.3 Aerial installation

In aerial installations, the use of totally dielectric cables, is recommended. In some cases, armouring the cable against hunters, squirrels or birds might be necessary depending on the environmental conditions.

An alternative to the use of totally dielectric cables, could be the use of Optical Fibre Ground Wire (OPGW) cables. When using this type of cable, care must be taken to avoid any trouble with the signalling system or traction line. The aspects raised in Recommendation ITU-T L.34 should be taken into account.

Usually, poles of the railways power supply line shall be used for suspending or anchoring the cable. Another possibility is to use additional line poles, which could belong to the telecommunication provider.

Pole material for railways power supply can be concrete or iron. Additional line poles should be made of wood, concrete, steel, fibre or plastic, depending on the costs and environmental impact study.

1.9.4 Cable installation along existing railway poles

(For further information on this type of installation, see Recommendation ITU-T L.56.)

When using the railway's power supply pole line in the installation of the optical cable, cable can be suspended from the field side or from the railway side.

Minimum vertical distance from ground level (when cable is installed on the field side) or from the top of the rail (when cable is installed on the railway side) to aerial cable shall be more than 5 metres and less or equal to 10 metres. Horizontal separation from the live conductor will depend upon the design of the pole line, taking into account the safety requirements for workers.

Span length (distance between poles) depends on the laying characteristics and the cable design.

A nominal cable sag not exceeding 3% is recommended.

Cable should be suspended on all the poles in the appropriate way, depending on the cable design and the laying characteristic. A common way to do it is using clamps or pulleys.

At special positions (splice points, end of the route, every given number of poles, etc.), the cable should be fixed to the pole.

1.9.5 Particular cases

Cable installation through singular points, like tunnels or bridges, requires some additional protection or special precautions (e.g. fire retardant sheaths).

In case the cable is installed in tunnels, it shall be bound in an appropriate way: fixing it on a support, on the wall with staples or using ducts.

In case the cable is installed on bridges, it is recommended to use ducts.

1.9.6 Splice points along railways

When splices are installed in manholes, the suitability of making the splices inside or outside the manhole should be considered, as well as the characteristics of the splice box, cable, manhole and personal security. In any case, a length of cable should be stored in the manhole in order to allow the correct fulfilment of the splice. Usually, a minimum length of 5 metres from each end is recommended when splicing takes place inside the manhole. When splicing takes place outside the manhole, a minimum length of 10 metres is recommended. Anyway, stored cable length will depend on the characteristics and dimensions of the manhole and the splice box.

In aerial installations, splicing can take place on the top of the pole or on the ground. As in the previous case, a length of cable should be stored in the pole for cable splicing purposes. Stored cable length will depend on the position of the splice box and the place where the splice is carried out. The suitability of making the splice at the top of the pole or on the ground should be considered, according to personal security and the characteristics of the cable and the splice box.

In any case, cable should be wound and fastened in such a way that the minimum bending radii indicated by the manufacturer is respected.

Inside the manhole, the splice box should be fixed directly on the wall or using an appropriate support, depending on the box design.

In aerial installations, it is recommended fixing the splice box on the pole, avoiding fixing it in line with the cable.

It is recommended to avoid the installation of the splice box inside tunnels or bridges. If it is not possible to avoid its installation inside a tunnel, the splice box should be fixed on a support or directly on the wall.

1.10 Installation of cables in sewer ducts

(For further information on this type of installation, see Recommendation ITU-T L.77.)

Optical cable installation in sewer ducts presents many advantages compared with traditional trench installation techniques, such as: less time for cable laying, not limited by weather conditions, increased protection of cable against damage, no traffic disruption, no noise pollution, no excavation, no damage to road surfaces and underground installations, no heavy equipment, no inconvenience to businesses or to citizens.

In general, there are two categories of sewers: man-accessible and non-man-accessible sewers.

The definition of whether a sewer is man-accessible or not depends not only on national regulations, but also on the individual regulations of different sewer network operators. Usually, non-man-accessible sewers have diameters between 200 mm and 700 mm.

Installation in non-man-accessible sewers is carried out with the help of robots. In man-accessible sewers, both robot-assisted and manual installation of cables is feasible.

Basically, there are three different methods to install optical cables into sewer ducts:

i) traditional optical cables or micro-cables, designed to be installed in protective ducts which have to be installed before the cable installation;

ii) self-supporting optical cables, designed to be directly suspended at the top part of sewers;

iii) special armoured optical cables, designed to be directly installed at the bottom of the sewers.

The sewer optical cables and/or related infrastructure should be designed and manufactured for an expected operating lifetime of at least 15 years. It should be possible to install or remove the cable to/from the sewer throughout the operation lifetime. The materials in the sewer optical cable and/or the related infrastructure shall not present a health hazard within its intended use.

1.10.1 Sewer assessment

Exact information about the structural condition of the sewer networks in which cable systems are to be installed is to be considered as a prerequisite. It must be clarified whether the pipes are suitable with respect to their structural/operating condition, capable of being used for the installation of an optical cable. Furthermore, in the case of non-man-accessible sections, it must be determined whether these are suitable for installation by a robot. Thus, for example, significant structural changes in the sewers (collapse) or promontory pipe junctions can hinder the use of robots or even make their use impossible if other remedial measures are unable to solve the problem.

The static bearing capacity of the sewers and their suitability for rehabilitation measures must be estimated using the results of the assessment. Equally important to the assessment of the static bearing capacity, the hydraulics must be checked with respect to the reduction of the section caused by installation of the cable. This will determine whether one or, if necessary, even several cables can be installed in a pipe or sewer. In planning the cable routes, the experience of the sewer network operator with respect to loading and strategic planning for the future, additional discharges into the sewer must be taken into account.

The operation of the sewer networks must not be affected by the installation of cables. The cables must adhere as much as possible to the pipe ceiling. The technology used must also ensure that the sewer ducts are not damaged during the installation or the operation of the cable network. In the area of the manholes, the cables must be laid so that solids cannot be caught on them and in such a way as to ensure safe accessibility to the manhole.

A suitable grounding system is documented to avoid the formation of high induced voltage and sparking, which is absolutely not acceptable in locations with explosion hazards, such as the sewer systems. At the entry and exit of sewer pipes, a connecting point for equipotential bonding between all the metallic parts of the infrastructure and the cables must be provided, measured and documented.

1.10.2 Installation in non-man-accessible sewers

Installation in non-man-accessible sewers is made by robots and shall be damage-free when using all types of pipe material (vitrified clay, plastics, concrete, etc.). Anchoring installation methods in non-man-accessible sewers are not recommended as the sewer pipe wall thickness is weakened by drilled holes and might break due to the heavy load or pipe sagging. Later alterations and extensions of manhole installations and/or of the telecommunications network shall be possible.

The optical cable infrastructure consists of protective conduits fixed, by using a robot, to the sewer duct by special clamps equipped with clips. All the materials used for the infrastructure in the sewer pipes must be of stainless steel type to ensure the mechanical protection in the sewer environment and the protection against rodents for the optical cable.

Protective conduits shall be corrugated tubes. The corrugated steel tubes are available with an outer diameter of 11.5 mm or 15.5 mm in order to cause only a negligible reduction of cross section.

Flexible cable trays can be used to guide and protect the optical cables in sewer manholes if the protective conduits cannot pass the manhole or if an over-length storage box or a cable closure has to be installed in the manhole.

All the parts shall be designed to guarantee the minimum allowed cable bending radius on the entire network installed into the sewers.

The optical cables are blown into the conduits. The necessary equipment and procedures are similar to the standard installation of optical cables outlined in § 1.1.8.

It is recommended that the maximum diameter of the cable be 70-80% of the corrugated steel tube diameter. For example, for the installation in a 11.5 mm corrugated steel tube, the maximum diameter of the cable is 9.2 mm; for a 15.5 mm tube, the maximum cable diameter is 11.5 mm.

1.10.3 Installation in man-accessible sewers

The optical cable infrastructure consists of protective conduits fixed to the sewer wall by special clip holders equipped with clips, in which protective conduits can be fitted. All the materials used for the infrastructure in the sewer pipes must be of stainless steel type to ensure mechanical protection in the sewer environment and protection against rodents for the optical cable.

The clip holders are straps fixed by the operators with expansion bolts. The wall thickness in sewers with a nominal diameter of 800 mm and above allows for the holes drilled to accommodate expansion bolts without causing any problems. The maximum number of protective conduits to be installed depends on the clip holder size. In general, each clip holder allows the operator to install up to four clips and conduits.

1.10.4 Installation of special armoured optical cables into the sewer ducts

The installation of an optical cable pulled in and laid on the pipe invert is the easiest solution to deploying an optical cable. Fastening the cable into sewer pipes is not necessary because gravity keeps the cable on the floor. The condition of the pipe is not very important. Future development of the optical network and of the sewer system must be carefully taken into account, as their upgrade is quite difficult after installation. Access to the cable in every manhole is important in order to fix and survey the installation process, as well as for maintenance purposes.

As the cable lies on the invert of the sewer pipe, it is also recommended to plan maintenance operations and eventual pipe rehabilitation with liners, as in small pipes the cable might cause wrinkle formation in the invert area.

Bonding methods (fixing cables or conduits to the sewer by means of plastic bonding) are not recommended since a lasting bonding of the adhesive cannot be guaranteed, costly surface treatment would be required to prepare the bonding; later damage-free removal or adding of the conduits would not be possible, and the sewer pipes concerned would need to be completely drained.

Tightening methods (cable wound under high tension from manhole to manhole at the sewer top, a high tensile load of several tons is created by means of tension fixtures) are not recommended for several reasons: the tension fixtures exert tremendous tensile loads on the manhole shafts, which are usually not capable of taking such loads; rehabilitation with liners is difficult; and it can happen that the cable runs in front of a tap, which might cause a blockage of that tap.

1.10.5 Guidelines for the selection of the most appropriate installation method

The criteria reported in Table 3-3 shall be observed to select the appropriate method for the installation of optical cables in sewer ducts.

Table 3-3 – Comparison of installation methods

No.	Requirement	Special armoured optical cables	Infrastructure and conventional optical cables	Self-supporting optical cables
1	Applicable sewer pipe diameter	No limitations	From DN 200	From DN 300
2	Position in the sewer	Bottom	Top	Top
3	Sewer visual inspection before installation	Optional	Mandatory	Optional
4	Maintenance of the sewer	To be planned before installation	To be planned before installation	To be planned before installation
5	Risk of blockage	Depending on the water level and on the water flow	No	No
6	Upgrading of the optical network	Very difficult	Possible	Possible
7	Maximum number of cables and fibres	Maximum one cable (i.e., 144 optical fibres)	Up to nine cables (one in each corrugated steel tube)	Maximum two cables (i.e., 216 optical fibres each)
8	Flexibility of the optical network	Only for point-to-point connections	Very high	Medium
9	Access to optical network	No	Yes	Yes
10	Cable type	Special armoured	Standard	Self-supporting
11	Installation cost	Low	Medium	Low

Note – DN is Nominal Diameter.

1.10.6 Pressure washing and finishing brush

In general, sewer ducts must be cleaned every two years. Pressure washing using a high-pressure water washer and vacuum cleaning system are adopted. Therefore, any cable or conduit placed into a sewer must withstand the rigors of the pressure washing as frequently as every two years.

A finishing brush attachment is also used for detailed cleaning work. Since the brush is a little smaller than the sewer pipe, it can be pulled along the sewer pipe, loosening any debris that remains after the high-pressure washing. Cables and infrastructure must withstand the action of the finishing brush without damage.

1.10.7 Safety

Safety practices should follow the guidelines of local regulations and/or the state laws. Guidelines shall be observed that address confined spaces, hazardous underground utilities, trench safety, traffic safety, equipment safety and safety training. Personnel must be trained for those guidelines and regulations. There must always be a competent person trained to recognize dangerous conditions, to protect the personnel, and to manage the traffic with appropriate resources. All construction equipment and personal protective gear must meet guidelines and be kept in good condition. Prior to starting a project, a safety plan should be prepared and documented by the installer or the owner’s designated representative. This plan should be implemented and followed by the personnel involved in the installation process.

1.11 Installation of marinized and submarine optical cables

(For further information on this type of installation, see Recommendations ITU-T G.971, ITU-T G.972, ITU-T G.976, and ITU-T G.978; Supplement 41 to the ITU-T G-series Recommendations and the ITU-T Handbook, *Marinized Terrestrial Cables*.)

As outlined in Chapter 2, underwater optical fibre cables are classified in this Handbook (according to the ITU-T Recommendations), in the three following categories:

i) marinized terrestrial cable;

ii) repeaterless submarine cable;

iii) repeatered submarine cable.

Marinized terrestrial cables are generally used for crossing lakes and rivers. Repeaterless submarine cable is suitable for use in both shallow and deep waters for lengths up about 300 km. Repeatered submarine cables can be used in all underwater applications, mainly for deep waters on lengths that require the deployment of submerged repeaters.

The installation aspects of these three types of cables have many points in common, so that a unique description is made in the following, while specific requirements for each type are given where necessary.

1.11.1 Survey and route planning

Prior to any marinized/submarine system implementation a survey normally is conducted in order to find the optimum route and to give the cable the optimum protection along this route. This survey is usually divided several phases.

1.11.1.1 Desk route study

The purpose of a desk route study is to assess the factors affecting the selection of a marinized/submarine cable route between the terminal stations.

The following items are investigated, as appropriate:

i) land routes and landfalls (suitable places for the beach closures or manholes);

ii) study of existing nautical charts;

iii) study of existing data over tide and sea currents, wrecks, other underwater cables (planned, existing, power or telecom) in the neighbourhood of the planned cable route. The same apply also for pipeline or over seabed installations;

iv) fault history of nearby located cables;

v) shipping activities;

vi) navigation restriction and military exercise areas;

vii) contact and cooperation with authorities and other interested parties (i.e. defence, port, maritime, public works and any other cable owners, etc.) in order to get permissions or relevant information;

viii) fishing activities, in particular in areas where the trawl nets and other fishing devices represent a risk for the integrity of the cable.

The desk route study for international submarine links should also determine all political, economic and practical aspects related to the presence of landing points placed in different countries.

All the above information put together results in a tentative route which can be further investigated, depending by the characteristics of the link, e.g. by its length. Such further investigation (route survey) is normally carried out with a small boat or with a special survey ship, once again depending on the link characteristics.

1.11.1.2 Route survey

Route survey is performed prior to cable laying so as to select the cable route and means of cable protection (lightweight protection, armour, burial). The route survey consists of studying the sea depth profile, the sea bottom temperature and seasonal variations, the morphology and nature of the sea bottom, the position of existing cables and pipes, the cable fault history, fishing and mining activities, sea current, seismic activity, laws, etc.

The route survey may not be required if a comprehensive desk study has been carried out, including site visits, or the proposed route is a short, shallow route (e.g. river crossing).

In a route survey it is essential to have high accuracy of navigation along the route. Today this is normally achieved by means of differential Global Position System (GPS) receivers or other high precision radio navigation methods interfaced to a PC calculating the position. Such equipment can have a typical horizontal accuracy better than ± 5 m.

The bathymetric investigation normally is carried out using an echo-sounder (sometimes with multi beam or rotating) along a pre-selected cable route in a corridor manner of an adequate width. In areas with steep slopes or very rugged seabed, the density of survey lines can be increased so that the result covers all possible hazards.

In order to be able to find obstacles along the route, side scan sonar is used. If the route is investigated with side scan sonar, it is sometimes favourable to have an overlap of the survey lines along the route corridor. Also, the width of the corridor must be such that a cable normally can be laid within the pre-selected width.

Especially close to the landfalls, but also in other cases, it could be useful to have a visual inspection and this can be performed using Remotely Operated Vehicles (ROVs). For very shallow water, a diver inspection should give the same result in a cost-effective manner. Divers can also sometimes provide some assessment of burial, e.g. by obtaining core samples.

In order to ascertain results from the route survey and determine the "burial feasibility", seabed samples (grab or core ones) are usually taken on sites where the geophysicist, in charge of the survey, deems it necessary. Taking the samples which have been analyzed (bulk density, water content, undrained shear strength, etc.), it can be easier to judge if a slope is stable or not, and to evaluate the cable protection and burial feasibility.

1.11.1.3 Route planning

The results of the desk study and of the electronic route survey, if necessary, are used to finalize the cable route planning. Before the manufacture and installation of the cable, the chosen protection is summarized in a Straight Line Diagram or presented in the form of a diagram or scheme accompanied by the appropriate list of positions (way points).

1.11.2 Characteristics of vessels

1.11.2.1 Survey vessels

A survey vessel is only normally required for long or complex routes, as highlighted in the desk study and agreed by the parties concerned.

The definition of a suitable survey vessel is very much dependent on where and when the survey has to be made. In protected waters quite a small vessel-of-opportunity might do, but for surveys off the coast, a conventional survey vessel may be necessary. The choice of vessel will depend upon the application.

The season is also of great importance. If the survey vessel must be used during a rough season, it must be of a bigger and sturdier kind.

In general, when the survey requires more than one day in open water, more requirements are usually necessary for survey vessels (room for equipment, adequate working space, communication facilities, good power supply, etc.).

1.11.2.2 Laying vessels

Generally, it can be said that important parameters for the vessel are:

i) cable handling according to the manufacturer's specifications;

ii) precise navigation equipment (differential GPS);

iii) professional manning.

Data on cable ships and submersible equipment (ROV Remotely Operated Vehicle, submersible ploughs, etc.) used worldwide are listed in Recommendation ITU-T G.971, together with their geographic areas of work and their owners. A representative drawing of one of these cableships is shown in Figure 3-13.

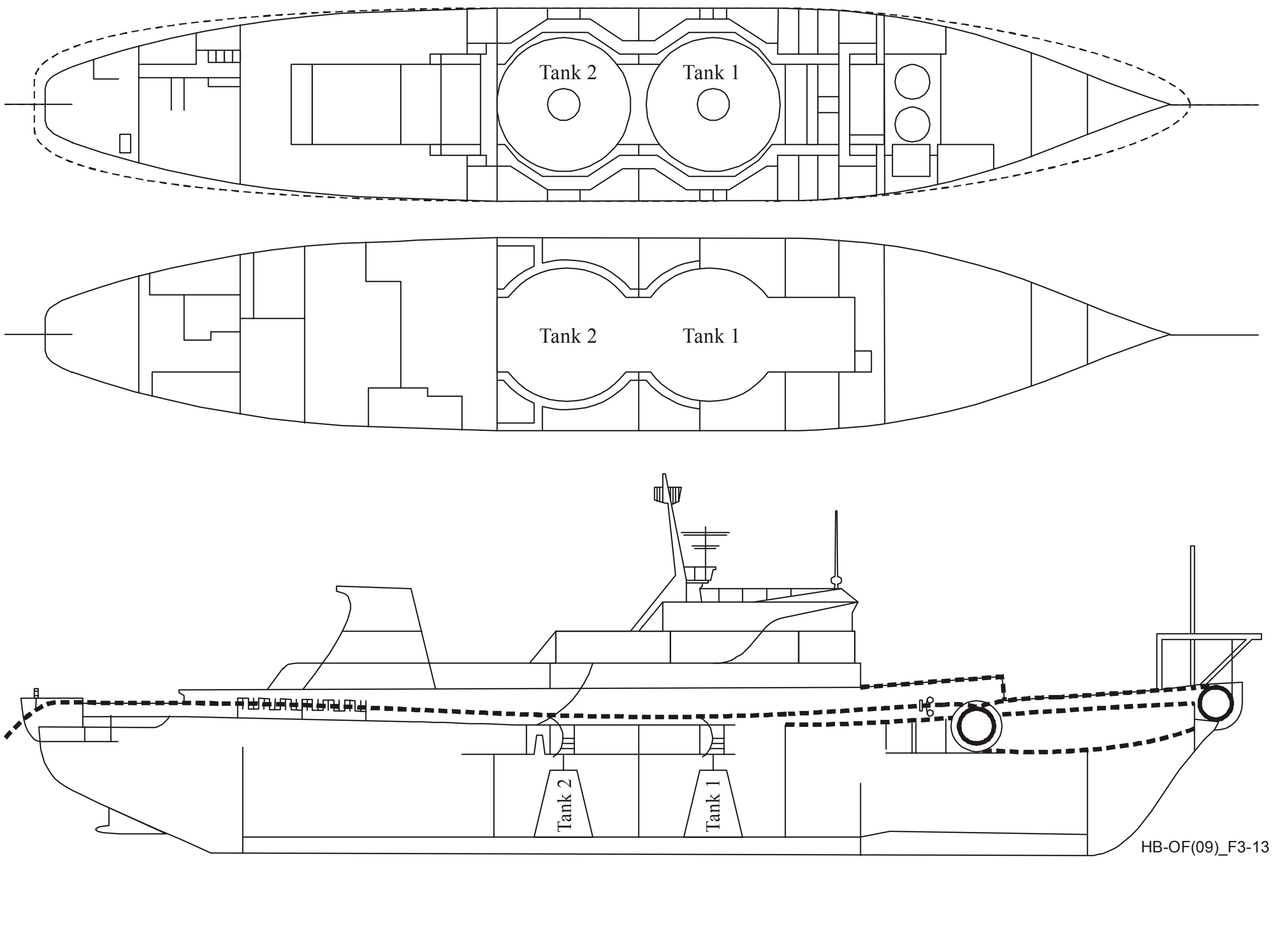

Figure 3-13 – Cableship suitable for laying long submarine cables

Depending on the application, vessels' general characteristics include, among others, the following: containerized equipment and control rooms, jointing and storage space, open cable tanks with elevated cable track ways.

1.11.3 Installation

The cable installation should follow approved procedures in order to guarantee the required lifetime performance of the complete system.

Installation techniques are different for various environments such as sea, river or lake.

1.11.3.1 Cable loading

Usually a submarine cable is manufactured in cable plants close to the beach in order to facilitate the loading aboard of a vessel. For marinized cables to be installed in rivers or lakes, with the cable to be delivered by terrestrial transportation, the loading method adopted is the same as that for terrestrial cables.

For this reason, only the loading technique for sea-going vessels will be presented in the following.

Before the loading, the whole cable length of the marinized and repeaterless submarine cables to be laid is jointed in order to cover the total link length. For the repeatered submarine cables the single elementary factory lengths are prepared in the factory. The cable, usually stored in coils, in pay-off tanks or turntables, is transferred aboard the vessel by means of a specially designed path passing through crane wheels, a pier and a system of driving rollers. In practice, a rope, having an outer diameter similar to that of the cable, is pulled up to the pier end. From that point the rope is removed from the cable end and another one, coming from the vessel, is fastened to the cable end. The cable is then pulled by the vessel machinery forming a catenary, to be controlled, between the pier end and the vessel. The pulling machine aboard of the vessel can sometimes be a linear cable engine.

The cable is then stored in coils in the tanks of the vessel having the two, or more, cable ends available for testing.

During loading, the control of such parameters as attenuation regularity, ohmic continuity (if applicable), pulling load, etc., should be monitored.

Care must be taken when storing the cables into the tanks in order to avoid uncoiling conditions, kinks, etc. During the loading, counter metres must be available along the cable gangway, both from the factory and from the vessel, in order to monitor the length of cables or the closure positions (if any) along the cable sections.

The loading speed depends on the tank size, vessel equipment, cable structure and weight. As an example, the speed for single armoured cables is typically 2-2.5 knots, and for double-armoured cables 1-1.5 knots. For closures, the maximum speed is typically 0.5 knots.

For the repeatered submarine cable systems, after the loading, the single elementary factory lengths are jointed to the submerged repeaters and to all the other submerged equipment in order to form on the cable ship the link to be laid without stopping the ship (Figure 3-14).

These systems should be tested during the laying and at the end of laying, so as to ensure that no significant system degradation has been induced. Laying testing includes transmission and functional tests, and may include tests on redundant subassemblies. To permit test during cable-laying, the link may be powered, provided that safety regulations are respected.

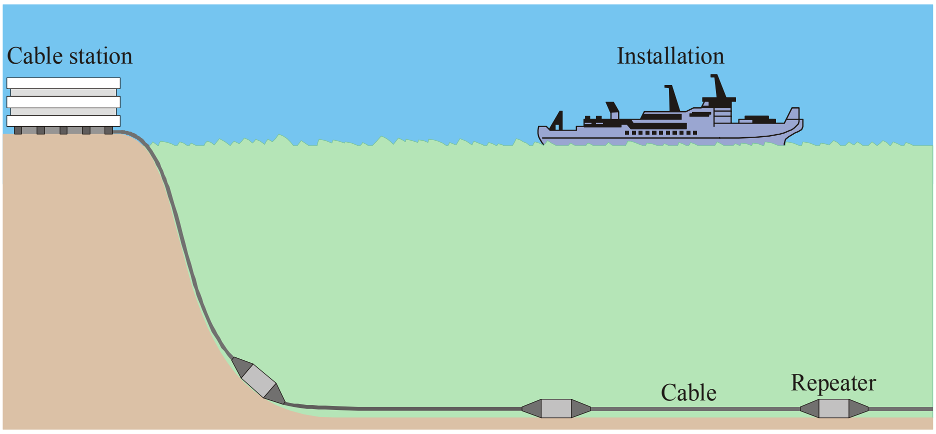

Figure 3-14 – Laying of repeatered submarine cables

1.11.3.2 Shore-end operations

The shore-end operations are those performed to lay the first cable portion close to the coast. The laying activities must ensure the foreseen reliability and the lifetime of the link.

Usually, in repeaterless systems, the shore end is not separated from the main laying in order to avoid the so-called initial or final splice operations.

Taking into account the results of the survey, the vessel is positioned on the foreseen cable route, by means of previously calibrated radio-positioning system, at a distance from the beach suitable to guarantee safe activities.

When all the equipment and personnel are ready for the laying, the cable is drawn out of the vessel by a service boat and is floated by means of balloons. Such balloons are distributed at regular intervals depending on the cable weight and length.

The boat moves towards the beach assisted by divers and other boats in order to correct deviations from the route due to currents. When the cable is closer to the beach (about 100 m), a rope will be moored to its end to pull it up to the beach manhole, or directly to the station (if it is very near), by means of roller guides.

As soon as the cable is set on the landing route, the balloons will be taken off by the divers between the vessel and the beach. If it is included in the technical requirements, the cable will afterwards be protected by means of burial, articulated pipes, etc. Starting from the completion of the shore end operation, the main laying will start.

In the shore ends the cable may be buried in the seabed to increase cable protection. Burial can be undertaken during laying using a sea plow towed by the laying cable ship, or after laying using a self-propelled submersible robot or other means.

1.11.3.3 Sea laying operations

Laying is normally undertaken only when weather and sea conditions do not create severe risk of damage to the submarine portion, cable ship and laying equipment, or of injury to the personnel.

During laying, all appropriate measures should be taken to control the vessel's route, speed, and laying slack, together with the pulling tension applied to the cable. During the laying, an echo sounder is used in order to compare data related to the structure of the seabed in comparison with those resulting from the survey. With such elements, the required slope, slack and vessel speed can be adapted for the necessary laying conditions.

At constant vessel’s speed, the cable is laid in a straight line and the slope depends on the cable type and vessel's speed. To adapt the speed to the seabed profile, the slope must never be less than that of the bottom. Otherwise, suspensions and risks of faults could occur.

Usually armoured cables are laid at a speed of 2-3 knots. In some cases it is necessary to reduce the speed due to particular bottom conditions. Anyway care must be taken in order to avoid the risk of kink formations.

During the laying, the slack parameter is under appropriate control in order to allow the cable to cover the bottom irregularities. Such slack is the percentage of the excess cable length laid with respect to the geographical distance covered by the vessel and allows the recovery of the cable for maintenance purposes. The slack to be adopted is usually decided on the basis of experience and any requirements arising from the desk study/survey reports (if applicable).

1.11.3.4 Laying in lakes

The procedures for laying in lakes do not differ much from those adopted in the marine sector. The main differentiation factors are:

i) it is impossible to load the cable on the lay vessel directly from the manufacturer and, therefore, it is necessary to transport the cable by land, on a spool, to the final location of the lay;

ii) it is more convenient to employ vessels already present in the basin and adapt them for the purpose or, if this fails, to utilize modular pontoons;

iii) particular attention would have to be given to the slack allowance of the cable because the slopes in the lake bottom may be higher than those in shallow sea water.

1.11.3.5 Laying in rivers

The laying of optical cables in rivers is undertaken only in situations where an aerial crossing is not possible, because river environments present complex problems. The laying itself is similar to that shown for short sections in lakes.

Actually, the stability of the cable and the stress and tension applied to it by the current, presents greater limitations in this kind of installation.

Particular attention is given to the type of cable protection adopted, and also to the considerable variability of sedimentary dynamics on the river bed.

An alternative to an aerial or submerged installation could be the construction of the crossing in a drilled tunnel under the riverbed, with techniques analogous to those used for oil and gas pipelines drilling.

1.11.4 Controls after the laying

After the completion of the laying, a check of the optical parameters of the cable is carried out in order to ensure that the design technical requirements are met, with particular attention to the total attenuation and cable margin. Moreover, an insulation test, made in order to verify the integrity of the cable sheaths, could be advisable. Such tests can be performed only if in the cable structure a suitable metallic element is available, which could be used for electroding purposes, if necessary, to help locate the cable.

The final as-laid report is intended for area operating companies of the cable network (for telecommunications and other services), for national hydrographic institutes and other interested authorities.

To allow other systems installers and operators to properly design routes for future submarine services, and to carry out safe maintenance over existing lines, the final report should contain, as a minimum, a general layout map with the whole cable route and a detailed landing point map.

1.12 Installation of indoor cables

Within buildings various types of optical fibre cable construction can be used and it is important to ensure that the most appropriate type for each part of the indoor network is employed. It may be that the bending criteria of the incoming cable is more stringent than internal types and it may be advantageous, where possible, to site line terminating equipment near the building cable entry or a cable riser.

Where cables are routed along the floor, a short straight route is preferable with cable passing through, rather than around, walls to avoid sharp bends. For under floor installation, computer type flooring is normally satisfactory. Non-ruggedized cable is best run in conduit, racks or trays, but care must be taken to ensure that turning points are properly constructed so that cable bending criteria can be satisfied.

Where cable is fitted directly to walls, care must be taken to ensure proper cleats and straps are used and that they are not over tightened. Much internal optical fibre cable installation is done by hand; therefore, the possibility of fibre overstrain during this handling should be borne in mind.

2 Safety, in-service protection and location

2.1 Safety

Additional safety precautions when installing optical fibre cable in duct, by direct burying, or in an aerial route relate mainly to proper handling and disposal of broken fibre. The fibre should be handled very carefully, because broken fibre can be very sharp and must be kept well away from eyes. Small pieces of cable or fibre must be collected and disposed of in suitable containers. Technicians must be made aware of the dangers associated with handling optical fibres.

2.2 In-service protection

Optical fibres are not susceptible to lightning surges, but they are usually incorporated in cables with a metallic content. Therefore, apart from the possibility of adopting non-metallic cable designs, the methods used to protect optical fibre cables are of the same type used for metallic cable adapted to suit the longer lengths, and the guidance of Recommendation ITU-T K.25 should be observed.

2.3 Location

Where optical fibre cables, with little or no metallic content in their construction, are directly buried, the question of location at a later date should be considered at the time of installation. It may be appropriate to use an over ground post marking system, or to bury a locating wire with the cable and use discrete buried markers at the splice points.

CHAPTER 4

OPTICAL SPLICES, CONNECTORS AND PASSIVE NODES

Introduction

This Chapter covers some optical passive elements used in the optical networks, such as optical fibre splices (clause 1), optical connectors (clause 2), passive node elements (clause 3), optical distribution frames (clause 4), optical closures and fibre organizers (clause 5), passive nodes elements for marinized and submarine optical cables (clause 6).

The attention is focused on aspects related to installation, service conditions, transmission, environmental and mechanical characteristics.

1 Optical fibre splices

(For further information, see Recommendations ITU-T L.12 and ITU-T G.671.)

Splices are critical points in the optical fibre network, as they strongly affect not only the quality of the links, but also their lifetime. In fact, the splice shall ensure high quality and stability of performance with time. High quality in splicing is usually defined as low splice loss and tensile strength near that of the fibre proof-test level. Splices shall be stable over the design life of the system under its expected environmental conditions.

At present, two technologies, fusion and mechanical, can be used for splicing glass optical fibres and the choice between them depends upon the expected functional performance and considerations of installation and maintenance. These splices are designed to provide permanent connections.

A suitable procedure for splicing should be carefully followed in order to obtain reliable splices between optical fibres. This procedure applies both to single fibres or ribbons (mass splicing).

All optical fibre splices mentioned in this Chapter should be suitable for indoor applications as well as for outdoor environments, when suitably protected in appropriate accessories.

1.1 Splice losses

As shown in Table 4-1 splice losses can be divided into two categories.

Table 4-1 – Extrinsic and intrinsic splice loss factors

Extrinsic joint loss factors	– transverse offset
	– longitudinal offset
	– axial tilt
	– fibre end quality
	– Fresnel reflections
Intrinsic joint loss factors	– fibre diameter variation (core and cladding)
	– refractive index profile mismatch (multimode)
	– Numerical Aperture (NA) mismatch (multimode)
	– mode field diameter mismatch (single-mode)
	– non-circularity and non-concentricity of fibre mode field (single-mode)

The first category of losses is related to the techniques used to splice fibres and is caused by extrinsic (to the fibre) parameters such as separation and transverse offset between the fibre cores, axial tilt and fibre end quality, as shown in Figure 4-1.

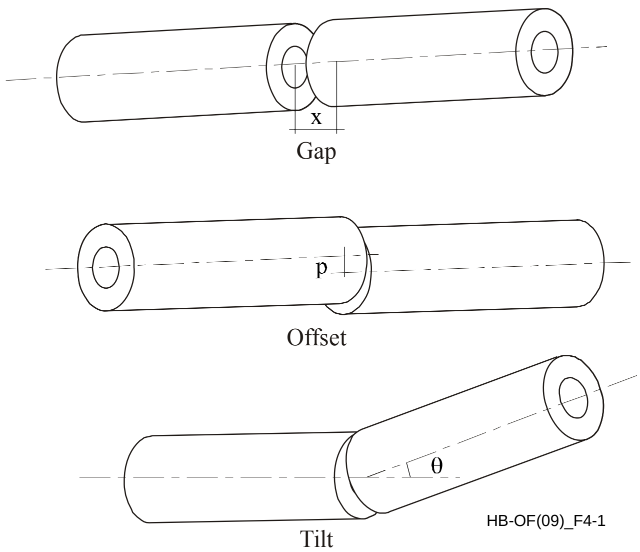

Figure 4-1 – Fibre misalignment

The second category of losses is related to the properties of the fibres spliced and is referred to as intrinsic splice loss. Intrinsic parameters include variations in fibre diameter (both core and cladding), index profile (shape factor and delta mismatch) and non-circularity of the fibre cores. In addition, bending stresses imposed upon the fibre by the splice protection package and/or the fibre organizer must be considered.

1.2 Fusion splices

Different methods exist to obtain a fusion splice of fibres or ribbons. Electric arc-fusion is the most widely used method to make reliable single or mass optical splices in the field. The fusion process is realized by using specially-developed splicing machines.

To make a fusion splice, all the protective coatings are removed from the fibre, the fibres are cleaved and then positioned and aligned between two electrodes in the splicing machine. An electric arc heats the silica glass until the "melting" or softening point is reached and at the same time the fibres are brought together longitudinally in such a way that a geometrically continuous splice is obtained. This process produces a continuous glass filament. The fibre alignment in these machines can be passive (v-groove alignment) or active (light injection and detection system or core/cladding profile monitoring and alignment system). A suitable protection device is then applied to the splice to protect the bare fibre and to allow handling and storage without adversely affecting the physical integrity of the splice. The cleave quality and the intensity and the duration of the arc as well as the differences between the two fibres to be spliced determine the splice loss. In addition, the quality of coating removal, fibre cleaving and splice protection contribute to the long-term mechanical reliability in the field.

1.3 Mechanical splices

Mechanical splices have different structures and physical designs, and usually include the following basic components:

i) surface for aligning mating fibre ends;

ii) a retainer to keep the fibres in alignment;

iii) an index matching material (gel, grease, adhesive, etc.) placed between the fibre ends.

They can be used for single fibres or ribbons. Some designs allow installation on the fibres at the end of a cable in the factory for faster jointing in the field.

An optical matching material between the ends of the fibres can be used to reduce Fresnel reflections. This material shall be chosen to match the optical properties of the fibre. Common index matching materials include silicon gels, UV-curable adhesive, epoxy resins and optical greases. The index of refraction of these materials has a temperature dependence different from the glass fibre.

1.4 Splicing procedure steps

1.4.1 Fibre preparation

For jelly-filled cables, the fibres shall be mechanically cleaned of the water-blocking jelly of the cable using lint-free paper tissue or cotton cloth. Care shall be taken so that the ribbon matrix material and fibre coatings are not damaged either mechanically or chemically. Long-term soaking in solvents can damage the fibre coating.

Where applicable, secondary coatings (tight buffer or loose tube constructions) shall be removed to the distance recommended by the splice protector manufacturer using an appropriate tool in order to expose the primary coating.

Coating removal could be the most critical operation in the splicing procedure, especially if it has to be performed on fibres that have been in the field for many years. The ability to remove coating may be more difficult due to ageing. Therefore, this step must be performed carefully, because the final strength of the completed splice depends on minimizing the exposure that can cause flaws on the bare fibre.

The stripping method could be chemical, thermal or mechanical, depending on the applications and on the desired performance.

When fibre end cleaning is needed, the bare ends shall be cleaned with paper tissue soaked with reagent grade alcohol to eliminate residual coating, paying attention not to break them. Avoid wiping the fibre more than necessary to clean off debris.

The bare fibre ends shall be cleaved perpendicularly with respect to the longitudinal axis; the cut surface shall be mirror-like without chips or hackle.

For fusion splices, end angles shall be typically less than 1° from perpendicular for single fibres and less than 3° to 4° for ribbons (depending on the fibre type) to achieve a satisfactory splice. The cleaving tool shall be capable of achieving these values with a controlled length of bare fibre, compatible with the splicing system and protection device.

For mechanical splices, two types can be identified: perpendicular cleaved, with typically the same cleave angle as fusion splices; and angle cleaved, with a cleave angle of at least 4°.

1.4.2 Splicing

1.4.2.1 Electric arc-fusion splicing

Before using the splicing machine, it is fundamental to check its performance. The condition of the electrodes is a critical factor determining whether fusion splicing will proceed normally, especially when working at environmental extremes.

Machine performance is sensitive to atmospheric variations. Either automatic or manual adjustment of arc parameters shall be made to optimize for the existing conditions.

Since the optimal splice conditions (arc current, arc time, etc.) may depend on both the characteristics of the type of fibre as well as the characteristics of the splicing machine, it is recommended to use an arc test procedure, available in many splicing machines.

When testing of the arc condition is completed, splicing can commence. The fibre shall be positioned in the v-grooves of the splicing machine (Figure 4-2).

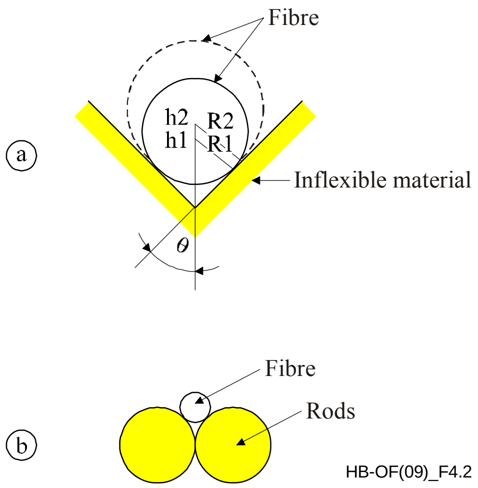

Figure 4-2 – V-groove or two-cylinder alignment

Fusion splicing machines, in general, are divided into two types: active or passive alignment. The use of either type depends on how the fibres are aligned. Active alignment machines use either a vision system or local injection/local detection system and three-dimensional movement of the fibres to actively align the cores or the outside diameters of the two fibres being spliced. The splicing machine minimizes the splice attenuation by either focusing on the core or cladding of the fibres with its vision system to directly align them or optimizing the transmitted light through the fibres and providing an estimate of the splice attenuation after the splice is complete (Figure 4-3).

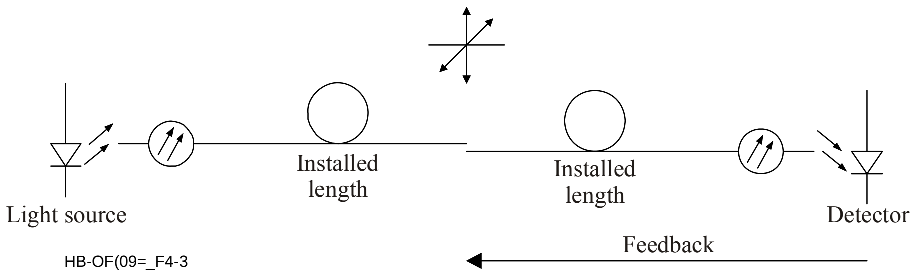

Figure 4-3 – Example of active core alignment

Those systems that compensate for core concentricity errors provide better results in terms of splice attenuation. Splicing machines that use active alignment systems are only suitable for single fibre splicing at this time.

Passive alignment machines use only fibre longitudinal movement so accurate core alignment depends on good fibre geometry. The passive alignment system is currently used to splice ribbons and is also used in single fibre splicing machines where an estimate of splice attenuation may also be provided. For ribbon cables, however, all of the current mass fusion machines estimate splice attenuation by observing fibre alignment before and/or after splicing.

After the splice is completed, it is necessary to check its minimum strength. It is very important to establish a defined level of mechanical strength for the splice that is related to its expected lifetime. As performed for optical fibres just after manufacturing, the splice is subjected to a tensile proof-test for a short period of time. Some splicing machines perform this test with the spliced fibres in the splicing chucks and some perform it after placing the spliced fibres in the holders for heat-shrink protector application. Splices that have their strength below the proof-test level shall be eliminated.

After the proof-test, the protector shall be positioned over the spliced point. The “protector” is a mechanical device or restored coating that provides both mechanical and environmental protection to the single or multiple splices. In all cases, the protection device shall affect neither the attenuation of the splice, nor its functional properties.

Protector designs may include heat-shrink sleeve, “clam-shell”, fibre re-coating, re-coating devices and encapsulating protectors. The protectors for single fibre fusion splices shall be capable of accepting either 250 µm (nominal) diameter coated fibres, 900 µm (nominal) diameter buffered fibres, or 250 µm/900 µm combinations. Typically, these protectors require tools or equipment to install or make.

The protector designs shall be suitable for either aerial, underground or buried applications while stored inside an appropriate enclosure. The manufacturer shall provide information on the compatibility with the splice organizer trays and on the tools or equipment for its application. In particular, the manufacturer shall provide information on the minimum/maximum fibre strip lengths that the protector will accommodate and on the storage dimensions for the completed protector (length, width and height) and on the application details.

1.4.2.2 Mechanical splicing

The mechanical method allows fixing the fibres in a splice-protective housing, generally without the need for electrical power. Some mechanical splices can be tuned by hand for minimum splice loss. An example of multiple mechanical splice is in Figure 4-4.

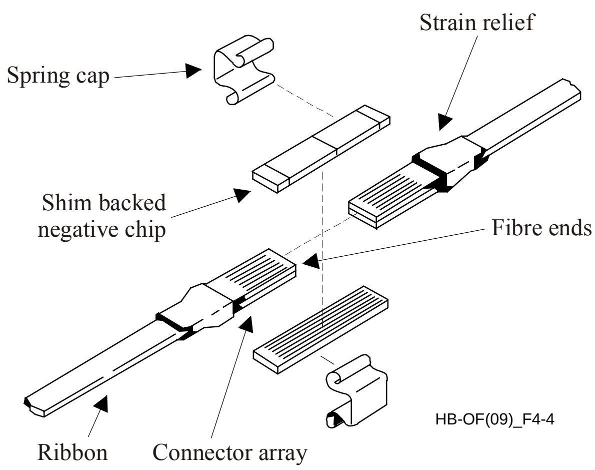

Figure 4-4 – Multiple fibre mechanical splice

After stripping and cleaving operations, described in § 1.4.1, the fibre bare ends are inserted in the mechanical housing (in a guiding structure, for instance a v-groove) and checked for their physical contact. For angle-cleaved splices, it is recommended to maintain the relative orientation of the angled end faces of the fibres during installation in order to obtain optimal optical performance.

For mechanical splices, the proof-test is generally not a part of the installation sequence as it is for fusion splices.

Sometimes, the fibre ends are prepared for splicing by grinding and polishing procedures, especially in factory pre-terminated mass splices.

The mechanical splices shall be versatile, allowing the splicing of different types of fibres, for example, 250 µm with 900 µm diameter buffered fibres.

The integral housing of the splice (different for single or multiple splices) provides mechanical and environmental protection. They shall be suitable for aerial, underground or buried applications. The manufacturer shall provide information on the compatibility with the splice organizer trays and on the tools or equipment for their application.

The index matching material used between the ends of the mating fibres shall be chosen to match the optical properties of the glass. The supplier of the index matching material shall provide complete information about its behaviour at different temperatures (especially the extremes) and its estimated lifetime in terms of maintaining the initial optical performance.

In mechanical splicing, the splice protection is built into the splice design and separate protectors are not required.

1.4.2.3 Field splice loss measurements

One critical requirement for an optical fibre communication system is the total end-to-end loss of each link. Considering the number of splices in a link, a realistic maximum splice loss should be set.

In practice, the field measurement of each splice loss during construction of a fibre route can be indicated by the fusion splicing machine (when loss estimation is a facility) to decide whether the splice should be remade; the use of one-way OTDR (Optical Time Domain Reflectometer) measurement is not recommended. After construction is complete, the actual splice loss in the field should be determined by bidirectional OTDR if necessary.

For single-mode fibre the true splice loss is determined by the bidirectional average of the OTDR readings at a splice. A one-way OTDR measurement should not be used as actual splice loss because Mode Field Diameter (MFD) tolerances and other intrinsic parameter differences in fibres can cause gross errors. In case of single-mode fibres, OTDR single direction readings can be high, being either positive or negative. In addition, any measurable spike from a fusion splice requires that the splice be remade. Acceptance levels for splice loss before remake depend on the loss budget of the link.

Recommendation ITU-T G.671 gives a maximum value of 0.3 dB for the insertion loss of fusion splices with active alignment and a maximum value of 0.5 dB for the mechanical splices and for fusion splices with passive alignment. All these values should be considered as worst-case end-of-life values over all specified temperature, humidity and perturbations.

2 Optical connectors

(For further information, see Recommendations ITU-T L.36 and ITU-T G.671.)

Fibre optic connectors provide a method for jointing the ends of two optical fibres. Such a joint is not a permanent one, but it can be opened and closed several times. The optical connectors are required in the points of the network in which it is necessary to have flexibility in terms of network configuration and test access. A generic connector is shown in Figure 4-5.

Fibre optic connectors have application in all types of network, at the input and output ports of the transmission systems and are also used to connect test equipment and instrumentation.

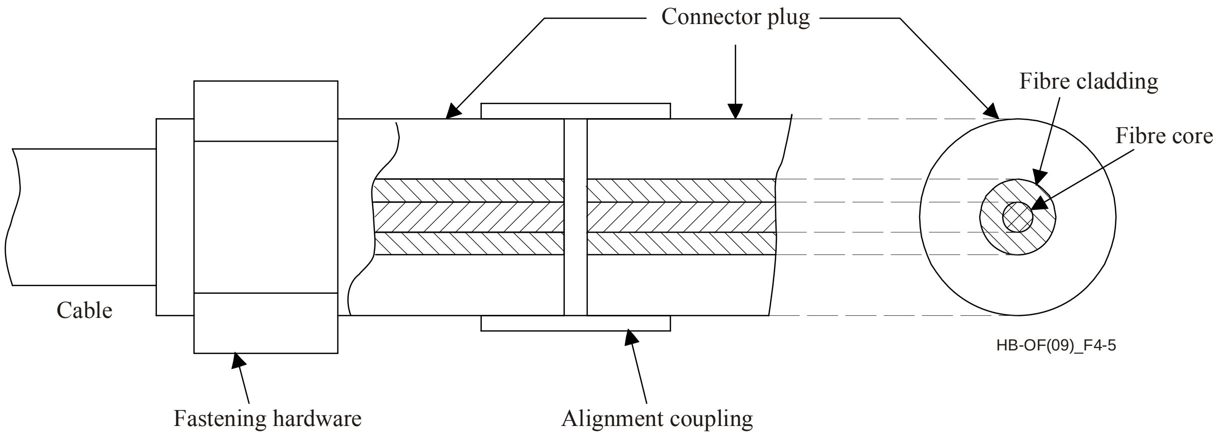

Figure 4-5 – Generic connector

The connection can have a plug-adapter-plug or a plug-socket configuration.

The main effects of the introduction of a connector in an optical line are attenuation of the transmitted signal and reflection of part of the signal.

2.1 Types and configurations

Fibre optic connectors can be classified on the basis of:

i) the type of fibre;

ii) the type of cable;

iii) the fibre alignment system;

iv) the fibre end face finish;

v) the type of coupling mechanism;

vi) the number of jointed fibres;

vii) the outer diameter of the ferrule *(*2.5 mm or 1.25 mm*)*;

viii) the connector mating lay out ("plug and socket" or "plug-adapter-plug").

Additionally, the fibre density achievable with different type of connectors (the connector "Form factor") plays an important role in situations where a high number of connectors has to be packed in limited space (e.g. in an optical distribution frame, as shown in § 4.3.2).

2.1.1 Fibre types

The type of connector and in particular its grade of mechanical accuracy depend on the type of fibre to be jointed. The fibres to be considered are those specified in Recommendations ITU-T G.651.1 through ITU-T G.657. Note that great accuracy is necessary to align two single mode fibres in which the light is guided in a core of about 9 µm or less.

2.1.2 Cable types

The connector can be assembled with:

i) primary coated fibre (250 µm);

ii) secondary coated fibre (900 µm);

iii) single fibre cable (typically from 1 mm to 3 mm).

2.1.3 Fibre alignment system

i) *Direct alignment*: In this type of solution the bare fibre is directly aligned by V-groove or capillary tubes;

ii) *Secondary alignment*: In this case the fibre is fixed in a structure. These structures are usually cylindrical ferrules for single or duplex fibre connections, or rectangular section bodies for duplex or multiple fibre joints. These structures are aligned by means of sleeves, pins or other systems;

iii) *Lens alignment*: The optical alignment of the fibres is obtained by means of a lens.

The alignment ii) is the most commonly applied. Loss criteria of most standards are established for this type of connector.

2.1.4 Fibre end face finish

For both direct alignment and ferrule-based connectors, the end face of the fibre or the ferrule is prepared (normally by polishing) to give fibre-to-fibre contact, either where the end faces are perpendicular to the fibre axis, or at a small angle to the perpendicular.

2.1.5 Coupling mechanism

The most common systems for mating together two plugs (or the plug and the socket) are:

i) push-pull mechanism;

ii) screw mechanism;

iii) bayonet mechanism.

2.1.6 Number of jointed fibres

Essentially, all of the connectors used today join single fibres. However, to join fibre ribbons or join ribbons to individual fibres (fanouts), there is application for a multiple-fibre connector. Multiple-fibre connectors permit higher spatial density of fibre connections.

Connections can be made between ribbons, fanouts or ribbons to fanouts. Examples of fanout connectors are shown in Figure 4-6.

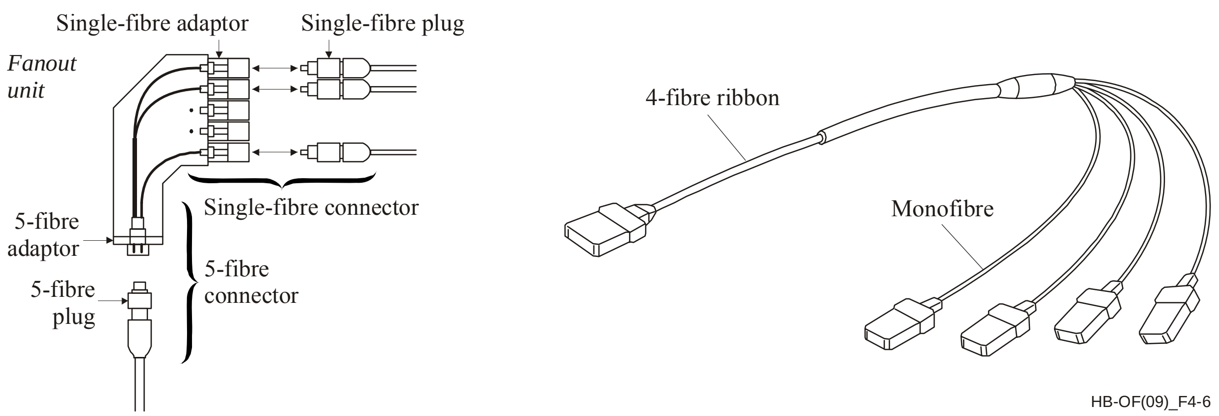

Figure 4-6 – Fanout connectors

2.2 Connector performance parameters

The primary factors affecting optical performance of fibre optic connectors are insertion loss and return loss. Both of these should be measured and expressed in terms of randomly selected product-to-product mating.

The intrinsic properties of the fibres, circularity, concentricity, numerical aperture, mode field diameter, etc., affect connectors in the same way as they do splices. They may lead to variations in insertion loss that are not attributable to connector performance and should be selected to minimize these effects. In connectors the dominant cause of insertion loss is fibre-to-fibre transverse offset, but the angular offset of the fibre also has a significant effect.

Optical-fibre connectors shall be constructed so that they will survive the normal mechanical handling and stresses that occur in the outside plant applications without degradation of optical performance. Standard post-handling cleaning procedures, as recommended by the manufacturer, should be in place to guarantee optical performance along the life span of the connector.

The outside plant environment varies greatly from season to season and from one geographic area to another. For an optical transmission system to operate satisfactorily under changing environmental conditions, the components of the system should be insensitive to these changes. A number of tests have been developed to stress the connectors in a controlled manner to allow a prediction to their performance in the outside plant environment.

More information on the tests to be carried out on the optical connectors, on the test methods and on the values which could be expected is in Recommendation ITU-T L.36. In particular, the transmission parameters that characterize the optical connectors are listed, with the relevant test methods, in Recommendation ITU-T G.671.

3 Passive node elements for fibre optical networks

(For further information, see Recommendation ITU-T L.51.)

The quality of an optical network is determined by the performance of each of its individual components. Nodes in this network are one of the key components of the physical network.

A "node" is defined as a point of intervention in the network, e.g. it occurs at each opening or end of a cable jacket. "Passive" applies to nodes that do not contain active electronics or other devices that are exothermic. Examples of passive nodes are optical distribution frames, joint closures for underground and aerial applications, street cabinets etc. Each node shall be capable of performing its expected function in the network, while exposed to the environment in which it is intended to reside.

3.1 General requirements for passive node elements

In order to achieve and to maintain a suitable network performance level the passive optical nodes should be able to properly store and protect all compatible passive devices without altering their performance characteristics. Examples of passive devices are:

i) splices and splice protectors;

ii) optical connectors;

iii) other optical components.

In order to obtain an end-to-end reliable network, all different network nodes shall be evaluated using the same methods and metrics.

A network node should be able to fulfil its optical functionalities, including the ability to be reconfigured, in all conditions of the environment, in which the node will reside.

3.2 Fibre reconfiguration

In a node, the optical fibres are to be properly managed and guided from where a cable or pigtail enters the node, to where it leaves again. A *fibre organizer*, put inside the node, comprises the whole of the means and features that are intended to guide and store fibres, pigtails, splices, connectors and passive devices inside a node, at any location where they are not protected by the cable sheath. (See also Recommendation ITU-T L.50).

Moreover, the fibre organizer system of a node shall provide features and methods to store fibre excess lengths (over-length) in a reliable and consistent way. The organizer system shall provide the means to manage the related over-length in an orderly manner (i.e., controlled bend radius, accessibility). Fibre over-length is related to:

i) *Splices*. The fibre over-length is typically to be stored on the same organizer element as the splices. It will permit the removal of the splice to the splicing equipment or tools and back to the splice holder. The length should be such that it allows at least 3 resplices. If reconfiguration is necessary, the over-length should be sufficient to allow rerouting and storage of a splice in any other splice position in the organizer system;

ii) *Uncut fibre at initial installation*. The unused fibres remaining after opening the cable shall not be cut, but shall be stored together or separately. These fibres may be branched at some future time. Therefore, the over-length of the uncut fibres shall be sufficient to meet the splicing requirements of the above paragraph i);

iii) *Patchcords and pigtails*. Optical connectors are used at nodes where frequent reconfiguration is expected. Connectors may need to be rerouted to different positions with the same pigtail length. The length of pigtails and patchcords should be such that they can reach all required positions within the organizer system;

iv) *Unspliced fibre ends*. At some nodes, non-live fibre ends need to be stored. Depending on the future destination, they may be stored *en masse*, by element, or individually. This can be done in a storage basket, a dedicated storage area for unspliced fibre, or on splice trays.

3.3 Application environments

Once installed, optical nodes typically may reside in one of the basic environments quoted in Table 4-2.

Table 4-2 — Application environments

Indoor	temperature controlled	IC
	non-temperature controlled	IN
Outdoor	above ground	OA
	at ground level	OG
	under ground (sub-terrain)	OS

The five basic environmental classes indicated in Table 4-2 cover the majority of the applications around the globe and can be described as follows:

i) IC: Indoor temperature controlled

– inside buildings protected by a roof and walls all around, heating or air-conditioning available;

– contact with chemical and biological contaminants is negligible, e.g. inside central offices, some remote network buildings/houses, residential buildings.

ii) IN: Indoor non-temperature controlled

– inside buildings protected by a roof and walls all around, no heating or air-conditioning available;

– contact with chemical and biological contaminants is negligible, e.g. cable vaults, basements, remote network buildings/houses, inside garages, warehouses, homes.

iii) OA: Outdoor above ground

– all outdoor non-sheltered locations, above ground level;

– no other sources of heat or extreme temperatures than the surrounding air or solar radiation;

– exposed to contaminants and dust that may occur in the atmosphere in rural, city or industrial areas, e.g. wall mounted, pole mounted, strand mounted nodes.

iv) OG: Outdoor ground level

– outdoor, standing on the ground, perhaps with a base that resides partially below the ground; this class may also apply to outdoor, wall mounted products that are close to ground level;

– exposed to contaminants and dust that may occur in the atmosphere in rural, city or industrial areas. The base of the product may be permanently in contact with soil, biological and chemical contaminants that occur at or just below ground or street-level, e.g. along roads, pavements and railroads.

v) OS: Outdoor underground (sub-terrain)

– outdoor below ground level;

– exposed to soil or water-borne contaminants, including organic and inorganic agents related to the presence of roads and traffic, e.g., in manholes, handholes or direct buried.

Table 4-3 summarizes the typical parameters for the five basic environmental classes.

When a node is exposed to conditions that are more extreme than those defined in these five basic environmental classes, this is to be classified as an "*extreme*" *environment (E)* which is defined as:

– any environment for which at least one of the environmental parameters exceeds the boundaries of the five basic environmental classes as specified above: e.g. more extreme temperature excursions.

In this case specific test settings are to be agreed between supplier and customer.

Table 4-3 – Summary of typical parameters for the basic environmental classes

	Indoor		Outdoor		
	IC	IN	OA	OG	OS
Exposure	**Temp controlled**	**Temp non-controlled**	**Above ground**	**Ground level**	**Underground**
Temp Min (°C)	+5	–10	–40	–40	–30
Temp Max (°C)	+40	+60	+65	+65	+60
Solar Radiation	No		Yes	Yes	No
Relative Humidity (max) (%)	93% (decreasing once above 30° C)		100% (occasional/permanent exposure to water possible)		
Precipitation	No		Rain, Snow, etc.	Rain, Snow, etc.	N.A.
Submersion	No (Note 2)		No	No (Note 2)	Yes
Vibration (m/s^2)	10-55 Hz 1 m/s^2 (~0.1 g) (whole system) 5 m/s^2 (~0.5 g) (components)		5-500 Hz 10 m/s^2 (~1 g) (due to e.g., traffic, wind, etc.)		
Chemical	Negligible (Note 1)		Atmospheric	Atmospheric + Soil (base only)	Soil/waterborne
Biological	Negligible		Atmospheric	Atmospheric + Soil (base only)	Soil/waterborne

NOTE 1 – In areas where corrosive atmospheres can be expected (marine and coastal areas, industrial areas, urban pollution), increased corrosion protection may be requested as an additional requirement.

NOTE 2 – If accidental flooding may occur, e.g., in vaults or basements, this is to be added as a conditional requirement.

4 Optical distribution frames

(For further information, see Recommendation ITU-T L.50.)

An optical passive node, which resides in a central office environment, is generally contained in a rack or frame. This is commonly referred to as an optical distribution frame (ODF) or optical termination frame (OTF).

The term *ODF* refers to a frame including the fibre organizer and the means to store and guide pigtails and cables inside the frame. ODF does not include the means for routing cables or pigtails outside the frame (also known as pigtail ducts or "raceway" systems).

The term *Frame* refers to the mechanical structure to which cables are attached and that holds all other elements of the ODF. It may be a rack and shelve type of structure, similar to what is used to contain the electronics, as well as any other type of structure. Its main functions are: mechanical support and a basic level of protection of its content.

Since ODFs are optical passive nodes, the general principles outlined in § 3.1 are applicable.

The specific requirements for ODFs are given below, sorted by their typical functions. Not all of these functions are necessarily present simultaneously in each individual ODF.

4.1 General characteristics

The ODFs provide for the general functions of test access and organizing the cable fibre, connectors and jumpers at termination nodes and distribution nodes in the fibre network (Figure 4-7). The functionality and flexibility of a fibre distribution unit is especially important when the fibres in the network are to be brought into service over a period of time, with types of service, geographic distribution of service, connector type and activation procedures which may change.

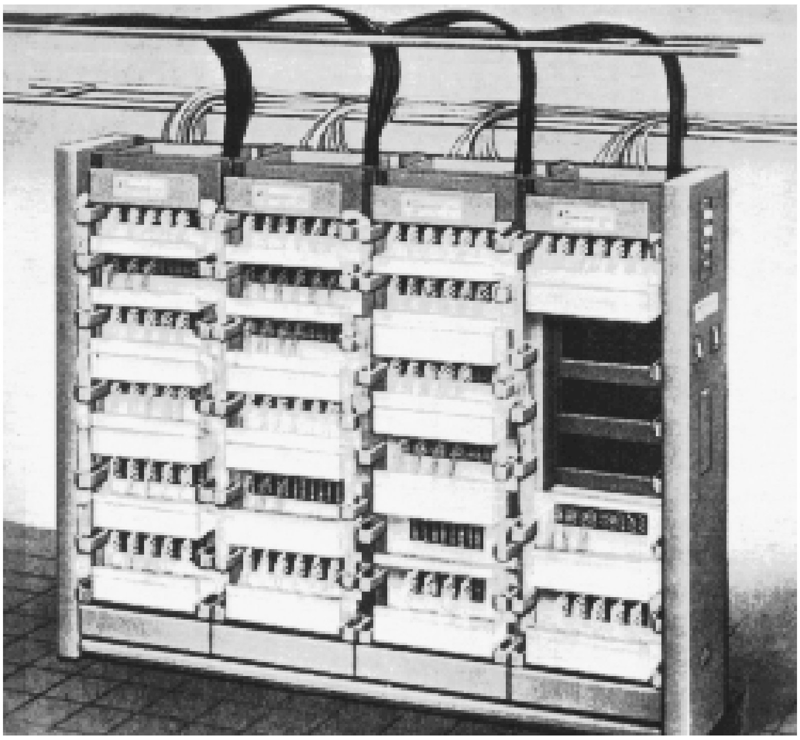

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Figure 4.7 – Optical fibre distribution frame (with jumpers)

There are two main configurations for terminating cable fibres at a distribution frame. Connectors can be installed on the cable fibres that are then connected to a bulkhead connector on the frame, or a connectorized pigtail is spliced to the cable fibre. The pigtail is then connected to the bulkhead connector.

Jumpers then connect the distribution frame to the transmission equipment. Jumpers are comprised of two connectors joined by a length of fibre with strength members and protective means. A jumper is used to connect a bulkhead connector to nearby transmission equipment. A jumper is also used to connect two bulkhead connectors and establish a network path that can be readily rearranged. Jumpers usually are long enough to reach the longest distance expected. Many of them have excess lengths that must be organized.

In cases where rearrangements are not expected to occur, the cable fibres may be taken directly to the equipment frames and connected directly to the transmission equipment eliminating the distribution frame or patch panel (Figure 4-8).

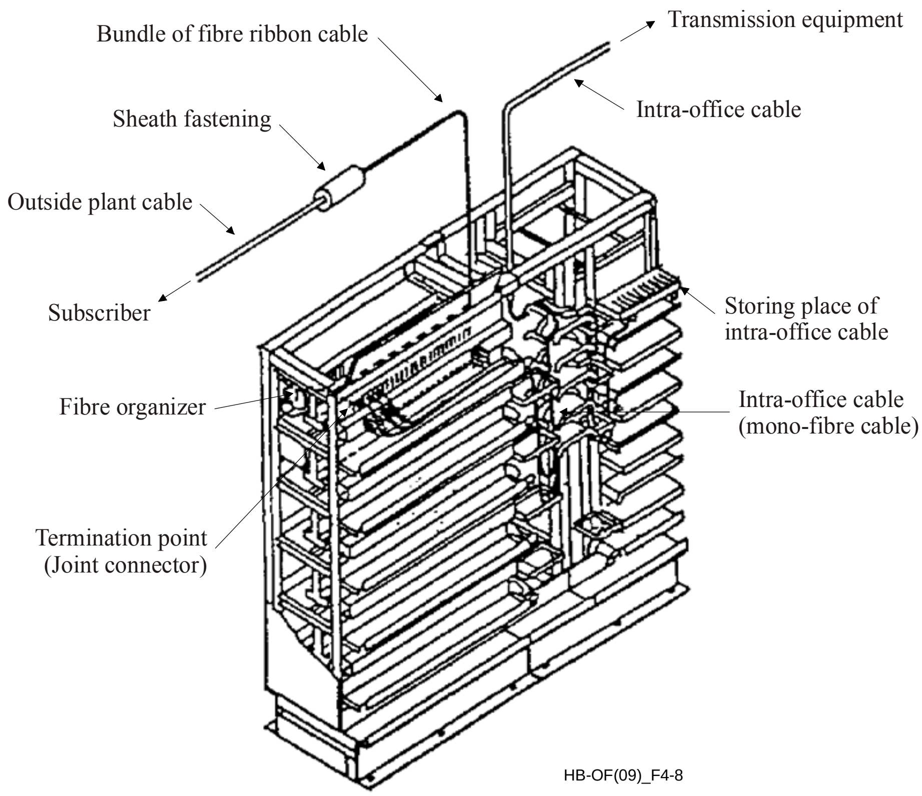


Figure 4-8 – Optical fibre distribution frame (without jumpers)

In order to provide for replacement of connectors, pigtails and fibre splices, due to errors or rearrangement, excess fibre is stored in a *fibre organizer* near the fibre splice. Frequent changes may require access to individual fibres. Frequently the organizer and the fibre splice holder are integrated into one unit. Furthermore, the ability to accommodate various connector types within the same organizer unit may also be considered. For more information about fibre organizers see § 5.2.

4.2 Applications

Typical applications of the ODFs are the following:

i) *Fibre termination at transmission equipment*. The rapid pace of technological change in electro-optic transmission equipment implies that the fibre network will be used to connect several generations of transmission equipment. A fibre distribution unit is used to provide a standard termination node for the fibre network to which transmission equipment can be readily connected. Sometimes the fibre distribution unit is mounted in the same rack of cabinet as the transmission equipment. The connectors in a termination application are sometimes replaced by fibre splices, reducing the number of connectors in the link.

ii) *Fibre rearrangement at network nodes*. Changes in types of topography, wavelength, fibre, service, geographic distribution of service, response to service interruptions, etc., imply that a high degree of flexibility is needed.

An ODF should be re-accessible without interruptions to the live circuits, other than the ones that are subject to reconfiguration.

An ODF should allow the termination of one or more cable ends of various cable construction and diameter (attachment of the cable sheath, termination of strength members, and electrical connection of metallic cable elements).

The ODF should be able to properly store fibre splices, different types of passive devices (including coupler and filter devices, used for network testing purposes) and the related bare fibre or ribbon overlengths.

It should be possible to connect and reroute any incoming circuit to any outgoing circuit, with a fixed length of patchcords or pigtail end. Each individual connector must be accessible, without the need to disconnect other (adjacent) connectors.

An ODF contains an organizer (see § 5.2) with the necessary means to guide and store pigtail overlengths in an orderly manner;

iii) *Testing*. The connectors in a fibre distribution unit permit attachment of test equipment such as power meters or optical time domain reflectometer to locate breaks and measure loss.

iv) *Signal modification*. The connectors are also convenient locations to attach passive signal modification devices such as attenuators. Couplers or wavelength division multiplexers may also be attached, although it is more common for them to be separated.

4.3 Design consideration

4.3.1 Cable fibre and jumper management

It is recommended that the bend radius of a fibre should not be smaller than 30 millimetres to ensure the residual strain of the fibre will not exceed 0.2%. However, for some fibre designs, a larger bend radius may be necessary to prevent an increase in optical loss at long wavelengths.

Splices of fibres in service should not be disrupted by installation of new fibres or maintenance of other installed fibres. There are many types of fibre splices. It can be expected that there will be new ones in the future. Fibre distribution units should be chosen to accommodate all the types of splice that are anticipated to be used, and to adapt easily to new ones.

A suitable slack should be foreseen so that the cable fibre stored in the fibre organizer should not experience bends below the above-referred value. In addition, the fibres in service should not experience such bends, e.g. when other fibres are being brought into service or when fibre splices are replaced. This includes bends in the fibre outside the organizer due to motion of the fibre organizer in storing or gaining access to it.

4.3.2 Connectors management

There is a large range in the number of connections in a fibre distribution unit. In central offices and network nodes, there may be up to 500 or more connections. At customer premises there may be only one or a few connections. Furthermore, more fibres are usually installed than are needed; some are connected at once, with the remainder being brought into service as demand increases. Usually the excess fibres are not connectorized and, therefore, the number of connectors usually increases with time.

There is also a large range in the available space at a network node or termination node. Usually the space originally planned for the fibre termination unit becomes too small, as unexpected demand and growth occurs. A fibre distribution unit should provide for a high density of connectors while maintaining easy access and allowing effective management.

Technological evolution, ordinary wear and breakage imply a shorter life for the bulkhead connector than for the fibre network. A fibre distribution unit should provide for easy replacement of a bulkhead connector without affecting the fibres in service.

4.4 Climatic considerations

As pointed out above there is a wide range of climatic factors for fibre distribution units. Many are installed inside human-occupied spaces and have mild temperature and humidity variation. Some may be installed in the outside plant and need to endure broad temperature and humidity variations. Fibre distribution units installed in the open and exposed to the sun's radiation typically receive more thermal stress than those installed in central offices near transmission equipment.

4.5 Mechanical considerations

Fibre distribution units are installed in a wide variety of situations, including rack, cabinet and wall mounting. As fibre is often added to an existing network, small size is important.

Fibre distribution units installed in the open and in manholes will receive more mechanical stress than those installed in central offices and other buildings near transmission equipment.

Experience indicates that more fibre optic cables are added to the network over time. A fibre distribution unit that can grow in incremental additions will gracefully accommodate new cables.

5 Fibre closures and fibre organizers

(For further information, see Recommendation ITU-T L.13.)

5.1 Optical closures

A node occurs at each opening or end of a cable sheath. When an optical node resides in an outdoor environment, it is generally contained in a sealed enclosure. This is commonly also referred to as an optical closure, optical cable joint or optical sheath joint. Here the term "optical closure" will be used.

An optical closure comprises a mechanical structure (closure housing) that is attached to the ends of the sheaths joined and a means (organizer) for containing and protecting the fibres and passive optical devices.

The term closure housing only refers to the sealed container or box, not including the organizer system. Its main functions are: sealing to the cables, mechanical attachment of the cable and protection of its content.

The fibre organizer is described in § 5.2.

The optical closure will:

- i) restore the integrity of the sheath, including mechanical continuity of strength members when required;
- ii) protect the fibres, fibre joints and optical devices from the environment in all types of outdoor plant (aerial, direct buried, in ducts and underwater);
- iii) provide for the organization of the fibre joints, passive devices and the storage of fibre overlength;
- iv) provide electrical bonding and grounding of the metal parts of the sheath and strength members where required.

An example of fibre closure is in Figure 4-9.

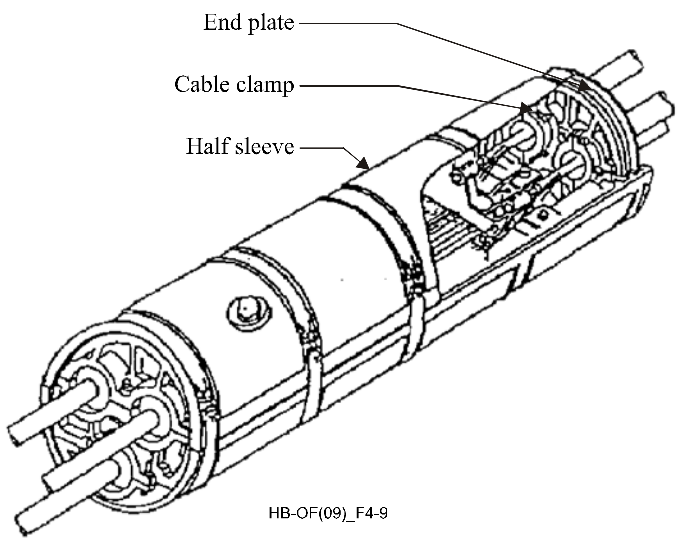


Figure 4-9 – Example of closure

5.1.1 Design characteristics of optical closures

Each optical closure must comply with the general requirements listed in § 3.1.

Closure housing designs employ either cold or hot systems depending on the sealing methods used. Mastic, tapes, grommets, o-rings, cured rubber shapes, pastes, potting compounds, rubber gels and (cold) adhesives are cold processes. Thermo-shrinkable materials, hot-melts and polyethylene injection welding are the primary hot processes. The heat source may be electrical resistance heating, infrared heating, hot air, or a gas flame. Regardless of which of these processes is used, the following shall be considered:

i) the materials used for making the cable joint shall be compatible with each other, with the materials of the sheath and with other materials normally used in the outside plant;

ii) a design may allow for jointing together two or more cable ends. The cables entering the closure may be of differing sizes and/or types;

iii) a design should allow for jointing together at least one pair of cables which are not at the end of a cable i.e., without cutting all the fibres between both cable ends (this application is also known as “external node”, “mid-span closure” or “balloon splice”);

iv) it is desirable that closures can be re-opened when necessary and remade without interruptions to working circuits;

v) a single design, which may be used for all of the above applications and in all outdoor environments;

vi) if joint sealing encapsulant is used, information is required for adjustments in setting time due to variations in ambient temperature and humidity; the use of encapsulant is not recommended for re-enterable closures;

vii) if a heat source is required to seal the closure and/or closure to the sheath, a suitable heat source (gas flame or electrical power) needs to be available at the jointing points. Consideration shall be given to control of the heat source to protect personnel and prevent damage to the closure or cable;

viii) all materials that are exposed to the environment must be sufficiently resistant to fungi. Materials that will be exposed to solar radiation must be UV-resistant.

5.2 Fibre organizers

5.2.1 Design of the organizer system

Fibre organizers are an integral part of an optical closure. The organizers are comprised of one or more sheets or trays that have means for routing and holding fibre joints and fibre over-length in an orderly manner, and should minimize fibre strain.

5.2.2 Characteristics of fibre organizers

The functions of an optical fibre organizer are:

i) to provide means for routing, storing and protecting fibre joints or other passive devices in a predetermined order, from one cable sheath end to another;

ii) to separate optical circuits in one of the separation levels defined in Recommendation ITU-T L.51. The number of fibre joints in one organizer may vary according to the size and shape of the fibre joint and the number of fibres in a cable sub-unit;

iii) to ensure that the fibre bend radius shall not be less than 30 mm in general applications. For special applications a minimum bend radius of 20 mm may be agreed between customer and supplier. Even lower curvature radii may be acceptable when using ITU-T G.657 fibres. In order to maintain mechanical reliability and minimize losses in the network, the cumulative length of fibre, exposed to this smaller bend radius should be limited;

iv) to provide easy identification and access to any stored fibre joint for re-jointing;

v) to separate optical circuits up to the appropriate separation level as indicated in Recommendation ITU-T L.51. This will limit the risk of interruption of traffic to those fibres that belong to the same group of circuits;

vi) to provide a means for storing the fibre over-length required for jointing and for possible re-jointing in the future.

The materials used for making the organizer shall be compatible with the other materials in the cable joint and the degreasing agents as recommended in the installation instructions.

5.2.3 Configurations of optical fibre organizers

The trays or sheets of an organizer may be configured in one of the following ways:

i) lateral sliding from a frame – similar to removing a book from a shelf;

ii) rotation about a hinge – similar to turning a page in a book (Figure 4-10);

iii) lifting from a stack – similar to lifting a book from a stack;

iv) unrolling – similar to locating a page on a scroll.

All movements of the organizer parts should proceed in a predetermined way in order to eliminate optical losses or interruption of traffic due to organizer manipulations.

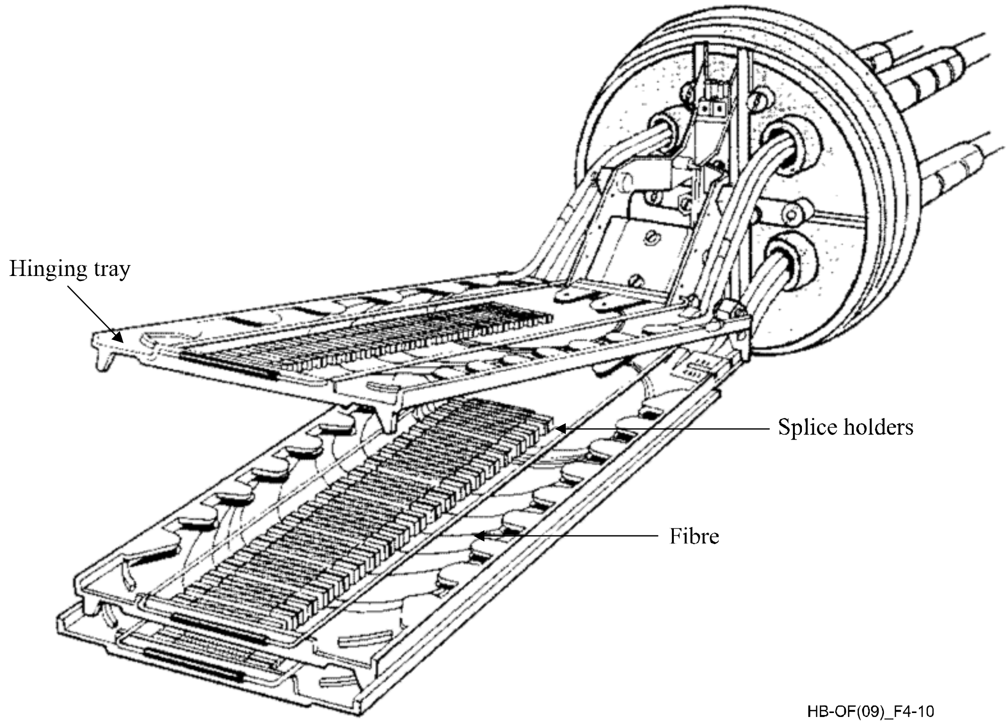


Figure 4-10 – Example of organizer

6 Passive node elements for marinized and submarine optical cables

(For further information, see Recommendations ITU-T G.972 and L.54, Supplement 41 to the ITU-T G-series of Recommendations, and the ITU Handbook, *Marinized Terrestrial Cables*.)

The components of these systems are quite similar, in many respects, to those used in terrestrial cable systems; however, there some specific requirements, which are outlined in this clause.

6.1 Marinized cables

6.1.1 Fibre splices

Fusion splicing is more common for marinized terrestrial cables due to the small size, low-loss and low reflection characteristics of the splices as well as reliability over the long life of these cables. Mass fusion splicing of ribbonized fibres may be used to reduce splicing time. Fibre ribbons, typically up to 12 fibres per ribbon, may be spliced all at once or in subsets of the fibres in a ribbon. The electric arc fusion splices are often reinforced by heat-shrinkable sleeves in order to protect the splices from stresses. The electrical arc fusion splices are essentially the same as splices in terrestrial fibre cables.

The spliced area of the fibre may also be recoated to the same size of the virgin fibre, using the same, or similar, materials used to originally coat the fibre. This provides a very small size splice, which may be virtually indistinguishable from the unspliced fibre.

As for the terrestrial cables, there are two main objectives:

i) to minimize the splice losses;

ii) to ensure a strength reliability suitable for the long-term through appropriate proof-test.

6.1.2 Fibre organizers

Organizers accommodate the spliced optical fibres and their splices. A certain amount of slack fibre is required when splicing optical fibres and it is necessary that this slack be accommodated so that its bending radius is greater than the minimum allowable fibre bending radius (typically ≥ 30 mm).

The following factors should be considered for fibre organizers:

i) *Bending radius*. Fibres should be accommodated so that their minimum bending radii are not violated, to prevent increased loss and possible reduction of long-term reliability;

ii) *Accommodation of slack*. Accommodation of an amount of slack necessary to permit the splicing of the optical fibres and for a few splice remakes is desirable. Design and assembly should preclude pinching the fibres, or degrading the fibres/splices over the life of the system;

iii) *Heat resistance*. When a heating process, such as moulding of PE, heat shrinkable sleeves, etc., is used during the assembly of a splice closure, organizers should have suitable heat resistance characteristics in order to withstand the temperatures involved;

iv) *Vibration-resistance characteristics*. The splice organizer should accommodate the splices such that vibrations during installation and service will not cause the splices to move within the organizer and violate the allowable minimum bend radii requirement. It is especially important to secure any splice reinforcement points, since these are comparatively harder and heavier than the fibres;

v) *Design*. The design of the organizer should be chosen to be suitable for the cable design, size and number of fibres.

6.1.3 Closures

A splice closure for terrestrial marinized cables (TMC) applications is designed:

i) to restore the integrity of sheath, including mechanical continuity of strength members of TMC;

ii) to protect the fibres, fibre splices and optical devices, from the external environment (water) and unwanted handling;

iii) to provide proper storage of fibre splices, passive devices (if any) and excess of fibres;

iv) to resist corrosion;

v) to prevent hydrogen effects;

vi) to allow re-intervention on cables and splices;

vii) to provide for electrical continuity, if required.

6.1.3.1 Physical and structural factors

The closure should be of a simple design and construction in order to expedite its assembly. With this in mind, the following factors should be considered:

i) *Size*. It is preferable that the closure be a minimum size to meet all the strength and material properties above, while protecting the splice organizer(s) and fibre splices. It should be compatible with the installation method proposed, including any cable-laying equipment, and take into account any corrosive environment;

ii) *Weight*. It should be as light in weight as possible, while meeting all of the strength and material properties above while protecting the slice organizer(s) and fibre splices. Ability to be handled by a single person is desirable;

iii) *Bending forces*. Significant bending forces can be encountered during the lay/recovery of long and/or large diameter closures over a sheave, if applicable;

iv) *Strength members*. Tensile strength members for marinized terrestrial cables can be anchored in the closure to prevent a cable unit from being pulled out or pushed in when the cable is subjected to tensile force. The tensile strength provided should be greater than the operational strength of the cables joined;

v) *Mechanical strength*. Mechanical strength greater than the operational strength of the unspliced cable with respect to: tensile force, lateral pressure and water pressure;

vi) *Corrosion-resistant characteristics*. In order to function for a long period of time, the components of the closure, and any auxiliary structure that are in direct contact with the water, should have excellent corrosion-resistant characteristics;

vii) *Moulding*. If a moulding process is used during the splicing operation, the closure design should limit the temperature so as not to damage the fibre coating and/or fibre splices.

6.1.3.2 Components

The main components of a closure for marinized cables are the following:

i) *Cable-anchoring section*: In this section strength members of the cable are anchored to the closure and the operational strength of the cable is restored;

ii) *Pressure-resistant chamber*: A pressure-resistant chamber can be used to protect the optical fibres and splices from water pressure, tensile force, and other external forces. It should be provided with sufficient strength to withstand lateral pressures as well as tensile forces;

iii) *Seals*: This may be a layer that provides a water-tight seal around the splices and cable entries, or seals between the cables and a water tight closure, that should adequately withstand the required water pressures;

iv) *Boots*: Tapered rubber boots may be used to smooth the closure/cable transition in its passage through the cable transporter and over the sheave in installations where such equipment is used.

6.1.4 Beach closures

The marinized terrestrial cable is normally joined to the terrestrial cable in a manhole near the landing point. A beach closure is used to make the connection. This may be a specially designed closure or may be a terrestrial splice closure with auxiliary components for anchoring the marinized terrestrial cable.

6.2 Submarine cables

(For further information, see Recommendation ITU-T G.977.)

What has been said in § 6.1 about fibre splices, fibre organizers, closures and beach closures of marinized cables applies also to submarine cables, taking account the different depth of laying of the cables (up to 7 500 m for the submarine cable and around 300 m for the marinized cable).

Moreover there are two passive nodes that are specific to submarine cables: the submarine repeater housing and the branching Unit.

6.2.1 The submarine repeater housing

The submarine repeater housing is the mechanical piece-part of a repeater.

A submarine repeater is equipment that essentially includes one or more regenerators or amplifiers and associated devices.

Submarine repeater housing must be designed to allow operation, laying, recovery, and re-laying in large depths with no degradation in mechanical, electrical and optical performance.

Technical requirements for submarine repeater housings are as follows:

i) *The internal unit*. Inside the repeater housing, the internal unit can contain several power feed modules and OFA (optical fibre amplifiers) pairs to amplify in both directions optical signals from one or several fibre pairs;

ii) *Corrosion protection*. The external housing of an OSR (optical submarine repeater) should be designed to not suffer from corrosion due to sea water;

iii) *Water pressure resistance*. The OSR must be designed to support large pressure strengths in deep sea water;

iv) *High-voltage insulation*. High-voltage insulation is required between the repeater housing and the internal unit to ensure repeater operations;

v) *Thermal management*. Heat generated by the electronic components inside the OSR may be dissipated sufficiently via thermal conduction with the repeater housing;

vi) *Repeater housing sealing*. The repeater must be provided with a protection against water and gas ingress, both directly from the surrounding sea and from axial cable leakage resulting from a cable break close to the repeater;

vii) *Ambient atmosphere control*. Reliability and proper operation of components may require a controlled internal atmosphere regarding relative humidity or any expected gas that may be generated inside the repeater.

6.2.2 The branching unit

The branching unit (BU) is an optical node in which it is possible to interconnect three cable (and not only two, as in terrestrial closures), allowing a complete connectibility among the cables (Figure 4-11).

Figure 4-11 – Example of branching unit

With the use of the branching units it is possible to interconnect three landing points (three terminal stations) with only one submarine cable. The deployment of two BU on the same cable widens the number of landing points that can be reached with the same submarine cable.

Technical requirements for a branching unit housing are very similar to those of a submarine repeater housing.

CHAPTER 5

ACTIVE AND PASSIVE COMPONENTS / SUBSYSTEMS

Introduction

This Chapter describes the characteristics of the most relevant components of the optical fibre systems such as optical transmitters, sources and modulators (Clause 1), optical receivers (Clause 2), optical amplifiers and their different applications (Clause 3), adaptive chromatic dispersion compensators (Clause 4), PMD compensators (Clause 5), OADMs / ROADMs (Clause 6), Photonic Cross-Connects (Clause 7). Optical wavelength MUX/DMUX, regenerators and transponders, optical attenuators and optical branching devices are dealt with in Clauses 8, 9, 10 and 11.

1 Optical Transmitters

The objective of the optical transmitters is to convert an electrical input signal into a corresponding optical signal and then launch it into the optical fibre serving as a communication channel. The major components of optical transmitters are the optical sources and the modulators.

Optical transmitters use semiconductor optical sources such as light-emitting diodes (LEDs) and semiconductor lasers because of several advantages offered by them, such as compact size, high efficiency, good reliability, correct range of wavelengths, small emissive area compatible with fibre-core dimensions, and possibility of direct modulation at relatively high frequencies.

In some cases, a direct modulation is not suitable and an external modulator is necessary. The two most used types of optical modulators developed for optical systems are the electro-absorption modulator and the $LiNbO_3$ modulator with a Mach-Zehnder (MZ) interferometer.

The parameters which characterize the optical transmitters are dealt with in Chapter 6.

1.1 Light-emitting diodes

A light-emitting diode (LED) is a device that emits light (optical signal) when voltage (electrical signal) is applied across its two terminals. In this way an LED converts an electrical data signal into a corresponding optical signal. An example LED is shown in Figure 5-1.

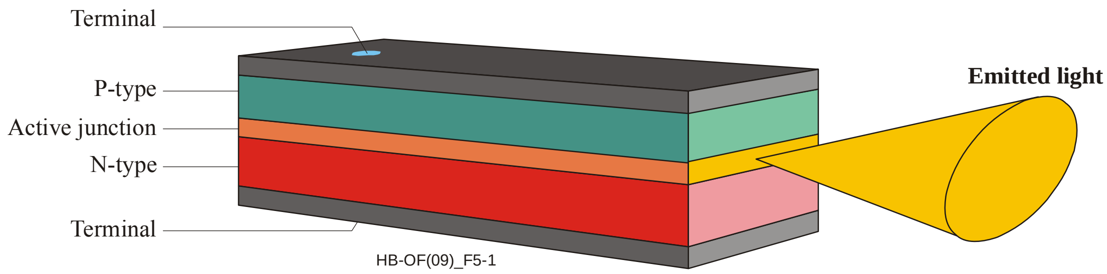


Figure 5-1 – Example LED

The main characteristics of LEDs are the following:

i) LEDs transmit light within a relatively wide cone. The power coupled into the fibre depends on many parameters, such as the numerical aperture of the fibre and the distance between fibre and LED. With a proper design, LEDs can couple up to 1% of the internally generated power into an optical fibre;

ii) LEDs emit a limited optical power (≈ a few mW);

iii) LEDs exhibit a relatively wide spectral width ($\Delta\lambda = 50\text{-}70$ nm). Because of this large spectral width, the bit rate – distance product (BL) is limited considerably by fibre dispersion;

iv) Modulation bandwidth of LEDs is in the range 50-140 MHz;

v) LEDs are inexpensive relative to laser diodes.

In spite of a relatively low optical power and low modulation bandwidth compared with those of lasers, LEDs are useful for low-cost applications requiring data transmission at bit rates of 100 Mbit/s or less over a few kilometres.

1.2 Semiconductor Lasers

Semiconductor lasers (Light Amplification by Stimulated Emission of Radiation) are also devices which convert an electrical input signal into a corresponding optical signal and launch it into the optical fibre (Figure 5-2). The difference from LEDs is that lasers emit light trough stimulated emission.

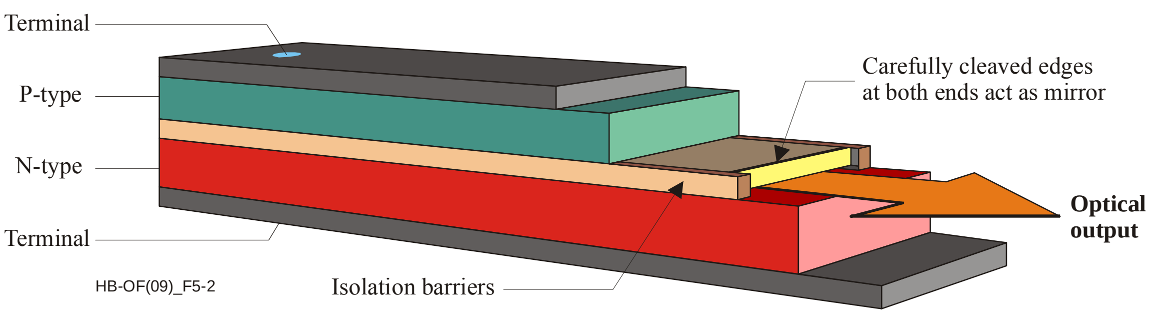


Figure 5-2 – Laser structure based on the Fabry-Perot principle

As a result of the stimulated emission, they have the following characteristics:

i) a relatively narrow angular spread of the output beam compared with LEDs which permits high power coupling efficiency (≈ 50%) into single-mode fibres;

ii) emission of high powers (≈ 100 mW for transmitter lasers);

iii) a relatively narrow spectral width of emitted light which allows operation at high bit rates (>40 Gbit/s), since fibre dispersion becomes less critical for such an optical source;

iv) possibility to be directly modulated at high frequencies (up to 25 GHz).

In spite of their higher cost and technological complexity, most optical communication systems use semiconductor lasers as an optical source because of their superior performance compared with LEDs.

1.2.1 Types of lasers

A *Fabry-Perot (FP) laser* generally emits light in several longitudinal modes. Some of neighbouring modes on each side of the main mode carry a significant portion of the laser power together with that of the main mode. Such lasers are called *Multi Longitudinal Mode* (MLM) *semiconductor lasers*. Since each mode propagates inside the fibre at a slightly different speed because of group-velocity dispersion, the multimode nature of these semiconductor lasers limits the bit-rate-distance product BL to values below 10 (Gbit/s)-km for systems operating near 1.55 µm.

Distributed Feedback (DFB) semiconductor lasers are designed such that the power carried by the side modes is usually a small fraction (< 1 %) of the power of the main mode. Such lasers are called Single Longitudinal Mode (SLM) semiconductor lasers. Despite their technological complexity, DFB lasers are routinely produced commercially and are used in nearly all 1.55 µm optical communication systems operating at bit rates of 2.5 Gbit/s and more.

Multi-section DFB lasers. Modern WDM lightwave systems require, as said above, single-mode, narrow-linewidth lasers whose wavelength remains fixed over time. DFB lasers satisfy this requirement, but their wavelength stability comes at the expense of tunability. The large number of DFB lasers used inside a WDM transmitter make the design and maintenance of such a lightwave system expensive and impractical. The availability of semiconductor lasers whose wavelength can be tuned over a wide range would solve this problem. Multi-section DFB lasers meet the somewhat conflicting requirements of stability and tunability. In this type of laser, the laser wavelength can be tuned almost continuously over a large range of wavelengths (35-40 nm).

Vertical-Cavity Surface-Emitting Lasers (VCSELs) also operate in a single longitudinal mode. Their specific properties result in a number of advantages (wavelengths can be tuned over wide range, low-cost packaging, etc.). However, their main disadvantage is that they cannot emit more than a few milliwatts of power. For this reason they are mostly used only in local area networks where they have virtually replaced LEDs.

1.3 Optical sources reliability

An optical transmitter should operate reliably over a relatively long period of time (10 years or more) in order to be useful as a major component of optical systems. By far the major reason for failure of optical transmitters is the optical source itself. It is common to quantify the lifetime by a parameter known as "mean time to failure" (MTTF). Its use is based on the assumption of an exponential failure probability. Typically the MTTF of the optical sources should exceed 10^5 hours (about 11 years).

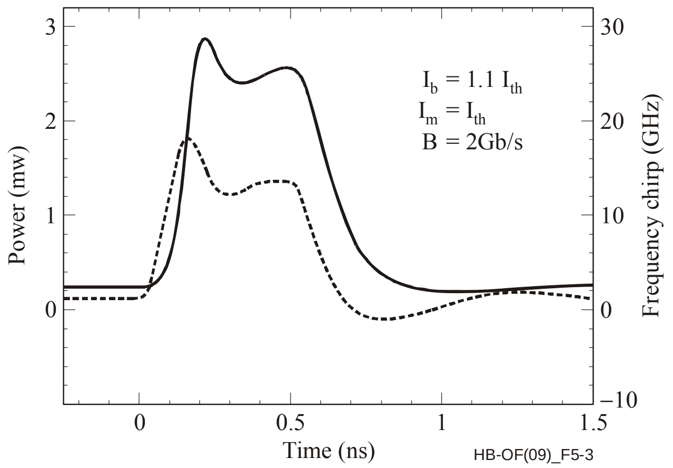
Both LEDs and semiconductors lasers can stop operating suddenly (catastrophic degradation), or they may exhibit a gradual mode of degradation in which the device efficiency degrades with aging. Attempts are made to identify devices that are likely to degrade catastrophically. A common method is to operate the device at high temperatures and high current levels. This technique is referred as accelerated aging.

Extensive tests have shown that LEDs are normally more reliable than semiconductor lasers under the same operating conditions. Nevertheless the reliability of semiconductor lasers is large enough to allow their use also in submarine optical systems designed to operate reliably for a period of 25 years.

It is important to say that, because of the adverse effect of high temperature on device reliability, most transmitters use a thermoelectric cooler to maintain the source temperature near 25°, even when the ambient temperature may be high as 80°.

1.4 Optical modulators

In optical systems the laser can be directly modulated by large signal, but the optical pulses do not have sharp leading and trailing edges and exhibit a rise time (≈ 100 ps) and a fall time (≈ 300 ps). As a consequence the optical pulse from the direct modulation is not an exact replica of the applied electrical pulse (Figure 5-3), even if deviations are small enough that semiconductor lasers can be used in practice.



Note – The solid curve shows the pulse shape and the dashed curve shows the frequency chip imposed on the pulse.

Figure 5-3 – Modulation response of a semiconductor laser

The problem is that amplitude modulation (from the direct modulation) in semiconductor lasers is accompanied by phase modulation. A time-varying phase is equivalent to transient changes in the mode frequency. Such a pulse is called "chirped". The dashed line in Figure 5-3 shows the frequency chirp across the optical pulse. Such a frequency shift implies that the pulse spectrum is considerably broader than that expected in the absence of frequency chirp. This means that the frequency chirp can limit the performance of optical systems due to the increase of the dispersion impairments. It turns out that 1.55 µm optical systems with direct modulation can be limited to distances below 100 km, even at a bit rate of 2.5 Gbit/s, because of the frequency chirp.

Higher bit rates and longer distances can only be realized with a laser continuously operated and with an external modulator placed next to the laser. In this way the frequency chirp due to direct modulation can be avoided. In practice, optical systems operating at 10 Gbit/s, or more, use external modulators.

There are two most used types of external optical modulators used in optical systems. The first type is the *electro-absorption modulator*, which has the advantage that it is made using the same semiconductor material that is used for the laser, and thus it can be easily integrated on the same chip. The second type is the *$LiNbO_3$ modulator with a Mach-Zehnder (MZ) interferometer* for intensity modulation.

The performance of an external modulator is quantified through the on-off ratio (called also "extinction ratio") and the modulation bandwidth. Modern $LiNbO_3$ modulators provide an extinction ratio in excess of 20 dB (measured at low frequency) and can be modulated at speeds up to 75 GHz, suitable for system bit rates of 10 Gbit/s and of 40 Gbit/s.

One can even design a modulator to reverse the sign of the chirp resulting in improved system performance (see Chapter 7).

2 Optical receivers

The role of an optical receiver is to convert the optical signal back into electrical form and recover the data transmitted through the optical system. Its main component is a *photodetector* that converts light into electricity through the photoelectric effect. The requirements for a photodetector are similar to those of an optical source (compact size, high efficiency, good reliability, right wavelength range, small emissive area compatible with fibre-core dimensions). These requirements are best met by photodetectors made from semiconductor materials.

The most widely used photodetectors are PIN photodiodes and avalanche photodiodes.

The optical parameters which characterize the optical receivers are described in Chapter 6.

PIN photodiodes. PIN (pronounced "pee-eye-en") photodiodes have a layer of undoped (or lightly doped) semiconductor material between the p- and n-doped regions. Since the middle layer consists of nearly intrinsic material, such a structure is referred as a p-i-n photodiode. Most of the incoming photons are absorbed in the intrinsic region, and carriers generated therein can efficiently contribute to the photocurrent.

The responsivity (output current / input optical power) is one of the most important parameters that characterize a PIN.

Avalanche photodiodes (APD). Avalanche photodiodes differ in their design from that of PIN photodiodes mainly in one respect: an additional layer is added in which secondary electron-hole pairs are generated through impact ionization.

The responsivity (output current / input optical power) of an APD is about two orders of magnitude higher than that of a PIN photodiode.

3 Optical amplifiers

(For further information, see Recommendations ITU-T G.661, ITU-T G.662 and ITU-T G.663.)

The transmission distance of optical fibre systems is generally limited by fibre losses. For long-haul systems, the loss limitation has traditionally been overcome using regenerators (see § 8), in which the optical signal is first converted into an electric current and then regenerated using a transmitter. Such regenerators become quite complex and expensive for wavelength division multiplexed (WDM) systems. An alternative approach to compensate this loss makes use of optical amplifiers, which amplify the optical signal directly without requiring its conversion to the electrical domain. Several types of optical amplifiers were developed during the 1980s and the use of optical amplifiers for long-haul optical systems became widespread during the 1990s.

3.1 Application of optical amplifiers

Optical amplifiers (OAs) are devices based on conventional laser principles. They receive one or more optical signals, each within a window of optical frequencies and simultaneously amplify all wavelengths. That is, they coherently release more photons at each wavelength.

Application of OAs in optical transmission systems offers a number of advantages. Chief among these advantages is the ability to realize very long unregenerated system lengths. Deployment of OAs is likely to permit the retirement of many existing conventional regenerator sites and, in the case of new routes, to render unnecessary the construction of many new sites. OAs also enable consideration of new optical system architectures for application in terrestrial and submarine long haul and access networks. Two examples of this are wavelength division multiplexing and point-to-multipoint applications, approaches heretofore generally considered prohibitively complex and expensive. OAs also offer potential advantages with respect to network upgrade options, due to their independence from modulation format and bit rate.

However, the application of OAs also brings to light some new and potentially serious system impairments, which result from the high power levels produced by the OAs and the long distances between regeneration. These transmission effects include optical fibre nonlinearities, polarization effects and effects due to the amplification characteristics of the OA itself. Chromatic dispersion also becomes increasingly significant for the long unregenerated systems enabled by the OA. In addition the dispersion characteristics of the fibre influence the severity of the impairment produced by several of the dominant nonlinear effects. In the following the OA applications are described.

OAs find application in single-channel and in multichannel systems. In addition to the transmission impairments found in single-channel systems, multichannel systems may also suffer degraded performance due to certain non-linear effects. These include four-wave mixing (FWM), cross phase modulation (XPM) and, potentially, stimulated Raman scattering (SRS). As a result, special precautions must be taken when designing multichannel systems to avoid or alleviate these impairments (see Chapter 7).

3.1.1 Booster amplifier

The booster (power) amplifier (BA) is a high saturation-power OA device to be used directly after the optical transmitter to increase its signal power level. The BA does not need stringent requirements for noise and optical filtering.

The application of BAs (often in conjunction with pre-amplifiers) is very attractive, especially in those cases where intermediate locations with active equipment are either undesirable or inaccessible, as in submarine systems. In any case, fewer intermediate locations imply easier maintenance for the network operator.

Because of the relatively high level of input power, the undesirable amplified spontaneous emission (ASE) noise, inherently present due to the statistical process of photon generation inside the OA, is usually negligible. However, application of BAs may result in fibre nonlinearity induced system penalties, due to the high optical power levels produced by BAs and the long interactive lengths provided by the optical path.

3.1.2 Pre-amplifier

The pre-amplifier (PA) is a very low noise OA device to be used directly before an optical receiver to improve its sensitivity. The requisite low level of ASE noise may be achieved through the use of narrow-band optical filters. In this case, automatic tuning of the centre wavelength of the pre-amplifier filter to the transmitter wavelength would be advantageous, since it would permit the relaxation of requirements on both the initial transmitter wavelength tolerance and its long-term stability. As noted previously, the use of PAs (usually in conjunction with BAs) is a straightforward means to realize significant increases in available power budget.

3.1.3 Line amplifier

The line amplifier (LA) is a low-noise OA device to be used between passive fibre sections to increase the regeneration lengths or, in correspondence with a multipoint connection, to compensate for branching losses in the optical access network.

As noted previously, line amplifiers might replace some or all conventional regenerators in long-haul fibre sections. It can be envisioned that more than one conventional regenerator can be replaced by a single LA, with the evident advantage of reduced equipment in transmission links. Furthermore, a situation can be envisaged where both line amplifiers for compensation of signal attenuation and conventional regenerators for compensation of signal distortion appear in long-distance networks.

A typical configuration of an OA (as LA) in a multichannel application is shown in Figure 5-4.

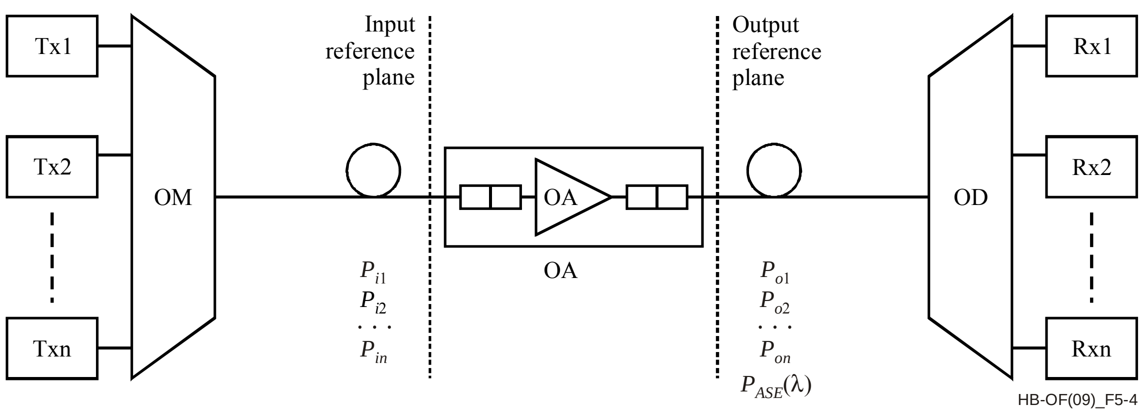
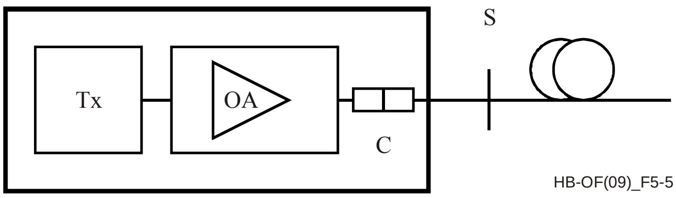


Figure 5-4 – Line amplifier in a multichannel application

At the transmitting side *n* signals, coming from *n* optical transmitters, Tx1, Tx2, . . . Txn, each with a unique wavelength, λ_1, λ_2, . . . λ_n, respectively, are combined by an optical multiplexer (OM). At the receiving side, the *n* signals at λ_1, λ_2, . . . λ_n, are separated with an optical demultiplexer (OD) and routed to separate optical receivers, Rx1, Rx2, . . . Rxn, respectively.

3.1.4 Optically amplified transmitter

The optically amplified transmitter (OAT) is an OA sub-system in which a power amplifier is integrated with the laser transmitter, resulting in a high-power transmitter (Figure 5-5).



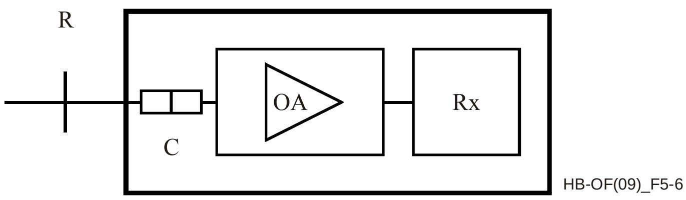
S Reference point in the optical fibre just after the optical connection (C) of the OAT

Figure 5-5 – OAT reference diagram

The connection between the transmitter and the OA is proprietary and it is not specified. The application considerations of OATs are generally the same as those for BAs.

3.1.5 Optically amplified receiver

The optically amplified receiver (OAR) is an OA sub-system in which a pre-amplifier is integrated with the optical receiver, resulting in a high sensitivity receiver (Figure 5-6).



R Reference point in the optical fibre just before the optical connection (C) of the OAR

Figure 5-6 – OAR reference diagram

The connection between the receiver and the OA is proprietary and it is not specified. The application considerations of OARs are generally the same as those for PAs.

3.2 Types of optical amplifiers

There are several types of OAs. Among them: erbium-doped fibre amplifier (EDFA), semiconductor optical amplifiers (SOA), and Raman amplifiers. OAs require electrical or optical energy to excite the state of electron-hole pairs. Energy is typically provided by injecting electrical current (in SOA), or optical light in EDFA and Raman amplifiers.

3.2.1 EDFA-type amplifiers

An EDFA is a fibre segment, a few metres long, that is doped with the rare earth element erbium. The erbium ions may be excited by being pumped at a number of optical frequencies. The two more convenient excitation wavelengths are 980 nm and 1 480 nm.

When these wavelengths propagate through the active fibre, erbium ions are excited and an incoming optical signal can be amplified by stimulated emission, releasing photon energy in the wavelength range 1 530-1 565 nm (the C-band). By modifying the design of the amplifier, this range can also be shifted to longer wavelengths (the L-band) (see Chapter 6).

The basic structure of an EDFA consists of a coupling device, an erbium-doped fibre and two isolators (one at each end) (Figure 5-7).

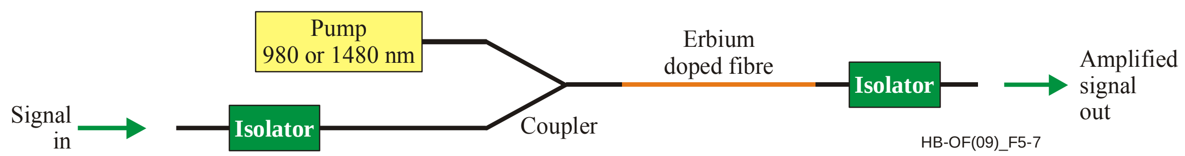


Figure 5-7 – An example of EDFA amplifier

The fibre carrying the signal is connected via the isolator that suppresses optical reflections. The EDFA is stimulated by a laser source, known as the pump laser. The pump power (980 nm or 1 480 nm) is coupled into the EDFA together with the incoming data signal. The pump excites the fibre dopant ions, resulting in amplification of the data signal passing through at a wavelength in the 1 550 nm region.

3.2.2 SOA type amplifiers

The physical mechanism providing gain in semiconductor optical amplifiers (SOAs) differs in various aspects from that of the above EDFA amplifiers. Basically, SOAs are semiconductor lasers without the optical cavity feedback (the facets of the chip have an anti-reflection coating), and so the population inversion is generated in the active region by an electrical current. The stimulated emission of photons occurs via electron-hole recombination processes induced by the signal photons (at wavelengths included in the amplification band of the semiconductor material).

3.2.3 Raman amplifiers

(For further information, see Recommendation ITU-T G.665.)

Stimulated Raman Scattering (SRS) amplifiers are non-doped fibre amplifiers that employ high-power pumps to take advantage of the non-linear properties of the fibre. Figure 5-8 shows how a fibre can be used as a Raman amplifier.

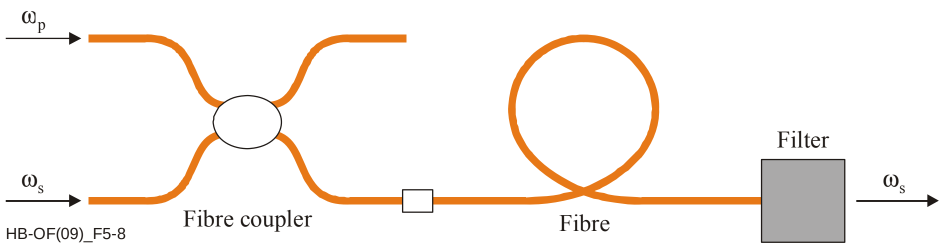


Figure 5-8 – Schematic of a Raman amplifier

The pump and the signal are injected into the fibre through a fibre coupler. The energy is transferred from the pump beam to the signal beam through SRS as the two beams co-propagate inside the fibre. The pump and the signal beams counter-propagate in the backward-pumping configuration commonly used in practice.

Raman amplifiers are called distribute or discrete, depending on their design. In the discrete case, a discrete device is made by spooling 1-2 km of an especially prepared fibre. The fibre is pumped at a wavelength near 1.45 µm for amplification of 1.55 µm signals. In the case of distributed Raman amplification, the same fibre that is used for signal transmission is also used for signal amplification. The pump light is often injected in the backward direction and provide gain over relatively long lengths (> 20 km).

The most important feature of the Raman amplifiers is a large bandwidth range which can extend over the complete useful spectrum from 1 300 nm to 1 600 nm with no restriction to gain over bandwidth, thus enabling a multi-terabit transmission. On the negative side, Raman amplification require pump lasers with high optical power (> 1 W), with the related thermal management issues as well as safety issues.

3.2.3.1 Distributed Raman amplifiers

Distributed Raman amplifiers are amplifiers where the amplification effect is achieved via a portion of the optical fibre used for transmission. Such amplifiers are deemed to be distributed, since part or all of the transmission fibre is used for amplification purposes. Distributed Raman amplifiers can be further classified into three sub-categories.

Reverse-pumped Raman amplifier: The pump energy and signal propagate in opposite directions in the transmission fibre. These Raman amplifiers can have their pump near the receiver and the pump light travels in opposite direction towards the source (Figure 5-9, where RP_i is the reverse-pumped signal input reference point, RP_o is the reverse-pumped signal output reference point and GMP is the gain measurement point).

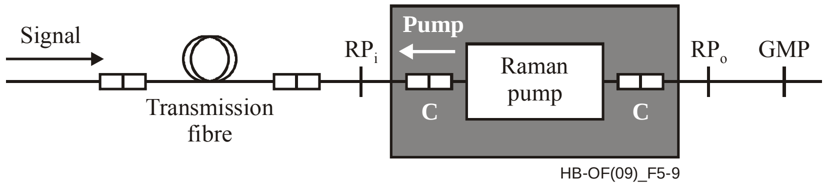


Figure 5-9 – Reverse-pumped Raman amplifier

Thus the pump is strongest at the receiver and weakest at the source. This arrangement has an important advantage: the pump power is where it is most needed (at remote distance from the source) and less needed (in the vicinity of the source). Consequently the signal is amplified where it is weakest and less where it is strongest.

Forward-pumped Raman amplifier: The pump energy and signal co-propagate along the transmission fibre (Figure 5-10, where FP_i is the forward-pumped signal input reference point, FP_o is the forward-pumped signal output reference point and GMP is the gain measurement point).

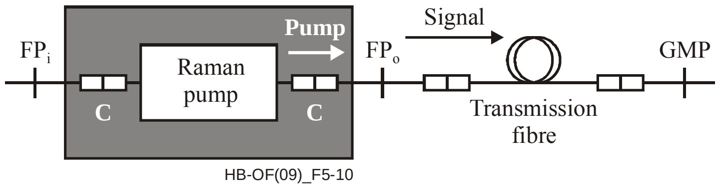


Figure 5-10 – Forward-pumped Raman amplifier

Bidirectionally-pumped Raman amplifier: The pump energy is applied in both ends of the transmission fibre. This configuration features two pumps, one at the transmitting side and one at the receiving side, with each pump at different wavelengths, e.g. to meet a simultaneous C- and L-band amplification or to realize a specific power versus wavelength shape of the used channels. In this case, part of the pump energy co-propagates with the signal and part of the pump energy counter-propagates with the signal inside the transmission media (Figure 5-11).

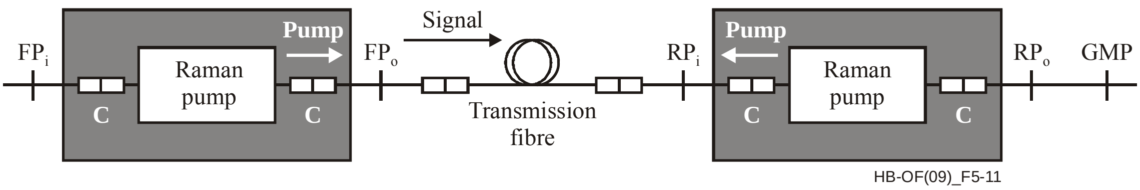


Figure 5-11 – Bidirectionally-pumped Raman amplifier

3.2.3.2 Discrete Raman amplifiers

A discrete Raman amplifier is an amplifier for optical signals whose amplification effect is achieved via the fibre stimulated Raman scattering effect, where all of the physical components of the amplifier are completely contained inside the device (Figure 5-12, where A_i and A_o mark the input and output reference points). In many cases a specific optical fibre (other then the transmission fibre) is used, in order to reduce the needed pump power for achieving a specific gain.

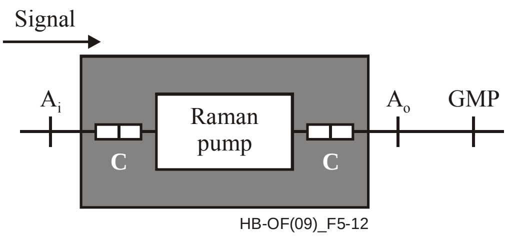


Figure 5-12 – Discrete Raman amplifier

3.2.3.3 Applications of EDFAs, SOAs and Raman amplifiers

EDFAs represent the most mature OFA technology and have been distributed on the market for several years and are produced by various manufacturers worldwide. The EDFA OA is particularly attractive for WDM optical systems and it is widely used for these applications.

On the other hand, SOAs are still at the R&D stage. Today, very few manufacturers produce them and the yield is very low. Even though the technology of SOAs is based on the very well assessed semiconductor laser technology, several important problems related to packaging, pig tailing, anti-reflection coating and polarization sensitivity have not found yet satisfactory mass-scale production solutions.

Moreover, field trials with SOAs have started recently and there is today only a limited experience in using SOAs in the field.

At the present stage of the SOA technology, the most suitable applications of SOAs, as gain blocks in optical point-to-point systems, seem to be as booster amplifiers, integrated with the emitter laser, even though there are some limitations in terms of output power.

Problems related to line and pre-amplifier applications (such as polarization sensitivity and relatively high noise figure) are going to be solved. SOAs have a great potential as functional devices in optical switches, to simultaneously provide gain and fast gating functions, and in other signal processing devices (wavelength converters, optical multiplexers and demultiplexers), due to the strong non-linear response they have in the saturation regime. They can also be integrated in optical switch matrices to compensate for the losses internal to the matrix itself.

Raman amplifiers are mainly used in long haul or ultra long haul transmission systems with very high capacity where the signal degradation coming from the noise of the EDFAs is not tolerable or the required optical bandwidth is larger then what an EDFA can support. Especially distributed Raman amplifiers can help to improve the optical signal-to-noise ratio (OSNR) by using the transmission fibre as active media. Due to the higher component cost, especially caused by the high pump power, this type of amplifier is not widely installed in today’s network but furthermore dedicated for specific applications.

4 Adaptive chromatic dispersion compensators

(For further information, see Recommendation ITU-T G.667.)

Chromatic dispersion in a single-mode fibre is a combination of material dispersion and waveguide dispersion and it contributes to pulse broadening and distortion in a digital signal (see Chapter 1). It does this by inducing a frequency dependent phase shift of the signal travelling in the fibre, which causes pulse broadening of the optical waveform at the receiver.

For links where the chromatic dispersion would otherwise be too large, a dispersion compensation device is used to compensate the chromatic dispersion of the optical path. Presently, various different types of dispersion accommodation (DA) technology are used. For example: passive dispersion compensation (PDC), self phase modulation (SPM), prechirp (PCH) and dispersion supported transmission (DST).

Moreover in some applications, the chromatic dispersion of the optical path varies with time or optical network re-configuration to such an extent that, to avoid signal degradations at the receiver, an adaptive dispersion compensator (ADC) is used to dynamically compensate the chromatic dispersion change of the optical link.

4.1 ADC applications

Adaptive dispersion compensators are expected to be used in at least two applications: compensation of slow changes in link dispersion and compensation of step changes in link dispersion.

i) Slow change link dispersion application

In this application, the ADCs are used to compensate for slow changes of link dispersion over time due to environmental effects.

One example application is an ultra-long haul 10 Gbit/s optical transmission system. Since the chromatic dispersion in a fibre varies with time/temperature, the residual dispersion of each channel varies accordingly. If the variation of channel residual dispersion exceeds the dispersion tolerance of the transmitter – receiver pair, a single or multichannel adaptive dispersion compensator is needed to dynamically compensate for the chromatic dispersion change of the optical link.

Similarly, for a long distance 40 Gbit/s optical transmission system, since the dispersion tolerance of a transmitter – receiver pair is typically much lower than that of 10 Gbit/s systems, dynamically adjusted dispersion compensation may also be needed to compensate for the optical link fibre dispersion variation with time/temperature.

Since the variation of fibre chromatic dispersion with time/temperature is slow, the minimum rate of change of dispersion compensation parameter is used to specify the tuning performance of the ADCs.

ii) Step change link dispersion application

In this application, the ADCs are used to compensate for sudden step changes of link dispersion due to switching or other transmission link re-configuration process.

One example application is illustrated in Figure 5-13.

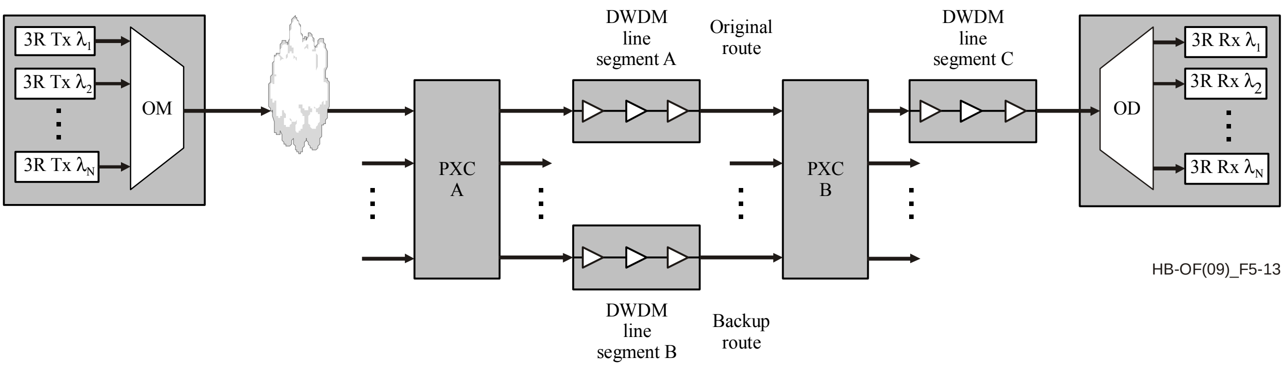


Figure 5-13 – Example step change link dispersion application

A dense wavelength division multiplexing (DWDM) optical signal is originally routed through DWDM line segment A.

After re-configuration, the route is changed from segment A to segment B. Since the link dispersion of DWDM line segment A is different from DWDM line segment B, a step change of channel residual dispersion occurs. If the step change of channel residual dispersion exceeds the dispersion tolerance of the transmitter – receiver pair, a single or multichannel adaptive dispersion compensator is needed to dynamically compensate the chromatic dispersion change of the optical link.

Since the change of dispersion in this case occurs as a step, the maximum dispersion compensation tuning time parameter is used to specify the tuning performance of the ADCs.

4.2 ADCs reference configurations

A generic configuration of a transmission system with ADC(s) is shown in Figure 5-14 (where MPI-S is the single channel source main path interface reference point and MPI-R is the single channel receive main path interface reference point). It consists of a transmitter terminal, a receiver terminal and a transmission link, with optional Line ADC(s), in between.

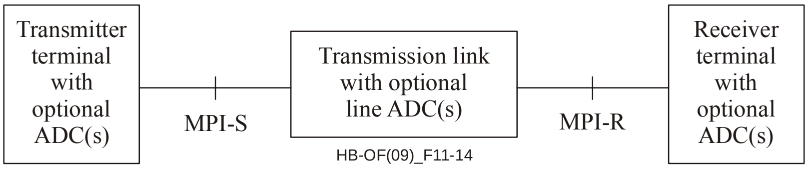


Figure 5-14 – Generic configuration of a transmission system with ADCs

Line ADCs, ADC transmitters, and receivers are all described in Recommendation ITU-T G.667.

Figure 5-15 shows, as an example, an ADC receiver (ADC-Rx) in which the ADC functionality is embedded in the receiver black-box.

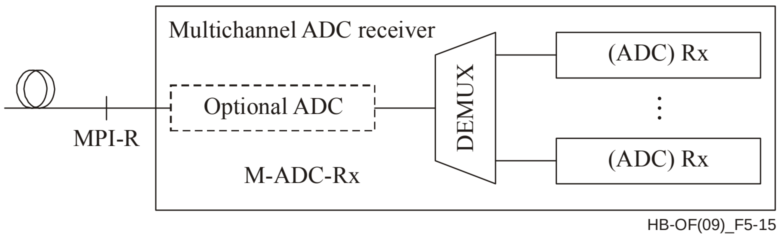


Figure 5-15 – Reference configuration of a multichannel ADC receiver

There are several different types of receiver-based electronic dispersion compensation (EDC) techniques. In all cases, however, an adaptive data processor is used to reduce the inter-symbol interference of the optical to electrical converted signal that was introduced by chromatic dispersion and other non-linear effects. The different adaptive data processor technologies that are currently being used are: feed forward equalization (FFE), decision feedback equalization (DFE), and maximum likelihood sequence estimation (MLSE). They are all described in Recommendation ITU-T G.667.

5 PMD compensators

(For further information, see Recommendation ITU-T G.666.)

Polarization mode dispersion is the differential group delay (DGD) time between two orthogonal polarized modes, which causes pulse spreading in digital systems and distortions in analogue systems.

Polarization mode dispersion compensators (PMDCs) are intended to be used in optical transmission systems in order to reduce PMD-induced signal degradations. Therefore, characteristics of PMDCs must be considered – at least in part – in conjunction with a whole transmission system.

The requirements and key parameters for first- and higher-order PMD compensators, including dynamic PMD characteristics are in Recommendation ITU-T G.666.

A transmission system with PMDC(s) consists of a transmitter terminal, a receiver terminal and a transmission link, with optional line PMDC(s), in between. The receiver terminal, which contains PMDC functionalities, is called in this case a “PMDC receiver”.

An example of the various possible PMDC configurations of a multichannel PMDC receiver is presented schematically in Figure 5-16. A multichannel optical signal enters the receiver terminal at the reference point MPI-R. There it either passes a PMDC before entering a demultiplexer (DEMUX) and the receivers Rx for the individual optical channels, or it passes directly through the demultiplexer where all of the receivers are PMDC Rx.

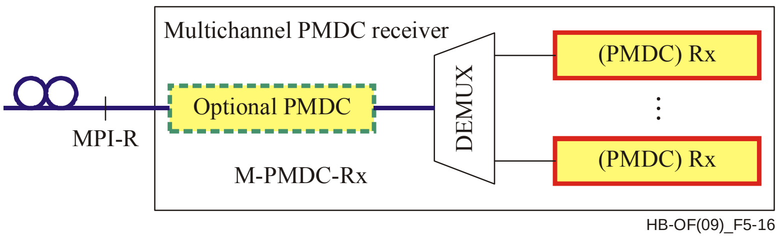


Figure 5-16 – Reference configuration of a multichannel PMDC receiver

6 OADMs and ROADMs

(For further information, see Recommendations ITU-T G.671 and ITU-T G.680.)

An optical add/drop multiplexer (OADM) subsystem is a wavelength selective branching device (used in WDM transmission systems) having a wavelength “drop” function in which one or more optical signals can be transferred from an input port to either an output port or drop port(s) depending on the wavelength of the signal. An OADM also has a wavelength “add” function in which optical signals presented to the add port(s) are also transferred to the output port as shown in Figure 5-17.

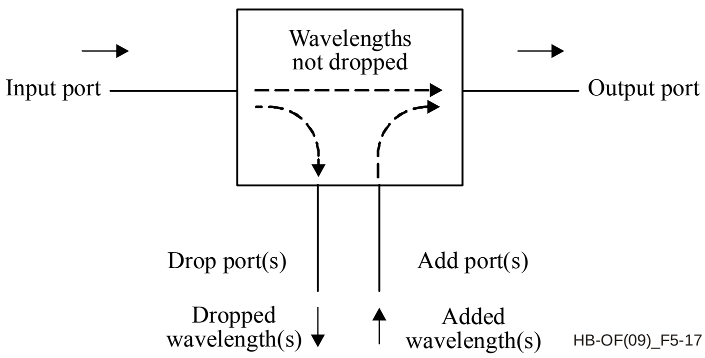


Figure 5-17 – Optical add/drop multiplexer (OADM) subsystem

The add/drop functionality can be of two types:

i) *OADM with fixed wavelengths*. The wavelength(s) to be dropped / inserted are selected and remain(s) the same until human intervention changes them;

ii) *ROADM (Reconfigurable OADM) with dynamically wavelengths selectable*. The wavelengths between the optical demultiplexer and multiplexer to be added / dropped may be dynamically changed, usually, by a remote management system. An example of ROADM is in Figure 5-18, where OLAs are Optical Line Amplifiers.

OADMs and ROADMs are needed for the backbone and for the metropolitan area networks, in which one or more channels need to be dropped or added while preserving the integrity of the other channels.

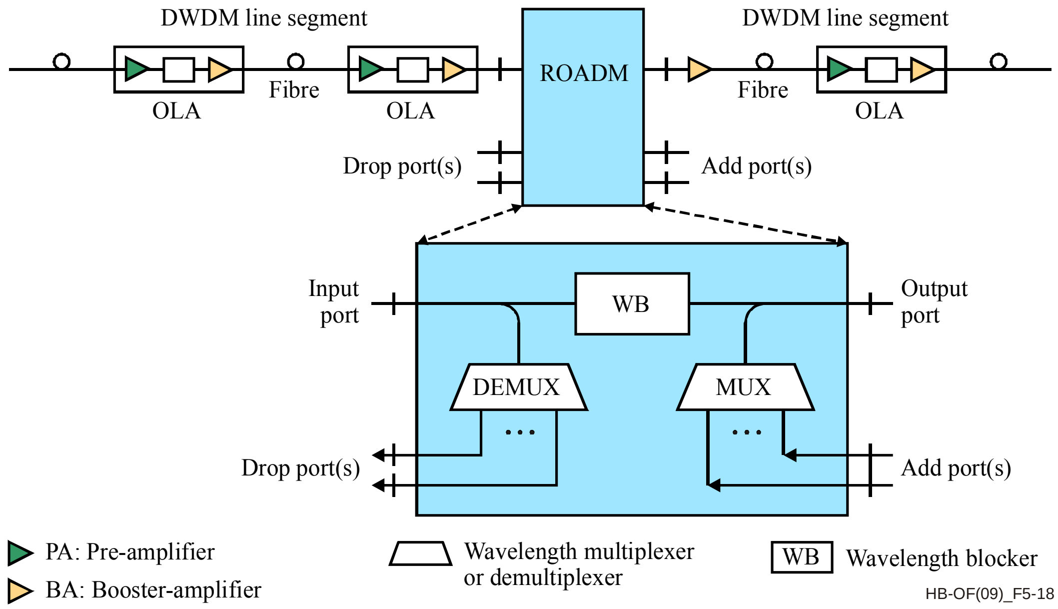


Figure 5-18 – Example of ROADM

7 Photonic Cross-Connects

(For further information, see Recommendation ITU-T G.680.)

The development of wide-area WDM networks requires a dynamic wavelength routing scheme, which can reconfigure the network. This functionality is provided by photonic cross-connect (PXC) which performs the same functions as that provided by electronic digital switches in telephone networks.

The PXC is a cross-connect device, used in WDM transmission systems, in which one or more signals can be cross-connected from one of a number of input ports to one of a number of output port(s). An example of reference diagram for a PXC is shown in Figure 5-19.

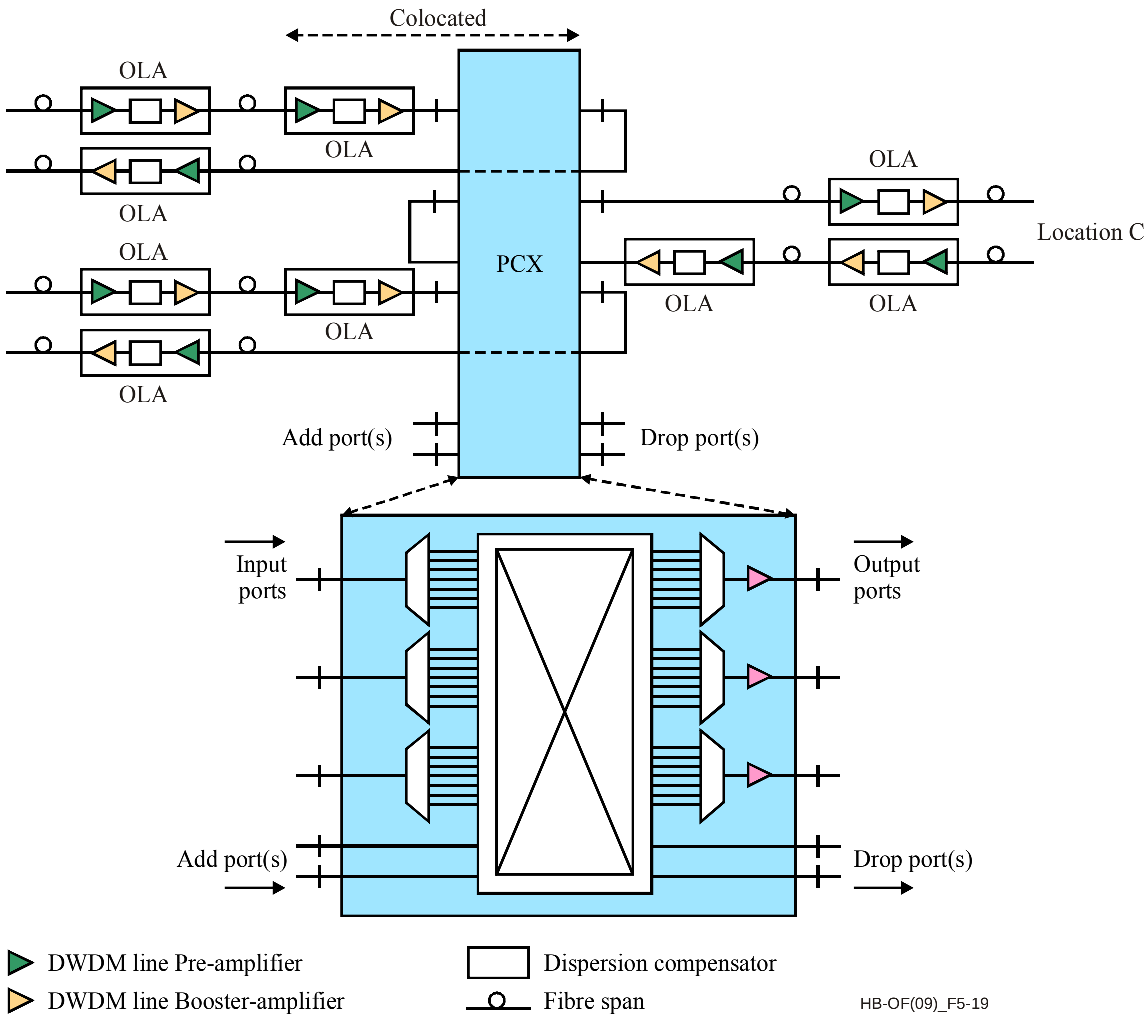


Figure 5-19 – Example of PXC

In this example the PXC has the additional feature that one or more single channel ports are directly available at the input or output side of the switch, thereby enabling to additionally perform the function of adding or dropping individual channels.

A variety of PXC types are included within this definition such as devices which switch from any input port to any output port:

i) any wavelength;

ii) groups of wavelengths;

iii) all wavelengths;

iv) a combination of the above.

These PXCs may also include additional optical functions such as chromatic dispersion compensation, PMD compensation, etc.

8 Optical wavelength MUX/DMUX

A wavelength multiplexer (MUX) (or optical multiplexer (OM)) is a branching device with two or more input ports and one output port, where the light in each input port is restricted to a preselected wavelength range and the output is the combination of the light from the input ports.

A wavelength demultiplexer (DMUX) (or optical demultiplexer (OD)) is a device which performs the inverse operation of a wavelength multiplexer, where the input is an optical signal comprising two or more wavelength ranges and the output of each port is a different preselected wavelength range.

Both wavelength multiplexers (MUX) and wavelength demultiplexers (DMUX) are generally called "WDM Devices" since often the same device can be used to multiplex and demultiplex channels.

An application of MUX and DMUX is shown in Figure 5-4 where they are used in two terminal stations for transmitting on an optical fibre several signals at different wavelengths. Another application is in Figure 5-19 where they are used for cross-connecting optical channels among different traffic directions.

9 Regenerators and transponders

9.1 3R regenerators

(For further information, see Recommendations ITU-T G.680 and ITU-T G.959-1.)

A 3R regenerator is a device or sub-system that performs simultaneously the "re-amplification", "re-shaping" and "re-timing" functions on an optical signal. Thus, this device or sub-system restores the amplitude of the signal to a level suitable for onward transmission, removes any amplitude noise or distortion present on the waveform and also re-times the signal to remove any timing jitter that may be present.

From the transmission viewpoint, an optical connection shows a behaviour like an analogue connection (e.g. the optical transmission impairments due to attenuation, dispersion, fibre nonlinearity, amplified spontaneous emission, etc., accumulate in a manner similar to the accumulation of noise and other impairments in analogue networks). Within digital networks, mitigation of such impairments is achieved at 3R regeneration points, located in the transmission path according to engineering guidelines designed to achieve the required link error performance objective. As a consequence 3R regeneration is used at certain locations to maintain the error performance objectives. Currently, the 3R process typically relies on electro-optic conversion. The technology of all-optical 3R regeneration is not still mature for deployment in the telecommunication networks.

A regenerator is nothing but a receiver-transmitter pair that detects the incoming optical signal, recovers the electrical bit stream and converts it back into optical form by modulating an optical source (Figure 5-20).

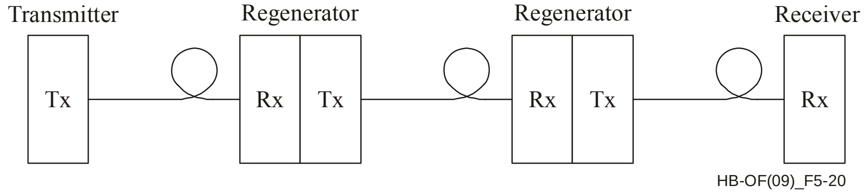


Figure 5-20 – 3R Regenerators

Fibre attenuation can also be compensated by using optical amplifiers (see § 3), which amplify the optical bit stream directly without requiring conversion of the signal in the electrical domain. However, even with the use of optical amplifiers, periodically it is necessary to regenerate the optical bit stream with regenerators, which compensate for all sources of signal degradation.

9.2 Transponders

The transport network of most operators is based on the use of equipment from a variety of different vendors. In order to allow coexistence of equipment from different vendors at the border of DWDM optical transmission, optical transponders are used, as shown in Figure 5-21.

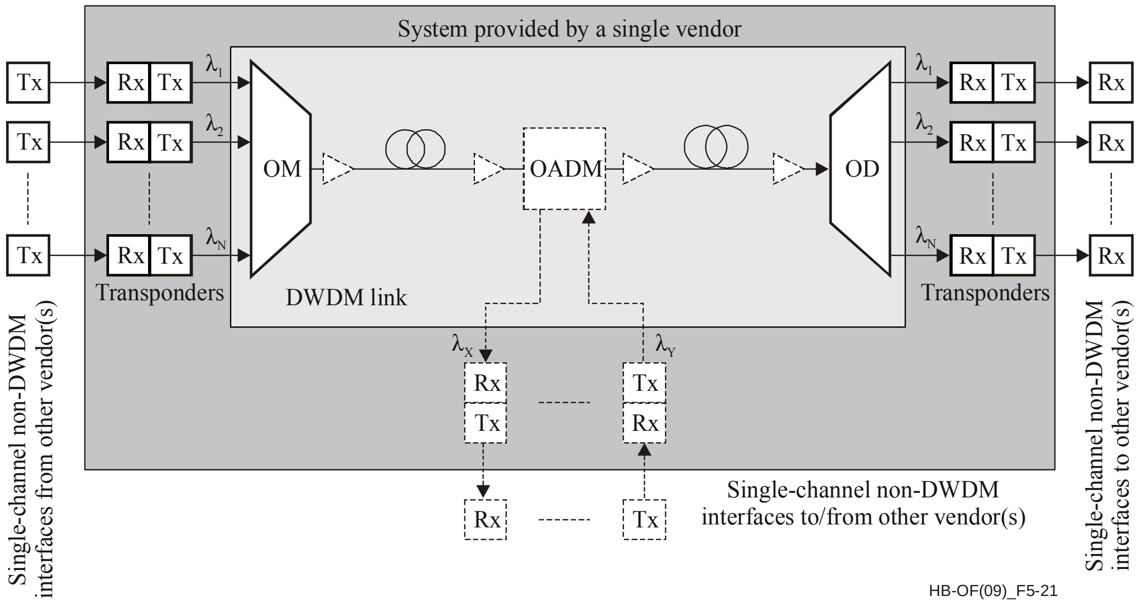


Figure 5-21 – Transponders

The optical interfaces labelled in the figure, "Single-channel non-DWDM interfaces from other vendor(s)", can then be any short–reach, standardized optical interface that both vendors support, such as those found in Recommendations ITU-T G.957, ITU-T G.691, ITU-T G.693, ITU-T G.959.1, etc. This arrangement allows the direct connection of a wide variety of equipment to the DWDM line system such as:

i) a digital cross-connect with multiple optical interfaces supplied by a different vendor from the line system;

ii) multiple optical client devices, each from a different vendor supplying one channel each;

iii) a combination of the above.

Through the use of the single channel DWDM interfaces specified in some ITU-T Recommendations (e.g. ITU-T G.698.1, and ITU-T G.698.2), however, this interconnection can also be achieved while removing the need for one short-reach transmitter and receiver pair per channel (eliminating the transponders), with obvious associated cost savings, as shown in Recommendation ITU-T G.698.2.

10 Optical attenuators

(For further information, see Recommendation ITU-T L.31.)

Optical fibre attenuators are passive optical components that are often required in an optical fibre transmission link to reduce the optical power incident on the photodetector.

They can introduce a fixed level of attenuation (fixed attenuators) or they may have a tuning control to set the level of attenuation into a range of selectable values (variable attenuators).

Typical applications for optical fibre attenuators are:

i) to assure the linear behaviour of optical fibre receivers avoiding optical power overloading;

ii) to balance the optical power into passive optical network (PON) branches or DWDM links;

iii) to make measurements on an optical telecommunication system.

Regarding the first application, the optical power emitted by the source in a transmission system usually exceeds the needed power budget: the aim is to guarantee the operating condition of the system, even if some degradation phenomena occur in the link. The direct control of the optical emission of the sources can be made only for a limited dynamic range and may produce undesired modification of the characteristics of the emitted optical beam, like modal distribution or change of central wavelength. Therefore, attenuators are used in optical telecommunication systems to limit the optical power level at the receiver.

The second application of these components is justified by the non-uniformity of the link losses in a real point-to-multipoint network. In fact, due to the topology of the network, different optical paths may suffer different losses so that specific optical attenuators may be needed in some branches of the network to assure the same linear operating range at each optical receiver.

Finally, the third application mainly concerns variable optical attenuators. In fact, these kinds of components can be very important for making several measurements in an optical telecommunication system, for example, each time the performance (bit error ratio) as a function of the received optical power has to be characterized.

Every type of optical attenuator is normally inserted at the receiving end of the link: in fact, light intensity regulation at the transmitting end would require remote power monitoring of the received level of the optical signal.

In particular, the ideal attenuator should have a stable attenuation over a wide temperature range and under mechanical stresses; it should be independent of wavelength and state of polarization and should not cause reflection or interference of the optical signal. In addition, other desired characteristics for an ideal variable attenuator are low insertion loss, wide attenuation range and accurate mechanical or non-mechanical control of attenuation.

Until recently the most common types of attenuator that are permanently installed in optical fibre plant were fixed. However, with the increase of capacity, bit rate and transmission distances in modern DWDM systems, more and more tuneable attenuators are used to optimize transmission performance and to allow for more flexible re-configuration of optical routes through a network. Therefore, technological efforts are aimed at optimizing the reliability and minimizing the dimensions of, not only fixed, but also tuneable attenuators by meeting the specifications to allow for the usage in wide bandwidth DWDM systems.

11 Optical branching devices including PON splitters

(For further information, see Recommendations ITU-T L.37 and ITU-T G.671.)

An optical branching component (wavelength non-selective) is a passive component possessing three or more ports, which shares optical power among its ports in a predetermined fashion, without any amplification, switching, or other active modulation.

Optical branching components provide a method for splitting optical signals between M input and N output ports (Figure 5-22). Optical branching components are required when an optical signal has to be split into two or more fibre lines or when several signals coming from different fibre lines have to be mixed in a single fibre line; in general, optical branching components are dividers/combiners of transit signals.

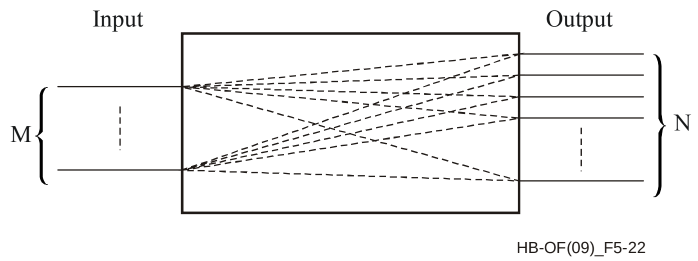


Figure 5-22 – Schematic of an MXN branching component

In passive optical networks (PON) with a point-to-multipoint distribution architecture (see Chapter 9), optical branching components are used to connect an OLT located at a central office to several ONUs located in outside plant or on subscriber premises. The specified values for PONs are 1 input port and X output ports, where X = 4, 8, 16, 32.

Optical branching components can be designed to operate at a single wavelength (e.g. 1 310 or 1 550 nm), to be wavelength flat (e.g. insensitive to wavelength variations within a single window) or to be wavelength independent (e.g. insensitive to wavelength variations within both the second and third windows, 1 260-1 360 nm and 1 450-1 600 nm.

Optical branching components for PONs are characterized by several parameters, the most important of which are: insertion loss, reflectance, optical wavelength range, polarization-dependent loss, directivity and uniformity.

All these parameters are defined and specified in Recommendation ITU-T G.671.

For the application of the PON splitters in the optical access networks, see Chapter 9.

CHAPTER 6

OPTICAL SYSTEMS: ITU-T CRITERIA FOR SPECIFICATIONS

Introduction

The real research phase of fibre-optic communication systems started around 1975. The enormous progress realized over the 30-year period extending from 1975 can be grouped into several distinct phases, which are described with some detail in the Introduction to this Handbook. During each phase, a "family" of optical systems had been developed, consistent with the corresponding ITU-T Recommendations. Some of these optical systems are still used, while others are obsolete.

The purpose of this Chapter is to outline the general specification criteria used in ITU-T for describing optical interfaces. The general objective of all ITU-T optical interface Recommendations is to achieve interworking among equipment from different manufacturers. In the cases where optical interworking is achieved, the relevant interfaces are called "transversely compatible interfaces". To this intent, an unambiguous and appropriate set of parameters and associated set of values is defined. In the cases where optical interworking is not achieved, the relevant interfaces are called "longitudinally compatible". This could be because optical technology isn't sufficiently mature or when design rules are significantly complex, whereby it was not possible to generate a specification of a transversely compatible interface with a reasonable amount of effort. Details on "transversely compatible interfaces" and "longitudinally compatible" interfaces are given in Clause 2.

This Chapter starts by giving the criteria used in ITU-T for the classification of the optical systems (Clause 1). A description of the ITU-T objectives for specifying each type of systems follows (Clause 2). Finally, the main parameters used for the specification are described (Clause 3).

1 Classification of the optical systems

Optical transmission systems can be classified by various criteria: operating wavelength range, single-channel and multichannel, type of WDM, bit rate and client classes, channel spacing and number of channels, characteristics of the interfaces, etc. These criteria are described in the following.

1.1 Operating wavelength range

(For further information see Recommendation ITU-T G.957 and Supplement 39 to the ITU-T G-series of Recommendations).

To provide a very high capacity for optical transmission systems, it is desirable to allow as wide a range as possible for the system operating wavelengths. The choice of operating wavelength range depends on several factors, including fibre type, source characteristics, system attenuation range, and dispersion of the optical path.

In ITU-T Recommendations, the following spectral bands are defined for single-mode fibre systems:

i) **"Original" O-band, 1 260 nm to 1 360 nm.**

   The lower limit is determined by the cable cut-off wavelength, which is 1 260 nm. The upper limit 1 360 nm is determined by the rising edge of the "water" attenuation band peaked at 1 383 nm, so 1 360 nm was chosen as the upper limit;

ii) "Extended" E-band, 1 360 nm to 1 460 nm.

Recommendation ITU-T G.652 also includes fibres with a low water attenuation peak, which allows the utilization of the band above 1 360. The effects of a small water peak are negligible at wavelengths beyond about 1 460 nm;

iii) "Conventional" C-band, 1 530 nm to 1 565 nm.

Initially, erbium-doped fibre amplifiers (EDFAs) had useful gain bands beginning at about 1 530 nm and ending at about 1 565 nm. This gain band had become known as the "C-band";

iv) "Short wavelength" S-band, 1 460 nm to 1 530 nm.

The lower limit of this band is taken to be the upper limit of the E-band. The upper limit is taken to be the lower limit of the C-band. EDFAs have become available with relatively flatter and wider gains and application of EDFAs to this band is possible at least in a part of the band. Some wavelengths of this band may also be utilized for pumping of optical fibre amplifiers, both of the active-ion type and the Raman type;

i) "Long wavelength" L-band, 1 565 nm to 1 625 nm.

For the longest wavelengths above the C-band, fibre cable performance over a range of temperatures is adequate up to 1 625 nm for current fibre types;

vi) "Ultra-long wavelength" U-band, 1 625 nm to 1 675 nm.

In some cases it is desirable to perform a number of maintenance functions (preventive, after installation, before service and post-fault) on fibre cables in the outside plant. These involve surveillance, testing, and control activities utilizing optical time domain reflectometer (OTDR) testing, fibre identification, loss testing, and power monitoring. A wavelength region, that is intended to be never occupied by transmission channels, may be attractive for maintenance, even if enhanced loss occurs. The U-band has been defined exclusively for possible maintenance purposes. Transmission of traffic-bearing signals is not currently foreseen in this band. The use for non-transmission purposes must be done on a basis of causing negligible interference to transmission signals in other bands. Sufficiently low fibre loss is not ensured in this band.

Table 6-1 summarizes single-mode spectral bands:

Table 6-1 – Single-mode spectral bands

Band	Descriptor	Range [nm]
O-band	Original	1 260 to 1 360
E-band	Extended	1 360 to 1 460
S-band	Short wavelength	1 460 to 1 530
C-band	Conventional	1 530 to 1 565
L-band	Long wavelength	1 565 to 1 625
U-band	Ultra-long wavelength	1 625 to 1 675

The applicability of all of the wavelength bands, listed in Table 6-1, for system operation or maintenance purposes is not guaranteed by the ITU-T G.65x-series Recommendations, each of which in general cover a limited set of bands, depending on its application area.

1.2 Single-channel and multichannel system interfaces

Optical system interfaces can be divided in two broad categories: single-channel and multichannel interfaces.

On a *single-channel interface* only one optical channel (one wavelength or frequency) is present on an optical fibre. One example is shown in Figure 6-1a), where an optical transmitter is connected to an optical receiver via an optical fibre.

On a *multichannel interface* several optical channels (several wavelengths or frequencies) are present on an optical fibre. One example is shown in Figure 6-1b). A multichannel system is generally described as a wavelength division multiplexing (WDM) system.

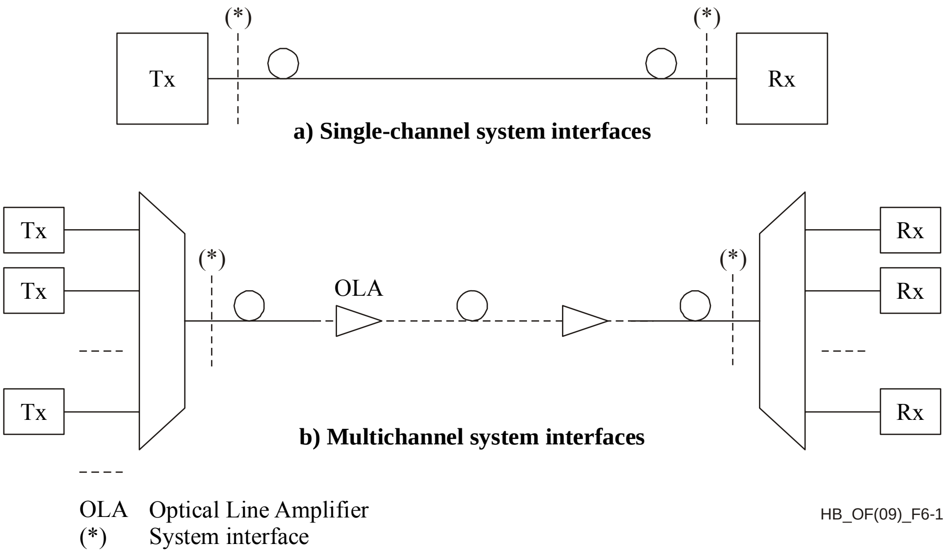


Figure 6-1 – Single-channel and multichannel systems

1.3 Channel spacing in WDM systems

The "Conventional" C-band defined above has a spectral range of 35 nm (1 530-1 565 nm, operating range of conventional optical fibre amplifiers), which exceeds 40 THz (0.8 nm = 100 GHz; 1 THz = 1 000 GHz).

Currently the maximum capacity of single-channel links is 40 Gbit/s.

A better utilization of the transmission capacity of an optical fibre can be obtained with the wavelength division multiplexing technique. With this technique multiple optical channels, each operating at a different wavelength, are combined on a single fibre by an optical multiplexer and then they are transmitted on the same fibre (Figure 6-1b). At the receive side the multiple signals are demultiplexed by an optical demultiplexer into separate optical channels. In this way, as an example, many 10 Gbit/s channels can be transmitted over the same fibre.

The ultimate capacity of a WDM fibre system depends on how closely optical channels can be packed in the wavelength domain. In the case of dense WDM (DWDM) applications optical channels are very densely spaced. For this case of DWDM applications the so-called "channel spacing" is expressed in the frequency domain. The maximum number of channels in a DWDM system operating in a given spectral band (e.g. 1 530-1 565 nm for the C-band) is determined by the channel spacing. For transversely compatible applications the channel spacing is fixed. Further details are provided in § 1.5.1. Current channel spacings specified in Recommendation ITU-T G.694.1 are multiples of 12.5 GHz up to a maximum of 100 GHz.

§ 1.5.1 also provides some further information for applications with channel spacing equal or larger than 200 GHz. Furthermore, there are some specific applications, e.g. operation on ITU-T G.653 fibres, where fixed channel spacing cannot be used because of the so-called four-wave-mixing (FWM) non-linear effect. Further details can be found in Chapter 7 of this Handbook.

The channel spacing is defined to be the nominal difference in frequency or wavelength between two adjacent optical channels. The minimum channel spacing is limited by interchannel crosstalk and it is related to many factors: the channel bit rate, the modulation format, the filter passband, and central wavelength variations (due to laser manufacturing and laser temperature variations).

1.4 Categories of WDM systems

Recommendation ITU-T G.671 defines three categories of WDM systems (Figure 6-2):

i) *Coarse WDM* (CWDM), having a channel wavelength spacing less than 50 nm, but greater than 1 000 GHz (about 8 nm at 1 550 nm and 5.7 nm at 1 310 nm). The value of "c" (speed of light in vacuum) that should be used for converting between frequency and wavelength is 2.99792458×10^8 m/s;

ii) *Dense WDM* (DWDM), having a channel spacing less than or equal to 1 000 GHz;

iii) *Wide WDM* (WWDM), having a channel wavelength spacing greater than or equal to 50 nm.

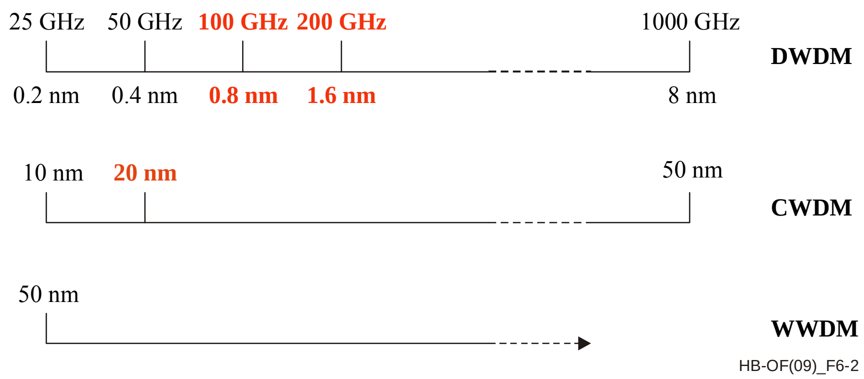


Figure 6-2 – Types of WDM systems

1.5 Number of channels in WDM systems

ITU-T uses "grids" for location of nominal central frequencies in WDM systems. Recommendation ITU-T G.694.1 defines a set of frequency grids for DWDM applications. Recommendation ITU-T G.694.2 defines a wavelength grid for CWDM applications. In a given spectral band (e.g. 1 530-1 565 nm for the C-band), the number of channels in a WDM system depends upon the particular channel spacing of the grid. At present a specification of a frequency grid for WWDM applications is not anticipated to be useful.

1.5.1 Number of channels in DWDM systems

In Recommendation ITU-T G.694.1, which provides the definition of frequency grids to support dense wavelength division multiplexing applications, currently four specific frequency grids are defined:

i) 12.5 GHz spacing;

ii) 25 GHz spacing;

iii) 50 GHz spacing;

iv) 100 GHz spacing.

All four frequency grids include 193.1 THz (1 552.52 nm) as one of their members, and there are no frequency limits beyond which the grid is not defined. This grid in fact is a "ruler" with no limits or end points.

Clause 6.2.2.1 of Supplement 39 to the ITU-T G-series Recommendations summarizes the above four frequency grids. In addition it shows that, using a specific formula, all the possible channel frequency grids can be derived.

Additional, wider spacing frequency grids can be used by taking integer multiples of 100 GHz spacing, i.e. 200 GHz, 300 GHz, 400 GHz, etc. The grids for these wider spacings are intentionally not specified to provide the user with complete freedom for choosing central frequencies.

ITU-T Recommendations defining applications that utilise these DWDM frequency grids include Recommendations ITU-T G.692, ITU-T G.698.1, ITU-T G.698.2 and ITU-T G.959.1. The number of channels is not specified, but, as an indication, about 40 channels with 100 GHz spacing (100 GHz × 40 ch. = 4,000 GHz = 4 THz) can occupy the complete C-band of 1 530-1 565 nm. Of course, the number of channels can double when using a channel spacing of 50 GHz.

1.5.2 Number of channels in CWDM systems

Recommendation ITU-T G.694.2 provides the definition of a wavelength grid with channels spaced at 20 nm to support coarse wavelength division multiplexing applications. This CWDM grid has been initially defined to allow simultaneous transmission of several optical 2.5 Gbit/s signals with sufficient separation to permit the use of uncooled sources.

The channel spacing of 20 nm was determined mainly by three factors (Figure 6-3):

i) the laser manufacturer is allowed a wavelength variation around the nominal wavelength in order to achieve a higher yield and/or relax manufacturing tolerances;

ii) the laser wavelengths are allowed to change over a sufficiently wide temperature range to permit usage of uncooled lasers;

iii) a sufficiently wide guardband is left between the channels to allow the use of low cost filter technologies.

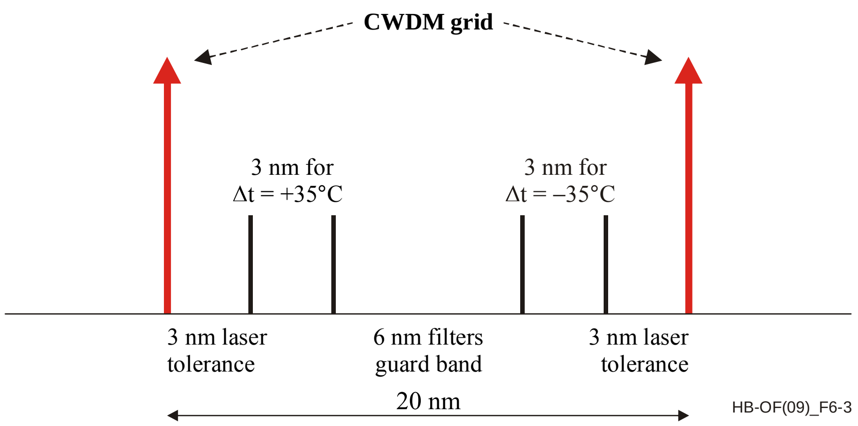


Figure 6-3 – Channel spacing for CWDM systems

The channel spacing of 20 nm allows the allocation of 18 wavelengths in the frequency range 1 271-1 611 nm. However, applications using this CWDM grid, specified in Recommendation ITU-T G.695, have a maximum of 16 optical channels (Figure 6-4).

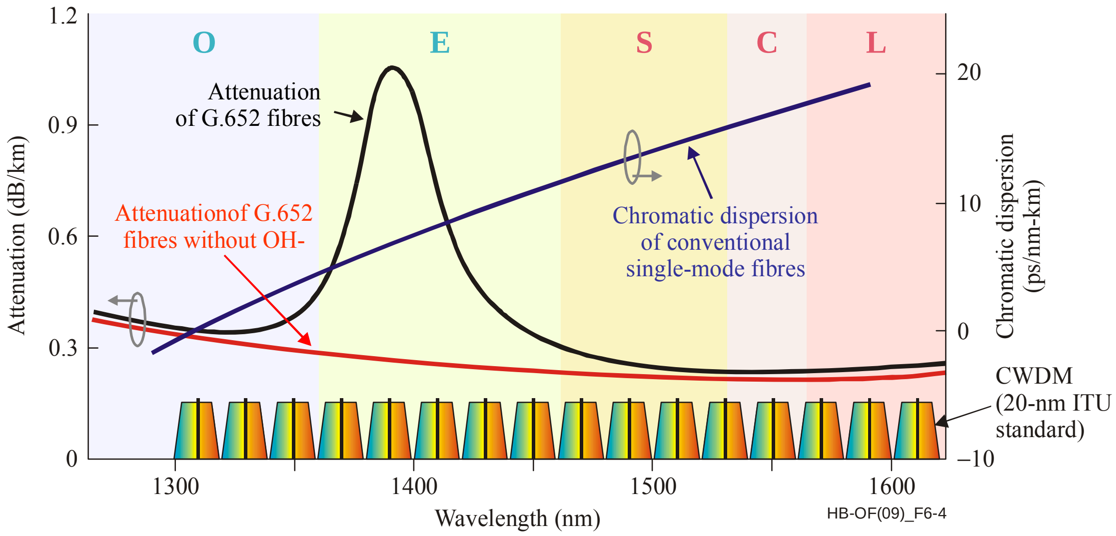


Figure 6-4 – Allocation of the CWDM channels

1.6 Bit rates and client classes

(For further information see Recommendation ITU-T G.959.1).

A single channel signal that is placed within (or converted to) an optical channel for transport across the optical network is called "optical tributary signal".

In ITU-T optical interface Recommendations, the digital optical signals are defined in the following different optical tributary classes:

i) optical tributary signal class NRZ 1.25G (non-return to zero), which applies to continuous digital signals with non-return to zero line coding, from nominally 622 Mbit/s to nominally 1.25 Gbit/s. Optical tributary signal class NRZ 1.25G includes a signal with STM-4 (synchronous transport module) bit rate according to Recommendation ITU-T G.707;

ii) optical tributary signal class NRZ 2.5G which applies to continuous digital signals with non-return to zero line coding, from nominally 622 Mbit/s to nominally 2.67 Gbit/s. Optical tributary signal class NRZ 2.5G includes a signal with STM-16 bit rate according to Recommendation ITU-T G.707 and OTU1 bit rate according to Recommendation ITU-T G.709;

iii) optical tributary signal class NRZ 10G which applies to continuous digital signals with non-return to zero line coding, from nominally 2.4 Gbit/s to nominally 10.76 Gbit/s. Optical tributary signal class NRZ 10G includes a signal with STM-64 bit rate according to Recommendation ITU-T G.707, OTU2 bit rate according to Recommendation ITU-T G.709 and OTL3.4 bit rate (OTU3 striped across four physical lanes) according to Recommendation ITU-T G.709;

iv) optical tributary signal class NRZ 25G which applies to continuous digital signals with non-return to zero line coding, from nominally 9.9 Gbit/s to nominally 28 Gbit/s. Optical tributary signal class NRZ 25G includes a signal with OTL4.4 bit rate (OTU4 striped across four physical lanes) according to Recommendation ITU-T G.709;

v) optical tributary signal class NRZ 40G which applies to continuous digital signals with non-return to zero line coding, from nominally 9.9 Gbit/s to nominally 43.02 Gbit/s. Optical tributary signal class NRZ 40G includes a signal with STM-256 bit rate according to Recommendation ITU-T G.707 and OTU3 bit rate according to Recommendation ITU-T G.709;

vi) optical tributary signal class RZ 40G which applies to continuous digital signals with return to zero line coding, from nominally 9.9 Gbit/s to nominally 43.02 Gbit/s. Optical tributary signal class RZ 40G includes a signal with STM-256 bit rate according to Recommendation ITU-T G.707 and OTU3 bit rate according to Recommendation ITU-T G.709.

As a consequence, the bit rates of the optical signals foreseen in ITU-T Recommendations are the following: 1.25 Gbit/s, 2.5 Gbit/s, 10 Gbit/s, 25 Gbit/s and 40 Gbit/s.

1.7 Unidirectional and bidirectional systems

(For further information see Recommendation ITU-T G.692).

Unidirectional WDM is the transmission of all optical channels on a fibre propagating simultaneously in the same direction (Figure 6-5).

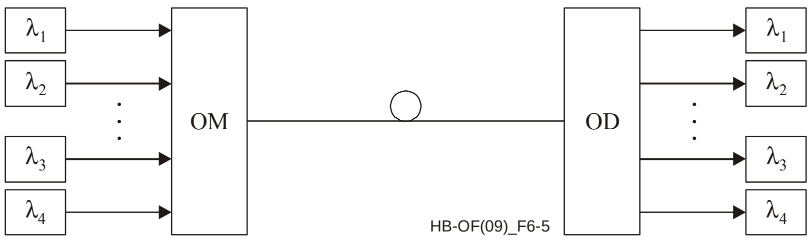


Figure 6-5 – Unidirectional WDM

Bidirectional WDM is the transmission of optical channels on a fibre propagating simultaneously in both directions (Figure 6-6).

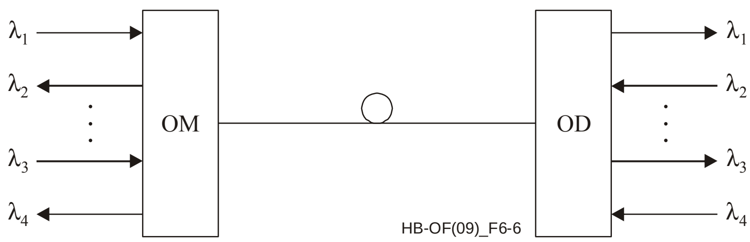


Figure 6-6 – Bidirectional WDM

Bidirectional WDM can lead (when a high number of channels is not required) to a reduction in the number of fibres and line amplifiers required, as compared to systems using unidirectional WDM. A further benefit of bidirectional WDM may be performance improvement with respect to four-wave mixing (FWM), particularly when being deployed with ITU-T G.653 fibres (See Chapter 7).

In bidirectional WDM designs, several key systems issues should be taken into account. Care must be taken to avoid optical reflections in order to prevent multi-path interference. Some additional considerations are types and values of crosstalk, values and interdependence of power levels for both directions of transmission, OSC (Optical Supervisory Channel) transmission (if present), and automatic power shutdown or reduction.

Optical interfaces with bidirectional transmission are currently only specified in ITU-T for CWDM systems (see Recommendation ITU-T G.695).

1.8 Linear and ring configurations

(For further information see Recommendation ITU-T G.698.2 and Supplement 39 to the ITU-T G-series Recommendations).

The generic representation of a linear configuration is shown in Figure 6-7 where the DWDM network elements include an optical multiplexer (OM) and an optical demultiplexer (OD), which are used as a pair with the opposing element, one or more optical amplifiers and may also include one or more OADMs. *n* WDM optical channels are carried on one output fibre of a multichannel transmitter equipment.

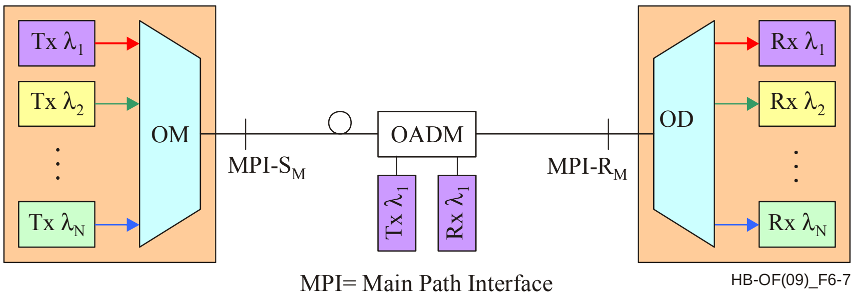


Figure 6-7 – Linear configuration

In Figure 6-8 an example is shown of a ring configuration where the DWDM network elements include one or more amplifiers and two or more OADMs connected in a ring.

1.9 Fibre type

Single mode optical fibre types are chosen for the optical systems from those defined in the ITU-T G.65x-series Recommendations.

1.10 Line coding

(For further information see ITU-T Supplement 39 to the ITU-T G-series Recommendations).

Optical interfaces defined, for example, in Recommendations ITU-T G.957, ITU-T G.691, ITU-T G.692 and ITU-T G.959.1, are currently based on non-return to zero (NRZ) transmission. The related parameters (as well as the definition of the logical "0" and logical "1") are defined in those Recommendations. For more demanding applications or transmission at rates of 40 Gbit/s or above, other line codes could be of advantage.

Return-to-zero (RZ) line-coded systems, for example, are significantly more tolerant to first-order PMD-induced DGD and could, therefore, be better suited for ultra-long-haul transmission of high rate signals. However, RZ coding has (due to the broader signal bandwidth) a potential drawback of being less spectrally efficient compared to NRZ (see Chapter 7).

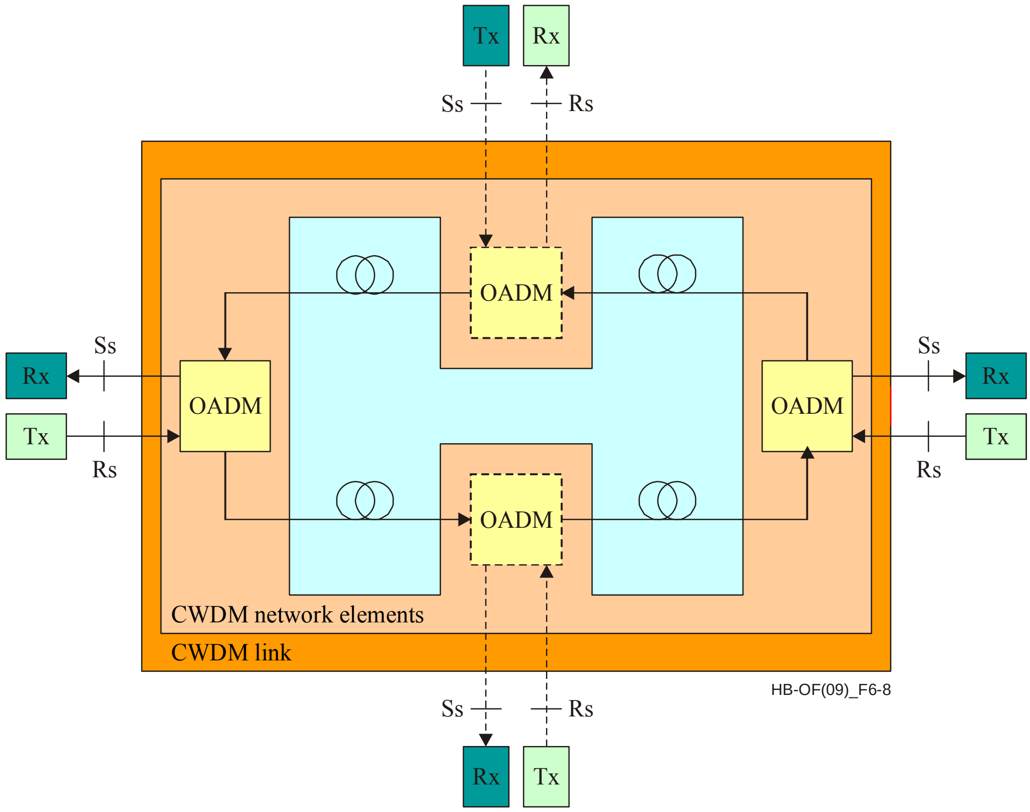


Figure 6-8 – Ring configuration

1.11 Bit Error Ratio

Because of noise inherent in any receiver, there is always a finite probability that a bit could be identified incorrectly by the decision circuit. Optical systems are generally designed to operate in such a way that the error probability in the digital receivers is smaller than a specified value (see Chapter 7).

Figure 6-9a) shows schematically the fluctuating signal received by the decision circuit, which is sampling the received signal at the decision instant (which is determined by clock recovery). The sampled value fluctuates from bit to bit around an average value I_1 or I_0 depending on whether the bit corresponds to 1 or 0 in the bit stream. The decision circuit compares the sampled value with a threshold value I_D (normally in the middle between the logical 1 and 0 levels if the same error probability is associated to these) and calls it bit 1 if $I > I_D$, or bit 0 if $I < I_D$. An error occurs if $I < I_D$ for bit 1 because of the receiver noise. An error also occurs if $I > I_D$ for bit 0. Both sources of errors are included in the error probability.

Figure 6-9b) shows that both the probability of an error on 1 and on 0 depends on the probability density of the sampled value I. The probability density depends on the statistics of noise sources responsible for current fluctuations.

All the system's parameters are specified in relation to an optical section design objective of a bit error ratio (BER) not worse than the value specified by the application code. In each application, this value applies to each optical channel under the extreme case of optical path attenuation and dispersion conditions.

For all applications in Recommendations ITU-T G.691, ITU-T G.692, ITU-T G.693, ITU-T G.695, ITU-T G.698.1, ITU-T G.698.2 and ITU-T G.959.1, an optical section design objective of an end-of-life BER not worse than 10^{-12} has been specified. The requirement for SDH applications is derived from Recommendation ITU-T G.826 and, more recently, from Recommendation ITU-T G.828, while corresponding requirements for OTN applications are given in Recommendation ITU-T G.8201.

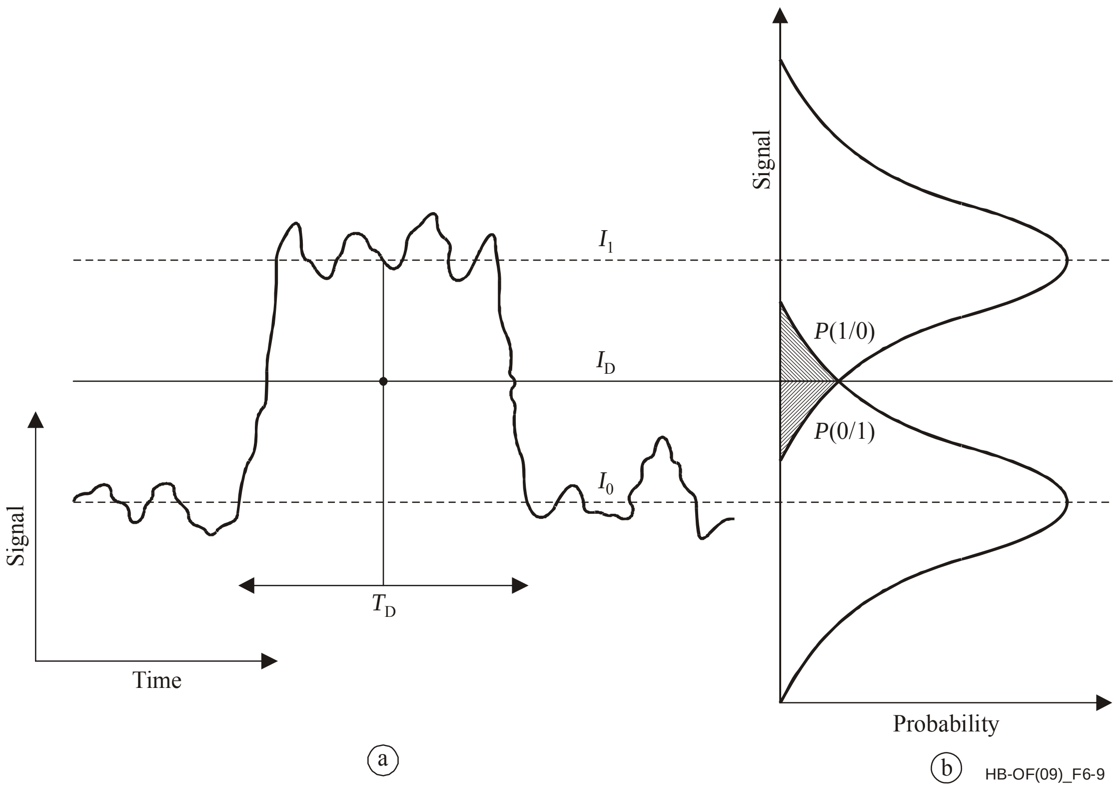


Figure 6-9 – Errors on bits

Applications in Recommendation ITU-T G.957, however, have an end-of-life BER requirement of 10^{-10} due to less stringent requirements being in place at the time of their development.

In order to "migrate" applications from a BER of 10^{-10} to 10^{-12}, a convention has been adopted where application codes with a maximum attenuation range of 12 dB at a BER of 10^{-10} were reduced to 11 dB at a BER of 10^{-12}, and application codes with a maximum attenuation range of 24 dB at a BER of 10^{-10} were reduced to 22 dB at a BER of 10^{-12}.

1.12 The Q-factor

(For further information see Supplement 39 to the ITU-T G-series Recommendations).

Often the Q-factor is used instead of the BER. As a matter of fact, the lower the value of the reference BER, the more difficult it is to actually verify the receiver performance, due to the extended measurement time required. Two approaches have been proposed to address this problem. The first is to use a particular length of error-free operation to establish a certain probability of the error rate being below the required level. The required number of error free bits (n) can be found as:

$$n = \frac{\log(1 - C)}{\log(1 - P_E)}$$

where:

C: required confidence level (e.g. 0.95 for 95% confidence), and

P_E: BER requirement (e.g. 10^{-12}).

Therefore, if a confidence level of 95% for the BER to be less than 10^{-12} is required, 3×10^{12} error free bits are needed (20 minutes at 2.5 Gbit/s).

Since this still requires long measurement times at lower rates, an alternative method is to measure the *Q* factor. The *Q* factor is the signal-to-noise ratio at the decision circuit in voltage or current units, and is typically expressed by:

$$Q = \frac{(\mu_1 - \mu_0)}{(\sigma_1 + \sigma_0)}$$

where $\mu_{1/0}$ is the mean value of the marks/spaces voltages or currents, and $\sigma_{1/0}$ is the standard deviation. A BER of 10^{-12} corresponds to $Q \approx 7.03$.

Since practical *Q* measurement techniques make measurements in the upper and lower regions of the received "eye" in order to infer the quality of the signal at the optimum decision level, *Q* can be considered as only a qualitative indicator of the actual BER.

The mathematical relations to BER (in case of non-FEC operation) when the threshold is set to the optimum value are:

$$BER = \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right)$$

where:

$$\mathrm{erfc}(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{\beta^2}{2}} \, d\beta$$

A commonly used approximation for this function is: $BER \approx \dfrac{1}{Q\sqrt{2\pi}} e^{-\frac{Q^2}{2}}$

for $Q > 3$.

A graph comparing these mathematical relationships and the approximations for *Q*-values less than 5 is given in Figure 6-10.

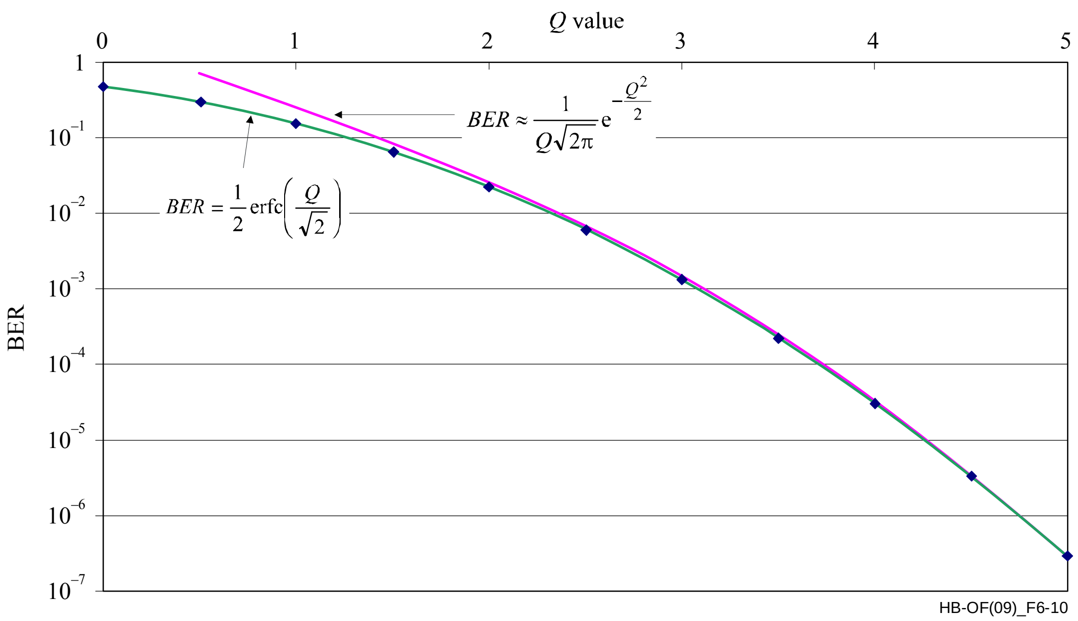


Figure 6-10 – Approximations relating BER and *Q*

1.13 Forward Error Correction

(For further information see Supplement 39 to the ITU-T G-series Recommendations).

Forward error correction (FEC) is rapidly becoming an important way of improving the performance of large-capacity long-haul optical transmission systems and is already well established in wireless communication systems. Employing FEC in optical transmission systems yields system designs that can accept relatively large BER before decoding (around 10^{-5} to 10^{-6}) in the optical transmission line. FEC application may allow the optical parameters to be significantly relaxed and encourages the construction of large capacity, long-haul optical transmission systems in a cost-effective manner.

Definitions of FEC terminology are provided in Table 6-2:

Table 6-2 – FEC terminology

Information bit (byte)	Original digital signal to be FEC encoded before transmission
FEC parity bit (byte)	Redundant bit (byte) generated by FEC encoding
Code word	Information bit (byte) plus FEC parity bit (byte)
Code rate R	Ratio of bit rate without FEC to bit rate with FEC (R = 1 for in-band FEC)
Coding gain	Reduction of Q values at specified BER (e.g. 10^{-12}) assuming white Gaussian noise and a theoretical reference receiver
Net coding gain (NCG)	Coding gain corrected by the increased noise due to bandwidth expansion needed for FEC bits assuming white Gaussian noise (out-of-band FEC)
Q b factor	Q factor corrected by the bandwidth expansion factor $1/\sqrt{R}$
BER_{in}	BER of the encoded line signal (= BER of the input signal of the FEC decoder)
BER_{out}	BER of the decoded client signal (= BER of the output signal of the FEC decoder)
BCH codes	Bose – Chaudhuri – Hocquenghem codes: the most commonly used BCH codes are binary codes
RS codes	Reed-Solomon codes: the most commonly used non-binary subclass of BCH codes
xxx (n, k) code	xxx = code class (BCH or RS) n = number of code word bits (bytes) k = number of information bits (bytes)

For the relevant optical interface Recommendations where application codes are specified with the mandatory use of FEC, it is indicated that the system BER is required to be met only "after the error correction has been applied". In these specific cases, the optical parameters are specified at a BER not worse than 10^{-12} at the FEC decoder output.

This is illustrated in Figure 6-11 which shows the theoretical BER at the receiver output (point A) is 1.8×10^{-4} for 10^{-12} BER at the FEC decoder output (point B).

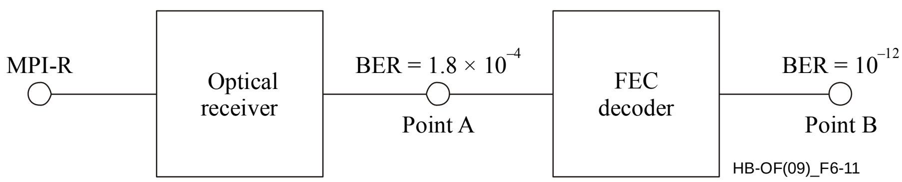


Figure 6-11 – Effect of usage of FEC on receiver performance in relation to BER

At present, two FEC schemes are recommended in ITU-T for optical transmission systems. They are *"in-band FEC"* for SDH systems, and *"out-of-band FEC"* for optical transport networks (OTNs). The terminology "in" or "out" refers to the client bandwidth. In-band FEC parity bits are embedded in a previously unused part of the section overhead of SDH signals, so the bit rate is not increased. In contrast to SDH, OTN signals including space for FEC bits (OTUk) have a higher bit rate than the equivalent signal before the FEC is added (ODUk). Therefore, OTN signals are encoded using out-of-band FEC, resulting in a slightly increased line-rate.

1.13.1 In-band FEC in SDH systems

The in-band FEC specified for SDH systems is described in Recommendation ITU-T G.707. The code is triple-error correcting binary BCH code, more exactly a shortened BCH (4359,4320) code. Up to three bit errors can be corrected in a 4359-bit code word. The code word is an 8-bit interleaved signal stream of 270×16 bytes from 1 row of the STM-N frame. Therefore, up to 24-bit continuous errors in each row of an STM-16, -64 or -256 frame can be corrected. Currently optical interface specifications for applications with in-band FEC are not provided by the ITU-T Recommendations concerned with optical interfaces.

1.13.2 Out-of-band FEC in optical transport networks (OTNs)

The out-of-band FEC specified for OTN (optical transport network) is described in Recommendation ITU-T G.709. This code is a symbol error correcting RS code. Up to eight bytes in the code word can be corrected. The frame employs 16-byte interleaving, so 1 024 bits continuous errors can be corrected. Currently optical interface specifications for applications with out-of-band FEC are provided in several ITU-T Recommendations (e.g. in Recommendations ITU-T G.698.2 and ITU-T G.959.1).

1.13.3 Coding gain and net coding gain

In the case of randomly distributed errors within the encoded line signal, a FEC decoder reduces the line or raw BER to a required reference BER value within the payload signal. Coding gain could therefore be regarded as the relation of these bit error ratios. In order to define a coding gain parameter as a more system-related parameter, the BER reduction by the FEC is usually transformed into a dB value based on a theoretical reference system. It is common practice to define the coding gain as the reduction of signal-to-noise ratio at a reference BER. This definition is directly applicable to an in-band FEC because its use implies neither an increase of the bit rate nor of the noise at the decision circuit due to receiver bandwidth expansion. The performance of an out-of-band FEC can be characterized better by a modified coding gain parameter. In wireless transmission systems the net coding gain (NCG) parameter is well established for out-of-band FEC. It takes into account the fact that the bandwidth extension needed for these FEC schemes is associated with increased noise in the receiver.

Based on the NCG value, the achievable system gain in optical signal-to-noise ratio (OSNR) limited systems can be estimated accurately. In this case, the reduction of the electrical signal-to-noise ratio as a consequence of higher line BER reflects the allowable reduction in OSNR. In systems involving additional non-white noise contributions, the trade-off between sensitivity reduction due to bandwidth expansion and coding gain is much more complicated. For comparison of high efficiency FEC schemes with different (but similar) code rates used in long-haul systems, the NCG parameter is a good measure. It should be noted, however, that this comparison is only valid in systems limited by white noise sources. In case there is a significant penalty due to (nearly deterministic) signal degradation, the penalty may increase rapidly with increasing bit rate and invalidate the comparison. Even in systems operating in a very non-linear regime of the transmission fibre, the application of NCG is of limited value due to the fact that the associated noise cannot be characterized by white Gaussian noise.

Figure 6-12 gives a performance estimation of the ITU-T G.709 FEC showing the coding gain and the net coding gain.

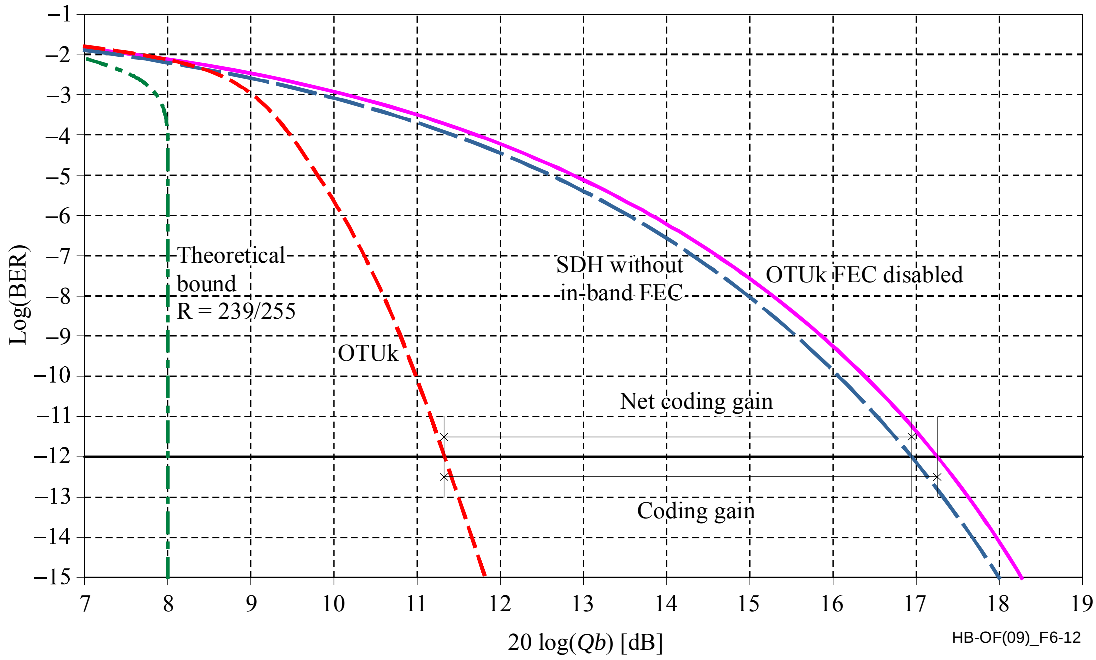


Figure 6-12 – Performance estimation of G.709 FEC

It should be noted that:

$$20 \log_{10} Qb = 20 \log_{10} Q - 10 \log_{10} R$$

The horizontal axis is 20 $\log_{10}$ *Qb* in dB (see Table 6-2) and the vertical axis is Log(BER). Net coding gain in terms of 20 $\log_{10}$ *Qb* is equivalent to allowable OSNR reduction when the line system uses optical amplifiers and ASE induced noise is the only significant noise source at the decision circuit.

Table 6-3 gives the theoretical performance of both the above-quoted ITU-T standard FECs.

Table 6-3– Performance of standard FECs

Application	In-band FEC BCH (4359,4320)	Out-of-band FEC RS (255,239)
	SDH	OTN
BER_{in} for $BER_{out} = BER_{ref} = 10^{-12}$	2.9×10^{-6}	1.8×10^{-4}
Coding gain ($BER_{ref} = 10^{-12}$) (dB)	3.8	5.9
Net coding gain ($BER_{ref} = 10^{-12}$) (dB)	3.8	5.6
Code rate	1	239 / 255

1.13.4 Theoretical NCG bounds for some non-standard out-of-band FECs

Based on basic results from information theory, the theoretical NCG bounds, for some non-standard out-of-band FECs, as a function of code rate can be determined. Some results are shown in Table 6-4 for $BER_{ref} = 10^{-12}$.

Table 6-4 – Theoretical NCG bounds for some non-standard out-of-band FECs

Bandwidth expansion (%)	Code rate *R*	NCG (dB) ($BER_{ref} = 10^{-12}$)
5	0.952	8.6
7	0.935	9.0 (Note)
10	0.909	9.4
15	0.870	9.9
20	0.833	10.3
25	0.800	10.6
NOTE – Corresponds to the code rate of standard out-of-band FEC.		

2 Objectives for standardizing optical systems

As mentioned in the introduction, the optical interfaces defined in ITU-T Recommendations are generally defined with the purpose to enable the optical interworking between the equipment from different manufacturers. Where this interworking is possible, the interfaces are called "transversely compatible" and appropriate sets of parameters and associated values are provided by the interface Recommendations. In the other cases the interfaces are called "longitudinally compatible".

2.1 Transversely compatible and longitudinally compatible optical interfaces

(For further information see ITU-T Supplement 39 to the ITU-T G-series Recommendations).

As said above, the physical layer specifications for optical transmission systems are divided into two general types: transversely compatible and longitudinally compatible optical interfaces.

In Recommendations ITU-T G.691, ITU-T G.693, ITU-T G.695, ITU-T G.698.1, ITU-T G.698.2, ITU-T G.957 and ITU-T G.959.1, the applications are defined to be "transversely compatible", which implies that the ends of an optical section may be terminated by equipment from different manufacturers. This is illustrated in Figure 6-13.

"Transverse Compatibility" is the capability to mix equipment of various manufacturers within a single optical transmission section. In this case each of the relevant applications is characterised by an appropriate, and unambiguous, set of optical parameters and associated parameter values, valid at the defined optical interface points.

In the example shown in Figure 6-13, a full set of parameter definitions and associated values at interface point MPI-S (multi-path interface at the source) and MPI-R (multi-path interface at the receiver) are necessary to enable such an interface.

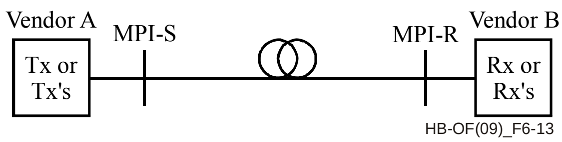


Figure 6-13 – Single-span physical layer transverse compatibility

In contrast to the above, an application that is defined to be "longitudinally compatible" implies that both ends of an optical section are terminated by equipment from the same manufacturer. The specification also allows the deployment of systems from different vendors on the optical fibres of the same cable.

In this case a more limited set of parameters than for transversely compatible systems is required, and usually only the characteristics of the optical path (e.g. attenuation, dispersion, reflections, etc.) are specified.

A single-span longitudinally compatible system is illustrated in Figure 6-14.

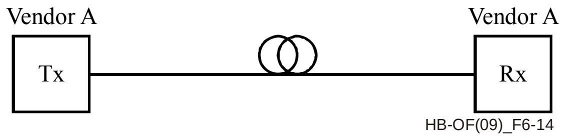


Figure 6-14 – Single-span physical layer longitudinal compatibility

For multi-span systems, longitudinal compatibility is also possible. This is similar to the single-span longitudinally compatible system, where all the active equipment comes from a single source. This is illustrated in Figure 6-15. As in the case of single span, only a limited number of parameters are required to be specified.

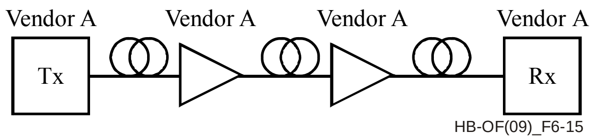


Figure 6-15 – Multi-span physical layer longitudinal compatibility

2.2 Joint engineering

(For further information see Recommendation ITU-T G.957 and Supplement 39 to the ITU-T G-series Recommendations).

In some cases the link performance provided by ITU-T Recommendations is not sufficient to cover operator needs for optical interfaces. Then, "joint engineering" can provide a means to improve the link performance to meet the specific operator requirements.

Joint engineering is a process by which operators and manufacturers jointly agree on a set of interface characteristics that support a link performance exceeding the performance available from optical interface specifications in ITU-T Recommendations. This will probably be done in those cases where the required section loss is greater (e.g. 2 dB) than that specified, but it may also be considered for other parameters.

For those cases, it is up to the operators concerned to specify more closely the aspects of the system where the specifications of the relevant Recommendation are not satisfactory. It is important to stress that every situation requiring "joint engineering" is likely to be different. Therefore, it is for the operators and/or manufacturers concerned to come to an agreement as to what is required and as to what is actually feasible. This process is very likely to lead to both ends of a transmission link being supplied by the same manufacturer, who meets the required performance by jointly optimizing the transmitters and receivers.

It should be pointed out that for "jointly engineered" systems, it would be advisable for operators or manufacturers involved to follow the general guidelines and system engineering approach used in the ITU-T Recommendations. In particular, it would be helpful to use the same parameter definitions (e.g. receiver sensitivity at R reference point including all temperature and aging effects).

2.3 Specification method: black-box and black-link

The general specification method used in ITU-T Recommendations can be categorized into two types.

The first one, the most general case, is a "black-box" approach. This means that it is not intended to restrict or specify the implementation details of the internal elements and/or the connections between the elements within the black-box.

The black-box is characterised by a set of parameters and associated values at its output (S-type interface point) and/or its input (R-type interface point). This approach enables transverse compatibility between "sending" black-box, optical link and "receiving" black-box. An example is shown in Figure 6-16 for a multi-channel interface with the multichannel interfaces points MPI-S_M and MPI-R_M.

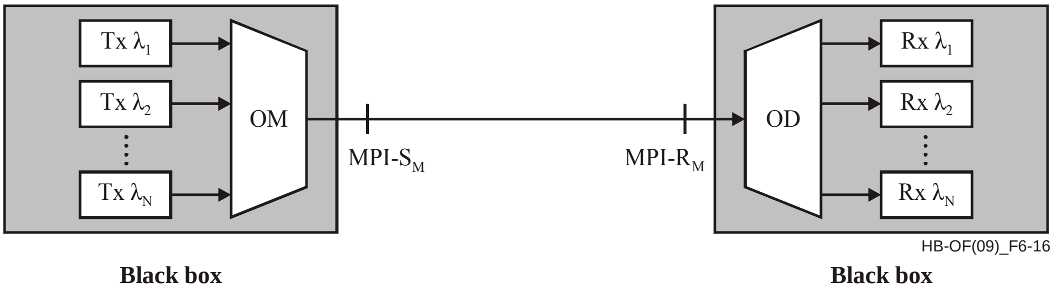


Figure 6-16 – Black-box approach

This specification method can be used for both single-channel transmission and multi-channel transmission. It has currently been used in Recommendations ITU-T G.691, ITU-T G.692, ITU-T G.693, ITU-T G.695, ITU-T G.696.1, ITU-T G.957 and ITU-T G.959.1.

The second type is a "black-link" approach which means that optical interface parameters are specified at the single-channel interface inputs and outputs of the "black-link". The link itself is considered "black" and it may consist of passive elements (e.g. fibres, optical multiplexers, optical demultiplexers, OADMs, etc.) and active elements like optical amplifiers. The details of the black-link design are proprietary to the black-link designer. This specification method has currently been used in multi-channel transmission specified in Recommendations ITU-T G.695, ITU-T G.698.1 and ITU-T G.698.2. Additional informative descriptions are provided for the fibre link parameters of the multichannel section, such as maximum attenuation, chromatic dispersion and polarization mode dispersion. This approach enables transverse compatibility between the single-channel input and output points of a black-link. However, it does not enable transverse compatibility at the multichannel points inside the black-link. An example is shown in Figure 6-17, where the OM and OD are treated as a single set of optical devices and OADMs are also included.

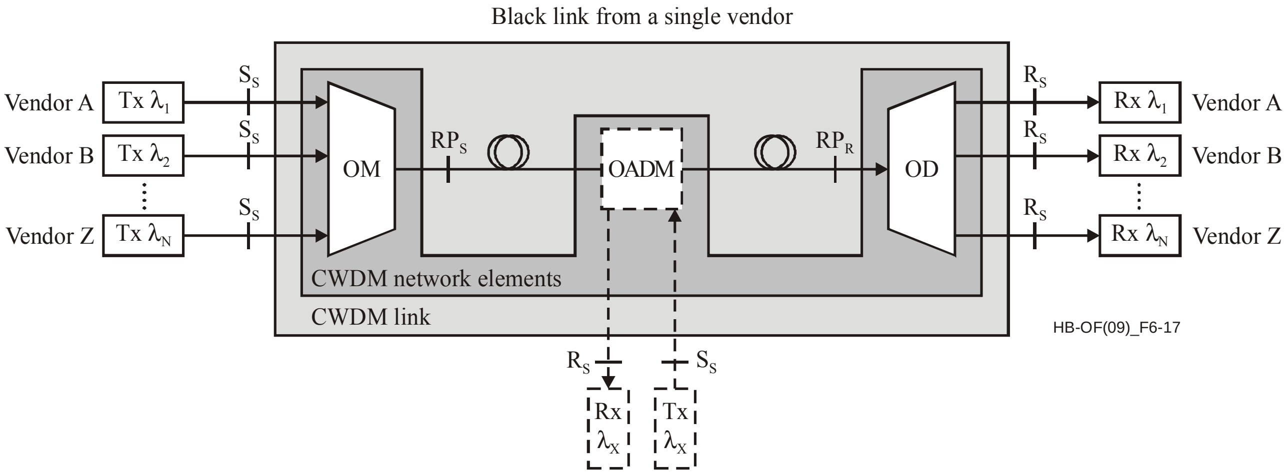


Figure 6-17 – Linear black-link approach

2.4 Application codes

For all of the Recommendations specifying optical systems, the various parameter sets in each document are termed the "applications" of the Recommendation, and each one is given its own short reference code (called the "application code"). The application codes take into account the many possible combinations of channel counts, optical tributary signal types, span distances, fibre types and system configurations.

The structure of these codes varies from one Recommendation to another, depending on the characteristics required to distinguish one application from another.

Two elements of the application code, that are common to all of the Recommendations, are an indication of the bit rate and the type of fibre over which the application operates. To illustrate how these application codes work, two examples are given. The first (Figure 6-18) is from Recommendation ITU-T G.957 which has a very simple application code structure and the second (Figure 6-19) is a more complex example from Recommendation ITU-T G.698.2.

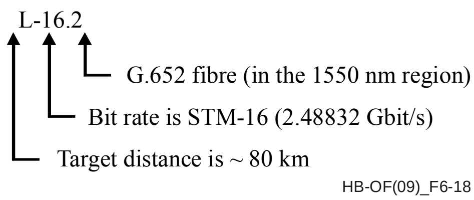


Figure 6-18 – Example of Recommendation ITU-T G.957 application code

Details of the structure and interpretation of the application codes can be found in each Recommendation.

For all the Recommendations, with the exception of those covering black-link applications, the application code includes some indication of the distance that can be covered by the link. In the example for Recommendation ITU-T G.957 in Figure 6-18, the letter L indicates a "target distance" of approximately 80 km in the 1 550 nm window, and approximately 40 km in the 1 310 nm window.

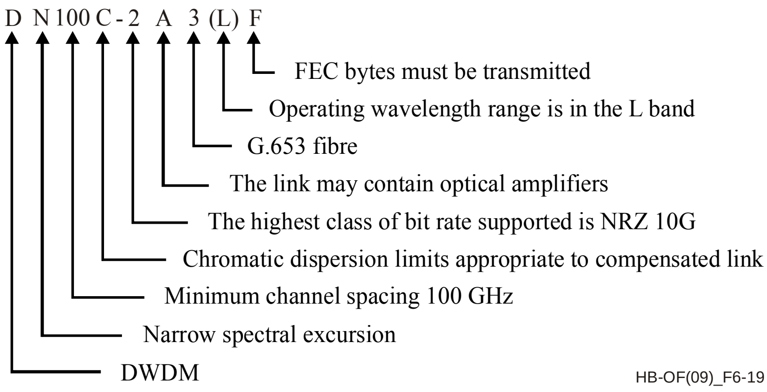


Figure 6-19 – Example of ITU-T G.698.2 application code

These target distances are for classification purposes only and do not guarantee that a link of that distance can be accommodated (or, conversely, that a link that is somewhat longer cannot). The specifications for each application code are given in terms of the maximum (and sometimes minimum) attenuation that the link must have, the limits for chromatic dispersion, the maximum reflections and (in most cases) the maximum DGD (differential group delay – a parameter related to polarisation mode dispersion) that can be tolerated.

The applications in each Recommendation do not cover all possible combinations of distance category, optical tributary signal class, and fibre type. The included applications are intended to satisfy a broad range of network requirements with low-cost implementations.

3 Parameters for the specification of the optical interfaces

Each ITU-T Recommendation has its own definition for each parameter, all being potentially slightly different in each case. To get a common basic understanding, the definitions of Recommendation ITU-T G.959.1 are used in the following.

3.1 Interface at point MPI-S and MPI-S_M

(For further information see Recommendation ITU-T G.959.1).

The interfaces MPI-S (main path interface) for a single-channel shown in Figure 6-20 and MPI-S_M for a multichannel optical system shown in Figure 6-21 are characterized by a complete set of parameters. Some of them are described in the following.

3.1.1 Output power

Two parameters specify the output power:

i) The maximum and minimum mean (*channel*) output power. The mean launched power of each optical channel at reference point MPI-S_M or MPI-S is the average power of a pseudo-random data sequence coupled into the fibre from the transmitting equipment. It is given as a range (maximum and minimum), to allow for some cost optimization and to cover allowances for operation under the standard operating conditions, connector degradations, measurement tolerances, and aging effects.

ii) The maximum mean *total* output power is the maximum value of the mean launched total optical power at point MPI-S_M.

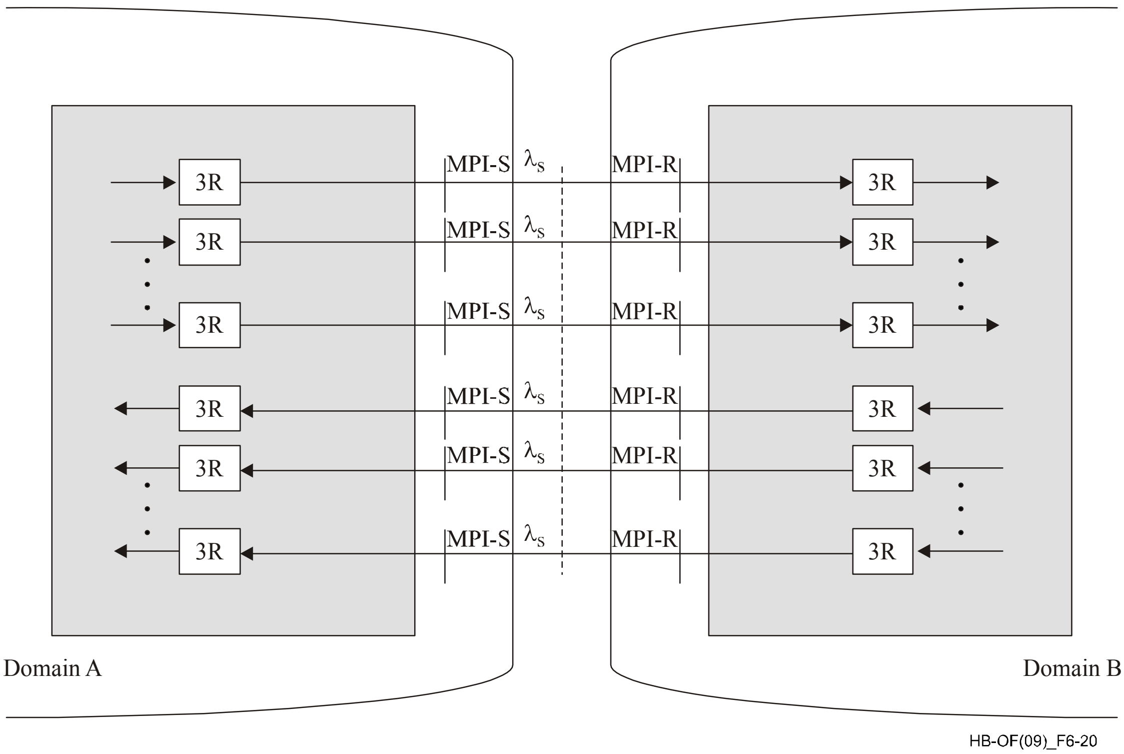


Figure 6-20 – Single-channel applications

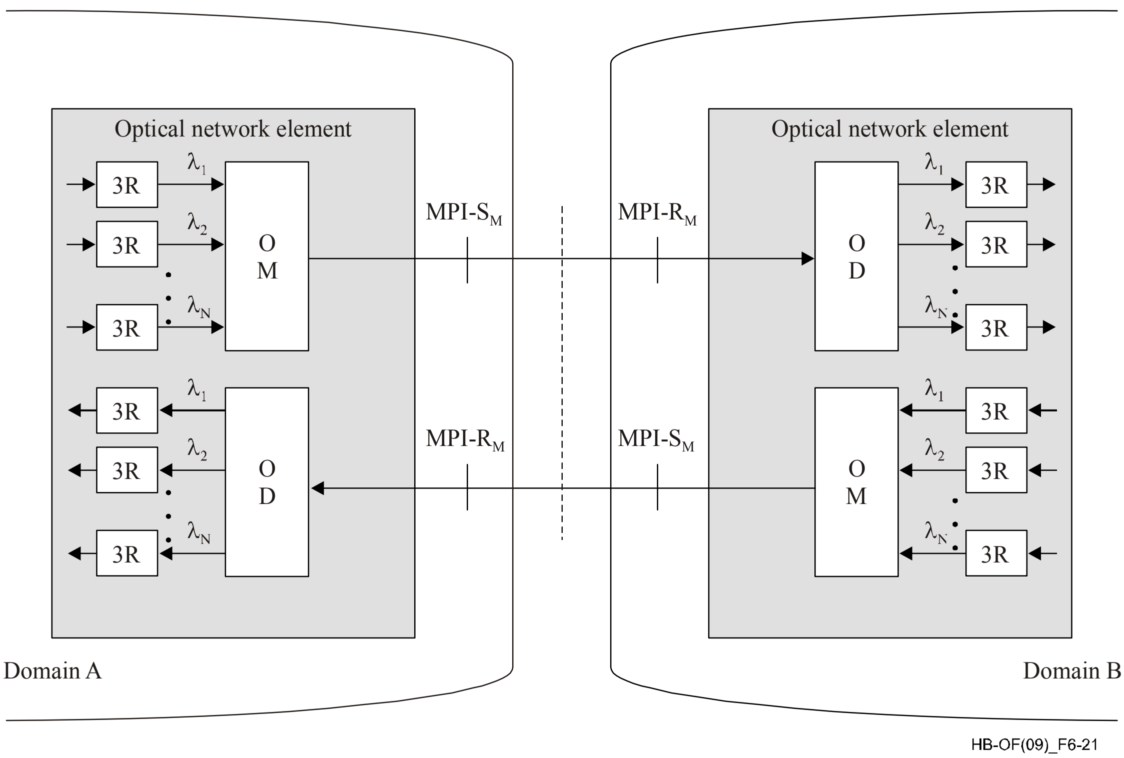


Figure 6-21 – Non-amplified multichannel applications

3.1.2 Source type

Depending on attenuation/dispersion characteristics and hierarchical level of each application codes, feasible transmitter devices use LEDs, multi-longitudinal mode (MLM) lasers and single-longitudinal mode (SLM) lasers (see Chapter 5).

For each of the applications, the Recommendations indicate a nominal source type. It is understood that the indication of a nominal source type in the Recommendation is not a requirement, so that SLM devices can be substituted for any application showing MLM as the nominal source type, without any degradation in system performance.

3.1.3 Transmitter minimum (channel) extinction ratio

Most transmitters emit some power even in the off state (logical 0 bits). The energy carried by 0 bits can be a source of power penalty in the optical receiver due to reduced eye opening. It is characterised by the parameter "transmitter extinction ratio".

The transmitter extinction ratio (EX) is defined as:

$$EX = 10 \log_{10} (A/B)$$

where:

A : average optical power level at the centre of the logical "1";

B : average optical power level at the centre of the logical "0".

The convention adopted for optical logic levels is:

- emission of light for a logical "1";
- no emission for a logical "0".

3.1.4 Eye diagram and eye mask

An indication of the quality of an optical signal can be achieved by measuring its *eye diagram* and checking whether it fits with a specified *eye mask*. In general, one could carry out this measurement at any point on the optical fibre, at the beginning (at the transmitting side), in the middle of the optical fibre path or at the end (at the receiving side). At the end of a link the optical eye contains all distortion effects encountered by transmission through the fibre (including chromatic dispersion and non-linear effects). In ITU-T Recommendations this indication of signal quality for optical interfaces is "quantified" by the definition of an eye mask for the signal at the transmitting S-type reference point.

In optical systems transmitter pulse shape characteristics (including rise time, fall time, pulse overshoot, pulse undershoot and ringing to be controlled to put limits to transmitter waveform distortion in order to prevent excessive degradation of the receiver sensitivity), are specified in the form of a mask of the transmitter eye diagram at point MPI-S. For the purpose of an assessment of the transmit signal, it is important to consider not only the eye opening, but also the overshoot and undershoot limitations.

Eye diagram. The data recovery section of optical receivers consists of a decision circuit and a clock-recovery circuit. The purpose of the latter is to isolate a spectral component at $f = B$ from the received signal. This component provides information about the bit slot ($T_B = 1/B$) to the decision circuit and helps to synchronize the decision process. In the case of RZ (return-to-zero) format, a spectral component at $f = B$ (bit frequency) is present in the received signal. In the case of NRZ (non-return-to-zero) format, a spectral component at $f = B/2$ (half bit frequency) is present in the received signal.

The decision circuit compares the output from the linear channel to a threshold level at sampling times determined by the clock recovery circuit and decides whether the signal correspond to bit value “1” or to bit value “0”. The best sampling time corresponds to the situation in which the signal level difference between 1 and 0 is maximum. This difference can be determined from the eye diagram formed by superposing 2-3 bit long electrical sequences in the bit stream on top of each other. The resulting pattern is called an eye diagram because of its appearance. Figure 6-22 shows an ideal eye diagram together with a degraded one in which the noise and the timing jitter lead to a partial closing of the eye. The best sampling time corresponds to maximum opening of the eye.

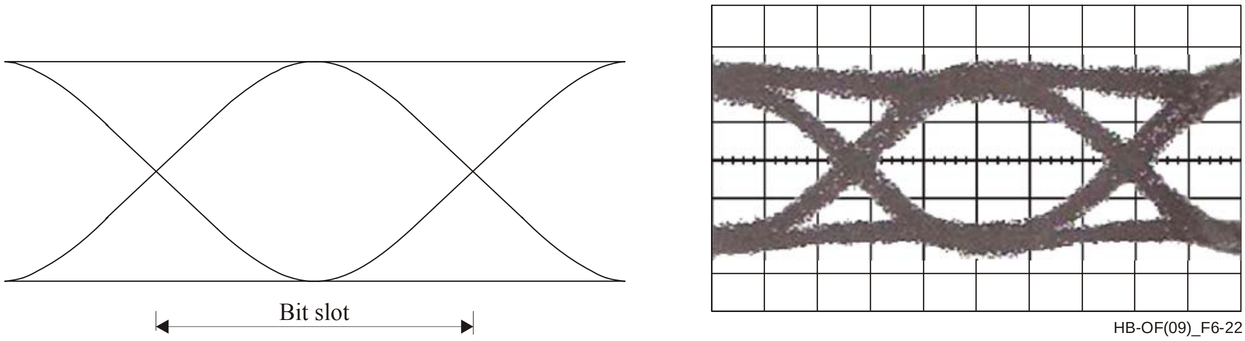


Figure 6-22 – Ideal and degraded eye mask for the NRZ format

The closure of the eye diagram at the receive side can provide the total degradation of the optical signal due to cumulative effects from the optical path.

Eye mask. The parameters specifying the mask of the transmitter eye diagram for a 2.5 Gbit/s NRZ optical transmit signals are shown in Figure 6-23. For each SDH/OTN hierarchical level optical system a different eye diagram is defined. Acceptable transmitter eye diagrams must avoid crossing any of the hatched lines. The values of x_i and y_i for the bit rate of each optical signal are specified in the relevant Recommendations.

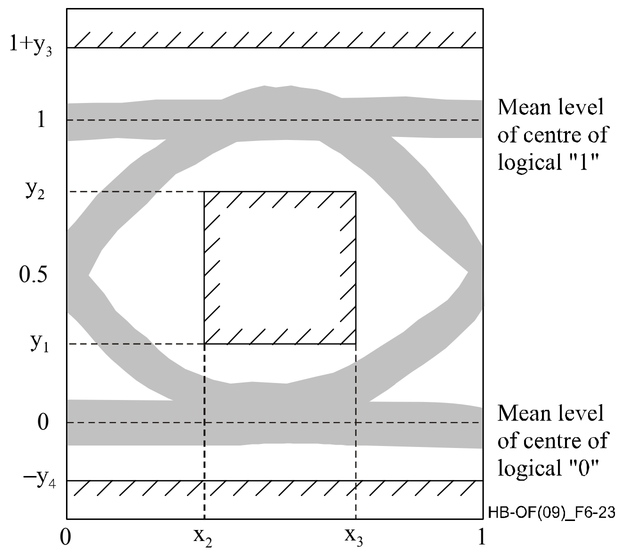


Figure 6-23 – Mask of the eye diagram for NRZ optical transmit signals

3.2 Optical path (single span MPI-S to MPI-R or MPI-S_M to MPI-R_M)

(For further information see Recommendation ITU-T G.959.1).

3.2.1 Attenuation

The minimum and maximum path attenuation is the minimum and maximum loss in dB of the optical path between transmitting, S-type, and receiving, R-type, reference points, where the system in question operates under end-of-life conditions at a BER of 10^{-12} (or as given by the application code), under worst-case, transmit-side signal.

Moreover, attenuation specifications are assumed to be worst-case values, including losses due to splices, connectors, optical attenuators (if used) or other passive optical devices and any additional cable margin to cover allowances for:

i) future modifications to the cable configuration (additional splices, increased cable lengths, etc.);

ii) fibre cable performance variations due to environmental factors;

iii) degradation of any connectors, optical attenuators or other passive optical devices involved between points MPI-S and MPI-R (if used).

Within Recommendation ITU-T G.959.1, the maximum attenuation values required are based on the assumption of 0.275 dB/km installed fibre loss (including splices and cable margin) in the 1 530-1 565 nm range, and on an assumption of a 0.55 dB/km value at 1 310 nm. From a practical point of view, attenuation spans of 11 dB for 40 km and 22 dB for 80 km at 1 550 nm and 11 dB for 20 km and 22 dB for 40 km at 1 310 nm are defined. It should be noted that this method, gives a theoretical value of span distance. In black-link based ITU-T Recommendations, like ITU-T G.695, ITU-T G.698.1 and ITU-T G.698.2, other assumptions are made for link-loss calculations.

3.2.2 Maximum chromatic dispersion at upper and lower wavelength limit

In Recommendation ITU-T G.959.1 the maximum chromatic dispersion at upper and lower wavelength limit is used to define the maximum uncompensated value of the main path chromatic dispersion that the system shall be able to tolerate. For wavelengths between the upper and lower of the wavelength range adopted, the maximum dispersion is linearly interpolated between the values given for the extreme wavelengths.

Furthermore, in Recommendation ITU-T G.959.1 the required maximum dispersion tolerance at the upper and lower wavelength limits is set to a value equal to 1.05 times the theoretical chromatic dispersion value appropriate for the target distance. These dispersion values are considered a practical upper limit for field deployments with distances at about the relevant target distances.

3.2.3 Reflections

Reflections are caused by refractive index discontinuities along the optical path. If not controlled, they can degrade system performance through their disturbing effect on the operation of the optical source or amplifier, or through multiple reflections which lead to interferometric noise at the receiver. Reflections from the optical path are controlled by specifying:

i) the minimum optical return loss of the cable plant at the source reference point (e.g. MPI-S_M, MPI-S), including any connectors. The optical return loss is the ratio of the incident optical power to the total returned optical power from the entire fibre, including both discrete reflections and distributed backscattering such as Rayleigh scattering;

ii) the maximum discrete reflectance between transmitting S-type and receiving R-type reference points. Reflectance denotes the reflection from any single discrete reflection point. Optical reflectance is defined to be the ratio of the reflected optical power present at a point, to the optical power incident to that point.

The maximum number of connectors or other discrete reflection points that may be included in the optical path (e.g. for distribution frames, or WDM components) must be such as to allow the specified overall optical return loss to be achieved. If this cannot be done using connectors meeting the maximum discrete reflections requested in the Recommendations, then connectors having better reflection performance must be employed. Alternatively, the number of connectors must be reduced. It also may be necessary to limit the number of connectors, or to use connectors having improved reflectance performance, in order to avoid unacceptable impairments due to multiple reflections.

3.2.4 Maximum differential group delay

Differential group delay (DGD) is the time difference between the fractions of a pulse that are transmitted in the two principal states of polarization of an optical signal. For distances greater than several kilometres, and assuming random (strong) polarization mode coupling, DGD in a fibre can be statistically modelled as having a Maxwellian distribution (see Chapter 1).

The maximum differential group delay is defined to be the value of DGD that the system must tolerate with a maximum sensitivity degradation of approximately 1 dB.

Due to the statistical nature of polarization mode dispersion (PMD), the relationship between maximum DGD and mean DGD can only be defined probabilistically. The probability of the instantaneous DGD exceeding any given value can be inferred from its Maxwellian statistics. Therefore, if we know the maximum DGD that the system can tolerate, we can derive the equivalent mean DGD by dividing by the ratio of maximum to mean that corresponds to an acceptable probability. Some example ratios are given below in Table 6-5.

Table 6-5 – DGD means and probabilities

Ratio of maximum to mean	Probability of exceeding maximum
3.0	4.2×10^{-5}
3.5	7.7×10^{-7}
4.0	7.4×10^{-9}

3.3 Interface at point MPI-R_M and MPI-R

(For further information see Recommendation ITU-T G.959.1).

3.3.1 Input power

The following parameters specify the input power:

i) *maximum mean channel input power*, which is the maximum acceptable value of the average received channel power at point MPI-R_M or MPI-R to achieve the specified maximum BER of the application code;

ii) *minimum mean channel input power*, which is the minimum value of the average received channel power at point MPI-R_M. This power is the minimum mean channel output power minus the maximum attenuation of the application;

iii) *maximum mean total input power*, relevant only in the case of multi-channel operation, which is the maximum acceptable total input power at point MPI-R_M.

3.3.2 Minimum receiver sensitivity

In general the minimum receiver sensitivity is the minimum value of average received power at point MPI-R (single-channel interface) to achieve the specified maximum BER of the application code. In most cases the minimum receiver sensitivity is specified at a BER of 10^{-12}, except in Recommendation ITU-T G.957 applications where a reference BER of 10^{-10} is defined. This must be met with a transmitter with worst-case values of transmitter eye mask, extinction ratio, optical return loss at points MPI-S, connector degradations, optical amplifier noise, and measurement tolerances. This does not have to be met in the presence of dispersion or reflections from the optical path; these effects are specified separately in the allocation of maximum optical path penalty.

3.3.3 Minimum equivalent sensitivity

This is the minimum sensitivity that would be required by a receiver placed at MPI-R_M (multichannel interfaces) to achieve the specified maximum BER of the application code, if all except one of the channels were to be removed (with an ideal loss-less filter) at point MPI-R_M. This must be met with a transmitter with worst-case values of transmitter eye mask, extinction ratio, optical return loss at point MPI-S_M, connector degradations, transmit-side crosstalk, optical amplifier noise, and measurement tolerances. This does not have to be met in the presence of dispersion, non-linearity, or reflections from the optical path; these effects are specified separately in the allocation of maximum optical path penalty.

3.3.4 Maximum optical path penalty

Within Recommendation ITU-T G.959.1 the path penalty is defined as the apparent reduction of receiver sensitivity (or equivalent sensitivity in the case of multichannel applications) due to distortion of the signal waveform during its transmission over the path. It is manifested as a shift of the system's BER-curves towards higher input power levels. This corresponds to a positive path penalty. Negative path penalties may exist under some circumstances, but are generally expected to be sufficiently small. Ideally, the BER-curves should be shifted only towards higher receiver input power levels, but shape variations of the BER-curves are not uncommon. Within Recommendation ITU-T G.959.1 the path penalty is defined at a BER-level of 10^{-12}.

For application codes requiring FEC bytes to be transmitted, both receiver sensitivities (with and without the degradation due to the optical path) are measured after the error correction has been applied.

For Recommendation ITU-T G.959.1 applications with channel bit rates corresponding to NRZ 2.5G and NRZ 10G, a maximum path penalty of 1 dB or 2 dB is defined. The actual value depends on the application and on the fibre type (Recommendations ITU-T G.652, ITU-T G.653 and ITU-T G.655). The path penalties are not made proportional to the target distances to avoid operating systems with high penalties.

Power penalties associated with the optical path (like chromatic fibre dispersion or polarization-mode dispersion, jitter, reflections) are contained in the maximum optical path penalty, but not in the minimum receiver sensitivity. As a consequence the maximum optical path attenuation is the difference between minimum transmitter output power and the minimum receiver sensitivity additionally reduced by the value of the optical path penalty (Figure 6-24).

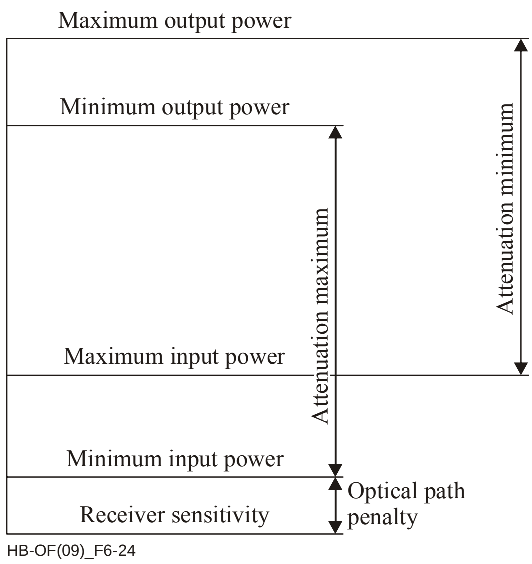


Figure 6-24 – Relationship of the optical parameters in a single-channel system

4 Example of an optical interface specification

Table 6-6 contains an example of specification for an optical system taken from Recommendation ITU-T G.959.1.

It refers to a single-span DWDM system with 32 channels operating at 10 Gbit/s in the C-band on ITU-T G.652 fibres.

Table 6-6 – Example of a multi-channel optical interface specification

Parameter (Note)	Units	
General information		
Maximum number of channels	–	32
Bit rate/line coding of optical tributary signals	–	NRZ 10G
Maximum bit error ratio	–	10^{-12}
Fibre type	–	G.652
Interface at point MPI-S_M		
Maximum mean channel output power	dBm	+3
Minimum mean channel output power	dBm	0
Maximum mean total output power	dBm	+18
Central frequency	THz	192.1 + 0.1 m, m = 0 to 31
Channel spacing	GHz	100
Maximum spectral excursion	GHz	20
Minimum channel extinction ratio	dB	8.2
Eye mask	–	NRZ 10G amplified
Optical path (single span) from point MPI-S_M to MPI-R_M		
Maximum attenuation	dB	11
Minimum attenuation	dB	0
Maximum chromatic dispersion at upper wavelength limit	ps/nm	800 for the G.652 fibre
Maximum chromatic dispersion at lower wavelength limit	ps/nm	800 for the G.652 fibre
Minimum optical return loss at MPI-S_M	dB	24
Maximum discrete reflectance between MPI-S_M and MPI-R_M	dB	–27
Maximum differential group delay	ps	30
Interface at point MPI-R_M		
Maximum mean channel input power	dBm	+3
Minimum mean channel input power	dBm	–11
Maximum mean total input power	dBm	+18
Maximum channel power difference	dB	NA
Maximum optical path penalty	dB	2
Minimum equivalent sensitivity	dBm	–13 for ITU-T G.652 fibre
Maximum reflectance of optical network element	dB	–27

The parameters quoted in Table 6-6 with their values (relevant for the specific optical system) are those listed in the above § 3.

CHAPTER 7

OPTICAL SYSTEMS DESIGN

Introduction

This chapter describes design and engineering criteria for single-channel and multichannel digital optical line systems supporting PDH, SDH and OTN signals in intra-office, inter-office, and long-haul terrestrial networks. Two cases will be considered: optical systems without optical line-amplifiers (clause 1) and with optical line-amplifiers (clause 2).

The forward error correction impact on optical system design is dealt with in clause 3. Some reliability considerations for submarine optical systems are in clause 4.

The general concepts outlined in this Chapter can be also applied to the optical systems deployed in optical access networks (see Chapter 9).

1 "Worst case" design for systems without line amplifiers

(For further information see Supplement 39 to the ITU-T G-series of Recommendations).

For "worst-case" system design, optical systems in client networks (PDH, SDH and OTN) are specified by optical and electrical system parameters with maximum and minimum values at the end-of-life within Recommendations ITU-T G.957, ITU-T G.691, ITU-T G.692, ITU-T G.693, ITU-T G.695, ITU-T G.698.1 and ITU-T G.959.1.

Optical systems design is mainly based on the power budget. An optical power budget is a performance budget, which guarantees the system performance to be better than the minimum required BER performance objective derived from Recommendations ITU-T G.826 and ITU-T G.828.

1.1 Relevant parameters for power budget

Power budgets of *single-channel* (TDM) optical systems are given in Recommendations ITU-T G.957, ITU-T G.691, ITU-T G.693 and ITU-T G.959.1 and those for *multichannel* optical systems (WDM) in Recommendations ITU-T G.695, ITU-T G.698.1 and ITU-T G.959.1. The majority of optical systems without line amplifiers are single-channel systems.

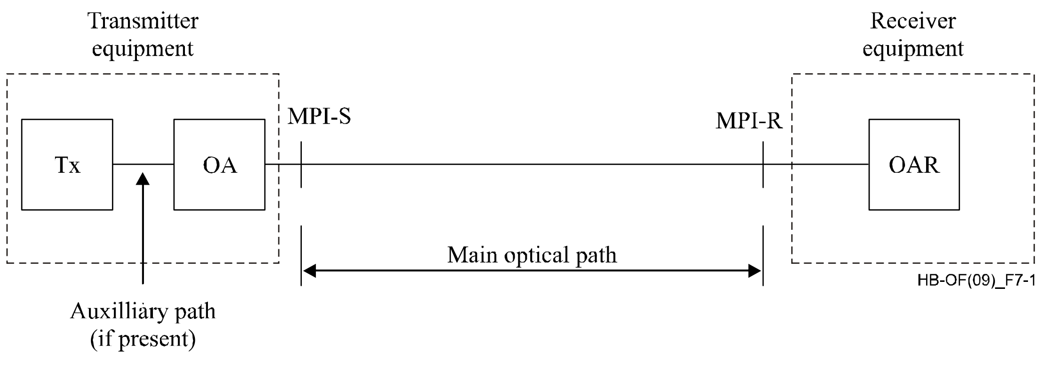
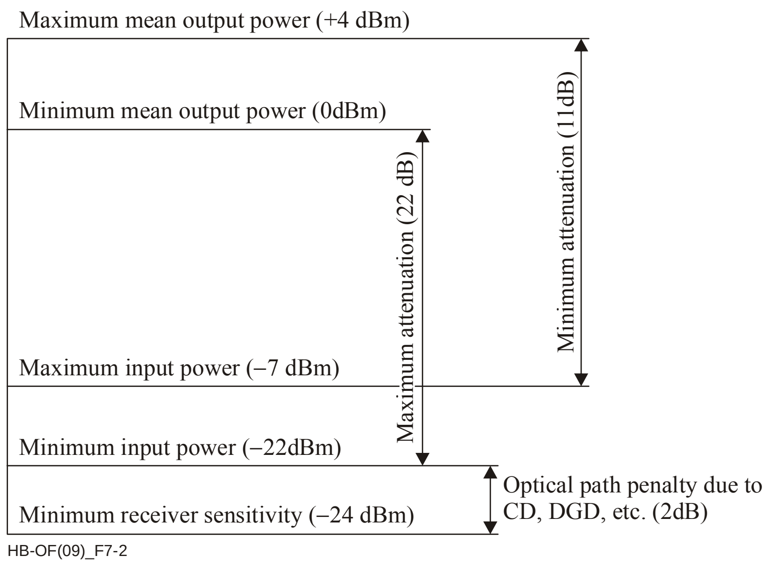


Figure 7-1 – A single-channel, single-span optical system

For a single-channel and single-span optical system, as in Figure 7-1, the following optical parameters are considered in a "worst-case" approach:

– maximum mean output power;
– minimum mean output power;
– maximum attenuation;
– minimum attenuation;
– maximum chromatic dispersion;
– minimum chromatic dispersion;
– maximum differential group delay (DGD);
– maximum mean (channel) input power;
– minimum receiver sensitivity;
– maximum optical path penalty.

An example of power budget for a single-channel and single span system operating at 10 Gbit/s on 80 km without optical amplifier and with a BER objective of 10^{-12} is shown in Figure 7-2.



Note – This corresponds to application code P1L1-2D2 of Recommendation ITU-T G.959.1

Figure 7-2 – Example of power budget for a single-channel single-span 10G system operating on 80 km with a BER objective of 10^{-12}

This example reproduces the values of the application code P1L1-2D2 of Recommendation ITU-T G.959.1. This figure shows that:

i) the difference between the maximum mean output power and the maximum mean (channel) input power gives the minimum attenuation;

ii) the difference between the minimum mean output power and the minimum mean (channel) input power gives the maximum attenuation;

iii) the minimum average optical power at the receiver must be greater than the minimum receiver sensitivity by the value of the optical path penalty;

iv) the minimum receiver sensitivity takes into account transmitter extinction ratio, transmitter eye closure, optical return loss at point MPI-S, receiver connector degradation, measurement tolerances and aging effects;

v) the maximum optical path penalty contains power penalties associated with the optical path (like chromatic fibre dispersion, polarization-mode dispersion related DGD and reflections).

The definitions of all these parameters are given in Chapter 6. In particular the minimum *receiver sensitivity* is defined (for the worst-case and end-of-life) as the minimum acceptable value of mean received optical power at point MPI-R to achieve a BER of 1×10^{-12}. Worst-case transmitter extinction ratio, transmitter eye closure, optical return loss at point MPI-S, receiver connector degradation, measurement tolerances and aging effect cause the worst-case condition for the receiver sensitivity.

Optical systems that would otherwise be limited in transmission length by optical fibre attenuation can be operated with the use of optical (booster-, or/and pre-) amplifiers (see Chapter 5 and Recommendations ITU-T G.661, ITU-T G.662 and ITU-T G.663).

Optical systems that would otherwise be limited in transmission length by chromatic dispersion require certain dispersion accommodation (DA) processes, discussed in Recommendation ITU-T G.691, to overcome fibre length limitation.

The following clauses show the limits that are to be put to the parameters, which mainly contribute to the optical path penalty (chromatic dispersion, differential group delay, reflections) in order to ensure that the specified value (2 dB in the example of Figure 7-2) is complied with.

Recommendation ITU-T G.959.1 reports that a maximum path penalty of 1 dB for low-dispersion systems (systems on Recommendation ITU-T G.655 and ITU-T G.653 fibres), and of 2 dB for high-dispersion systems (systems on Recommendation ITU-T G.652 fibres), is allowed. The path penalties are not made proportional to the target distance to avoid operating systems with high penalties.

1.2 Chromatic dispersion penalty

Chromatic dispersion in a single-mode fibre is a combination of material dispersion and waveguide dispersion, and it contributes to pulse broadening and distortion in a digital signal (see Chapter 1). From the point of view of the transmitter, this is due to two causes.

One cause is the presence of different wavelengths in the optical spectrum of the source. Each wavelength has a different phase delay and group delay along the fibre, so the output pulse is distorted in time (see Recommendation ITU-T G.957).

The other cause is the modulation of the source, which itself has two effects.

One effect is that of the Fourier frequency content of the modulated signal. As bit rates increase, the modulation frequency width of the signal also increases and can be comparable to or can exceed the optical frequency width of the source (see Recommendation ITU-T G.663).

Another effect is that of chirp, which occurs when the source wavelength spectrum varies during the pulse.

1.2.1 Relation between maximum chromatic dispersion and power penalty

Based on calculations shown in Supplement 39 to the ITU-T G-series of Recommendations, Table 7-1 shows the *theoretical* values of the maximum chromatic dispersion for 1 or 2 dB penalty and for several NRZ bit rates.

Table 7-1 – Maximum theoretical allowable chromatic dispersion for a chirp-free narrow-linewidth source at 1 550 nm for several unchirped NRZ bit rates and power penalties

Unchirped NRZ bit rate (Gbit/s)	Maximum chromatic dispersion (ps/nm)	
	1-dB penalty	2-dB penalty
2.5	18 820	30 110
10	1 175	1 880
40	73.5	118

1.2.2 Relation between chromatic dispersion coefficient and link length

From the values of Table 7-1 and from the values of the chromatic dispersion coefficient of the ITU-T specified optical fibres it is possible obtain the *theoretical* length limitations for a chirp-free narrow-linewidth NRZ bit rates for a 1 dB penalty (Table 7-2).

Table 7-2 – Theoretical length limitations for a chirp-free narrow-linewidth source at 1 565 nm with 3 fibre types and 2 unchirped NRZ bit rates for a 1 dB penalty

Fibre type		G.652	G.653	G.655
Dispersion coefficient at 1 565 nm (ps/(nm · km))		19	3.5	10
Dispersion-limited length (km)	NRZ 10G	61	333	116
	NRZ 40G	3.8	20.8	7.3

Now it is possible to compare the dispersion limited lengths of Table 7-2 with the system application codes considered in the ITU-T Recommendations. In the 1 550 nm region these are: intra-office I (≤ 25 km), short-haul S (≤ 40 km), long-haul L (≤ 80 km) and very-long-haul V (≤ 120 km):

i) NRZ 10G systems with ITU-T G.653 fibre for I, S, L, and V applications or with ITU-T G.655 fibre for I, S, and L applications usually are not limited by chromatic dispersion;

ii) NRZ 10G systems with ITU-T G.652 fibre for L and V applications are limited by chromatic dispersion and require chromatic dispersion accommodation;

iii) NRZ 40G systems require dispersion accommodation for all fibre types and for I, S, L and V applications. For ITU-T G.652 fibre the NRZ 40G length limitation starts at a few km.

Active and/or passive dispersion accommodation techniques as given in clause 2.4 below and in Chapter 5, can be applied to overcome fibre length limitations due to chromatic dispersion, in order to respect the path penalty limit.

1.2.3 Relation between maximum chromatic dispersion and line code

The theoretical maximum chromatic dispersion for unchirped sources has been calculated in the previous examples for NRZ modulation format. Table 7-3 shows the theoretical maximum chromatic dispersion for several RZ formats at 40 Gbit/s.

Table 7-3 – Maximum theoretical allowable chromatic dispersion for a chirp-free narrow-linewidth source at 1 550 nm for several unchirped RZ 40 Gbit/s formats and a 2-dB power penalty

Format (unchirped)	Maximum chromatic dispersion (ps/nm)
NRZ	118
RZ(⅔)	78
RZ(½)	59
RZ(⅓)	39
NOTE – The value given above for RZ(⅔) is for conventional RZ modulation and not for carrier-suppressed RZ.	

1.3 DGD power penalty

As shown in Chapter 1, PMD leads to broadening of optical pulses because of random variations in the birefringence of an optical fibre along its length. This broadening is in addition to the chromatic dispersion induced pulse broadening. The use of chromatic dispersion accommodation can eliminate chromatic dispersion broadening, but does not affect the PMD induced broadening.

The differential group delay (DGD) is the difference in arrival times of the two polarization modes at a particular wavelength and time. For a link with a specific PMD coefficient, the DGD of the link varies randomly with time and wavelength as a Maxwell distribution that contains a single parameter, which is the product of the PMD coefficient of the link and the square root of the link length. The system impairment due to PMD at a specific time and wavelength depends on the DGD at that time and wavelength.

The power penalty induced by DGD at the receive point R is a function of the relative power of the two orthogonal polarization modes. This varies as the relative alignment of the principle states of polarization of the optical fibre cable, and the polarization of the source, varies. The maximum link DGD is set to allow no more than a given power penalty in the worst-case power splitting ratio (equal power in both modes). The worst-case power penalty is also affected by the transmission format, NRZ or RZ.

1.3.1 The statistical distribution of PMD

(For further information see Recommendation ITU-T G.691).

The differential group delay between the polarization states in a non-polarization preserving fibre is a random variable. It is often assumed to have a Maxwellian distribution with the following probability density function:

$$f(\Delta\tau) = 32\,\frac{\Delta\tau^2}{\pi^2 < \Delta\tau >^3}\,\exp\left(\frac{4\Delta\tau^2}{\pi < \Delta\tau >^2}\right) \tag{7-1}$$

where:

$\Delta\tau$: DGD, and

$<\Delta\tau>$: mean DGD.

Figure 7-3 shows the probability density function $f(\Delta\tau)$.

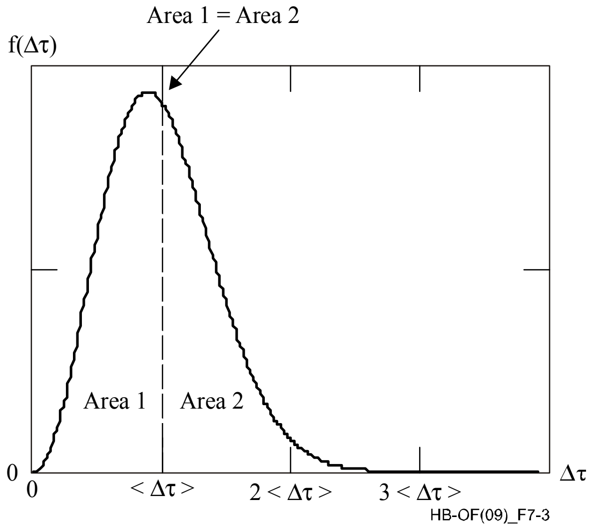


Figure 7-3 – The Maxwellian distribution function –
Probability density function $f(\Delta\tau)$ vs differential group delay, $\Delta\tau$

At a given instant, however, the system will experience a specific DGD, $\Delta\tau$, that is some realization of the random distribution of DGD values, with the average given by the PMD of the link. A pulse train may thus suffer from a delay difference that is smaller or larger than the average PMD of the link.

Integrating this probability density function from $\Delta\tau_1$ to $+\infty$ gives the probability $P(\Delta\tau \geq \Delta\tau_1)$:

$$P(\Delta\tau \geq \Delta\tau_1) = \int_{\Delta\tau_1}^{\infty} f(\Delta\tau) d(\Delta\tau) \tag{7-2}$$

This probability $P(\Delta\tau \geq \Delta\tau_1)$ is depicted in Figure 7-4.

For example, if DGD is greater than 3 times the mean DGD, $\Delta\tau_1 = 3 <\Delta\tau>$, then it can be read from Figure 7-4 that $P(\Delta\tau \geq 3 <\Delta\tau>) \approx 4 \times 10^{-5}$.

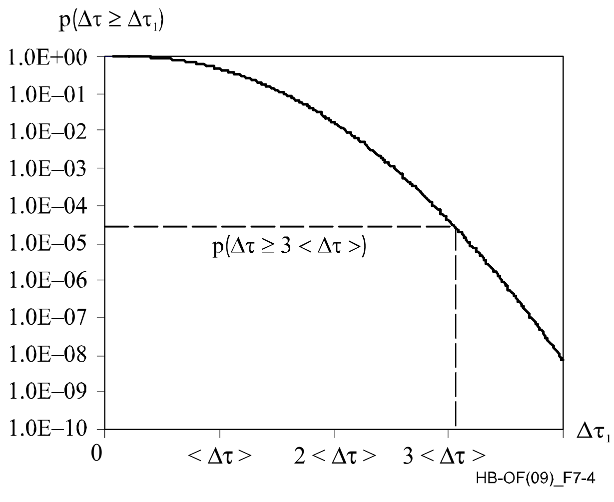


Figure 7-4 – Probability $P(\Delta\tau > \Delta\tau_1)$

The DGD variations depend on the polarization states excited in the fibre, the strain in different parts of the fibre, temperature variations, etc. For links where the fibre is buried and undisturbed, this means that the DGD typically changes fairly slowly. However, if the link includes some aerial fibre or is disturbed the DGD can change on a sub-millisecond timescale.

1.3.2 The path penalty due to PMD

Now let us see the amount of total PMD in the link corresponding to a worst-case path penalty of 1 dB. The worst case is based on a DGD of 0.3 bit period in conjunction with the assumption that both principal states of polarization (PSP) carry the same optical power.

A Maxwellian distribution function is assumed for the DGD (see Figure 7-3). The connection between the DGD (being in direct coincidence with the PMD-induced signal pulse width broadening if the same optical power in both PSPs is assumed) and the corresponding path penalty is a receiver characteristic, and is illustrated in Figure 7-5.

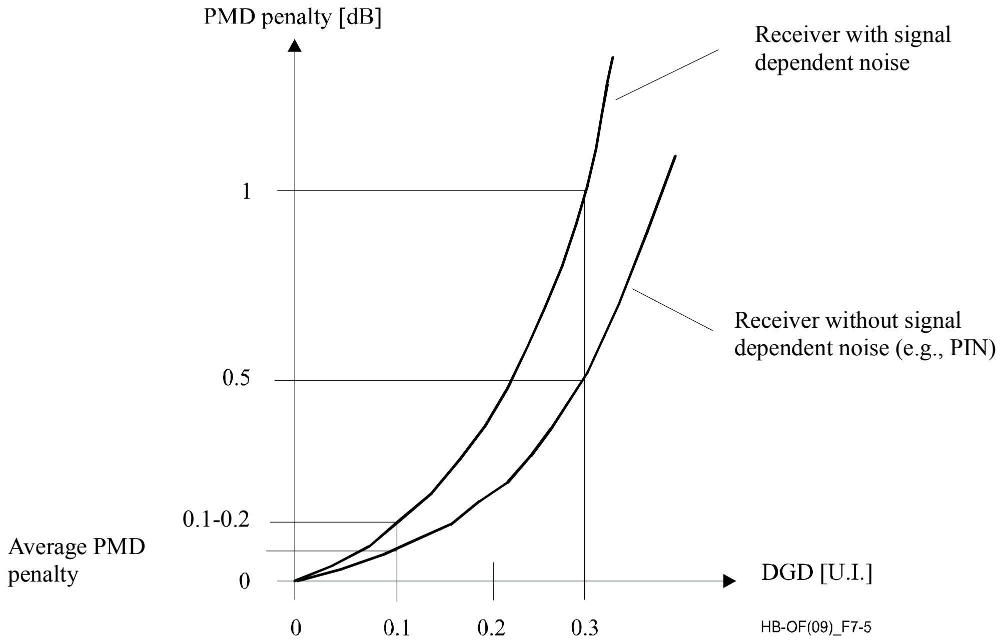


Figure 7-5 – Dependence of the receiver penalty on the actual DGD

With realistic assumptions and a well-designed receiver, it can be deduced that an actual DGD of 0.3 bit period (and 50% of optical power in both PSPs) will give a penalty of about 0.5 dB for a receiver with signal independent noise (PIN-receiver), and up to 1 dB for a receiver with signal dependent noise (APD or preamplifier).

For 10 Gbit/s NRZ applications in Recommendations ITU-T G.691 and ITU-T G.959.1, a 1-dB first-order penalty allowance corresponds to a 30 ps (about one third of the pulse width 100 ps) limit on DGD at point R.

If the PMD coefficient PMD_Q value (as specified in the ITU-T G.65 x-series of Recommendation) is not greater than 0.5 ps/km$^{1/2}$, this gives a total link length of 400 km, while with a maximum PMD coefficient PMD_Q = 0.2 ps/km$^{1/2}$, the total link length becomes 2 500 km. More details are given in § 2.3.

PMD compensation techniques may be used for links with excessive PMD (see Chapter 5). To establish the extent to which PMD compensation is required, a careful investigation of the outside plant may be needed.

1.4 Penalty due to reflections

Reflections are caused by refractive index discontinuities along the optical path. If not controlled, they can degrade system performance through their disturbing effect on the operation of the optical source or amplifier, or through multiple reflections which lead to interferometric noise at the receiver. Reflections from the optical path are controlled by specifying:

i) the minimum optical return loss of the cable plant at the source reference point (e.g. MPI-S), including any connectors; and

ii) the maximum discrete reflectance between source reference points (e.g. MPI-S) and receive reference points (e.g. MPI-R).

Reflectance denotes the reflection from any single discrete reflection point, whereas the optical return loss is the ratio of the incident optical power to the total returned optical power from the entire fibre, including both discrete reflections and distributed backscattering such as Rayleigh scattering.

1.4.1 Minimum optical return loss at MPI-S

Measurement methods for reflections are described in Recommendation ITU-T G.957. For the purpose of reflectance and return loss measurements, points MPI-S and MPI-R are assumed to coincide with the endface of each connector plug. It is recognized that this does not include the actual reflection performance of the respective connectors in the operational system. These reflections are assumed to have the nominal value of reflection for the specific type of connectors used.

The minimum optical return loss of the cable plant at MPI-S is usually limited to 24 dB, but for some interfaces it is 14 dB.

1.4.2 Maximum discrete reflectance between MPI-S and MPI-R

Optical reflectance is defined to be the ratio of the reflected optical power present at a point, to the optical power incident to that point. Control of reflections is discussed extensively in Recommendation ITU-T G.957. The maximum number of connectors or other discrete reflection points, which may be included in the optical path (e.g. for distribution frames, or WDM components), must be such as to allow the specified overall optical return loss to be achieved. If this cannot be done using connectors meeting the maximum discrete reflections cited here, then connectors having better reflection performance must be employed. Alternatively, the number of connectors must be reduced. It may also be necessary to limit the number of connectors or to use connectors having improved reflectance performance in order to avoid unacceptable impairments due to multiple reflections.

The maximum discrete reflectance between MPI-S and MPI-R is generally limited to –27 dB.

2 "Worst case" design for system with optical line amplifiers

(For further information see Supplements 39 and 41 to the ITU-T G-series of Recommendations).

For systems without line amplifiers as described above, the optical budget is based on optical power levels needed to give the required BER in the presence of the receiver electrical noise (see Figure 7-2). In contrast, for multichannel systems with line amplifiers the optical budget is based on OSNR (optical signal to noise ratio) that is needed to give the required BER.

For an optical system without line amplifiers the minimum average optical power at the receiver must be greater than the minimum receiver sensitivity by the value of the optical path penalty. (See § 1.1). For an optical system that includes line amplifiers, because the dominant noise component is ASE (amplifier spontaneous emission) generated in the line amplifiers rather than in the receiver, the equivalent relationship is that the minimum OSNR at the receiver must be greater than the minimum receiver OSNR tolerance by the value of the optical path OSNR penalty. In order to ensure that the electrical noise in the receiver is small compared to the optical noise, there are also constraints on the minimum optical power at the receiver input.

In typical submarine optical transmission systems the budget starts from a linear Quality Factor (Q-factor) which only takes into account degradation due to the ASE (amplifier spontaneous emission) of amplifiers. Then, the optical power budget allocates the penalties/impairments for all types of degradation (due to the optical path, due to terminal equipments, etc., …). The Q-factor, as described in Chapter 6, is related to the BER of the optical systems.

As an example a BER of 10^{-12} corresponds to $Q \approx 7.03$ (≈ 17 dB).

The relation between the Q-factor written in terms of decibels and in linear values is the following:

$$Q \text{ (decibels)} = 20 \times \log_{10} Q \text{ (linear)} \tag{7-3}$$

Since practical Q-factor estimation techniques make measurements in the upper and lower regions of the received "eye" in order to infer the quality of the signal at the optimum decision threshold, Q can be considered as only a qualitative indicator of the actual BER.

The "worst case" approach adopted in the following clauses is suitable for a system with a small number of components providing reasonable margins to the system. However, for a system with a large number of components, for example a multi-span, multichannel system, the margins obtained from deterministic (worst-case) designs may become unreasonably large. In that situation, network operators, as well as manufacturers, should consider the use of statistical design, which is described in Annex A.

2.1 Relevant parameters for Optical Power Budget

Power budgets of *multi-channel* and multi-span optical systems have been given in Recommendation ITU-T G.698.2. The majority of optical systems with line amplifiers are multichannel systems. The scheme of such a system is in Figure 7-6.

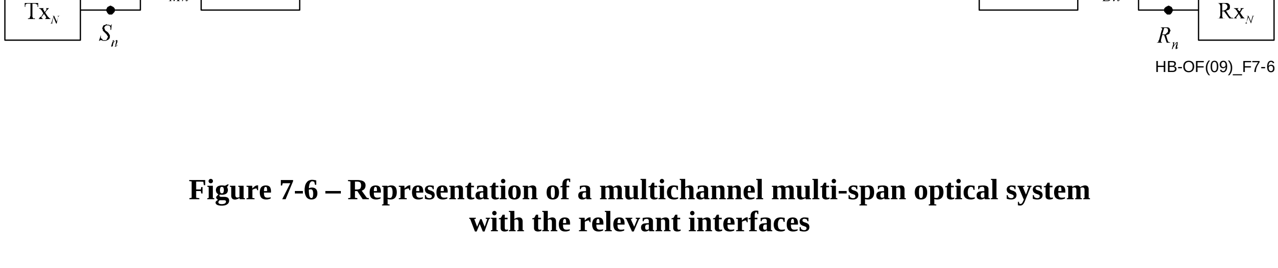
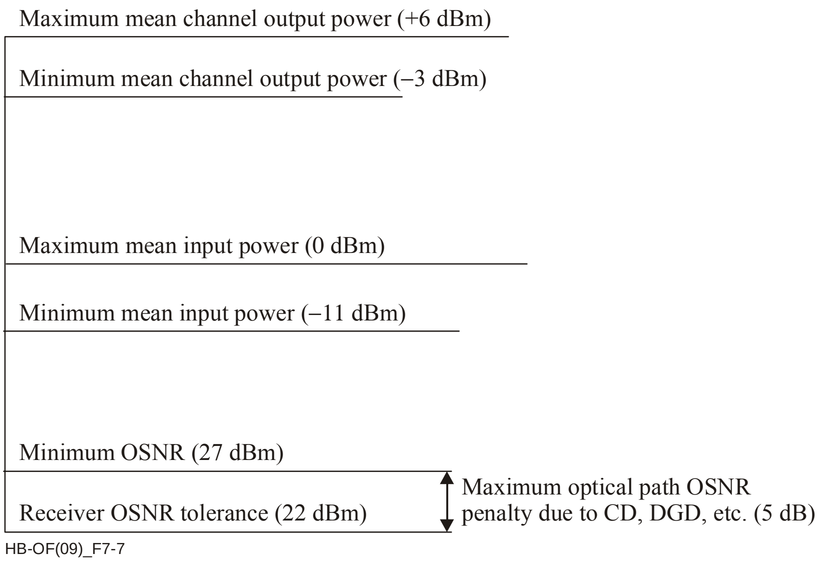


Figure 7-6 – Representation of a multichannel multi-span optical system with the relevant interfaces

An example of a power budget for a multi-channel system with 4-5 spans and with channels operating at 10 Gbit/s with 3-4 optical line amplifiers and with a BER objective of 10^{-12} is shown in Figure 7-7. In this power budget, as an example, are also shown the values of the application code DN100C-2A2(C) of Recommendation ITU-T G.698.2.



Note – This corresponds to application code DN100C-2°2(C) of Rec. ITU-T G.698.2.

Figure 7-7 – Example of power budget for a multi-channel system with 4-5 spans and with a BER objective of 10^{-12}

For this class of systems the following optical parameters are considered:

- maximum mean channel output power;
- minimum mean channel output power;
- maximum mean channel input power;
- minimum mean channel input power;
- minimum OSNR;
- receiver OSNR tolerance;
- maximum optical path OSNR penalty.

The maximum mean channel output power is given in order to limit the non linear effects and consequent penalties.

The minimum mean channel output power is given in order to ensure that there is a sufficiently high optical power at the input to the first optical amplifier in the link that it has an acceptable OSNR at its output.

The minimum OSNR takes into account the noise accumulation of all of the optical amplifiers in the link.

The maximum optical path OSNR penalty is defined as:

Lowest OSNR at R_S – Lowest OSNR at S_S

where:

– lowest OSNR at S_S is the lowest OSNR that meets the maximum BER of the application at point S_S i.e., *before* transmission through the link;

– lowest OSNR at R_S is the lowest OSNR that meets the maximum BER of the application at point R_S i.e., *after* transmission through the link.

This penalty contains the dispersion OSNR penalty, fibre non linearities penalty, interchannel crosstalk penalty, interferometric crosstalk penalty, reflection penalty from the optical path, PMD and polarization dependant loss (PDL) penalty.

It has to be noted that in this power budget there is not the minimum receiver sensitivity because with the use of a pre-amplifier the input level to the electrical receiver is always sufficient to guarantee a BER better than 10^{-12} due to electrical noise Recommendation ITU-T G.663. This means that multi-span optical systems are not limited by the receiver electrical noise.

A suitable margin should be allocated for future modifications of cable configurations and equipment parameters. An example of criteria adopted for the system margin referred to submarine systems is in Annex C.

If it is assumed that the link optical attenuation is compensated by means of optical amplifiers and the chromatic dispersion is compensated by means of chromatic dispersion compensators, then ASE noise and PMD become the most important impairments that limit the capacity and transmission distance of DWDM applications.

The following clauses discuss the fundamental limits for the transmission distance based on cascaded optical amplifiers (ASE noise) and fibre PMD. Moreover a description will be made of the other effects that limit the transmission distance by contributing to the value of the maximum optical path OSNR penalty (residual chromatic dispersion, optical non-linearity, etc.), in order to ensure that the specified value (5 dB in the example of Figure 7-7) is met.

2.2 Limit to the transmission distance due to optical signal to noise ratio

Optical systems that would otherwise be limited in transmission length by optical fibre attenuation can be operated with the use of optical (booster-, line- or/and pre-) amplifiers (see Chapter 5), as considered in the following.

The scheme of an optical system with line amplifiers has been shown in Figure 7-6.

In such a system with a cascaded optical amplifier chain, ASE noise accumulates from the contributions of all optical amplifiers. Therefore, the OSNR degrades after each optical amplifier. OSNR is useful for monitoring and characterizing optical amplifier performance. Equations to estimate the worst-case OSNR, when various simplifying assumptions are made, are given below.

Figure 7-6 depicts a multichannel N span reference system with a booster amplifier, $N - 1$ line amplifiers and a preamplifier. For this reference system, the following main assumptions are made:

i) all optical amplifiers in the chain including booster and preamplifier have the same noise figure;

ii) the losses (per channel) of all spans are equal;

iii) the output powers (per channel) of the booster and line amplifiers are the same.

In this case, the OSNR at the input of the receivers (point R_i in Figure 7-6, $I = 1, \ldots n$) can be approximated as:

$$OSNR = P_{out} - L - NF - 10\log\left(N + \frac{10^{\frac{G_{BA}}{10}}}{10^{\frac{L}{10}}}\right) - 10\log\left(h\nu\nu_r\right) \quad (7\text{-}4)$$

where:

P_{out}:	output power (per channel) of the booster and line amplifiers (dBm),
L:	span loss (dB) (which is assumed to be equal to the gain of the line amplifiers),
G_{BA}:	gain of the optical booster amplifier (dB),
NF:	signal-spontaneous noise figure of the optical amplifier (dB),
h:	Planck's constant (in mJ · s to be consistent, with P_{out} (dBm)),
ν:	optical frequency (Hz),
ν_r:	reference bandwidth (Hz), typically 0.1 nm, and
$N - 1$:	total number of line amplifiers.

The above equation takes into account the shot noise and the signal-spontaneous beat noise as the most dominant noise contributions.

Equation 7-4 indicates that the ASE noise is accumulated from all $N + 1$ amplifiers. It can be simplified in the following cases:

1) If the gain of the booster amplifier is approximately the same as that of the line amplifiers, i.e. $G_{BA} \approx L$, equation 7-4 can be simplified to:

$$OSNR = P_{out} - L - NF - 10\log(N+1) - 10\log(h\nu\nu_r) \quad (7\text{-}5)$$

2) The ASE noise from the booster amplifier can be ignored only if the span loss L is much greater than the booster gain $G_{BA.}$ In this case, equation 7-5 can be simplified to:

$$OSNR = P_{out} - L - NF - 10\log(N) - 10\log(h\nu\nu_r) \quad (7\text{-}6)$$

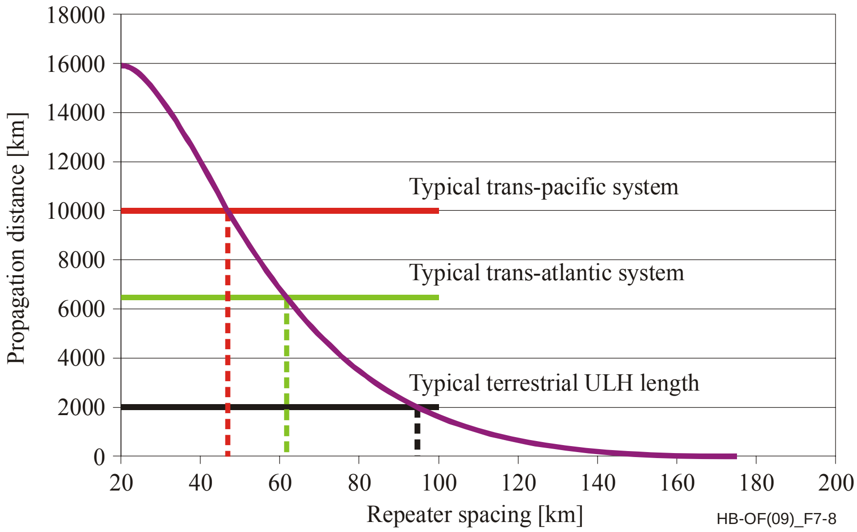
3) Equation 7-5 is also valid in the case of a single span with only a booster amplifier, (e.g. short-haul multichannel) in which case it can be modified to:

$$OSNR = P_{out} - G_{BA} - NF - 10\log(h\nu\nu_r) \quad (7\text{-}7)$$

4) In case of a single span with only a preamplifier, Equation 7-5 can be modified to:

$$OSNR = P_{out} - L - NF - 10\log(h\nu\nu_r) \quad (7\text{-}8)$$

From the above equations it is possible to evaluate the impact of multiple amplifiers. From equation 7-6 it is clear that OSNR can become quite small for large values of L (span length) and N (number of amplifiers in cascade). For a defined OSNR (necessary for achieving the BER objective) there is a relationship between the length of the link and the repeater spacing (Figure 7-8).



NOTE – The parameters used are: $OSNR$ = 16 dB in a reference bandwidth B_r = 0.1 nm, NF = 4.7dB, N_λ = 64 channels, P_{out} = 14 dBm and fibre attenuation α = 0.21dB/km.

Figure 7-8 – Example of repeater spacing required to achieve typical submarine and terrestrial transmission distances

As the system length increases, the possible repeater spacing decreases, in order to maintain the OSNR objective. For links up to 2 000 km (terrestrial links) the repeater spacing can be 80-100 km, while, for transoceanic submarine links (6 000-8 000 km), the maximum repeater spacing is around 50 km. The output power from each of the amplifiers should be chosen to be high enough to maintain a good OSNR, while being low enough to avoid the impairments due to the fibre non linearities.

In practical transmission systems, the losses of the spans are not equal, so equations 7-4 to 7-8 can not be applied. In this case, a general equation to account for the OSNR of any end-to-end path through an optical network is given in equation 7-9.

$$OSNR_{out} = -10\log\left(10^{-\left(\frac{P_{in1}-NF_1-10\log(h\nu_r)}{10}\right)} + 10^{-\left(\frac{P_{in2}-NF_2-10\log(h\nu_r)}{10}\right)} + \ldots + 10^{-\left(\frac{P_{inN}-NF_N-10\log(h\nu_r)}{10}\right)}\right) \quad (7\text{-}9)$$

where:

P_{in1}, P_{in2} to P_{inN}: channel powers (dBm) at the inputs of the amplifiers,

NF_1, NF_2 to NF_N: noise figures (dB) of the amplifiers.

2.3 Limit to the transmission distance due to maximum differential group delay

The maximum differential group delay applies to the whole link between a transmitter and the corresponding receiver (Figure 7-6).

The equation below can be used to calculate the maximum DGD of a link (containing multiple components and fibre sections) with a defined probability of being exceeded:

$$DGD\max_{link} = \left[DGD\max_F^2 + S^2 \sum_i PMD_{Ci}^2 \right]^{1/2} \tag{7-10}$$

where:

$DGD\max_{link}$: maximum link DGD (ps),

$DGD\max_F$: maximum concatenated optical fibre cable DGD (ps),

S: Maxwell adjustment factor (see Table 7-4),

PMD_{Ci}: PMD value of the ith component (ps).

This equation assumes that the statistics of the instantaneous DGD are approximated by a Maxwell distribution, with the probability of the instantaneous DGD exceeding $DGD\max_{link}$ being controlled by the value of the Maxwell adjustment factor taken from Table 7-4.

Table 7-4 – S values and probabilities

Ratio of max. to mean (S)	Probability of exceeding max.	Ratio of max. to mean (S)	Probability of exceeding max.
3	4.2×10^{-5}	4	7.4×10^{-9}
3.2	9.2×10^{-6}	4.2	9.6×10^{-10}
3.4	1.8×10^{-6}	4.4	1.1×10^{-10}
3.6	3.2×10^{-7}	4.6	1.2×10^{-11}
3.8	5.1×10^{-8}		

Further details can be found in Recommendations ITU-T G.650.2 and ITU-T G.691. The value of $DGD\max_F$ (the maximum DGD due to the fibre part) can either be measured or, alternatively, an upper limit can be calculated for a given fibre length using the PMD_Q coefficient in the corresponding fibre Recommendation (see Chapter 1).

The DGD limits to ensure 1 dB penalty for the entire link are given in Table 7-5 for NRZ systems. These values are about one third of the pulse width. In the same table the value of the PMD (mean DGD) not to exceed for an outage probability with "five nines" (1×10^{-5} or 5 minutes/year) are given. These values have been obtained using the Maxwell adjustment factor 3.2 given in Table 7-4.

The total PMD of a fibre link, with total length L and a PMD coefficient for the individual cable sections PMD_Q, is given by $PMD = \sqrt{L} \cdot PMD_Q$. If the PMD coefficient PMD_Q value is not greater than 0.5 ps/km$^{1/2}$, this gives a total link length of 400 km for an optical channel at 10 Gbit/s and with a maximum PMD coefficient $PMD_Q = 0.2$ ps/km$^{1/2}$, the total link length becomes 2 500 km at 10 Gbit/s.

Examples of calculation of the maximum allowed length for an optical link are given in Annex B.

Table 7-5 – Maximum link differential group delay for NRZ

Client class	Units	Pulse width	DGD limit for 1 dB penalty	PMD (mean DGD) limit for an outage probability less than 1×10^{-5}
1.25G	ps	800	240	80
2.5G	ps	400	120	40
10G	ps	100	30	10
40G	ps	25	7.5	2.5

2.4 Penalty due to residual chromatic dispersion after accommodation

Optical amplifiers solve the attenuation problem but, at the same time, worsen the dispersion problem, since, in contrast with the electronic regenerators, an optical amplifier does not restore the amplified signal to its original state. As a result, dispersion-induced degradation of the transmitted signal accumulates over multiple amplifiers. As shown in clause 1.2.2, chromatic dispersion can strongly limit the maximum transmission distance of an optical system. In principle, the group velocity dispersion effects can be minimized using a narrow-linewidth lasers and operating close to the zero-dispersion wavelength of the fibre. However it is not always practical to operate near the zero-dispersion wavelength because of the effects on the non linearities (see § 2.7).

Dispersion accommodation attempts to solve this practical problem by cancelling the pulse broadening caused by the chromatic dispersion so that at the receiver the input signal can be restored. These methods can be classified as *active* methods (used at the transmitter or at the receiver) or as *passive* methods (use of dispersion compensating optical elements along the fibre link).

Some *active* dispersion accommodation techniques are reported in Recommendation ITU-T G.691, such as a prechirp applied in the optical transmitter to obtain pulse compression.

However the most widely used technique is the passive one. The *passive* chromatic dispersion accommodation technique, defined in Recommendation ITU-T G.691, can be used in a long-haul / multi-span high data rate transmission system. A passive dispersion compensator (PDC) can be composed of dispersion-compensating fibres (DCF) or fibre gratings. It can be applied in an optical transmitter with booster amplifier and/or an optical receiver with preamplifier as well as in the mid-stage of an optical line amplifier. The condition for perfect dispersion compensation is that:

$$D_1 \times L_1 = -D_2 \times L_2 \tag{7-11}$$

where:

D_1 and L_1: dispersion coefficient and the length of the transmission fibre, while

D_2 and L_2: dispersion coefficient and the length of the DCF.

The practical solution for a system with 10G channels is to add a DCF module (with 6-8 km of DCF) to optical amplifiers spaced at about 80 km. The DCF compensate the chromatic dispersion and the amplifier takes care of the transmission and DCF fibre attenuation. This simple scheme suffers from two problems. The DCF attenuation can be compensated by increasing the amplifier gain at the expense of enhanced ASE (amplified spontaneous emission) noise. Second, because of the small mode field diameter of the DCF, the non linear effects are considerably enhanced. The two problems can be solved by inserting the DCF within a two-stage amplifier (one pre-amplifier and another booster amplifier) (Figure 7-9).

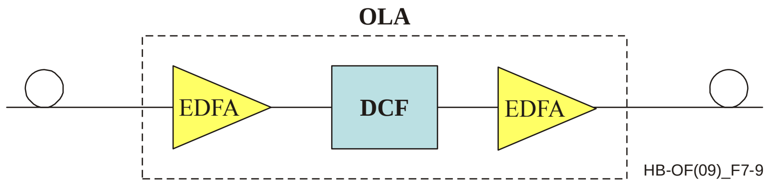


Figure 7-9 – Scheme for passive dispersion compensation for a line amplifier

In order to give a picture of the behaviour of the chromatic dispersion along a link, a dispersion map is used. A dispersion map is the plot of local chromatic dispersion, for a given operating wavelength, as a function of distance from the optical transmitter to the optical receiver. It plots the cumulative dispersion, i.e. the dispersion measured between the output of the terminal transmitter and any other point in the optical path.

In a DWDM system, the PDC can exactly compensate for the chromatic dispersion of one wavelength, but typically it cannot exactly compensate at the other wavelengths (Figure 7-10). The difference in residual dispersion between channels can be minimized in very long systems by applying dispersion compensation and dispersion slope compensation together. Since the chromatic dispersion in a fibre may vary with time/temperature, a high-speed system may need (in very long systems) to be compensated partly by PDC, and partly by dynamically adjusted adaptive compensation (see Chapter 5).

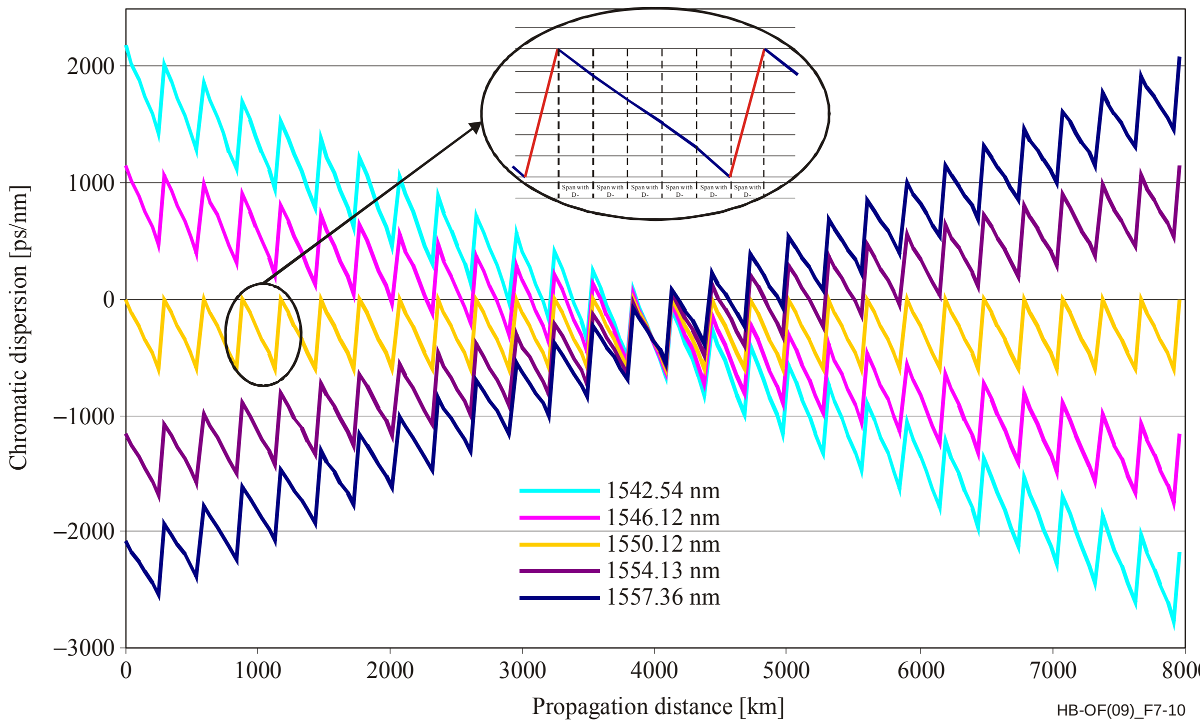


Figure 7-10 – Typical chromatic dispersion map for a submarine WDM system with 163 spans designed for 40 wavelengths centred around 1 550.12 nm

For acceptable operation of DWDM transmission systems over long distances with small channel spacing (e.g., 100 GHz), there is not only the limit for the maximum end-to-end dispersion value, but also a requirement for the local dispersion coefficient of the transmission fibre to have a minimum value, in order to avoid non-linear effects such as four wave mixing (FWM) and cross-phase modulation (XPM).

The value of local chromatic dispersion coefficient required to avoid significant penalties due to these effects depends on many factors of the transmission system design, such as the channel spacing, power level, link length, etc.

In conclusion, the design of the dispersion map for each optical section must be in accordance with the transmission requirements, mainly as a compromise between the limitation of non-linear effects and the pulse broadening.

2.5 Optical crosstalk penalty

(For further information see Supplement 39 to the ITU-T G-series of Recommendations).

One important issue in the design of DWDM systems is optical crosstalk. The system performance degrades whenever crosstalk leads to transfer of power from one channel to another. Optical crosstalk can occur in a perfectly *linear channel* because of the imperfect nature of various WDM components such as optical filters, demultiplexers and photonic cross-connects. Additionally, optical crosstalk can occur because of the *non linear effects* in optical fibres, a phenomenon referred to as nonlinear crosstalk as it depends on the nonlinear nature of the communication channel.

Linear inter-channel crosstalk is less of a problem, because of its incoherent nature, than the interferometric crosstalk that occurs during routing of DWDM systems from multiple nodes.

In the following linear crosstalk mechanisms will be considered as well as their impact on DWDM systems. Nonlinear crosstalk mechanisms will be described in § 2.7 dealing with non-linearities.

2.5.1 Definition of terms

Since the terms used to describe optical crosstalk and its effects are not entirely consistent across the industry, it is useful to briefly define them here (Table 7-6). Within ITU-T, there is a convention that the term "crosstalk" is reserved for description of system effects and that the properties of components use the term "isolation".

2.5.2 Inter-channel crosstalk penalty

A simple approach to calculating the crosstalk power penalty is based on the eye closure occurring as a result of the crosstalk.

The most commonly considered cause of the interchannel crosstalk is imperfect demultiplexing of a multichannel transmission signal into its individual channels prior to a set of single-channel receivers. This situation is depicted in Figure 7-11.

Here, a number of DWDM channels enter the common port of a demultiplexer. The worst case for any particular channel is for its power to be at the minimum and that of all of the other channels to be at the maximum. The maximum allowable difference between channels has been denoted as d (dB). When the channels emerge from the individual output ports, the disturbing channels have been attenuated with respect to the wanted channel by an amount equal to the Unidirectional Isolation I (dB).

The main parameter that governs the maximum level of optical crosstalk that can be tolerated in any given optical system is the inter-channel crosstalk penalty P_C. From this, and a small number of other parameters, it is necessary to be able to obtain the required isolation parameters of the demultiplexer.

Table 7-6 – Terms used

Parameter unit	Symbol	Defined in	Definition
System parameters			
Inter-channel crosstalk (dB)	C_C	ITU-T G.692	Ratio of total power in the disturbing channels to that in the wanted channel. (Wanted and disturbing channels at different wavelengths (k total)).
Interferometric crosstalk (dB)	C_I	–	Ratio of the disturbing power (not including ASE) to the wanted power within a single channel (wavelength). This parameter is also known as "Intra-channel crosstalk".
Inter-channel crosstalk penalty (dB)	P_C	–	Penalty assigned in the system budget to account for inter-channel crosstalk.
Interferometric crosstalk penalty (dB)	P_I	–	Penalty assigned in the system budget to account for interferometric crosstalk.
Channel power difference (dB)	D	ITU-T G.959.1	The maximum allowable power difference between channels entering a device.
Extinction ratio (linear used here)	*R*	ITU-T G.691	Ratio of power at the centre of a logical "1" to the power at the centre of a logical "0".
Eye-closure penalty (dB)	E	–	Receiver sensitivity penalty due to all eye-closure effects. This includes transmitter eye-closure and chromatic dispersion penalty.
Component parameters			
Insertion loss (dB)	IL	ITU-T G.671	The reduction in power from input to output port at the wanted channel wavelength.
Unidirectional Isolation (dB)	I	ITU-T G.671	The difference between the device loss at a disturbing channel wavelength and the loss at the wanted channel wavelength.
Adjacent channel isolation (dB)	I_A	ITU-T G.671	The isolation of the device at the wavelengths one channel above and below the wanted channel.
Non-adjacent channel isolation (dB)	I_{NA}	ITU-T G.671	The isolation of the device at the wavelengths of all disturbing channels except for the adjacent channels.

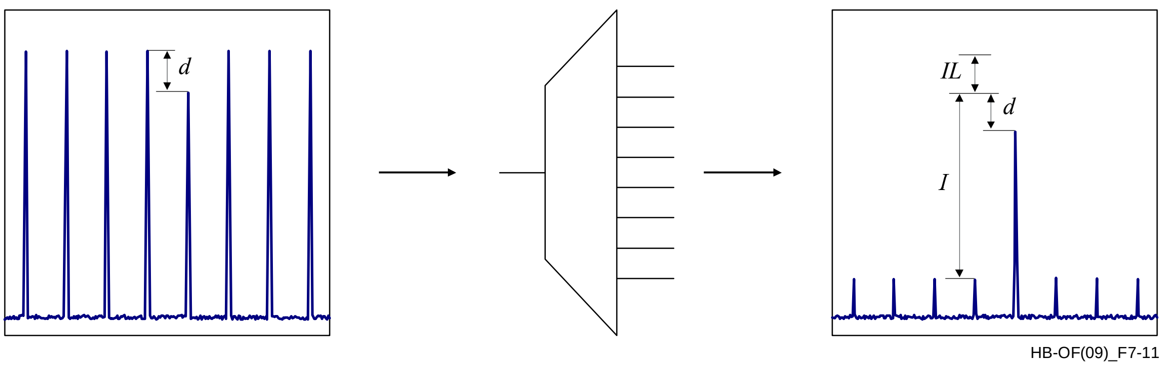


Figure 7-11 – Simple demultiplexer example

The induced optical penalty is plotted in Figure 7-12 against inter-channel crosstalk for different values of the extinction ratio (r), of the eye closure and of the DWDM channels which are the source of the crosstalk. The actual penalty incurred in a practical system lies somewhere below the highest curve.

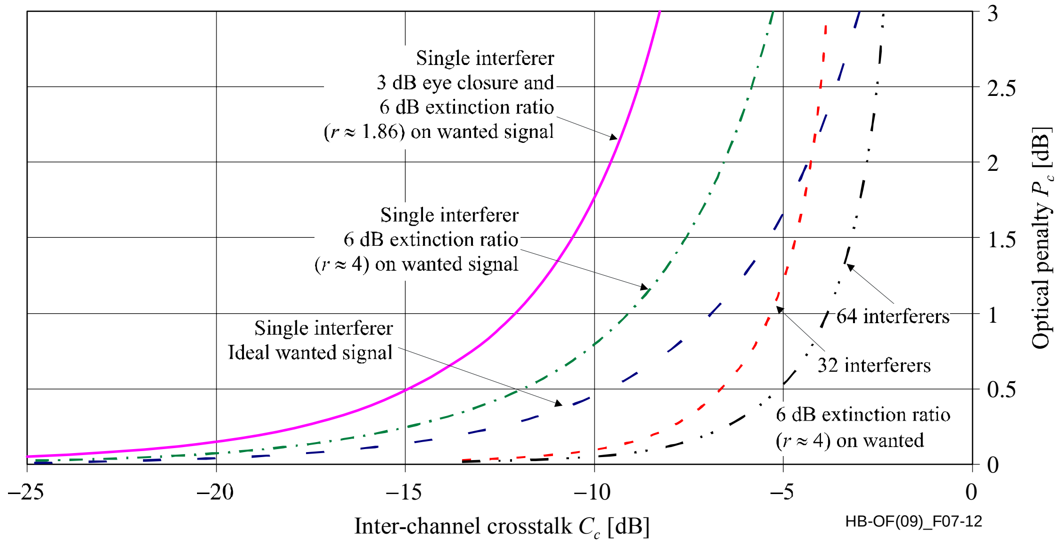


Figure 7-12 – Graph of optical penalty vs inter-channel crosstalk

The crosstalk penalty may also be dependent on the line code (RZ or NRZ) and the relative bit rates of the wanted and the number of the interferer signals.

As an example, a value of –16 dB is specified in Recommendation ITU-T G.698.2, which, according with the above figure, means a power penalty of about 0.5 dB.

2.5.3 Interferometric crosstalk penalty

Interferometric crosstalk results from DWDM components used for routing and switching along an optical network. The impact of the interferometric crosstalk on system performance should again be seen on the basis of the power penalty.

Interferometric crosstalk occurs when the disturbing channel and the wanted channel are at the same nominal wavelengths. Four examples of this are:

i) in an optical add-drop multiplexer where the wavelength in question is incompletely dropped before the new signal is added;

ii) in an optical multiplexer where one transmitter may be emitting power at the wavelength of another channel (e.g. due to inadequate side-mode suppression ratio); this is termed transmit-side crosstalk in Recommendation ITU-T G.692;

iii) in an optical cross-connect where lack of sufficient switch isolation causes light from more than one source fibre to reach the receiver;

iv) in any component or group of components where there is more than one path that the light can take to reach the receiver. This is called multi-path interference.

Interferometric crosstalk behaves differently from inter-channel crosstalk when the two optical signals are sufficiently close together that their beat frequency is within the electrical bandwidth of the receiver. In this case, it is the optical fields which interact to produce the crosstalk instead of the optical powers and, consequently, the levels of crosstalk required to produce a particular penalty are much smaller.

For a single interferer the crosstalk can be modelled as having a bounded probability density function (PDF). The interferometric crosstalk penalty for a wanted signal with 6-dB extinction ratio is plotted in Figure 7-13.

As an example, a value of –40 dB is specified in Recommendation ITU-T G.698.2, which, according with the above figure, means a power penalty of about 0.3 dB.

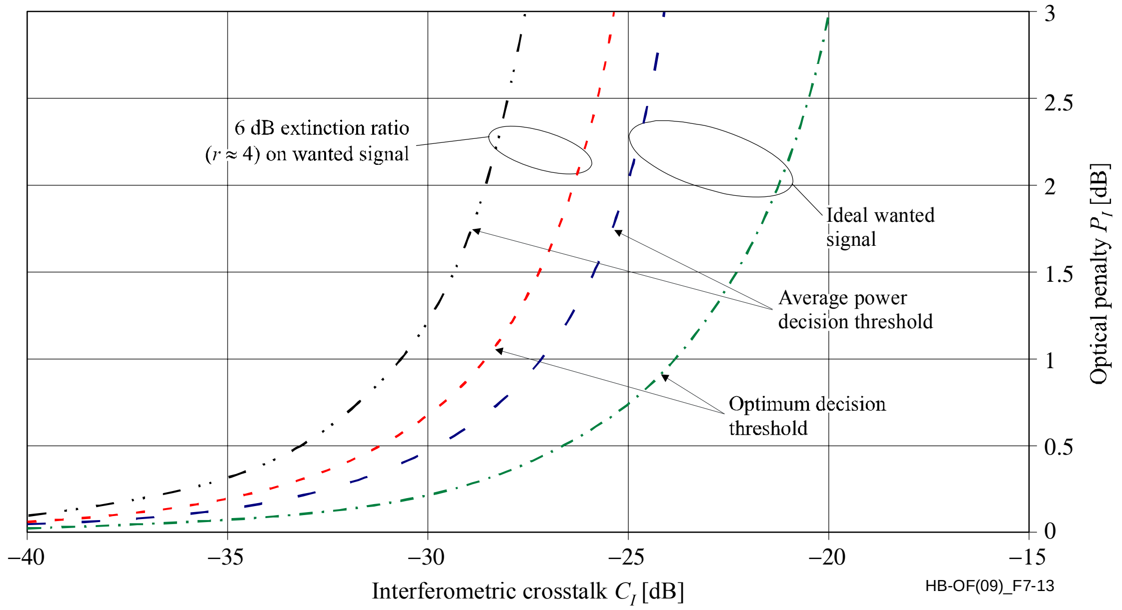


Figure 7-13 – Graph of optical penalty vs interferometric crosstalk for multiple interferers (Gaussian model)

2.6 Penalty due to reflections

The same considerations apply here as for clause 1.4 only changing the interface notation from single-channel (MPI-S) to multichannel (MPI-S_M) at the source reference point and (MPI-R) to (MPI-R_M) at the receiver reference point.

2.7 Penalty due to fibre non linearities

(For further information see Recommendations ITU-T G.650.3, ITU-T G.663 and Supplement 41 to the ITU-T G-series of Recommendations).

Non-linear interactions between the signal and the transmission medium (silica fibre) begin to appear as optical signal powers are increased to achieve longer span lengths at high bit rates. Consequently, non-linear fibre behaviour has emerged as an important consideration, both in high capacity systems and in long unregenerated routes. These non-linearities can be generally categorized as either *scattering effects* (stimulated Brillouin scattering and stimulated Raman scattering) or *effects related to the Kerr effect*, that is, the intensity dependence of the refractive index (particularly self-phase modulation in single-channel systems, cross-phase modulation and four wave mixing in multi-channel systems).

The influence of these non-linear phenomena increases with the optical input power. As a consequence, the system performance can be strongly degraded by such effects, if the fibre input optical power is very high. On the other side, the system performance is also degraded at low fibre optical input power, due to the low optical signal-to-noise ratio at the receiver. Therefore, a compromise should be found for a given system performance (BER) between the minimum input power level (to limit the noise) and the maximum output power threshold to limit the non-linearity effects.

Moreover a variety of parameters, in addition to the optical input power, influence the severity of these non-linear effects, including fibre dispersion characteristics, the effective area of the fibre, the non linear coefficient, the number and spacing of channels in multiple channel systems, overall unregenerated system length, the degree of longitudinal uniformity of the fibre characteristics, as well as source line width. A description of the influence of all these parameters on the non-linear phenomena is given in the following.

2.7.1 Stimulated Brillouin Scattering

In a lightwave communication system using an optical source with a narrow line width, significant optical power may be transferred from a forward-propagating signal to a backward-propagating signal when the stimulated Brillouin scattering (SBS) power rating of the optical fibre is exceeded. The scattered light is downshifted (or Brillouin-shifted) by approximately 11 GHz at 1 550 nm.

Of the single channel non-linear effects described here, SBS has the lowest threshold power. While studies have shown that the SBS threshold can vary between fibre types and even among individual fibres, it is typically in the order of 5 to 10 mW for externally modulated, narrow linewidth sources, but may be 20 to 30 mW for directly modulated lasers. The SBS threshold for a system deployed on ITU-T G.653 fibre is slightly lower than that for a system using ITU-T G.652 fibre, due to the smaller effective area of ITU-T G.653 fibre. This is generally true for all of the non-linear effects. The SBS threshold is sensitive to the source linewidth and power level. It is independent of the number of channels.

SBS effectively limits the amount of light that can be transmitted through a fibre path. Figure 7-14 shows this effect for a narrow-band source, where all of the signal power falls within the Brillouin bandwidth. The transmitted power becomes saturated and the backscattered power rapidly increases.

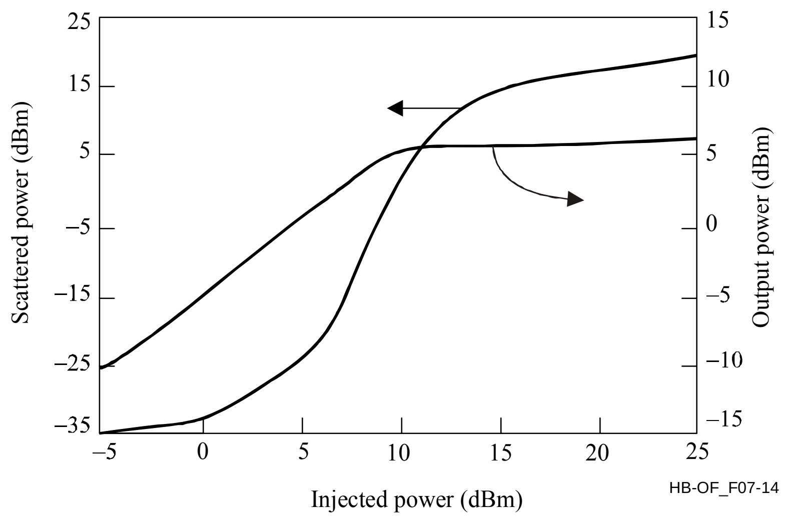


Figure 7-14 – Stimulated Brillouin scattering effect for narrow-band source

Stimulated Brillouin scattering impairments will not arise in systems where the source linewidth significantly exceeds the Brillouin bandwidth or where the signal power is below the threshold power.

Several possible definitions of SBS power rating are provided. The common concept among these, however, is that the input power at which SBS becomes important is in the regime where the backscatter power begins increasing rapidly. Because of the exponential increase in backscatter power, the range of input powers in this regime is rather narrow, so all definitions give similar (though not identical) results.

SBS does not present a practical limitation to the deployment of current long haul DWDM transmission systems because XPM (see clause 2.7.4) limits the performance at lower power levels than SBS.

2.7.2 Stimulated Raman scattering

Stimulated Raman scattering (SRS) causes a signal wavelength to behave as a Raman pump for longer wavelengths. In this case, the shorter wavelength signal is attenuated by this process, which amplifies the longer wavelength signal.

Stimulated Raman scattering can occur in both single- and multiple-channel systems. Signal powers in the order of 1W or more are needed to experience impairment from this phenomenon with only a single channel without line amplifiers. However, shorter wavelength signals in multiple-channel systems with channels spanning a wide wavelength range can suffer degraded signal-to-noise performance when a portion of their power is transferred to longer wavelength channels through SRS. This results in total system capacity limitations based on the total number of channels, channel spacing, average input power and overall system length. In particular, the threshold for the observation of a 1 dB penalty in a multi-channel system due to Raman gain in dispersion-unshifted fibre can be estimated to be:

$$P_{tot} \bullet \Delta\lambda \bullet L_{eff} < 40 \text{ mW} \bullet \text{nm} \bullet \text{Mn} \tag{7-12}$$

where:

P_{tot}: combined power of all of the channels,

$\Delta\lambda$: optical spectrum over which the channels are distributed, and

L_{eff}: effective length (in units of 10^6 metres (Mm)).

The SRS threshold for a system deployed on ITU-T G.653 fibre is slightly lower than that for a system using ITU-T G.652 fibre, due to the smaller effective area of ITU-T G.653 fibre. SRS does not practically degrade single-channel systems; conversely it may limit the capability of WDM systems.

In single-channel systems, filters can be used to remove the unwanted spectrum. However, no practical techniques to eliminate the effects of SRS in multiple-channel systems have been reported. The effects of SRS may also be mitigated by reducing the input optical power. However, SRS does not present a practical limitation to the deployment of currently contemplated WDM systems because the SRS induced loss (and gain) values are modest for the power levels that are limited by XPM effects (see clause 2.7.4).

2.7.3 Self phase modulation

Because a fibre's refractive index depends on the optical intensity of the signal, the temporal variation of the optical intensity of the signal induces a modulation of its own phase. This effect is called self phase modulation (SPM). The fibre refractive index may be written as:

$$n = n_0 + \frac{n_2}{A_{eff}} P \tag{7-13}$$

hence:

$$\frac{\partial n}{\partial t} = \frac{n_2}{A_{eff}} \frac{\partial P}{\partial t} \tag{7-14}$$

where:

n_2: fibre nonlinear refractive index (m^2/W),

A_{eff}: fibre effective area, and

P: launched power.

In single wavelength systems, self phase modulation will gradually broaden the signal spectrum when changes in optical intensity result in changes in phase (Figure 7-15). Once spectral broadening is introduced by SPM, the signal experiences a greater temporal broadening as it propagates along the length of the fibre, due to the effects of chromatic dispersion, in the normal dispersion region of the fibre (i.e. below the zero-dispersion wavelength).

Generally, the effects of SPM are significant only in systems with high cumulative dispersion or in very long systems. Systems operating in the normal dispersion regime which are dispersion-limited may not tolerate the additional effects due to SPM. In multiple-channel systems with very closely spaced channels, the spectral broadening induced by SPM may also create interference between adjacent channels. The effect of SPM may also induce degradation when combined with narrowband optical filtering. Since SPM is essentially a single channel effect, it is not influenced by the greater channel counts. The distortion penalty of SPM is increased by larger launched channel powers. It is also increased by a higher channel bit rate, since signals with higher bit rates have higher rising/falling bit slopes.

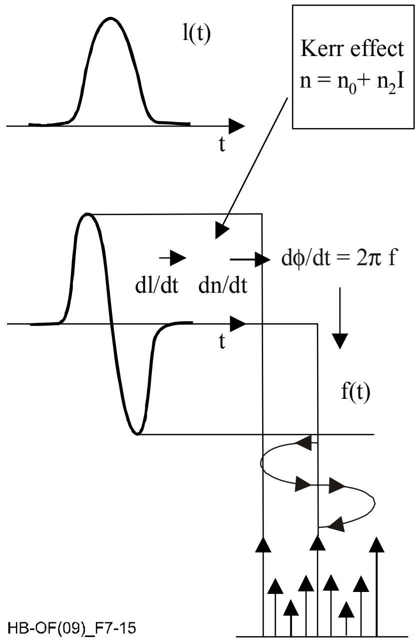


Figure 7-15 – Spectral broadening mechanism due to self phase modulation

The use of ITU-T G.653 fibre and the placement of the signal channel near the dispersion zero will reduce the impact of SPM. For systems less than approximately 1 000 km, SPM may be controlled through the implementation of dispersion compensation at appropriate intervals along the length of an ITU-T G.652 fibre system. The effects of SPM may be mitigated by operating at wavelengths above the zero-dispersion wavelength of ITU-T G.655 fibre. Fibres with attributes of increased fibre effective area, or decreased nonlinear refractive index, also reduce the SPM penalty. For all fibre designs, SPM effects may be reduced by decreasing the launched channel powers, though systems design trends call for larger powers to allow longer span distances.

2.7.4 Cross phase modulation

In multichannel systems, cross phase modulation (XPM) will gradually broaden the signal spectrum when changes in optical intensity result in changes in phase due to interactions between adjacent channels. The amount of spectral broadening introduced by XPM is related to the channel separation and fibre chromatic dispersion, since the dispersion-induced differential group velocities will cause the interacting pulses to separate as they propagate down the fibre. Once spectral broadening is introduced by XPM, the signal experiences a greater temporal broadening as it propagates along the length of the fibre due to the effects of chromatic dispersion.

The systems penalty from XPM is increased by smaller channel spacings and larger channel counts (though this saturates depending on distance). As noted for SPM, the change in signal phase is related to the change in fibre refractive index, which in turn is related to the channel power. Larger average launched powers lead to larger phase shifts, which when combined with dispersion effects lead to a larger system penalty.

The XPM penalty actually decreases for higher channel bit rates, since lower bit rate signals experience longer bit interactions or "walk-through". However, since higher bit rate receivers require higher OSNR for a given BER, these systems have to operate at higher power levels, which negates this effect.

The broadening due to XPM may result in interference between adjacent channels in multiple-channel systems. XPM can be controlled through appropriate selection of channel spacing. Studies have shown that only adjacent channels contribute significantly to XPM-induced signal distortion in multiple-channel systems. The Signal-to-Noise Ratio (SNR) of the centre channel of a three-channel system will approach that of a single-channel system as channel separation is increased. As a result, the effect of XPM can be rendered negligible with adequate spacing between the signal channels. Channel separations of 100 GHz were shown to be sufficient to reduce XPM effects in a simulation of a system with 5 mW of power/channel. Dispersion penalties due to XPM may also be controlled by the implementation of dispersion compensation at appropriate intervals along the length of the system. Fibres with attributes of increased fibre effective area, or decreased nonlinear refractive index, also reduce the XPM penalty.

For all fibre designs, XPM effects may be reduced by decreasing the launched channel powers, though systems design trends call for larger powers to allow longer span distances.

2.7.5 Four-wave mixing

Four-wave mixing (FWM), also called four-photon mixing, occurs when the interaction of two or three optical waves at different wavelengths generates new optical waves, called mixing products or sidebands, at other wavelengths.

This interaction can occur between signals in multiple-channel systems, between OA ASE noise and a single channel, as well as between the main mode and side modes of a single channel. In the case of two signals, the intensity modulation at their beat frequency modulates the fibre refractive index and produces a phase modulation at a difference frequency. The phase modulation creates two sidebands at frequencies given by this difference. In the case of three signals, more and stronger mixing products are produced (Figure 7-16) which will fall directly on adjacent signal channels when the channel spacings are equal in frequency. Two optical waves propagating along a fibre produce FWM with high efficiency if the phase matching condition is achieved between sidebands and initial signals.

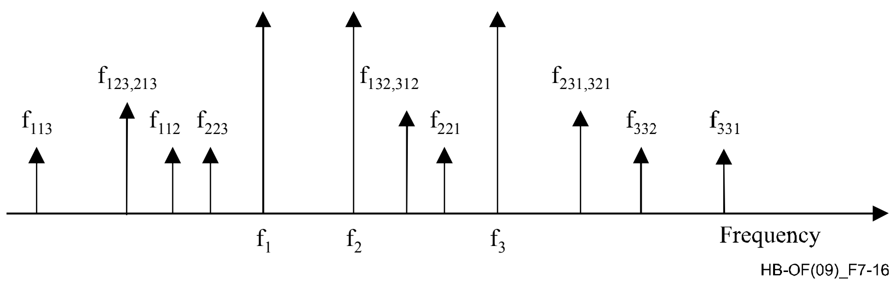


Figure 7-16 – Mixing products generated by four-wave mixing of three signals

Assuming that all channels have the same input power and equal channel spacing, the FWM efficiency, η, of a fibre can be expressed as the ratio of the FWM power to the per channel output power from the fibre and is proportional to:

$$\eta \propto \left[\frac{n_2 P}{A_{eff} D (\Delta\lambda)^2} \right]^2 \tag{7-15}$$

where:

- n_2: fibre nonlinear refractive index,
- P: channel input power,
- A_{eff}: fibre effective area,
- D: fibre chromatic dispersion coefficient, and
- $\Delta\lambda$: channel spacing.

Note that FWM efficiency is not influenced by increasing bit rate.

The generation of FWM sidebands can result in significant depletion of the signal power. Furthermore, when the mixing products fall directly on signal channels, they cause parametric interference which manifests as amplitude gain or loss in the signal pulse, depending on the phase interaction of the signal and sideband.

Parametric interference causes closure of the eye pattern at the receiver output, thereby degrading Bit-Error Ratio (BER) performance. Multichannel systems are trending towards greater channel counts, which increase the number of possible mixing products falling on signal channels.

As seen by the equation (7-15), increased frequency spacing and local chromatic dispersion reduce the efficiency of the FWM process by destroying the phase matching between the interacting waves. However, systems are trending towards decreased frequency spacings, to allow more channels to occupy the same OA passband. Furthermore, as launched channel powers increase, the FWM efficiency (and hence system penalty) also increases.

Multichannel systems deployed in the 1 550 nm operating window over ITU-T G.652 fibre experience much less FWM impairment compared to systems deployed over ITU-T G.653 fibre, because ITU-T G.652 fibre has much more local chromatic dispersion, as well as larger fibre effective area. Conversely, the placement of a signal channel directly at or near the dispersion zero can result in a very significant buildup of FWM products over a relatively short fibre length (i.e. some hundreds of metres).

In the 1 550 nm zero dispersion region, four-wave mixing can create serious system impairment in multi-channel systems on ITU-T G.653 fibre, since the signal channels experience only a small value of local chromatic dispersion.

The non-zero dispersion shifted fibre, ITU-T G.655 fibre, has been developed to eliminate FWM effect in the C-Band. As a matter of fact this fibre has a small, but not zero, chromatic dispersion coefficient around 1 550 nm, to limit both the effect of the chromatic dispersion and the FWM effects. However, four-wave mixing may also impair multichannel systems, even on ITU-T G.655 fibre, depending on channel spacings of 50 GHz or less, fibre dispersion, and fibre nonlinear coefficient (proportional to the nonlinear refractive index divided by effective area).

As previously noted, chromatic dispersion may be used to suppress the generation of the FWM sidebands. Fibres with attributes of increased fibre effective area, or decreased nonlinear refractive index, also reduce the FWM efficiency. Uneven channel spacing Recommendation ITU-T G.692 may also be incorporated to mitigate the severity of the FWM impairment. Uneven channel spacing ensures that mixing products generated by three or more channels do not fall directly on other channel wavelengths. Reduction of the input power levels in ITU-T G.653 fibre systems could permit multiple channel operation, but might compromise the economic advantages of optical amplification.

2.7.6 Examples of maximum power threshold due to non-linear effects

Some factors that affect the maximum power threshold due to non-linear effects are the following:

i) Type of fibre used for the transmission

Fibres characterized by different non-linear coefficients and dispersion coefficients have very different behaviours regarding non-linear effects.

As an example, dispersion-compensating fibres (DCFs) have a small effective area and consequently a large non-linear coefficient. It has been verified with simulations that for optical input powers $P_{in} > 3$ dBm SPM starts degrading the system performance.

ITU-T G.652 fibres have a small non-linear coefficient and consequently SPM is in general negligible except at very high optical input powers (e.g. for $P_{in} > 8$ dBm, post-compensation scheme and amplifiers spacing of 100 km, SPM starts degrading the ideal linear of behaviour). Moreover, the high local dispersion typical of ITU-T G.652 fibres makes XPM and FWM effects quite negligible, assuming that the dispersion is exactly compensated.

ITU-T G.655 fibres have approximately the same behaviour as ITU-T G.652 fibres with respect to SPM, but, having a smaller dispersion coefficient, FWM is not negligible.

ii) Scheme of dispersion compensation

The following three schemes for dispersion compensation are characterized to different behaviour with respect to SPM have been considered:

– *Pre-compensation:* The dispersion compensating device is placed at the beginning of each span before the transmission fibre. This scheme is strongly subject to SPM. Simulation with amplifier spacing of 100 km, link length of 500 km, and amplifiers $NF = 6$ dB, showed that the maximum input power for $Q = 7$ is $P_{in} = 4$ dBm.

– *Post-compensation:* The dispersion compensating device is placed at the end of each span after the transmission fibre. Simulation with amplifier spacing of 100 km, link length of 500 km, and amplifiers $NF = 6$ dB, showed that the maximum input power for $Q = 7$ is $P_{in} = 13$ dBm.

– *Post-compensation + prechirp:* As post-compensation, but at the beginning of the link the pulse is pre-chirped. The optimum prechirp value, calculated by means of simulations, strongly reduces SPM effects.

iii) Span length

Due to fibre losses, the optical input power decays according to an exponential law during propagation in a span. On the other hand, the influence of non-linear effects depends on the optical power value. As a consequence, the maximum input power threshold due to non-linear effects has different values for systems that differ only in the amplifier spacing parameter.

For example, consider a 500-km link on ITU-T G.652 fibre with post-compensation and amplifiers $NF = 6$ dB. If the span length is 100 km, simulations show that the maximum input power for $Q = 7$ is $P_{in} = 13$ dBm. If the span length is 50 km, simulations show that the maximum input power for $Q = 7$ is $P_{in} = 8$ dBm.

In conclusion it is impossible to pick out a single value for the maximum optical input power to achieve a Q-factor greater than 7 (BER = 10^{-12}). This maximum input constraint may be used to identify the best performance region of a system and can be determined by means of preliminary simulations with the desired system parameters (type of fibre, dispersion compensation, amplifier spacing, channel spacing). Finally, notice that all suggestions reported here are based on the assumption of RZ modulation format, and they investigate neither the number of WDM channels nor their frequency spacing.

3 Forward error correction impact on optical system design

Forward error correction (FEC) is an important way of improving the performance of large-capacity long-haul optical transmission systems. With the use of FEC system design can accept relatively large BER (much more than 10^{-12}) in the optical transmission line (before decoding). FEC application may allow the optical parameters to be significantly relaxed and encourages the construction of large capacity long-haul optical transmission systems in a cost-effective manner.

FEC characteristics (in-band FEC, out-of-band FEC, coding Gain, net-coding gain) have been described in Chapter 6. Some FEC aspects related to system design are dealt with in the following.

FEC has been proven to be effective in OSNR-limited systems as well as in dispersion-limited systems. As for non-linear effects, reducing the output power leads to OSNR limitations, against which FEC is useful. FEC is less effective against PMD, however.

Candidates of optical parameter relaxation with FEC are described below.

3.1 Relaxation of transmitter and/or receiver characteristics

The maximum BER can be relaxed from 10^{-12} toward the values listed in the third row in Table 7-7.

Table 7-7 – Performance of standard FECs

Application	In-band FEC BCH (4359,4320)	Out-of-band FEC RS (255,239)
	SDH	OTN
BER_{in} for $BER_{out} = BER_{ref} = 10^{-12}$	2.9×10^{-6}	1.8×10^{-4}
Coding gain ($BER_{ref} = 10^{-12}$) (dB)	3.8	5.9
Net coding gain ($BER_{ref} = 10^{-12}$) (dB)	3.8	5.6
Code rate	1	239/255

This allows a reduced signal-to-noise ratio at the decision circuitry. Assuming a given OSNR in a reference system without FEC is sufficient to produce the required BER, the coding gain provided by adding FEC to the system can be used to relax component parameters in the transmitter and/or receiver. There are many parameters which could benefit from this such as the requirements for total launched power, eye mask, extinction ratio, electrical noise of a PIN receiver, noise figure of an optical pre-amplifier, isolation of demultiplex filters or, to some extent, the characteristic of the receiver transfer function determining the intersymbol interference and noise bandwidth before decision.

3.2 Reduction of output power levels to save pump power

Reducing the output power levels of transmitter and line amplifiers by the net coding gain (NCG) value leads to reduced OSNR at the end of an optical amplifier chain. The associated higher electrical noise and, therefore, higher BER is compensated by FEC. The same principle can be applied to a single-span application with an optically pre-amplified receiver. Deploying FEC in a single-span system without an optically pre-amplified receiver gives a transmitter output power saving of only half of the NCG value because, in this case, the system is limited by receiver electrical noise.

3.3 Reduction in power levels to avoid non-linearity

Reducing the output and input power levels of the optical amplifiers forces a system limited by non-linear effects to become OSNR limited, provided that the other parameters are unchanged. For example, after the power levels are decreased, the multichannel system parameters for ITU-T G.652 and G.655 fibre can also be applied to ITU-T G.653 fibre. Thus, a common system specification becomes possible that is valid for all fibre types.

3.4 Increase in maximum span attenuation

If the multi-span system is not chromatic dispersion limited (using ITU-T G.652 fibre with dispersion accommodation, ITU-T G.653 fibre, or ITU-T G.655 fibre), target span distance can be extended. The input power of each line amplifier can be decreased by the amount of the net coding gain. Therefore, the maximum span attenuation can be increased by the amount of the net coding gain (maximum case). The relaxation may eliminate unnecessary repeaters in a system with slightly larger loss than that specified.

In a single-span system without preamplifier, the increase of maximum path attenuation is half of the NCG value only because, in this case, the system is limited by receiver electrical noise.

3.5 Increase in maximum number of spans for a long-haul system

The total target distance of a long-haul system can be extended enormously by increasing the number of spans (and also line amplifiers) assuming that chromatic and polarization mode dispersion do not become limiting factors (i.e., the system remains OSNR limited). Providing that the attenuation of each span is the same and remains constant, the maximum number of spans can be increased by a factor given by the NCG value. In the case of standard out-of-band FEC, the target distance may be increased by a factor of almost 4. An example is given in Annex B.

3.6 Increase in channel count for high-capacity systems

If a multi-span system is limited by the output power of the optical amplifiers, the channel count can be increased by a factor given by the NCG value. In the case of standard out-of-band FEC, the channel count may be increased by a factor of almost 4. It should be noted, that this approach can be used as long as the reference system was not supported by non-linear effects which may change by reducing the channel power. For example, SPM cannot be used to compensate for chromatic dispersion if the channel power becomes less than the SPM threshold.

4 Reliability consideration (for submarine optical systems)

(For further information see Supplement 41 to the ITU-T G-series of Recommendations).

Submarine networks require reliable and robust fibre optical systems to avoid costly repairs in the wet plant. Failures occurring during the system life may be due to internal faults (shunt fault, fibre loss increase, repeater failures, card failures, etc.) or external aggressions (e.g. anchors and fishing activities for wet plant and misoperation for dry plant).

4.1 Reliability requirement

Reliability is defined as the probability for a component or a subsystem to perform a required function under specific conditions for a given period of time. This can be expressed through different figures:

i) Failure rate (λ) generally expressed in FIT (Failure in time); 1 FIT represents 10^{-9} probability to fail during 1 hour of operation. This value tends to be temperature dependent and has to be recorded at the operating temperature;

ii) Mean time between failures (MTBF): expected time between 2 consecutive failures.

It should be noted that these statistical figures have no meaning for an individual device and only provide performance probabilities, rather than absolute expectations.

At first, the overall reliability constraint is used to estimate the reliability allowed for each subsystem and then for each component. Required reliability of a component for a given system life is then translated into failure rate (λ) or MTBF.

For a system or a subsystem, the following figures are defined:

– Mean time to repair (MTTR): expected time needed to repair a failure,

– Outage = MTTR / MTBF: amount of time usually expressed in minutes per year when the network is not available to perform its function,

– Networks availability (%) = (Total time – Outage) / Total time * 100%.

4.2 Internal fault

In order to achieve the reliability target in submarine systems (minimizing internal faults) and to establish a maintenance policy applicable during the entire system life, the failure root causes should be identified at component, sub-system and system levels.

4.2.1 Failure rate analysis

i) Infant mortality

At the beginning of life working condition, units or components used in submarine systems exhibit a high failure rate which is decreasing with time. This short period is called the infant mortality time (infant mortality: usually one or two years). It is mainly due to a non-ideal manufacturing process (defective raw materials, improper operations, contaminated environment, power surge, ineffective inspection, or inadequate shipping and handling). It should be noted that infant mortality relates to an entire batch of devices and cannot reflect the behaviour of a single device. In that particular case the single device will either fail or pass a test, whereas the failure rate of a number of units will follow a decreasing curve over time. For submerged equipment, the qualification process attempts to avoid this mortality.

ii) Random failure

The period next to the infant mortality is characterized by a lower failure rate. This period is called the useful life because the failure rate is almost constant until the beginning of the last phase (wear out period). While the failure rate is constant, failures occur randomly and are generally not detectable even with highly controlled processes.

iii) Ageing

The last period occurs when systems and associated components begin to wear out during use. Failures may result from ageing, material fatigue, excessive wear out, environmental corrosion, undesirable environment, or cumulative damage.

The failure rate behaviour is conventionally described as a bathtub curve during the life of the system, as shown in Figure 7-17.

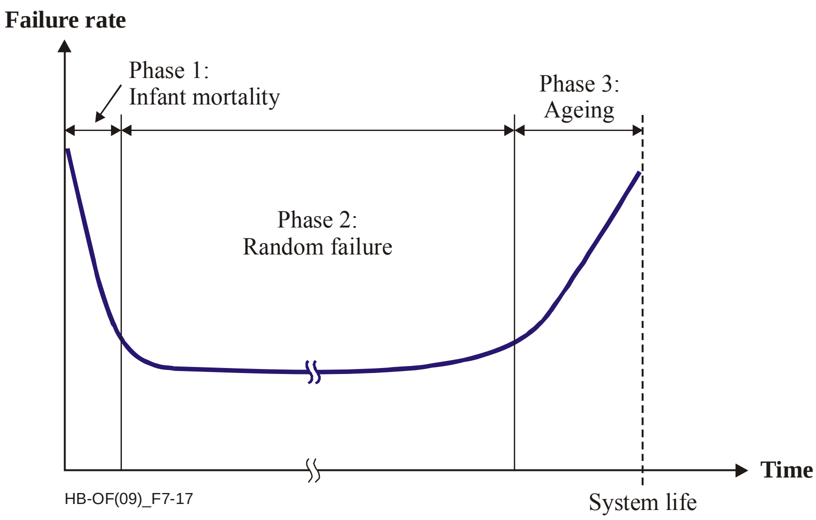


Figure 7-17 – Typical failure's rate behaviour during the life of a system

4.2.2 Submerged section reliability

The submerged section is more critical than the land section of a submarine system in terms of reliability because the MTTR is greater. Typical MTTR values give around 2 weeks (the intervention of a cableship is necessary) for the submerged section repair instead of 2 hours for the land section. From a reliability point of view, this is why the failure rate for laser pumps used within the repeaters is a sensitive issue for the system. For example, typical failure rates for amplifiers in terrestrial networks are within 1 000 to 10 000 FIT compared to submarine amplifiers, which are within 10 to 100 FIT (around 2 orders of magnitude lower).

Designing ultra-reliable submarine systems means that the probability of a wear-out failure occurring during the system life must be very low and the probability of random failure must be minimized as much as possible.

Repeaters are critical equipment as they contain electronic, optical and opto-electronic components. Consequently careful precautions must be taken to prevent and reduce the risk of failure. In particular, an optical failure occurring on a specific fibre must not affect the system performances of the other fibres.

Low failure rates are obtained through the use of heavily screened components, close control of raw materials, robust and simple design, careful manufacturing process and thorough quality control.

It is quickly apparent that a test condition is required to accelerate the time to failure in a predictable and understandable way. It should also be recognized that a system includes a variety of different manufacturing processes and assembly procedures and each one should be tested. For both economical purpose and technical feasibility, the reliability requirements make necessary the use of accelerated tests.

In order to achieve the required reliability and to reduce accordingly the failure rate of the subsystems, redundant configurations are generally used. For example, redundant pump laser configurations are usually employed to ensure that the amplifier reliability target is met.

4.3 External fault

External faults usually occur in the cable sections. As a matter of fact, the main causes of failure are aggressions such as bottom fishing, fishing trawlers, ocean currents, geological events (earthquakes and volcanoes) and thermal failures due to overload. Nearly 90 percent of the failures are caused by fishing activities and damage from ship anchors. To protect the cable against these various factors, the wet plant can be buried in the shallow water except in rocky areas, where seabed conditions don't allow burial. Additionally, the cable route is selected to avoid as much as possible geological hazards (See Chapter 4).

In case of failure in the submerged section marine operations are necessary and a cable ship is mobilized for the repair. The section of damaged cable is cut, recovered and replaced with spares on board. The mean time to repair (MTTR) is estimated to be from 1 to 3 weeks depending on the fault location, the sea depth, the ship availability, the damage root cause, and the weather that can dramatically slow down the marine operations.

In order to minimize the impact on traffic of such faults, the overall network availability is increased through route diversity when possible. In the event of a fault in the wet plant leading to a loss of transmission, the traffic is usually rerouted onto a protection path.

Annex A

Statistical design for systems with line amplifiers

For a system with a small number of components, deterministic (or "worst case") design is useful, providing reasonable margins to the system. However, for a system with a large number of components, for example a multi-span, multichannel system, the margins obtained from deterministic designs may become unreasonably large. In that situation, network operators, as well as manufacturers, should consider the use of statistical design.

A.1 Generic methodology for the statistical design

System parameters (e.g. maximum attenuation or maximum chromatic dispersion of the link) are distinguished from element parameters (e.g. attenuation coefficient or dispersion coefficient of fibre bobbin product). System parameters are to be determined by the system design in which statistical properties of the element parameters are considered. Examples of the relationship between system and element parameters are shown in Table 7A-1.

Table 7A-1 – Relationship between system and element parameters

System parameter	Element parameter	Described in
Maximum attenuation	Fibre cable attenuation coefficient, transmitter output power, receiver sensitivity, power penalty, splice loss, connector loss	A.5 Statistical design of loss and gain
Maximum chromatic dispersion	Fibre dispersion coefficient, transmitter spectral width	A.6 Statistical design of chromatic dispersion
Maximum DGD	Cable PMD coefficient, power division between principal states of polarization, other elements in the link	A.7 Statistical design of DGD
Maximum output power	Cable attenuation coefficient, fibre zero-dispersion wavelength, fibre effective area, fibre non-linear coefficient, channel spacing	Not described

Supplement 39 to the ITU-T G-series of Recommendations proposes that only one system parameter in any particular system should be considered statistically. For example, in dispersion-limited systems, maximum chromatic dispersion is statistically considered, while the other system parameters are treated using the ordinary, worst-case design approach.

A.2 System outage probability

System outage probability is usually defined as the probability of BER exceeding 10^{-12}. However, since BER depends on many parameters (e.g. transmitter and receiver characteristics), it is difficult to refer to BER in generic statistical design. This clause, therefore, proposes to consider "system significance level" rather than "system outage probability", and to not refer to BER. Significance level is commonly used terminology in statistics for testing hypotheses.

Regarding each system parameter, system significance level is defined as the probability at which the system parameter will exceed a certain value *x*. Of course, system significance level is a function of *x*. For instance, system significance level of DGD is 4.2×10^{-5}, when *x* equals 3 times the average DGD value, as indicated in Recommendation ITU-T G.691. As another example, system significance level of maximum chromatic dispersion is 1.3×10^{-3}, when *x* equals the summation of the average value and 3σ (σ is standard deviation).

A.3 Probability threshold for system acceptance

Probability threshold for system acceptance (P_{th}) is defined as maximum affordable significance level of each system parameter. The probability threshold will depend on network operation scenario, and also the trade-off relationship between probability of exceeding the value and cost.

It should be noted that for some parameters considered here, P_{th} refers to the probability that the value is exceeded at the time the link is commissioned. For example, in the case of chromatic dispersion, a P_{th} value of 10^{-3} means it is expected that on average one in a thousand links will exceed the specified dispersion when commissioned. For other parameters, however, P_{th} refers to the probability that the value is exceeded at any particular time in the life of a link. An example of this is PMD where a P_{th} of 10^{-5} means that, at any instant, the probability of exceeding the maximum DGD is one in one hundred thousand.

Table 7A-2 contains some example values of P_{th} together with the equivalent values of the number of standard deviations away from the mean for Gaussian statistics and the equivalent maximum to mean ratio for the Maxwell distribution (PMD).

Table 7A-2 – Probability threshold for system acceptance

Probability threshold, P_{th}	**Gaussian: Standard deviations away from the mean (σ)**	**Maxwell: Ratio of maximum to mean (S)**
10^{-3}	3.1	2.5
10^{-5}	4.3	3.2
10^{-7}	5.2	3.7
10^{-9}	6.0	4.2

A.4 Design flow chart

The generic flow chart is depicted on the left-hand side of Figure 7A-1. An example of maximum chromatic dispersion is illustrated on the right-hand side of the same Figure.

A.5 Statistical design of loss

A concatenated link usually includes a number of spliced factory lengths of optical fibre cable. The requirements for factory lengths are given in the optical fibre and cable Recommendations of the ITU. The transmission parameters for concatenated links must take into account not only the performance of the individual cable lengths but also the statistics of concatenation.

Link attributes are affected by factors other than optical fibre cables such as splices, connectors, and installation. For the purpose of link attribute values estimation, typical values of optical fibre links are provided in an appendix of each of the fibre and cable Recommendations.

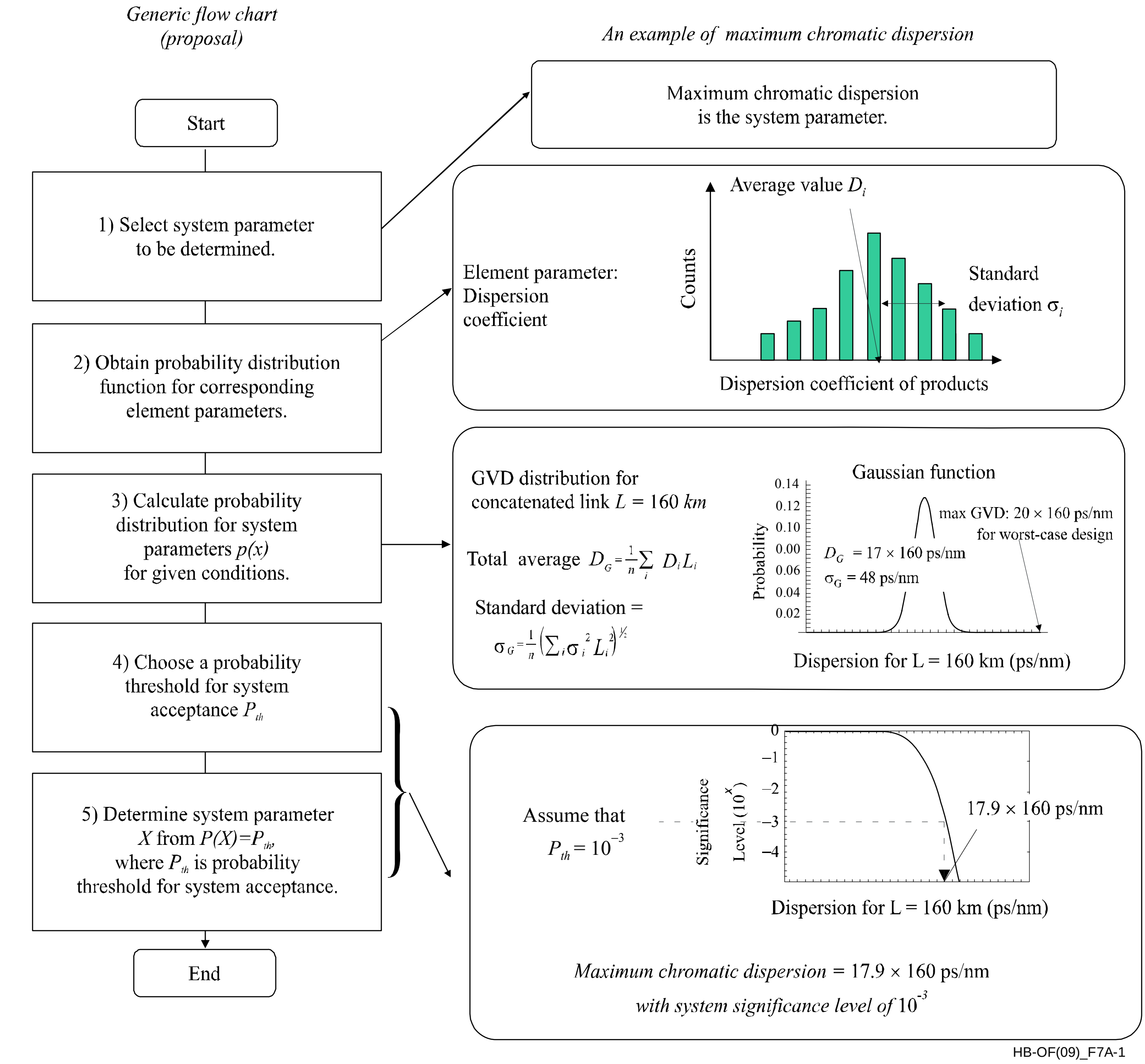


Figure 7A-1 – Generic flow chart and an example of maximum chromatic dispersion

1) Select the system parameter to be determined.

In the example of Figure 7A-1, the system parameter is maximum chromatic dispersion.

2) Obtain the probability distribution function for corresponding element parameters.

As can be seen in the histogram shown in the second right-hand box in Figure 7A-1, the average dispersion coefficient of fibre product i is assumed to be D_i, and standard deviation is σ_i.

3) Calculate the probability distribution for system parameter $p(x)$ for given conditions.

In this example, the given condition is a fibre link length of 160 km. The statistical distribution of the system parameter is obtained as the concatenation of the distributions of several fibre bobbins. From the central limit theorem, the distribution of concatenated links has a Gaussian profile. In this example, the total average of chromatic dispersion is $17 \times 160 = 2\,720$ ps/nm, while standard deviation is 48 ps/nm. It should be noted that, by using the ordinary worst-case design, maximum chromatic dispersion is $20 \times 160 = 3\,200$ ps/nm.

4) Choose a value for P_{th}, the probability threshold for system acceptance.

In this example, it is considered acceptable if one in a thousand links has a higher dispersion than the calculated value (P_{th} is 10^{-3}).

5) Determine system parameter X from equation $P(X) = P_{th}$, where P_{th} is the probability threshold for system acceptance.

In this example, maximum chromatic dispersion is determined to be $17.9 \times 160 = 2\,864$ ps/nm, assuming that P_{th} is 10^{-3}. Therefore, the dispersion requirement for the transmission system is relaxed by 336 ps/nm, compared to the worst-case system design.

The attenuation, A, of a link is given by:

$$A = \alpha L + \alpha_S x + a_C y \tag{7A-1}$$

where:

α: typical attenuation coefficient of the fibre cables in a link,

α_S: mean splice loss,

x: number of splices in a link,

α_C: mean loss of connectors,

y: number of connectors in a link (if provided),

L: link length.

A suitable margin should be allocated for future modifications of cable configurations (additional splices, extra cable lengths, ageing effects, temperature variations, etc.). The typical values found in an appendix of each of the fibre and cable Recommendations are for the attenuation coefficient of optical fibre links.

The combination of these attenuation contributors in combination with the system maximum attenuation value leads to a variation in the length of the spans. The span length is a targeted value for Recommendations such as ITU-T G.957 and ITU-T G.691, but may be exceeded up to the point where length is limited by chromatic dispersion.

The typical attenuation coefficient of the fibre, α, varies with wavelength, λ, due to a number of factors: Rayleigh scattering, water absorption, macrobending loss and microbending loss. For well-designed cables, the bending loss variation with wavelength can be negligible, but generally increases with wavelengths above 1 550 nm. For some cables, the microbending effect can, however, result in an elevated attenuation at higher wavelengths, which is called a bend edge. The Rayleigh scattering of ITU-T G.652 fibres is rather uniform across suppliers and time of manufacturing and follows a $1/\lambda^4$ relationship.

The peak water absorption wavelength is close to 1 383 nm and can be characterized roughly as a magnitude value multiplied with a distinctive curve around 1 383 nm. This peak can also be affected by hydrogen exposure and fibre hydrogen sensitivity. Over time, fibre manufacturers have learned to reduce the water absorption component, as well as the hydrogen sensitivity. Recommendation ITU-T Rec. G.652 includes two categories, ITU-T G.652.C and ITU-T G.652.D, for which the attenuation coefficient of the water peak in combination with hydrogen ageing is required to be less than or equal to the maximum value specified for the range 1 310 nm to 1 625 nm.

The attenuation values of some example ITU-T G.652 and ITU-T G.655 fibres are shown in Table 7A-3. The measurements included two 60 km lengths of 216 ITU-T G.655 fibres, and the same lengths of 55 ITU-T G.652 fibres.

The fitted attenuations values have been used to calculate attenuation statistics for both fibre types at the wavelengths covering the spectrum from 1 261 nm to 1 621 nm, which is the wavelength range of the CWDM systems (see Chapter 6). These calculations show that ITU-T G.655 fibres have on average 0.015-0.020 dB/km higher attenuation than ITU-T G.652 fibres in the wavelength range 1 261-1 341 nm, and 0.016-0.021 dB/km higher attenuation in the wavelength range 1 461-1 621 nm.

Figure 7A-2 illustrates the measurements of 308 links with ITU-T G.652 fibres, of 9 network operators, in the metro environment where the link length exceeded 20 km. These measurements have been made in the period of 2003 to 2005. (For further information see Recommendation ITU-T G.695 and the ITU-T G.65 x-series Recommendations).

Table 7A-3 – ITU-T G.655 and ITU-T G.652 fibre attenuation measurements

OTDR wavelength (nm)	ITU–T G.655 fibres				ITU–T G.652 fibres			
	Fitted attenuation (dB/km)		Measured values (dB/km)		Fitted attenuation (dB/km)		Measured values (dB/km)	
	Typical OH-model				OH-model			
	Average	Stdv	Average	Stdv	Average	Stdv	Average	Stdv
1241	0.443	0.007	0.439	0.007	0.423	0.009	0.42	0.011
1310	0.358	0.006	0.361	0.009	0.341	0.008	0.343	0.009
1383	0.412	0.042	0.413	0.043	0.51	0.227	0.508	0.224
1551	0.211	0.012	0.209	0.012	0.194	0.004	0.192	0.005
1621	0.227	0.016	0.23	0.017	0.207	0.006	0.209	0.006
1642	0.243	0.017	0.241	0.017	0.222	0.007	0.22	0.007
1650	0.25	0.017	–	–	0.229	0.008	–	–
1660	0.261	0.017	–	–	0.241	0.009	–	–
1670	0.274	0.017	–	–	0.254	0.011	–	–
1675	0.282	0.017	–	–	0.263	0.013	–	–

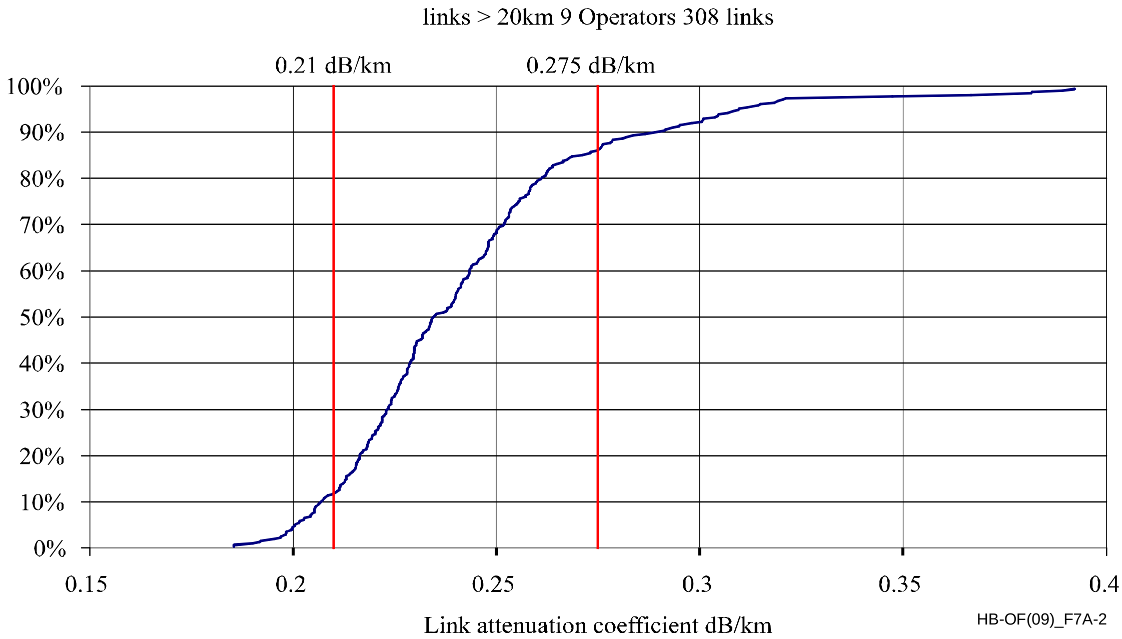


Figure 7A-2 – Probability of loss being met vs link 1 550 nm attenuation coefficient for links > 20 km

A.6 Statistical design of chromatic dispersion

When different components or fibres are combined, the chromatic dispersion of the combination is the total of the chromatic dispersion values of the individuals, on a wavelength-by-wavelength basis. The variation in the total dispersion of links will depend on the distributions of the products that are used in the links.

Some examples are given in the following for particular fibre and component types. These examples are not necessarily broadly representative.

The fibre chromatic dispersion coefficient, $D(\lambda)$, is measured as a function of wavelength λ.

The characterization methodology suitable for concatenation statistics for a single distribution, or for a combination of distributions, is to calculate the dispersion coefficient for each of the wavelengths in the range of the application – for each individual fibre segment. This creates a distribution of dispersion coefficient values for each wavelength. As an example, the distribution of a ITU-T G.655 fibre chromatic dispersion at 1 560 nm is shown in Figure 7A-3.

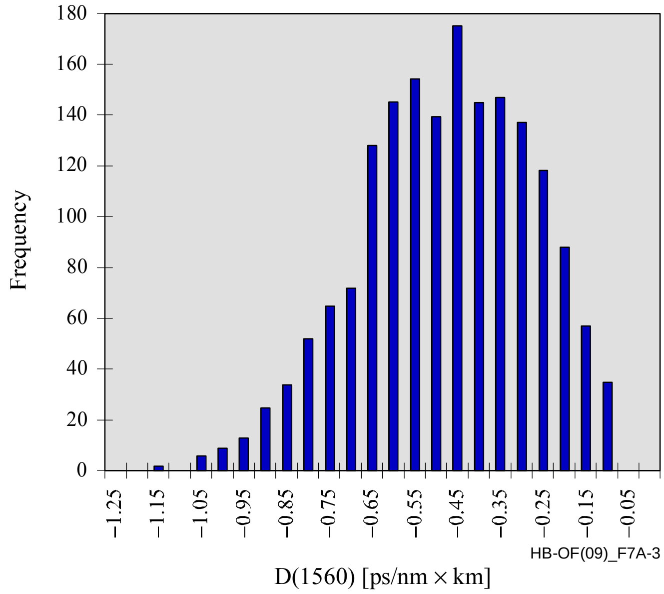


Figure 7A-3 – Histogram of dispersion coefficient values at 1 560 nm

As an application of the above method, the fibre statistics for chromatic dispersion coefficient (ps/nm · km) vs. wavelength (nm) are shown in Figures 7A-4 (dispersion values) and 7A-5 (standard deviation).

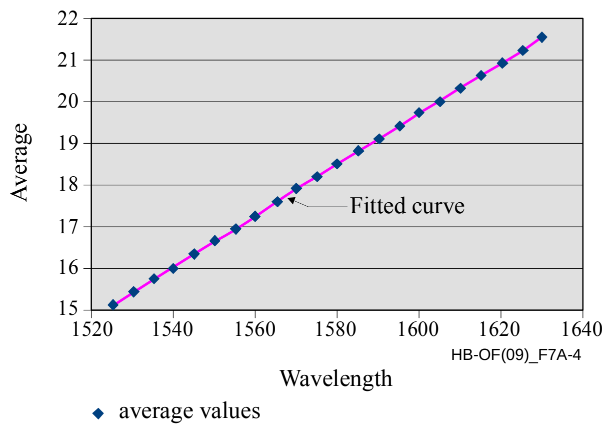


Figure 7A-4 – Average chromatic dispersion coefficient of G.652 fibre

The formula for the fitted line in Figure 7A-4 is:

$$\mu(\lambda) = -77.403 + 0.0607 \times \lambda \qquad \text{(ps/nm} \cdot \text{km)}$$

where λ is in nm.

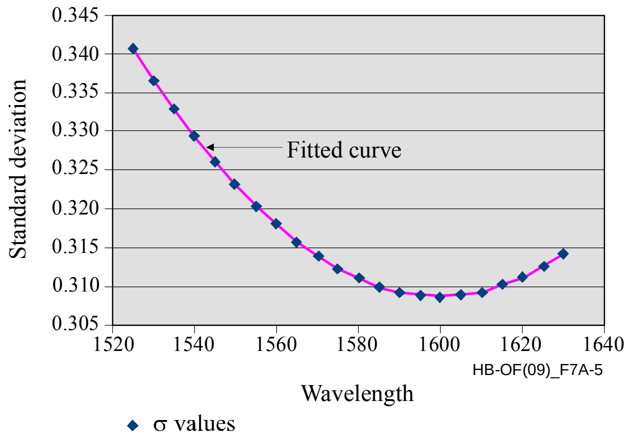


Figure 7A-5 – Standard deviation of chromatic dispersion coefficient of G.652 fibre

The formula for the fitted curve in Figure 7A-5 is:

$$\sigma(\lambda) = 15.013 - 18.384 \times 10^{-3} \times \lambda + 5.746 \times 10^{-6} \times \lambda^2 \qquad \text{(ps/nm} \cdot \text{km)}$$

In Figure 7A-6 and Figure 7A-7 the dispersion statistics of the DCFs (dispersion compensator fibres) are shown.

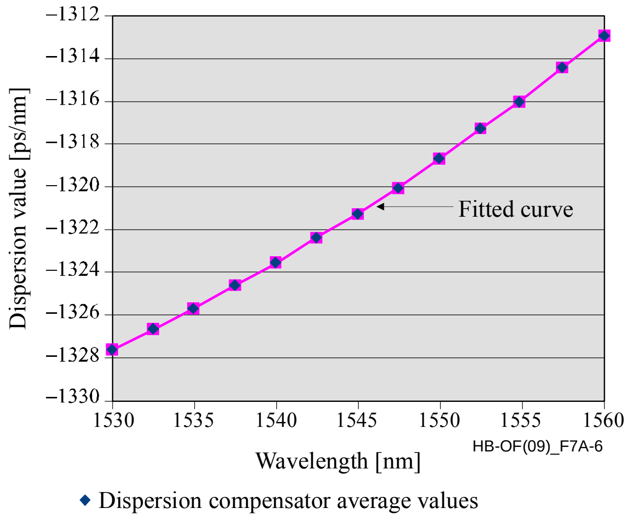


Figure 7A-6 – Dispersion compensator average values

The formula for the fitted curve in Figure 7A-6 is:

$$\mu(\lambda) = 8.010 \times 10^3 - 12.5698 \times \lambda + 4.227 \times 10^{-3} \times \lambda^2 \qquad \text{(ps/nm)}$$

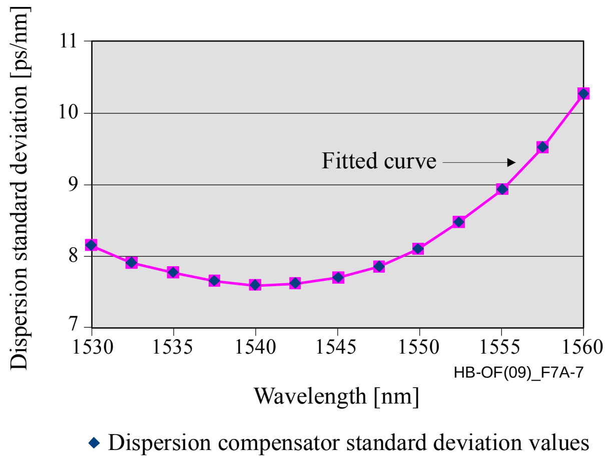


Figure 7A-7 – Dispersion compensator standard deviation values

The formula for the fitted curve in Figure 7A-7 is:

$$\sigma(\lambda) = 3.4612 \times 10^5 + 6.824 \times 10^2 \times \lambda - 0.4484 \times \lambda^2 + 9.818 \times 10^{-5} \times \lambda^3 \qquad \text{(ps/nm)}$$

Combining these statistics according to Supplement 39 of the ITU-T G-series of Recommendations, and using the link assumptions (400-km fibre, 10-km segments, 5 dispersion compensators), yields the results shown in Figure 7A-8.

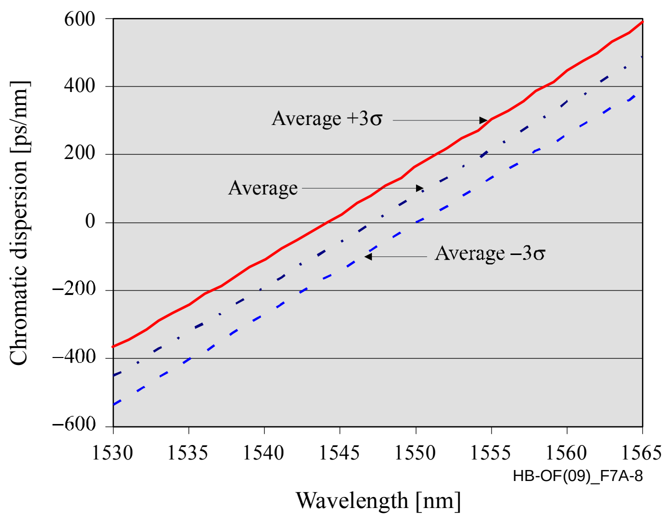


Figure 7A-8 – 3 σ limits for combined ITU-T G.652 fibre and compensators

For the C-band (1 530-1 565 nm) it appears from Figure 7A-8 that the chromatic dispersion of this compensated link is within ±600 ps/nm. In Recommendation ITU-T G.691, the limit for 10-Gbit/s transmission, with respect to chromatic dispersion alone, is indicated as approximately 1 000 ps/nm for transmitters and receivers that also conform to Recommendation ITU-T G.691.

A.7 Statistical design of DGD

The DGD varies randomly according to a Maxwell distribution characterized by the PMD value. As a consequence in § 7.2.3 DGD has already been dealt with the statistical approach.

Annex B

Example of design considerations for DWDM systems

This Annex presents some physical and technology limitations to the achievable link distances of DWDM optical transmission systems. For further in formation see Recommendation ITU-T G.696.1.

In § B.1, the fundamental limits due to ASE noise and PMD are discussed. This is followed in § B.2 with a discussion of other effects that limit the distances in practical systems and in § B.3, techniques to mitigate these effects are described. Finally, in § B.4, an example of the typical performance of currently available technology is given.

B.1 Enabling technologies and their limits

In this clause some of the fundamental constraints for the technological feasibility of DWDM applications are indicated.

It is assumed that the link optical attenuation is compensated for with optical amplifiers and the chromatic dispersion is compensated for with chromatic dispersion compensators.

ASE noise and PMD are the most important impairments that limit the capacity and transmission distance of DWDM applications.

The discussion in this § B.1 refers to NRZ line coding since this is commonly used in DWDM applications. Other line codings may give different results and might be more suitable in some cases (some alternatives to NRZ are discussed in § B.3).

B.1.1 ASE noise

The influence of ASE noise is essentially characterized by OSNR. As shown in § 2.2, the OSNR of a multichannel x span reference system with a booster amplifier, $x - 1$ line amplifiers and a pre-amplifier is given by:

$$\mathrm{OSNR} = P_{out} - L - NF_{eff} - 10 \cdot \log\left(x + \frac{10^{\frac{G_{BA}}{10}}}{10^{\frac{L}{10}}} \right) - 10 \cdot \log\left[\mathrm{h} \cdot \nu \cdot \nu_{\mathrm{r}}\right] \qquad (7B\text{-}1)$$

where:

- P_{out}: output power (per channel) of the booster and line amplifiers (dBm),
- L: span loss (dB) (which is assumed to be equal to the gain G_{LA} of the line amplifiers),
- G_{BA}: gain of the optical booster amplifier (dB),
- NF_{eff}: noise figure of the optical amplifier (dB),
- h: Planck's constant (in mJ * s to be consistent with P_{out} (dBm)),
- ν: optical frequency (Hz),
- ν_r: reference bandwidth (Hz, x – 1) is the total number of line amplifiers.

Equation 7B-1 takes into account the shot noise and the signal-spontaneous beat noise as the most dominant noise contributions. Other noise contributions might be considered in some cases.

This equation indicates that the ASE noise is accumulated from all $x + 1$ amplifiers.

For this reference system, the following main assumptions are made:

i) all optical amplifiers in the chain including booster and pre-amplifier have the same noise figure;

ii) the losses (per channel) of all spans are equal;

iii) the output powers (per channel) of the booster and line amps are the same.

For example, assuming the optical channel output power $P_{out} = 3$ dBm, the noise figure $NF_{eff} = 6.5$ dB, the reference bandwidth $\nu_r = 0.1$ nm and the span loss $L = 22$ dB, the solid curve shown in Figure 7B-1 is obtained.

For a 10 Gbit/s data rate, and assuming an OSNR limitation of 25 dB for a BER of 10^{-12} without FEC, a theoretical limiting distance of 5 spans is obtained.

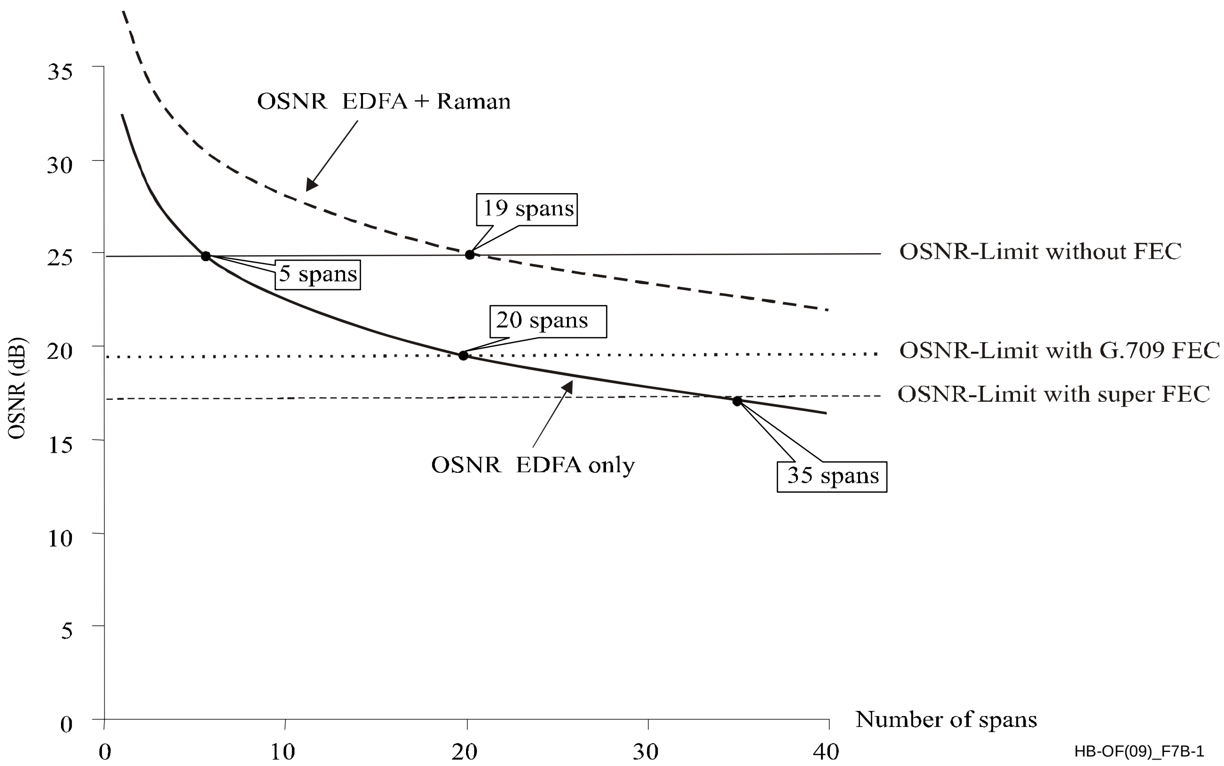


Figure 7B-1 – OSNR limits for a reference system, OSNR as a function of span number with and without Raman amplification

If one assumes the use of ITU-T G.709 FEC with a net coding gain of 5.6 dB, the limiting OSNR becomes 19.4 dB, which is reached at 20 spans.

Using stronger FEC, e.g. one of the schemes found in Recommendation ITU-T G.975.1, a net coding gain (NCG) of around 8 dB is feasible and the limiting OSNR becomes 17 dB, which is reached at 35 spans.

Distributed Raman amplification (DRA) is a further option to extend transmission distance. The OSNR improvement factor expected by DRA in backward pumping configuration can be calculated by the effective noise figure (NF_{eff}), which can be expressed by equation 7B-2.

$$NF_{eff} = 10 \cdot \log\left(\left(NF'_{LA} + \frac{P_{ASE,Raman}}{h \cdot \nu \cdot \nu_r}\right) \cdot \frac{1}{G'_{Raman}}\right) \tag{7B-2}$$

where:

NF'_{LA}: linear noise figure of the discrete line amplifier,

G'_{Raman}: linear gain of DRA,

$P_{ASE,Raman}$: ASE power resulting from DRA,

ν_r: reference bandwidth,

NF_{LA}: $10 \cdot \log (NF'_{LA})$ holds,

where:

NF_{LA}: noise figure of the discrete line amplifier (dB);

$P_{ASE,Raman}$ and $G_{Raman} = 10 \log \cdot (G'_{Raman})$ can be estimated analytically.

NF_{eff} as a function of Raman gain G_{Raman} is shown in Figure 7B-2.

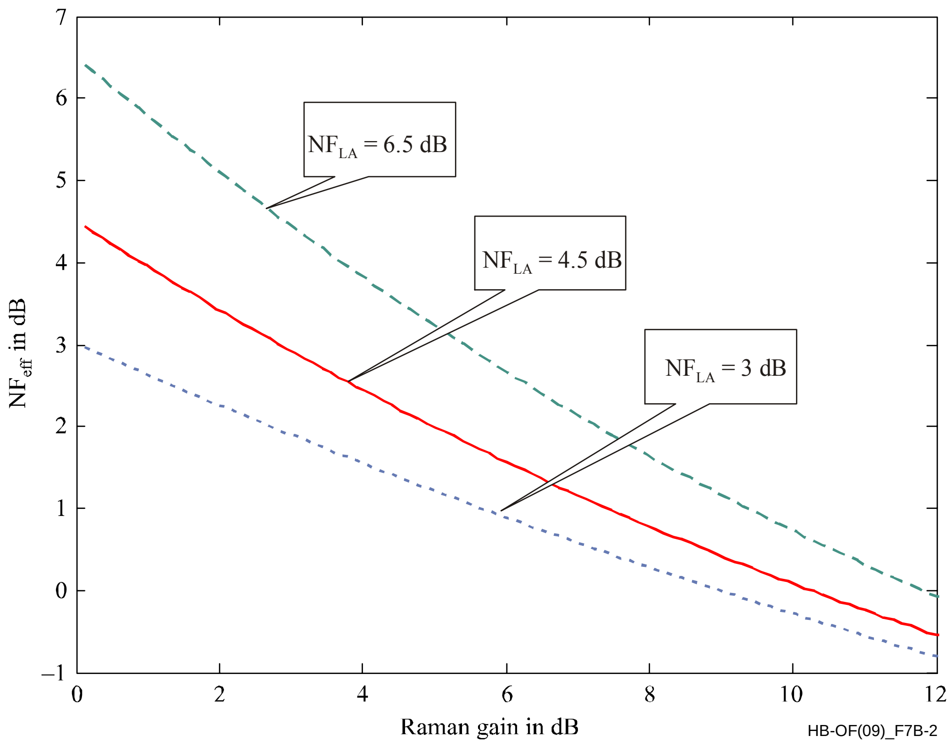


Figure 7B-2 – NF_{eff} as a function of Raman gain

Here, the following parameters are assumed: fibre length, 80 km; attenuation coefficient, 0.275 dB/km and 0.3 dB/km for signal and pump wavelength, respectively; effective area of fibre, 80 µm^2; and Raman gain coefficient, 3.1E-14.

The noise figures of the EDFA are 3 dB, 4.5 dB and 6.5 dB, respectively. The maximum transmission distance with Raman – EDFA combined amplifiers can be estimated by inserting NF_{eff} from equation 7B-2 in the OSNR equation 7B-1 and using $L = G_{Raman} + G_{LA}$ where again G_{LA} is the gain of the line amplifier in dB.

Assuming a Raman gain of approximately 9.3 dB and an EDFA noise figure of $NF_{LA} = 6.5$ dB, one obtains an effective noise figure of $NF_{eff} = 1$ dB, which gives the dashed curve shown in Figure 7B-1.

Now the theoretical limiting distance without FEC becomes 19 spans, and the addition of ITU-T G.709 FEC would allow a system with more than 40 spans.

B.1.2 PMD

The total PMD of a fibre link, with total length *L* and a PMD coefficient for the individual cable sections PMD_Q, is given by PMD = √ · PMD_Q. For a 10 Gbit/s NRZ interface, the total PMD should not exceed 10 ps (corresponding to an outage probability with "five nines" for a fibre induced maximum DGD = 30 ps). If the PMD coefficient PMD_Q value is not greater than 0.5 ps/km$^{1/2}$, this gives a total link length of 400 km; and with a maximum PMD coefficient $PMD_Q = 0.2$ ps/km$^{1/2}$, the total link length becomes 2 500 km, (Figure 7B-3).

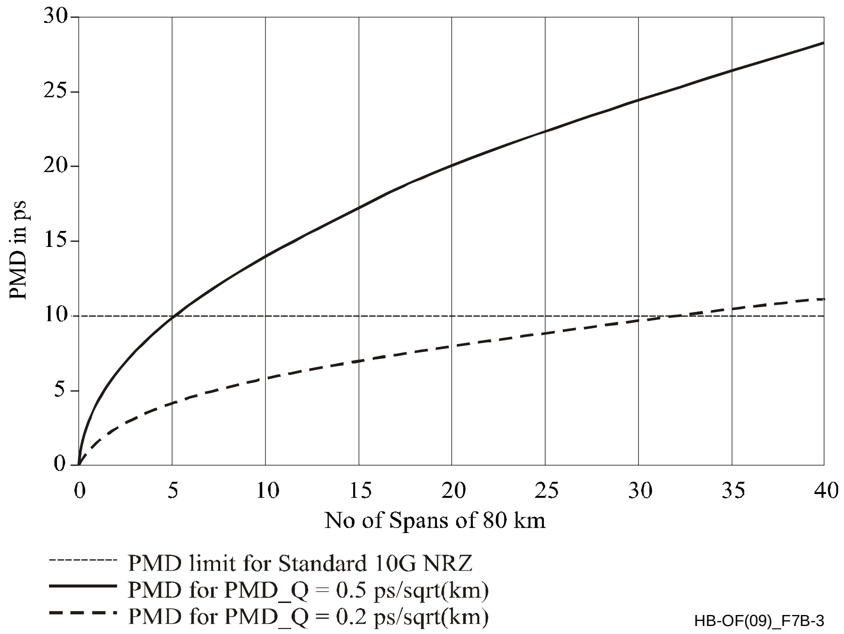


Figure 7B-3 – PMD vs distance for different PMD coefficients and PMD limit for 10 Gbit/s NRZ systems with 99.999% availability

Figure 7B-3 gives the guidance on maximum distance allowed according to the fibre's maximum PMD_Q for NRZ line coding based on its 1st-order DGD tolerance. This figure has not accounted for the PMD contribution from equipment.

A real system on a real fibre link should consider the PMD limit from the combined contribution of both fibre link and equipment which comprises all the nodes in a link.

In some circumstances, higher-order PMD should also be considered.

B.2 Other effects that limit transmission distance

The limiting link distances calculated in the previous clauses are the distances that might be achieved in ideal circumstances. There are, however, several effects in practical systems that reduce the maximum link length.

B.2.1 Accumulated gain ripples from EDFA cascading and tilt due to stimulated Raman effects

A real system in a real link needs to consider power divergence among channels due to accumulated gain ripple and stimulated Raman effects.

Technologies like gain flattening filters and dynamical gain/power equalization can be used to reduce the impact of such effects, but there will still be some impact, which will reduce the achievable distances to less than those shown in Figure 7B-1.

B.2.2 Non-uniform span length

The theoretical calculations above consider equal span lengths. For the discussion in this annex, a constant attenuation of 22 dB per span has been used. In real systems, the span lengths are usually not equal, actually depending on the real network topology and topographical constraints.

It is difficult to account for this "non-ideality" in a general manner, because, for the same system, longer spans mean an OSNR "debt" and shorter spans turn into an OSNR "credit".

The OSNR "debt" due to longer spans can be partially or completely compensated by increasing the output power of the amplifier preceding the span itself, provided that the increased power does not cause non-linear effects that cannot be tolerated without extra penalty.

Therefore, generally speaking, a link with longer spans may likely force the system to support a smaller number of spans, whereas a link with shorter spans may likely allow the system to support a larger number of spans. Given that this matter falls in the specific system design of the equipment vendor, it is simply mentioned here to give a more comprehensive view on these types of applications, without giving any details.

B.2.3 Optical non-linearity

Non-linear effects like self-phase modulation (SPM) and/or cross-phase modulation (XPM) accumulate over spans and become significant as the number of spans becomes large. Thus, non-linear penalty may not be ignored in a real link.

Higher channel power is good for OSNR, but is not necessarily good for BER. This is due to fibre non-linear effects.

Considering NRZ with average channel power of 3 dBm on ITU-T G.652 fibre (the same power assumed in Figure 7B-1), accumulated non-linear (SPM) phase, $\Phi_{NL} = \gamma P_{ch} L_{eff} N_{span}$ after 10 spans is close to 1 radian, and transmission is in a so-called "strong non-linear distortion" region where link distance may be non-linearity limited. Thus, the total link length could be much less than that predicted by Figure 7B-1, which is based on OSNR limits alone.

Some methods of mitigating these effects are discussed in § B.3.

B.2.4 Residual dispersion and dispersion tolerance

The curves in Figure 7B-1 assume that each channel in the WDM system is perfectly dispersion compensated. While dispersion compensation modules (DCMs) with an exactly inverse dispersion vs. wavelength slope to that of the fibre could be used, this is not usually the case and even then, higher order chromatic dispersion may need to be considered as the number of spans increases.

In addition to the mismatched slopes causing residual dispersion for some of the WDM channels, non-linear distortion can, if not mitigated, broaden the spectrum and thus reduce the dispersion tolerance after fibre transmission.

B.2.5 Accumulated PDL effects

Optical components such as WDM filters, VOAs or OAs exhibit finite polarization dependent loss (PDL) that may range from 0.1 to 0.3 dB per device or even more. PDL exerts stochastic intensity modulation on optical signals due to variations in the signal polarization with time. The induced power fluctuations are transformed at OAs under the effects of polarization dependent gain (PDG) into OSNR fluctuations.

In an extended long-haul system where many optical network elements are concatenated, the accumulated PDL can cause significant power fluctuation, which could degrade system performance and stability. However, the correlation between power fluctuations and OSNR variations may not necessarily be one-to-one. The power fluctuations may be too fast to be fully compensated by means of dynamic gain equalization.

B.3 Techniques used to mitigate impairments

There are several practical techniques which may improve the performance of a multi-span link, such as by choosing:

i) dynamic gain equalization;

ii) line coding;

iii) number of optical channels and their spacing;

iv) fibre types;

v) mixing different types of fibre within one span.

B.3.1 Dynamic gain equalization

In order to compensate for the gain tilt introduced by a long chain of amplifiers, the use of an integrated optical spectrum analyzer (OSA) or optical power monitor (OPM) and adjustable gain flattening filters can be used to ensure good equalization across all the channels of the DWDM aggregate signal.

B.3.2 Modulation format

Modulation formats other than NRZ can provide some advantages under certain circumstances.

As described in Supplement 39 to the ITU-T G-series of Recommendations, return to zero (RZ) line coded systems are significantly more tolerant to first-order PMD than NRZ systems. Also, modified RZ coding formats, such as phase-modulated RZ, can be additionally advantageous in terms of enhanced non-linear tolerance. These characteristics encourage the use of RZ line coding for very long link distances where PMD and non-linear effects are particularly significant.

On the other hand, RZ coding has (due to the broader bandwidth to be used) a potential drawback of being less spectrally efficient compared to NRZ (see Supplement 39 to the ITU-T G-series of Recommendations) and is usually more sensitive to residual chromatic dispersion than NRZ. For this reason, systems that adopt RZ modulation format require a more precise characterization and compensation of the dispersion associated with the link.

Line codes other than NRZ and RZ can also be applied to DWDM systems, each of them having benefits and drawbacks. In particular, for very long link lengths and ultra-high capacity DWDM signals, the choice of a particular line code depends on the individual optimal system design (see Supplement 39 to the ITU-T G-series of Recommendations).

B.3.3 Number of optical channels and their spacing

As a general trend, the maximum number of DWDM channels giving acceptable performance will tend to decrease with increasing link length and/or decreasing optical channel spacing, due to the increased impact of optical non-linearity.

B.3.4 Fibre types

One fibre type may have an advantage or disadvantage compared with another under certain conditions. In the C-band for example, ITU-T G.652 fibre has larger chromatic dispersion than ITU-T G.655 fibre or ITU-T G.653 fibre and, therefore, it may introduce less non-linear effects. However, Raman gain strongly depends on fibre type and ITU-T G.652 fibres, due to their large mode field diameters, show a smaller Raman gain for a given pump power than other fibres.

B.3.5 Mixing different types of fibre within one span

One technique that can be used to mitigate the effects of fibre non-linearity is to deliberately mix fibres with different characteristics within a single span. For example, a span containing alternating fibres with positive and negative dispersion results in a span with a high value of local dispersion (desirable to reduce the effects of XPM and four wave mixing) but a low net dispersion (which reduces the dispersion compensation requirements).

In cases where a link has different fibre types in different spans, the launch power may have to be different in each span depending on the fibre types of the first 20 km of each span, in order to minimize the non-linear distortion.

B.4 Practical example

From the preceding discussion, it is clear that the number of spans that can be practically achieved for a given channel spacing, operating wavelength region, bit rate and span loss depends upon many system design choices such as which FEC scheme to employ, whether to use dynamic gain equalization or whether to use Raman amplification, etc.

However, as an example of available technology, a system with the following attributes:

– Minimum channel spacing: 100 GHz;

– Operating wavelength region: C-band (1 530 to 1 565 nm);

– Client class: 10G;

– Span loss: 22 dB;

– ITU-T G.652 fibre type;

– ITU-T G.709 FEC,

can currently be cost effectively provided up to a maximum of about 15 spans.

Annex C

Example of margin calculation for the submarine systems

C.1 Systems margins

A submarine system typically has a design life of 25 years. It is subject to repair and ageing. The design life requires some provisional margins to be satisfied. These margins are called segment margins.

C.1.1 Impairments due to repair operations

After the submarine line lay, each cable repair requires the addition of some extra cable. This additional cable leads to a span loss enhancement and, consequently, to a Q-factor degradation.

The repair operation margin is evaluated by estimating the total number of repairs required during the system life. Usually the following scenario is used:

- land cable repair: 1 repair every 4 km with a minimum of 2 repairs,
- shallow water repair: 1 repair every 15 km with a minimum of 5 repairs,
- deep water repair: 1 repair every 1 000 km.

During a repair operation, an additional length of spare cable must be added to the system in order to keep the tensile load carried by the cable below the required values. This extra-length of spare cable depends on the sea depth at the repair location. Usually a value between 1.5 and 2.5 times the sea depth is used. To calculate the margin required for repair operations, the total additional cable length is evaluated in the worst case when all estimated repairs are added. Another Q-factor is calculated, with the sum of the total initial line length and the maximum extra cable added by repairs. The difference between the two Q-factors corresponds to the repairs allocation margin.

C.1.2 Impairments due to equipments ageing

The impairment due to the equipments ageing is mainly due to the fibre. As a matter of fact, its attenuation will slowly increase due to physical effects related to the environment. Two of them are usually taken into account:

- Hydrogen effects in the fibre: the degradation is usually approximated by an additional loss after 25 years of around 0.003 dB/km.
- Radiation effects: optical fibres are loss sensitive to high energy radiation (gamma rays) whose origins may be related to sediments, sea water or artificial sources (waste site). The loss increase is estimated to be lower than 0.002 dB/km after 25 years.

A Q-factor is calculated with these additional losses and compared to the mean Q value in order to obtain the margin value required for equipments ageing.

C.1.3 Impairments due to the foreseen faults of some components

Due to the cost and complexity of marine operations to replace or repair submerged equipment, the most sensitive components are redundant, in order to avoid interventions as much as possible. The major faults to take into account are the repeater pump failures. Pump redundancy avoids an output power shutdown in the case of a pump failure but such an incident will always induce an output power and noise figure degradation leading to a Q-factor decrease.

The additional margin required to take this into account depends on the reliability of the pump and the redundancy setup.

C.1.4 Unallocated margin

Unallocated margin is residual margin after taking into account all repair margins at the end of life condition. This margin can be required most of the time in order to be more confident with the system or to keep margin for an eventual non forecasted upgrade of the system.

CHAPTER 8

OPTICAL SYSTEMS APPLICATIONS

Introduction

This Chapter deals with the applications of the optical systems in the various parts of the Optical Transport Network with the exclusion of the optical access network which is described in Chapter 9.

Clauses 1, 2 and 3 cover general aspects of these applications. The other clauses are devoted to the various specific applications: intra-office (clause 4), metro access networks (clause 5), metro core networks (clause 6), backbone networks (clause 7) and submarine systems (clause 8).

At the end of the Chapter, a short reference is made in clause 9 to the wavelength switched optical networks (WSONs), considering that the present optical transport networks, with an ever decreasing number of O/E/O conversions within their boundaries, are evolving towards such optically transparent networks.

1 The Optical transport network

Optical networks are used to connect a large group of users spread over a geographical area. Optical networks can be subdivided in access networks, metropolitan access networks (or metropolitan networks), metropolitan core networks (or regional networks) and long-haul networks (or backbone networks) depending on the area they cover (Figure 8-1). All these types of networks can benefit in general from the optical transmission technologies and in particular of the WDM technologies.

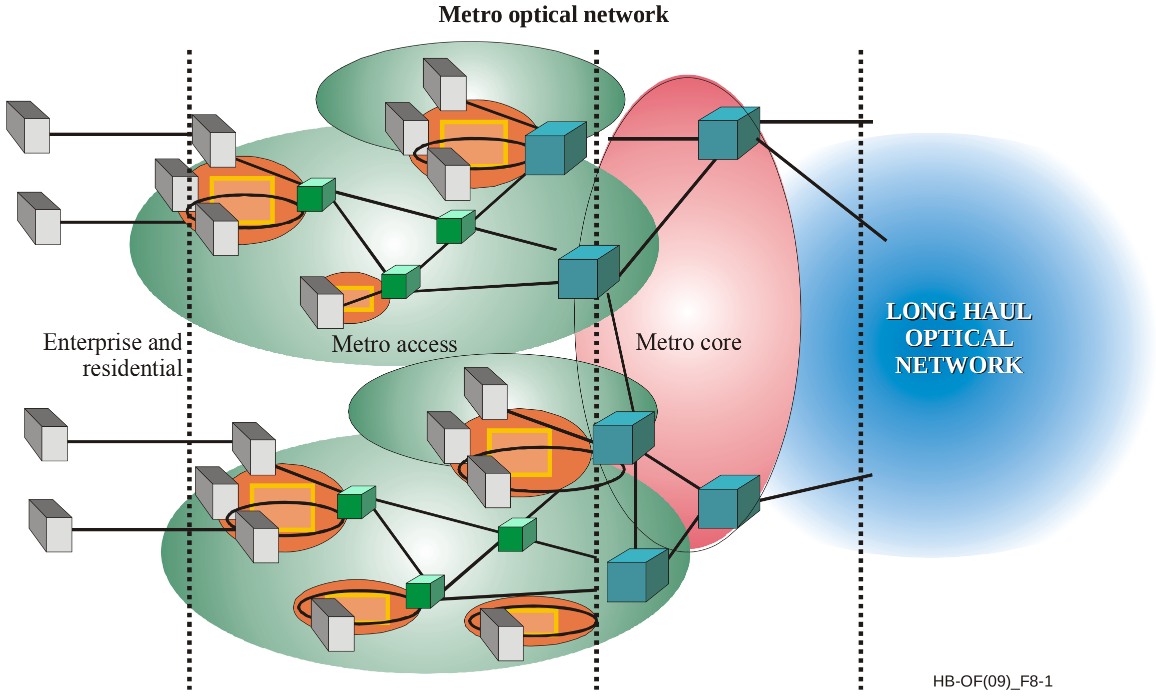


Figure 8-1 – Example of an optical network

An optical transport network (OTN) is composed of a set of optical network elements (ONEs) connected by optical fibre links, able to provide functionality of transport, multiplexing, routing, management, supervision and survivability of optical channels carrying client signals, according to the requirements given in Recommendation ITU-T G.872.

2 Optical network topologies

(For further information see Supplement 39 to the ITU-T G-series of Recommendations).

Recommendations ITU-T G.692, ITU-T G.693 and ITU-T G.959.1 currently concern point-to-point transmission systems, while Recommendations ITU-T G.695, ITU-T G.698.1 and ITU-T G.698.2 include more complex arrangements involving an optical add/drop function (bus structure). Recommendation ITU-T G.983.x and the ITU-T G.984 x-series of Recommendations cover a point-to-multipoint topology for optical access networks (see Chapter 9).

A point-to-multipoint topology is commonly used for access networks, while a ring topology is most practical for metro networks. Backbone nodes are usually interconnected by point-to-point WDM lines in a mesh topology.

In this clause, generic descriptions of typical examples of these network topologies are shown for the purpose of clarification.

2.1 Point-to-point links

The representation of a point-to-point DWDM link is shown in Figure 8-2. Light of *n* WDM channels is carried by one output fibre of a multichannel transmitter (M-Tx). This optical signal passes transmission sections with alternating fibre pieces and optical amplifiers before entering a multichannel receiver (M-Rx).

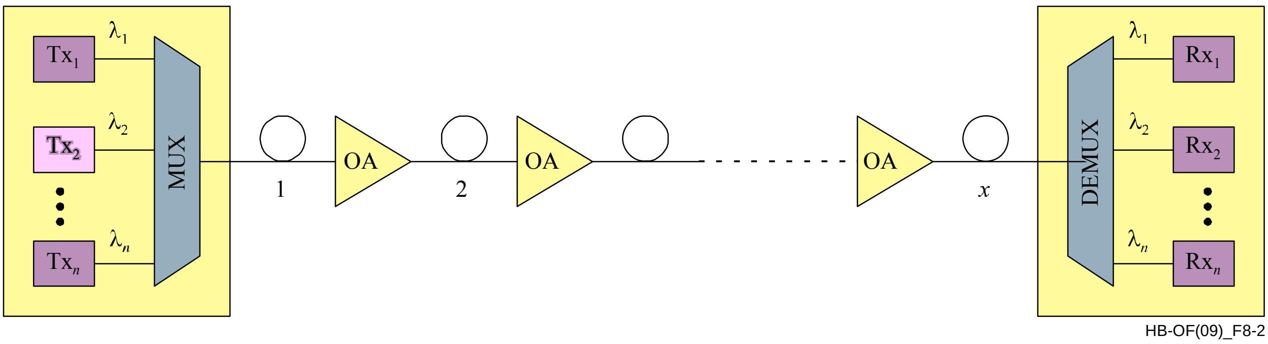


Figure 8-2 – Example of a WDM point-to-point link

Point-to-point links constitute the simplest kind of lightwave systems. Their role is to transport information available in the form of a digital bit stream, from one place to another. The link length may vary from a few kilometres to thousands of kilometres, depending on the specific application. For example, optical links are used to connect different equipment inside a building, or between two buildings placed a short distance apart. The low attenuation and wide bandwidth of optical fibres are not of primary importance for such links. Fibres are used mainly because of their other advantages, such as immunity to electromagnetic interference. The situation is different for lightwave systems, which are used for high speed transmission across continents with a link length of thousands of kilometres. Low attenuation and large bandwidths of optical fibres are important factors in transoceanic systems from the point of view of reducing the overall cost per unit transmission capacity.

When the link length exceeds a certain value, depending on the operating wavelength, it becomes necessary to compensate for fibre attenuation, as the signal would otherwise become too weak to be detected correctly. Fibre attenuation can be compensated by using optical amplifiers. Amplifiers are especially valuable for WDM systems as they can amplify many channels simultaneously.

Optical amplifiers solve the attenuation problem, but they add noise and worsen the impact of fibre dispersion and non-linearity because signal degradation continues to accumulate over multiple amplification sections. Indeed, periodically amplified systems are often limited by fibre dispersion, unless fibre compensation techniques are used. Most terrestrial systems employ dispersion compensation, but still place a 3R regenerator after a certain number of optical amplification sections in order to reset the accumulation of other impairments.

The spacing (L) between optical amplifiers (repeater spacing) is a major design parameter, because the system cost reduces as the repeater spacing increases. The BL product (where B is the signal bit rate) is often used as a measure of the system performance for point-to-point links. The achievable BL product depends on the signal wavelength, since both fibre attenuation and dispersion are wavelength dependent.

Point-to-point systems can be connected in a mesh structure.

2.2 Bus structures

The representation of a bus structure is shown in Figure 8-3.

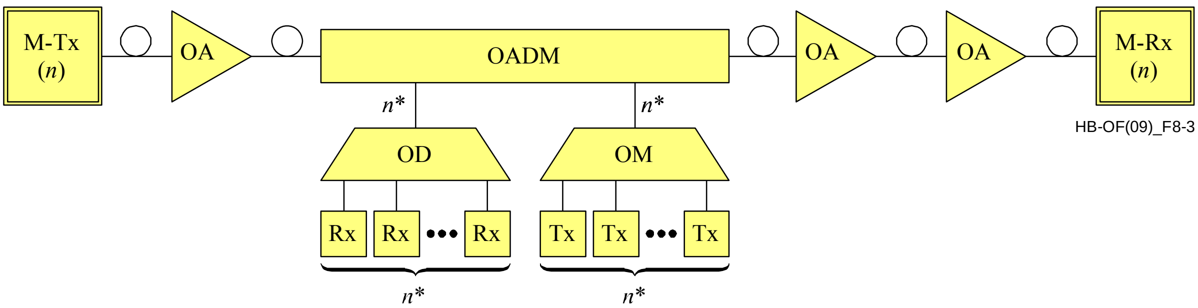


Figure 8-3 – Example of a bus structure with optical amplifiers and one OADM

A number (n) of WDM channels emitted from the M-Tx enters the OADM. A subset (n^*) of WDM channels is dropped and added by the OADM. The number n^* of dropped and added channels may range between 0 and n.

When $n^* = n$, all WDM channels are dropped and added. If $n^* = 0$, then no channel is added or dropped, i.e. the OADM is just a through-way network element. This scheme can be generalized by incorporating a sequence of optical amplifiers and optical add/drop multiplexers (OADMs).

2.3 Point-to-multipoint links

Optical networks using a passive coupler (optical branching component) are often called passive optical networks (PONs) because they avoid active switching. PONs have the potential for bringing optical fibres to the home (or to the curb). A PON structure is shown in Figure 8-4. For further information on the PONs see Chapter 9.

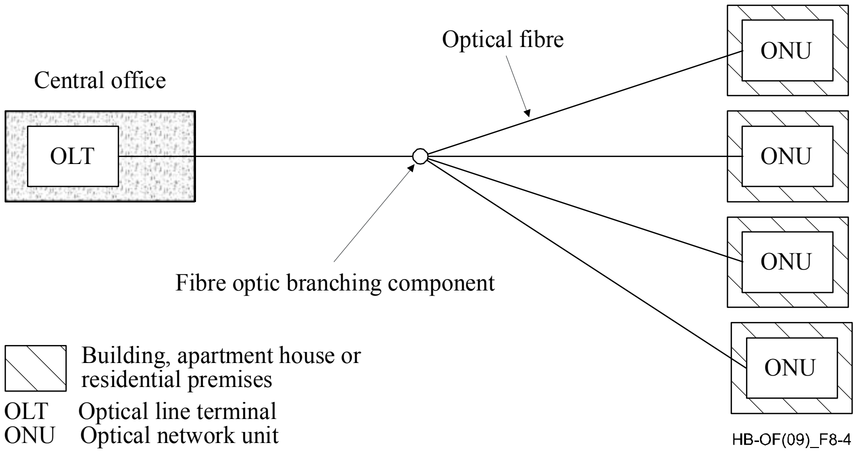


Figure 8-4 – Example of a point-to-multipoint structure

3 Classification of optical systems applications

In ITU-T Recommendations the optical systems are classified by their network application as:

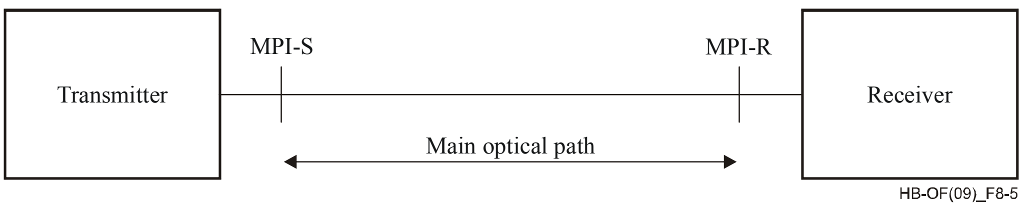
- intra-office systems;
- metro access (metro) systems;
- metro-core (regional) systems;
- long-haul (backbone) systems;
- repeaterless and repeatered submarine systems.

Moreover single-span systems are classified on the basis of their length as: intra-office (< 25 km), short-haul (40 km), long-haul (80 km), very long-haul (120 km) and ultra long-haul (160 km). The last three lengths are intended for system operating at 1 550 nm.

4 Intra-office systems

Intra-office systems are specified in Recommendations ITU-T G.693 and ITU-T G.959.1, which provide optical interface specifications to enable transverse (multivendor) compatibility of nominal 10 Gbit/s and 40 Gbit/s aggregate for link distances up to 2 km, per Recommendation ITU-T G.693 and up to 25 km, per Recommendation ITU-T G.959.1 over ITU-T G.652, ITU-T G.653 and ITU-T G.655 fibres.

Figure 8-5 illustrates a system of this type and shows the reference points used to specify optical interface parameters.



Note – The main optical path includes fibre and connectors, and may include other passive optical devices such as photonic cross-connects.

Figure 8-5 – Optical link example showing reference points

The black-box approach is used and, therefore, parameters are specified for the transmitter at point MPI-S, for the receiver at point MPI-R, and for the main optical path between points MPI-S and MPI-R.

The main optical path for some intra-office applications may include passive optical devices, e.g. photonic cross-connects (PXCs), which introduce significant attenuation.

For applications up to 2 km, total attenuation of the main optical path will, in general, be dominated by the loss of the passive optical devices rather than by fibre loss itself. In this case values of maximum attenuation may not be simply inferred from the target distances of applications.

Attenuation categories are used to distinguish among applications that have the same source, fibre type and target distance, and are intended for the same signal class, but have different values of maximum attenuation.

In particular, intra-office systems specified in Recommendation ITU-T G.693 refer to:

i) target distances: 0.6 km and 2 km (main optical path);

ii) highest class of optical tributary signal supported: NRZ 10G and NRZ 40G;

iii) maximum attenuation categories of the main optical path: 4 dB, 6 dB, 12 dB, 16 dB;

iv) source and fibre type: 1310 nm sources on ITU-T G.652 fibre, 1550 nm sources on ITU-T G.652 fibre, 1 550 nm sources on ITU-T G.653 fibre, 1550 nm sources on ITU-T G.655 fibre.

Some applications require FEC (forward error correction) bytes as specified in Recommendation ITU-T G.709 to be transmitted.

The application codes specified in Recommendation ITU-T G.693 are shown in Table 8-1 for single-channel systems. Those of Recommendation ITU-T G.959.1 for multichannel systems are in Table 8-2.

Table 8-1 – Application codes for single-channel systems specified in Recommendation ITU-T G.693

Target distance	**0.6 km**			**2 km**					
Attenuation category	4 dB	12 dB		4 dB	6 dB		12 dB		16 dB
Source nominal wavelength	1 310 nm	1 310 nm	1 550 nm	1 310 nm	1 310 nm	1 550 nm	1 310 nm	1 550 nm	1 550 nm
Type of fibre	ITU-T G.652	ITU-T G.652	ITU-T G.652 ITU-T G.653 ITU-T G.655	ITU-T G.652	ITU-T G.652	ITU-T G.652 ITU-T G.653 ITU-T G.655	ITU-T G.652	ITU-T G.652 ITU-T G.653 ITU-T G.655	ITU-T G.652 ITU-T G.653 ITU-T G.655
Application code signal class NRZ 10G	Yes	Yes	Yes	Yes	–	Yes	–	–	–
Application code signal class NRZ 40G	–	–	–	–	Yes	Yes	Yes	Yes	Yes

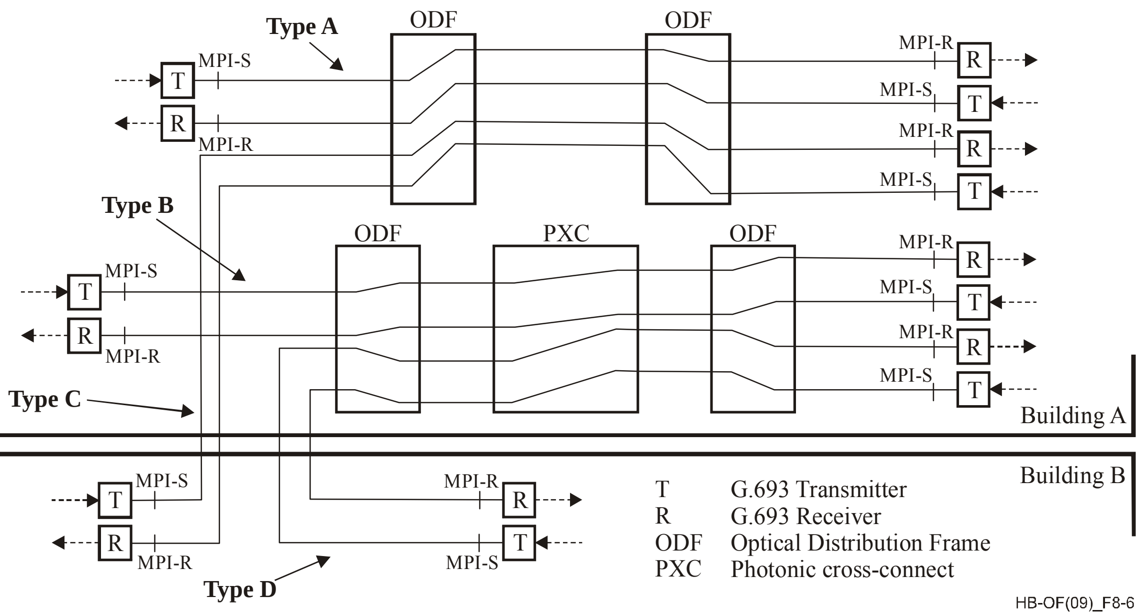
Note – "Yes" means that this application code is specified in Recommendation ITU-T G.693.

Table 8-2 – Application codes for multichannel systems specified in Recommendation ITU-T G.959.1

Application	Intra-office		
Source nominal wavelength (nm)	1550		
Type of fibre	G.652	G.653	G.655
Target distance (km)	20	2	20
Application code signal class NRZ 2.5G	–	–	–
Application code signal class NRZ 10G	Yes 16/32 channels	Yes 16 channels	Yes 16/32 channels

Note – "Yes" means that this application code is specified in Recommendation ITU-T G.959.1.

Figure 8-6 shows a system configuration with different combinations of attenuation category and target distance, corresponding to some ITU-T G.693 application codes.



Interface	Attenuation Category(s)	Target Distance
Type A	R (4 dB)	0.6km
Type B	M (12 dB)	0.6km
Type C	R (4 dB) or L (6 dB)	2km
Type D	M (12 dB) or H (16 dB)	2km

Figure 8-6 – Examples of system configurations using applications defined in Recommendation ITU-T G.693

The figure illustrates that, when selecting an application, attenuation category is determined by the devices in the main optical path, e.g. whether or not a PXC is included, while target distance is determined by the distance between the interconnected equipment.

Thus, for the choice of the most suitable application code, it is necessary to know the length of the intra office link, the bit rate of the signal, the type of fibre and the total loss of the network elements (e.g. ODF, PXC, connectors) placed in the link.

5 Metro access optical networks

CWDM or DWDM systems without line optical amplifiers are commonly used in metro access optical networks to cover distances up to about 80 km.

5.1 CWDM optical systems

Coarse wavelength division multiplexing (CWDM) systems are considered as a cheaper and simpler alternative to DWDM systems for metro access network applications. Since CWDM systems have wide channel spacing (20 nm), they do not require precise wavelength control for transmitter lasers. Thus, cost-effective non-cooled lasers as well as lower-cost passive components may be used for CWDM systems. On the other hand, the maximum number of optical channels in a CWDM system is lower than that of DWDM systems.

The specifications for CWDM systems in Recommendation ITU-T G.695 enable transversely (multi-vendor) compatible interfaces. Applications are defined using two different methods, one using multi channel interface parameters (black-box approach), and the other using single-channel interface parameters (black-link approach), (see Chapter 6). Both linear and ring structures as well as unidirectional and bidirectional applications are specified.

Figure 8-7 shows an example of a CWDM ring network including two or more OADMs. A set of reference points for a unidirectional ring "black-link" approach are described with single-channel connection (S_S and R_S) between transmitters (Tx) and receivers (Rx).

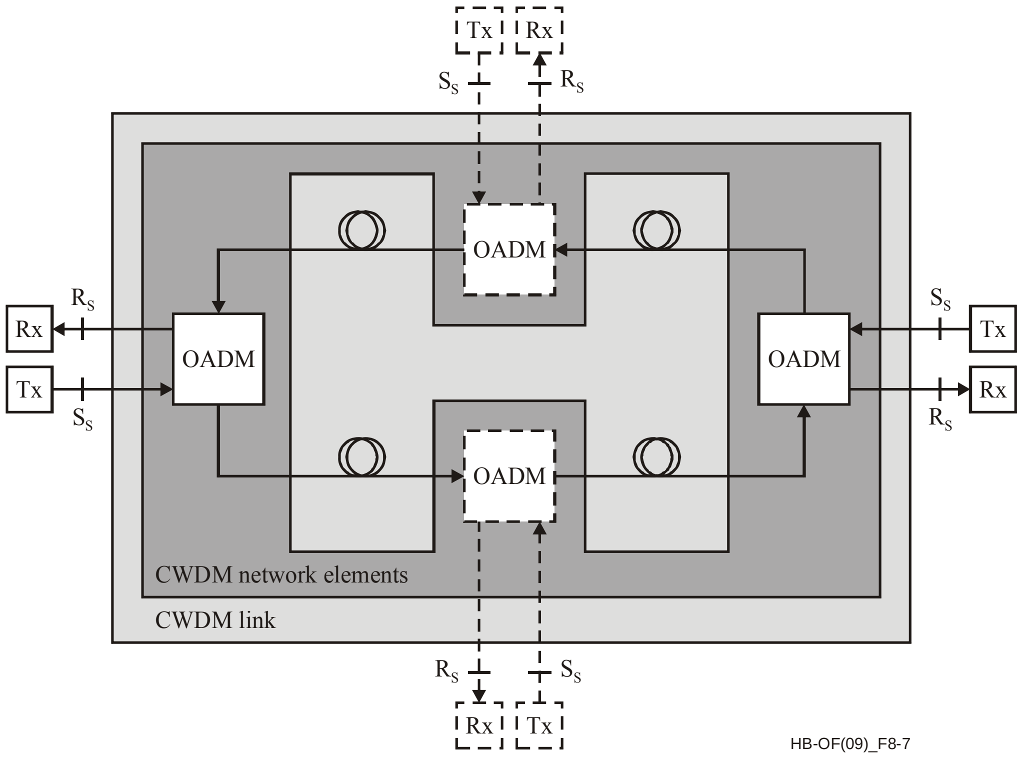


Figure 8-7 – Reference points for a unidirectional ring with "black-link" approach

Recommendation ITU-T G.695 defines optical interface parameter values without line amplifiers. In particular, Recommendation ITU-T G.695 describes CWDM optical line systems that include the following features:

i) target distances ranging from 20 km to 90 km;

ii) maximum number of channels up to 16 with a channel spacing of 20 nm, as specified in Recommendation ITU-T G.694.2 (see Chapter 6);

iii) single channel bit rate of NRZ 1.25 Gbit/s and 2.5 Gbit/s.

The specified application codes are shown in Table 8-3.

The maximum number of "express" OADMs in the link is constrained by several parameters, including maximum channel insertion loss, maximum optical multiplexer insertion loss, maximum optical demultiplexer insertion loss, numbers of connectors and their insertion loss, attenuation coefficient of the fibre, insertion loss of the OADM. An express OADM is one through which the wavelength of interest passes without being added or dropped.

As a matter of fact, the optical path from point S_S to R_S includes the optical path and a number of other network elements (NEs). In the case of ring black-link applications, the NEs include an OM, an OD and all of the OADMs that are traversed by the path from S_S to R_S being considered. The total insertion loss and the total chromatic dispersion of the CWDM network elements and of the optical path must not exceed the values specified for the optical path from point S_S to R_S.

The total loss of the path from S_S to R_S must be set between the minimum channel insertion loss and the maximum channel insertion loss described in the application code being used for the path. Therefore:

$$IL_{min} \le IL_{total} \le IL_{max}$$

where:

IL_{min}: minimum channel insertion loss for the application code,

IL_{max}: maximum channel insertion loss for the application code,

and:

$$IL_{total} = IL_{OM} + N_{OADM}\ IL_{OADM} + IL_{OD} + N_{con}\ IL_{con} + \alpha \bullet L$$

where:

IL_{OM}: OM insertion loss or OADM add loss at point S_S for the wavelength being used from S_S to R_S

N_{OADM}: number of express OADMs

IL_{OADM}: express OADM insertion loss for the wavelength being used from S_S to R_S

IL_{OD}: OD insertion loss or OADM drop loss at point R_S for the wavelength being used from S_S to R_S

N_{con}: number of connectors between S_S and R_S

IL_{con}: connector insertion loss

α: attenuation coefficient of the fibre (dB/km) for the wavelength being used from S_S to R_S

L: total length of fibre between S_S and R_S.

An express OADM is one through which the wavelength of interest passes without being added or dropped. The maximum number of express OADMs in a path between S_S and R_S is therefore given by:

$$N_{OADM} = \left\lfloor \frac{IL_{max} - IL_{OM} - IL_{OD} - N_{con} IL_{con} - \alpha L}{IL_{OADM}} \right\rfloor$$

where the square brackets express the floor function, which generates the largest integer less than or equal to the value of the expression in the brackets.

Table 8-3 – Application codes for CWDM systems specified in Recommendation ITU-T G.695

Application	4-channel unidirectional						4-channel bidirectional			8-channel unid.			12-channel unid.			16-channel unid.		
	Short-haul			Long-haul			Short-haul	Long-haul		Short-haul	Long-haul		Short-haul	Long-haul		Short-haul	Long-haul	
Type of fibre	ITU-T G.652	ITU-T G.653	ITU-T G.655	ITU-T G.652	ITU-T G.653	ITU-T G.655	ITU-T G.652	ITU-T G.652	ITU-T G.653	ITU-T G.652	ITU-T G.652	ITU-T G.653	ITU-T G.652	ITU-T G.652	ITU-T G.653	ITU-T G.652	ITU-T G.652	ITU-T G.653
Signal class NRZ 1.25G	–	–	–	–	–	–	–	Yes	Yes	–	Yes	Yes	–	Yes	–	–	–	–
Signal class NRZ 2.5G	Yes	Yes	Yes	Yes	Yes	Yes	–	Yes	Yes	Yes	Yes	Yes	–	Yes	–	Yes	Yes	–

Note – "Yes" means that an application code exists in Recommendation ITU-T G.695.

The evaluation of the maximum number of OADMs must be done for each S_S to R_S path in the network so that the maximum number of OADMs is not exceeded for any S_S to R_S path. This is quite simple for networks where all of the paths share a common hub (Figure 8-8), but becomes more complicated as the path topology becomes more complex (Figure 8-9).

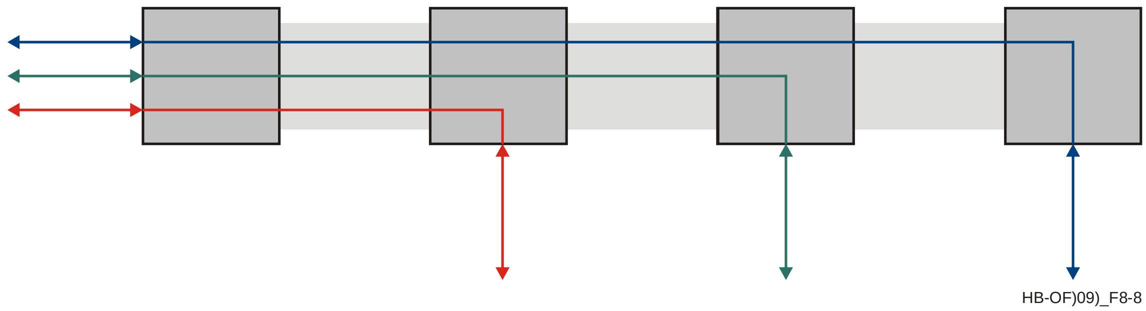


Figure 8-8 – Simple example of linear black-link topology

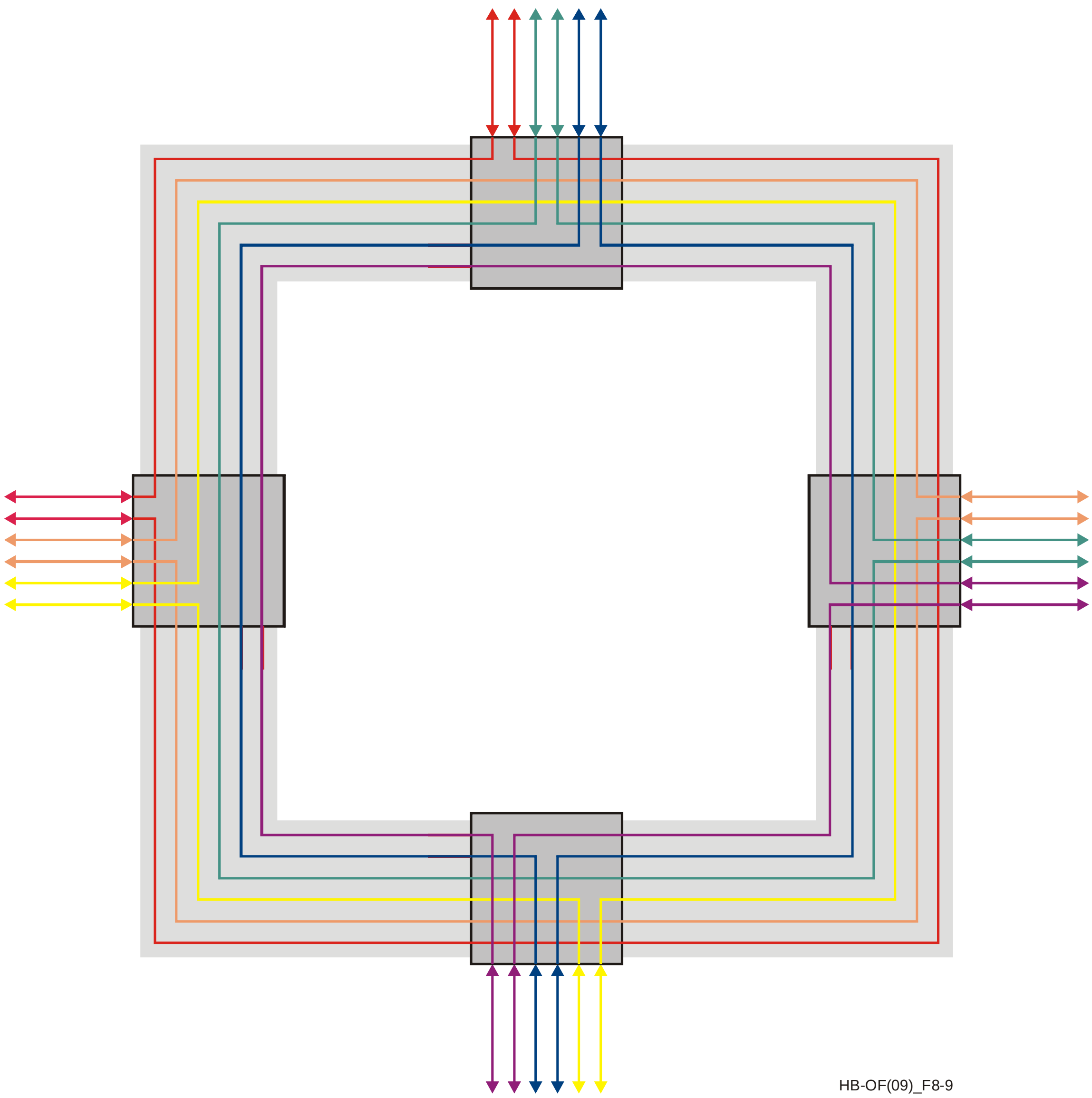


Figure 8-9 – Complex example of ring black-link topology

5.2 DWDM optical systems

DWDM systems for metro network applications are specified both with the black-box approach, in Recommendation ITU-T G.959.1, and with the black-link approach, in Recommendation ITU-T G.698.1.

5.2.1 Single-channel and DWDM optical systems (black-box approach)

Recommendation ITU-T G.959.1 provides transversely compatible optical interface specifications to enable multi-vendor interoperability with the black-box approach for links without line amplifiers.

This Recommendation provides the physical layer parameters and values for application codes corresponding both to the single-channel and multichannel interfaces with 3R regenerators on both sides of the interface as shown in Figure 8-10.

The reference points in Figure 8-10 are defined as follows:

- MPI-S is a (single channel) reference point just after each of the optical network element tributary interface output optical connectors;
- MPI-R is a (single channel) reference point on the optical fibre just before each of the optical network element tributary interface input optical connectors;
- MPI-S_M is a (multichannel) reference point on the optical fibre just after the optical network element transport interface output optical connector;
- MPI-R_M is a (multichannel) reference point on the optical fibre just before the optical network element transport interface input optical connector.

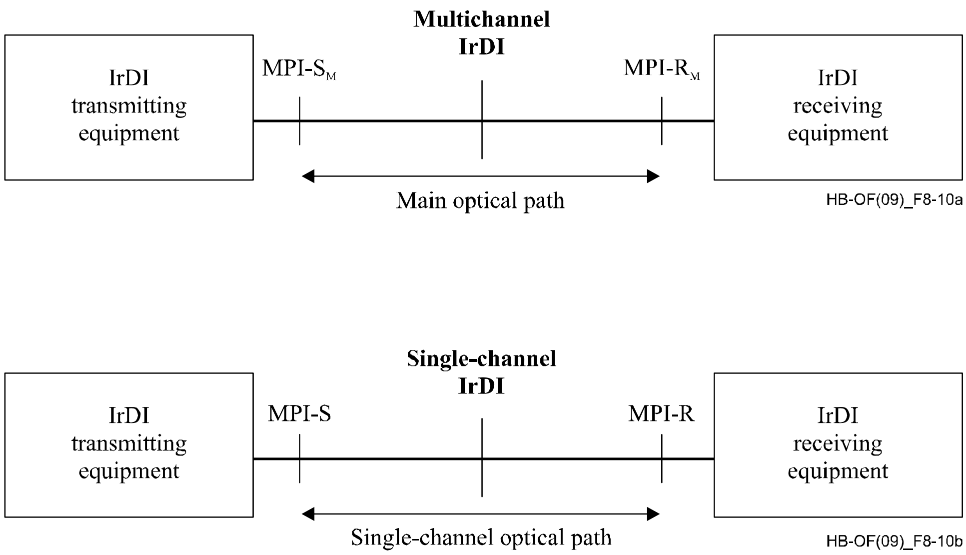


Figure 8-10 – Multichannel and single-channel IrDI reference configurations

The optical systems specified in Recommendation ITU-T G.959.1 cover:

i) target distances ranging from 20 km to 160 km;

ii) highest class of optical tributary signal supported: NRZ 2.5G, NRZ 10G and NRZ 40G;

iii) single and multi-channel applications;

iv) light sources and fibre types: 1 310 nm sources on ITU-T G.652 fibre, 1 550 nm sources on ITU-T G.652 fibre, 1 550 nm sources on ITU-T G.653 fibre, 1 550 nm sources on ITU-T G.655 fibre.

Some applications require FEC (forward error correction) bytes, as specified in Recommendation ITU-T G.709, to be transmitted to satisfy the target distance.

The specified application codes are shown in Tables 8-4 and 8-5.

The applications do not cover all possible combinations of distance category, optical tributary signal class, nominal source wavelength and fibre type. The applications included in Recommendation ITU-T G.959.1 are intended to satisfy a broad range of network requirements with low-cost implementations.

An example of these system interfaces with various clients is shown in Figure 8-11.

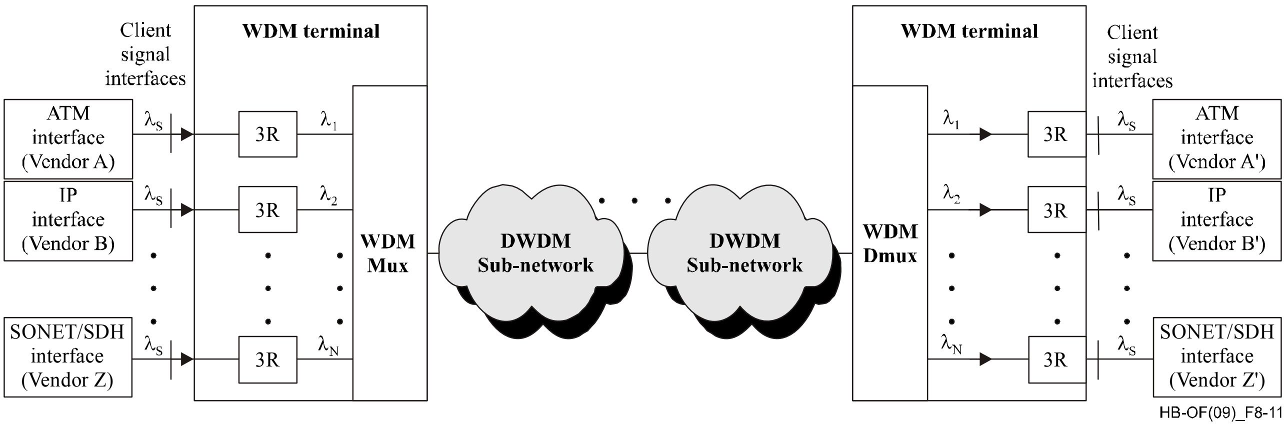


Figure 8-11 – Example of client signal interface with 3R regeneration

The interfaces specified in Recommendation ITU-T G.959.1 can be used for inter-domain and intra-domain connections. Inter-domain interfaces (IrDI) are intended to interconnect two different administrative domains. Such domains may consist of the equipment made by different vendors. The two administrative domains may also belong to different network operators. On the contrary, Intra-domain interfaces (IaDI) are those inside an administrative domain. Some examples of IrDI and of IaDI interfaces are shown in Figure 8-12.

As matter of fact, transverse (multivendor) compatibility is enabled for all IrDIs having exactly the same application code nWx-ytz. If a P16S1-2B2 interface of one vendor is implemented in domain A, it can be connected with a P16S1-2B2 interface of another vendor installed in domain B.

Interconnection between the interfaces with different application codes is a matter of joint engineering. Care must be taken, particularly with respect to critical parameters that must be matched, e.g. MPI-S_M output power, MPI-R_M power levels, maximum dispersion, minimum/maximum attenuation, etc. As an example, an interface P16S1-2B2 (booster amplifier power levels) in domain A should not be interconnected with an interface P16S1-2C2 (preamplifier power levels) in domain B without additional measures, e.g. adding an attenuator. In this example, the booster amplifier type interface output power may be +15 dBm and the minimum attenuation may be 0 dB. Thus, the input power to the preamplifier type interface may reach +15 dBm. Then, as the maximum receiver input power of the preamplifier type interface is +5 dBm, the receiver is overloaded by up to 10 dB. Care must also be taken to match the optical tributary signal bit rate and format.

Table 8-4 – Application codes for single-channel interfaces defined in Recommendation ITU-T G.959.1

Application	Short-haul				Long-haul				Very long-haul			Ultra long-haul		
Source nominal wavelength (nm)	1 310	1 550			1 310	1 550			1 550			1 550		
Type of fibre	ITU-T G.652	ITU-T G.652	ITU-T G.653	ITU-T G.655	ITU-T G.652	ITU-T G.652	ITU-T G.653	ITU-T G.655	ITU-T G.652	ITU-T G.653	ITU-T G.655	ITU-T G.652	ITU-T G.653	ITU-T G.655
Application code signal class NRZ 2.5G	Yes	Yes	–	–	Yes	Yes	–	–	–	–	–	Yes	Yes	Yes
Target distance for 2.5G (km)	20	40	–	–	40	80	–	–	–	–	–	160	160	160
Application code signal class NRZ 10G	Yes	Yes	Yes	Yes	Yes	Yes	–	–	Yes	–	Yes	–	–	–
Target distance for 10G (km)	20	40	40	40	40	80	–	–	120	–	120	–	–	–
Application code signal class NRZ 40G	Yes	Yes	Yes	Yes	–	Yes	Yes	Yes	–	–	–	–	–	–
Target distance for 40G (km)	20	40	40	40	–	80	80	80	–	–	–	–	–	–

Note – "Yes" means that an application code exists in Recommendation ITU-T G.959.1.

Table 8-5 – Application codes for multichannel interfaces defined in Recommendation ITU-T G.959.1

Application	Short-haul			Long-haul	
Source nominal wavelength (nm)	1550			1550	
Type of fibre	ITU-T G.652	ITU-T G.653	ITU-T G.655	ITU-T G.652	ITU-T G.655
Target distance (km)	40	40	40	80	80
Application code signal class NRZ 2.5G	Yes 16/32 channels	–	Yes 16/32 channels	Yes 16 channels	Yes 16 channels
Application code signal class NRZ 10G	Yes	Yes	Yes	Yes	Yes

Note – "Yes" means that an application code exists in Recommendation ITU-T G.959.1.

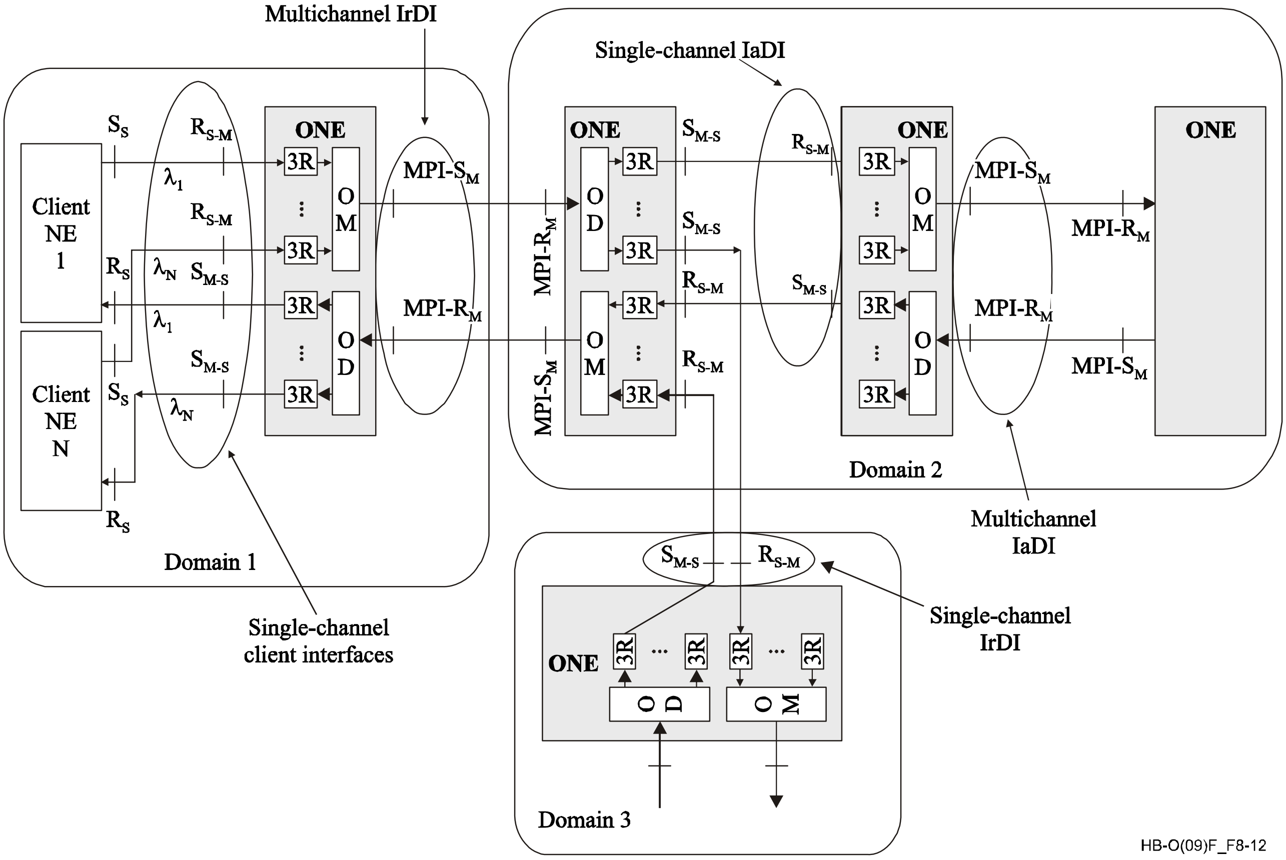


Figure 8-12 – Examples of multichannel and single-channel inter-domain and intra-domain interfaces

5.2.2 DWDM optical systems (black-link approach)

Optical interface specifications towards the realization of transversely compatible dense wavelength division multiplexing systems primarily intended for metro applications are also specified in Recommendation ITU-T G.698.1.

That Recommendation defines and provides values for single-channel optical interface parameters of physical point-to-point and ring DWDM applications (with transmission distance in the range of about 30 km to about 80 km) on single-mode optical fibres.

These DWDM systems with single-channel interfaces are primarily intended to be used in metropolitan area networks for a variety of clients, services and protocols.

The specification method in Recommendation ITU-T G.698.1 uses a "black-link" approach, which means that optical interface parameters for only (single-channel) optical tributary signals are specified. Additional specifications are provided for the black-link parameters such as maximum attenuation, chromatic dispersion, ripple and polarization mode dispersion. This approach enables transverse compatibility at the single-channel point using a direct wavelength-multiplexing configuration. However, it does not enable transverse compatibility at the multichannel points. In this approach, the OM and OD are treated as a single set of optical devices and OADMs can be included.

Figure 8-13 shows a set of reference points, for the *linear* "black-link" approach, for single-channel connection (S_S and R_S) between transmitters (Tx) and receivers (Rx). Here, the DWDM network elements include an OM and an OD, which are used as a pair with the opposing element, and may also include one or more OADMs.

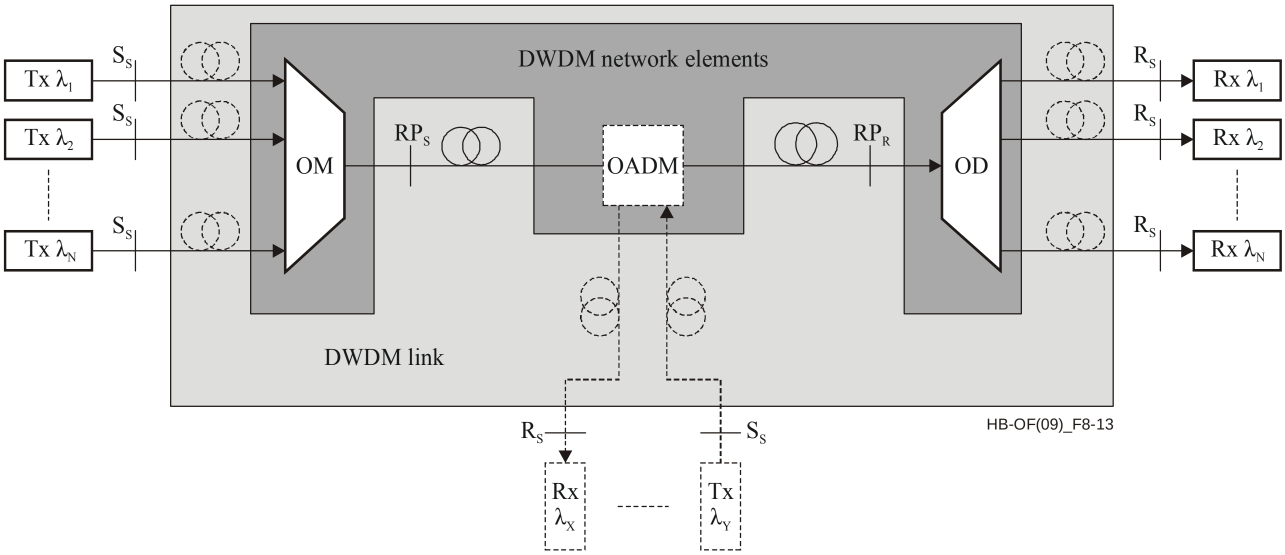


Figure 8-13 – Example of a linear configuration using black-link approach

As indicated in Figure 8-13, if the transmitter or receiver is located at a distance from the OM, OD or OADM, the fibre between point S_S or R_S and the DWDM network element is considered to be part of the black link.

Figure 8-14 shows a corresponding set of reference points for the *ring* "black-link" approach, for single-channel connection (S_S and R_S) between transmitters (Tx) and receivers (Rx). Here, the DWDM network elements include two or more OADMs connected in a ring.

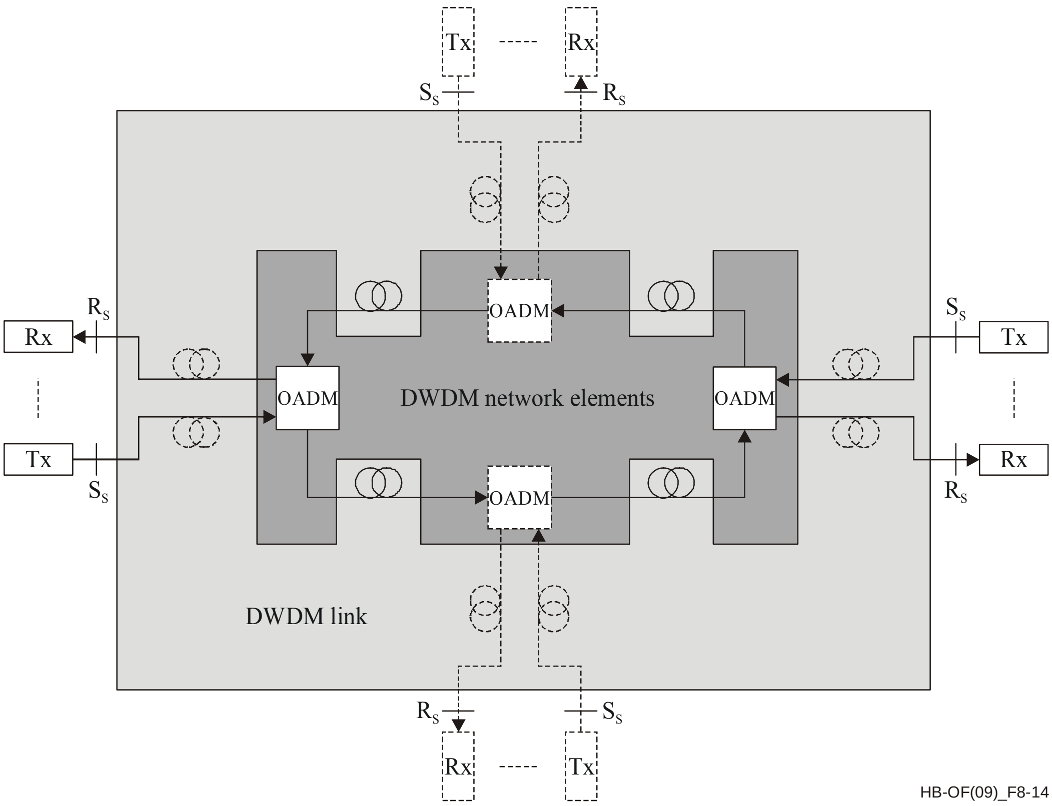


Figure 8-14 – Example of a ring configuration using black-link approach (without line optical amplifiers)

In this figure, single-channel reference points S_S and R_S are applied to systems for the "black-link" approach where every path from S_S to its corresponding R_S must comply with the parameter values of the application code.

All the reference models of Recommendation ITU-T G.698.1 do not include any optical amplifiers in the DWDM system.

DWDM systems described in Recommendation ITU-T G.698.1 include the following features:

i) channel frequency spacing: 100 GHz and above;

ii) signal channel bit rate: 2.5 Gbit/s and 10 Gbit/s.

The application codes of these types of systems are shown in Table 8-6, in which applications with and without forward error correction are listed.

Table 8-6 – Application codes for multichannel systems defined in Recommendation ITU-T G.698.1

Application	Short-haul		Long-haul		Short-haul		Long-haul	
Bit rate/ line coding	NRZ 2.5G	NRZ OTU1	NRZ 2.5G	NRZ OTU1	NRZ 10G	NRZ OTU2	NRZ 10G	NRZ OTU2
Fibre type	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655
Maximum channel insertion loss (dB)	16.5	19.5	25.5	28.5	18.5	21.5	24.5	27.5

The target distance is a function of the attenuation of the optical multiplexer and optical demultiplexer as well as the number of OADMs inserted in the system. The maximum number of OADMs that can be supported is constrained by the parameters which characterize the optical path between S_S and R_S (see, for example, Figure 8-13). In an Appendix to Recommendation ITU-T G.698.1, some formulas and calculations are given to determine the possible limitations and restrictions to the maximum number of OADMs, using the following parameters: maximum channel insertion loss, maximum ripple, maximum chromatic dispersion, reflections, maximum differential group delay and maximum interferometric crosstalk.

6 Metro core / regional optical networks

DWDM systems to be deployed in the metro core / regional networks can have lengths up to about 400 km. For these applications it is necessary to deploy DWDM systems with line optical amplifiers.

Optical parameter values for physical layer interfaces of DWDM systems primarily intended for metro applications including optical amplifiers are specified in Recommendation ITU-T G.698.2. Applications are defined using optical interface parameters at the single-channel connection points between optical transmitters and the optical multiplexer, as well as between optical receivers and the optical demultiplexer in the DWDM system (black-link approach). This means that optical interface parameters for only (single-channel) optical tributary signals are specified. This black-link approach uses a methodology which does not specify the details of the optical link, e.g. the maximum fibre length, explicitly. It enables transverse compatibility at the single-channel point using a direct wavelength-multiplexing configuration. However, it does not enable transverse compatibility at the multichannel points. The definition of single channel optical interfaces for DWDM systems enables the elimination of transponders, which would otherwise be needed in multi-vendor DWDM optical transmission networks. Chapter 6 of this Handbook shows two cases of interconnection between the DWDM line systems with transmitters and receivers: one with transponders (equipment non compliant) and one without transponder (equipment compliant).

Recommendation ITU-T G.698.2 provides the physical layer parameters and values for single-channel interfaces of DWDM multichannel optical systems in physical point-to-point and ring configurations. Figure 8-15 shows a ring application to illustrate the "black-link" approach together with the single channel reference points R_S and S_S. The arrangement of elements within the black-link is only an example, and Recommendation ITU-T G.698.2 does not intend to place constraints on the construction of such a black-link.

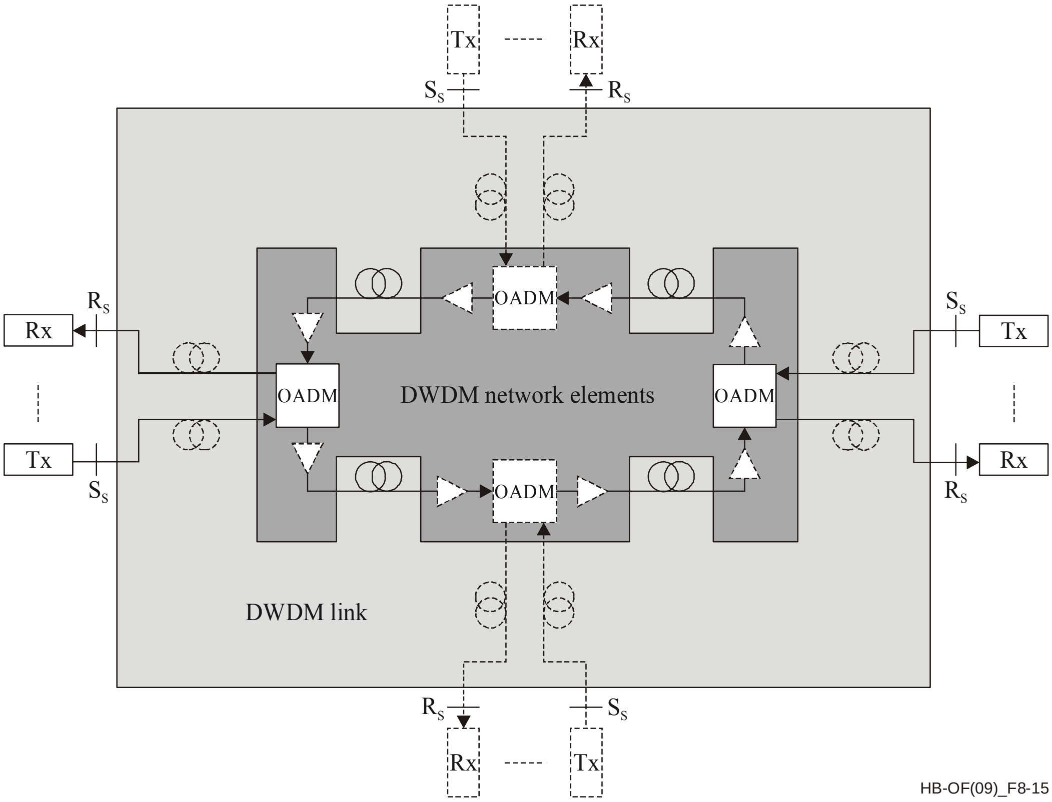


Figure 8-15 – Example of a ring configuration using black-link approach (with line optical amplifiers)

The current version of Recommendation ITU-T G.698.2 covers:

i) highest class of optical tributary signal: NRZ 2.5G and NRZ 10G;

ii) operating wavelength range: C-band, L-band;

iii) channel frequency spacing: 100 GHz;

iv) type of optical fibre: ITU-T G.652, ITU-TG.653 and ITU-T G.655 fibres;

v) black-link dispersion compensation regime: dispersion compensated (the black-link chromatic dispersion values are appropriate to a link that includes dispersion compensators between points S_S and R_S), dispersion un-compensated (the black-link chromatic dispersion values are appropriate to a link that does not include any dispersion compensators or is only partially compensated).

Some applications require FEC (forward error correction) bytes, as specified in Recommendation ITU-T G.709, to be transmitted.

Specifications are organized according to application codes, as shown in Table 8-7. These application codes are focused on features of the single-channel interfaces and do not define any elements or structure of the DWDM link.

Table 8-7 – Application codes defined in Recommendation ITU-T G.698.2

Bit rate/ line coding	NRZ 2.5G with dispersion compensation	NRZ 2.5G without dispersion compensation	NRZ OTU1 with dispersion compensation	NRZ 10G with dispersion compensation	NRZ OTU2 with dispersion compensation	NRZ OTU2 without dispersion compensation
Fibre type	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655

For the choice of the most suitable application code it is necessary to know the signal channel bit-rate at the connection points, the type of the fibre available, the wavelength range the DWDM link was designed for, the requirements of the DWDM link on the spectral excursion of the transmitters (narrow or wide spectral excursion), the minimum OSNR supplied by the DWDM link and the range of the optical power at point R_S. The requirements of the DWDM link on the spectral excursion of the transmitters are related to the optical bandwidth of the wavelength multiplexers, de-multiplexer and OADMs as well as the total number of these devices cascaded in the black-link.

7 Backbone/long haul networks

DWDM systems to be deployed in the backbone networks may cover distances of more than 1 000 km. Recommendation ITU-T G.696.1 provides physical layer specifications for intra-domain (IaD) DWDM optical networking applications, in which optical line amplifiers are included depending on the distance the system should cover.

The goal is to enable longitudinally compatible applications inside an administrative domain. The primary purpose of that Recommendation is to enable multiple vendors to design DWDM transmission equipment for fibre links that are compliant with that Recommendation. The corresponding reference configuration is shown in Figure 8-16.

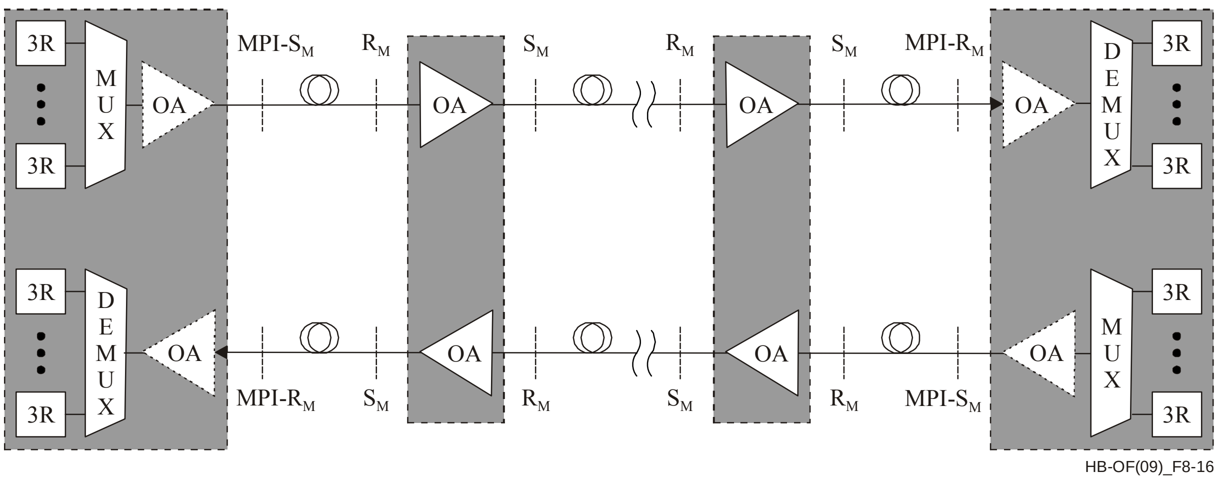


Figure 8-16 – Reference configuration for a multi-span DWDM system

Recommendation ITU-T G.696.1 specifies only longitudinally compatible applications because the specification of transversally compatible applications for DWDM systems with many line optical amplifiers (even if it gives more flexibility in the deployment of the systems) is very difficult and requires unacceptable margin.

This is due to the fact that the very long DWDM systems must be designed by a sophisticated optimization and considering compromise among a lot of different parameters and constraints which makes the coexistence in the same DWDM system of equipment from different manufacturers (as happens in transversally compatible applications) extremely difficult to standardize (see Chapter 7).

Recommendation ITU-T G.696.1 defines the generic term client class that refers to the client bit rate within an optical channel before additional FEC bytes have been added.

The specifications are organized according to application codes, which take into account parameters such as operating wavelength ranges of the optical amplifiers, combinations of channel counts, client classes, span distances, fibre types and system configurations. For these systems the application codes consist of two separable sections.

The application code notation is constructed as follows:

n . B – xWF(s)

where:

n : maximum number of channels supported by the application code,

B : client class: 1.25G, 2.5G, 10G, 40G,

x : number of spans within the application code,

W : letter indicating the span attenuation, such as:
S: indicating short-haul (up to 11 dB span attenuation),
L: indicating long-haul (up to 22 dB span attenuation),
V: indicating very long-haul (up to 33 dB span attenuation),

F : fibre type, such as ITU-T G.652.A, … ITU-T G.652.D denoted by "652A" … "652D" in the application code, respectively,

s : operating wavelength range in terms of spectral bands (see Chapter 6): O, E, S, C, L.

The first part "n . B" relates to the optical transmission system and the second part "xWF(s)" relates to the fibre infrastructure. Since this Recommendation covers longitudinally compatible systems, the parameters specified for intra-domain DWDM applications relate to the fibre infrastructure only, except for the system-related part of the application code affecting the fibre requirements. In case of a Raman amplified DWDM transmission system, a letter "R" shall be added at the end of the application code.

An example of a specific application could look like this:

40.10G-20L652A(C)R

This application indicates a 40-channel system with signal channels of the 10G payload class, 20 long-haul spans of ITU-T G.652A fibre which are suitable for use with Raman amplifiers. The C-band is used as the operating wavelength range.

Theoretical limits and design considerations for DWDM systems are indicated in an Appendix to Recommendation ITU-T G.696.1. In particular, ASE noise (characterized by OSNR) and PMD limits are illustrated by both general equations and specific examples based on reference systems with up 35 spans (2 800 km in length on the assumption of a mean value of 80 km per span). Moreover, there is an example showing the feasibility of a system with a maximum of about 15 span (1 200 km on the assumption of a mean value of 80 km per span).

Other effects that limit transmission distance are mentioned, as well, in the above-mentioned Appendix, such as accumulated gain ripples and stimulated Raman effects, non-uniform span length, optical non-linearity, residual dispersion, and accumulated PDL effects. Finally, a number of techniques used to mitigate impairments are summarized, including dynamic gain equalization, line coding (i.e. modulation format), number of optical channels and their spacing, fibre types, mixing different types of fibre within one span.

8 Repeaterless and repeatered optical fibre submarine systems

Optical fibre submarine cable systems are an important element of telecommunication networks because they allow the connection of terminal stations divided by a sea. These links can be of various lengths, starting from a few kilometres (for linking to islands just offshore) up to several thousands of kilometres (for linking different continents through the oceans). These very different applications require very different transmission capabilities.

Submarine systems are substantially different from terrestrial ones in many aspects, because the environmental conditions where they operate impose more severe requirements. There are essentially two basic requirements:

i) a very high reliability for the submerged plant, considering that each fault needs the intervention of a cable ship and each of these interventions lasts some days;

ii) a very long operational lifetime, considering the high costs of development, manufacturing and laying of a submarine link with the stringent reliability objectives noted above.

As a consequence all of the Recommendations on optical fibre, submarine cable systems deal not only with the electrical/optical characteristics, but also with the mechanical/reliability characteristics. Moreover, a detailed description is made of the tests to be carried out during the various phases of the realization from manufacturing to final acceptance.

There is another aspect that sets submarine systems apart from terrestrial ones and affects the manner in which Recommendations related to systems are written. Submarine systems, as terrestrial ones, are interconnected to terrestrial networks at the two terminal stations, and at these interfaces they have to be compliant with the SDH/OTN interfaces specified in Recommendations ITU-T G.707 and ITU-T G.709. In contrast to this, the situation of the submarine system itself (the connection between the two terminal stations) is different from that of the terrestrial systems for two main reasons:

i) the components of a terrestrial link often come from different vendors (fibres, cables, DWDM equipment, OADM, etc.), while the provision of a submarine link is usually made “turnkey” by a single vendor. This means that a single company supplies all that is necessary for the realization of the link between the two interfaces with the terrestrial networks;

ii) the installation of all of the submerged equipment required for the final capacity of the system (optical amplifiers, branching units, etc) is carried out at the time of the laying of the system.

These two differences have an impact on the way the specifications are written. For terrestrial systems, the applications specified are either longitudinally compatible or transversely compatible, in order to enable some level of multi-vendor interoperability. For submarine systems neither of these types of compatibility are generally very useful, because the equipment for all of the link and for all the optical fibres of the submarine cable are sourced from the same supplier at the time of the laying of the system. As a consequence, the Recommendations on submarine optical systems do not specify any particular application code with the values of the parameters at one particular interface, but they are focused on the identification of the parameters and of the characteristics of the submarine systems which should be carefully defined for each link. The specific values of these parameters for each system to be realized will be defined between the operator and the supplier, with the objective of achieving stringent quality objectives.

Based on the above general considerations, ITU has published several Recommendations which specifically deal with optical fibre submarine cable systems: Recommendations ITU-T G.971, ITU-T G.972, ITU-T G.973, ITU-T G.974, ITU-T G.975, ITU-T G.975.1, ITU-T G.976, ITU-T G.977 and ITU-T G.978.

8.1 Submarine systems topology

The types of topology for optical fibre submarine cable systems are in some way different from those applied for the terrestrial networks (see § 2). As shown in the following they are: point-to-point, star, branched star, trunk and branch, festoon, ring and branched ring.

8.1.1 Point to point

This configuration (Figure 8-17) consists of direct submarine link between two terminal transmission equipment (TTE) located in two different terminal stations (TS).

Figure 8-17 – Topology of point to point

8.1.2 Star

This configuration (Figure 8-18) consists of a main terminal station (TS) that links several other TSs with separate cables. In the basic star configuration, traffic is directly transmitted from TTE of the main TS to the TTE of the other TSs independently. Therefore, the star network requires a separate cable for each TS, which leads to a relatively costly configuration, particularly when TSs are geographically distant.

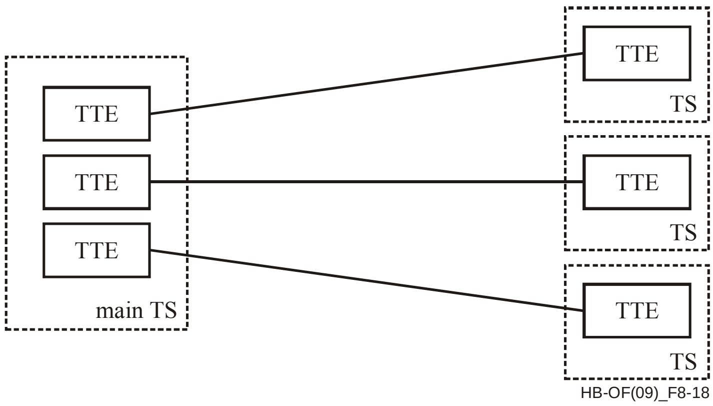


Figure 8-18 – Topology of star

8.1.3 Branched star

This configuration (Figure 8-19) provides the same capacity as the basic star, except that the splitting of traffic is done underwater, minimizing the cost of separate cable between remotely located TSs. Splitting of traffic is accomplished with a branching unit (BU) that interconnects the fibres of a single trunk cable with separate fibres inside two or more branches.

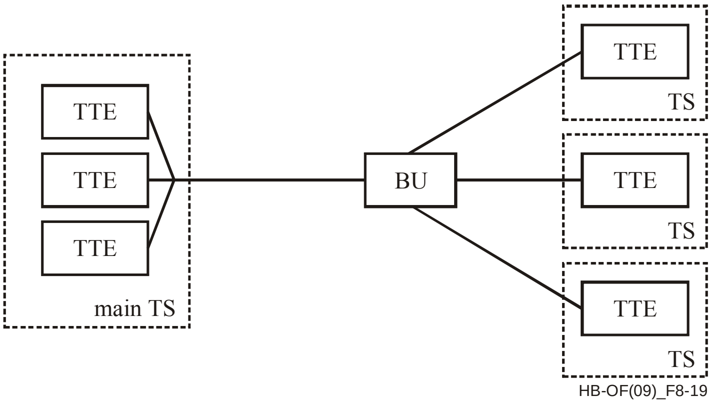


Figure 8-19 – Topology of branched star

8.1.4 Trunk and Branch

This configuration (Figure 8-20) connects several TSs including TTEs to a single trunk cable by means of branching units that allow the extraction of a part of the traffic in the direction of the TSs of the branches.

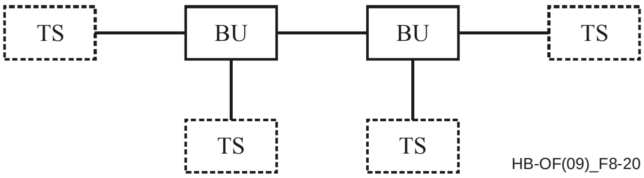


Figure 8-20 – Topology of trunk and branch

8.1.5 Festoon

The festoon (Figure 8-21) is basically a series of loops between major coastal landing points, and it is often deployed, though not always, as a repeaterless system. In anticipation of a future increased capacity requirement, these repeaterless applications are typically engineered with higher-fibre-count cables than those required for initial service. Thus, in the case of a need of additional capacity, terminal equipment is the only additional investment required. The architecture of a festoon frequently mirrors that of a typical, land-based installation. Such architecture may often be used as a supplemental, diverse route to an existing land-based system. This configuration is an increasingly popular alternative to a land-based system, especially when the continental terrain provides difficult installation and maintenance challenges.

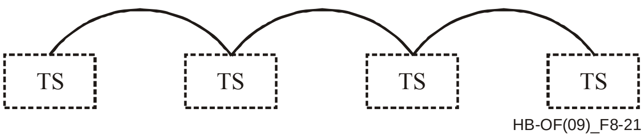


Figure 8-21 – Topology of a festoon

8.1.6 Ring

The ring configuration (Figure 8-22) is essentially a set of connected, point-to-point cables having twice the requisite transmission capacity.

In case any single failure occurs within the ring, such as a cable cut, traffic is routed around the ring, away from the inoperable segment, and on to its original destination. Shore-based transmission equipment provides automatic failure detection and switchover control for the entire ring without dropping a call.

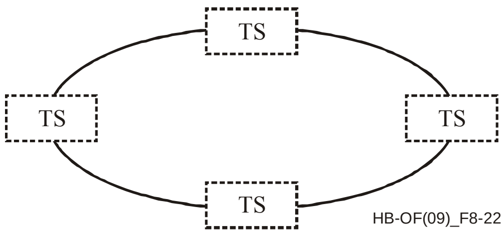


Figure 8-22 – Topology of a ring

8.1.7 Branched Ring

This configuration (Figure 8-23) extends the basic capability of the ring in a cost effective manner with the addition of a branching unit. The branched-ring structure retains the self-healing nature of the ring. The branched ring, then, can be thought of as a merger between the trunk-and-branch and the ring, retaining most of the benefits of each. This configuration can be made in a number of ways, including hook-up through other networks. With proper planning, a network can be installed as a trunk-and-branch arrangement and upgraded later to a branched ring.

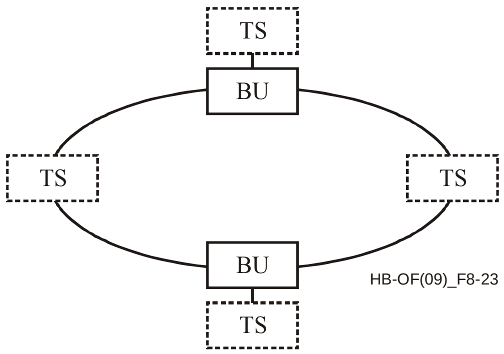


Figure 8-23 – Topology of a branched ring

8.2 Repeatered optical submarine systems

(For further information see Recommendation ITU-T G.977).

The use of the DWDM technique in combination with optical amplifiers, dispersion accommodation and FEC has completely changed the design of optical submarine systems. Starting from the first transatlantic optical cable system with a single-channel per fibre pair at 280 Mbit/s in 1988, the evolution of the technology has arrived at DWDM systems on transoceanic links with a capacity of 128×10 Gbit/s per fibre pair.

The characteristics of repeatered optical submarine systems using optical fibre amplifiers as line repeaters are dealt with in Recommendation ITU-T G.977. It refers to the system characteristics required to guarantee the performance, the reliability (usually 25 years, starting at the provisional acceptance date of the system) and the capacity upgradeability.

The following submerged equipment types are also defined:

- i) Optical Submarine Repeaters;
- ii) Branching Unit;
- iii) Optical Submarine Equalizer.

Mechanical, electrical, and optical characteristics; supervisory and fault location facilities; and reliability considerations are detailed for all of them.

An example of repeatered/branched optical submarine system is shown in Figure 8-24.

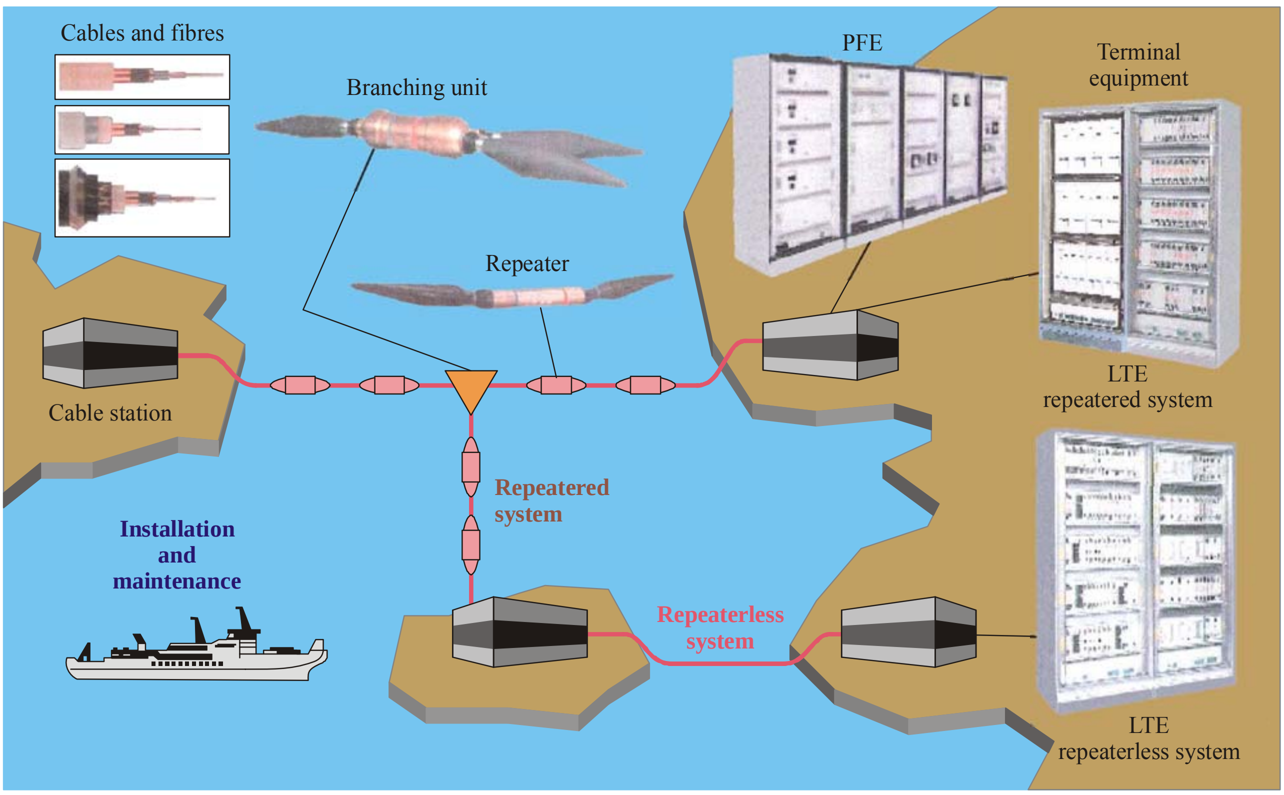


Figure 8-24 – Exampled of a repeatered/branched submarine system

8.2.1 System configuration

The configuration of a repeatered optical submarine system is in Figure 8-25 where:

- TTE (terminal transmission equipment) is the equipment terminating the optical submarine transmission line at the optical interface and connected to the system interface;
- CTE (cable terminating equipment) is the equipment providing the interface between the optical fibre from the TTE and the optical fibre cable, and the interface between the power feeding line from the PFE and the power feeding conductor from the optical fibre cable. The CTE is usually part of the PFE;
- BU (branching unit) is the equipment connecting more than two optical fibre submarine cable sections;
- PFE (power feeding equipment) is the equipment providing, through a power conductor in the optical fibre submarine cable, a stabilized constant electrical current for powering optical submarine repeaters and/or optical submarine branching units.

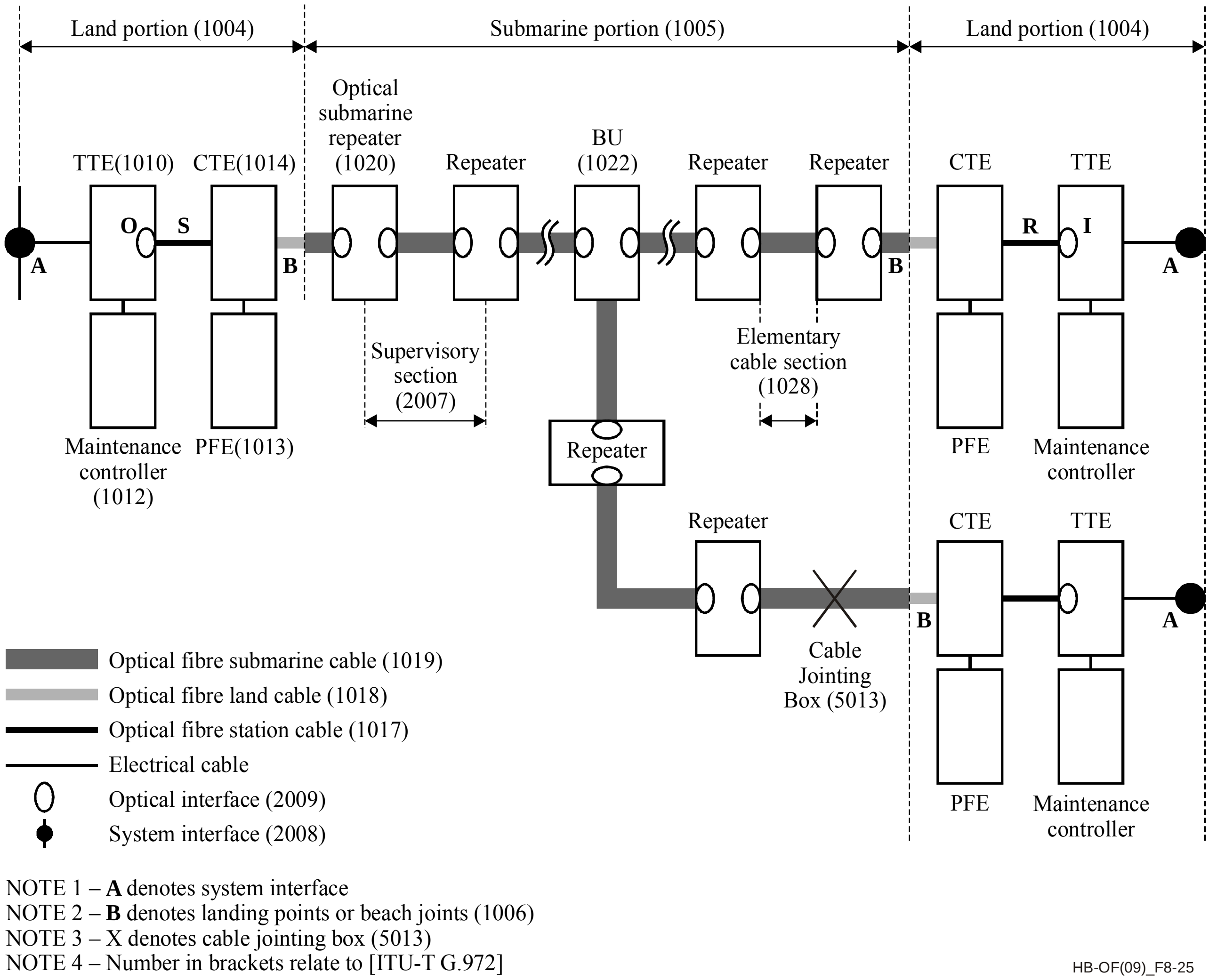


Figure 8-25 – Configuration of a repeatered optical fibre submarine cable systems

8.3 Repeaterless optical submarine systems

(For further information see Recommendation ITU-T G.973).

The purpose of a repeaterless optical fibre submarine cable system is to establish transmission links between two or more terminal stations located in a restricted geographical area. To reduce cost and complexity of this type of submarine system, no line optical amplifier is used. As a consequence, no power feeding equipment is necessary. As far as the branching unit devices are concerned, those considered in Recommendation ITU-T G.973 are the passive ones, thereby avoiding electronic components as well as supervisory and power feeding. Therefore, repeaterless optical submarine systems offer several advantages over the repeatered ones:

i) higher reliability because there are no submerged repeaters;

ii) lower cost because power feeding of the submerged repeaters and their supervision are not required;

iii) higher capacity because it is possible to lay submarine cables with a high number of fibres (e.g. 96 fibres) because there is not the constraint of the available space in the containers of the submerged repeaters;

iv) for these systems the principle "pay as you grow" applies because the first investment is only that related to the cable, while the terminal equipment can be installed/activated/paid for following the traffic demand.

The system performance and interface requirements of repeaterless optical fibre submarine cable systems are dealt with in Recommendation ITU-T G.973. It considers both single-channel systems and DWDM systems. A scheme of a multichannel system is illustrated in Figure 8-26.

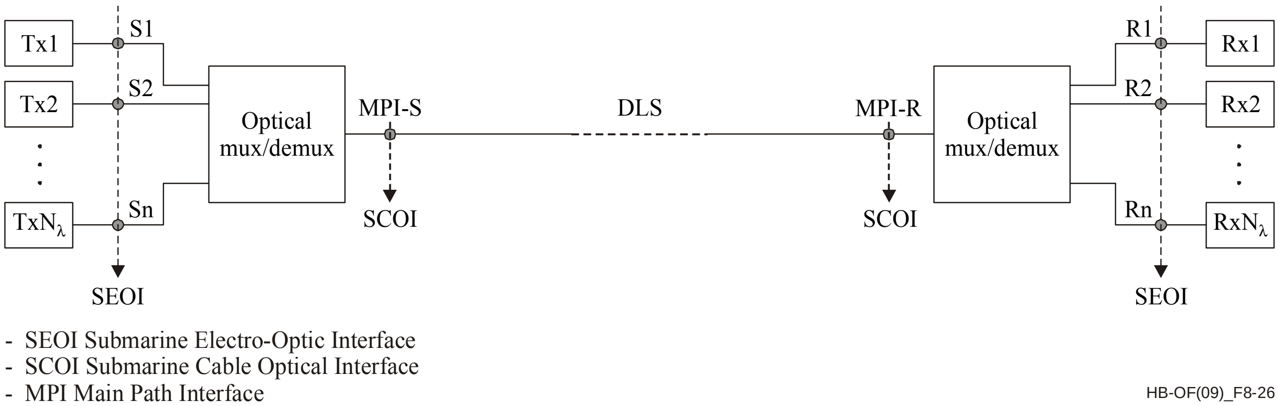


Figure 8-26 – Configuration of a repeaterless optical submarine system

The dispersion and nonlinear effects are of less concern for such systems than for transoceanic optical systems, but fibre attenuation becomes a major issue. The reason is easily appreciated, noting that a power budget of about 60 dB is necessary over a distance of about 300 km for transmitting about 30 channels at 10 Gbit/s. In order to realize such systems, it is necessary to use high performance FECs, Raman amplifiers and remote optically pumped amplifiers (ROPA), and specific types of fibres, which can also be different within the same link.

Recommendation ITU-T G.973 covers not only submarine systems with no optical amplifiers, but also submarine systems using discrete optical fibre amplifiers as power amplifiers, pre-amplifiers, Raman amplifiers and/or ROPA.

Optical amplifiers can be inserted in the system as power amplifiers just after the laser transmitter to increase the terminal output power, or as pre-amplifiers inserted just before the optical receiver to reduce the minimum optical signal power at the input of a composite receiver (pre-amplifier plus terminal receiver). In general, system enhancement can be achieved by power amplifier only, pre-amplifier only, or a combination of both.

Moreover, the application of remote optically pumped amplifiers (ROPA) and distributed Raman amplifiers (DRA) is also considered. A ROPA consists of a section of erbium-doped fibre (EDF) pumped from the terminal station at an appropriate wavelength, whereas the DRA use the fibre itself as an amplification medium and require the fibre pumped from the terminal station at appropriate wavelength. There is no electrical power propagation into the submarine portion. This technique can be employed at either the transmitter or the receiver side of a link although it is generally considered more efficient at the receive side. Generic characteristics of DRA are given in Chapter 5.

The possible system configurations are shown in Figure 8-27.

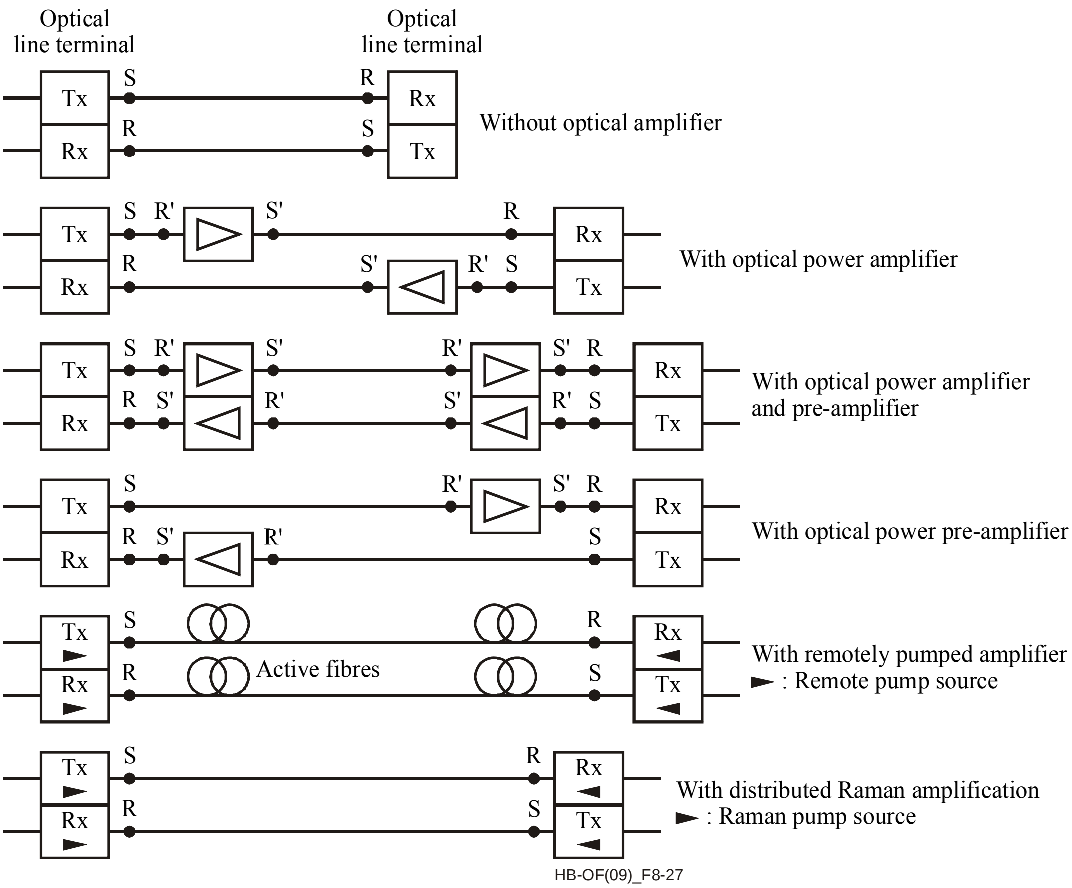


Figure 8-27 – Possible repeaterless system configurations

8.4 System reliability

The reliability of the submarine portion of an optical fibre submarine cable system is generally characterized by:

i) the expected number of repairs requiring intervention by a cableship and due to system component (e.g. splices, branching unit (BU), transitions, etc.) failures during the system design life. The usual requirements for the reliability of repeatered and repeaterless systems are less than three and one failure requiring cableship intervention, respectively, during the system design life:

ii) the system design life is the period of time over which the optical fibre submarine cable system is designed to be operational, in conformance with its performance specification. Usually, the system design life is a period of 25 years, starting at the provisional acceptance date of the system, i.e. the date following installation when the system is claimed to be compliant with the performance specification.

8.5 System upgradability

It may be advantageous to increase the transmission capacity by increasing the signal bit rate and/or the number of transmission channels. Such upgrading can be beneficial because the reuse of cables can be achieved cost-effectively over the equipment's long life, typically 25 years.

Bit-rate upgradeability demands that systems be constructed with cables optimized for the higher bit rate, while lower bit-rate TTE may be initially used. Even after upgrading, the bit rate of TTE output must comply with SDH/OTN specifications, to ensure compatibility with standard terrestrial equipment.

Upgradeability also demands that the initially installed cable be capable of carrying the maximum number of channels expected in the future.

Upgrading by increasing signal bit rate or by adding more channels is much different from many viewpoints of system design including the post-amplifier output power, pre-amplifier input power, power budget, signal-to-noise ratio, fibre chromatic dispersion, and fibre non-linearities. It is therefore recommended that the systems be designed properly, considering the possibility of future upgrades.

8.6 Optical Power Budget

Optical power budget, as defined in Recommendation ITU-T G.976, is a performance budget, which guarantees the system performance to be better than the minimum required BER performance defined in Recommendations ITU-T G.826 and ITU-T G.828.

The optical power budget starts from a simple linear quality factor (Q-factor) which only takes into account degradation due to the ASE noise of amplifiers (*mean Q*). Then, the optical power budget allocates the penalties/impairments for all types of degradation (due to the transmission, due to terminal equipment, etc., …). The degradation is estimated using a combination of theoretical analysis, computer simulations and direct measurements on experimental test-beds (see Chapter 7).

For each submarine system, it is recommended to establish two distinct power budgets, one at the beginning of life (BOL) and another one at the end of life (EOL) (Figure 8-28):

i) The BOL power budget provides the worst case digital line section performance which will be measured during the commissioning;

ii) The EOL power budget provides the estimated worst case digital line section performance at the end of system life and includes margins for ageing, internal failures and specified repair margins.

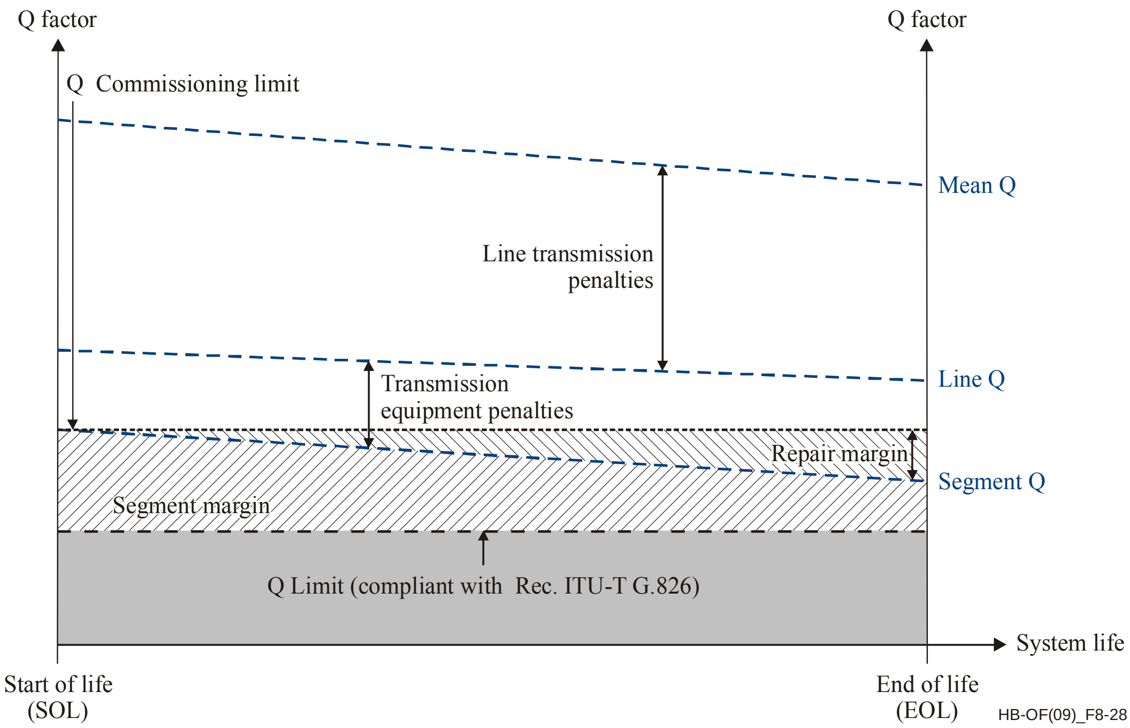


Figure 8-28 – Power budget structure example

The EOL margin is the difference between the worst Q-factor estimated at the end of system life and the minimum Q-factor needed to satisfy the required transmission performance. In addition, the optical power budget should clearly show the minimum Q-factor required to obtain the specified error performance of the system and include margin improvement provided by the use of FEC (if applicable).

The power budget tables should compute margins that should be considered as a minimum requirement for the system at BOL. In Recommendation ITU-T G.977 these margins should be expressed in terms of a Q-factor value. An example of a possible power budget template is shown in Table 8-8.

Table 8-8 – An example of a possible power budget template

	Parameter	**BOL Q (dB)**	**EOL Q (dB)**
1	Mean Q value (from a simple SNR calculation)		
1.1	Propagation impairments due to combined effects of chromatic dispersion, non-linear effect, four-wave mixing effects, stimulated Raman scattering effects, etc.		
1.2	Gain flatness impairment		
1.3	Non-optimal optical pre-emphasis impairment		
1.4	Wavelength tolerance impairment		
1.5	Mean PDL penalty		
1.6	Mean PDG penalty		
1.7	Mean PMD penalty		
1.8	Supervisory impairment		
1.9	Manufacturing and environmental impairment		
2	Time varying system performance (5 sigma rule)		
3	Line Q value (1 – (1.1 to 1.9) – 2)		
4	Specified TTE Q value (back-to-back)		
5	Segment Q value (computed from 3 and 4)		
5.1	BER corresponding to segment Q without FEC		
5.2	BER corresponding to segment Q with FEC		
5.3	Effective Segment Q value with FEC		
6	Q limit compliance with G.826 after FEC correction		
7	Repairs margins Components and fibre ageing penalty Pump(s) failure penalty Non-optimal decision threshold		
8	Segment margins		
9	Unallocated supplier margin		
10	Commissioning limits		

Table 8-8 should be completed as follows:

– Line 1 – Mean Q value (simple SNR calculation). (There exist different formulas: Simple noise accumulation with constant signal power or total output power and with/without extinction ratio, etc.) (see Chapter 7).

– Lines 1.1 to 1.9 give a non-exhaustive list of impairment sources that impact system performances. Those impairments have to be deducted from Line 1.

– Line 2 – Time varying system performance:

This defines an additional impairment due to polarization fluctuation phenomena that decrease the mean performances.

– Line 3 – Line Q value:

This line gives the line Q-factor. It is the result of this operation:

Line 3 = Line 1 – (line 1.1 to line 1.9) – line 2.

– Line 4 – Specified TTE Q value:

This line gives the specified LTE back-to-back Q factor at BOL and EOL.

– Line 5 – Segment Q value:

This line gives the segment Q-factor calculated from lines 3 and 4 using the following formula:

$$\frac{1}{Q^2 segment} = \frac{1}{Q^2 line} + \frac{1}{Q^2 TTEbacktoback}$$

– Line 5.1 – BER corresponding to segment Q without FEC:

Line 5 converted into bit error ratio (BER) before forward error correction.

– Line 5.2 – BER corresponding to segment Q with FEC:

BER after FEC correction.

– Line 5.3 – Effective segment Q value with FEC:

Line 5.2 converted into Q factor.

– Line 6 – Q limit for compliance with Recommendation ITU-T G.826 after correction:

Q-factor corresponding to the worst allowable bit error ratio before correction by FEC. For example, 11.2 dB corresponds to a BER of 2.4×10^{-4}. A BER of 2.4×10^{-4} is converted by the first generation FEC correction to a BER better than 10^{-11}. Therefore, a Q-factor of 11.2 dB covers all DLS lengths for the first generation FECs.

– Line 7 – Repairs, ageing and pump failures:

Line 7 is given by line 5 (BOL) minus line 5 (EOL).

– Line 8 – Segment margins:

Line 8 (EOL): the segment margins are usually 1 dB contractually at EOL.

Line 8 (BOL) is given by line 7 plus line 8 (EOL).

– Line 9 – Unallocated supplier margins:

Margin for other and unknown impairments.

– Line 10 – Commissioning limit:

This line gives the contractual commissioned Q limit for each DLS.

9 Wavelength switched optical networks (WSON)/all optical networks (AON)

(For further information see Recommendation ITU-T G.680).

A backbone network can extend to an entire geographical region (e.g. a country, which can have different dimensions such as USA or Italy) with a given topology (e.g. a mesh topology). The nodes in the network are connected through point-to-point DWDM links and they usually have 3R regeneration and switching made electronically (e.g. by digital cross-connects). Such transport networks are called "opaque" networks because they require optical-to-electronic conversion at the switching node. As a result, neither the bit rate nor the modulation format can be changed without changing the switching equipment.

An all optical network (AON) in which a DWDM signal can pass through multiple nodes (adding/dropping and/or switching the optical channels) is called optically "transparent". Transparent networks do not require optical-to-electronic conversion of all DWDM channels. The nodes in the transparent network may include optical add/drop channels through OADM or ROADM, and optical switching channels through PXC.

The present optical transport networks (OTN) are evolving towards all optical networks with an ever decreasing number of O/E/O conversions within their boundaries. The two main reasons for this evolution are the following:

i) DWDM systems are becoming capable of transporting optical signals for thousands of kilometres without electrical regeneration;

ii) Photonic cross-connects (PXC_S) and optical add/drop multiplexers ($OADM_S$) are becoming available with specifications suitable for their use in the telecommunication networks, including capacity, space requirements, power consumption, reliability and cost.

This evolution will lead to the deployment of an optically transparent domain that can be large enough to transparently transmit the signals in all the potential routes of the backbone network of a medium size country (optical paths up to around 2 000 km) (Figure 8-29).

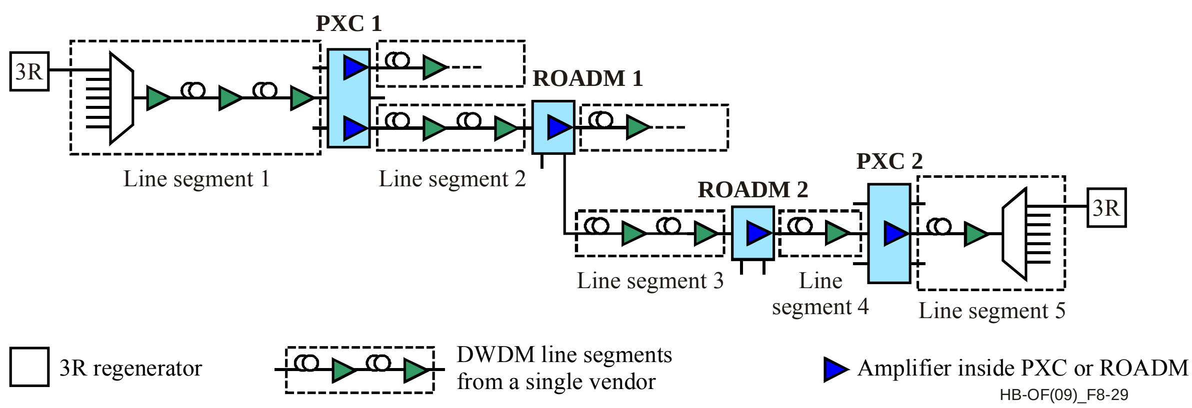


Figure 8-29 – Example of optical transmission system

Considering the OTN evolution described above, it is important to define a "degradation function" of optical network elements (ONE_S) such as photonic cross connects (PXC_S), optical add-drop multiplexers ($OADM_S$), etc. making up an optical network.

One application of the degradation functions is to enable, at the moment of the activation / rerouting of an optical channel, the calculation of the overall degradation of the chosen route on the basis of the "degradation function" of each ONE involved and to evaluate whether the overall degradation is compatible with the error performance objectives at the O/E/O 3R end-point. Figure 8-29 gives an example path. If this check gives a positive answer, the optical channel is activated. If the check is negative, it will be necessary either to find another route or to insert a 3R regeneration point at a suitable place along the route.

This calculation is done in terms of a list of parameters that characterize physical impairments (such as optical noise, chromatic dispersion etc.) and is intended to be independent from the network architecture that the devices are deployed in.

Recommendation ITU-T G.680 deals with this subject and covers a reference situation where the optical path between two consecutive electrical regenerators is composed of dense wavelength division multiplexing (DWDM) line segments from a single vendor and $OADM_S$ and PXC_S from other vendors as shown in Figure 8-30.

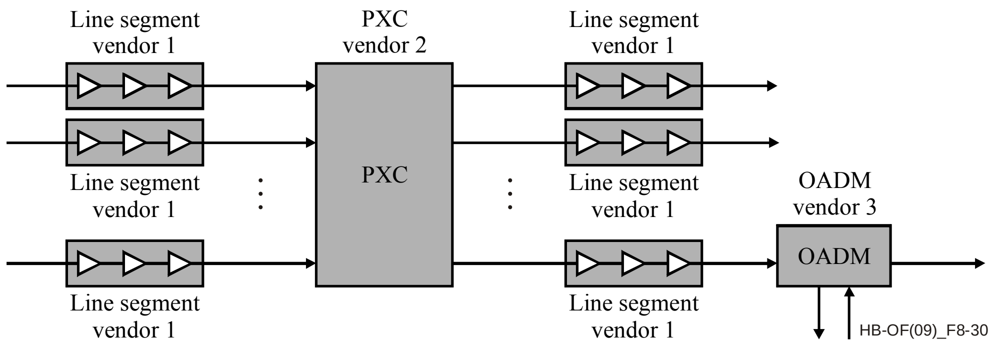


Figure 8-30 – Example of optical path with ONEs from different vendors

The information provided in Recommendation ITU-T G.680 (when taken together with the corresponding parameters from the DWDM line segments including any non-linear effects) enables the evaluation of the impact on line system performance of the combination of transfer parameters (OSNR, residual dispersion, PMD, PDL, channel ripple, transient phenomena, channel uniformity) related to the cascade of ONEs inserted in the optical path between the ingress and egress 3R electrical regenerators (Figure 8-29).

Recommendation ITU-T G.680 describes principles for calculating the effect of cascading multiple ONEs on the degradation of the optical signal quality for each parameter and for the combined effect of all of them. As an example, the impact of cascaded ONEs on line system OSNR and an example of calculation of this impact are given in the following. The impact of cascaded ONEs on the other parameter degradations, and the method of combining them, can be also found in Recommendation ITU-T G.680.

9.1 Impact of cascaded ONEs on line system OSNR

In the case that the ONEs considered contain optical amplifiers, the OSNR of the optical signals at the output or drop ports will be lower than the OSNR at the input or add ports. The magnitude of this reduction can be calculated using equation (8-1).

$$osnr_{out} = \frac{1}{\frac{1}{osnr_{in}} + \frac{1}{osnr_{one}}} \tag{8-1}$$

where:

$osnr_{out}$: linear OSNR at the output port of the ONE,

$osnr_{in}$: linear OSNR at the input port of the ONE,

$osnr_{one}$: linear OSNR that would appear at the output port of the ONE for a noise free input signal.

If the OSNR is defined in logarithmic terms (dB) and the equation for the OSNR due to the ONE being considered is substituted this equation becomes:

$$OSNR_{out} = -10\log\left(10^{-\left(\frac{OSNR_{in}}{10}\right)} + 10^{-\left(\frac{P_{in} - NF - 10\log(h\nu\nu_r)}{10}\right)}\right) \tag{8-2}$$

where:

$OSNR_{out}$: log OSNR (dB) at the output port of the ONE,

$OSNR_{in}$: log OSNR (dB) at the input port of the ONE,

P_{in}: channel power (dBm) at the input port of the ONE,

NF: noise figure (dB) of the relevant path through the ONE,

h: Planck's constant (in mJ · s to be consistent with in P_{in} (dBm)),

ν: optical frequency (Hz),

ν_r: reference bandwidth (Hz) (usually the frequency equivalent of 0.1 nm)

This equation can be generalized to account for the OSNR of any end to end path through an optical network (including the effect of the amplifiers in the WDM line segments). The resulting equation is Equation (8-3).

$$OSNR_{out} = -10\log\left(10^{-\left(\frac{P_{in1} - NF_1 - 10\log(h\nu\nu_r)}{10}\right)} + 10^{-\left(\frac{P_{in2} - NF_2 - 10\log(h\nu\nu_r)}{10}\right)} + \ldots + 10^{-\left(\frac{P_{inN} - NF_N - 10\log(h\nu\nu_r)}{10}\right)}\right) \tag{8-3}$$

where:

P_{in1}, P_{in2} to P_{inN}: channel powers (dBm) at the inputs of the amplifiers or ONEs on the relevant path through the network,

NF_1, NF_2 to NF_N: noise figures (dB) of the amplifiers or ONEs on the relevant path through the network.

The $OSNR_{out}$ value that is needed to meet the required system BER depends on many factors such as the bit rate, whether and what type of FEC is employed, the magnitude of any crosstalk or non-linear penalties in the DWDM line segments etc. and is outside the scope of reference situation considered within Recommendation ITU-T G.680.

An example calculation of the effect on OSNR of cascading multiple ONEs can be found in the next clause.

9.2 Example of calculation of the impact of cascaded ONEs on line system OSNR

In order to illustrate the effect of multiple ONEs on line system OSNR, an example system is shown in Figure 8-31.

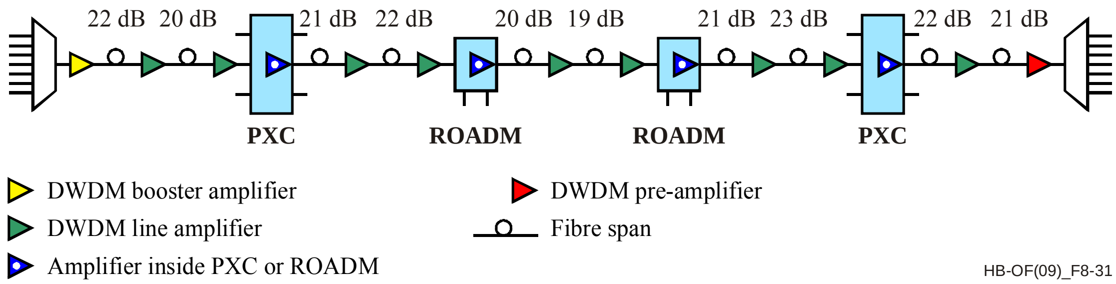


Figure 8-31 – Configuration of OSNR example system

This example also assumes:

– the channel signal-spontaneous noise figure for the ROADMs is 22 dB;

– the channel signal-spontaneous noise figure for the PXCs is 20 dB;

– the channel output power of all of the amplifiers is +1 dBm;

– the noise figures of the booster, line and pre-amplifiers are 7 dB;

– the gain of the booster amplifier is 10 dB.

Equation (8-3) can be applied to calculate the OSNR at the output of the demux for a channel wavelength of say 1 550.12 nm (193.4 THz). One element of this equation 10 log ($h\nu\nu_r$) for $\nu = 193.4$ THz and $\nu_r = 12.48$ GHz (0.1 nm) equals –58.0 dBm.

Equation (8-3) then becomes:

$$OSNR_{out} = -10\log\left(10^{-\left(\frac{-9-7+58}{10}\right)} + 10^{-\left(\frac{-21-7+58}{10}\right)} + 10^{-\left(\frac{-19-7+58}{10}\right)} + 10^{-\left(\frac{1-20+58}{10}\right)} + \ldots + 10^{-\left(\frac{-20-7+58}{10}\right)}\right)$$

Table 8-9 summarizes the values used for each term for P_{in} and NF and shows the resulting OSNR values at the output of each amplifier.

Table 8-9 – OSNR example summary

	Booster	**Line1**	**Line2**	**PXC1**	**Line3**	**Line4**	**OADM1**	**Line5**	**Line6**	**OADM2**	**Line7**	**Line8**	**PXC2**	**Line9**	**Pre1**
Pin (dBm)	–9	–21	–19	1	–20	–21	1	–19	–18	1	–20	–22	1	–21	–20
NF (dB)	7	7	7	20	7	7	22	7	7	22	7	7	20	7	7
Output OSNR	42.0	29.7	27.7	27.4	25.8	24.4	24.1	23.5	23.0	22.8	22.2	21.4	21.3	20.8	20.4

Hence, the OSNR at the output of the demux for the 1 550.12 nm channel would be 20.4 dB for this system.

The impact of cascaded ONEs on other parameter degradations and the method for combining them can be found in Recommendation ITU-T G.680.

CHAPTER 9

OPTICAL SYSTEM APPLICATIONS IN PASSIVE OPTICAL NETWORKS

Introduction

Progress in multimedia technologies has led to active development of many types of broadband services such as delivery of data, voice and video (triple-play) services. PONs (passive optical networks) can provide these services cost-effectively. PONs are optical access networks that extend from an operator central office into individual homes, apartment houses and business offices.

PONs are generally characterized by the absence of active components, with the exception of the sites where the OLT (optical line termination) and the ONU/ONT (optical network unit/optical network termination) are placed. However, a PON can also include a RE (reach extender), which contains active components, when a long distance between the OLT and the ONU is required. PONs are generally based on tree network topologies that use passive optical splitters. The general structure of a PON network is shown in Figure 9-1.

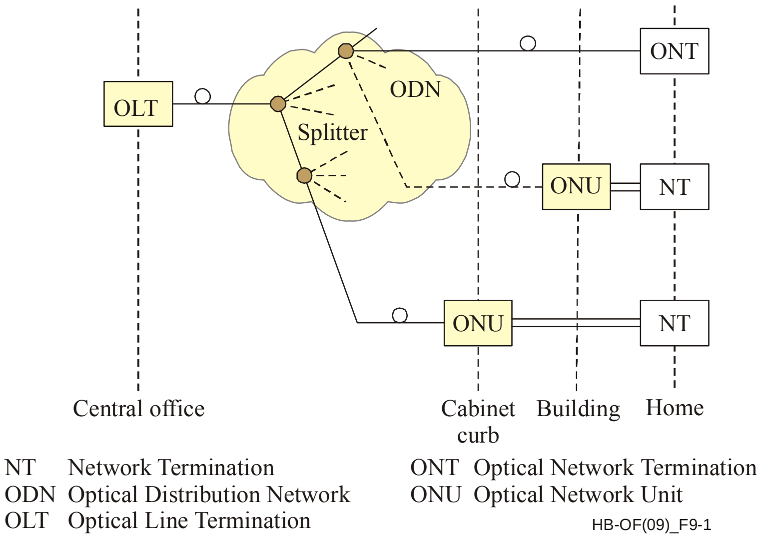


Figure 9-1 – General structure of a PON

At the network side there is an OLT, which is usually installed at the local central office (CO). The OLT is the interface between all the users connected to the given PON and the metro network.

Such users have access to the services offered by the network, through the network terminal (NT), and to the optical network through the ONU/ONTs.

The OLT and the ONUs are connected via an optical distribution network (ODN), which in many cases has a point-to-multipoint configuration with one or more splitters. Typical splitting factors include 1:16/1:32/1:64 or more.

PON splitters can be placed near the OLT or at the user sites, depending on the availability of fibres in the ODN, and/or on the ODN deployment strategy adopted by network operators.

The PON shown in Figure 9-1 is completely passive and the maximum distance between the OLT and the ONU is typically limited to 20 km at nominal split ratios. However, there are also solutions that include deployment of active elements in the network structure (e.g. optical amplifiers) when it is necessary to achieve a longer reach (e.g. up to 60 km) or to reduce the number of CO sites (CO concentration), or to connect a larger number of users to a single OLT port (e.g. where higher power budget is required due to a higher split ratio). Such solutions are typically referred to as “long-reach PON”.

As shown in Figure 9-1, a PON can be deployed in a FTTH (fibre to the home) architecture, where an ONU is provided at the subscriber’s premises, or in FTTB (fibre to the building), FTTC (fibre to the curb) or FTTCab (fibre to the cabinet) architectures, depending on local demands. In the latter cases, the optical link is terminated at the ONU, and the last stretch to the subscriber’s premises is typically deployed as part of the copper network using e.g. existing xDSL lines. Various types of xDSL family technologies are typically used, e.g. VDSL2 (very high speed digital subscriber line 2).

In the upstream channel (from subscriber to the OLT), access to a shared fibre channel is guaranteed by the use of the TDMA (Time Division Multiple Access) mechanism, where a certain bandwidth is assigned to each ONU by the OLT. In the downstream channel (from the OLT to the subscribers), there is only one transmitter located at the OLT, and data to individual ONUs is transmitted using TDM (Time Division Multiplexing). Figure 9-2 shows the use of these techniques in downstream and upstream channels.

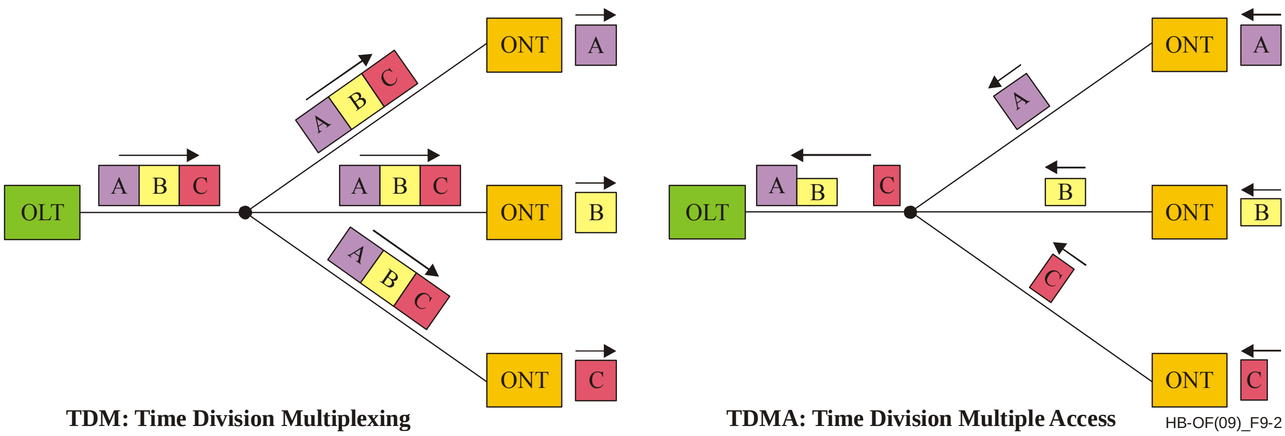


Figure 9-2 – TDM / TDMA technique

The downstream channel works in continuous mode, i.e. the cells/packets to be sent to the different ONTs are queued with no time gap between them. Idle cells/packets are generated by the OLT when necessary, in order to assure a continuous data flow in the downstream direction. This allows the ONTs to recover their own clock from the downstream data flow. The upstream channel works in burst mode instead, and when the cells/packets reach the OLT receiver, they have different amplitude, because the branches of the ODN have very likely different length and attenuation. A suitable guard time is guaranteed between consecutive cells/packets by the MAC (media access control) protocol. In case of poor upstream traffic, the OLT receiver must be able to cope with the reception of a cell/packet after a relatively long period of “silence”. Moreover, the length of the upstream cells/packets is not fixed, thanks to the DBA (Dynamic Bandwidth Assignment) algorithm, which assigns more bandwidth to the ONTs that have more upstream traffic to be transmitted at a particular moment. Also in the downstream direction, an ONT can receive more cells/packets than another one, but this is not reflected in Figure 9-2, for the sake of simplicity.

Based on the supported upstream and downstream data rate, there two main categories of PON: the BPON (broadband PON) and the G-PON (gigabit capable PON).

In order to reduce the need for dual fibre ODNs, the aforementioned PON systems can take advantage of the WDM signal multiplexing technique, where downstream and upstream channels are transmitted at different wavelengths: 1 260-1 360 nm for the upstream and 1 480-1 500 nm for the downstream. It is also possible to add another optical signal, to e.g. carry radio-frequency-video signals, in the bandwidth 1 530-1 580 nm, called the enhancement band.

BPON systems specifications are included in the ITU-T G.983 x-series of Recommendations, while those of the G-PON systems are included in the ITU-T G.984 x-series of Recommendations.

This handbook deals only with the network architecture (clause 1) and with the physical layer aspects of PON systems: the ODN (clauses 2-9) and the transmission systems (BPON / G-PON) between OLTs and ONUs (clauses 10-15). Aspects related with mechanisms for efficient use of downstream and upstream channels to guarantee collision-free data transmission using TDM/TDMA, as well as the management issues, are out of the scope of this handbook. Readers should refer directly to the above mentioned ITU-T Recommendations series for further information.

Moreover, considering that BPON and G-PON systems are very similar at the physical layer (with the main difference being the supported data rates), the remainder of this Chapter focuses on G-PON systems, which represent an evolutionary upgrade from BPON with:

i) higher capacity (BPON 622 Mbit/s downstream / 155 Mbit/s upstream, G-PON 2 488 Mbit/s downstream / 1 244 Mbit/s upstream);

ii) higher split ratio (BPON 1:32, G-PON 1:64 with potential support for 1:128);

iii) maximum reach (BPON 20 km, G-PON supports optical amplifiers in the ODN, called reach extenders, which extend the system reach up to 60 km).

1 Local access network architecture

An optical access network is the set of access links that share the same network-side interfaces and are supported by optical access transmission systems.

Figure 9-3 shows the optical access network architectures considered in the previously mentioned ITU-T Recommendations and that represent fibre to the cabinet (FTTCab), fibre to the curb (FTTC), fibre to the building (FTTB) and fibre to the home (FTTH) deployments.

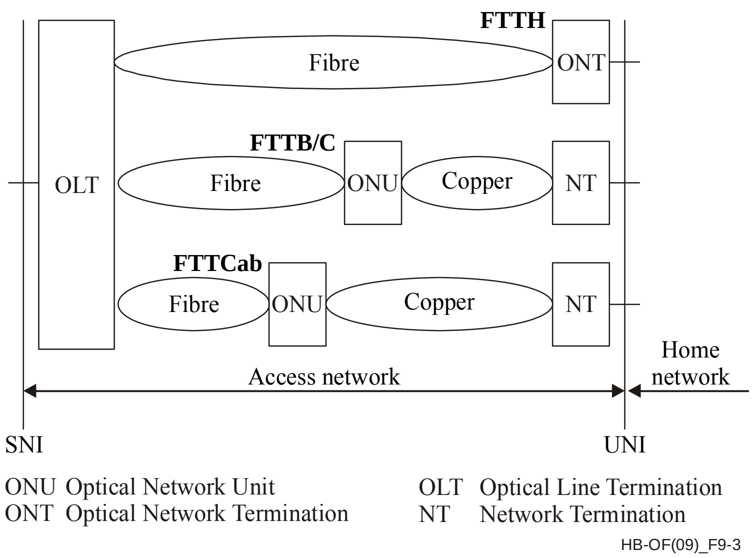


Figure 9-3 – Typical optical access networks architectures

In the FTTCab configuration, an ONU is installed in a street side cabinet. The connection between the OLT in the central office and the ONU is realized over an optical fibre link, while the connection between the ONU and the customer premises is realized using the copper lines of an existing local distribution network.

In the FTTB/FTTC configurations, an ONU is installed in a local curb or in the building (e.g. in the basement) where customers are located. Connectivity between individual network elements is realized exactly the same way as in the case of the FTTCab scenario described above.

In the FTTH configuration the complete link between the OLT and the ONU is realized with optical fibres, because the ONU is installed in the customer's premises.

The FTTCab, FTTC, FTTB, and FTTH network configurations can support different services.

As for the physical layer aspects, the meaning of the terms ODN, OLT and ONU is the following:

i) *optical distribution network (ODN)* is the physical network connecting the OLT and the ONU;

ii) *optical line termination (OLT)* is a device that terminates the common endpoint of an ODN;

iii) *optical network termination (ONT)* is a subscriber device that terminates any one of the distributed endpoints of an ODN. An ONT is a special case of an ONU;

iv) *optical network unit (ONU)* is a generic term denoting a device that terminates any one of the distributed endpoints of an ODN.

1.1 FTTC and FTTCab scenarios

For these deployment scenarios, the following service categories are typically considered:

i) Asymmetric data rate broadband services (e.g. digital broadcast services, VOD (video on demand), file download, online gaming, etc.);

ii) Symmetric data rate broadband services (e.g. content broadcast, e-mail, file exchange, distance learning, telemedicine, etc.);

iii) POTS and ISDN. The access network must be able to provide, in a flexible way, narrow-band telephone services with the appropriate timing;

iv) xDSL backhaul.

1.2 FTTB scenario

The FTTB scenario is divided into two sub-scenarios, one for multi-dwelling units (MDU) and the other one for business applications. Each scenario has specific service categories:

FTTB for MDU

i) Asymmetric data rate broadband services (e.g. digital broadcast services, VOD, file download, etc.);

ii) Symmetric data rate broadband services (e.g. content broadcast, e-mail, file exchange, distance learning, telemedicine, online-gaming, etc.);

iii) POTS and ISDN. The access network must be able to provide, in a flexible way, narrow-band telephone services with appropriate timing.

FTTB for business

i) Symmetric data rate broadband services (e.g. group software, content broadcast, e-mail, file exchange, etc.);

ii) POTS and ISDN. The access network must be able to provide, in a flexible way, narrow-band telephone services with the appropriate timing;

iii) Private line. The access network must be able to provide, in a flexible way, private line services at various rates, depending on customer needs.

1.3 FTTH scenario

In this scenario, the following service categories have been considered:

i) Asymmetric data rate broadband services (e.g. digital broadcast services, VOD, file download, etc.);

ii) Symmetric data rate broadband services (e.g. content broadcast, e-mail, file exchange, distance learning, telemedicine, online-gaming, etc.);

iii) POTS and ISDN. The access network must be able to provide, in a flexible way, narrow-band telephone services with the appropriate timing.

2 ODN Architectures

(For further information see Recommendation ITU-T L.42).

As already stated, an ODN is the physical network connecting the OLT and the ONU. It includes the optical fibres in the access network, power or wavelength splitters, filters, and other passive optical devices.

When designing or constructing an ODN, there are several possible architectures which can be considered. The most widely used ODN architectures include point-to-point and point-to-multipoint, each with specific advantages and drawbacks. The point-to-multipoint architecture seems to be at this moment the preferred one for most cases, mainly for its lower cost.

The following discussion will be mainly focused on the point-to-multipoint architecture.

2.1 Point-to-point ODN architecture

The basic configuration for a point-to-point optical access network is shown in Figure 9-4.

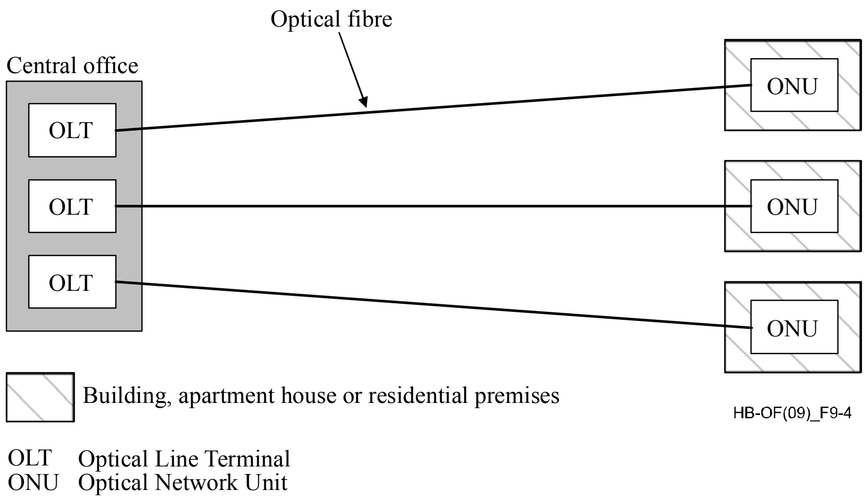


Figure 9-4 – Point-to-point network

Such an architecture distributes one or more fibres individually from the OLT located in the CO to ONUs typically located at customer premises. Therefore, a large number of fibres are installed in the outside plant and distributed from the CO to the customers. This configuration has typically low optical loss, does not require subscriber network resource sharing and supports a large distance between the CO and local customers. Moreover, such architecture may be suitable for customers with high bandwidth and/or high security requirements.

2.2 Point-to-multipoint ODN architecture

The basic configuration of a point-to-multipoint ODN architecture is shown in Figure 9-5.

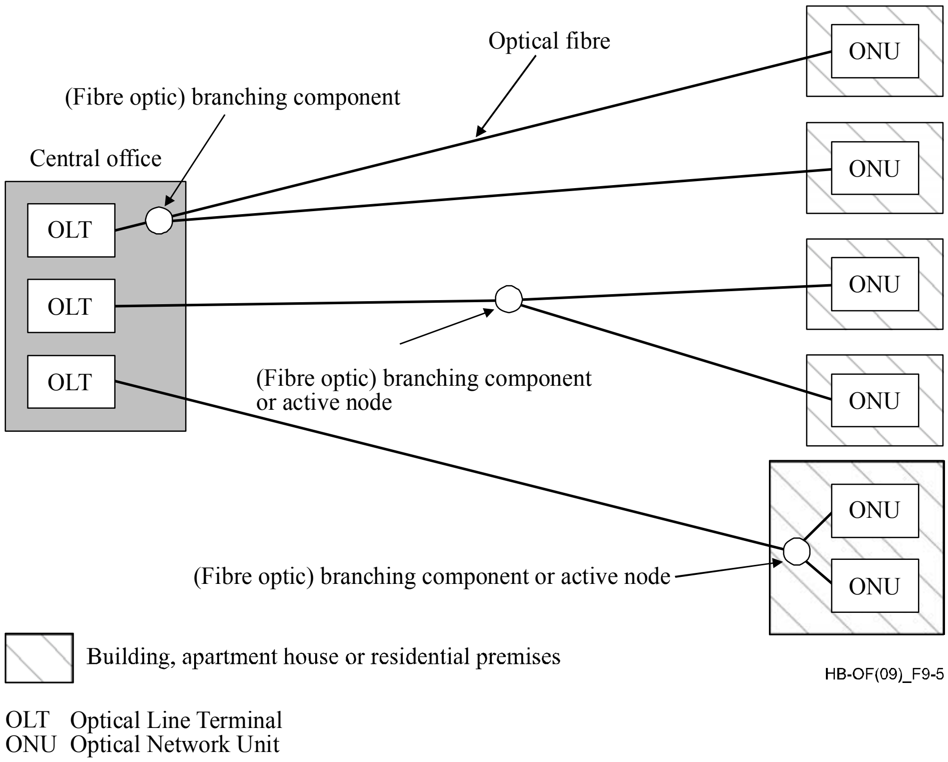


Figure 9-5 – Point-to-multipoint network

In the point-to multipoint ODN architecture an optical branching component is placed between the OLT and several ONUs connected to this OLT. As a consequence, the quantity of necessary fibre is less when compared with the point-to-point architecture.

Optical access networks based on a point-to-multipoint ODN architecture are usually referred to as *passive optical networks* (PONs).

3 Physical ODN configuration

A generic physical configuration of an optical distribution network is shown in Figure 9-6.

The ODN is defined between reference points S and R, which are defined as follows:

- S: Point on the optical fibre just after the OLT[a]/ONU[b] optical connection point (i.e. optical connector or optical splice).
- R: Point on the optical fibre just before the ONU[a]/OLT[b] optical connection point (i.e. optical connector or optical splice).

Definition [a] holds when considering optical signals travelling from the OLT to the ONU; definition [b] holds when considering optical signals travelling from the ONU to the OLT.

Depending on the physical realization of the ODN, the points S and R at each end of the ODN may be located either on the same fibre (i.e. they coincide) or on separate fibres.

At the physical layer, interfaces O_r and O_l may require more than one fibre, e.g. for separation of transmission directions or different types of signals (services).

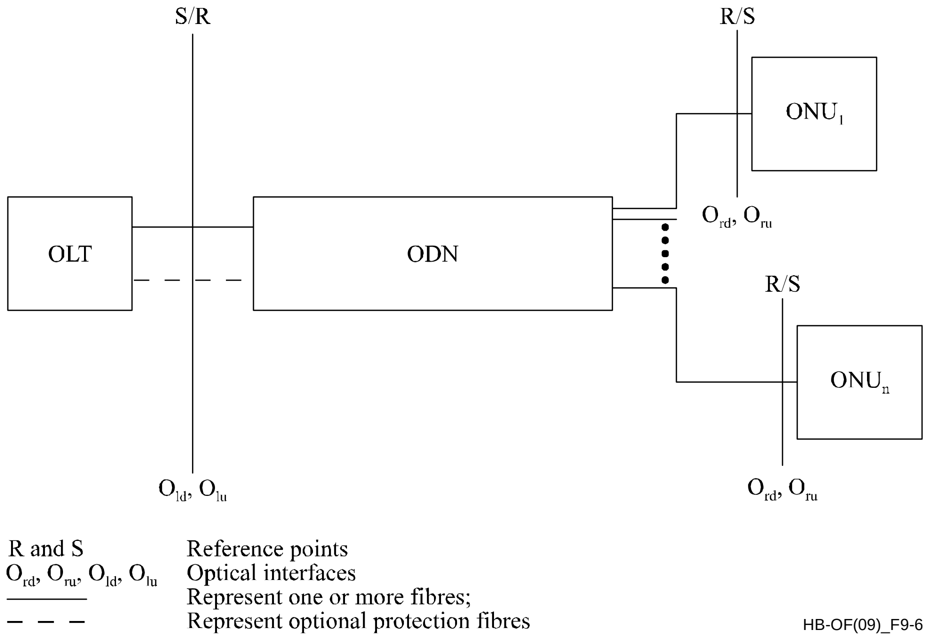


Figure 9-6 – Generic physical configuration of an ODN

The two directions for optical transmission in the ODN are identified as follows:

i) downstream: direction for signals travelling from the OLT to the ONU;

ii) upstream: direction for signals travelling from the ONU to the OLT.

Transmission in downstream and upstream directions can take place on the same fibre and components, or on separate fibres and components.

If additional connectors or other passive devices are needed for ODN rearrangement, they shall be located between S and R and their losses shall be taken into account in any optical loss calculation.

The location of optical branching components (in central offices, in outside plant or in customer premises) is the most important item in terms of this network design and construction.

In order to select the best location of splitters, the following network aspects should be considered:

i) the number and density of customers (including future demand);

ii) the network scalability (number of terminated fibres, total fibre length of network, etc.);

iii) the optical transmission performance (related to fibre type, attenuation range, differential optical path loss, return loss, dispersion, etc.) in accordance with Recommendations ITU-T G.983.x or ITU-T G.984.x;

iv) the construction, maintenance and upgrade costs.

Based on the characteristics of each access area and of the necessary ODN components, the most suitable of the following locations for the optical branching component should be selected.

The practical deployment of PON frequently shows that a multistage configuration is more suitable for optimizing both the cost of the network and the number of subscribers reached per OLT port. A multistage configuration is based on the insertion of two or more optical branching components in cascade.

3.1 Optical branching component in the central office

The basic configuration for an optical (or fibre-optic) branching component (also known as optical splitter) used in a central office is shown in Figure 9-7. Here, there is at least one fibre between the central office and the customer premises. Therefore, a large number of fibres are installed and distributed from the central office.

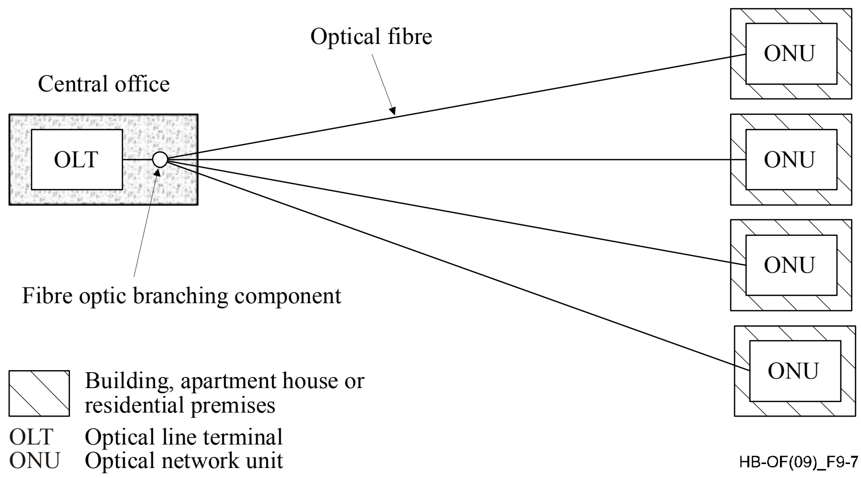


Figure 9-7 – PON configuration using optical branching components in a central office

The environmental conditions for the optical branching component are benign because it is installed inside a central office.

3.2 Optical branching component in outside plant

The basic configuration for an optical branching component used in an outside plant for a PON is shown in Figure 9-8. The optical branching component is located in a closure or cabinet in the outside plant. Therefore, the number of distributed fibres between an OLT and the optical branching component can be reduced.

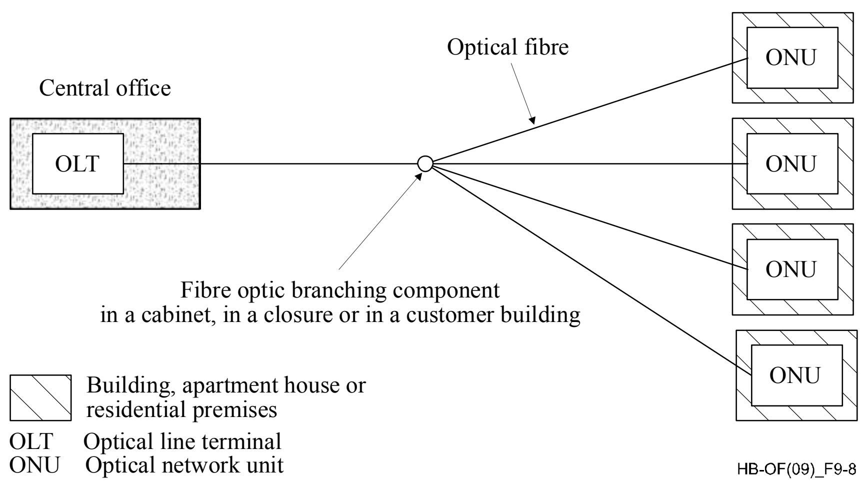


Figure 9-8 – PON configuration using optical branching components for outside plant

3.3 Optical branching component in the customer's building

The basic configuration of an optical branching component installed in the customer's building is shown in Figure 9-9. The branching component is normally located in a small enclosure inside the building.

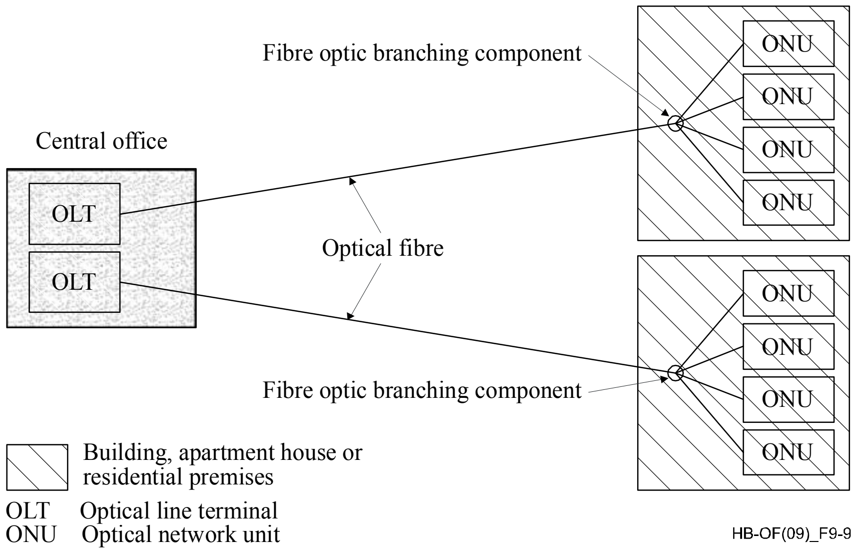


Figure 9-9 – PON configuration using optical branching components for a building

4 Evolutionary steps of ODNs

(For further information see Recommendation ITU-T L.65).

The development of ODNs can be divided into four stages based on the increasing number of customers, namely, the initial stage, the growth stage, the mature stage and the final stage (see Figure 9-10). The network design must take construction, maintenance, upgrade and operation into account.

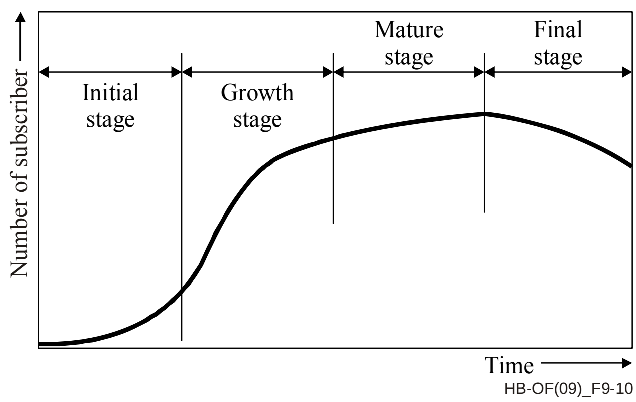


Figure 9-10 – Progressive increase in the number of PON users

4.1 Initial stage

At the initial stage, the demand for optical fibre will be dispersed over a wide area. Therefore it is important for the optical fibre distribution scheme to take into account the potential demand in the growth and mature stages. For example, the number of fibres in the cables and the number of branches for the branching devices in an optical distribution network are important parameters, as far as future demand is concerned. Technologies that support deferred cost for subsequent up-scaling of fibre capacity could be considered.

4.2 Growth stage

At the growth stage, the demand for optical fibres will occur randomly in a wide area. It is therefore very important for the optical fibre distribution scheme to be able to quickly respond to this demand. Moreover, at this stage it is important to be able to easily maintain and operate the optical access network infrastructure. For example, there will be a need to use the optical fibre network maintenance support, monitoring and testing system described in Chapter 10 and in Recommendations ITU-T L.40 and ITU-T L.53. In addition, an optical access network infrastructure database will need to be constructed and used to operate and administer the huge infrastructure expansion. Additionally, it is anticipated that overlay of fibre networks into areas of legacy copper networks will eventually occur, presenting challenges for both aerial and underground deployment.

It will be important to use existing facilities, such as cable ducts, for the effective and economical installation of optical fibre cables. For example, several optical fibre cables could be installed in a single cable duct. This is because the optical access network infrastructure will increase and the available facilities may become scarce. Consideration could be given to active cable duct management solutions to ensure their future economical usability.

4.3 Mature stage

At the mature stage, the demand for new optical fibres will be slow and a huge optical access network infrastructure will be already deployed. Therefore, it is of utmost importance that the optical fibre distribution scheme be easy to maintain and operate. This will require an optical fibre network maintenance support, monitoring and testing system, and a corresponding database.

In addition, customers who require very high reliability should be provided with two or more fibres using a ring network.

4.4 Final stage

At the final stage, demographic considerations may determine that the demand for optical fibre may decline and the plant and land re-used for a different purpose or purposes, e.g. industrial, commercial, retail or residential, or a mix of these uses. Such events may be common in urban areas. It is likely that there will be a threshold at which systems and networks will become uneconomic to operate and need to be decommissioned.

Telecom operators should select appropriate architectures and optical components (e.g. optical fibre cable and passive optical components), and design and construct optical access networks taking into account of the above factors in each stage.

5 Upgrading a PON

(For further information see Recommendation ITU-T L.42).

When the transmission capacity, transmission length and/or number of customers increase, it will be necessary to upgrade the passive optical network. At such a time, the alternatives contained in Table 9-1 should be considered in order to select the appropriate method for upgrading the network.

Table 9-1 – Network upgrade method

Upgrade method	Point-to-multipoint network
Increase transmission capacity	• Use a high bit rate system, • Use a WDM system (CWDM, DWDM)
Increase transmission length	• Use a WDM system (an optical branching component with wavelength multiplexer and demultiplexer), • Reduce number of branches or split ratios or change to point-to-point network, • Use optical fibre amplifiers, • Use equipment associated with a higher class PON (see Table 9.2), • Implement a PON reach extension technology (see ITU-T G.984.6)
Increase number of customers	• Increase the number of branches, • Install new cables

6 Passive optical components used in an ODN

The main passive optical components that constitute an ODN are: single-mode optical fibre cable, optical fibre joints and optical branching components.

6.1 Optical fibre cable

The single-mode optical fibres used in an ODN are described in Chapter 1 of this handbook and in Recommendations ITU-T G.652 and ITU-T G.657.

The optical fibre cables that are used in ODNs are described in Chapter 2 of this handbook and in Recommendations ITU-T L.10, ITU-T L.26, ITU-T L.43 and ITU-T L.58.

6.2 Optical fibre joints

Optical fibre joints are formed by using a fusion splice, a mechanical splice or a fibre optical connector.

The characteristics of fusion and mechanical splices are described in Chapter 5 and in Recommendations ITU-T G.671 and ITU-T L.12.

Various types of fibre optical connectors and their characteristics are described in Chapter 5 and in Recommendations ITU-T G.671 and ITU-T L.36.

6.3 Optical branching components

(For further information see Recommendations ITU-T L.52 and ITU-T G.671).

Two types of optical branching components can be used in an ODN. One type has a wavelength multiplexer and demultiplexer, the other does not.

The ports of the branching devices can be connectorized or not.

6.3.1 Optical branching components without wavelength multiplexer and demultiplexer

An optical branching component (wavelength non-selective) is a passive component without a wavelength multiplexer and demultiplexer, possessing three or more ports which distributes optical power among its ports in a predetermined fashion, without any amplification, switching, or other active modulation (see Figure 9-11a). It is also called an "optical splitter" or an "optical coupler".

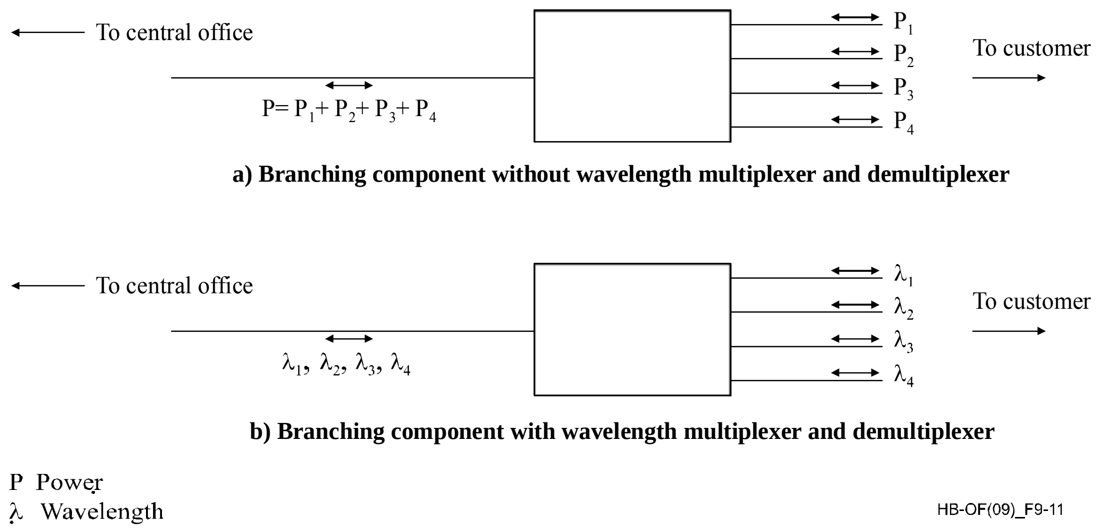


Figure 9-11 – Optical branching component

The optical branching components (wavelength non-selective) for PONs are characterized in Recommendation ITU-T G.671 by the term $1 \times X$, where $X = 4, 8, 16$ or 32. The insertion loss increases as the number of branches is increased.

6.3.2 Optical branching components with wavelength multiplexer and demultiplexer

An optical branching component with a wavelength multiplexer and demultiplexer (see Figure 9-11b) has two or more input (output) ports and one output (input) port, where the light in each input port is restricted to a preselected wavelength range (the output of each port is a different preselected wavelength range), and the output is a combination of the light from the input ports (the input is an optical signal comprising two or more wavelength ranges). Such elements are mainly used in WDM systems. When the number of channels increases in the WDM enabled splitters, the insertion loss does not grow rapidly like in the case of WDM-less splitters.

6.3.3 Other characteristics of the optical branching components

The number of branches of the optical branching component should be selected once the following factors are properly accounted for: number of potential customers (including future demand), the maximum transmission distance and the total optical loss. It is possible to respond to user demand in a flexible manner by increasing the number of branches. Such flexibility is however limited by the number of free ports on the optical branching component. Once all ports are populated, further increase in the customer density would require replacing the optical branching component, which in most cases warrants a redesign of the ODN, given the limitation of optical power budget.

The optical performance of the optical branching components (PON splitters) is described in Chapter 5 and in Recommendation ITU-T G.671.

Environmental conditions, namely, temperature, humidity and mechanical conditions, may affect performance. Such environmental conditions differ from region to region, especially when using an optical branching component in the ODN. The optical branching components should be designed and protected from the environmental conditions, such as temperature, vibrations, water, etc., to enable it to operate under such conditions taking into account Recommendation ITU-T L.37.

Moreover the optical branching component should be protected from adverse biological factors. For further information on this specific issue see Recommendation ITU-T L.46.

6.4 Other passive optical components

i) Optical attenuators

An optical attenuator with either fixed or variable attenuation may be necessary to adjust optical power budgets to the required ranges. The characteristics of the optical attenuators are described in Chapter 5 and in Recommendations ITU-T G.671 and Recommendation ITU-T L.31.

ii) Optical filters

An optical filter may be necessary to filter out the required wavelengths used for a particular service and to reject other service's wavelength bands or optical test wavelengths transported in the ODN. Such filters have properly formed spectral responses, in such a way that they can select very narrow or very broad wavelength regions depending on the target application. The optical filter performance should follow the specifications of Recommendation ITU-T G.671.

iii) Passive optical nodes

Passive optical nodes properly store and protect all compatible passive devices, such as splices, branching devices and connectors, without altering their performances. Moreover they contain, protect and manage the fibre extra length.

The general characteristics of the passive optical nodes are described in Chapter 5 and in Recommendation ITU-T L.51.

Depending on the environment, they can be classified as:

– for indoor applications (optical distribution frame, ODF), as described in Chapter 5 and in Recommendation ITU-T L.50;

– for the outside plant (joint closures) in aerial and underground applications (described in Chapter 5 and in Recommendation ITU-T L.13) or in street cabinets.

7 ODN model loss calculations

(For further information see Recommendation ITU-T G.982).

Loss allowance for the optical power budget is defined as the loss (expressed in dB), between specific reference points of the ODN (S/R and R/S). This includes the loss due to fibre length and passive optical components (e.g. optical branching devices, splices and connectors). The loss allowance has the same value both in the downstream and the upstream direction. Even if the fibre loss and all passive components losses are wavelength dependent, the loss allowance is assumed in ITU-T Recommendations to have the same value for both the downstream and the upstream directions.

The following parameters are important for the overall system performance:

– maximum difference of loss between the optical paths of the ODN;

– maximum allowable path loss, defined as the difference between minimum transmitter output power and maximum receiver sensitivity, both under end of life conditions (including variations due to temperature, ageing, etc.);

– minimum allowable loss, defined as the difference between maximum transmitter output power and minimum receiver overload, both under end of life conditions.

These maximum and minimum losses shall be defined as the worst case loss values over the required environmental and wavelength ranges and not just measured at a given wavelength, time and temperature.

These definitions are analogous to those of Recommendation ITU-T G.957, where the attenuation ranges for SDH optical interfaces are specified.

Figure 9-12 provides a schematic representation of the downstream optical path between the OLT and an ONU.

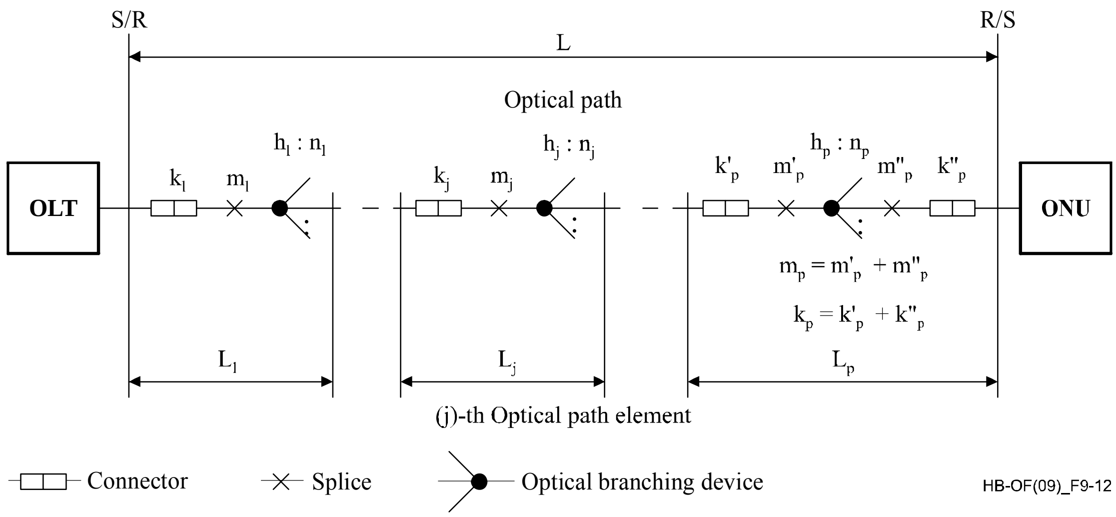


Figure 9-12 – Schematic representation of the optical path between the OLT and an ONU

The ODN comprises *P* splitting levels, even though 1 or 2 splitting levels are typically adopted.

Within the ODN, several optical paths can be identified. Each optical path connects a specific ONU to the OLT. The optical path between the OLT and an ONU, or more generally, between reference points S/R and R/S, is formed by a cascade of *P* optical path elements. The *P*-th splitting level is shown as a cascade of *P* optical path elements. The (j)-th optical path element begins at the output port of the (j – 1)-th optical branching device and ends at the output port of the (j)-th optical branching device, with the following exceptions:

– $j = 1$, the optical path element begins at the S/R reference point and ends at the output port of the first optical branching device (or, for $P = j = 1$, at the R/S reference point).

– $j = P$, the optical path element begins at the output port of the (P – 1)-th optical branching device (or, for $P = j = 1$, the S/R reference point) and ends at the R/S reference point, in order to take into account possible splices and connectors present at the output after the last optical branching device.

The (j)-th optical path element consists of optical fibre of length L_j and of the following passive optical components (the sequence of components in each path element is arbitrary):

– the (j)-th optical branching device with split ratio h_j:n_j ($h_j \geq 1$, $n_j \geq 1$);

– k_j connectors, with $k_j \geq 0$;

– m_j splices, with:

where:

$\overline{m}_{dj}$: the average number of planned splices per unit length of fibre in the first installation phase;

$\overline{m}_{rj}$: the average number of repair splices per unit length of fibre, foreseen in the operational phase;

m_{aj}: the number of additional planned splices not taken into account in the figure $\overline{m}_{dj} L_j$, in the first installation phase; m_{aj} takes into account the splices due to the installation of the optical branching device and the extra splices at the termination points of the ODN (e.g. at an optical distribution frame inside the central office, at the optical termination point at ONU side).

In conclusion, the whole optical path consists of the optical fibre of length $L = \sum_{j=1}^{p} L_j$ and of the following passive optical components:

– P = number of optical branching devices, with split ratio h_j:n_j ($h_j \geq 1$, $n_j \geq 1$, $j = 1, ..., P$);

– $k = \sum_{j=1}^{p} k_j$ connectors;

– $m = \sum_{j=1}^{p} m_j$ splices.

The overall split ratio of the optical path is: $n = \prod_{j=1}^{p} n_j$.

In the case of a point-to-point ODN configuration, there is no optical branching device in the optical signal path. Consequently, only one optical path element is considered, and the previous evaluations are still valid provided that any reference to the optical branching device is excluded from calculations.

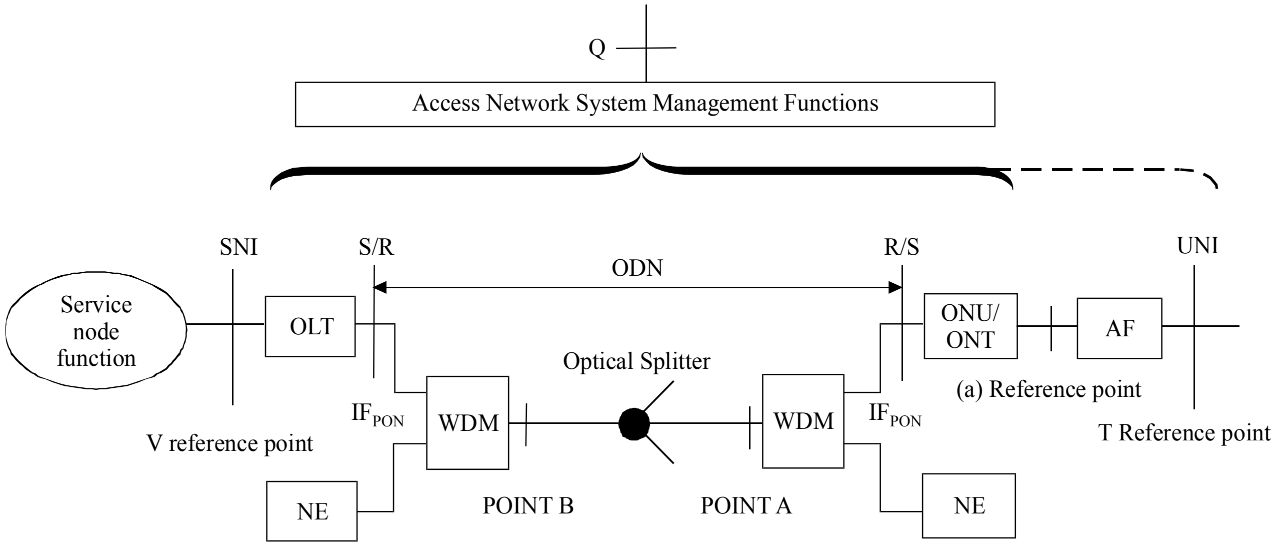
The optical loss of the given ODN optical path is calculated by adding the losses of all optical components along such an optical path. A statistical approach can be used in the summation of the terms related with the attenuation of the fibre, splices and connectors, in order to avoid over-specification of the ODN. The statistical distribution of the overall optical path loss can be obtained by combining the statistical distributions of losses of the various components of the optical path. This can be done using various statistical techniques, some being more accurate than others. For further information see Chapter 7, Recommendation ITU-T G.982 and Supplement 39 to the ITU-T G-series of Recommendations.

8 General characteristics of G-PON systems

The general characteristics of G-PON systems are described in Recommendation ITU-T G.984.1.

As said above, G-PON systems are characterized, in general, by an optical line termination (OLT) system and an optical network unit (ONU) or optical network termination (ONT) with a passive optical distribution network (ODN) interconnecting them. There is, in general, a one-to-many relationship between the OLT and the ONU, respectively. The optical section of a local access network system can be either active or passive, and its architecture can be either point-to-point or point-to-multipoint. The architectures considered are essentially fibre to the cabinet (FTTCab), fibre to the curb (FTTC), fibre to the building (FTTB) and fibre to the home (FTTH).

The reference configuration for a G-PON is shown in Figure 9-13.



ONU	Optical Network Unit
ONT	Optical Network Terminal
ODN	Optical Distribution Network
OLT	Optical Line Termination
WDM	Wavelength Division Multiplex Module (If WDM is not used, this function is not necessary.)
NE	Network Element which uses the different wavelength from the OLT and the ONU
AF	Adaptation Function (Sometimes, it may be included in the ONU.)
SNI	Service Node Interface
UNI	User Network Interface
S	Point on the optical fibre just after the OLT (Downstream)/ONU (Upstream) optical connection point (i.e., optical connector or optical splice)
R	Point on the optical fibre just before the ONU (Downstream)/OLT (Upstream) optical connection point (i.e., optical connector or optical splice
(a) Reference point	If AF is included in the ONU, this point is not necessary.
POINT A/B	If WDM is not used, these points are not necessary.

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NOTE – Whether or not the AF is an operating object of the Q interface depends on the service.

Figure 9-13 – Reference configuration for a G-PON

The service node interface (SNI) is an interface that provides customer access to a service node. See Recommendation ITU-T G.902.

The user network interface (UNI) is the interface between the terminal equipment and a network termination at which the access protocols apply (see Recommendation ITU-T I.112).

The interface at reference points S/R and R/S is defined as IF_{PON}. This is a PON-specific interface that supports all the protocol elements necessary to allow transmission between OLT and ONU.

The part of the G-PON between the two reference points S/R (IF_{PON}) and R/S (IF_{PON}) is indicated as ODN.

The wavelength division multiplexing (WDM) module allows bidirectional multiplexing using different optical wavelength for up and downstream signals.

9 Characteristics of the ODN physical layer

(For further information see Recommendation ITU-T G.984.2).

The physical medium dependent layers parameters of an ODN are shown in Table 9-2.

Table 9-2 – Physical medium dependant layer parameters of an ODN

Items	Unit	Specification
Fibre type (Note 1)	–	Recommendation ITU-T G.652
Attenuation range (Recommendation ITU-T G.982)	dB	Class A: 5-20 Class B: 10-25 Class C: 15-30
Differential optical path loss	dB	15
Maximum optical path penalty	dB	1
Maximum logical reach	km	60 (Note 2)
Maximum differential logical reach	km	20
Maximum fibre distance between S/R and R/S points	km	20 (10 as option)
Minimum supported split ratio	–	Restricted by path loss. PON with passive splitters (16, 32 or 64 way split)
Bidirectional transmission	–	1-fibre WDM or 2-fibre
Maintenance wavelength	nm	To be defined
NOTE 1 – For future extended reach (> 20 km), the use of different types of fibre is for further study, for a future PMD specification. NOTE 2 – This is the maximum distance managed by the higher layers of the system (MAC, TC, Ranging), in view of a future PMD specification.		

The meaning of the items listed in the above table are in the following.

Fibre type: See § 6.1

Attenuation range: Three classes of attenuation ranges have been specified in Recommendation ITU-T G.982:

Table 9-3 – Classes for optical path loss

	Class A	Class B	Class C
Minimum loss	5 dB	10 dB	15 dB
Maximum loss	20 dB	25 dB	30 dB
NOTE – The requirements of a particular class may be more stringent for one system type than for another, e.g. the class C attenuation range is inherently more stringent for TCM (time compression multiplexing) systems due to the use of a 1:2 splitter/combiner at each side of the ODN, each having a loss of about 3 dB.			

Two further classes for optical path loss (B+ and C+) have been defined respectively in Recommendation ITU-T G.984.2 Amend.1 and in Recommendation ITU-T G.984.2 Amend.2. These two new classes are described in § 11.2 and in § 11.3.

Attenuation specifications are assumed to be worst-case values and include losses due to splices, connectors, optical attenuators (if used) or other passive optical devices, and any additional cable margins, to cover allowances for:

i) future modifications to the cable configuration (additional splices, increased cable lengths, etc.);

ii) fibre cable performance variations due to environmental factors; and

iii) degradation of any connector, optical attenuators (if used) and other passive optical devices between points S and R, when provided.

Differential optical path loss means the optical path loss difference (i.e. between any two ONU) between the highest and lowest optical path loss in the same ODN. The maximum differential optical path loss should be 15 dB (see Recommendation ITU-T G.983.1).

Maximum optical path penalty. The receiver is required to tolerate an optical path penalty not exceeding 1 dB to account for total degradations due to reflections, inter-symbol interference, mode partition noise, and laser chirp.

Maximum logical reach is the maximum distance that can be achieved between ONU and OLT except for the limitation of the physical layer. In G-PON, the maximum logical reach is defined as 60 km (see Recommendation ITU-T G.982).

In other words, the maximum logical reach is the maximum distance managed by the higher layers of the system (MAC, TC, ranging), in view of a future PMD specification.

Maximum differential logical reach means the logical reach difference between the highest and lowest logical reach in the same ODN. The maximum differential logical reach should be 20 km.

The maximum fibre distance between S/R and R/S points is 20 km.

In G-PON, two options are defined for the physical reach: 10 km and 20 km. While MLM laser types are not applicable to support the full ODN fibre distance of 20 km, such lasers can be used if the maximum ODN fibre distance between R/S and S/R is restricted to 10 km.

Minimum supported split ratio is related to path loss.

Split ratios of up to 1:64 are realistic for the physical layer given the current technology. However, anticipating the continued evolution of optical modules, the traffic control (TC) layer also considers split ratios up to 1:128. While a 1:128 split is physically possible in G-PON, the maximum number of connected ONUs is limited by the addressing space of ONU-ID to 126 at most.

Basically, the larger the split ratio is for G-PON, the more attractive it is for operators. However, a larger split ratio implies greater optical splitting which creates the need for an increased power budget to support the physical reach. There is obviously a trade-off between increasing the optical budget and the cost of such a technical solution. Thus, operators must usually carefully balance deployment costs and business models. In practical cases, in order to increase income per central office, operators try to increase subscriber density per OLT port, using high split systems and maximizing take ratios. Such an approach is typically referred to as “deploy as you grow”, where additional branches of PON are added to infrastructure when the capacity of the existing branches is exhausted. Alternatively, some operators deploy a lot of dark fibre (ODN without connected subscriber units), which is lit when local demand occurs. Note however that such an approach requires higher up-front investment.

Bidirectional transmission can be made on the same fibre and components (diplex working/ duplex working) or on separate fibres and components (simplex working).

In Recommendation ITU-T G.983.1, diplex working and duplex working are defined as follows:

i) Diplex working: bidirectional communication using a different wavelength for each direction of transmission over a single fibre.

ii) Duplex working: a bidirectional communication using the same wavelength for both directions of transmission over a single fibre.

Currently deployed G-PON systems usually adopt diplex transmission.

Maintenance wavelength. (See § 14.)

10 G-PON systems: physical media dependent (PMD) layer specifications

The main functions of a G-PON system physical layer are shown in Figure 9-14.

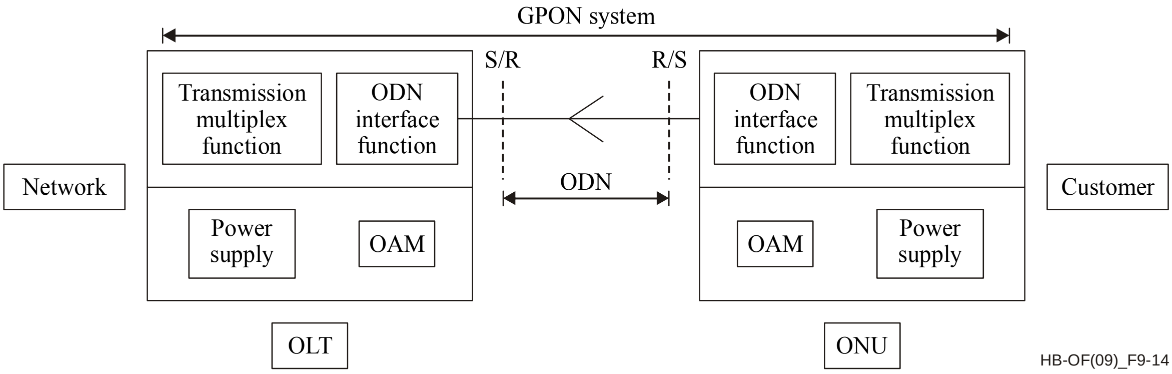

Figure 9-14 – General diagram of a G-PON system

Specific values of the parameters for each interface (e.g. downstream at 1 244 Mbit/s, upstream at 622 Mbit/s) are specified in Recommendation ITU-T G.984.2.

The nominal bit rates of the OLT-to-ONU (downstream) signal specified in Recommendation ITU-T G.984.2 are 1 244.16 or 2 488.32 Mbit/s.

The nominal bit rates of the ONU-to-OLT (upstream) signal specified in Recommendation ITU-T G.984.2 are 155.52, 622.08, 1 244.16 or 2 488.32 Mbit/s.

Among all the possible alternatives allowed by the combination of the above downstream/upstream bit rates, the only one that the industry is developing at present is: 2 488.32 Mbit/s (downstream) and 1 244.16 Mbit/s (upstream). All the parameters to be defined between the optical interfaces related to these two data bit rates are categorized in Recommendation ITU-T G.984.2.

There is a separate type of ONU for each optical path loss Class A, B or C.

All parameter values specified are worst-case values assumed to be met over the range of standard operating conditions (i.e. temperature and humidity ranges) including ageing effects. The parameters are specified relative to an optical section design objective of a bit error ratio (BER) not worse than 1×10^{-10} for the extreme case of optical path attenuation and dispersion conditions.

Bidirectional transmission is accomplished by use of either a wavelength division multiplexing (WDM) technique on a single fibre, or unidirectional transmission over two fibres.

The line code is scrambled NRZ downstream and upstream. For more information on line codes see Chapter 7.

The operating wavelength range for the downstream direction on single fibre systems shall be 1 480-1 500 nm.

The operating wavelength range for the downstream direction on two fibre systems shall be 1 260-1 360 nm.

The operating wavelength range for the upstream direction shall be 1 260-1 360 nm.

11 G-PON systems specification

11.1 2 488 Gbit/s downstream, 1 244 Gbit/s upstream G-PON

Table 9-4 contains one of the G-PON systems specified in Recommendation ITU-T G.984.2. It refers to the optical interface parameters of 2 488.32 Mbit/s in the downstream direction.

Table 9-4 – Optical interface parameters of 2 488 Mbit/s in the downstream direction

Items	Unit	Single fibre			Dual fibre		
OLT transmitter (optical interface O_{ld})							
Nominal bit rate	Mbit/s	2 488.32			2 488.32		
Operating wavelength	nm	1 480-1 500			1 260-1 360		
Line code	–	Scrambled NRZ			Scrambled NRZ		
Mask of the transmitter eye diagram	–	Figure 2 in ITU-T G.984.2			Figure 2 in ITU-T G.984.2		
Maximum reflectance of equipment, measured at transmitter wavelength	dB	NA			NA		
Minimum ORL of ODN at O_{lu} and O_{ld} (Notes 1 and 2)	dB	32			32		
ODN Class		A	B	C	A	B	C
Mean launched power MIN	dBm	0	+5	+3 (Note 4)	0	+5	+3 (Note 4)
Mean launched power MAX	dBm	+4	+9	+7 (Note 4)	+4	+9	+7 (Note 4)
Launched optical power without input to the transmitter	dBm	NA			NA		
Extinction ratio	dB	more than 10			more than 10		
Tolerance to the transmitter incident light power	dB	more than –15			more than –15		
If MLM Laser – Maximum RMS width	nm	NA			NA		
If SLM Laser – Maximum –20 dB width (Note 3)	nm	1			1		
If SLM Laser – Minimum side mode suppression ratio	dB	30			30		
ONU Receiver (optical interface O_{rd})							
Maximum reflectance of equipment, measured at receiver wavelength	dB	–20			–20		
Bit error ratio	–	less than 10^{-10}			less than 10^{-10}		
ODN Class		A	B	C	A	B	C
Minimum sensitivity	dBm	–21	–21	–28 (Note 4)	–21	–21	–28 (Note 4)
Minimum overload	dBm	–1	–1	–8 (Note 4)	–1	–1	–8 (Note 4)
Consecutive identical digit immunity	bit	more than 72			more than 72		
Jitter tolerance	–	Figure 5 in ITU-T G.984.2			Figure 5 in ITU-T G.984.2		
Tolerance to the reflected optical power	dB	less than 10			less than 10		

Notes to Table 9-4:

NOTE 1 – The value of "minimum ORL of ODN at point O_{ru} and O_{rd}, and O_{lu} and O_{ld}" should be more than 20 dB in the optional cases that are described in Recommendation ITU-T G.983.1, Appendix I.

NOTE 2 – The values on ONU transmitter reflectance for the case that the value of "minimum ORL of ODN at point O_{ru} and O_{rd}, and O_{lu} and O_{ld}" is 20 dB are described in Recommendation ITU-T G.983.1, Appendix II.

NOTE 3 – Values of maximum −20 dB width, and minimum side mode suppression ratio are referred to in Recommendation ITU-T G.957.

NOTE 4 – These values assume the use of a high-power DFB laser for the OLT transmitter and of an APD-based receiver for the ONU. Taking future developments of SOA technology into account, a future alternative implementation could use a DFB laser + SOA, or a higher power laser diode, for the OLT transmitter, allowing a PIN-based receiver for the ONU. The assumed values would then be (conditional to eye-safety regulation and practice):

Mean launched power MAX OLT Transmitter: +12 dBm,

Mean launched power MIN OLT Transmitter: +8 dBm,

Minimum sensitivity ONU Receiver: −23 dBm,

Minimum overload ONU Receiver: −3 dBm.

The meaning of all these parameters is explained in Recommendation ITU-T G.984.2. Most of them are also used for the metro and for the backbone networks and are dealt with in Chapter 6.

11.2 Attenuation class B+ for the 2 488 Gbit/s downstream, 1 244 Gbit/s upstream G-PON

(For further information see Recommendation ITU-T G.984.2, Amend.1).

The widespread interest in the 2.4 Gbit/s downstream, 1.2 Gbit/s upstream G-PON system has provided increased visibility into the feasibility of loss budgets for this system. The industry most recent best practices for this rate combination are outlined in the following.

The notable variations from the loss budgets described in § 11.1 include:

- overall loss budgets midway between class B and class C;
- different value of optical path penalties;
- the OLT must support FEC in the downstream.

These variations can provide increased capabilities for operation of G-PON systems.

The optical specifications for the OLT and ONU optics are given in Table 9-5. This table refers to power levels measured at the interface points shown in Figure 9-14. These specifications are meant to augment similar specifications found in Table 9-4. All other specifications found elsewhere in the table still apply.

The ONU sensitivity can be achieved either using an APD without FEC, or a PIN with FEC. The choice is a matter of ONU implementation. The APD solution is seen as an immediately available option, while the PIN with FEC solution is a longer-term option that depends on the introduction of higher performance receiver circuitry.

Table 9-5 – Optical power levels for the 2.4 Gbit/s downstream, 1.2 Gbit/s upstream system

Items	Unit	Single fibre	Items	Unit	Single fibre
OLT:		**OLT**	**ONU:**		**ONU**
Mean launched power MIN	dBm	+1.5	Mean launched power MIN	dBm	+0.5
Mean launched power MAX	dBm	+5	Mean launched power MAX	dBm	+5
Minimum sensitivity	dBm	–28	Minimum sensitivity	dBm	–27
Minimum overload	dBm	–8	Minimum overload	dBm	–8
Downstream optical penalty	dB	0.5	Upstream optical penalty	dB	0.5

The link budget is given in Table 9-6. This budget covers all optical components between the OLT and ONU, including non-integrated WDM filters for the multiplex of video overlays and other enhancement band services, and must include any Raman impairment from the overlay signal.

Table 9-6 – Loss budgets for the G-PON system

Items	Unit	Single fibre
Minimum optical loss at 1 490 nm	dB	13
Minimum optical loss at 1 310 nm	dB	13
Maximum optical loss at 1 490 nm	dB	28
Maximum optical loss at 1 310 nm	dB	28

The maximum optical loss of Class B+ (28 dB) is placed between those of Class B (25 dB) and Class C (30 dB).

This 28 dB loss budget is calculated for the worst case scenario, i.e. considering the minimum value of the Tx mean launched power and the minimum Rx sensitivity. For the upstream channel we have: +0.5 dB (ONU Tx) – (–28 dB (OLT Rx)) = 28.5 dB. An optical penalty of –0.5 dB must be applied to this value, obtaining 28 dB of maximum optical loss budget. The calculation on the downstream channel (OLT Tx and ONU Rx) leads to the same value.

11.3 Attenuation class C+ for the 2 488 Gbit/s downstream, 1 244 Gbit/s upstream G-PON

(For further information see Recommendation ITU-T G.984.2, Amend.2).

The single-sided extended (extension only at OLT side) 2 488/1 244 Gbit/s G-PON is achieved by using a more capable OLT interface. This interface would have all the characteristics of the existing S/R interface, with the exception of certain OLT optical parameters, as listed in Table 9-7.

Table 9-7 – Optical power levels for the 2.4 Gbit/s downstream, 1.2 Gbit/s upstream single-sided reach extended system (Class C+)

Items	Unit	Single fibre
Reach Extended OLT:		**OLT**
Mean launched power MIN	dBm	+3
Mean launched power MAX	dBm	+7
Downstream optical penalty	dB	1
Bit error ratio (pre-FEC) (Note 1)		10^{-4}
Minimum sensitivity (Note 1)	dBm	–32
Minimum overload	dBm	–12
Upstream wavelength range (ITU-T G.984.5)	nm	1 290 ~ 1 330
ONU:	**–**	**ONU**
Mean launched power MIN	dBm	+0.5
Mean launched power MAX	dBm	+5
Upstream optical penalty	dB	0.5
Upstream wavelength range (ITU-T G.984.5)	nm	1 290 ~ 1 330
Bit error ratio (pre-FEC) (Note 2)	–	10^{-4}
Minimum sensitivity (Note 2)	dBm	–30
Minimum overload (Note 3)	dBm	–8

NOTE 1 – The OLT sensitivity assumes the use of the optional RS (255,239) FEC capability of the G-PON TC layer, as well as intrinsic detector technology improvements, e.g. SOA pre-amplification.

NOTE 2 – The ONU sensitivity assumes the use of the optional RS (255,239) FEC capability of the G-PON TC layer with the current class B+ ONU detector technology.

NOTE 3 – The ONU overload is set at –8 dBm to be common with the class B+ value, even though in this application –10 dBm is sufficient.

The single-sided extended ODN link budget is given in Table 9-8.

Table 9-8 – Loss budgets for the single-sided extended G-PON system (class C+)

Items	Unit	Single fibre
Minimum optical loss at 1 490 nm	dB	17
Minimum optical loss at 1 310 nm	dB	17
Maximum optical loss at 1 490 nm	dB	32
Maximum optical loss at 1 310 nm	dB	32
Maximum fibre length	km	60

Class C+ allows the operation of G-PON systems with a maximum loss of 32 dB, i.e. higher than that of Class C (30 dB). As already stated, this improvement is achieved by using a more capable OLT interface. The ONU optical parameters of Table 9-6 are in fact those specified for the Class B+. Therefore, telecom operators and/or service providers can use a higher split ratio (up to 1:128) without changing the already deployed ONUs. Only a new C+ optical interface is necessary at the OLT side, i.e. in the central office.

12 Example of a G-PON system power budget

In this clause an example of power budget is given for a G-PON system operating at 2 448 Gbit/s downstream. The example is based on worst case values for the involved parameters. Therefore, it does not take into account the possible improvements obtainable by adopting a statistical approach.

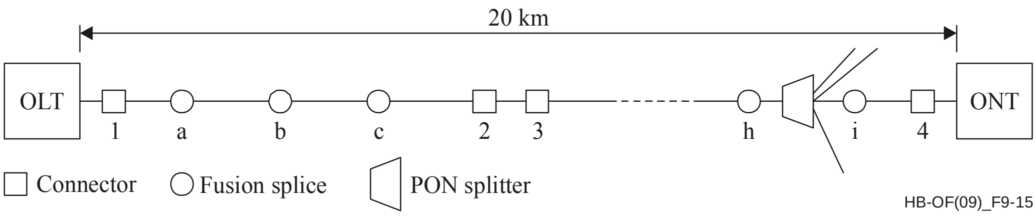

Figure 9-15 – ODN configuration assumed for the example of power budget

The configuration of the G-PON assumed in the example is indicated in Figure 9-15. The length is 20 km and the overall attenuation of the ODN is shown in Table 9-9.

Table 9-9 – Maximum attenuation for the ODN shown in Figure 9-15

Parameter	Value	Unit	Quantity	Total
Fibre attenuation	0.4	dB/km	20 km	8.0
Fusion splice attenuation	0.1	dB	15	1.5
Connector attenuation	0.35	dB	4.0	1.4
Design margin	0.05	dB/km	20 km	1.0
Maintenance margin	1.0	dB	1.0	1.0
Splitter 1:32	17.1	dB	1.0	17.1
TOTAL		dB		30

The attenuation category C for the G-PON system operating at 2 448 Mbit/s downstream with a maximum value 30 dB is able to satisfy this maximum attenuation of the ODN.

13 Operating wavelengths

13.1 Basic band

The wavelength range of the G-PON specified in Recommendation ITU-T G.984.2 is 1 480-1 500 nm for the downstream signal (single fibre system) and 1 260-1 360 nm for the upstream signal.

13.2 Enhanced wavelength allocation plan

In Recommendation ITU-T G.984.5 other wavelength ranges are reserved for additional service signals to be overlaid via wavelength division multiplexing (WDM) in future G-PONs for maximizing the value of ODN.

Figure 9-16 and Table 1 show the enhanced wavelength allocation plan with the wavelength bands reserved for additional services, including NGA and video services. The original wavelength range of the G-PON downstream signal is referred to as the "basic band". Reserved bands are referred to as the "enhancement band". The wavelength range for video services remains as defined in Recommendation ITU-T G.983.3.

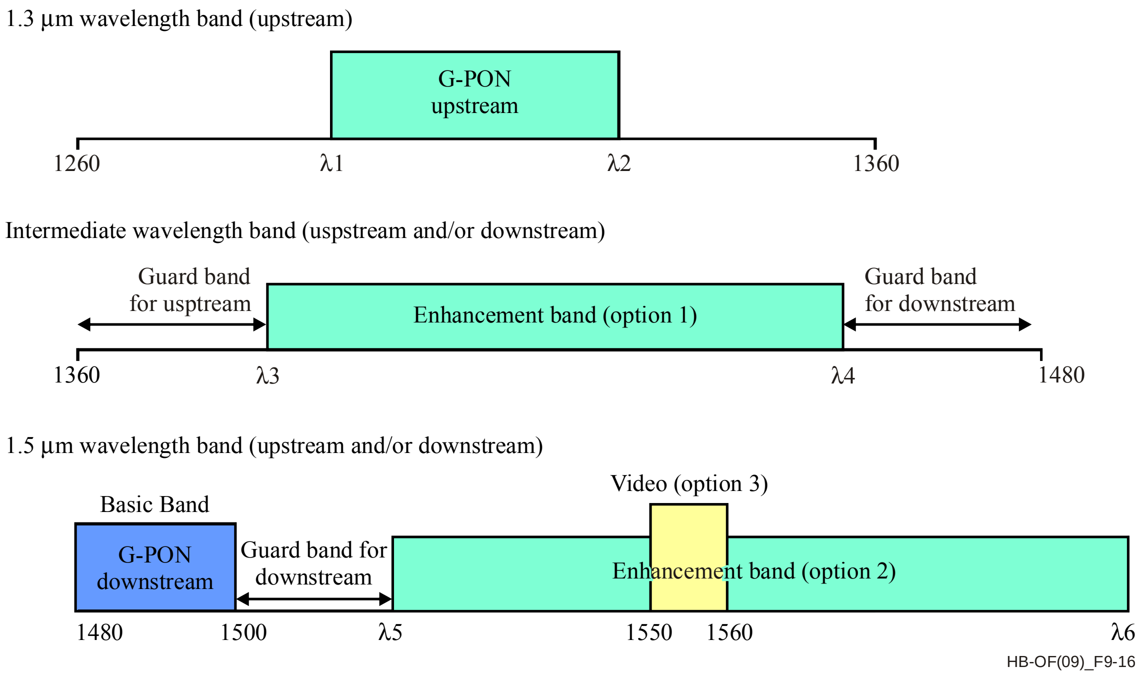

Figure 9-16 – Wavelength allocation

NGA (next generation access) is a potential new optical access system that will have to coexist with G-PON on the same ODN.

A guard band separates the G-PON upstream and/or basic band from the enhancement band. The interference between signals in these two bands causes signal degradation to each other, which must be kept negligible. wavelength blocking filters (WBFs) are used to obtain the required isolation outside the guard band. The wavelength values specified in Table 9-10 take into account guard bands that may be achievable by commercially available low-cost WBFs.

Wavelength blocking filters (WBFs) are optical filters used to prevent an optical receiver from receiving unwanted optical signals at different wavelengths.

Table 9-10 – Parameters for wavelength allocation in Figure 9-16

Items	Notation	Unit	Nominal value	Application examples
1.3 μm wavelength band				For use in G-PON upstream
– Regular wavelength band option				e.g. ONU based on Fabry-Perot lasers
Lower limit	λ1	nm	1 260	
Upper limit	λ2	nm	1 360	
– Reduced wavelength band option				e.g. ONU based on ordinary DFB lasers
Lower limit	λ1	nm	1 290	
Upper limit	λ2	nm	1 330	
– Narrow wavelength band option				e.g. ONU based on wavelength selected lasers
Lower limit	λ1	nm	1 300	
Upper limit	λ2	nm	1 320	
Enhancement band (option 1-1)				For next generation access (NGA). NOTE – The values are informative. The loss in this band is not guaranteed in optical branching components for PON (i.e. power splitters) specified in Rec. ITU-T G.671 neither in optical fibres specified as Rec. ITU-T G.652A & B (non-low-water-peak fibres)
Lower limit	λ3	nm	1 415 *(Informative)*	
Upper limit	λ4	nm	1 450 *(Informative)*	
Enhancement band (option 1-2)				For next generation access (NGA). Applicable for low-water-peak fibre only. NOTE – The values are informative. The loss in this band is not guaranteed in optical branching components for PON (i.e. power splitters) specified in Rec. ITU-T G.671
Lower limit	λ3	nm	1 400 *(Informative)*	
Upper limit	λ4	nm	1 450 *(Informative)*	
Basic band				For use in G-PON downstream
Lower limit	–	nm	1 480	
Upper limit	–	nm	1 500	
Enhancement band (option 2)				For next generation access (NGA). NOTE – The upper-limit value is determined as an operator's choice from 1 580 to 1 625 nm, considering the following factors: – Bending loss of optical fibre that increases at longer wavelengths. – Loss of a filter that separates/combines a monitoring signal and NGA signal(s) (if an optical monitoring system is used)
Lower limit	λ5	nm	1 530	
Upper limit	λ6	nm	1 580 to 1 625	
Enhancement band (option 3)				For video distribution service
Lower limit	–	nm	1 550	
Upper limit	–	nm	1 560	

13.3 G-PON reference diagrams with enhanced bands

There can be several types of ODN architectures to achieve the coexistence of G-PON and additional services including next generation access (NGA) and video distribution services.

Figure 9-17 is a reference diagram of optical access network architectures; it assumes that wavelength blocking filters (WBF) are used when G-PON, video and NGA share the same ODN.

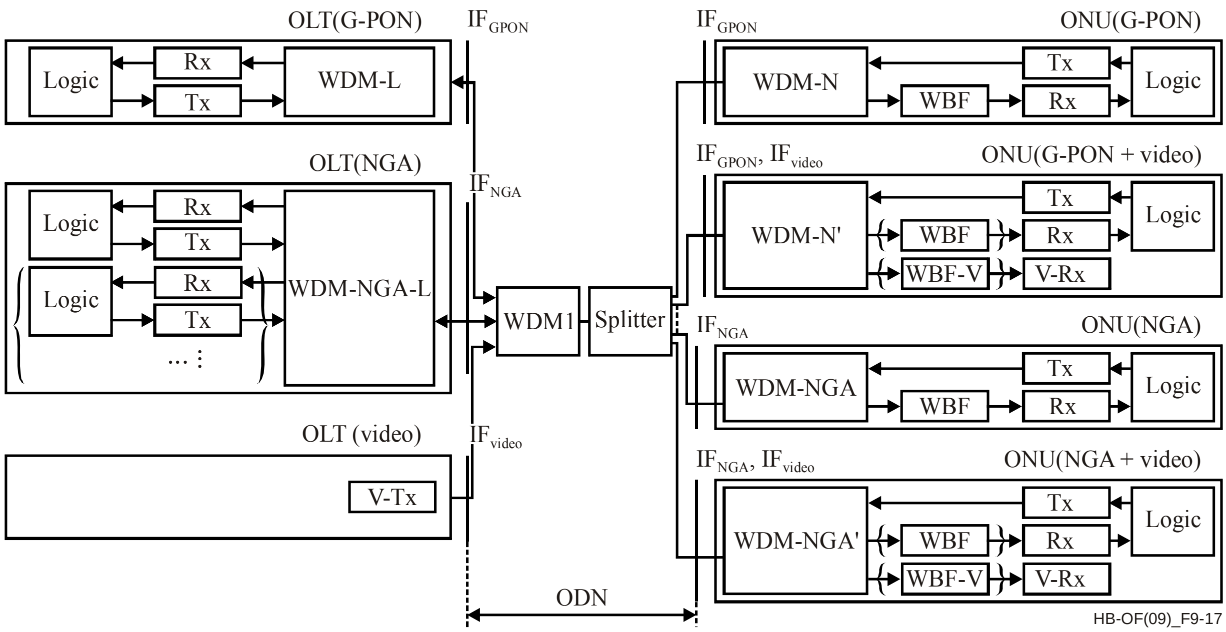

Figure 9-17 – G-PON reference diagram with enhanced bands

The following abbreviations are used in Figure 9-17:

Tx	Optical transmitter.
Rx	Optical receiver.
V-Tx	Video transmitter.
V-Rx	Video receiver.
WBF	Wavelength blocking filter for blocking interference signals to Rx.
WBF-V	Wavelength blocking filter for blocking interference signals to V-Rx.
WDM-N	WDM filter in G-PON ONU to combine/isolate the wavelengths of G-PON upstream and downstream.
WDM-N'	WDM filter in G-PON ONU to combine/isolate the wavelengths of G-PON upstream and downstream and isolate the video signal(s).
WDM-NGA	WDM filter in NGA ONU to combine/isolate the wavelengths of NGA upstream and downstream.
WDM-NGA'	WDM filter in NGA ONU to combine/isolate the wavelengths of NGA upstream and downstream and isolate the video signal(s).
WDM-L	WDM filter in G-PON OLT to combine/isolate the wavelengths of G-PON upstream and downstream.
WDM-NGA-L	WDM filter in NGA OLT to combine/isolate the wavelengths of NGA upstream and downstream of one or more channels.
WDM1	WDM filter that may be located in the central office to combine/isolate the wavelengths of G-PON and NGA signals and combine the video signals.

14 Wavelength for maintenance

(For further information see Recommendation ITU-T L.41).

In-service maintenance of optical fibre should be done in such a way that it does not interfere with the normal operation and expected performance of the information channels. The wavelengths for in-service maintenance shown in Table 9-11 should be used.

Table 9-11 – Maintenance wavelength assignment

	1 310 nm-window	1 550 nm-window	1 625 nm-window[b)]	1 650 nm-window[a), b)]
Case 1	Active	Vacant or maintenance	Vacant or maintenance	Vacant or maintenance
Case 2	Vacant or maintenance	Active	Vacant or maintenance	Vacant or maintenance
Case 3	Active	Active	Vacant or maintenance	Vacant or maintenance
Case 4	Active or vacant	Active	Active	Vacant or Maintenance

a) When there is no optical light (nominally below −60 dBm) from the OTDR laser at all wavelengths equal to or below the maximum client signal wavelength (see case 4) at point "R", it is not necessary to consider interference with transmission.

b) These OTDR wavelengths are suitable only for systems with client signals at wavelengths less than 1 565 nm. Applicability for client signals at longer wavelengths is under study.

Case 1: This usually applies to single mode fibre. Transmission system uses only the 1 310 nm-window.

Case 2: This usually applies to dispersion shifted fibre. Transmission system uses only the 1 550 nm-window.

Case 3: This usually applies to single mode fibre. Transmission system uses two or more wavelengths in the 1 310 nm and 1 550 nm windows.

Case 4: The maximum transmission wavelength is under study in ITU-T, but is limited to less than or equal to 1 625 nm.

Wavelength is independent of types of fibre (single mode fibre or dispersion shifted fibre).

15 Reach extension of the G-PON

Recommendation ITU-T G.984.6 describes G-PON systems with optical link budgets up to the logical limits (60 km) of the transmission convergence (TC) layer. This increased optical capability, which includes both increased overall fibre length and increased overall split ratio, is referred in the following as "reach extension".

For reach extension, Recommendation ITU-T G.984.6 considers mid-span extension, which uses an active extension node placed in the middle of the ODN. Two system architectures are considered as providing reach extension at the physical layer: optical amplification, and optoelectronic regeneration. The key interfaces and functional blocks in each of these architectures are specified in Recommendation ITU-T G.984.6.

15.1 Optical extension schemes and architectures

The architecture considered for an ODN with reach extension is illustrated in Figure 9-18. A mid-span extender device is inserted between the ODN and an optical trunk line (OTL) that is connected to the OLT. This architecture extends the reach of the PON by the length of the OTL, and may also increase the split ratio of the PON.

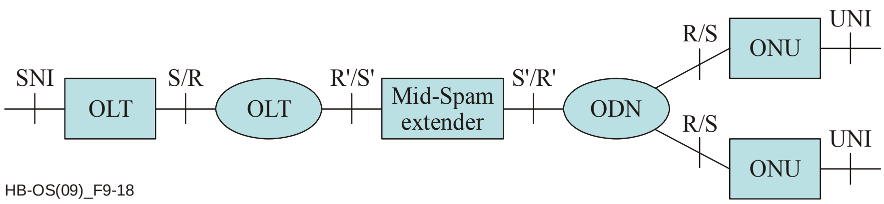

Figure 9-18 – Mid-span reach extension

As said above, there are two general classes of extenders. The first is an optical amplifier (OA), shown in Figure 9-19, which provides gain in optical power.

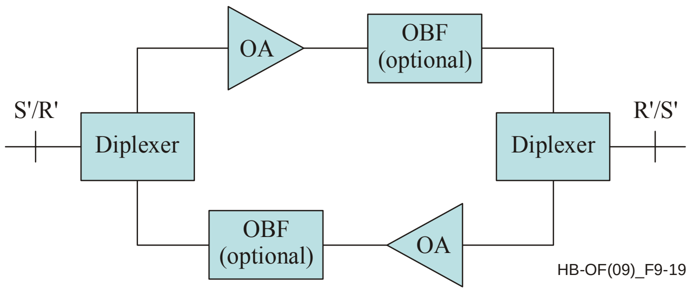

Figure 9-19 – The two basic extender architectures: a) Optical Amplifier

The second is an optical-electrical-optical (OEO) regenerator (Rx + Tx) (Figure 9-20), which receives an optical signal, reshapes and retimes it in the electrical domain and retransmits in the optical domain. Further hybrid schemes are possible, for example, to use optical amplification in the downstream and regeneration in the upstream.

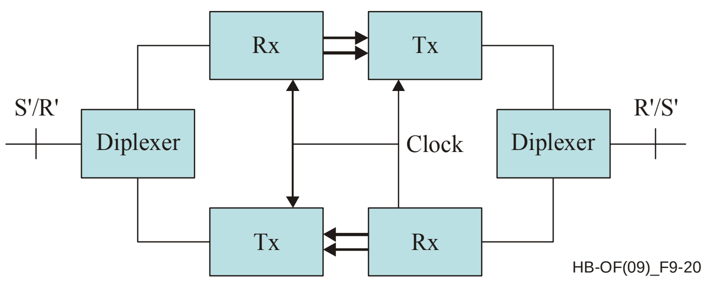

Figure 9-20 – The two basic extender architectures: b) Regenerator

The mid-span extender will require electrical power. This may be an issue when the extender is located in the field. Also, the power source will need to have protection against failures of the primary power source, typically using batteries as a backup. Therefore, power consumption should be reduced as much as possible.

15.2 Specifications for mid-span extenders

The optical parameters of the optical trunk line are given in Table 9-12.

Table 9-12 – Physical medium dependant layer parameters of OTL

Items	Unit	Specification
Fibre type	–	ITU-T G.652
Attenuation range for 1 290-1 330 nm range applicable for OEO type of extenders	dB	14-27.5 (Note 1)
Maximum attenuation for 1 290-1 330 nm range applicable for OA type of extenders	dB	28 (Note 2)
Minimum attenuation for 1 290-1 330 nm range applicable for OA type of extenders	dB	(Note 3)
Attenuation range for 1 480-1 500 nm range applicable for OEO type of reach extenders	dB	11-23 (Note 1)
Maximum attenuation for 1 480-1 500 nm range applicable for OA type of reach extenders	dB	23 (Note 2)
Minimum attenuation for 1 480-1 500 nm range applicable for OA type of reach extenders	dB	(Note 3)
Maximum optical path penalty	dB	1
Maximum fibre distance between S/R and R'/S' points	km	60 minus the distance used in the ODN
Bidirectional transmission	–	1-fibre WDM
Maintenance wavelength	nm	To be defined

NOTE 1 – For lower attenuation values, external optical attenuators can be used.

NOTE 2 – May be varied depending on implementation.

NOTE 3 – OA implementation-dependent; for low attenuation values, an appropriately designed OA type extender or external optical attenuators can be used.

CHAPTER 10

MAINTENANCE, SAFETY AND ENVIRONMENTAL ASPECTS

Introduction

Maintenance aspects are very important in a telecommunication network. A suitable maintenance of the optical fibres, cables and systems is a crucial element for offering to the customers a high level of quality and availability of the services. Moreover, maintenance has a direct impact on the amount of the operational expenditures (OPEX). Clause 1 of this Chapter points out the ITU-T specifications related to the maintenance of the optical fibres, cables, facilities and systems.

Also, safety and environmental aspects are becoming more and more important for the telecommunication networks and the optical plants. Clause 2 deals with the optical power safety aspects, with the fire hazards and with some environmental aspects such as life cycle analysis of products and processes, environmentally friendly materials and waste disposal.

1 Maintenance aspects

Communication traffic is increasing rapidly due to the increase in new services.

Also, the number of FTTx subscribers in the world is increasing rapidly and broadband access network provision currently requires thousands of optical fibres to be accommodated in a single central office. Additionally, new telecommunication infrastructures are deployed in the access networks, using a lot of elements such as enclosures, cabinets and passive optical components.

At the same time, the DWDM technology is widening its application in metro and backbone networks with the deployment of a great number of optical network elements (optical amplifiers, OADM, ROADM, optical multiplexers and demultiplexers, photonic cross-connects, etc.) able to transport an ever increasing number of channel count and channel speed.

Concrete solutions for managing all these items are becoming essential, from the point of view of optical facility operations, to reduce maintenance costs and to improve service reliability.

1.1 Maintenance aspects of optical fibres

(For further information see Recommendation ITU-T L.40).

Maintenance and testing are required to provide high reliability and quick response to faults for optical fibres in access / metro / long-haul / submarine networks.

After a cable is installed, functions like fibre monitoring and control have to be done without interfering with the data transmission signals. By monitoring dark fibres (that is, without signal traffic) an indication is given of the performance of the in-service fibres as the degradation and breaks that a cable undergoes affects all fibres in the same way. Nevertheless, greater reliability is achieved by monitoring the fibres with traffic. Also, fibre identification is important to control fibre networks because several fibres may have to be chosen from within a cable, even if the cable has many fibres in service.

In particular, an outdoor optical fibre maintenance support, monitoring and testing system for optical fibre cable networks is necessary. In the following clauses, fundamental requirements, principles, and architecture to develop a suitable support system are described. A specific application to the access network can be found in Recommendation ITU-T L.53 both for point-to-point and for ring topologies.

1.1.1 Fundamental requirements for a maintenance support system

The maintenance support, monitoring and testing system should have the functions shown in Table 10-1. In this Table the term "surveillance" means the monitoring of the condition of network elements (NE). Surveillance has two functions: to inform of NE degradation before trouble occurs and to inform of NE abnormality when trouble occurs.

The term "control" means the restoration of the NE to normal functioning or to take action to maintain service quality.

Table 10-1 – Functions and status

Category	Activity	Functions	Status
Preventative maintenance	Surveillance. (e.g. Periodic testing, continuous testing)	• Detection of fibre loss increase. • Detection of signal power loss increase. • Detection of water penetration	Optional Optional Optional
	Testing. (e.g. Fibre degradation testing)	• Measurement of fibre fault location. • Measurement of fibre strain distribution. • Measurement of water location	Optional Optional Optional
	Control. (e.g. Network element control)	• Fibre identification. • Fibre transfer	Optional Optional
After installation before service or post-fault maintenance	Surveillance. (e.g. Reception of transmission system alarm or customer trouble report)	• Interface with path operation system. • Interface with customer service operation system	Optional Optional
	Testing. (e.g. After installation testing, Fibre fault testing)	• Confirmation of fibre condition. • Fault distinction between transmission equipment and fibre network. • Measurement of fibre fault location	Required Required Required
	Control. (e.g. Cable install/repair/ replacement)	• Fibre identification. • Fibre transfer. • Interface with outside plant database. • Interface with mapping system	Required Optional Required Optional

The support system can be controlled by humans or by other systems. The system shall be able to be remotely controlled. So, operation terminals with HMI (human-machine interface) should be included in the system. The system shall be able to gather data about outdoor fibres from the outside plant database and it should have an interface with the path operation and customer service system.

1.1.2 Testing and maintaining principle

(For further information see Recommendation ITU-T L.25).

There are several ways commonly used to implement the functions listed in Table 10-1:

i) OTDR testing;

ii) loss testing with the measurement of the level of a specific wavelength injected into the fibre outside the wavelengths of the data signal;

iii) monitoring a proportion of the data signal power (power monitoring);

iv) identification light detection.

Table 10-2 shows where these methods are used.

Table 10-2 – Suitable test methods

Category	Activity	Functions	Methods
Preventative maintenance	Surveillance	• Detection of fibre loss increase. • Detection of signal power loss increase. • Detection of water penetration	OTDR/loss testing. Power monitoring. OTDR/loss testing
	Testing	• Measurement of fibre fault location. • Measurement of fibre strain distribution. • Measurement of water location	OTDR testing. B-OTDR testing. OTDR testing
	Control	• Fibre identification. • Fibre transfer	ID light detecting[a)] Switching[b)]
After installation before service, or post-fault maintenance	Surveillance	• Interface with path operation system. • Interface with customer service operation system	On-line/external medium. On-line/external medium
	Testing	• Confirmation of fibre condition. • Fault distinction between transmission equipment and fibre network. • Measurement of fibre fault location	OTDR/loss testing. OTDR/loss testing. OTDR testing
	Control	• Fibre identification. • Fibre transfer. • Interface with outside plant database. • Interface with mapping system	ID light detecting. Switching[b)]. On-line/external medium. On-line/external medium

a) ID light means identification light such as 270 Hz, 1 kHz, 2 kHz modulated light.

b) Switching includes mechanical and manual switching.

The OTDR-based monitoring systems are capable of periodic measurements of the fibres' attenuation coefficient and, when integrated with transmission equipment alarms, they are capable of immediate reporting fault location data in case of cable damage.

Loss testing and power monitoring, through the continuous monitoring of a power level received at the end of the optical fibre (just before the receiving equipment), are able to collect and store power-level data and provide an immediate detection of fibre faults through the activation of an OTDR function when the monitored power decreases below a certain level.

All these systems are designed to minimize the service outages as well as the economic loss through the immediate location of failures and alarm generation and, at different degrees, are intended to predict failures due to the degradation of fibre performance.

1.1.3 Wavelengths for maintenance

(For further information see Recommendation ITU-T L.41).

For the power monitoring system it is important to choose the correct wavelength to be monitored. Specifically, maintenance functions have to be performed without interfering with data transmission signals. Table 10-3 shows appropriate wavelengths for given functions.

The wavelength allocation of PON and WDM applications are defined in Recommendations ITU-T G.983.3 and ITU-T G.694.2, and in Supplement 39 to the ITU-T G-series of Recommendations, as shown in Figure 10-1. Moreover, Recommendation ITU-T G.694.1 specifies a frequency grid for DWDM systems with a minimum channel spacing of 12.5 GHz (for further details see Chapter 6).

Table 10-3 – Wavelength selection

Category	Activity	Functions	Wavelength
Preventative maintenance	Surveillance	• Detection of fibre loss increase. • Detection of signal power loss increase. • Detection of water penetration	Maintenance wavelength[a)] Signal wavelength. Any wavelength on fibres not carrying signals
	Testing	• Measurement of fibre fault location. • Measurement of fibre strain distribution. • Measurement of water location	Any wavelength on fibres not carrying signals. Any wavelength on fibres not carrying signals. Any wavelength on fibres not carrying signals
	Control	• Fibre identification. • Fibre transfer	Maintenance wavelength[a)] None
After installation before service, or post-fault maintenance	Surveillance	• Interface with path operation system. • Interface with customer service operation system	None. None
	Testing	• Confirmation of fibre condition. • Fault distinction between transmission equipment and fibre network. • Measurement of fibre fault location	Any wavelength. Any wavelength. Any wavelength
	Control	• Fibre identification. • Fibre transfer. • Interface with outside plant database. • Interface with mapping system	Any wavelength. None. None. None
a) Refer to the Recommendation of maintenance wavelength on fibres carrying signals, Recommendation ITU-T L.41.			

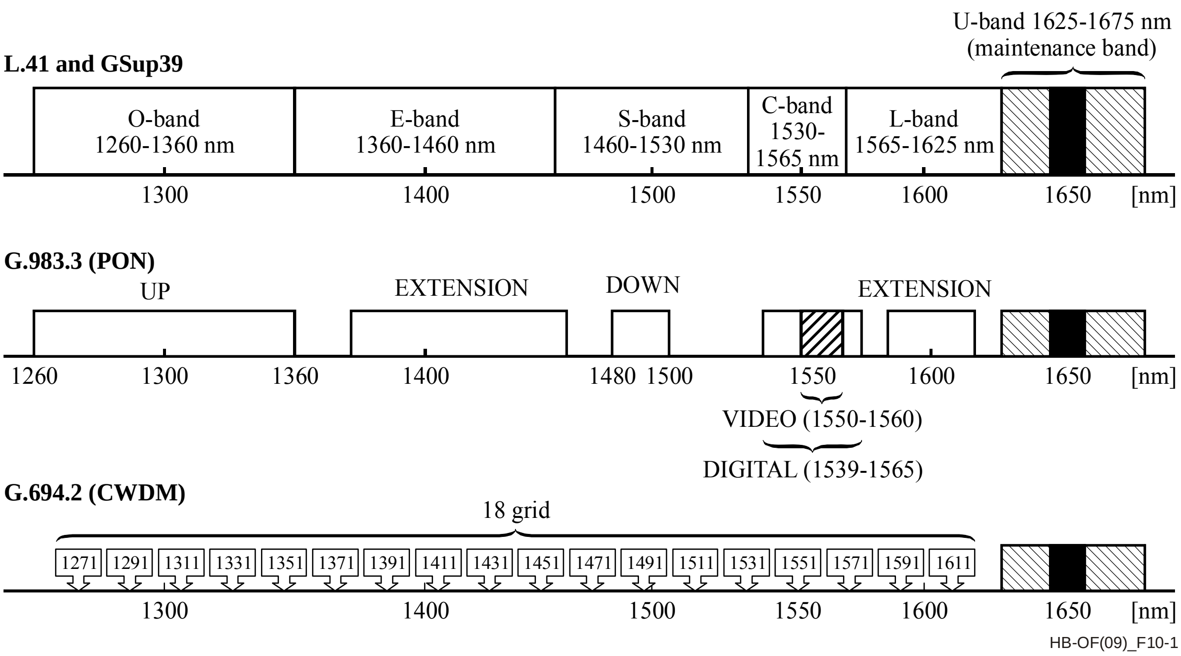

Figure 10-1 – Maintenance wavelength allocation

Figure 10-1 shows that communication wavelength bands extend to the long wavelength band (L-band: 1 565-1 625 nm). To eliminate interference with the test light, the maintenance test light wavelength must not be a wavelength used for communication signals.

The maintenance wavelength assignment for in-service testing, shown in Table 10-4, is defined in Recommendation ITU-T L.41. There are several recommended maintenance wavelength bands, depending on the communication light wavelength used by a given transmission system. When the communication wavelength band extends to the L-band, the 1650 nm wavelength in the ultra long wavelength band (U-band: 1 625-1 675 nm) is used for maintenance testing, as shown in Figure 10-1.

Table 10-4 – Maintenance wavelength assignment

	1 310 nm-window	**1 550 nm-window**	**1 625 nm-window[a)]**	**1 650 nm-window[a)]**
Case 1	Active	Vacant or maintenance	Vacant or maintenance	Vacant or maintenance
Case 2	Vacant or maintenance	Active	Vacant or maintenance	Vacant or maintenance
Case 3	Active	Active	Vacant or maintenance	Vacant or maintenance
Case 4	Active or vacant	Active	Active	Vacant or Maintenance

a) More details are shown in Recommendation ITU-T L.41.

1.1.4 In-service fibre line testing

(For further information see Recommendation ITU-T L.66).

With a view to realizing a highly reliable optical network that transports WDM signals with a wide spectral bandwidth, in-service fibre line monitoring techniques are important in terms of providing effective and efficient maintenance of optical cable networks. The fundamental requirements of in-service fibre line testing are as follows:

- i) it should be carried out without degrading optical communication signals;
- ii) it must be capable of evaluating optical fibre characteristics even if there is interference with the communication light.

Figure 10-2 shows a test set-up for an in-service line in an optical access network.

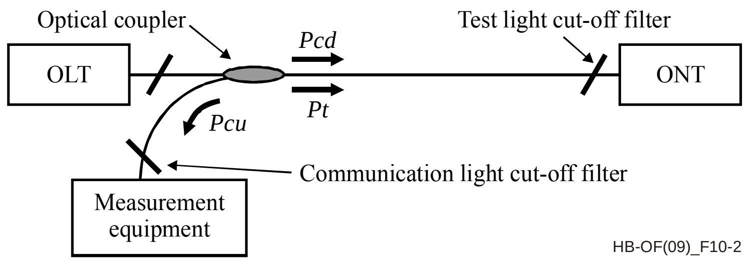

Figure 10-2 – Test set-up for in-service line

The wavelength bandwidth and the output power of the test light source should be designed taking into consideration the cut-off bandwidth and cut-off value of the optical filter, respectively. Moreover, in order to accurately measure the characteristics of the optical fibre line carrying communication signals, the measurement equipment (such as an OTDR and an optical power meter (OPM)) should have a tolerance to the communication light power.

1.1.5 General support system architecture

(For further information see Recommendation ITU-T L.40).

Support systems for fibre monitoring must have at least an operation terminal and an optical testing module (OTM). The minimum system consists of only these two items. This type of system is convenient for initial installation. A server can improve performance by keeping outside plant, test results, and interfaces with other systems. The server can also control OTMs.

There are several choices for the data communication network (DCN), which connects the server and the OTM(s), including POTS, ISDN and X.25. Traffic analysis is important for an economical high-performance system.

Two typical configurations of a support system are shown in Figure 10-3.

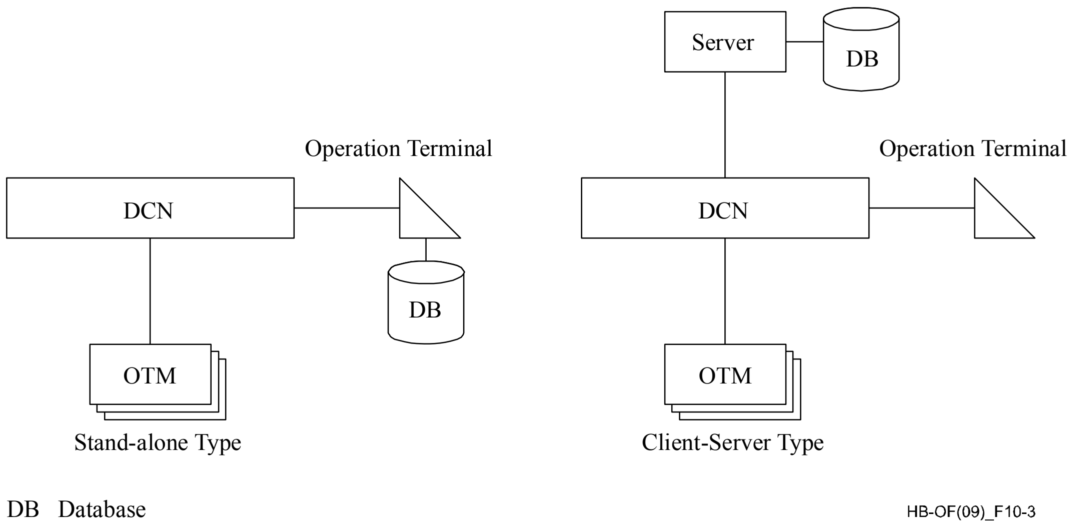

Figure 10-3 – Typical support system configurations

There are several kinds of interfaces between an operating system (OS), which runs on an operation terminal or server, and the OTM. A proprietary interface is convenient for closed systems, and standard interfaces are useful for open systems, but a hybrid type is also possible.

1.1.6 Main features of the support system

The main features of the optical cable supervisory system allowing the attainment of the mentioned maintenance objectives are listed below:

i) *non-intrusiveness* on the service traffic, due to the design of a completely passive optical probe: non-intrusiveness is a key characteristic of the monitoring system, especially where cable owners are not permitted to adopt an OTDR-based monitoring process on in-service fibres (e.g. leased fibres);

ii) *sensitivity* to even very rapid degradation effects, which can have a negative influence on optical fibre performance in the long period (e.g. mechanical vibrations due to road and railway traffic);

iii) *real-time alarm reporting*: optical power and attenuation threshold-crossing events are immediately detected and reported to the system presentation interface, in order to fully exploit preventive maintenance capabilities;

iv) *automated OTDR measurement activation* when a threshold-crossing event referring to a variation of attenuation is reported, in order to have a minimum location time when a sudden fault or anomaly is faced;

v) *permanent storage of monitoring results* and fibre reference traces, in order to enable a powerful analysis of the optical fibre attenuation trend.

1.1.7 Optical fibre cable maintenance system for optical fibre cable carrying high total optical power

(For further information see Recommendation ITU-T L.68).

There are several fibre-optic components in optical fibre cable maintenance systems for optical fibre cables that carry a high total optical power. When the components have a larger optical loss than usual, this may pose a fire-hazard, in the worst case.

Table 10-5 shows the functions in optical fibre cable maintenance systems for optical fibre cables carrying high optical power. The list below includes the system requirements for high power light input and the methods employed to achieve them.

Table 10-5 – Functions in optical fibre cable maintenance systems

Functions	System requirements for high power light input	Methods
Connection	No fibre fuse or intense temperature increase	Use of fusion splices. No need for optical connectors or polishing and cleaning of connector endfaces
Termination	No tight bending of optical fibre	Minimum bending radius R ≥ 30 mm for testing optical fibre cords in optical distribution frames; but fibres with improved bending capability will allow more severe conditions
Testing access for optical fibre line	No fibre fuse or intense temperature increase	Use of fusion splices. Optical branching component with high tolerance to high power light exposure
Optical switch with butt-joint splice connection mechanism (e.g. fibre selector)	No intense temperature increase or optical loss increase	Attenuation of high power light or gap between fibres at butt-joint splice $d < 10$ µm

1.2 Optical fibre and cable restoration

The very large transmission capacity contained within a single sheath of an optical fibre cable necessitates the development and implementation of a plan for rapid restoration of cable failures. The plan should detail the action from receipt of an alarm to completion of restoration. Its primary objective should be to re-establish service as quickly as possible employing the following general strategy:

i) re-route as much traffic as possible;

ii) locate the cable damage;

iii) temporarily re-connect the damaged cable, if required;

iv) restore service.

After the transmission of an alarm, the fault must be located before restoration can begin. Fault locating instruments are used to locate cable faults. Sheath faults in optical fibre cables containing metallic pairs can be located with standard earth leakage test sets, pulse echo tests, and DC bridge sets. The presence of optical power in a fibre may be checked by the appropriate test sets (see § 1.1). Fibre breaks may be located with an optical time domain reflectometer (OTDR) using a backscattering measurement.

1.2.1 Restoration methods

The choice of an appropriate emergency restoration method for a damaged optical fibre cable, as well as its permanent repair, depends on the extent of the damage and particularly on the distribution of fibre breaks. Thus, a basic understanding of the mechanics of cable behaviour, with regard to the mechanical tension applied to the cable, in damage situations is important in developing and applying these methods.

Cable damage mechanisms fall into two broad categories: low-tension and high-tension. Damage mechanisms with low (or zero) tension include fires, most lightning strikes, and most types of vandalism. If the damage can be visually confirmed to be low-tension, it is likely that fibre damage will be confined to a small area. In these cases a local repair at the damage site is quite likely to restore all service.

If, however, the damage results from a high-tension mechanism, e.g. a backhoe dig up or a fallen utility pole, the choice of restoration method must now consider more than the visually obvious damage. Cables damaged in high-tension dig ups should be replaced with a spare cable (joint-to-joint) as the preferred emergency restoration method.

In principle, permanent repair has priority. This is primarily to avoid duplication of work and service interruption in the permanent repair after emergency restoration. Nonetheless, emergency restoration is required in some cases, such as when conduits are broken by a backhoe.

1.2.2 Restoration procedures

The restoration procedures presented below are based on the premise that optical fibre cable systems carry large traffic cross sections and warrant a substantial investment of manpower and other resources to ensure that service interruptions are minimal.

Planning and readiness are critical to the speed and success of restoration. Initial system design should be based in part on restoration considerations. Alarm and voice communication systems must be efficient and well maintained. Emergency materials and equipment should be centrally located, and systematically inventoried and maintained. Documentation on circuit assignments and their relative priorities must be up-to-date and readily available, along with a corresponding circuit rearrangement plan.

Also, designated restoration coordinators and teams should be well trained and available 24 hours a day.

When damage to an optical fibre cable has been reported, located and evaluated, a method will have to be chosen for its *provisional repair*. The method for provisional repair preferred in most situations, because it is fast and reliable, is joint-to-joint cable replacement. With this method, teams disconnect the joints at each end of the damaged cable and provide in its place, either in a spare duct or aboveground, an emergency cable. For most protected routes it is sufficient to stock one long and one short cable of appropriate (maximal) fibre count and fibre grade. This method avoids excavation and precise fault location, works in spite of distributed fibre breakage, and permits substantial advance planning to eliminate roadblocks.

An example of provisional repair for a duct cable is shown in Figure 10-4.

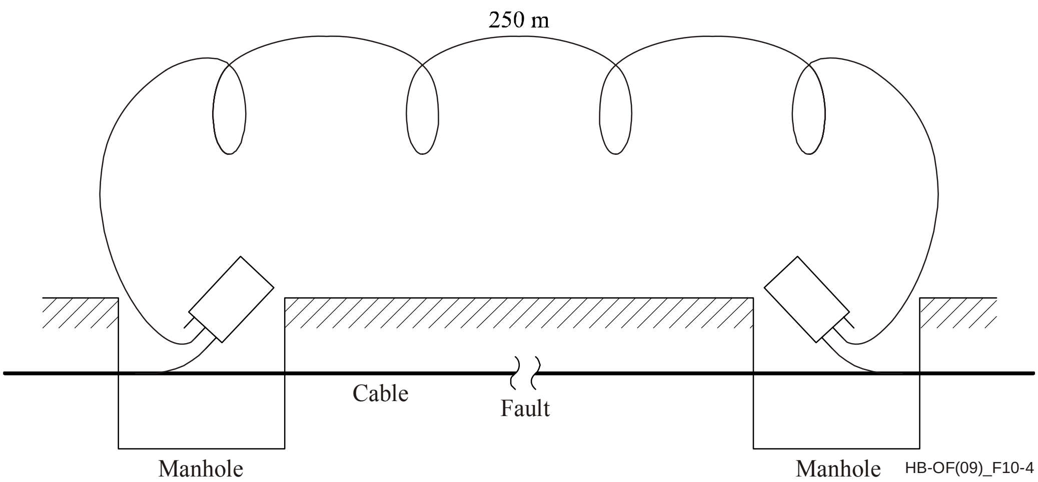

Figure 10-4 – Provisional repair of a duct cable

After service has been provisionally restored through one of the above methods, a number of important decisions will remain relating to the *permanent repair* of the damaged cable section. If there is assurance that fibre damage was localized, the original cable may be put back into service, provided it has been suitably and permanently repaired and tested. On the other hand, if the original cable suffered scattered fibre breakage or structural damage, it will probably be more economical and service-effective to replace it, joint-to-joint, with a new permanent cable. Temporary materials, if used, would normally be carefully removed from service, tested, and restocked for future emergency use.

Regardless of the implemented permanent repair, appropriate service rearrangements must be done to correct any temporary circuit assignments, and end-to-end conformance tests performed to ensure that system standards are met.

1.3 Maintenance of underground plastic ducts

(For further information see Recommendation ITU-T L.73).

Placing cables in conduits is preferred because it has a principle advantage that the cable placement operation is separated in time from the actual conduit construction phase. Moreover, the protection of the cable with the passage of time and the possibility of repeated access, cable removal and delayed cable installation make the method of placing cables in ducts more attractive. The method, however, has a disadvantage in that the initial cost of conduit construction is expensive. It is noted that underground ducts are prone to being deformed by the burden of earth pressure, which makes it necessary to check the ducts before cable installation, and to repair defective ducts before placing cables in conduits.

After a conduit is installed in a trench and has been backfilled, but before any surface construction begins, it is common practice to check duct quality because certain plastic conduits can become oval-shaped, pierced or broken. A classification of these possible defects is shown in Table 10-6. The description of inspection methods, such as the use of test mandrels and closed-circuit television (CCTV) systems, to check duct quality can be found in Recommendation ITU-T L.73, which also describes various methods that are used to repair underground conduits.

Table 10-6 – Classification of defects

Defects	Causes
Crack or fracture	Excessive pressure. Insufficient duct strength
Duct failure	Ground settlement. Excessive loads
Pointed deformation	Sharp shaped crushed stone
Oval shaped deformation	Excessive pressure. Insufficient duct strength. Dynamic compacting loads during construction
Soil intrusion	Disconnection of ducts
Offset	Faulty construction. Ground settlement

A classification of repair methods is given in Table 10-7.

Table 10-7 – Duct repair methods

<table>
<tr><th colspan="2">Test</th><th rowspan="2">Inspection by CCTV
(Note 2)</th><th rowspan="2">Repair methods</th></tr>
<tr><th>Duct rod
(Note 1)</th><th>Mandrel</th></tr>
<tr><td rowspan="3">Can pass the whole length without any difficulties</td><td rowspan="2">Can pass the whole length without any difficulties</td><td>The whole length of duct is clean and does not have any defects</td><td>No need to repair</td></tr>
<tr><td>Debris or sludge that may block test mandrel is observed inside a duct</td><td>High pressure water jetting</td></tr>
<tr><td>Cannot pass the whole length without any difficulties</td><td>If defective parts such as cracks, duct failure, oval-shaped deformation, and offset are observed, it is considered that the defective parts are not severe and are limited to a small extent</td><td>Conventional methods (dig and replace).
Methods for removing irregularities or enlarging a duct:
– re-rounder method;
– robotic repair system</td></tr>
<tr><td colspan="2">Cannot pass the whole length without difficulty</td><td>If the CCTV camera cannot pass because of blockage or obstruction, it is considered that the defects are severe and affect a large section of the duct</td><td>Conventional method (dig and replace method).
Pipe bursting and/or splitting method</td></tr>
<tr><td colspan="4">NOTE 1 – A duct rod is a tool that is used to manually insert pulling lines through the duct.
NOTE 2 – Inspection by CCTV is applied only when the mandrel cannot pass due to defects in the duct.</td></tr>
</table>

The conventional repair methods are "open-cut" or "dig-and-replace". These methods involve direct replacement of the defective section with a new duct in the open-cut trenches. Although conventional methods are simple and reliable, they involve social and traffic costs.

When these costs are not negligible, it is recommended to use trenchless techniques. Several different trenchless techniques are used. As an example: high pressure water jetting, insertion of an expansion device, remote controlled device (e.g. a robot) with CCTV monitoring. More details are given in Chapter 3.

1.4 Maintenance of cable tunnels

(For further information see Recommendation ITU-T L.74).

Cable tunnels (see Chapter 3) can also present dome issues related to cracks or water leakage caused by deterioration of steel-reinforced concrete or reinforcing steel. The typical deteriorations that may occur in cable tunnels are cracks, water leakage and the corrosion of reinforcing steel. If such deteriorations are left unrepaired, additional large-scale repair and reinforcement projects will probably be required, which will further increase cost in the future. The purpose of preventive maintenance in this case is to detect the defects in cable tunnels at an early stage and to take appropriate actions in order to enhance its durability and serviceability.

1.4.1 Inspection

Notwithstanding how well a cable tunnel is constructed, it will require preventive maintenance to preserve its integrity and to prolong its life. Maintenance will necessarily require inspection and testing to determine the condition of the structures and to establish appropriate repair and maintenance measures. The inspection of cable tunnels is performed to detect damage or defects that are detrimental to the structural safety and durability. When crucial damage or defects are observed, they are evaluated by skilled experienced engineers, and then appropriate and prompt countermeasures, such as repair and reinforcement work, are taken. Inspections can be divided into regular and detailed inspections, as follows:

Regular inspections, also called routine inspections, are usually performed visually to check the degradation status of the concrete surface such as cracks, water leaks, or exposed reinforced steel. At this stage, deformation is detected, and is evaluated to judge whether or not detailed inspections and/or temporary countermeasures are needed.

It is recommended that procedures be established for the manager of the cable tunnel to schedule/undertake regular inspections. These inspections are mainly done by observing the surface of the cable tunnel using visual inspection, and measuring crack width with a crack gauge. The inspection is carried out using comprehensive identification sheets on which observations and measurements can be conveniently recorded.

Detailed inspections are carried out when the defects and deformations are critical to the safety of the cable tunnel. These inspections are also carried out when there is degradation that cannot be identified by visual inspection or when the cause of degradation must be clarified to judge whether countermeasures are needed and to select the optimum method. At this stage, a detailed investigation of the measurements and deformation detected in the regular inspection are conducted by a specialist.

These inspections use destructive testing of a concrete sample and chemical analysis of a core sample to determine the degree of degradation. In addition, non-destructive testing methods can be used to determine abnormalities, defects and voids.

1.4.2 Inspection technologies

Items used for inspection differ depending upon the type of cable tunnel. Cable tunnels are generally divided into two categories as follows:

i) rectangular cross-section (box type);

ii) circular cross-section.

A rectangular cross-section cable tunnel is constructed by a cut and cover method, and is made of reinforced steel concrete. On the other hand, a circular cross-section cable tunnel is constructed by methods such as shield driving, boring, drilling and blasting, and jacked tunnelling. The cross-sections of these two types of cable tunnels are shown in Figure 10-5.

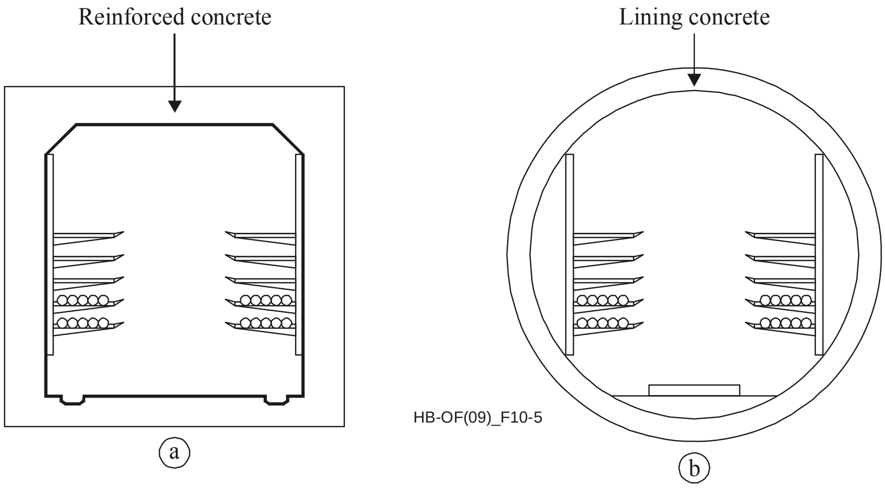

Figure 10-5 – Typical types of cable tunnel: rectangular or box type and circular type

Since the design and construction procedures of these cable tunnels are different, deteriorations occur differently. Typical inspection items are summarized in Table 10-8.

Table 10-8 – Typical inspection items

	Regular inspection	**Detailed inspection**
Rectangular cross-section cable tunnel	Cracks; water leakage; exposed steel	Include regular inspection items; compressive strength of concrete; corrosion of reinforcing steel; carbonation depth, etc.
Circular cross-section cable tunnel	Cracks in lining surface; water leakage; contamination of lining concrete; spall of lining concrete	Include regular inspection items; deformation of lining; heaving of tunnel bottom; settlement of tunnel bottom; cavities inside lining concrete; voids behind lining

Figure 10-6 shows some typical deteriorations of a tunnel.

Inspection methods mainly consist of visual inspection and non-destructive testing methods. When a defect is found during visual inspection, its cause is then established and its size and condition are investigated in detail. Since the crack is one of the most important inspection items, it is recommended to measure the crack width and depth using a crack gauge, and to check whether or not the crack propagates. Table 10-9 summarizes typical inspection technologies, including non-destructive testing methods.

Figure 10-6 – Typical deteriorations: a) cracks; b) water leakage; and c) the corrosion of reinforcing steel

1.5 Optical monitoring of optical DWDM systems

(For further information see Recommendation ITU-T G.697).

DWDM technology is improving at a rapid pace, continuously stretching the channel count, channel speeds and reach limits. Long haul multi-span DWDM systems are capable of taking optical signals thousands of kilometres without using electrical terminations or regeneration. This continuing trend is driving the increasing importance of optical monitoring.

As a matter of fact, fully regenerated optical networks traditionally had optical-to-electrical conversions in all network elements, including the 3R regenerators. Transmission performance is measured at the electrical layer using performance parameters such as errored seconds (ES) and severely errored seconds (SES) (see Recommendation ITU-T G.826), since SDH and OTN have built an overhead in its frame structure to measure error performance. So, it is relatively easy to measure network performance in all network elements within fully regenerated SDH and OTN networks.

While these methods give a reliable measure of the end-to-end performance of an optical channel, they cannot be applied inside a transparent optical domain where no 3R regenerators are available to terminate the frame overhead. Therefore, they may not provide sufficient information to isolate root cause of problems in complex DWDM networks.

This necessitates performance monitoring in the optical domain to assess the health of the optical channel (OCh), as optical monitoring provides the function of monitoring the optical signal directly without processing the electrical frame.

Table 10-9 – Typical inspection technologies

Typical inspection items	Technologies	Descriptions
Cracks, water leakage, and exposed steel	Visual inspection	Crack width can be measured by a crack gauge with magnifier
Carbonation depth	Phenolphthalein indicator	Core cut from hardened concrete is sprayed with phenolphthalein indicator, and then a purple-red coloration will be obtained where alkaline concrete has been unaffected by carbonation, but no coloration will appear in carbonationed zones
Voids, water leakage	Infrared thermo-graphy (Note)	This method measures the thermal radiation emitted by the tunnel's walls, and can identify defects in the lining, and voids. Infrared techniques allow visual presentation of the temperature distribution on the surface
Compressive strength of concrete	Testing of cores	This is a well-established method. Cores are cut from hardened concrete by a core drill, and compressive testing is performed
	Surface hardness method (Note)	This test is based on the principle that the rebound of an elastic mass depends on the hardness of the surface. The results give a measure of the relative hardness of this zone, as there is a close correlation between the number of rebounds and the compressive strength of the concrete
	Ultrasonic pulse velocity method (Note)	This method injects ultrasonic waves into the concrete to analyse it internally by detecting the wave transmitted and reflected by substances with different elastic properties in the concrete wall. This method can identify structural abnormalities such as cracks, thickness variations and degradation of the compressive strength
Defects inside lining concrete	Stress wave propagation method (Note)	This method is based on the use of impact-generated stress waves that propagate through concrete and are reflected by internal flaws and external surfaces. This method can be used to determine the location and extent of flaws such as cracks and voids
Voids inside lining concrete	Ground penetrating radar (GPR) (Note)	This is a geophysical method that uses radar pulses to image the subsurface. This method uses electromagnetic radiation and detects the signals reflected from subsurface structures. GPR uses transmitting and receiving antennae. The transmitting antenna radiates short pulses of high-frequency (usually polarized) radio waves into the ground. When the wave hits a buried object or a boundary with different dielectric constants, the receiving antenna records variations in the reflected return signal. The depth range of GPR is limited by the electrical conductivity of the ground and the transmitting frequency. Higher frequencies do not penetrate as far as lower frequencies, but give a better resolution. In cable tunnels, the wave frequencies are between 900 and 2 000 MHz. This method can identify structural abnormalities such as voids, thickness variations and interface voids between the lining and the ground in a cable tunnel
NOTE – Non-destructive testing technologies.		

Optical Monitoring can help in DWDM systems to perform the following activities:

i) configuration management for system and channel activation, addition of new channels, etc.;

ii) fault management to detect and to isolate faults;

iii) degradation management in order to keep the system running and to detect degradations before a fault occurs.

In other words an appropriate level of optical monitoring gives some visibility inside optical networks ensuring that channel paths are properly configured and optical parameters are appropriate for reliable service delivery. The collection of optical monitoring data in a network operations centre (NOC) makes the management of complex DWDM networks easier.

1.5.1 Signal monitoring

Optical monitoring does not measure every impairment, but, rather, the effect of these impairments on the parameters that can be measured.

The monitoring equipment can be classified in two categories: embedded and external monitoring equipment.

Embedded monitoring equipment is usually tightly integrated with the management functions of an optical network element. For cost reasons, embedded monitoring is usually limited to a few basic parameters.

External monitoring equipment typically serves a different purpose than embedded monitoring equipment. It is normally used for measuring additional, more sophisticated performance parameters, or when a more accurate value of certain performance parameters is required.

The main applications of external monitoring equipment are the location of hard-to-find failures that cannot be isolated by the embedded monitoring devices, as well as function tests and accurate parameter measurements during installation, commissioning or repair.

1.5.2 Optical monitoring parameters

The list of the optical parameters that can be measured using current technology in optical transmission systems is given below:

i) Channel power;

ii) total power;

iii) optical signal-to-noise ratio (OSNR) when no significant noise shaping is present;

iv) channel wavelength;

v) Q-factor.

The list of correlation between the impairments and the monitoring parameters is given in Table 10-10.

Table 10-10 – List of correlation between the underlined impairments and monitoring parameters

Parameters	Total power	Channel power	Channel wavelength	OSNR	Q-factor
Variation of attenuation	X	X		X	X
Frequency (or wavelength) deviation from nominal		X	X	X	X
Optical channel power changes due to gain variations		X		X	X

1.5.3 Applications

While optical monitoring is implemented (and in service) in many current optical transmission systems, there are significant differences between the optical monitoring deployments between them. This is due to the presence of different transmission and control systems design, the size of the network and the different strategies for impairment management in the various systems. For this reason, a general requirement as to which parameter value with which particular accuracy is a reliable indicator of the operational condition of such a system cannot be generalized.

The choice of which option to deploy depends upon the specific characteristics of the ONE. In particular for a DWDM system, it depends on characteristics like length, number of spans, number of channels and inaccessibility of the sites, as well as cost/benefit considerations. In particular, it has to be considered that as the number of the monitoring points grows, there is an increasing consumption of signal power with the consequent reduction of the DWDM system reach.

In conclusion, several monitoring choices could be considered for internal monitoring in DWDM systems, with the resulting data available both locally and at a remote location.

An example of positioning of embedded monitoring equipment (EME) in a long distance DWDM line segment with optical channels operating at 10 Gbit/s is shown in Figure 10-7.

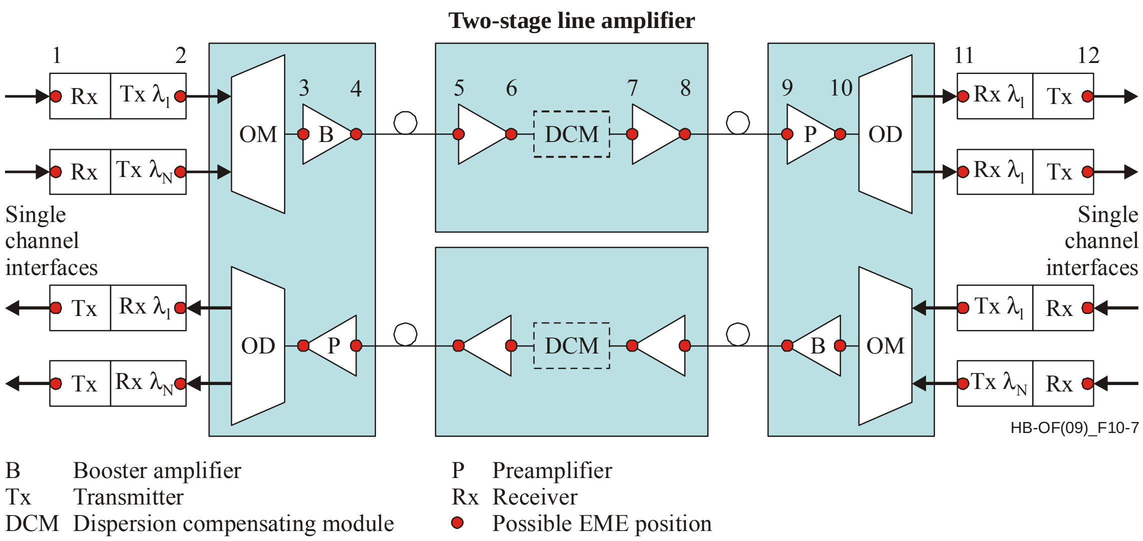

Figure 10-7 – Example of EME positioning inside a long distance DWDM line segment

The optical parameters that can be measured at the various monitoring points of Figure 10-5 are shown in Table 10-11.

Table 10-11 – Possible monitoring in a DWDM line segment

Monitoring parameters	EME position
Total power at the input of various stages of optical amplification	3, 5, 7, 9
Total power at the output of various stages of optical amplification	4, 6, 8, 10
Channel input power	1, 11
Channel output power	2, 12
Channel power at the output of various stages of optical amplification	4, 6, 8, 10
Channel OSNR at the output of various stages of optical amplification	4, 6, 8, 10
Channel wavelength	2
NOTE – This table lists possible monitoring positions. The appropriate choice of monitoring depends on the particular system.	

1.6 Maintenance aspects of submarine optical systems

(For further information see Recommendation ITU-T G.977 and the ITU-T Handbook on Marinized Terrestrial Cables).

Maintenance of submarine optical systems is mainly carried out by a routine control and by fault location.

1.6.1 Routine maintenance

Routine maintenance is performed from the terminal stations using the supervisory system. It consists of periodic monitoring of the system parameters and, when required, in preventive redundancy switching.

A supervisory and maintenance controller located in the terminal, in association with the repeater (or BU) supervisory unit, normally provides for fault localization, repeater performance monitoring and remote controlled redundancy switching.

The supervisory facilities commonly include one or more of the following:

- i) provision, on an in-service basis, of sufficient information to enable preventive maintenance, particularly if switchable redundancy is provided;
- ii) provision for further out-of-service fault location or system monitoring through loopback, remotely controlled from appropriate terminals;
- iii) indication of approaching failure of the in-service equipment, so that preventive action may be undertaken or planned;
- iv) the means to locate hard faults and intermittent faults (of duration and frequency), that cause the system to fail.

1.6.2 Fault localization

In *repeaterless* systems it may be sufficient to perform optical tests with an OTDR to locate, within instrumentation accuracy, the fault. If the cable contains metallic parts of known resistance per kilometre, it may be possible to evaluate if the damage is limited to the fibres or to the whole cable by means of resistance DC measurements.

The position of the fault can normally be determined from OTDR measurements, taking into account any fibre overlength.

Another alternative method that can be used is the electroding method, if both the cable and repair vessel offer such possibility. A low frequency signal (4-50 Hz) is injected into the cable. A repair vessel may be able to detect, by means of sensors, the signal along the cable route. When the signal disappears, the vessel is above the fault. This method is suitable up to a distance of typically over 100 km from the station.

For *repeatered* systems equipped with optical submarine repeaters, a first localization to within one supervisory section is obtained using the supervisory system.

For the end cable sections, cable fault localization may be achieved from the terminal stations, using adequate electrical measurement (resistance, capacitance, insulation, etc.) and optical reflectometry.

Similarly, cable fault localization may be achieved from the cable ship after cable recovery, using the same methods.

1.6.3 Fault repair

During *cable recovery* it may be necessary, in order to limit the mechanical tension applied to the cable, to cut the cable on the sea bottom prior to recovering both ends separately.

Several methods can be used for *sea repair*, depending on the sea depth:

i) the shallow water repair may necessitate the addition of a cable length, but not that of a repeater; a repair margin is generally included in the shallow water optical power budget since the shallow water sections are the most exposed to risk from external aggression, even though precautions are taken;

ii) the deep sea repair usually necessitates the addition of a cable length and sometimes of a repeater to compensate for the extra attenuation, if the extra attenuation incurred cannot be accommodated in the available margin; generally, a very low repair margin is included in the deep water optical power budget, since deep sea repairs are not frequent.

Repair safety procedures are applied on board the cable ship and in the terminal station, so as to ensure the safety of the personnel operating on board the cable ship. In particular, power safety procedures involve earthing the cable in the terminal station, on board the cable ship and at the branching unit.

2 Safety and environmental aspects

With the introduction of concepts of environmental sustainability, and standards such as ISO 9000 and ISO 14000 in telecommunications segments, safety and environmental aspects have become of great importance.

2.1 Safety aspects for optical power

2.1.1 Safe working conditions on optical interfaces

Recommendation ITU-T G.664 provides guidelines and requirements for techniques to enable optically safe working conditions (for the human eye and skin) on optical interfaces of the optical transport network, in particular, for systems employing high-power Raman amplification techniques.

The actual definition and specification of optically safe levels are considered outside the scope of ITU-T. The IEC is the organisation responsible for these matters. Therefore in Recommendation ITU-T G.664 specific references are made to IEC 60825-1, “Safety of laser products – Part 1: Equipment classification, requirements and user’s guide”, IEC 60825-2, “Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCS)” and IEC/TR 61292-4, “Optical amplifiers – Part 4: Maximum permissible optical power for the damage-free and safe use of optical amplifiers, including Raman amplifiers”.

The historical background of Recommendation ITU-T G.664 is very important for understanding its content and its objectives.

When (around 1990) the first transversely compatible optical interface (see Recommendation ITU-T G.957) was created, the optical levels specified therein were not considered completely safe according to the version of IEC 60825-1, which was then valid. In order to achieve interworking between equipment from different vendors, it was considered necessary to specify a transversely compatible procedure that would guarantee optically safe levels under all working conditions, including fibre break. Therefore, in the first version of Recommendation ITU-T G.664 the automatic laser shutdown (ALS) procedure was specified.

More recently, the IEC decided that much higher levels were considered optically safe and newer versions of IEC 60825-1 and IEC 60825-2 were issued. As a consequence, all of the optical levels currently specified in any of the ITU-T optical interface Recommendations on transversely compatible optical interfaces Recommendations ITU-T G.691, ITU-T G.693, ITU-T G.695, ITU-T G.698.1, ITU-T G.698.2, ITU-T G.957 and ITU-T G.959.1 are considered to be safe in “restricted locations”. As a result, for none of these systems it is necessary to perform optical shutdown or power reduction to achieve optically safe working conditions. Therefore, in the present version of ITU-T G.664, the description and specification of the ALS procedure has been moved from the normative (mandatory) main body to a non-normative (informative) appendix in order to preserve it for historical reasons. It is specifically mentioned that the inclusion of the ALS procedure in this appendix does not imply that it should be used.

The same considerations apply to the automatic power shut-down (APSD) procedure specified several years later for systems that use optical amplifiers.

Despite the fact that, as noted above, none of the existing ITU optical interface Recommendations contain optical power levels that are not considered safe, there are many non-interworking (proprietary or single-vendor) systems that are operated at potentially hazardous or dangerous optical power levels. Examples are optical transport systems using Raman amplification and DWDM systems with large channel counts. Recommendation ITU-T G.664 provides guidance on maintaining optically safe working conditions for the designers and users of these systems, by outlining some basic requirements for designing automatic power reduction (APR) techniques that are recommended by the IEC documents for maintaining safe conditions in these particular cases. Furthermore, some examples of APR techniques are described in an informative appendix to Recommendation ITU-T G.664. It should be noted that APR refers to a situation in which the optical power is not switched off totally, but reduced to a level sufficiently low to be considered safe.

2.1.2 Best practices for optical power safety

(For further information see Supplement 39 to the ITU-T G-series of Recommendations).

Optical transport systems using Raman amplification and DWDM systems with large channel counts are one of the most critical from the point of view of the safety because they can operate at sufficiently high powers that can also cause damage to fibre or other components. In the following, the best practices to be adopted for these systems are shown.

Before activating the Raman power:

i) calculate the distance to where the power is reduced to less than 150 mW;

ii) if possible inspect any splicing enclosures within that distance. If tight bends, e.g. less than 20 mm diameter, are seen, try to remove or relieve the bend, or choose other fibres;

iii) if inspection is not possible, a high resolution OTDR might be used to identify causes of bends or connector losses that could lead to damage at high power;

iv) if connectors are used, it should be verified that the ends are very clean. Metallic contaminants are particularly prone to causing damage. Fusion splices are considered to be the least subject to damage.

While activating Raman power:

i) in some cases, it may be possible to monitor the reflected light at the source as the Raman pump power is increased. If the plot of reflected power vs. injected power shows a non-linear characteristic, there could be a reflective site that is subject to damage;

ii) other sites subject to damage, such as tight bends in which the coating absorbs the optical power, may be present without showing a clear signal in the reflected power vs. injected power curve.

Operating considerations:

i) if there is a reduction in the amplification level over time, it could be due to a reduced pump power or to a loss increase induced by some slow damage mechanism such as at a connector interface. Simply increasing the pump power to restore the signal could lead to even more damage or catastrophic failure;

ii) the mechanism for fibre failure in bending is that light escapes from the cladding and some is absorbed by the coating which results in local heating and thermal reactions. These reactions tend to increase the absorption and thus increase the heating. When a carbon layer is formed, there is a runaway thermal reaction that produces enough heat to melt the fibre which then goes into a kinked state that blocks all optical power. Thus, there will be very little change in the transmission characteristics induced by a damaging process until the actual failure occurs. If the fibre is unbuffered, there is a flash at the moment of failure which is self-extinguishing because the coating is gone very quickly. A buffered fibre could produce more flames, depending on the material. For unbuffered fibres, sub-critical damage is evidenced by a coloring of the coating at the apex of the bend.

The complete list of the practices to be followed is rather long and can be found in Supplement 39 to the ITU-T G-series of Recommendations.

More information on the safety for the optical fibre cable maintenance support, monitoring and testing system for optical fibre cable networks carrying high total optical power can also be found in Recommendation ITU-T L.68.

2.2 Fire hazards

During maintenance work, operators must handle optical fibres or fibre-optic components carefully in central offices that employ high power systems, in order to prevent fire hazards.

2.2.1 Fire protection

(For further information see Recommendation ITU-T L.22).

Taking into account the serious damage that can occur when fires break out and the importance of fire prevention to the security, service provision and economics of communication systems, there are several aspects that should be considered, such as:

i) reduction of the fire-load coefficient;

ii) division of the building into compartments (fire sectors) to reduce and delay the spread of fire;

iii) fire statistics.

Reduction of the fire-load coefficient

For a fire to start, develop and spread, three factors must take place simultaneously:

i) the existence of sufficient quantity of combustible materials (combustible charge);

ii) the presence of oxygen;

iii) the temperature to produce ignition of the materials.

From the three factors described above, the most important is the amount of combustible materials in the building. Building designers can exert significant control on the use of combustible materials, which will benefit fire prevention by reducing the fire-load that would feed the fire. If the extra combustible charge from decorative items and soft furnishings is added, the amount of combustible material (fire-load) reaches a limit that could be dangerous in the event of a fire. For example, in most telecommunication buildings the fire-load is formed by:

i) plastic and natural or synthetic wood elements used for floors, dividing walls, partitions, cabinets and suspended ceilings;

ii) materials of organic origin such as paints, papers and textiles;

iii) insulating materials, ducts, plastic or rubber equipment parts;

iv) decorative items and furnishings such as curtains, upholstery and combustible foam padding, carpets, pictures, books and writing materials.

Creation of fire sectors

Combustion is an oxidation process which, once initiated, keeps going if combustible materials are heated over their ignition temperature and continue to receive enough oxygen through the air supply. This creates a thermal exchange by conduction, radiation and convection to surrounding materials that encourages the fire to spread. By dividing the building into compartments to form fire sectors, the fire can be contained or delayed from spreading. The compartments are created using partitions of high-performance fire-stopping elements which are difficult to ignite. The degree of fire resistance of the partition elements will depend on the size of the compartments and their use, for example, as offices or storage areas.

The elements of the structure that form the boundaries of a fire sector should have fire resistance despite through-cable penetration points. The fire resistance of the boundaries should be such as to ensure that the propagation of smoke and fire between fire sectors is avoided before the extinction system is activated. For further details see Recommendation ITU-T L.32.

Fire statistics

Fires are isolated catastrophes affecting a limited number of people and buildings at any one time. Once the fire has broken out, every effort is applied to fighting the fire with the activation of various systems and devices, such as detection systems, alarm systems, extinguisher systems and fire-fighting personnel.

When the fire has been controlled and extinguished, investigations are started to find the possible causes of the fire. The reports produced can be turned into fire statistics, which can be taken into account in the design of new buildings and procedures to reduce the outbreaks of fire.

2.2.2 Fire detection and alarm systems, detector and sounder devices

In order to protect property and, when applicable, life, protective fire detection and alarm systems can be installed to initiate a number of different activities:

- i) detection and location of a fire;
- ii) provision of assistance to contain and/or extinguish the fire;
- iii) emergency evacuation procedures;
- iv) summoning of fire-fighting forces.

It should be noted that a fire detection and alarm system can do nothing to reduce the incidence of fires. It can however reduce the delay between ignition and effective fire-fighting. A satisfactory alarm system for the protection of property will automatically detect the fire at an early stage, raise an effective alarm in time to summon the fire-fighting forces, and indicate the location of the fire. An early alarm of fire enhances the safety of personnel by increasing their chances of escape.

Taking into account the risk of fire and the action needed to reduce the magnitude of the fire hazard, quick detection is the first criterion to be considered, followed by the activation of measures to extinguish the fire.

Detection devices are part of the automatic fire detection and alarm systems. These systems monitor continuously, or at frequent intervals, the physical and/or chemical characteristics of a protected fire area (zone).

The description of the various types of fire detectors (automatic; heat, smoke, flame detectors; etc.) and the criteria for their location can be found in Recommendation ITU-T L.21.

2.2.3 Equipment and installation for fire extinction

The different functions taking place in a telecommunication building generates possibilities and provides strong causes for fires on the premises. Fire extinction action involves concentrating the fire fighting at the origin of the fire, inside the building itself, using a choice of extinguishing systems.

The fire-fighting means to be adopted in a telecommunication building, may vary according to the usage and location of the premises and whether it is occupied. These are factors which determine the amount of fire service assistance initially allocated in case there should be a fire.

Fire extinction can involve a number of systems which are mutually supportive, although each may be independent of the others. The success of one or more systems may make unnecessary or reduce the need for the others. These systems are:

– *Initial fire fighting* with transportable or movable fire-fighting devices, such as portable extinguishers, fire blankets, etc., and other equipment that assist fire fighting personnel, such as masks, insulated garments, etc.

– *Fixed fire extinguishing systems* which involve non-transportable fire-fighting fixtures that are fixed extinguishing installations incorporated into the building and other accessory installations, such as hydrants, water supply networks, water spraying installations, sprinklers, automatic powder or gaseous extinguishers, water hoses, etc.

– *Action by the fire service*. This involves using their own equipment and/or using non-transportable fire-fighting fixtures, such as hydrants, hose reels and foam inlets.

– *Portable fire extinguishers* should be placed in all telecommunication buildings. The type should be appropriate for the fire risk.

– *Fire sectors* should be established that can be equipped with fixed extinguishing installations.

More details on types and placement of the above equipment and systems can be found in Recommendation ITU-T L.23.

Methods for the inspection and maintenance of every component of fire extinction systems should be introduced, with a view to guaranteeing their effectiveness in the event of a fire. Details can be found in Recommendation ITU-T L.33.

The safety practices for personnel and fire protection in outdoor installations are also important for telecommunications installations such as duct systems; manholes; tunnels; aerial, underground and buried networks; and subscriber equipment within the outside plant. More information on this issue is in Recommendation ITU-T L.63.

2.3 Environmental aspects

(For further information see Recommendation ITU-T L.45).

As a result of climate change, the interest on environmental issues is growing in areas that include life cycle analysis of products and processes, environmentally friendly materials and waste disposal.

Environmental sustainability can be defined as the ability to maintain the qualities that are valued in the physical environment, taking care of the aspects of the environment that produce renewable resources such as water, energy and air.

Products used in outside plant are typically manufactured using thermoplastic materials, lead, copper and wood, and preservative substances or antioxidants are added to ensure the long term performance of products. The proper replacement and final disposal of these materials is a goal for all environmentally correct countries. Moreover, new classes of materials that minimize environmental impact have to be studied, also taking into account that huge quantities will be deployed as developing countries extend their networks.

On the other hand, not only materials and equipment, but also the related installation and operation processes can affect the environment.

Therefore, the mitigation of these sources of environmental damage must also be considered:

i) to contribute in all industrial activities to reduce the effects of global warming;

ii) to minimize energy consumption and reduce greenhouse gases in accordance with the technique of life-cycle analysis in ISO 14040;

iii) to use ISO 14020 and ISO 14025 as criteria for an environmental declaration on products and systems;

iv) that each organization involved should have an environmental policy and an environmental plan with measurable goals on how to improve products and methods for a reduction of the energy consumption;

v) to keep track of toxic and dangerous substances and to have a waste management system.

2.3.1 Life-cycle analysis

In an attempt to cover the whole life cycle using a "cradle to the grave" perspective for cables and equipment, the life cycle is divided into several phases:

Manufacturing. The manufacturing phase includes raw material, transportation and production of a product. It is important to use materials with low impact on the environment and to follow the legislation in each country and the recommendations regarding banned materials.

Usage. The "usage" phase can be divided into installation, operation and maintenance. It is established that optical cables, due to their light weight and improved installation capability technique, use less energy and emit less CO_2 than copper cables.

During the installation phase of the cables it is also very important to organize transportation in an optimal way. This is done by using a fleet of well-maintained vehicles and machinery that causes minimal pollution by using suitable fuel and having catalyst exhaust fume cleaning systems.

Scrapping. Scrapping of cables is divided into disassembling and recycling/waste. Scrapping of optical cables is not common today. Scrapping of the optical cable ends (short cable pieces) is currently performed when splicing cables and the cable waste is disposed of in a way similar to the one used in the manufacturing process. Scrapping of old copper cables is industrialized in most parts of the world. The copper is recycled and the plastic materials are burned or disposed of as waste. If cables or batteries contain lead, the recycling process should be carried out according to safety requirements. Scrapping of old telephone poles impregnated with preservatives also requires sound environmental practices.

Disassembling. Excluding the duct and poles, optical cables can be removed with the same technique with which they were installed (blowing, floating and pulling). Due to the ease of their removal, it is potentially possible to reuse the cable or to recycle the cable material. They can also be left in the duct (if allowed), as they cause no contamination underground.

Recycling/waste. Sheath materials from optical cables and fibres can easily be separated mechanically and most of the plastic materials recycled.

Where optical cables are metal free and only contain thermoplastic plus optical fibres, the energy content in the thermoplastic can be regained as heat when burnt in heating plants, as its content is similar to petroleum oil.

For poles, attention should be paid to local legislation concerning their disposal or reuse.

ABBREVIATIONS AND ACRONYMS

ADC	Adaptive Dispersion Compensator
ALS	Automatic Laser Shut-down
AON	All Optical Networks
APD	Avalanche Photodiodes
APR	Automatic Power Reduction
APSD	Automatic Power Shut-Down
ASE	Amplified Spontaneous Emission
ATM	Alternative Test Method
BA	Booster Amplifier
BCH codes	Bose- Chaudhuri - Hocquenghem codes
BER	Bit Error Ratio
BOL	Beginning Of Life
B-OTDR	Bidirectional OTDR
BPON	Broadband PON
BU	Branching Unit
CCTV	Closed-Circuit Television
CO	Central Office
CTE	Cable Terminating Equipment
CWDM	Coarse Wavelength Division Multiplexing
DA	Dispersion Accommodation
DA Cable	Double Armoured Cable
DBA	Dynamic Bandwidth Assignment
DC	Direct Current
DCF	Dispersion-Compensating Fibres
DCN	Data Communication Network
DEMUX	Demultiplexer
DFB	Distributed Feedback
DFE	Decision Feedback Equalization
DGD	Differential Group Delay
DRA	Distributed Raman Amplifier
DST	Dispersion Supported Transmission
DWDM	Dense Wavelength Division Multiplexing
EDC	Electronic Dispersion Compensation
EDFA	Erbium-Doped Fibre Amplifier

EME	Embedded Monitoring Equipment
EOL	End-of-Life
ES	Errored Seconds
FEC	Forward Error Correction
FFE	Feed Forward Equalization
FP	Fabry-Perot
FTTB	Fibre-to the-Building
FTTC	Fibre-to-the-Curb
FTTCab	Fibre-to-the-Cabinet
FTTH	Fibre-to-the-Home
FTTx	Fibre-to-the-x
FWM	Four-Wave Mixing
G-PON	Gigabit capable PON
GRP	Ground Penetrating Radar
HMI	Human Machine Interface
IrDI	Inter-Domain Interface
ISDN	Integrated Service Digital Network
LA	Line Amplifier
Laser	Light Amplification by Stimulated Emission of Radiation
LED	Light-Emitting Diodes
LW	Lightweight Cable
LWP	Low Water Peak
LWP	Lightweight Protected Cable
MAC	Media Access Control
MCVD	Modified Chemical-Vapour Deposition
MDU	Multi-Dwelling Units
MFD	Mode Field Diameter
MLM	Multi Longitudinal Mode
MLSE	Maximum Likelihood Sequence Estimation
MPI-R	Multi-Path Interface at the Receiver (Single-channel)
MPI-R_M	Multi-Path Interface at the Receiver (Multichannel)
MPI-S	Multi-Path Interface at the Source (Single-channel)
MPI-S_M	Multichannel Multi-Path Interface at the Source (Multichannel)
MTTF	Mean-Time-to-Failure
MUX	Multiplexer
MZ	Mach-Zehnder
NA	Numerical Aperture

NCG	Net Coding Gain
NE	Network Element
NGA	Next Generation Access
NOC	Network Operations Centre
NRZ	Non-Return-to-Zero
OA	Optical Amplifier
OADM	Optical Add/Drop Multiplexer
OAR	Optically Amplified Receiver
OAT	Optically Amplified Transmitter
OD	Optical Demultiplexer
ODF	Optical Distribution Frame
ODN	Optical Distribution Network
ODUk	Optical Data Unit (k)
OFA	Optical Fibre Amplifier
OLA	Optical Line Amplifier
OLT	Optical Line Termination
OM	Optical Multiplexer
ONE	Optical Network Element
ONT	Optical Network Termination
ONU	Optical Network Unit
OPGW	Optical Fibre Ground Wires
OPM	Optical Power Monitor
OPM	Optical Power Meter
ORL	Optical Return Loss
OS	Operating System
OSA	Optical Spectrum Analyser
OSC	Optical Supervisory Channel
OSNR	Optical Signal-to-Noise Ratio
OSR	Optical Submarine Repeater
OTDR	Optical Time Domain Reflectometer
OTF	Optical Termination Frame
OTL	Optical Trunk Line
OTM	Optical Testing Module
OTN	Optical Transport Network
OTUk	Optical Transport Unit (k)
OVD	Outside-Vapor Deposition
PA	Pre-Amplifier

PCH	Prechirp
PCVD	Plasma-activated Chemical-Vapor Deposition
PDC	Passive Dispersion Compensation
PDC	Passive Dispersion Compensator
PDF	Probability Density Function
PDH	Plesiochronous Digital Hierarchy
PDL	Polarization Dependent Loss
PE	Polyethylene
PFE	Power Feeding Equipment
PMD	Polarization Mode Dispersion
PMD	Physical Media Dependent
PMDC	Polarization Mode Dispersion Compensators
PON	Passive Optical Network
POTS	Plain Old Telephone Service
PSP	Principal States of Polarization
PVC	Polyvinyl Chloride
PXC	Photonic Cross-Connect
RA Cable	Rock Armoured Cable
RE	Reach Extender
ROADM	Reconfigurable Optical Add/Drop Multiplexer
ROPA	Remote Optically Pumped Amplifier
RS codes	Reed-Solomon codes
RTM	Reference Test Method
RZ	Return to Zero
SA Cable	Single Armoured Cable
SBS	Stimulated Brillouin Scattering
SDH	Synchronous Digital Hierarchy
SES	Severely Errored Seconds
SLM	Single Longitudinal Mode
SNI	Service Node Interface
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifiers
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
STM-N	Synchronous Transport Module (order N)
TC	Transmission Convergence
TCM	Time Compression Multiplexing

TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TMC	Terrestrial Marinized Cables
TS	Terminal Station
TTE	Terminal Transmission Equipment
UNI	User Network Interface
VAD	Vapor-Axial Deposition
VCSEL	Vertical-Cavity Surface-Emitting Lasers
VDSL2	Very high speed Digital Subscriber Loop
VOD	Video On Demand
WBF	Wavelength Blocking Filter
WDM	Wavelength Division Multiplexing
WPNS	Water Peak Not Specified
WSON	Wavelength Switched Optical Network
WWDM	Wide WDM
xDSL	x Digital Subscriber Line
XPM	Cross Phase Modulation

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