International Telecommunication Union

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

Series G

Supplement 41

(02/2018)

SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Design guidelines for optical fibre submarine cable systems

ITU-T G-series Recommendations – Supplement 41

ITU-T G-SERIES RECOMMENDATIONS

TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

For further details, please refer to the list of ITU-T Recommendations.

Supplement 41 to ITU-T G-series Recommendations

Design guidelines for optical fibre submarine cable systems

Summary

Supplement 41 to the ITU-T G-series of Recommendations describes design considerations for repeatered, repeaterless and optically amplified systems supporting synchronous digital hierarchy (SDH) and optical transport network (OTN) signals in optical submarine cable systems.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T G Suppl. 41	2005-05-27	15	11.1002/1000/8490
2.0	ITU-T G Suppl. 41	2007-06-15	15	11.1002/1000/9193
3.0	ITU-T G Suppl. 41	2010-06-11	15	11.1002/1000/10929
4.0	ITU-T G Suppl. 41	2018-02-09	15	11.1002/1000/13583

Keywords

Guidelines, optical power budget, physical layer, reliability, repeatered systems, repeaterless systems, submarine, submarine topology, upgradeability.

* To access the Recommendation, type the URL http://handle.itu.int/ in the address field of your web browser, followed by the Recommendation's unique ID. For example, http://handle.itu.int/11.1002/1000/11830-en.

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications, information and communication technologies (ICTs). The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this publication, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

Compliance with this publication is voluntary. However, the publication may contain certain mandatory provisions (to ensure, e.g., interoperability or applicability) and compliance with the publication is achieved when all of these mandatory provisions are met. The words "shall" or some other obligatory language such as "must" and the negative equivalents are used to express requirements. The use of such words does not suggest that compliance with the publication is required of any party.

INTELLECTUAL PROPERTY RIGHTS

ITU draws attention to the possibility that the practice or implementation of this publication may involve the use of a claimed Intellectual Property Right. ITU takes no position concerning the evidence, validity or applicability of claimed Intellectual Property Rights, whether asserted by ITU members or others outside of the publication development process.

As of the date of approval of this publication, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this publication. However, implementers are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database at http://www.itu.int/ITU-T/ipr/.

Table of Contents

Supplement 41 to ITU-T G-series Recommendations

Design guidelines for optical fibre submarine cable systems

1 Scope

This supplement describes design considerations for repeatered, repeaterless and optically amplified systems supporting synchronous digital hierarchy (SDH) and optical transport network (OTN) signals in optical submarine cable systems. In particular, this supplement focuses on specific matters that are relevant to optical fibre submarine cable systems.

This supplement also describes a common way of thinking of the requirements for designing optical fibre submarine cable systems and aims to consolidate and expand on material related to several Recommendations, including [ITU-T G.971], [ITU-T G.972], [ITU-T G.973], [ITU-T G.973.1], [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].

This supplement should also allow a reader to better understand the specifications in the fibre, components, and system interface Recommendations. This supplement should not prevent technical development relevant to optical fibre cable system technologies.

2 References

[ITU-T G.650.1] Recommendation ITU-T G.650.1 (2018), *Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable*.

[ITU-T G.650.2] Recommendation ITU-T G.650.2 (2015), *Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable*.

[ITU-T G.652] Recommendation ITU-T G.652 (2016), *Characteristics of a single-mode optical fibre and cable*.

[ITU-T G.653] Recommendation ITU-T G.653 (2010), *Characteristics of a dispersion-shifted single-mode optical fibre and cable*.

[ITU-T G.654] Recommendation ITU-T G.654 (2016), *Characteristics of a cut-off shifted single-mode optical fibre and cable*.

[ITU-T G.655] Recommendation ITU-T G.655 (2009), *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable*.

[ITU-T G.656] Recommendation ITU-T G.656 (2010), *Characteristics of a fibre and cable with non-zero dispersion for wideband optical transport*.

[ITU-T G.661] Recommendation ITU-T G.661 (2007), *Definitions and test methods for the relevant generic parameters of optical amplifier devices and subsystems*.

[ITU-T G.663] Recommendation ITU-T G.663 (2011), *Application-related aspects of optical amplifier devices and subsystems*.

[ITU-T G.671] Recommendation ITU-T G.671 (2012), *Transmission characteristics of optical components and subsystems*.

[ITU-T G.691] Recommendation ITU-T G.691 (2006), *Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers*.

[ITU-T G.692] Recommendation ITU-T G.692 (1998), *Optical interfaces for multichannel systems with optical amplifiers*.

[ITU-T G.693] Recommendation ITU-T G.693 (2009), *Optical interfaces for intra-office systems*.

[ITU-T G.694.1] Recommendation ITU-T G.694.1 (2012), *Spectral grids for WDM applications: DWDM frequency grid*.

[ITU-T G.694.2] Recommendation ITU-T G.694.2 (2003), *Spectral grids for WDM applications: CWDM wavelength grid*.

[ITU-T G.826] Recommendation ITU-T G.826 (2002), *End-to-end error performance parameters and objectives for international, constant bit-rate digital paths and connections*.

[ITU-T G.828] Recommendation ITU-T G.828 (2000), *Error performance parameters and objectives for international, constant bit-rate synchronous digital paths*.

[ITU-T G.911] Recommendation ITU-T G.911 (1997), *Parameters and calculation methodologies for reliability and availability of fibre optic systems*.

[ITU-T G.957] Recommendation ITU-T G.957 (2006), *Optical interfaces for equipment and systems relating to the synchronous digital hierarchy*.

[ITU-T G.959.1] Recommendation ITU-T G.959.1 (2018), *Optical transport network physical layer interfaces*.

[ITU-T G.971] Recommendation ITU-T G.971 (2016), *General features of optical fibre submarine cable systems*.

[ITU-T G.972] Recommendation ITU-T G.972 (2016), *Definition of terms relevant to optical fibre submarine cable systems*.

[ITU-T G.973] Recommendation ITU-T G.973 (2016), *Characteristics of repeaterless optical fibre submarine cable systems*.

[ITU-T G.973.1] Recommendation ITU-T G.973.1 (2009), *Longitudinally compatible DWDM applications for repeaterless optical fibre submarine cable systems*.

[ITU-T G.974] Recommendation ITU-T G.974 (2007), *Characteristics of regenerative optical fibre submarine cable systems*.

[ITU-T G.975] Recommendation ITU-T G.975 (2000), *Forward error correction for submarine systems*.

[ITU-T G.975.1] Recommendation ITU-T G.975.1 (2004), *Forward error correction for high bit-rate DWDM submarine systems*.

[ITU-T G.976] Recommendation ITU-T G.976 (2014), *Test methods applicable to optical fibre submarine cable systems*.

[ITU-T G.977] Recommendation ITU-T G.977 (2015), *Characteristics of optically amplified optical fibre submarine cable systems*.

[ITU-T G.978] Recommendation ITU-T G.978 (2010), *Characteristics of optical fibre submarine cables*.

[ITU-T G.8201] Recommendation ITU-T G.8201 (2011), *Error performance parameters and objectives for multi-operator international paths within optical transport networks*.

[ITU-T G.Sup.39] ITU-T G-series Recommendations – Supplement 39 (2016), *Optical system design and engineering considerations*.

[IEC/TR 61282-3] IEC/TR 61282-3 (2006), *Fibre optic communication system design guides – Part 3: Calculation of link polarization mode dispersion*.

[IEC 61709] IEC 61709 (2017), *Electric components - Reliability - Reference conditions for failure rates and stress models for conversion*.

3 Definitions

Formal definitions are found in the primary Recommendations.

4 Abbreviations and acronyms

This supplement uses the following abbreviations and acronyms:

3R Regeneration of power, shape and timing

ASE Amplified Spontaneous Emission

BER Bit Error Ratio

BoL Beginning of Life

BPSK Binary Phase Shift Keying

BU Branching Unit

COTDR Coherent Optical Time Domain Reflectometry

CF Compression Factor

CSF Cut-off Shifted single mode Fibre

CTB Cable Terminal Box

CWDM Coarse Wavelength Division Multiplexing

DCF Dispersion Compensation single-mode Fibre

DGD Differential Group Delay

DLS Digital Line Section

DPSK Differential Phase Shift Keying

DSF Dispersion Shifted single mode Fibre

DWDM Dense Wavelength Division Multiplexing

DWDMS Dense Wavelength Division Multiplexing System

EDF Erbium-Doped Fibre

EoL End of Life

ER Extinction Ratio

FEC Forward Error Correction

FIT Failure In Time

FWM Four-Wave Mixing

GF Gain Flatness

LOC Line Optical Channel

IrDI Inter Domain Interface

MDC Maximum Design Capacity

MPI-R Multi-Path Interface at the Receiver

MPI-S Multi-Path Interface at the Source

MTBF	Mean Time Between Failures
MTC	Marinized Terrestrial Cable
MTTR	Mean Time To Repair
NDSF	Non-Dispersion Shifted single mode Fibre
NF	Noise Figure
NG	Nominal Gain
NOTS	Nominal Operating Tensile Strength
NRZ	Non-Return to Zero
NSIP	Nominal Signal Input Power
NSOP	Nominal Signal Output Power
NTTS	Nominal Transient Tensile Strength
NZDSF	Non-Zero Dispersion Shifted single mode Fibre
OA	Optical Amplifier
OD	Optical De-multiplexer
OFA	Optical Fibre Amplifier
OM	Optical Multiplexer
OOK	On – Off Keying
OSNR	Optical Signal-to-Noise Ratio
OSR	Optical Submarine Repeater
OTDR	Optical Time Domain Reflectometry
OTN	Optical Transport Network
PBT	Power Budget Table
PDG	Polarization Dependent Gain
PDL	Polarization Dependent Loss
PFE	Power Feeding Equipment
PHB	Polarization Hole Burning
PMD	Polarization Mode Dispersion
QPSK	Quadrature Phase Shift Keying
R	Single channel optical interface point at the Receiver
RX	(optical) Receiver
RZ	Return to Zero
S	Single channel optical interface at the Source
SDH	Synchronous Digital Hierarchy
SEOI	Submarine Electro-Optic Interface
SHB	Spectral Hole Burning
SLD	Straight Line Diagram
SoP	State of Polarization

SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
SSG	Small Signal Gain
SWS	Single Wavelength System
TS	Terminal Station
TTE	Terminal Transmission Equipment
TX	(optical) Transmitter
UC	Ultimate Capacity
WDM	Wavelength Division Multiplexing
WDMS	Wavelength Division Multiplexing System
XPM	cross-Phase Modulation

5 Parameters of system elements

5.1 Transmitter parameters

These parameters are defined at the transmitter output reference points S or MPI-S, as given in [ITU-T G.957], [ITU-T G.691], [ITU-T G.692] and [ITU-T G.959.1].

5.1.1 System operating wavelength range

The operating wavelength ranges for single channel SDH systems up to 10 Gbit/s are given in [ITU-T G.691] and [ITU-T G.957]. The operating wavelength ranges for single channel and multichannel IrDIs up to 50 Gbit/s are defined in [ITU-T G.959.1]. Other applications may use different wavelength bands and ranges within bands as defined in this supplement.

5.1.2 Spectral characteristics

Spectral characteristics of single channel SDH interfaces up to 10 Gbit/s are given in [ITU-T G.957] and [ITU-T G.691]. For higher bit rates and longer distances, in particular in a wavelength division multiplexing (WDM) environment, additional specifications may be needed.

5.1.3 Maximum spectral width of SLM sources

This parameter is defined for single channel SDH systems in [ITU-T G.691].

5.1.4 Maximum spectral width of MLM sources

This parameter is defined for single channel SDH systems in [ITU-T G.691].

5.1.5 Chirp

This parameter is defined in [ITU-T G.691]. For higher bit rate or longer distance systems, possibly also operating on other line codes, it is likely that additional specifications of a time-resolved dynamic behaviour might be required. This, as well as the measurement of this parameter, is for further study.

5.1.6 Side-mode suppression ratio

The side-mode suppression ratio of a single longitudinal-mode optical source is defined in [ITU-T G.957], [ITU-T G.691] and [ITU-T G.959.1]. Values are given for SDH and OTN IrDI systems up to 50 Gbit/s.

5.1.7 Maximum spectral power density

Maximum spectral power density is defined in [ITU-T G.691].

5.1.8 Maximum mean channel output power

Maximum mean channel output power of a multichannel optical signal is specified and defined in [ITU-T G.959.1].

5.1.9 Minimum mean channel output power

This property of a multichannel optical signal is specified and defined in [ITU-T G.959.1].

5.1.10 Central frequency

Central frequencies of WDM signals are given in [ITU-T G.694.1]. Here, frequencies are given down to 12.5 GHz spacing.

5.1.11 Channel spacing

Channel spacing is defined in [ITU-T G.694.1] for dense wavelength division multiplexing (DWDM) as well as in [ITU-T G.694.2] for coarse wavelength division multiplexing (CWDM). A complete classification of WDM systems is in [ITU-T G.671].

5.1.12 Maximum central frequency deviation

Maximum central frequency deviation for NRZ coded optical channels is defined in [ITU-T G.692] and [ITU-T G.959.1]. Other possibilities using asymmetrical filtering may require a different definition which is for further study.

5.1.13 Minimum extinction ratio

The minimum extinction ratio, as a per-channel value for NRZ coded WDM systems, is defined in [ITU-T G.959.1]. For RZ coded signals, the same method applies. For other line codes, this definition is for further study.

5.1.14 Eye pattern mask

The eye pattern masks of SDH single-channel systems are given in [ITU-T G.957], [ITU-T G.691], [ITU-T G.693] and other Recommendations. The eye pattern mask for NRZ coded IrDI multichannel and single-channel interfaces is defined in [ITU-T G.959.1].

5.1.15 Polarization

This parameter gives the polarization distribution of the optical source signal. This parameter might influence the PMD tolerance and is important in case of polarization multiplexing.

5.1.16 Optical signal-to-noise ratio of an optical source

This value gives the ratio of optical signal power relative to optical noise power of an optical transmitter in a given bandwidth coupled into the transmission path. Calculation and estimation of the optical signal-to-noise ratio is defined in [ITU-T G.Sup.39].

5.2 Submarine cable parameters

The submarine cable is designed to ensure protection of optical fibres against water pressure, longitudinal water propagation, chemical aggression and the effects of hydrogen contamination throughout the cable design life.

The cable is designed also to ensure that there will be no fibre performance degradations when the cable is laid, buried, recovered and operated using standard submarine practices.

The relevant specifications as well as implementation-related aspects of the optical fibre submarine cables are given in [ITU-T G.978].

5.2.1 Classification of the submarine cable

5.2.1.1 Classification based on application

An underwater optical fibre cable can be:

- a repeatered submarine cable;
- a repeaterless submarine cable;
- a marinized terrestrial cable.

Repeatered submarine cables can be used in all underwater applications, mainly for deep waters.

The repeaterless submarine cable is suitable for use in both shallow and deep waters. Marinized terrestrial cables (MTCs) are generally used for crossing lakes and rivers. All submarine cables are normally tested extensively to show that they can be installed and repaired in situ, even in the worst weather conditions, without any impairment of optical, electrical or mechanical performance or reliability.

5.2.1.2 Classification based on cable protection

The optical fibre submarine cable should provide protection against the environmental hazards at its depth of utilization: protection against marine life, fish bites and abrasion, and armours against aggression and ship activities. Different types of protected cable are defined in [ITU-T G.978], in particular:

- the single-armoured cable;
- the double-armoured cable;
- the rock-armoured cable.

5.2.1.3 Classification based on fibre protection by the cable structure

The strength of the cable structure together with that of the fibre determine the overall cable mechanical behaviour. They 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 cable structure are commonly used to protect the optical fibres:

- 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;
- 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 value.

5.2.2 Transmission parameters of fibre in a submarine cable

Generally, the transmission characteristics of the fibres before cabling (installation in the cable) will be similar to, or the same as, those specified in [ITU-T G.652], [ITU-T G.653], [ITU-T G.654], [ITU-T G.655] and [ITU-T G.656]. Types of fibre are chosen to optimize the system's overall cost and performance.

The transmission characteristics of the fibres in an elementary cable section should be within a specified limit of variation from the characteristics of the fibre before cabling; in particular the design of the cable, cable joints and fibre should be such that fibre bending and microbending create negligible attenuation increase. This is to be taken into account for determining the minimum fibre bending radius in the cable and in the equipment (optical cable joints, termination, repeaters, etc.).

The fibre attenuation, chromatic dispersion and PMD should remain stable within specified limits for the system design life; in particular, the design of the cable should minimize to acceptable levels both hydrogen penetration from outside and hydrogen generation within the cable, even after a cable break at the depth of utilization; the sensitivity of optical fibre to gamma radiation should also be taken into account.

The main parameters that characterize an optical fibre are:

- the attenuation coefficient at all the operating wavelengths, expressed in dB/km;
- the chromatic dispersion coefficient at all the operating wavelengths, in ps/nm·km;
- the zero dispersion wavelength, λ_0, in nm;
- the dispersion slope around the operating wavelengths, in ps/nm^2·km;
- the non-linear refractive index, n_2, in m^2/W;
- the effective area, A_{eff}, in µm^2;
- the non-linear coefficient n_2/A_{eff} in W^{-1};
- the ensemble average polarization mode dispersion (PMD), in ps/(km)^{½}.

Regarding these parameters, submarine system designers may distinguish several types of optical fibre. Among them are:

- non-dispersion shifted single mode fibre (NDSF) defined in [ITU-T G.652];
- dispersion-shifted single-mode fibre (DSF) defined in [ITU-T G.653];
- cut-off shifted single-mode fibre (CSF) defined in [ITU-T G.654];
- non-zero dispersion-shifted single-mode fibre (NZDSF) defined in [ITU-T G.655] and [ITU-T G.656];
- dispersion compensation single-mode fibre (DCF);
- negative dispersion slope fibre;
- very large effective area fibre.

Depending on the system specifications (data bit rate and coding, number of wavelengths, amplifier span, amplifier output power, length of the link, etc.), various combinations of these fibre types may be used to ensure system performance. In this case, the system is said to be dispersion managed.

5.2.2.1 Fibre loss

The loss of an optical fibre is characterized by the attenuation coefficient expressed in dB/km (log value) or in km^{-1} (linear value).

5.2.2.2 Fibre non-linearity

Non-linear effects should be considered when long-haul optical links are designed with high output power optical fibre amplifiers (OFAs). These effects are cumulative along the optical link and may degrade significantly the propagation. In the single wave system (SWS), the predominant non-linear effect is generally self-phase modulation of the signal proportional to the non-linear coefficient (ratio n_2/A_{eff}) multiplied by the square of its normalized amplitude. This non-linearity, in the presence of chromatic dispersion, induces a pulse broadening in the time domain, and a consequent impairment of system performance. In WDMS or DWDMS, the predominant effect is normally cross-phase modulation due to the presence of adjacent wavelengths. This non-linearity induces performance degradation.

5.2.2.3 Polarization mode dispersion (PMD)

Small departures from perfect cylindrical symmetry in the fibre core leads to birefringence because of a different mode index associated with the orthogonal polarized components of the fundamental mode. PMD induces pulse spreading and should be bounded to a maximum value. This value may be expressed for the whole link and is generally fixed to a certain ratio of the bit time-slot. PMD is expressed in ps/(km)^{½}.

5.2.2.4 Chromatic dispersion

Chromatic dispersion is the wavelength dependency of group velocity so that all the spectral components of an optical signal will propagate at different velocities. This induces pulse spreading and can be a major impairment. Depending on the system design and especially on the number of wavelengths (WDM systems), it may be of interest to manage it quite differently to limit pulse spreading and other propagation effects. Generally, this management leads to a dispersion map that shows how dispersion is managed along the whole link.

5.2.3 Fibre mechanical parameters

The fibre mechanical performance is largely dependent on the application of a proof test to the whole length of fibre. The optical fibre proof test is characterized by the load applied to the fibre or the fibre elongation, and the time of application. The level of the proof test should be determined as a function of the cable structure. Fibre splices should be similarly proof tested. It is recommended that the duration of the proof tests be as brief as possible.

The mechanical strength of the fibre and splices is to be taken into account for determining the minimum bending radius of the fibre in the cable and in the equipment (repeaters, branching units, cable jointing boxes or cable terminations).

5.2.4 Cable mechanical parameters

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; 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.

In the event of the cable being 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 the cable should be replaced; its length should stay within a specified value.

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

- the cable breaking load, measured during qualification test;
- the fibre-breaking cable load, measured during qualification test;
- the nominal transient tensile strength, which could be accidentally encountered, particularly during recovery operations;
- the nominal operating tensile strength, which could be encountered during repairs;
- the nominal permanent tensile strength, which characterizes the status of the cable after laying;
- the minimum cable bending radius, which is a guide for cable handling.

5.2.5 Cable electrical parameters

The cable should enable remote power feeding of repeaters or branching units, and include a power conductor with a low linear resistance, and an insulator with a high voltage insulation capacity.

5.2.6 Factory length of the submarine cable

The submarine cable factory length should be as long as possible. The factory length should be larger than 25 km commonly.

5.2.7 Physical parameters of the submarine cable

The physical parameters of the submarine cable include outer diameter, weight in air, weight in water.

5.2.8 Repair cable

Repair cable is used when submarine cable is broken or damaged. The repair cable should be in accordance with the cable to be repaired as for optical characteristics, electronic characteristics, and mechanical characteristics as defined in [ITU-T G.978].

5.3 Submarine repeater parameters

Submarine repeater parameters refer to [ITU-T G.974] and [ITU-T G.977].

5.3.1 Repeater types

There are three types of repeaters:

- optical repeater with 3R electrical regeneration;
- optical repeater with EDF amplifier;
- optical repeater with Raman amplification.

NOTE – In other clauses in this supplement, OFA is used to include EDF amplifiers and Raman amplifiers.

5.3.2 Parameters of the optical repeater with 3R electrical regeneration

5.3.2.1 Optical parameters

The signal at the optical interface should be in agreement with the power budget of the optical section. In particular, at the time of system assembly, certain limits should be respected:

- Minimum repeater mean input power (dBm): the mean optical power in the optical line signal which must be present at the time of link assembly at the repeater optical input interface so that the optical power budget of the cable section offers the guaranteed margin.
- Minimum repeater mean output power (dBm): the mean optical power in the optical line signal which must be present at the time of link assembly at the repeater optical output interface so that the optical power budget of the cable section offers the guaranteed margin.

For integrated systems, similar parameters should be specified as part of the integration specification at the integration line optical interface.

5.3.2.2 Jitter parameters

The jitter performance of the repeater (jitter tolerance, maximum output jitter, jitter transfer characteristics) at the optical interface needs to be compatible with the system specification.

For integrated systems, the same parameters, the output repeater jitter spectral density and the alignment jitter should be specified as part of the integration specification at the integration line optical interface.

5.3.3 Parameters of the optical repeater with EDF amplification

5.3.3.1 Optical parameters

[ITU-T G.661] deals with definition and tests methods for the relevant generic parameters of EDF amplifiers. For EDF amplifiers in repeaters it is necessary to take into account the following parameters:

- small signal gain (SSG);
- nominal gain (NG);
- noise figure (NF);
- nominal signal output power (NSOP);
- nominal signal input power (NSIP);
- compression factor (CF);
- minimum repeater mean input power (in dBm);
- minimum repeater mean output power (in dBm);
- jitter performance;
- phase shifter performance.

Moreover, especially for WDMS, it is also necessary to take into account:

- gain flatness (GF).

5.3.3.2 Polarization effects

The individual optical components of an EDF amplifier may be chosen to ensure that its performance is reasonably insensitive to polarization effects such as PDL and PMD, depending on the system requirements. Some other polarization effects such as PDG and PHB are intrinsic effects and can only be avoided or limited by the use of external means (e.g., signal polarization scrambling in the TTE transmitter).

5.3.4 Parameters of the optical repeater with Raman amplification

For further study.

5.3.5 Mechanical parameters of repeaters

5.3.5.1 Repeater housing

Repeater housing must be designed to allow operation, laying, recovery, and relaying of optical repeaters in large depths with no degradation in mechanical, electrical and optical performance.

Technical design considerations of the repeater housing are as follows:

- performance, reliability and ease of manufacturing must be considered in determining the basic structure design and component allocations;
- a repeater housing with an effective heat-dispersive and shock-absorbing structure is needed;
- highly reliable, pressure-proof, gas-tight, and low-loss feedthroughs are required so that fibres and electric power lines can enter the repeater housing;
- highly reliable and low-loss cable coupling with pressure proof and adequate tensile strength is needed;
- cable to repeater joint structure.

5.3.5.2 The internal unit

Inside the repeater housing, the internal unit can contain several power feed modules and OFA pairs to amplify in both directions optical signal from one or several fibre pairs.

5.3.5.3 Corrosion protection

The external housing of OSRs should be designed to not suffer from corrosion due to sea water.

5.3.5.4 Water pressure resistance

The OSR must be designed to support large pressure strengths in deep sea water.

5.3.5.5 High voltage insulation

High voltage insulation is required between the repeater housing and the internal unit to ensure repeater operations.

5.3.5.6 Thermal management

Heat generated by the electronic components inside the OSR may be dissipated sufficiently via thermal conduction with the repeater housing.

5.3.5.7 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.

5.3.5.8 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.

5.3.6 Electrical parameters of repeaters

5.3.6.1 Power modules

OSRs are powered from the terminal end station at a constant current via the electrical conductor on the cable. Power modules feed the OFA pairs to ensure the optical amplification. The OSR may accept both electrical polarities.

5.3.6.2 Surge protection

The OSR must be protected against power surges which may result from sudden interruption of the high voltage supply on the cable (cable break or PFE short circuit).

5.4 Cable joint parameters

Cable joints allow two cable segments to be joined, which provide optical, electrical, and mechanical continuity between contiguous cable sections. Cable jointing provides the ability to:

- splice subsections of cables together to form sections;
- join cables to repeaters during system assembly;
- terminate the ends of cables for later conversion to cable-to-cable joints during system installation;
- join submarine cables to land cables at the beach join.

A submarine cable joint is designed to provide reliable connections between the cables or repeater and cable during the rigours of ship loading, deployment, recovery, repair and redeployment at depths of up to 7500 metres. Appropriate cable joint designs are available to meet the various requirements of armoured submarine cable.

5.4.1 Optical parameters

5.4.1.1 Splice loss

Splice loss means the increased loss due to fibre splicing and excess optical fibre when a cable is joined. It is most desirable to minimize the splice losses. Its test methods should follow [ITU-T G.650.1] where appropriate.

5.4.2 Mechanical parameters

5.4.2.1 Strength

The cable strength members are terminated with a plug-in socket design, whose breaking strength exceeds 90 per cent of the cable's required minimum breaking strength.

5.4.2.2 Tensile strength

The tensile strength is defined in [ITU-T G.972]. Other possibilities are for further study.

5.4.2.3 Corrosion protection

The joint must be protected to prevent it from corrosion due to sea water.

5.4.2.4 Water pressure resistance

The joint must be designed to support large pressure strengths.

5.4.2.5 Joint sealing

The joint must be provided with a protection against water and gas ingress from the surrounding sea.

5.4.2.6 Bend characteristic

Bend-limiting boots assure a gradual transition in bending stiffness across the joint, and are designed to pass through the cable-handling machinery on board cable ships.

5.4.3 Electrical parameters

This connection terminates the electrical conductor in the cable and provides electrical continuity across the joint.

5.4.3.1 High voltage insulation

High voltage insulation is required between the cable’s power conductor and the sea to ensure joint operations.

5.4.4 Physical parameters

The physical parameters of the cable joint include length, outer diameter, weight in air, weight in water.

5.5 Receivers parameters

These parameters are defined at the receiver reference points R or MPI-R as given in [ITU-T G.957], [ITU-T G.691], [ITU-T G.692] and [ITU-T G.959.1].

5.5.1 Sensitivity

Receiver sensitivities for SDH single-channel systems up to 10 Gbit/s are defined in [ITU-T G.957] and [ITU-T G.691]. Sensitivities for SDH and OTN IrDI receivers are defined in [ITU-T G.959.1].

Receiver sensitivities are defined as end of life, worst-case values taking into account ageing and temperature margins as well as worst-case eye mask and extinction ratio penalties as resulting from transmitter imperfections given by the transmitter specification of the particular interface.

Penalties related to path effects, however, are specified separately from the basic sensitivity value.

5.5.2 Overload

Receiver overload definition and values for SDH single channel systems up to 10 Gbit/s are defined in [ITU-T G.957] and [ITU-T G.691]. Overload definition and values for SDH and OTN IrDI receivers up to 50 Gbit/s are defined in [ITU-T G.959.1].

5.5.3 Minimum mean channel input power

The minimum mean channel input power of optically multiplexed IrDIs of up to 10 Gbit/s for multichannel receivers is defined in [ITU-T G.959.1].

5.5.4 Maximum mean channel input power

The maximum mean channel input power of optically multiplexed IrDIs of up to 10 Gbit/s for multichannel receivers is defined in [ITU-T G.959.1].

5.5.5 Optical path penalty

Optical path penalty definition and values for SDH single channel systems up to 10 Gbit/s are defined in [ITU-T G.957] and [ITU-T G.691]. Path penalty definition and values for both single and multichannel OTN IrDI receivers up to 10 Gbit/s are defined in [ITU-T G.959.1]. Path penalty definitions and values for single-channel SDH and OTN IrDI receivers up to 50 Gbit/s are also defined in [ITU-T G.959.1].

5.5.6 Maximum channel input power difference

This parameter indicates the maximum difference between channels of an optically multiplexed signal and is defined in [ITU-T G.959.1].

5.5.7 Minimum OSNR at receiver input

This value defines the minimum optical signal-to-noise ratio that is required for achieving the target BER at a receiver reference point at a given power level in OSNR limited (line amplified) systems. It should be noted that this is a design parameter.

6 Optical network topology

The types of optical network topology for optical fibre submarine cable systems are point-to-point, star, branched star, trunk and branch, festoon, ring and branched ring. This clause is based on information given in [b-Zsakany].

6.1 Point-to-point

This configuration consists of a direct submarine link between two items of terminal transmission equipment (TTE) located in two different terminal stations (TSs).

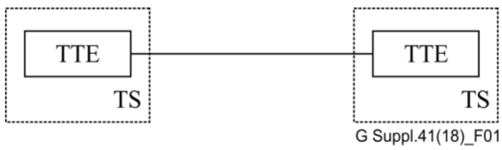


Figure 1 – Point-to-point topology

6.2 Star

This configuration 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.

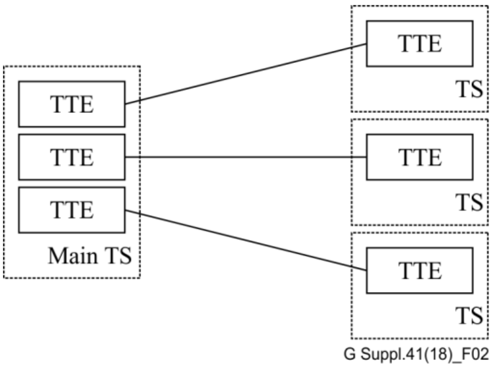


Figure 2 – Star topology

6.3 Branched star

This configuration provides the same capacity as the basic star, except that the splitting of traffic is done underwater, minimizing the cost of separate cables 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.

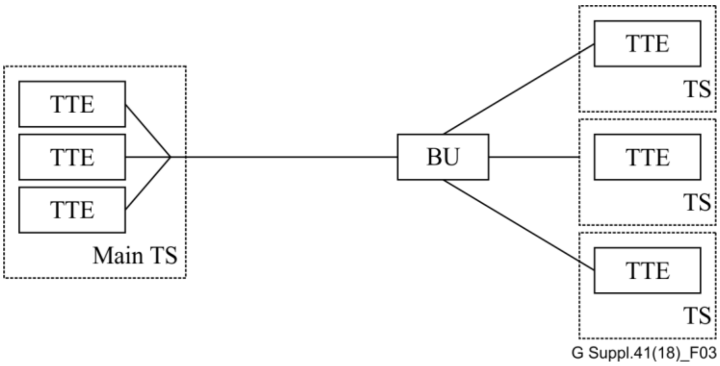


Figure 3 – Branched star topology

6.4 Trunk and branch

This configuration connects several TSs including TTE 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.

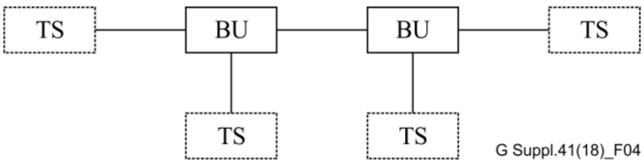


Figure 4 – Trunk and branch topology

6.5 Festoon

The festoon 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 the initial service. Thus, in the case of a need for additional capacity, terminal equipment are the only additional investments 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.

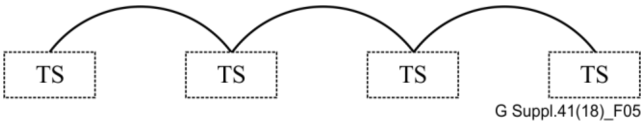


Figure 5 – Festoon topology

6.6 Ring

The ring configuration is essentially a set of connected, point-to-point cables having twice the requisite transmission capacity. In case 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.

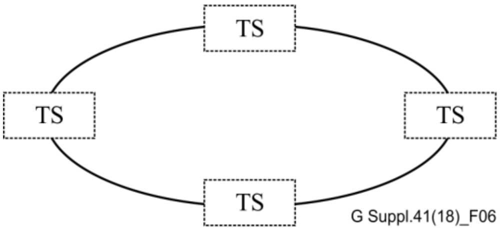


Figure 6 – Ring topology

6.7 Branched ring

This configuration 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 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.

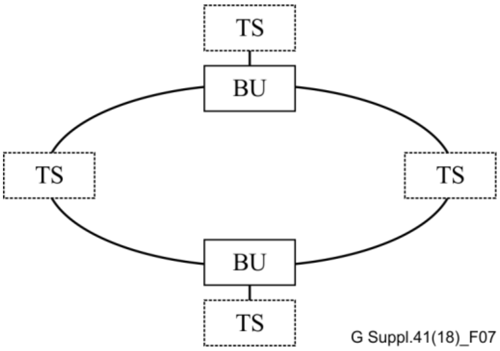


Figure 7 – Branched ring topology

7 System design considerations

7.1 Optical power budget

Optical power budget, as defined in [ITU-T G.977], is a contractual performance budget which guarantees the system performance to be better than the minimum required BER performance defined in [ITU-T G.826] and/or [ITU-T G.828].

Example 1 of 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.

Example 2 of the optical power budget starts from the linear quality factor (Q factor) of the SEOI which takes into account degradation due to the ASE noise of amplifiers in addition to the SEOI implementation penalty (*back-to-back Q*). Then, the optical power budget allocates the penalties/impairments for all types of degradation (due to the transmission, pre-emphasis, manufacturing, etc.). The degradation is estimated using a combination of theoretical analysis, computer simulations and direct measurements on experimental test beds.

For each submarine digital line section, 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):

- The BoL power budget provides the worst-case digital line section performance which will be measured during the commissioning.
- 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.

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).

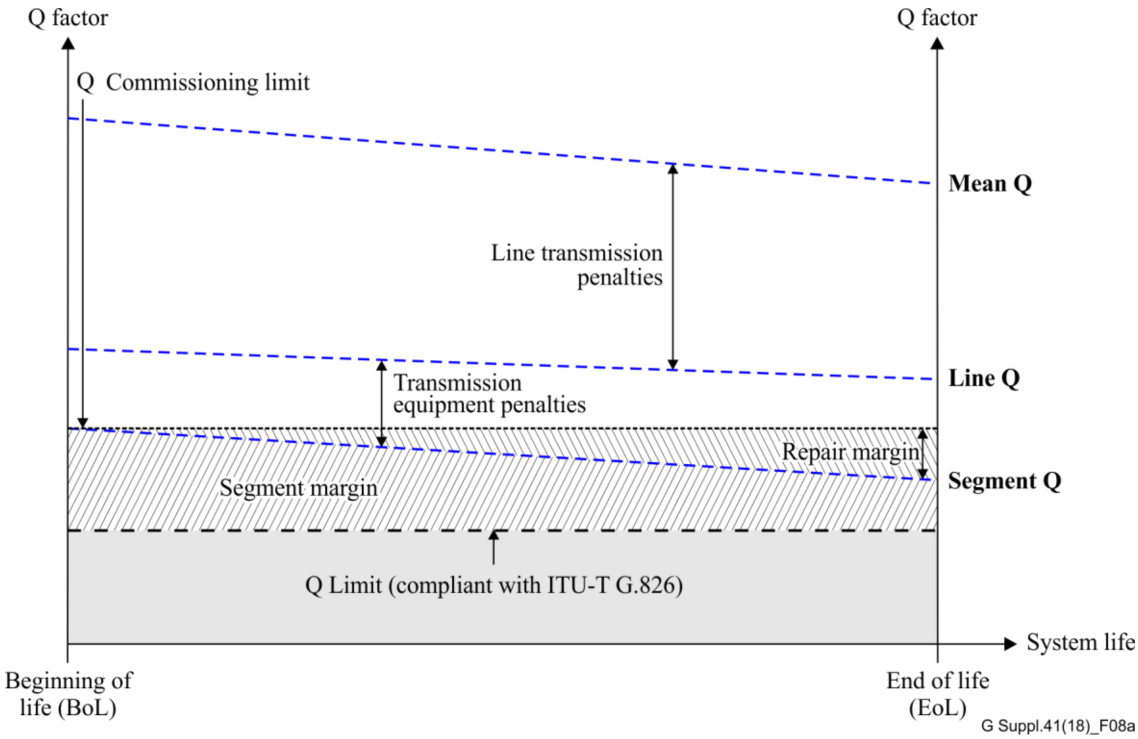


Figure 8-a – Power budget structure of example 1

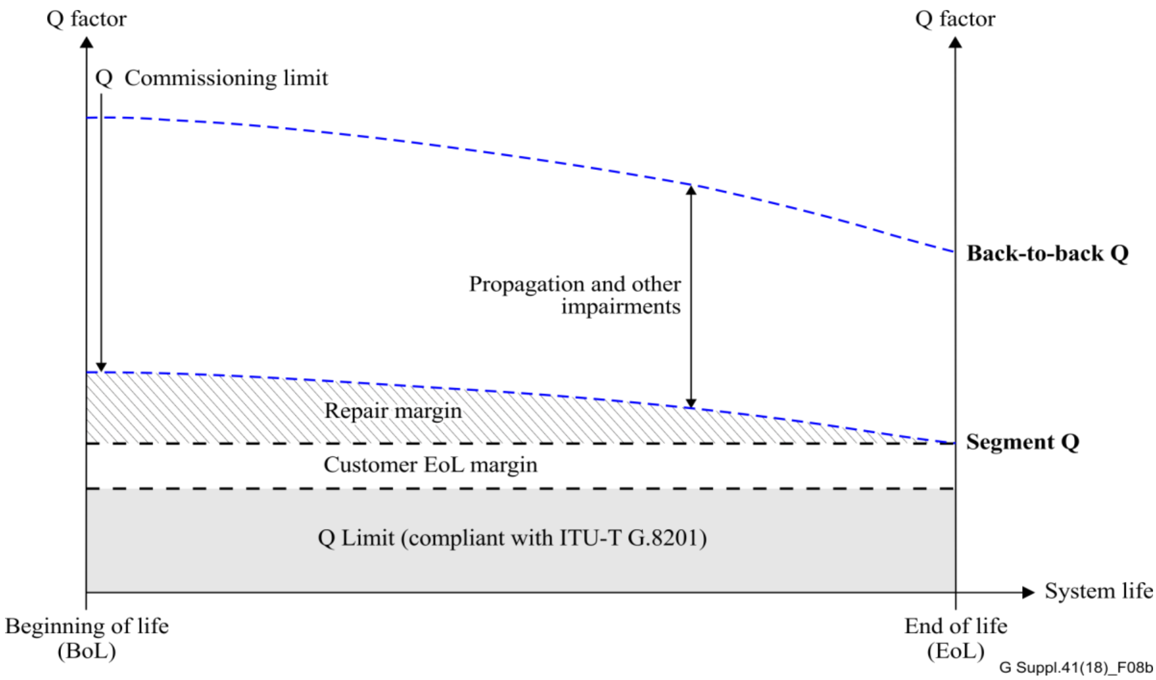


Figure 8-b – Power budget structure of example 2

7.1.1 Quality factor (Q factor)

The optical power budget table of a submarine digital line section uses Q factors as described in Annex A of [ITU-T G.977] and is expressed in decibels.

The Q factor, defined in Annex A of [ITU-T G.976], is the signal-to-noise ratio at the decision circuit in voltage or current units, and is defined by:

$$Q = \frac{(\mu_1 - \mu_0)}{(\sigma_1 + \sigma_0)} \tag{7-1}$$

where $\mu_{1,0}$, is the mean value of the marks/spaces voltages or currents, and $\sigma_{1,0}$ is the standard deviation. For example, a BER of 10^{-12} corresponds to $Q \approx 7.03$.

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 analytic mathematical relation to BER (in case of non-FEC operation) when the threshold is set to the optimum value is:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{7-2}$$

where:

$$erfc(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{\beta^2}{2}} d\beta \tag{7-3}$$

A commonly used approximation for this function is:

$$BER \approx \frac{1}{Q\sqrt{2\pi}} e^{-\frac{Q^2}{2}} \tag{7-4}$$

for $Q > 3$ (Gaussian assumption).

An alternative expression that gives accurate values over the whole range of *Q* [b-Spirit] is given in:

$$BER \approx \frac{e^{-\frac{Q^2}{2}}}{\sqrt{2\pi}\left(\left(1-\frac{1}{\pi}\right)Q+\frac{\sqrt{Q^2+2\pi}}{\pi}\right)} \tag{7-5}$$

A graph showing these two approximations for *Q*-values lower than or equal to 5 is given in Figure 9.

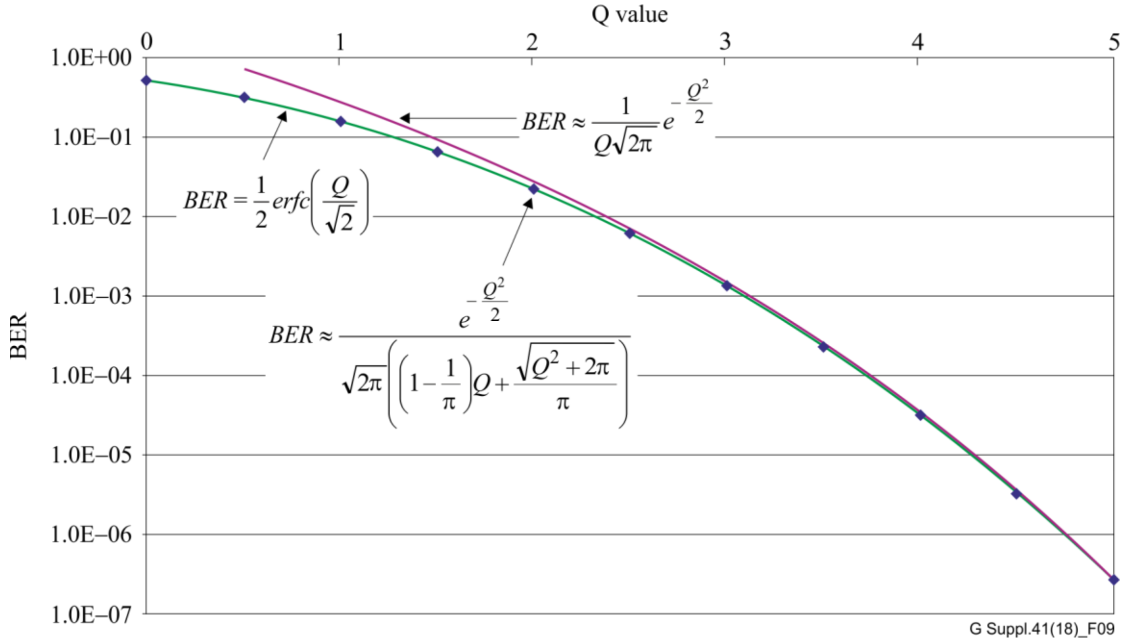


Figure 9 – Approximations relating BER and Q

The Q factor is written in terms of decibels rather than in linear values:

$$\text{Q (decibels)} = 20 \times \text{Log}_{10}\ \text{Q (linear)} \tag{7-6}$$

The performance of a submarine digital line section should be characterized by the measurement of its Q factor or by a direct BER measurement that should meet the contractual Q factor commissioning limits indicated in the optical power budget.

Please note that equations 7-2 to 7-5 are valid in the case of Gaussian noise distribution only. This approximation is accepted for modulation formats based on the OOK technique which is widely used in submarine systems. Modulation formats based on phase modulation like DPSK, which has been re-studied in the past few years for undersea applications, will need to be further studied.

7.1.2 Relevant parameters for optical power budget

According to [ITU-T G.977], it is recommended that the optical power budget takes into account, as a minimum, the impairments arising from the following effects and considerations:

- optical noise accumulation (clause 7.1.3) → Mean Q factor calculation or back-to-back Q;
- propagation impairments (clause 7.1.4) → Line Q factor calculation:
  - – propagation impairments due to the combined effects of chromatic dispersion and non-linear effects (self-phase modulation, cross-phase modulation, four-wave mixing effects between line optical channels, stimulated Raman scattering, etc.) (clause 7.1.4.1);

– propagation impairments due to optical polarization effects such as polarization mode dispersion (PMD), polarization dependent loss (PDL) and polarization dependent gain (PDG). As these impairments fluctuate with time, a distinct provision should be taken for performance variations with time (clause 7.1.4.2);
– impairments due to the non-flatness of the cumulative gain curve on the whole segment (clause 7.1.4.3);
– non-optimal pre-emphasis impairment (clause 7.1.4.4);
– impairments due to the misadjustment of the wavelength(s) of the submarine digital line section (clause 7.1.4.5);
– impairments due to supervision (clause 7.1.4.6);
– manufacturing and environmental impairments (clause 7.1.4.7);

• impairments to take into account non-ideal characteristics of the terminal transmission equipment (related to back-to-back Q factor performance of the terminal transmission equipment) (clause 7.1.5) → Segment Q factor calculation;
• specifically for the EoL power budget, some additional margins should be added (clause 7.1.6) → Segment margin:
– margins due to specified repair operations (repair splices, additional loss and change in dispersion map due to extra cable length after repair, etc.) (clause 7.1.6.1);
– margins due to cable and component ageing (clause 7.1.6.2);
– margins due to foreseen failures of some components, such as pump laser failures (clause 7.1.6.3);
– unallocated margins (clause 7.1.6.4).

Cross-phase modulation and four-wave mixing between optical channels, stimulated Raman scattering, non-flatness of the cumulative gain curve and non-optimal relative powers of optical channels are impairments especially applicable to WDM and DWDM systems as they deal with simultaneous propagation of several optical signals on the same fibre.

7.1.3 Optical noise accumulation

7.1.3.1 Optical signal-to-noise ratio calculation

In a system including a cascaded optical amplifier chain, ASE noise accumulates from the contribution of each optical amplifier. The optical signal-to-noise ratio (OSNR) decreases after having passed through each optical amplifier. Thus, OSNR is a useful parameter for monitoring and characterizing optical amplifier performance. Figure 10 depicts a multichannel system that is used as a benchmark (N span, N – 1 line amplifiers).

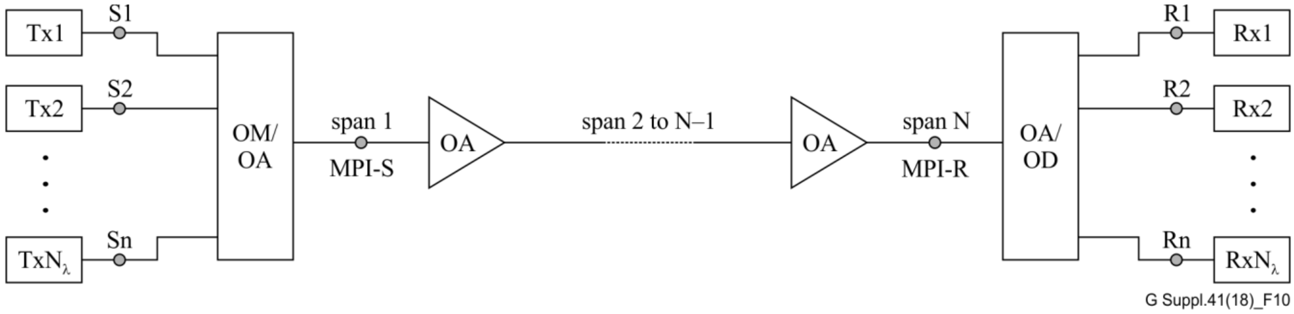


Figure 10 – Representation of optical line system interfaces (a multichannel N-span system)

Two different ways for OSNR calculation exist:

i) simple noise accumulation with constant signal power; and

ii) noise accumulation with total output power constant.

Even if the most realistic assumption is ii), the formula obtained with hypothesis i) is a good approximation of ii), and is widely used.

This clause will develop method i), where signal power is kept unchanged.

For the system shown in Figure 10, the following main assumptions are made:

- all optical amplifiers contained in the chain have the same noise figure (NF);
- losses of all spans are equal;
- total output powers of all in-line amplifiers are the same.

In this case, the OSNR at the input of the receivers (point R_i in Figure 10, i = 1, ... n) can be approximated by:

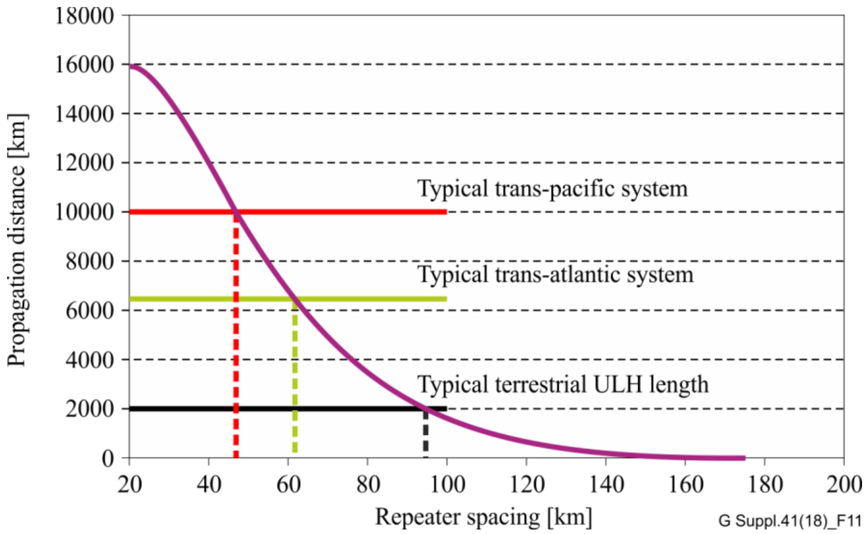
$$OSNR = \frac{P_{out}}{N_\lambda \cdot N_{amp} \cdot \left(NF - \frac{1}{G} \right) \cdot G \cdot h\nu \cdot B_r} \qquad (7\text{-}7)$$

where P_{out} is the amplifier total output power in W, G is the amplifier gain (which is assumed to be equal to the total span losses), NF is the noise figure of the optical amplifier, h is Planck's constant in Js, ν is the optical frequency in Hz, B_r is the optical reference bandwidth in Hz, N_λ is the total number of wavelengths and N_{amp} is the total number of amplifiers. Equation 7-7 indicates that the ASE noise is accumulated from all N_{amp} amplifiers.

If the line amplifiers gain is very high, i.e., $G >> 1$, equation 7-7 can be simplified to:

$$OSNR = \frac{P_{out}}{N_\lambda \cdot N_{amp} \cdot NF \cdot G \cdot h\nu \cdot B_r} \qquad (7\text{-}8)$$

where the gain G is equal to $e^{\alpha L}$, with L the span length. As a consequence, for a given OSNR, the total length achievable is a function of the span length. Figure 11 shows an example of typical span lengths for usual submarine and terrestrial systems.



NOTE – The parameters used are: OSNR = 16 dB in a reference bandwidth B_r = 0.1 nm, NF = 4.7 dB, N_λ = 64 channels, P_{out} = 14 dBm and fibre attenuation α = 0.21 dB/km.

Figure 11 – An example of repeater spacing required to achieve typical submarine and terrestrial transmission distances

In the case that the system is repeaterless and includes only a pre-amplifier, equation 7-8 can be modified to:

$$OSNR = \frac{P_{out}}{N_{\lambda} \cdot NF \cdot G_{pre-amplifier} \cdot h\nu \cdot B_r} \quad (7\text{-}9)$$

where L is the length of the cable in km and α its total loss in km^{-1}.

In the case of repeaterless systems with remote amplification and a single booster amplifier at the transmitter, equation 7-7 can be modified to:

$$OSNR = \frac{P_{Trans} \cdot e^{-\alpha L}}{N_{\lambda} \cdot h\nu \cdot B_r \cdot \left(NF_1 + \frac{NF_2}{G_1} \right)} \quad (7\text{-}10)$$

where L is the total cable length in km, α its total loss in km^{-1}, P_{Trans} the output power of the transmitter (point MPI-S in Figure 10), NF_1 and NF_2 the noise figures of the remote amplifier and the booster amplifier and G_1 the gain of the remote amplifier.

The case of repeaterless submarine systems with Raman amplification has to be further investigated.

7.1.3.2 Q factor calculation

When neglecting the thermal noise and shot noise of the receiver and applying the approximations given in clause 7.1.1, the theoretical linear Q factor can be approximated by the following relation:

$$Q_{lin} = \frac{\frac{2 \cdot OSNR \cdot (1 - ER)}{1 + ER} \sqrt{\frac{B_r}{B_e}}}{\sqrt{1 + \frac{4 \cdot ER \cdot OSNR}{1 + ER}} + \sqrt{1 + \frac{4 \cdot OSNR}{1 + ER}}} \quad (7\text{-}11a)$$

Another approximation can also be used:

$$Q_{lin} = \frac{\frac{2M \cdot OSNR \cdot (1 - ER)}{1 + ER} \sqrt{\frac{B_r}{B_e}}}{\sqrt{1 + \frac{4M \cdot ER \cdot OSNR}{1 + ER}} + \sqrt{1 + \frac{4M \cdot OSNR}{1 + ER}}} \quad (7\text{-}11b)$$

where *OSNR* is the optical signal-to-noise ratio expressed in the optical bandwidth B_r, *ER* is the transmitter extinction ratio expressed in linear units, B_e is the receiver electrical bandwidth in Hz, B_r is the receiver optical bandwidth in Hz, and *M* is a coefficient relating to the modulation format (only for equation 7-11b, M = 1 for NRZ, M~1.4 for RZ [b-Winzer]). Note that coefficient M also depends on the extinction ratio parameter and transfer functions of the optical and electrical filters.

In coherent applications (BPSK/QPSK) the theoretical linear Q factor can be more accurately expressed by the following relation [b-Gaudette]:

$$Q_{lin}^2 = \frac{EC}{\frac{B_e}{B_r \cdot OSNR_{ASE}} + \frac{1}{SNR_{MODEM}} + \frac{1}{SNR_{PROPAGATION}}}$$

where *EC* is an eye closure factor that accounts for degradations due to waveform distortions caused by modem implementation imperfections, SNR_{MODEM} is the maximum Q^2 of the coherent modem determined by noise-like implementation penalties, and $SNR_{PROPAGATION}$ is the maximum achievable Q^2 after propagation, ignoring OSNR and modem distortions, and includes contributions from fibre nonlinearities, polarization-dependent loss (PDL), and filter penalties.

7.1.4 Propagation impairments

Propagation impairments cause some additional penalties in comparison to the *Mean Q* value calculated with simple ASE noise accumulation considerations. In the PBT example 1 they have to be deducted from the *Mean Q* factor to obtain the *Line Q* value (see Figure 8). In the PBT example 2 they have to be deducted from the *back-to-back Q* factor to obtain the *BoL segment Q*.

7.1.4.1 Propagation impairments due to non-linear effects

Non-linear interactions between the signal and the transmission medium begin to appear when the optical signal power density becomes high. It should be noted that high optical signal power is necessary in order to get an acceptable OSNR value without reducing the span lengths. Consequently, fibre non-linearity has received an important consideration both in high capacity systems and in long routes without electronic regeneration and particularly in the case of long optically amplified submarine links. Two types of non-linearities are generally distinguished: those which relate to the fibre's intensity dependent index of refraction known as the Kerr effect (self-phase modulation, cross-phase modulation and four-wave mixing) and those which are linked to scattering effects (stimulated Raman mainly). Several parameters influence the severity of these non-linear effects, including the fibre dispersion characteristics, the effective area and non-linear refractive index of fibres, the number and spacing of channels in WDM systems as well as the signal intensity and data rate. These non-linear effects are described in Appendix II of [ITU-T G.663]. A review of the main non-linear effects is presented in the following clauses (7.1.4.1.1, 7.1.4.1.2, 7.1.4.1.3 and 7.1.4.1.4).

7.1.4.1.1 Self-phase modulation (SPM)

The following text is based on clause II.3.1 of [ITU-T G.663] and it is reproduced here for the benefit of the reader.

Since the fibre's refractive index depends on the optical signal intensity, the temporal variation of the optical signal intensity induces a modulation of its own phase. This effect is called self-phase modulation (SPM).

In optical transmission systems, self-phase modulation gradually broadens the signal spectrum because of phase change due to optical intensity change (see Figure 12). In the presence of spectral broadening caused by SPM, the signal experiences a greater temporal broadening while propagating along the fibre, due to the effects of chromatic dispersion, in the normal dispersion region of the fibre (i.e., below the zero-dispersion wavelength). Conversely, in the anomalous dispersion region, the chromatic dispersion and SPM can compensate each other, giving less temporal broadening. The well-known soliton propagation is based on this phenomenon.

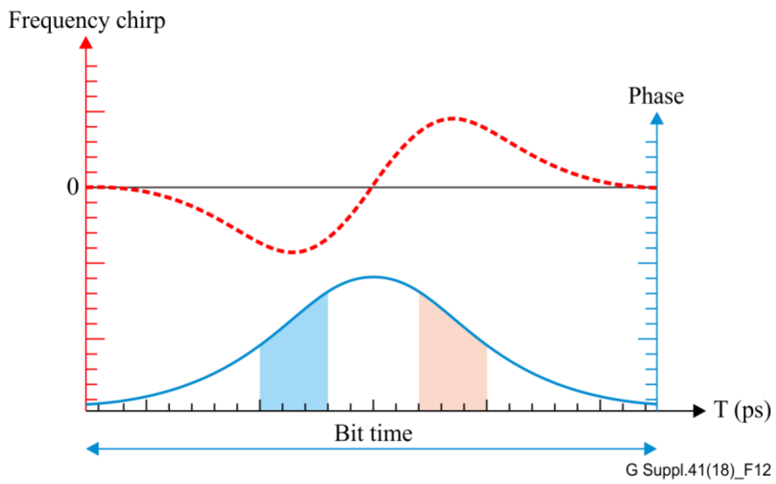


Figure 12 – Temporal variation of the phase shift and the frequency chirp induced by SPM [b-Agrawal]

Generally, the effects of SPM are significant only in systems exhibiting high cumulative dispersion or very long reaches like optically amplified submarine systems. Systems operating in the normal dispersion regime which are dispersion-limited may not tolerate the additional effects due to SPM. In WDM systems with very small channel spacing, 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.

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 non-linear refractive index, also reduce the SPM penalty. For all fibre designs, SPM effects may be reduced by decreasing the launched channel powers, though system design trends call for larger powers to allow longer span distances.

7.1.4.1.2 Cross-phase modulation (XPM)

The following text is based on clause II.3.3 of [ITU-T G.663] and it is reproduced here for the benefit of the reader.

In multichannel systems, cross-phase modulation (XPM) will gradually broaden the signal spectrum when the temporal optical intensity evolution results in changes in phase due to interactions between adjacent channels. The amount of spectral broadening introduced by XPM is related to the channel spacing 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 system penalty from XPM is increased by smaller channel spacing. 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 impairments from XPM are more significant in ITU-T G.652 fibre systems, relative to ITU-T G.653 and ITU-T G.655 fibre systems. The broadening due to XPM may result in interference between adjacent channels in WDM systems.

For all fibre designs, XPM effects may be reduced by decreasing the launched channel powers, though system design trends call for larger powers to allow longer span distances.

7.1.4.1.3 Four-wave mixing (FWM)

The following text is based on clause II.3.5 of [ITU-T G.663] and it is reproduced here for the benefit of the reader.

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 occurs mainly between signals in WDM systems.

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 (see Figure 13) which will fall directly on adjacent signal channels when the channel spacing is 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.

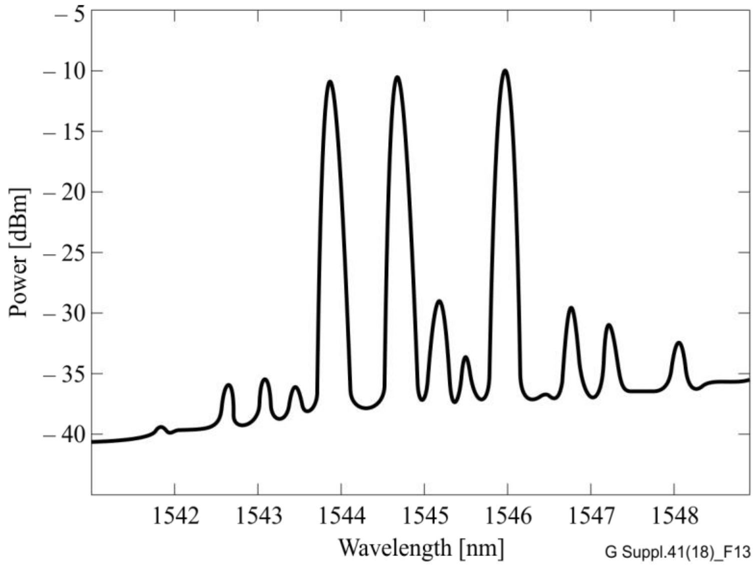


Figure 13 – Optical power spectrum measured at the output of 25 km length of dispersion shifted (D = –0.2 ps/nm · km at the central channel) when 3 mW channels are used [b-Tkach]

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.

The system penalties induced by FWM can be reduced by increasing the frequency spacing and chromatic dispersion in order to break the phase matching between the interacting waves. However, systems are trending towards decreased frequency spacing to allow more channels for the same optical bandwidth. Furthermore, as launched channel powers increase the FWM efficiency (and hence system penalty) also increases.

7.1.4.1.4 Stimulated Raman scattering (SRS)

The following text is based on clause II.3.7 of [ITU-T G.663] and it is reproduced here for the benefit of the reader.

Stimulated Raman scattering is a broadband effect which involves the interaction of light and the vibrational modes of silica molecules. SRS causes a signal wavelength to behave as a Raman pump for longer wavelengths, either other signal channels or spontaneously scattered Raman-shifted light. In any case, the shorter wavelength signal is attenuated by this process, which amplifies the longer wavelength signal.

Stimulated Raman scattering (SRS) impacts mainly WDM systems with large bandwidth. The shorter wavelength signals in WDM systems can suffer degraded signal-to-noise performance because 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.

No practical technique to eliminate the effects of SRS in WDM systems has been reported. A gain filter can be used to correct the induced OSNR tilt. The effects of SRS may also be mitigated by reducing the input optical power.

7.1.4.1.5 Influence of non-linear effects

A multi-span high speed transmission system with complete dispersion compensation is in a general way affected by non-linear optical phenomena such as SPM in single channel systems or XPM and FWM in WDM systems. Their impact increases with the optical input power. As a consequence the system performance can be strongly degraded by such non-linear effects, if the fibre input optical power becomes very high.

Usually, the influence of non-linear effects on WDM systems is evaluated by means of numerical simulation tools based on the split step Fourier method [b-Agrawal]. Results are most of the time validated by experimental tools like a recirculating loop [b-Bergano] or test bed.

The system performance is obviously degraded at low optical input power because of the low optical signal-to-noise ratio received at the end of the transmission line (see clause 7.1.3).

Therefore, there exists a trade-off to be found between low input powers (OSNR limitation) and high input powers (non-linear effects limitation). The following aspects have been taken into consideration to find the optimum operating point in order to guarantee the best system performance:

- type of fibre used for the transmission;
- scheme of dispersion compensation;
- span length;
- in-line optical output power;
- channel spacing.

7.1.4.1.6 Conclusions

It is impossible to pick out a single value for the minimum optical input power to achieve a given Q factor, for example, greater than 7. Between this minimum value and the maximum power value achievable before dramatic non-linear penalty, one can determine the best performance region of a system by means of preliminary simulations with the desired system parameters (type of fibre, dispersion compensation, amplifier spacing, channel spacing, etc.).

7.1.4.2 Propagation impairments due to optical polarization effects

The following text is based on clause II.4.1 of [ITU-T G.663] and it is reproduced here for the benefit of the reader.

It is well-known that optical components and subsystems are more or less sensitive to the polarization state of the optical signal. These polarization effects can be separated in three parts:

- the PMD: polarization mode dispersion;
- the PDL: polarization dependent loss;
- the PDG: polarization dependent gain.

They are described in detail in [ITU-T G.663], [ITU-T G.671], [ITU-T G.650.2] and [IEC/TR 61282-3].

All these effects introduce some penalties on the optical signal and have to be taken into account in the line design of optical submarine transmission systems. In particular, they depend on external conditions like temperature that leads to a fluctuation of performance with time. A statistical approach is recommended to calculate the induced penalty.

7.1.4.2.1 Polarization mode dispersion (PMD)

The optical fibre birefringence, due to the non-uniform geometrical properties occurring during the manufacturing process, induces a modification of the propagation time, which depends on the state of polarization (SoP). The polarization mode dispersion value is the average differential group delay

(DGD) time between two orthogonally polarized modes, which causes pulse spreading in optical transmission systems.

The following text is based on [ITU-T G.Sup.39] and is reproduced here for the benefit of the reader.

The DGD varies randomly in time describing a Maxwell distribution characterized by the PMD value. The PMD of an optical fibre cable is also linked to a statistical behaviour that can be combined with the PMD of the other elements composing the link in order to determine a maximum DGD that is defined as a probability limit. On one hand, see Appendix I of [ITU-T G.650.2] and Appendix II of [ITU-T G.663] for a description of the statistical specification of PMD for optical fibre cable. On the other hand, [ITU-T G.671] contains a description of how to combine the PMD specifications of other link elements with those of optical fibre cables to determine a combined maximum DGD for the link.

$$DGD\max_{link} = \left[DGD\max_F^2 + S^2 \sum_i PMD_{Ci}^2 \right]^{1/2} \tag{7-12}$$

where:

- $DGD\max_{link}$ is the maximum DGD of the link (ps)
- $DGD\max_F$ is the maximum DGD obtained after concatenated optical fibre cable (ps)
- S is the Maxwell adjustment factor (see Table 1)
- PMD_{Ci} is the PMD value of the i-th component (ps)

This equation assumes that the statistics of the instantaneous DGD can be 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 1.

Table 1 – DGD means and probabilities referred to [ITU-T G.959.1]

Ratio of maximum to mean (s)	Probability of exceeding maximum
3.0	4.2×10^{-5}
3.5	7.7×10^{-7}
4.0	7.4×10^{-9}

Therefore, if we know the maximum DGD that the system can tolerate, we can derive the equivalent mean DGD by dividing DGD_{max} by the ratio of maximum to mean that corresponds to an acceptable probability.

See [ITU-T G.Sup.39] and [ITU-T G.959.1] for more details, including the calculation of a DGD maximum of 30 ps for a 10 Gbit/s NRZ application at a probability of 1×10^{-5}.

PMD power penalty

As explained in [ITU-T G.Sup.39], the power penalty induced by DGD at the receive point R (see Figure 10) is a function of the relative power of the two orthogonal polarization modes. This gap varies in time because the relative alignment of the main states of polarization in the optical fibre cable and the polarization of the source varies. The maximum link DGD is set to allow no more than a given first-order power penalty in the worst-case power splitting ratio (equal power in both modes). The worst-case first-order power penalty is also affected by the transmission format, NRZ or RZ.

For 10 Gbit/s NRZ applications (referred to in [ITU-T G.691] and [ITU-T G.959.1]), a 1 dB first-order penalty allowance corresponds to a 30 ps limit on the DGD at point R.

The RZ case is for further study.

7.1.4.2.2 Polarization dependent loss (PDL)

Polarization dependent loss is defined in [ITU-T G.971] as the maximum variation of insertion loss due to a variation of the state of polarization (SoP) over all SoPs. In amplified systems, one mode of amplifier control is to operate at a constant signal power. Both the signal and noise are affected by polarization dependent losses. However, because the noise is unpolarized, the signal and noise are affected differently. The noise can be resolved into a component parallel to the signal and a component orthogonal to the signal. It can be shown that the combined effect of PDL and optical amplification is always to increase the component of the noise orthogonal to the signal. Furthermore, the magnitude of the orthogonal noise component changes with time as the signal polarization changes due to polarization mode dispersion. This leads to a reduction in the OSNR and the Q-value at the receiver. Furthermore, the fluctuations time lead to fading of the OSNR and Q-value at the receiver, both of which lead to an impairment in system performance.

The system penalties induced by the accumulated PDL of each optical component can be reduced by minimizing the PDL of each of them. It should be noted that the impact of PDL on the system performance increases as the number of amplifiers increases. In long submarine systems the requirements are extremely tight, because the number of amplifiers can be several hundred. Polarization modulation, or scrambling, has been shown to improve system performance by reducing fluctuations and improving the average Q.

7.1.4.2.3 Polarization dependent gain (PDG)

Polarization dependent gain is defined in [ITU-T G.661] as the maximum variation of gain due to a variation of the state of polarization of the input signal at nominal operating conditions. The system penalties induced by polarization dependent gain are for further study.

7.1.4.3 Impairments due to the non-flatness of the cumulative gain curve

The impairments due to the non-flatness of the cumulative gain curve are linked to the non-optimal pre-emphasis impairment (clause 7.1.4.4).

7.1.4.4 Non-optimal pre-emphasis impairment

Pre-equalization or pre-emphasis can be used at interface MPI-S to mitigate the impact of the amount of in-line amplifier gain variation and gain tilt that can occur during propagation in the system.

Pre-emphasis partially compensates amplifier gain variation and gain tilt using the following scheme:

The highest optical power at MPI-S is assigned to the channel that will undergo the lowest in-line amplifier gain, whereas the lowest optical power at MPI-S is assigned to the channel that will undergo the higher in-line amplifier gain. The difference between the highest and the lowest optical power values is called the pre-emphasis value, for each wavelength.

Thus channel power pre-emphasis allows equalizing system transmission performance of all channels. Nevertheless, with the power level of each channel being different, the propagation in an optical fibre will induce additional penalties.

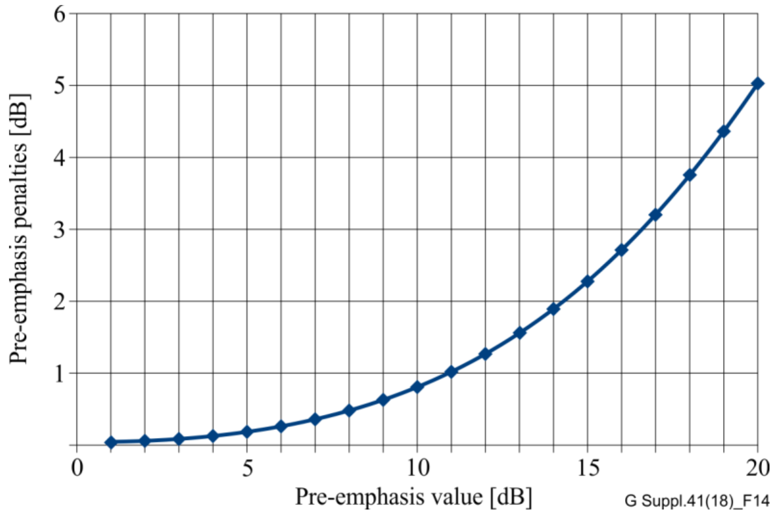


Figure 14 – An example of penalties induced by the pre-emphasis adjustment

7.1.4.5 Impairments due to the misadjustment of the wavelength(s)

Some additional impairment can result from misadjustments of the signal wavelengths or of all optical components responsible for a filtering function (optical filters, multiplexers and de-multiplexers). For example, a wavelength shift between a laser and the middle of the corresponding multiplexer bandwidth can introduce additional losses responsible for Q factor degradation.

7.1.4.6 Impairments due to supervision

These impairments are related to the use of optical commands sent on the line to supervise certain submerged equipment. For example, most of the repeaters used in submarine systems can be interrogated and answered by modulating the optical signal with a low frequency. This modulation amplitude is small compared to the data modulation amplitude to disturb as little as possible the signal performance. Impairments due to this additional modulation are evaluated and taken into account for the Line Q estimation.

7.1.4.7 Manufacturing and environmental impairments

During the manufacturing process, it cannot guaranteed that all the equipment manufactured behaves in exactly the same manner or, in other words, exhibits the same performance. Therefore, some impairment should be allocated to take into account the transmission performance variation resulting from these differences. This item also concerns the variation of environmental conditions that can occur in the system (temperature and pressure for example).

7.1.5 Impairments due to the terminal transmission equipment imperfections

Impairments due to terminal transmission equipment are usually expressed by the Q factor measured when the transmitter and receiver are arranged in a back-to-back configuration. To calculate the real Q factor of the whole segment, it is necessary to take into account the real characteristics of transmitter and receiver. The following formula is used:

$$\frac{1}{Q^2_{Segment}} = \frac{1}{Q^2_{Line}} + \frac{1}{Q^2_{TTE\ \ back\text{-}to\text{-}back}} \qquad (7\text{-}13)$$

7.1.6 Segment margins

A submarine system 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.

7.1.6.1 Impairments due to repair operations

After the submarine line lay, a cable repair requires at each time to add 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 1000 km.

During a repair operation, an additional length of spare cable must be added to the system in order to keep the tensile strength carried by the cable below the NOTS and NTTS 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 time 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 this Q factor and the mean Q corresponds to the repairs allocation margin.

7.1.6.2 Impairments due to equipment ageing

The impairment due to the equipment 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;

In the same way as for repair operation (clause 7.1.6.1), 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 equipment ageing.

7.1.6.3 Impairments due to 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 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 set up.

7.1.6.4 Unallocated margin

Provisional margins are residual margins after taking into account all repair margins at the end of life condition. These margins can be required most of the time by purchasers in order to be more confident with the system or to keep margin for an eventual non-forecasted upgrade of the system.

7.1.7 Conclusion

Optical power budget tables describe how the system performance will be met. A template of the recommended optical power budget table is available in Annex A of [ITU-T G.977].

In submarine systems using optical amplifiers ([ITU-T G.973] and [ITU-T G.977]), regeneration occurs only in the terminal transmission equipment at the submarine electro-optic interface. Between the emission and the reception, the channels will suffer impairments due, for example, to optical noise accumulation, propagation (fibre non-linearities, chromatic dispersion, etc.). Therefore, it is recommended to establish the optical power budget at the submarine digital line section level. As some systems may accommodate several submarine digital line sections with different impairments, it is further recommended that an optical power budget be established for each submarine digital line section.

A further consideration is that, in some cases (presence of WDM-BU for example), the two routes (trunk and branch) may suffer different impairments: in this case, a separate power budget should be established for each route and the worst case should be considered.

Additionally, in the case where the design of a multi-landing point system has been optimized for the longest submarine digital line section in terms of optical signal-to-noise ratio degradation and repeater spacing, extra margins may be available for the shorter ones. These extra margins, usually called unallocated supplier/segment margins, should be clearly reported in the power budget tables.

The supplier should provide sufficient information in order to support the validity of the power budget tables, in particular but not limited to:

- the overall transmission distance and the span length values;
- the number of transmitted wavelengths;
- the extinction ratio at the transmitter;
- the nominal repeater output power value;
- the nominal noise figure value;
- the optical and electrical bandwidth values at the receiver;
- the back-to-back Q specification for the terminal;
- the forward error correcting code characteristics (including BER before FEC and BER after FEC curves).

The supplier should also clarify if any device located either at the transmitter/receiver end, such as polarization scramblers and/or dummy channels, or within the submerged plant, such as gain equalization filters, tilt equalizers and/or slope equalizers, are used for improving the transmission performance.

7.2 Dispersion considerations

Chromatic dispersion is the wavelength dependency of group velocity so that all the spectral components of an optical signal will propagate at different velocities. This induces pulse spreading and can be a major impairment. Depending on the system design and especially on the number of wavelengths (WDM system), it may be of interest to manage it quite differently to limit pulse spreading and other propagation effects. Generally, this management leads to a dispersion map that shows how dispersion is managed along the whole link.

7.2.1 Pulse spreading due to chromatic dispersion

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. The main 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.

7.2.2 Chromatic dispersion mapping

As explained in [ITU-T G.973] for the case of single channel systems and in [ITU-T G.977] for WDM systems, the dispersion map is the principal tool for describing the chromatic dispersion characteristics of a system. Cumulative dispersion is defined as the dispersion measured between the output of the terminal transmitter and any other point in the optical path. The 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. The dispersion map will depend mainly on the type of system (SWS or WDMS).

For an SWS, typically the fibres with low negative chromatic dispersion close to zero but not zero are used along the link corresponding to main sections and the fibres with higher positive chromatic dispersion are used for the link corresponding to a few sections of dispersion compensation. The aim of this management is to keep close to zero the cumulative dispersion of the whole link while keeping local chromatic dispersion non-zero.

For a WDMS at 10 Gbit/s, typically the fibres with low negative chromatic dispersion but far from zero (around –2 ps/(nm · km)) are used for most sections (sometimes two types of fibre can be used: at the beginning of the section with large effective area fibre and at the end with low slope fibre) while the fibres with higher positive chromatic dispersion are regularly used for dispersion compensation sections. The aim of this management is to keep close to zero the cumulative dispersion of the whole link while keeping local chromatic dispersion higher and non-zero to limit the four-wave mixing and cross-phase modulation.

For a WDMS at 10 Gbit/s with a large number of line optical channels (LOCs) (Figure 15), typically the fibres with large chromatic dispersion are used along the link for all the sections. One portion of the section is typically positive dispersion with positive slope (normally with very large effective area) and the remaining portion is negative dispersion with negative slope (normally very small effective area).

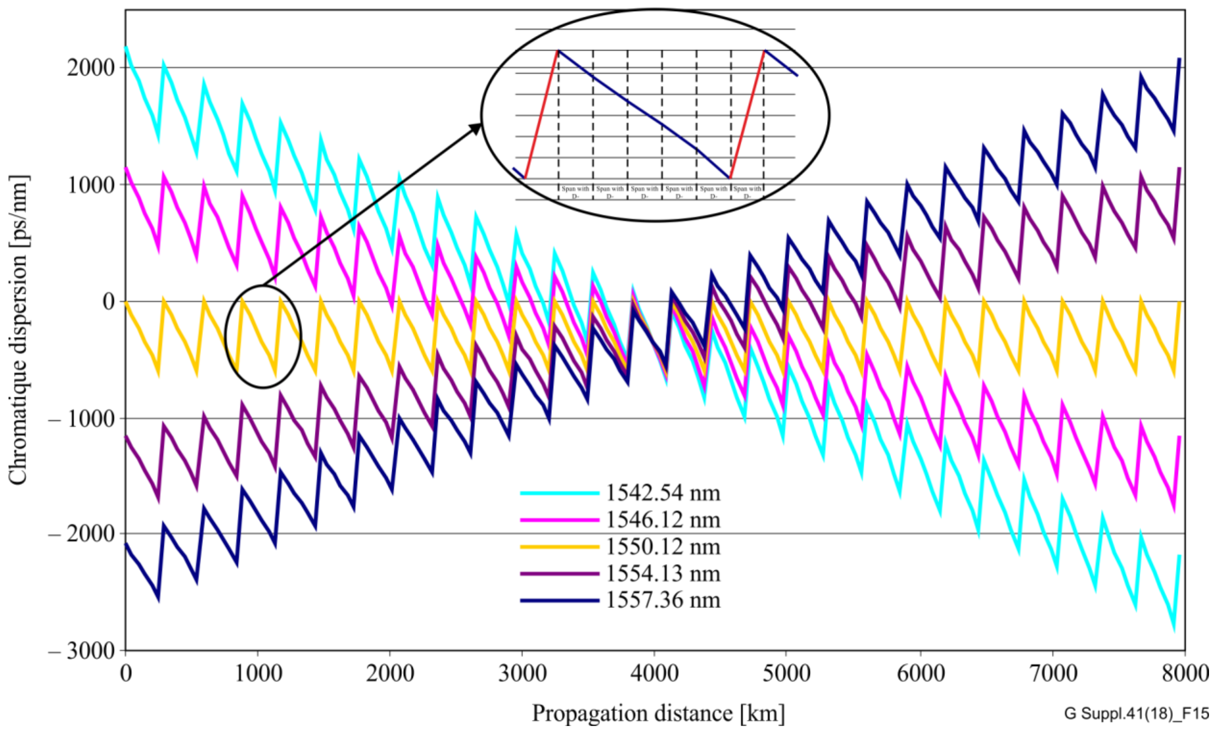


Figure 15 – Typical chromatic dispersion map for a submarine WDM system with 163 spans designed for 40 wavelengths centred around 1550.12 nm

7.2.3 Dispersion management implementation

The design of the dispersion map for each optical section must be in accordance with the transmission requirements (limitation of non-linear effects, pulse broadening, etc.).

Residual cumulative dispersion for each wavelength may be compensated by using a length of equalization fibre or other passive dispersion compensation devices at the transmit (pre-compensation) and/or receive side (post-compensation) in submarine terminal transmission equipment. Typically, the compensation is made for a single channel system only at the receive end and for a WDM system at both transmit and receive ends.

The system design should take into consideration all causes of variation from the planned dispersion map, both random and systematic, including, but not limited to:

- uncertainty in the measurements of zero dispersion wavelength, dispersion, and dispersion slope of constituent DSF, NDSF, DCF, NZDSF, CSF, negative slope fibres, EDF; etc.
- uncertainty resulting from reordering and "random" selection of portions of fibre sets in the assembly of elementary cable sections;
- uncertainty in temperature, pressure, and strain coefficients of these fibres in the cable and pressure vessels;
- uncertainty of the exact temperature and strain of these fibres during dispersion measurements;
- uncertainty of the temperature of the installed fibre;
- ageing;
- repair operations.

7.3 Power feeding subsystem design

7.3.1 Power feeding subsystem configuration

The power feeding equipment supplies DC power to the repeaters. Using sea water as a return path, the PFE supplies a constant DC current through the metallic conductor of the cable.

If power can be supplied from dual ends of one segment, the power feeding subsystem should be configured as double-end feeding and enabled to support single-end feeding from one station in the event that a PFE fails in the other terminal stations, and/or a cable fault occurs. If power can only be supplied from one end of one segment, the power feeding subsystem should be configured as single-end feeding.

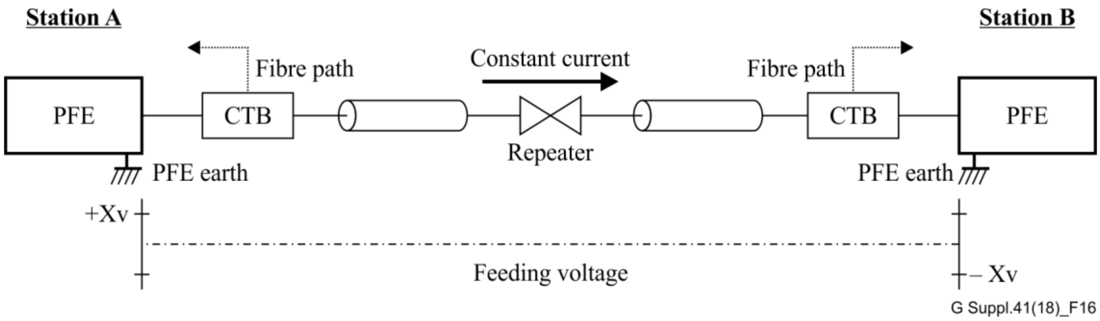


Figure 16 – Double-end feeding

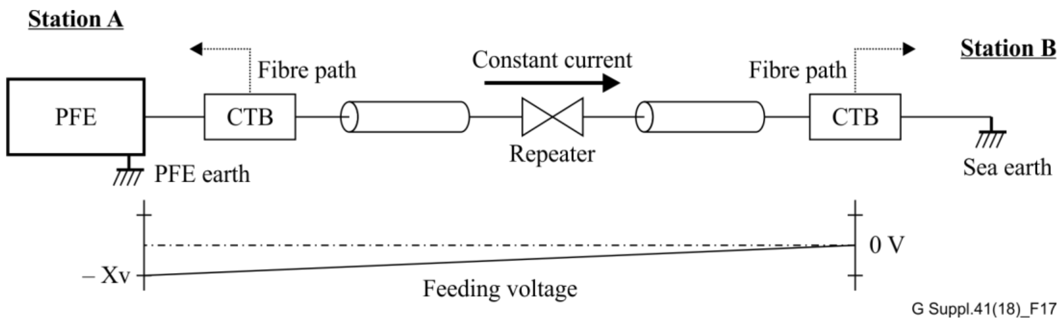


Figure 17 – Single-end feeding

In the case of trunk and branch topology, the power-feeding configuration shall be designed and configurable in such a way that it is possible to power the segments not affected by external cable fault(s). Switchable branching units (BU), which enable the switching of the power-feeding paths, should be used to achieve this. When a trunk cable fault occurs in one side of the BU, the power path could be switched to double-end feeding of the branch to the other side of the trunk; or to single-end feeding of both branch to the BU and the other side of the trunk to the BU.

Power path switching of the BU could be controlled through a feeding current or a command sent from terminal stations through the optical path; the PFE shall be of polarity switching function, and the repeaters in the branch segment shall be of the bipolar type.

Interruptions and errors that could be induced into the traffic being carried when the PFE is switched from double-end feeding to single-end feeding or from in-service equipment to redundant equipment and vice versa should be minimized.

The power feeding subsystem should be of an electroding function for the localization of cable faults in the in-service and out-of-service modes.

7.3.2 Power feeding budget

Since the power feeding subsystem of the submarine cable system is a constant current electrical circuit, the power feeding budget is done to estimate the power path voltage drop, and to confirm the PFEs' configuration at both ends of the path, after taking into account the necessary redundancy. The principle for the budget is that all possible power feeding paths should be capable of single-end feeding, but subject to economical and routing considerations.

The power-feeding budgets for each end of the PFEs can be computed as follows:

power feeding budget=cable voltage drop + repeater voltage drop + BU voltage drop + Marginal voltage drop for repair cable + earth potential difference.

Where the earth potential difference per km could be between 0.1 V to 0.3 V, based on past experience in the cable installation area.

8 Forward error correction

This clause is for further study.

9 Reliability consideration

Submarine networks require reliable and robust fibre optic systems to avoid costly repairs in the wet plant. Moreover, considering that technologies may change during the life of the system, a maintenance scheme is to be established at the beginning of system life to ensure the repairs during the contractual system lifetime, if any.

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 a wet plant, and misoperation for a dry plant).

9.1 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:

– 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 is temperature dependent and has to be recorded at the operating temperature.

– Mean time between failures (MTBF): expected time between two 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. The 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 whenever the network is not available to perform its function.

– Network availability (%) = (Total time – Outage)/Total time * 100%.

9.2 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, subsystem and system levels. Therefore, the reliability of all components used within the system must be demonstrated for the period of contractual system life (generally 25 years). Predicted reliability is often based on [ITU-T G.911], [IEC 61709], [b-Telcordia SR-332] and the components' suppliers data.

9.2.1 Failure rate analysis

9.2.1.1 Infant mortality

At the beginning of the life working condition, units or components used in submarine systems exhibit a high failure rate which decreases with time. This short period is called the infant mortality time (usually one or two years). It is mainly due to the non-ideal manufacturing process (defective raw materials, improper operations, contaminated environments, power surges, 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 this 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. For submerged equipment, the qualification process allows to avoid this mortality.

9.2.1.2 Random failure

The period following 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). Constant failures obey random processes and are generally not detectable even with a highly controlled process.

9.2.1.3 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's rate behaviour is conventionally described as a bathtub curve during the life of the system, as shown in Figure 18.

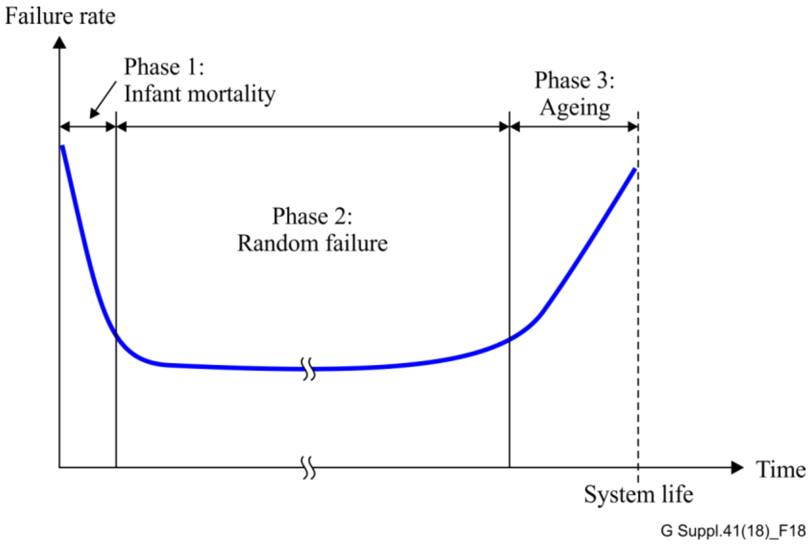


Figure 18 – Typical failure rate behaviour during the life of a system

9.2.2 Wet plant reliability

The wet plant is more critical than the dry plant in terms of reliability because the MTTR is greater. Typical MTTR values give around 2 weeks for wet plant repair instead of 2 hours for a dry plant. 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 1000 to 10000 FIT compared to submarine amplifiers that are within 10 to 100 FIT (around two 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 quasi non-existent and the probability of random failure must be minimized as much as possible.

Repeaters are a critical equipment as they contain electronic, optical and opto-electronic components. In addition to that, one must keep in mind that any internal damage, whatever the cause is, may directly impact the transmission quality. 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 performance of the other fibres. The tests required before and during the cable installation are detailed in [ITU-T G.976].

9.2.2.1 General requirements

Low failure rates are obtained through the use of heavily screened components, close control of raw materials, robust and simple designs, careful manufacturing processes 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. Each failure should be attributed to a single failure mechanism and should not be correlated to a potential interaction between the device under test and the test procedure itself. For both economical purposes and technical feasibility, the reliability requirements make necessary the use of accelerated tests.

9.2.2.2 Redundancy

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.

9.2.3 Example of reliability calculation

In the case of a repeater designed with a four-fold redundant pumps scheme, the failure probability of each pump, assuming 25 years lifetime, is as follows (assuming a constant failure rate):

$$p = 1 - e^{21.9 \times 10^{-5} \lambda} \tag{9-1}$$

The failure rate value (defined for 10^9 devices) that is considered in the above formula is equal for all four pumps. The value 21.9×10^{-5} in equation 9-1 comes from:

$$\frac{25\ years \times 365\ days \times 24\ hours}{10^9\ devices} = 21.9 \times 10^{-5}\ h/device \tag{9-2}$$

Figure 19 shows the number of pumps failed during the 25 years of system lifetime for a typical transatlantic cable (150 repeaters) with one fibre pair only. The typical failure rate for a submarine laser pump is assumed to be 25 FIT. The number of pumps failed is estimated by the product between p and the total number of pumps.

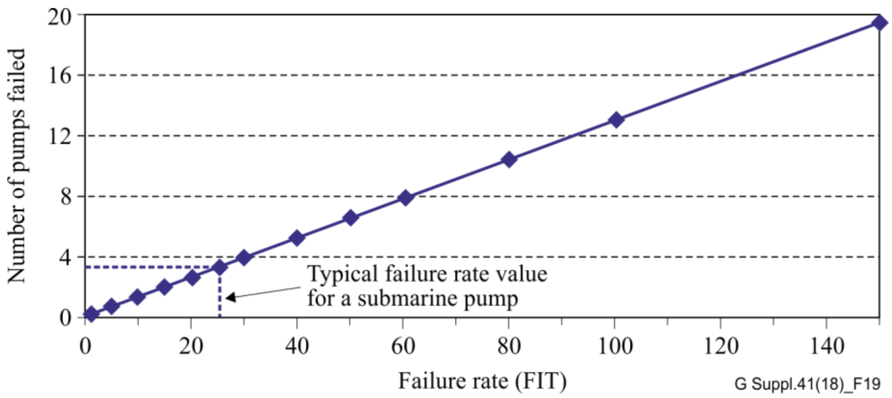


Figure 19 – Estimated number of pumps failed in 25 years for a typical transatlantic link composed of one fibre pair and 150 repeaters containing four pumps each

These failures are randomly located within the transmission line, meaning that no indication can be given either on the repeater(s) impacted or on the transmission penalty.

Assuming that the probability of failure for a laser pump is p, and calling N the total number of pumps (four times the repeaters count), we can express the probability of facing exactly one failure in the whole system.

Denote each pump by a random variable X_i $(X_1 \leq X_i \leq X_N)$. Thus we have N random variables which obey the following law:

i) the pump X_i is out of order ($X_i = 0$) with a probability $p(X_i = 0) = p$

ii) the pump X_i works ($X_i = 1$) with a probability $p(X_i = 1) = 1 - p(X_i = 0) = 1 - p$

The estimated number of pumps failed is $N \cdot p$ (Figure 19) and the variance $Np(1 - p)$. This probability law obeys the binomial law and the probability to have exactly n pumps failed during the system life is:

$$P(n, N) = \frac{N!}{(N-n)!n!} p^n (1-p)^{N-n} \tag{9-3}$$

Assuming we have already one pump failed in a repeater, the probability to have a second pump failure in the same repeater is:

$$P_2(N) = P(1,3) = 3p(1-p)^2 \quad (9\text{-}4)$$

With the same typical system as the one used in Figure 19 and using equation 9-4, this probability leads to the MTBF value between the first and second failure into the same repeater represented in Figure 20. The MTBF obtained for a typical failure rate equal to 25 FIT is more than 1500 years!

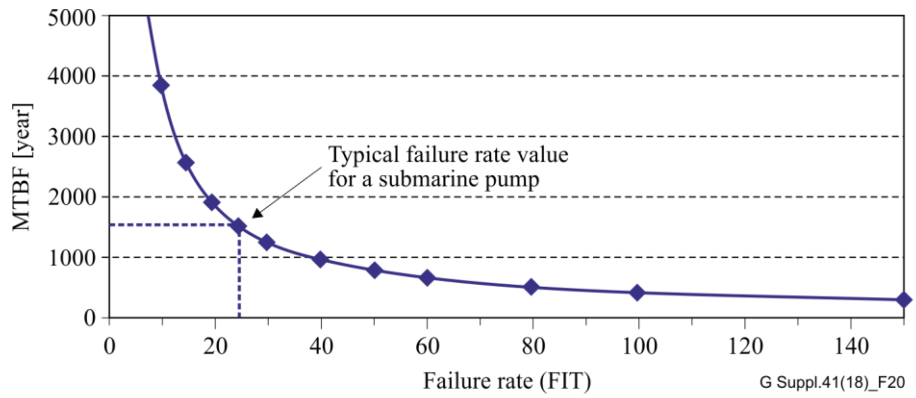


Figure 20 – MTBF for a second pump failure in the same repeater in a typical transatlantic link composed by one fibre pair and 150 repeaters with four redundant pumps each

9.3 External fault

External faults usually occur in cable sections. 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 failures are caused by fishing activities and ship anchors' damage. To protect the cable against these various factors, the wet plant can be buried in shallow waters, except in rocky areas where seabed conditions do not allow burial. Additionally, the cable route is selected to avoid as much as possible geological hazards.

In case of failure in the wet plant, 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 one to three weeks, depending on fault location, sea depth, ship availability, the damage root cause, and the weather, which can dramatically slow down marine operations.

In order to minimize the impact on traffic of such faults, the overall network availability is increased through route diversity when possible (see clause 6 for details on submarine network topologies). In the event that a fault in the wet plant leads to a loss of transmission, the traffic is usually rerouted onto a protection path.

9.4 Fault localization

In most cases a careful design does not prevent unexpected failures. Quick diagnosis and the removal of faults is required to minimize traffic interruption. Therefore, key parameters should be monitored (using a supervisory mechanism) and used to detect the sudden or progressive failures and their locations.

As detailed in [ITU-T G.976], some tests may be performed in service and others out of service from the terminal station depending on the facility that is used (repeater supervisory or external means such as OTDR, coherent OTDR, resistance or capacitance measurements on the conductor). These tests are used to find and to identify the type of fault with the best accuracy. Generally, OTDR is employed to check the quality of the cable that is located between the TTE and the first submerged repeater and COTDR for the long distance repeatered systems' fault location.

During the repair, an electroding technique (when applicable) may be used from the ship to locate the cable route. It allows the recovery of the faulty section of cable, or submerged equipment in a timely manner.

10 Upgradeability considerations

Most submarine systems initially operate below the final capacity they are designed for, allowing carriers to apply the well-known "pay-as-you-grow" concept. The original supply contract covers their progressive equipment commercially and technically (standard upgrades). In some cases, the designed capacity can be exceeded by using enhanced technologies in the terminal equipment. Upgrades then become challenging. They depend on the system design as well as on the margins available at the time that it is considered.

These two different types of upgrades make it necessary to specify the meaning of the word "upgrade" itself. This clause is based on information given in [b-André].

10.1 Upgrade definitions

10.1.1 The maximum designed capacity (MDC)

The maximum design capacity (MDC) is the maximum capacity allowed by the original design of the system.

10.1.2 Standard upgrade

A standard upgrade is defined by the capacity increases that occur from the initial loading (BoL) to the MDC using the contractual technologies.

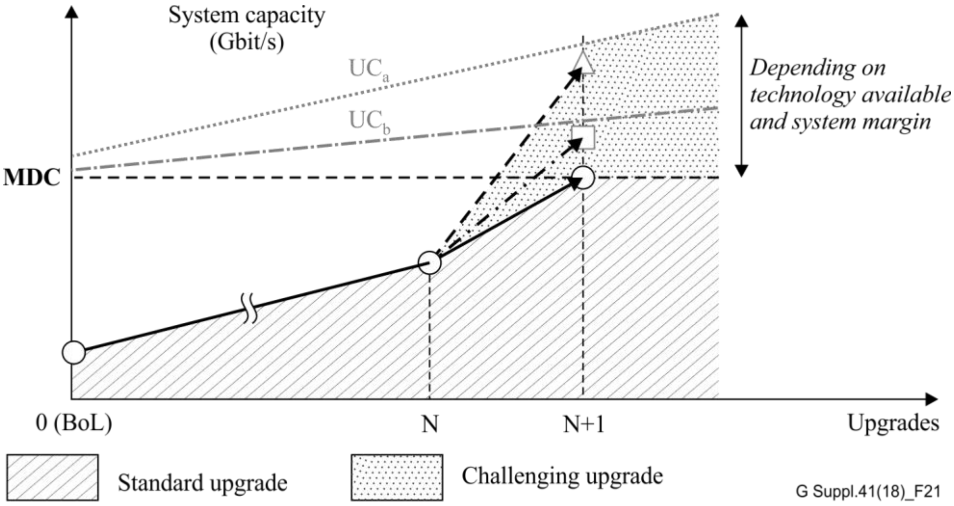
10.1.3 Challenging upgrade

A challenging upgrade is performed with alternative technologies in the terminal equipment, whenever it is conducted.

10.1.4 Ultimate capacity (UC)

The ultimate capacity (UC) is defined as the maximum capacity achievable after one or a few upgrade(s).

By definition, UC is greater than MDC. Note that UC cannot be predicted as a single value because it depends on the choice of removing, or not, the existing terminal equipment to fully take advantage of new technologies (Figure 21). UC is also time dependent because it is based on technology improvements. It is basically limited by the design of the submerged plant.



NOTE – UC_a (resp. UC_b) is UC when replacing (resp. keeping) the existing equipment. Note that curve UC_b is deduced from curve UC_a and the actual system loading. For clarity purposes, curve UC_a was assumed quasi linear.

Figure 21 – Upgrade and capacity definitions

10.2 Standard upgrades

10.2.1 Power budget aspects

The computation of optical power budgets (see clause 7) is crucial because it involves the responsibility of the suppliers to provide a system with adequate and guaranteed performance both at the beginning and at the end of life (25-year lifetime). In particular, it includes the commissioning limit that is the addition of the FEC Q limit and the various EoL margins. Note that by definition the commissioning limit is independent on the channel count and is used as a minimum target.

10.2.2 Progressive loading

Usually, systems have a scalable and modular architecture and standard upgrades are planned by contract. Indeed, they may happen several times up to their MDC. No major issue is expected since the capacity is increased with a field proven technology already put in place in the existing equipment. An upgrade plan is sometimes attached to the contract as a guideline to define the sequence of channels to be added. In the case of large band systems, channels should be homogeneously distributed in the bandwidth to avoid the spectral hole burning (SHB) effect.

Standard upgrades may imply the modification of some settings, e.g., pre-emphasis adjustment (automatic process done on-line), the characteristics of active equalizers incorporated in the wet plant and the loading tone(s) power if any.

Integrating equipment coming from different suppliers is always possible but induces some special rules in terms of responsibility and warranty. It also necessitates some equipment compatibility (see clause 11).

10.3 Challenging upgrades

Challenging upgrades are to the benefit of the system's owners because it allows them to maintain the exploitation of submarine systems with a higher capacity than designed. Thereby getting a much better return of investment than initially expected.

10.3.1 Data collection

The first step in the process of determining the UC is to collect as much information as possible on the system. Actual data is preferred to estimations based on contract figures. It should include, but is not limited to:

i) optical spectra at the transmitter and receiver (pre-emphasis setting, end-to-end gain shape, channel spectrum spread and optical signal-to-noise ratio performance);

ii) straight line diagram (SLD) data (chromatic dispersion map); and

iii) Q factor performance over time (Q distribution shape, system stability, average margin to FEC limit or updated commissioning limit).

10.3.2 Estimation of available margin

Data collection aims to assess in detail what the overall margin on the system is and how it could be used to increase the capacity. Margin is the real critical issue of challenging upgrades. Four types of margin should be considered here:

i) the repair margins;

ii) the 1 dB EoL margin that is often required by purchasers in the original power budgets;

iii) the unallocated and "security" margins accounted for in the power budgets; and

iv) the margin that comes from the wet plant when comparing the assumptions made in the power budgets and the actual figures measured during equipment manufacturing.

10.3.3 Technological solutions

The second indicative tool that can be used to assess the system UC is the calculated line optical signal-to-noise ratio (OSNR). It is implicitly referred to in the first line of the power budgets when calculating the mean Q factor (see clause 7). It allows evaluating various system configurations depending on the current/new channel features. Then the best upgrade scenario is evaluated through Q penalty estimations based on linear and non-linear propagation effects.

10.3.3.1 Data rate increase

One technique to increase the overall capacity is to increase the data rate of some (or all) channels by replacing transponders in the terminal equipment. In some cases, it may be necessary to modify the bandwidth of optical filters or mux/demux within the existing terminal to deal with the new channel bandwidth. The OSNR sensitivity always increases linearly with the bite rate and propagation effects become more impacting, most of the time being the limiting factors to the data rate increases. However, even after challenging upgrades, the bit rate of TTE output must stay compliant with SDH specifications to ensure compatibility with standard terrestrial equipment.

10.3.3.2 Modulation format

A fundamental channel feature is the choice of the modulation format. The use of new modulation formats can be applied to relax the OSNR sensitivity and/or non-linear effects constraints put on the channels.

10.3.3.3 FEC

Another central aspect of transponders is their error correction capability. For example, second-generation versions such as Slim, Enhanced or Super FEC [ITU-T G.975.1] provide a Q limit threshold gain of about 3 dB at BER = 10^{-13} compared to the RS(255, 239) standardized in [ITU-T G.975]. The use of a better FEC than the one used in the original system could dramatically increase the margins available.

10.3.3.4 Additional channels

When the end-to-end ASE gain shape and the margin of existing channels allow it, some extra channels may be inserted in the terminal equipment. In this case, more efficient FEC and a modulation format can be used to relax the requirement on the receive Q factor for the new channels. Consequently, their receive OSNR can be decreased, what typically arises when channels are added, without affecting the BER after correction.

The loading scheme becomes a vital management. The two extreme solutions are either to leave the channel spacing as it is and extend accordingly the bandwidth or to keep the bandwidth unchanged and modify the channel spacing. Most of the time, both solutions are used in a complementary way. Then the penalties associated to the accumulation of chromatic dispersion for the new channels, their relative power and their spacing can be estimated by means of engineering rules established with laboratory experiments and/or numerical simulations.

Note that in practice couplers are used to connect old equipment, if it is kept (existing channels), and new ones (added channels). The proportion of old equipment to keep in the stations should be investigated in terms of capacity, price and footprint.

10.4 Conclusion

Standard upgrades are planned in the original contract and no specific issue is expected (ordinary and foreseen steps). On the other hand, challenging upgrades are non-automatic, might be risky when involving new technologies but can lead to enhancing the expected performance of the system.

11 Physical layer compatibility

This clause describes physical layer longitudinal and transverse compatibility using the same terminology as the one used in terrestrial systems' Recommendations ([ITU-T G.957], [ITU-T G.691], [ITU-T G.693] and [ITU-T G.959.1]). Definitions are also provided for the possible configurations that might form the basis for future standardization of repeatered and repeaterless submarine cable systems.

All of the configurations discussed here are for point-to-point systems. Arrangements more complex than this are for further study.

11.1 Single-span longitudinal compatibility

Systems are defined to be "longitudinally compatible" when both ends of an optical section are terminated by equipment from the same manufacturer. Systems from different vendors can be installed on the various optical fibres of the cable. In this case, only the cable characteristics (attenuation, dispersion, DGD, reflections) are specified. A single-span longitudinally compatible system is illustrated in Figure 22.

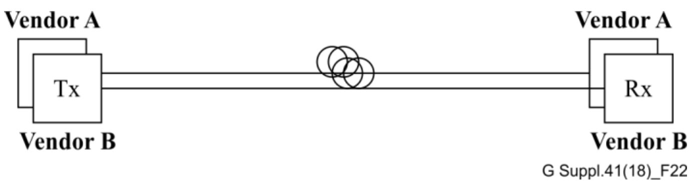


Figure 22 – Single-span longitudinal compatibility

NOTE – For multi-span systems, longitudinal compatibility is so far impossible to achieve because all fibre pairs make use of the same repeaters. It means that each amplifier module of each fibre is located in the same repeater housing which is supplied by one single vendor. The same applies for the other equipment of the wet plant (e.g., equalizers, branching units).

11.2 Single-span black-box transverse compatibility

The systems are defined to be "transversely compatible" with the black-box approach when the ends of an optical section may be terminated by equipment from different manufacturers. This is illustrated in Figure 23.

A full set of parameter definitions and associated values at interface point MPI-S and MPI-R are necessary to enable such an interface.

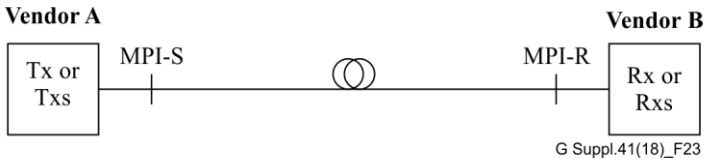


Figure 23 – Single-span black-box transverse compatibility

11.3 Multi-span black-box full transverse compatibility

Figure 24 shows the case of a full transverse compatibility with the black-box approach where all the different types of submerged equipment are provided by different vendors from its terminating equipment.

This case may also require the specification of some parameters such as loss and power levels on a per-span basis, and also other parameters such as chromatic dispersion, accumulated gain shape, PMD and non-linearity to be "managed" over the whole link.

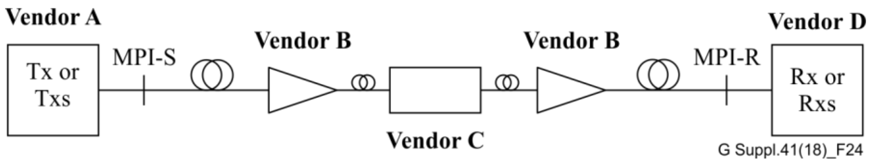


Figure 24 – Multi-span black-box full transverse compatibility

11.4 Multi-span black-box single-link transverse compatibility

It is also possible to define an additional configuration with partial transverse compatibility where the terminating equipment at either end of the link is provided by a single vendor and line equipment being manufactured by a different single vendor. This is called black-box single-link transverse compatibility and is illustrated in Figure 25.

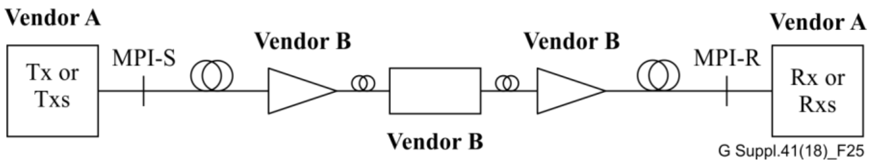


Figure 25 – Multi-span black-box single-link transverse compatibility

This alternative possibility could require most of the same specifications for the physical characteristics as for multi-span full transverse compatibility except that the exact channel plan need not be specified. The operating wavelength range of the system would be required.

11.5 Multi-span black-box multiple-link transverse compatibility

It is also possible to define an additional configuration, again with partial transverse compatibility, where all the submerged plant is provided by a single vendor for all fibre pairs, while the terminal equipment may be provided by different vendors. This configuration could be called multi-span black-box multiple-link transverse compatibility and is illustrated in Figure 26.

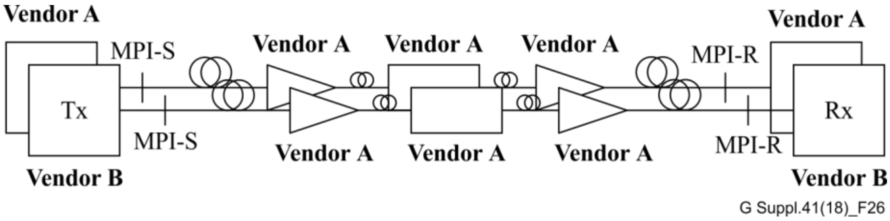


Figure 26 – Multi-span black-box multiple-link transverse compatibility

11.6 Single-span black-link transverse compatibility

An alternative approach to define systems "transversely compatible" is possible with the black-link approach, as illustrated in Figure 27. In this case, the vendors of the transceivers at the ends of an optical section may be different from the vendor of the equipment of the DWDM optical submarine link.

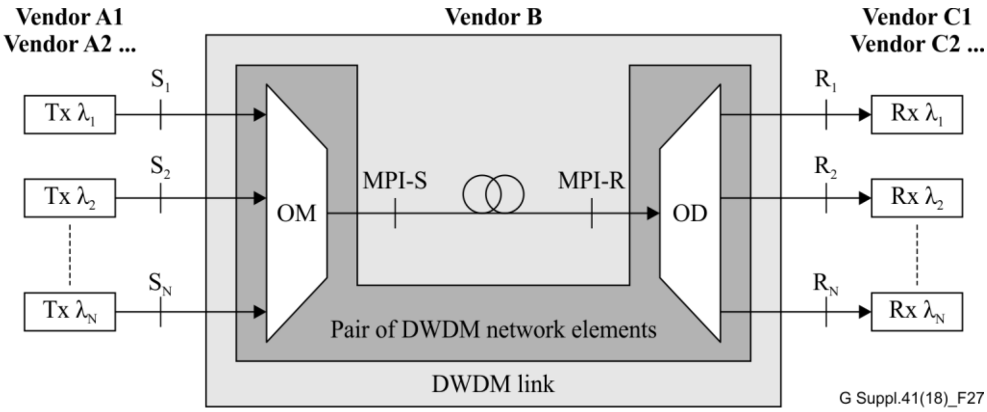


Figure 27 – Single-span black-link transverse compatibility

11.7 Multi-span black-link transverse compatibility

The alternative black-link approach can be applied to define systems "transversely compatible" also for multi-span systems, as illustrated in Figure 28. In this case, the vendors of the transceivers at the ends of an optical section and the equipment of the DWDM submarine optical link may be different.

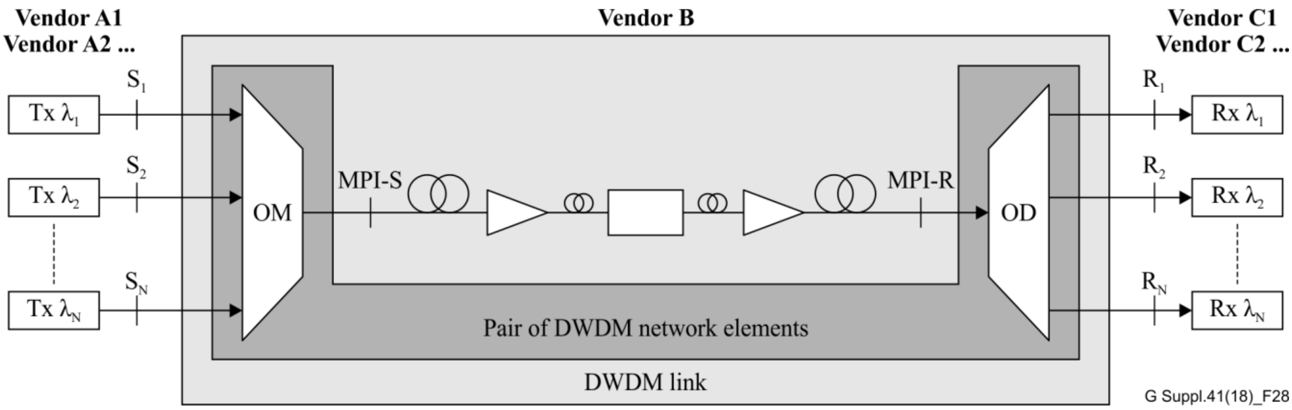


Figure 28 – Multi-span black-link transverse compatibility

Bibliography

[b-Agrawal]	Agrawal, G.P. (1989), *Nonlinear Fibre Optics*, Academic Press.
[b-André]	André, M., Brochier, N. (2007), *Overview of submarine system upgrades*, SubOptic 2007, ThB1.1, May.
[b-Bergano]	Bergano, N.S., Aspell, J., Davidson, C.R., Trischitta, P.R., Nyman, B.M., Kerfoot, F.W. (1991), *Bit Error Rate Measurements of 14000 km 5 Gbit/s Fibre-Amplifier Transmission System using Recirculating Loop*, *Elec. Letters*, Vol. 27, No. 21, October.
[b-Spirit]	Spirit, D.M., O'Mahony, M.J., (1995), *High Capacity Optical Transmission Explained*, John Wiley & Sons.
[b-Telcordia SR-332]	Telcordia technologies Special Report SR-332 (2001), *Reliability procedure for electronic equipment*, Issue 1.
[b-Tkach]	Tkach, R.W., Chaplyvy, A.R., Forghieri, F., Gnauck, A.H., Derosier, R.M. (1995), *Four Photon Mixing and High-Speed WDM Systems*, JLT, Vol. 13, No. 5, May.
[b-Winzer]	Winzer, P.J., Kalmár, A. (1999), *Sensitivity Enhancement of Optical receivers by impulse Coding*, JLT, Vol. 17, No. 2, February.
[b-Zsakany]	Zsakany, J.C., Marshall, N.W., Roberts, J.M., Ross, D.G. (1995), *The Application of Undersea Cable Systems in Globe Networking*, AT&T Technical Journal, January/February, Vol. 74, No. 1, pp. 8-15.
[b-Gaudette]	Gaudette, J., Booi, P., Hartling, E.R., Andre, M., O'Sullivan, M. (2013), *Using Coherent Technology for Simple, Accurate, Performance Budgeting*, SubOptic 2013, We1A-2, April.

SERIES OF ITU-T RECOMMENDATIONS

Series A	Organization of the work of ITU-T
Series D	Tariff and accounting principles and international telecommunication/ICT economic and policy issues
Series E	Overall network operation, telephone service, service operation and human factors
Series F	Non-telephone telecommunication services
Series G	**Transmission systems and media, digital systems and networks**
Series H	Audiovisual and multimedia systems
Series I	Integrated services digital network
Series J	Cable networks and transmission of television, sound programme and other multimedia signals
Series K	Protection against interference
Series L	Environment and ICTs, climate change, e-waste, energy efficiency; construction, installation and protection of cables and other elements of outside plant
Series M	Telecommunication management, including TMN and network maintenance
Series N	Maintenance: international sound programme and television transmission circuits
Series O	Specifications of measuring equipment
Series P	Telephone transmission quality, telephone installations, local line networks
Series Q	Switching and signalling, and associated measurements and tests
Series R	Telegraph transmission
Series S	Telegraph services terminal equipment
Series T	Terminals for telematic services
Series U	Telegraph switching
Series V	Data communication over the telephone network
Series X	Data networks, open system communications and security
Series Y	Global information infrastructure, Internet protocol aspects, next-generation networks, Internet of Things and smart cities
Series Z	Languages and general software aspects for telecommunication systems

Printed in Switzerland
Geneva, 2018