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

Transmission media and optical systems characteristics – Characteristics of optical systems

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Optical monitoring for dense wavelength division multiplexing systems

Recommendation ITU-T G.697

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Recommendation ITU-T G.697

Optical monitoring for dense wavelength division multiplexing systems

Summary

Recommendation ITU-T G.697 defines optical monitoring (OM) that can help in dense wavelength division multiplexing (DWDM) systems to perform the following activities:

- configuration management for system and channel activation, addition of new channels, etc.;
- fault management to detect and to isolate faults;
- degradation management in order to keep the system running and to detect degradations before a fault occurs.

DWDM technology is improving at a rapid pace, continuously stretching the channel count, channel speeds and reach limits. Long-haul multi-span DWDM systems are capable of taking optical signals thousands of kilometres without electrical terminations or regeneration.

This continuing trend is driving the increasing importance of OM, which is the subject of this Recommendation.

This edition of this Recommendation provides additional information on OM for 40 Gbit/s and 100 Gbit/s signals, adds beat noise method to the clause for optical signal-to-noise ratio (OSNR) measurements, and introduces a new clause on security considerations.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
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[*] 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.

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Optical monitoring for dense wavelength division multiplexing systems

1 Scope

The purpose of this Recommendation is to indicate a minimum, but not exhaustive, set of optical parameters that can be used to perform optical monitoring (OM) functions in dense wavelength division multiplexing (DWDM) systems and optical network elements [ONEs, e.g., reconfigurable optical add-drop multiplexers (ROADMs)], particularly relevant to those network elements without optical-electrical-optical conversions. In order to achieve this objective, this Recommendation:

1) indicates methods for measuring the optical signal degradation;
2) classifies those methods by type;
3) defines suitable optical parameters to detect optical signal degradation; and
4) describes the applications or conditions where these optical parameters can be relevant.

This Recommendation refers to DWDM systems and ONEs with optical channels with bit rates up to approximately 10 Gbit/s using non-return to zero (NRZ) or return to zero (RZ) line coding and bit rates at approximately 40 Gbit/s and 100 Gbit/s using advanced modulation formats, such as (dual polarization) quadrature phase shift keying. Bit rates above 100 Gbit/s and systems employing other modulation formats are for further study.

2 References

2.1 Normative references

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

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

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

[ITU-T G.664] Recommendation ITU-T G.664 (2012), *Optical safety procedures and* requirements *for optical transmission systems*.

[ITU-T G.692] Recommendation ITU-T G.692 (2005), *Optical interfaces for multichannel systems with optical amplifiers*.

[ITU-T O.201]	Recommendation ITU-T O.201 (2003), Q-*factor test equipment to estimate the transmission performance of optical channels*.
[ITU-T X.805]	Recommendation ITU-T X.805 (2003), *Security architecture for systems providing end-to-end communications*.

3 Terms and definitions

3.1 Terms defined elsewhere

This Recommendation uses the following term defined in [ITU-T G.650.2]:

- stimulated Brillouin scattering (SBS)

This Recommendation uses the following terms defined in [ITU-T G.663]:

- polarization mode dispersion (PMD) (1st and higher orders)
- four-wave mixing (FWM)
- amplified spontaneous emission (ASE) noise in optical amplification (OA)
- chromatic dispersion
- reflections (see reflectance)
- cross-phase modulation (XPM)
- self-phase modulation (SPM)
- stimulated Raman scattering (SRS)

This Recommendation uses the following term defined in [ITU-T G.692]:

- Frequency (or wavelength) deviation from nominal (see central frequency deviation)

This Recommendation uses the following term defined in [ITU-T. O.201]:

- *Q*-factor

This Recommendation uses the following terms defined in [b-ITU-T G-Sup.39]:

- optical signal-to-noise ratio (OSNR)
- inter-channel crosstalk
- interferometric crosstalk

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.2.1 chromatic dispersion slope: The slope of the curve of chromatic dispersion coefficient versus wavelength.

3.2.2 fully regenerated optical network: Optical network where optical-electrical-optical conversion is performed in each network element using re-amplification, reshaping and retiming (3R) regeneration.

3.2.3 transparent optical network element: An optical network element where there is no optical-electrical-optical conversion of the optical signal.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

3R	Re-amplification, Reshaping and Retiming
ASE	Amplified Spontaneous Emission
BER	Bit Error Ratio
CWDM	Coarse Wavelength Division Multiplexing
DCM	Dispersion Compensation Module
Demux	Demultiplexer
DGD	Differential Group Delay
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexing
EME	Embedded Monitoring Equipment
EMP	External Monitoring Point
ESR	Errored Second Ratio
FEC	Forward Error Correction
FWM	Four-Wave Mixing
Mux	Multiplexer
NOC	Network Operations Centre
NRZ	Non-Return to Zero
OA	Optical Amplification
OADM	Optical Add-Drop Multiplexer
OD	Optical Demultiplexing
O/E	Optical to Electrical
OM	Optical Monitoring
ONE	Optical Network Element
OSA	Optical Spectrum Analyser
OSNR	Optical Signal-to-Noise Ratio
OTDR	Optical Time Domain Reflectometer
OTN	Optical Transport Network
PDL	Polarization-Dependent Loss
PMD	Polarization Mode Dispersion
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RZ	Return to Zero
SBS	Stimulated Brillouin Scattering
SDH	Synchronous Digital Hierarchy

SESR	Severely Errored Second Ratio
SLA	Service Level Agreement
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
XPM	cross-Phase Modulation

5 Optical monitoring overview

The management of existing synchronous digital hierarchy (SDH) networks relies on monitoring digital parameters such as bit error ratio (BER), errored second ratio (ESR) and severely errored second ratio (SESR), which are measured at the electrical layer (at 3R regenerators), as described in [b-ITU-T G.826].

A similar approach is used in the optical transport network (OTN), using ITU-T G.709 framing, for monitoring the end-to-end connections and the optical connections at the electrical level.

While these methods give a reliable measure of the end-to-end performance of an optical channel, they cannot be applied inside a transparent optical domain where no 3R regenerators are available to terminate the frame overhead. Therefore, they may not provide sufficient information to isolate the root cause of problems in complex DWDM networks.

Moreover, the rapid progress in optical technology is leading to ever-increasing channel counts and transmission speeds and to longer all-optical connections inside an optical domain.

This leads to the increasing influence of linear and non-linear distortions, which makes system commissioning an increasingly complex task.

An optimum solution for an OTN combines:

- proper network design to limit noise sources, dispersion and intermodulation effects;
- suitable alarms for the active optical components and the optical fibre links within the network for fault detection and isolation;
- the use of appropriate OM throughout the network to monitor the most critical optical parameters.

Individually, these three actions cannot guarantee a suitable optical quality but, when combined, they provide a suitable solution for the management of OTNs.

An appropriate level of OM gives some visibility inside optical networks ensuring that channel paths are properly configured and optical parameters are appropriate for reliable service delivery. The collection of OM data in a network operations centre (NOC) makes the management of complex DWDM networks easier.

The objectives of OM are to detect anomalies, defects, degradations and faults affecting the quality of the optical layer. The optical parameters to be monitored should be established and defined according to specific requirements.

The ability to improve end-to-end monitoring with distributed OM may have both reliability and cost benefits for configuration management and fault/degradation management, since some defects, degradations and faults affecting the quality of the optical layer are more easily detected and isolated through OM.

Aging effects, changes in noise due to changes in the temperature and humidity, are impairments that can seriously degrade the quality of the signal transmission. OM makes it possible to detect these degradations in a reliable way.

OM is a proactive process that can help to manage service level agreements (SLAs) and to mitigate operational costs (although often at the expense of increased equipment costs). OM is increasingly important in the maintenance of a high degree of equipment reliability, coupled with the ability to diagnose degradations and failures quickly, and locate and repair network problems. The technique is also becoming more and more challenging as network complexity increases.

OM is an important complement to the monitoring techniques applied at the digital client layers of the optical layer network.

OM is a key element in the management of the optical networks, since it is possible to manage only what it is possible to measure.

While OM is implemented (and in service) in many current optical transmission systems, there are significant differences in OM requirements between them. This is due to the presence of different transmission and control system designs, and different strategies for impairment management in the various systems. For this reason, a general requirement for a set of parameters with a defined accuracy as a reliable indicator of the operational condition of such a system cannot be generalized. Even within a single system, the parameters that are of importance may vary between different network elements and the monitoring requirements, even for internal control, are different for the various network elements. Consequently, a general requirement for supervision of particular parameters will normally lead to a sub-optimal (and, therefore, non-cost-effective) solution. An appropriate optical supervision scheme will, for this reason, always be related to the particular transmission and control system design, engineering rules and implementation of impairment management of such a system. However, based on what is feasible from the technological point of view and on what network operators need, some monitoring choices can be identified, as outlined in this Recommendation.

6 Classification of monitoring methods

Clauses 6.1 to 6.6 describe two different forms of signal monitoring, namely time domain and frequency domain methods, and explain the differences between signal monitoring and equipment monitoring, as well as the differences between embedded and external monitoring devices.

6.1 Signal monitoring

This Recommendation is limited to non-intrusive measurements that allow in-service monitoring of the optical signal quality.

The measurements defined in this Recommendation do not measure every single impairment listed in Table 1 for up to 10 Gbit/s systems or Table 2 for 40 Gbit/s and 100 Gbit/s systems, but rather the effect of these impairments on the parameters that can be measured.

A distinction between frequency and time domain measurement methods can be made.

6.1.1 Time domain methods

Methods which analyse the behaviour of the optical signal in the time domain tend to be closer to the full BER measurement than those in the frequency domain. These methods are sensitive to both noise and distortion effects. Sampling oscilloscopes and Q-factor metres, as described in [b-ITU-T O.201], are representative of sampling methods (synchronous methods). However, time domain methods generally need optical demultiplexing (OD), optical to electrical conversion and, in the case of sampling methods, synchronization to the bit rate. Also, the difference in the characteristics of the reference receiver compared to the system receiver and the effect of residual dispersion at the measurement point, as discussed in clause III.2, has to be considered.

NOTE – The above description of sampling oscilloscopes and *Q*-factor metres is for up to 10 Gbit/s NRZ or RZ signals. Sampling oscilloscope and *Q*-factor measurements may not provide useful results for 40 Gbit/s or 100 Gbit/s signals with advanced modulation formats.

6.1.2 Frequency (or wavelength) domain methods

Frequency/wavelength domain methods of OM analyse the spectral characteristics of the optical signal. These spectral methods have in common that they do not sample the signal or synchronize to it, thereby eliminating the entire reference receiver. Typically, they employ a spectrum analyser device, which may be of varying resolution, and may or may not sense all channels simultaneously.

The simplest form of a spectral analysis is simple power monitoring of each channel. This can be done with, for example, a diffraction grating and detector array to sense all of the channel powers simultaneously. At the expense of an increase in the complexity and resolution, this method can also be extended to look at the precise shape of the signal spectrum.

The fundamental property of these spectral methods is that they are averaging methods that, by definition, do not sense the pulse distortion. This means that quality monitoring by spectral methods will be insensitive to all of the effects due to distortions.

6.2 Equipment monitoring (indirect methods)

Indirect methods make use of an empirical correlation between equipment failures and signal quality. Equipment failures, such as power supply failures and laser temperature, may be detected by built-in self-test functions. These indicators are likely to be very system and implementation dependent.

Indirect methods mainly indicate that the system is operating, and it is assumed that the signal quality is also degraded, when an equipment parameter is outside the specified range.

However, a correct equipment parameter is no guarantee of signal integrity, since there may be other impairments that affect the signal quality (e.g., fibre attenuation).

6.3 Fibre link monitoring

An optical time domain reflectometer (OTDR), which may be embedded, can detect and locate fibre link failures, such as fibre cut and abnormal attenuation. Fibre link monitoring indicates the current state of fibre link, and can be used to detect and to isolate fibre link faults. However, a normal fibre link status is no guarantee of signal integrity, since there may be other impairments that affect the signal quality.

6.4 Monitoring based on received signals

Coherent receivers are commonly used in 40 Gbit/s and 100 Gbit/s systems using advanced modulation formats. Digital signal processing (DSP) in coherent receivers may include chromatic dispersion compensation, nonlinear compensation, polarization equalization, and forward error correction (FEC) processing. From these processing steps, parameters can be extracted that provide information on the transmission quality of the optical path (transmitter to receiver) of the received channel. Some optical impairments, such as chromatic dispersion and differential group delay, could be estimated from the DSP. However, chromatic dispersion or differential group delay are not expected to be likely faults in a DWDM network using coherent receivers.

6.5 Embedded monitoring equipment

Embedded monitoring equipment (EME) is usually tightly integrated with the management functions of an optical network element (ONE). For cost reasons, embedded monitoring is usually limited to a few basic parameters.

Different monitoring points placed in the same network element can share the EME.

6.5.1 Embedded monitoring equipment accuracy

It is desirable that the accuracy of embedded monitoring devices is sufficiently high to provide meaningful input for automated management decisions, should any be defined. This can often be achieved with relatively low effort compared to a general purpose test instrument since, in many cases, only the deviation from a known nominal value is of interest, and the normal operating range of network elements is narrow.

6.6 External monitoring equipment

External monitoring equipment typically serves a different purpose than EME. It is normally used to measure additional, more sophisticated performance parameters or when a more accurate value of certain performance parameters is required.

The main applications are the location of hard-to-find failures that cannot be isolated by the embedded monitoring devices, as well as function tests and accurate parameter measurements during installation, commissioning or repair.

In contrast to EME, external monitoring instruments are usually not permanently installed, but rather connected on-demand to critical network segments and used in an interactive mode, often remote controlled from an NOC.

6.6.1 External monitoring equipment accuracy

External monitoring equipment generally has higher accuracy and a wider measurement range than embedded monitoring devices, since it must provide reliable absolute measurements over the full operating range of an optical transmission system and the higher cost implied by this can be shared over a large number of ONEs.

7 Optical impairments

This clause lists and categorizes the main systems impairments at the optical layer that limit the capacity of the system to transport information.

Lists of the possible main system impairments are given in Table 1 for up to 10 Gbit/s systems using NRZ or RZ line coding, and in Table 2 for 40 Gbit/s and 100 Gbit/s coherent systems using advanced modulation formats, respectively.

Table 1 – Optical impairments in up to 10 Gbit/s systems using non-return to zero or return to zero line coding

Variation of the impairment	Relative frequency of occurrence	Description
Attenuation	High	
Optical channel power changes due to gain variations	High	
Frequency (or wavelength) deviation from nominal	High	[ITU-T G.692]
Polarization mode dispersion (PMD) (1st and higher orders)	Medium	Appendix II of [ITU-T G.663]
Four-wave mixing (FWM)	Medium	Appendix II of [ITU-T G.663]
Amplified spontaneous emission (ASE) noise in optical amplification (OA)	Medium	Appendix II of [ITU-T G.663]
Chromatic dispersion	Medium	Appendix II of [ITU-T G.663]
Chromatic dispersion slope	Medium	[ITU-T G.652], [ITU-T G.653], [ITU-T G.655]
Reflections	Medium	Appendix III of [ITU-T G.663]
Laser noise	Medium	
Inter-channel crosstalk	Medium	[b-ITU-T G-Sup.39]
Interferometric crosstalk	Medium	[b-ITU-T G-Sup.39]
Cross-phase modulation (XPM)	Low	Appendix II of [ITU-T G.663]
Self-phase modulation (SPM)	Low	Appendix II of [ITU-T G.663]
Stimulated Brillouin scattering (SBS)	Low	Appendix II of [ITU-T G.650.2], Appendix II of [ITU-T G.663]
Stimulated Raman scattering (SRS)	Low	Appendix II of [ITU-T G.663]

Table 2 – Optical impairments in 40 Gbit/s and 100 Gbit/s coherent systems using advanced modulation formats

Variation of the impairment	Relative frequency of occurrence	Description
Attenuation	High	
Optical channel power changes due to gain variations	High	
Frequency (or wavelength) deviation from nominal	High	[ITU-T G.692]
Polarization mode dispersion (PMD) (1st and higher orders)	Low	Appendix II of [ITU-T G.663]
Four-wave mixing (FWM)	Medium	Appendix II of [ITU-T G.663]

Table 2 – Optical impairments in 40 Gbit/s and 100 Gbit/s coherent systems using advanced modulation formats

Variation of the impairment	Relative frequency of occurrence	Description
Amplified spontaneous emission (ASE) noise in optical amplification (OA)	Medium	Appendix II of [ITU-T G.663]
Chromatic dispersion	Low	Appendix II of [ITU-T G.663]
Chromatic dispersion slope	Low	[ITU-T G.652], [ITU-T G.653], [ITU-T G.655]
Reflections	Medium	Appendix III of [ITU-T G.663]
Laser noise	Medium	
Inter-channel crosstalk	Medium	[b-ITU-T G-Sup.39]
Interferometric crosstalk	Medium	[b-ITU-T G-Sup.39]
Cross-phase modulation (XPM)	Low	Appendix II of [ITU-T G.663]
Self-phase modulation (SPM)	Low	Appendix II of [ITU-T G.663]
Cross-polarization modulation (XPolM)	Low	Appendix II of [ITU-T G.663]
Stimulated Brillouin scattering (SBS)	Low	Appendix II of [ITU-T G.650.2], Appendix II of [ITU-T G.663]
Stimulated Raman scattering (SRS)	Low	Appendix II of [ITU-T G.663]

All these impairments are capable of being severe enough to cause severe degradation of an optical signal up to a level where the receiver is no longer able to detect the data with a reasonable error ratio. For any of the impairments, there exists a curve of penalty versus the probability of occurrence per unit time (see Appendix I).

The levels of relative frequency of occurrence in Table 1 and Table 2 are as follows.

– Low: When the probability of the effect being severe enough to cause a penalty of *x* dB is ~1 event per 10 years.

– Medium: When the probability of the effect being severe enough to cause a penalty of *x* dB is ~1 event per year.

– High: When the probability of the effect being severe enough to cause a penalty of *x* dB is ~10 events per year.

NOTE 1 – The figures in the preceding paragraph refer to the steady state period of the life of the systems. An event could cause *x* dB penalty on a single optical channel, or on a multichannel system. Indicative values for *x* dB penalty are given in Appendix II.

NOTE 2 – The relative frequency of occurrence of the optical impairments given in Table 1 refers to optical signals with bit rates up to approximately 10 Gbit/s, and that in Table 2 refers to optical signals with bit rates of approximately 40 Gbit/s and 100 Gbit/s for advanced modulation formats. Impairments for optical signals with bit rates higher than 100 Gbit/s are for further study.

8 Optical monitoring parameters

The list of the optical parameters that can be measured using current technology in optical transmission systems is:

– channel power;

– total power;

- OSNR when no significant noise shaping is present;
- channel wavelength;
- *Q*-factor.

Appendix III contains information about the performance obtainable from currently available monitoring technology.

9 Correlation between impairment effects and optical monitoring parameters degradation

See Table 3.

Table 3 – List of correlation between the underlined impairments and monitoring parameters

Parameters	Total power	Channel power	Channel wavelength	Optical signal-to-noise ratio	*Q*-factor
Variation of attenuation	×	×		×	×
Frequency (or wavelength) deviation from nominal		×	×	×	×
Optical channel power changes due to gain variations		×		×	×

9.1 Variation of attenuation

For further study.

9.2 Frequency (or wavelength) deviation from nominal

There is a direct correlation between the impairment of "frequency deviation from nominal" and the OM parameter "channel wavelength". The required measurement accuracy for the channel wavelength depends upon the "maximum central frequency deviation" for the channel. [ITU-T G.692] gives a value for this parameter of $n/5$ (where n is the channel spacing) for applications with channel spacing of 200 GHz and above, but no value is given for channel spacing below this.

9.3 Optical channel power changes due to gain variations

There is a direct correlation between the impairment "optical channel power changes due to gain variations" and the OM parameter "channel power". For slow variations in channel gain, optical channel power monitoring will provide adequate information to establish the location of the gain variation. However, DWDM systems may involve many built-in control loops, such as laser wavelength tuning and output power control, channel equalization power control, amplifier gain control and transient control and channel receiver power and dispersion controls, to maintain end-to-end transmission performance. These control loops may operate over millisecond or even microsecond timescales and will respond to or even create sub-second photonic events that may impact end-to-end transmission quality. Since it is not practical to monitor channel power with a time granularity sufficiently small to capture these events, it is helpful to acquire the maximum and minimum of control function input and output parameters within a coarser time granularity.

10 Applications

In DWDM systems, OM could help in the following activities:

i) configuration management for system and channel activation, addition of new channels, etc.;

ii) fault management to detect and to isolate faults;

iii) degradation management in order to keep the system running and to detect degradations before a fault occurs.

In order to achieve the above objectives, one or more of the following monitoring choices could be considered for internal monitoring in DWDM systems with the resulting data available both locally and from a remote location. The choice of which option to include depends upon the specific characteristics of the DWDM system (e.g., length, number of spans, number of channels, inaccessibility of the sites) as well as cost/benefit considerations:

a) total power at input of various stages of OA;

b) total power at output of various stages of OA;

c) channel power at the DWDM transmitter output before the multiplexer (mux);

d) channel power at the DWDM receiver input after the demultiplexer (demux);

e) channel power at the output of various stages of OA;

f) channel OSNR at the output of various stages of OA;

g) channel wavelength deviation at least at one point along the optical path.

A tap at the output of the various stages of OA enables a more detailed analysis of the optical channel status to be performed via external measurement equipment. Whether to include this tap depends upon the specific characteristics of the DWDM system as well as cost/benefit considerations.

11 Optical safety considerations

See [ITU-T G.664] for optical safety considerations.

12 Security considerations

EMPs might be exposed to malicious or inadvertent access and appropriate actions may be necessary to keep them secure. Security aspects relevant to the OM of DWDM systems may include, but are not limited to, communication security, non-repudiation, access control, availability and data integrity as described in [ITU-T X.805]. The description of the appropriate actions is considered to be outside the scope of this Recommendation.

Appendix I

Severity of optical impairments

(This appendix does not form an integral part of this Recommendation.)

The optical impairments listed in Table 1 and Table 2 are all capable of causing severe degradation of an optical signal to the point of failure of the receiver to be able to detect the data with a reasonable error ratio. For any of the impairments, it is possible to plot a curve of penalty versus occurrence rate (the probability of occurrence per time). An example curve in the case of attenuation might take the form of the curve in Figure I.1.

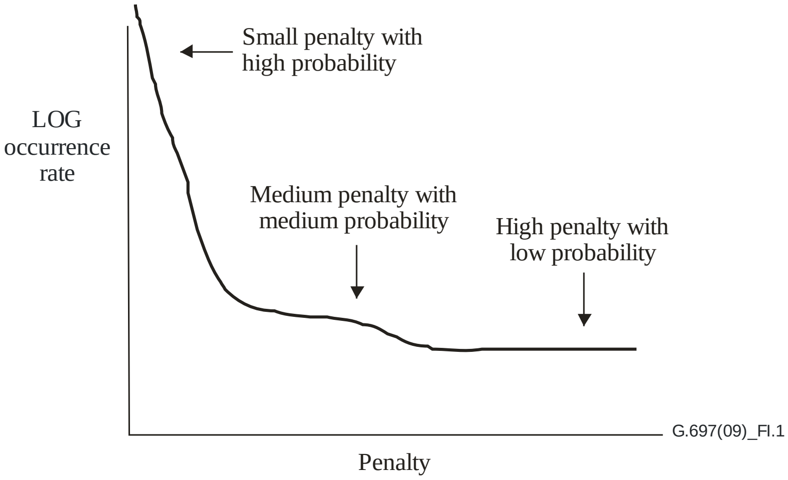

Figure I.1 – Example curve of penalty versus occurrence rate due to attenuation variation

The shape of the curve and the probability levels will, of course, be different for each of the impairments on the list. On the curve for attenuation, small impairments of the order of 0.1 dB being very probable and large impairments (for example, 6 dB or greater) being very much less probable. The curve for a different impairment will have a different shape. For example, SBS might look like the curve in Figure I.2.

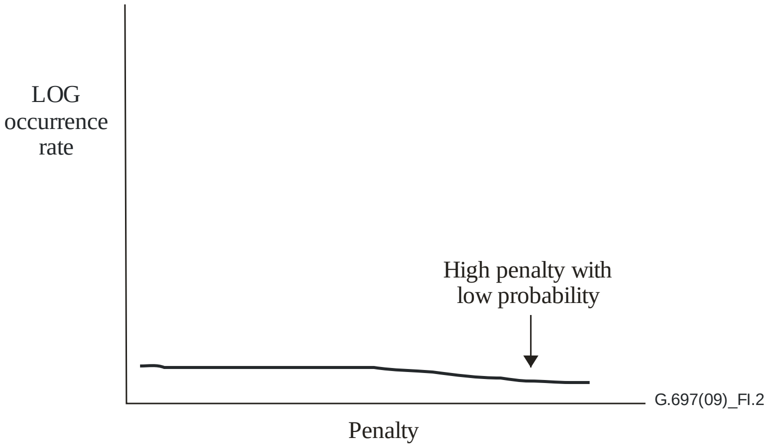

Figure I.2 – Example curve of penalty versus occurrence rate due to stimulated Brillouin scattering variation

Here, the occurrence rate is very low (failure of the dither circuit or very much higher power in the fibre than expected) but the penalty generated can be very severe.

Since this is the case, the approach that has been taken within this Recommendation is to define an approximate penalty that is considered as constituting a significant impairment (e.g., 3 dB) and then give an indication of the frequency with which this occurs in a typical optical network.

Appendix II

Penalty severity value X

(This appendix does not form an integral part of this Recommendation.)

One operator, referring to a 10 000 km DWDM network, suggests defining the *x* value equal to a 3 dB penalty as a figure that constitutes a significant impairment.

Appendix III

Optical monitoring performance

(This appendix does not form an integral part of this Recommendation.)

This appendix contains information concerning the performance obtainable from currently available OM technology. This information should not be interpreted as a requirement or specification, but is intended to help in identifying those cases where a particular desired OM performance requirement can (or cannot) be met using currently available technology. Requirements for OM performance can only be generated with respect to a particular function and for a particular system design and, in most cases, practical and cost-effective specifications for any individual monitoring solution may be very different from the data given in Tables III.1 to III.4.

Table III.1 gives information on the standard measurement performance that might be obtainable with low-cost measurement equipment embedded in the ONEs at the DWDM receiver input. Table III.2 gives information on the standard measurement performance that might be obtainable with low-cost measurement equipment embedded in the ONEs at multichannel points where there is no requirement to measure OSNR. Table III.3 gives the same information for low-cost measurement equipment embedded in the ONEs that can measure OSNR. Table III.4 gives measurement performance for premium measurement equipment with costs appropriate to measurements in a much-reduced number of places in the network by the maintenance staff.

Table III.1 – Performance of embedded optical monitoring at the dense wavelength division multiplexing receiver input

Parameter	Accuracy	Repeatability	Measurement range
Channel power	±2 dB (Note 1)	±0.5 dB	Receiver operating range (Note 2)

NOTE 1 – Since this function must be performed within every DWDM receiver, it must be very simple to remain cost effective and, for this reason, this value is relaxed compared to the value in Table III.2.

NOTE 2 – The input power range over which the receiver would normally be expected to operate.

Table III.2 – Performance of embedded optical monitoring without optical signal-to-noise ratio

Parameter	Accuracy	Repeatability	Measurement range
Total power	±1 dB (Note 1)	±0.5 dB	(–60 to +5) + tap loss dBm (Note 2)
Channel power	±1 dB (Note 1)	±0.5 dB	(–60 to –10) + tap loss dBm (Note 2)

NOTE 1 – This value includes contributions from both measurement uncertainty and tap loss variation. In some systems, the tap loss variation may lead to worse accuracy than this, although this may be compensated by calibration (with additional cost).

NOTE 2 – Since different systems use monitoring taps with different splitting fractions (e.g., 5% or 2%), the measurement range is shown at the output of the tap. To derive the measurement range, the tap loss must be added to the values. For example, a 2% tap would make the values 17 dB higher.

Table III.3 – Performance of embedded optical monitoring with optical signal-to-noise ratio

Parameter	Accuracy	Repeatability	Measurement range
Total power	±1 dB (Note 1)		
Channel power	±1 dB (Note 1)	±0.5 dB	(–40 to –10) + tap loss dBm (Note 2)
Channel wavelength	±75 pm		
OSNR where no significant noise shaping is present (in 0.1 nm optical bandwidth)	±1.5 dB	±0.5 dB	For channel power ≥25 dBm OSNR 10 to 30 dB for ≥100 GHz spacing OSNR 10 to 25 dB for 50 GHz spacing (Note 3)
NOTE 1 – This value includes contributions from both measurement uncertainty and tap loss variation. In some systems, the tap loss variation may lead to worse accuracy than this, although this may be compensated by calibration (with additional cost). NOTE 2 – Since different systems use monitoring taps with different splitting fractions (e.g., 5% or 2%), the measurement range is shown at the output of the tap. To derive the measurement range, the tap loss must be added to the values. For example, a 2% tap would make the values 17 dB higher. NOTE 3 – This measurement range may not be obtainable if there is significant spectral broadening due to non-linear effects in the link.			

Table III.4 – Performance of premium optical monitoring equipment

Parameter	Accuracy	Repeatability	Measurement range
Total power	±0.2 dB (Note 1)		
Channel power	±0.4 dB (Note 1)	±0.2 dB	(–80 to +23) + tap loss dBm (Note 2)
Channel wavelength	±0.5 pm		
OSNR where no significant noise shaping is present (in 0.1 nm optical bandwidth)	±0.4 dB OSNR < 20 ±0.7 dB OSNR < 30		0 to 42 dB for 100 GHz spacing 0 to 28 dB for 50 GHz spacing (Note 3)
Q-factor	±10%	±5%	4 to 14
Others			
NOTE 1 – This value does not include any contribution from tap loss variation, which would have to be compensated by calibration. NOTE 2 – Since different systems use monitoring taps with different splitting fractions (e.g., 5% or 2%), the measurement range is shown at the output of the tap. To derive the measurement range, the tap loss must be added to the values. For example, a 2% tap would make the values 17 dB higher. NOTE 3 – This measurement range may not be obtainable if there is significant spectral broadening due to non-linear effects.			

III.1 Optical signal-to-noise ratio measurement

OSNR measurement currently uses the principle of measuring the noise between channels in order to estimate the noise at the channel wavelength. See Figure III.1.

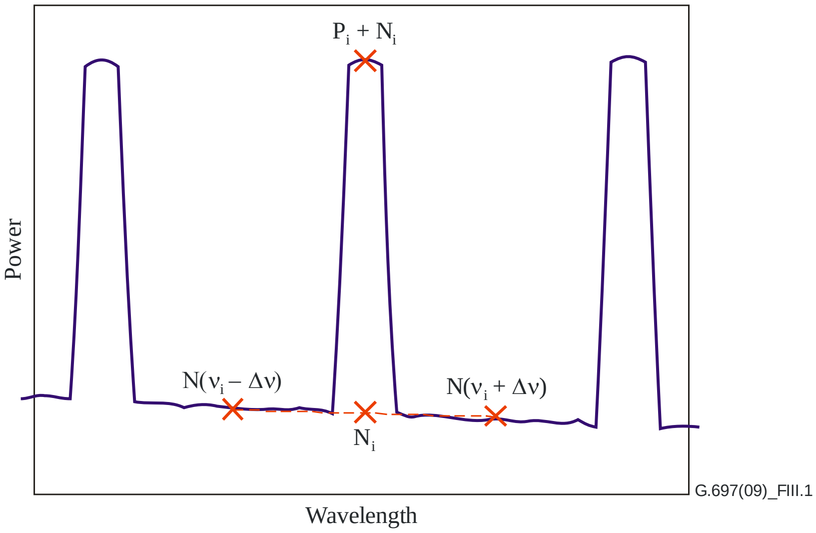

Figure III.1 – Optical signal-to-noise ratio measurement method

This method works well for simple point-to-point systems with nothing but fibre and amplifiers in the optical path. For more complex DWDM systems, however, the introduction of any element which causes shaping of the noise between channels renders this method inaccurate.

In the section of a DWDM system illustrated in Figure III.2, for example, there is a simple optical add-drop multiplexer (OADM), which is configured to drop and add a single channel.

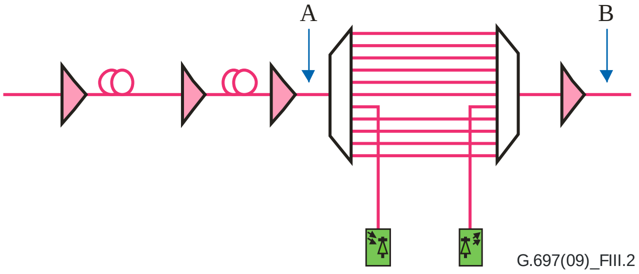

Figure III.2 – Section of a dense wavelength division multiplexing system with an optical add-drop multiplexer

The optical spectra that might be found at points marked A and B are shown in Figures III.3 and III.4, respectively.

As can be seen from Figure III.3, at point A the method of OSNR measurement illustrated in Figure III.1 gives accurate results as the variation in noise with wavelength is fairly slow.

NOTE – Channel 3 of this hypothetical 10-channel system is not present.

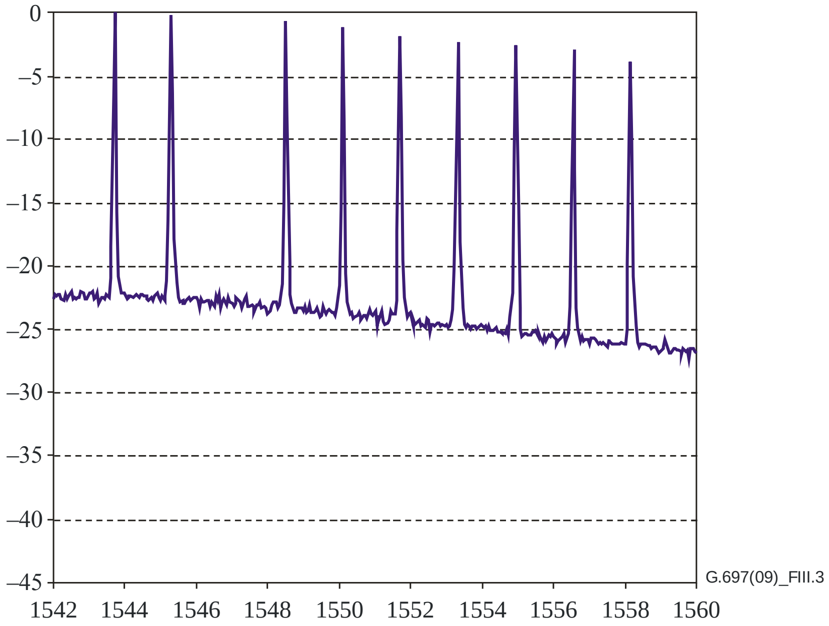

Figure III.3 – Optical spectrum at point A

Figure III.4 shows the spectrum after the mux of the OADM and a booster amplifier. Here, the situation is radically different. The noise between the channels has been strongly shaped by the combined filtering function of the demux/mux. As can be seen by the noise peak at the wavelength of the missing channel in this example, there is about 15 dB more noise at the channel wavelengths than at the mid-points between channels and, hence, the OSNR estimate at this point is about 15 dB optimistic. For the wavelength that has been added, however, we have the reverse situation and the noise level at the mid-points is much higher than the noise added at the channel wavelength. The OSNR estimate for this channel is, therefore, seriously pessimistic.

[b-IEC 61280-2-9] could be a useful reference for additional information on OSNR measurements.

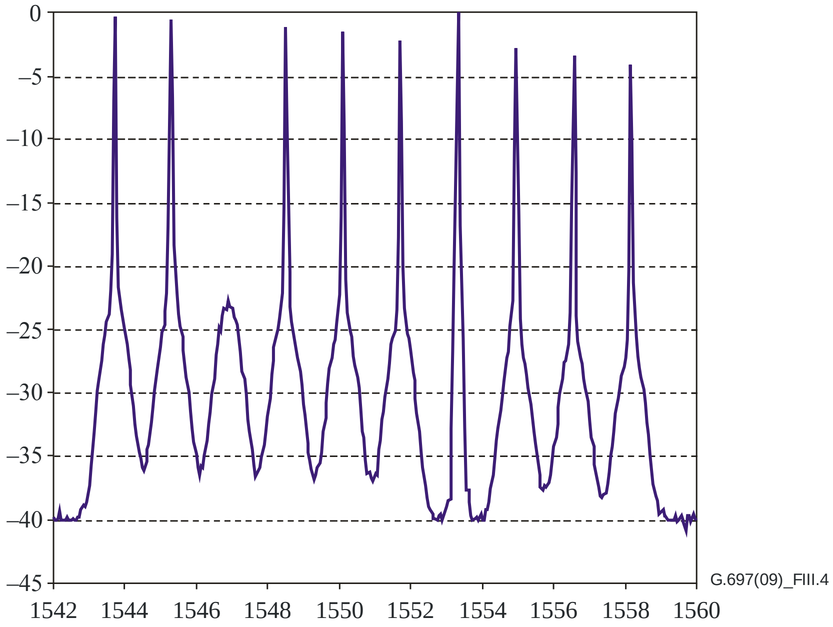

Figure III.4 – Optical spectrum at point B

For a realistic OSNR measurement in the presence of noise shaping, it is essential to measure the filtered noise value in the passband of the optical filters in a system (often called "in-band" OSNR measurement). Three methods of achieving this are described in clauses III.1.1 to III.1.4.

III.1.1 Narrow-band optical spectrum analyser method

If the signal spectrum does not occupy the full channel bandwidth and the optical filter shape has a flat region, the OSNR can be measured with a narrow-band optical spectrum analyser (OSA). An example of this is shown in Figure III.5 for the case of a 10 Gbit/s signal in a 100 GHz channel spacing system. Here, the OSNR can be estimated by measuring the signal power and the noise in the flat region away from the signal. Care must be taken to measure the signal with a sufficiently large resolution bandwidth to capture all of the signal power, while measuring the noise with a small enough resolution bandwidth to exclude the signal. This may require a different resolution bandwidth for each part of the measurement and for the noise power to be scaled from the measurement bandwidth to the usual reference value of 0.1 nm.

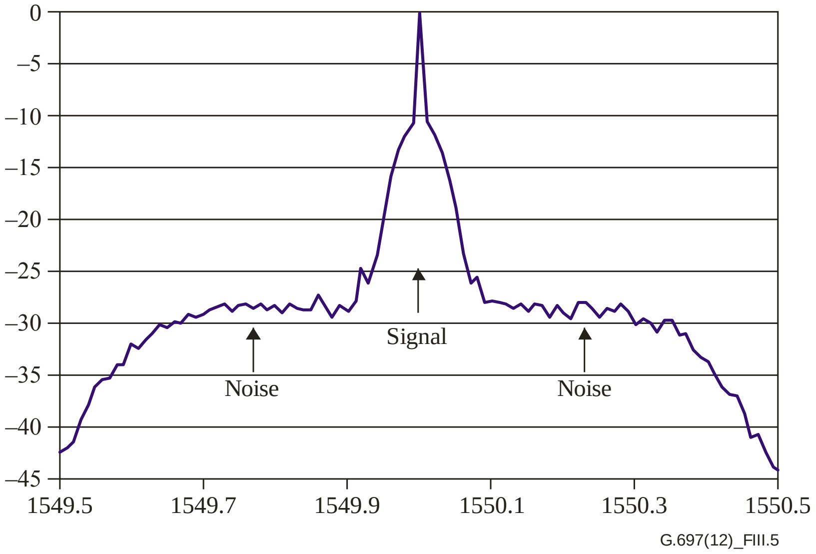

Figure III.5 – Optical spectrum where signal does not occupy full channel bandwidth

However, as the baud rate becomes comparable with the channel spacing, the signal spectrum completely overlaps with the noise floor as illustrated in Figure III.6. In this case, a different measurement principle is required. Also, if the signal traverses multiple optical filters, the combined filter function becomes progressively less flat topped, thereby making accurate determination of the noise level more difficult.

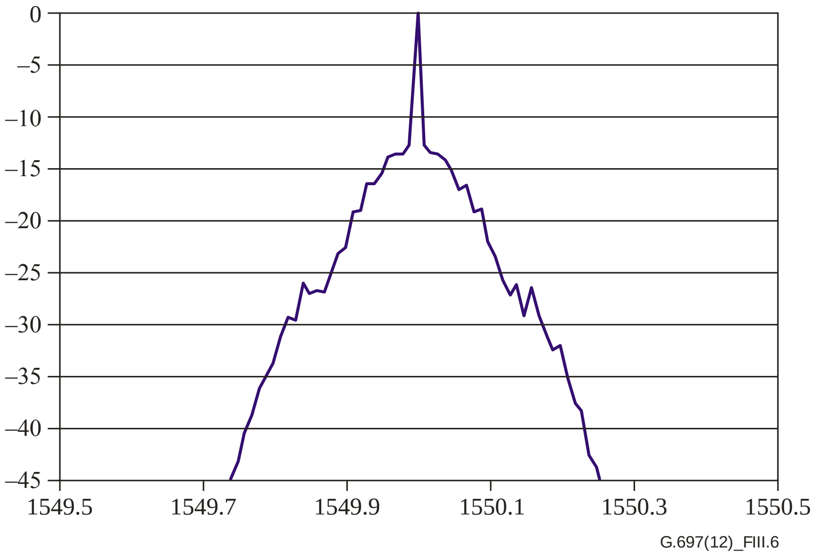

Figure III.6 – Optical spectrum where signal occupies full channel bandwidth

III.1.2 Time domain extinction measurement

In this method, the signal for the channel to be measured is gated on and off at the entry point into the optical system using an acoustic-optical switch. The signal at the point to be measured is then sampled using a second switch, either in phase to measure the signal or out of phase to measure the noise power. This method requires fast high-extinction acoustic-optical switches or a gated OSA. The average signal level of the channel being measured is kept the same as during normal operation to maintain the operating point of the amplifiers.

Obvious drawbacks of this method of measurement are that it requires equipment to be inserted at multiple points in the system and that it cannot be used to measure OSNR while the channel is in service.

III.1.3 Polarization extinction measurement

An alternative method of separating the signal from the noise is to exploit the fact that, to a first approximation, the optical transmission signal is polarized, whereas the ASE noise is unpolarized. In its simplest form, a combination of a variable polarization controller and a polarization splitter/filter is used to separate the polarized signal from the unpolarized noise as shown in Figure III.7.

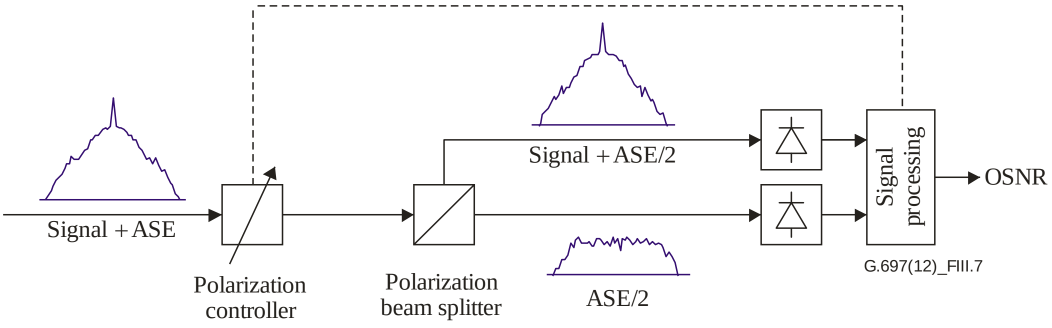

Figure III.7 – Polarization extinction method block diagram

By variation of the polarization controller in front of the polarization beam splitter, it is possible to suppress the polarized signal and get access to the non-polarized in-band noise at one branch, where the other branch shows the signal plus noise [b-Rasztovits-Wiech, 1998].

Four problems with this measurement method are:

- if the polarization state of the signal at the measurement point evolves rapidly (this is likely to be a particular problem with aerial fibre) or the signal becomes de-polarized, then it is very difficult to obtain a good extinction of the signal;
- if there is crosstalk between the channels, the crosstalk may or may not be included in the noise measurement depending on the relative polarizations of the signal and the crosstalk;
- polarization-dependent loss (PDL) can lead to significant measurement error due to the noise with the same polarization as the signal having a different amplitude to the noise with the orthogonal polarization;
- for a polarization multiplexed signal, there is a separate signal on each of the two orthogonal polarizations, so it is not possible to extinguish the signal using a polarization beam splitter. Hence, it is not possible to use this method of OSNR measurement for these signals.

III.1.4 Beat noise measurement

In this OSNR measurement method, the tapped optical signal with ASE noise is first photodetected with a low-bandwidth receiver. The optical to electrical-converted (O/E-converted) signal is split into two branches and its DC component and AC component, respectively, are obtained with a low-pass filter (LPF) and a band-pass filter (BPF) as shown in Figure III.8. Then the signal processing unit calculates the OSNR based on the obtained DC component, the obtained AC component and calibration information that depends on the modulation format and bit rate of the optical signal.

The basic principle of this method is as follows. The DC component of the O/E-converted signal is related to the optical signal power and ASE power, while the AC component of the O/E-converted signal, mainly comprising signal–ASE beat noise and ASE–ASE beat noise, is also related to the optical signal power and ASE power [b-Chung, 2000]. Therefore, with some calibration, the optical signal power and ASE power can be extracted from the DC component and AC component and subsequently the OSNR can be obtained.

This OSNR monitoring method is more suitable for optical phase-modulated signals, and may not work well for intensity-modulated signals. Moreover, since the O/E converted spectrum of an optical tributary signal often includes a number of tones, special care should be taken to exclude any tones within the AC component in the signal processing.

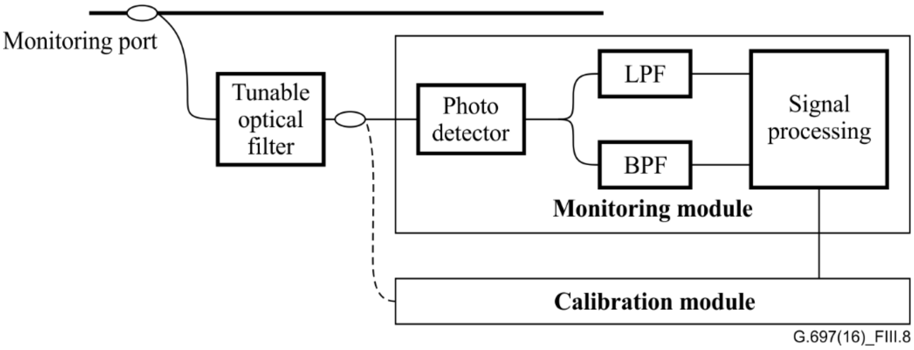

Figure III.8 – Schematic configuration of the beat noise measurement method

III.2 *Q*-factor measurement (for up to approximately 10 Gbit/s signals)

A *Q*-factor measurement occupies an intermediate position between the classical optical parameters (power, OSNR and wavelength) and the digital end-to-end performance parameters based on BER.

A *Q*-factor is measured in the time domain by analysing the statistics of the pulse shape of the optical signal. Full details can be found in [ITU-T O.201]. A *Q*-factor is a comprehensive measure for the signal quality of an optical channel taking into account the effects of noise, filtering and linear/non-linear distortions on the pulse shape, which is not possible with simple optical parameters alone.

Under ideal conditions (only additive Gaussian noise, no linear or non-linear distortions, etc.), the BER of a binary optical channel should be the same as that indicated by a *Q*-factor measurement. However, these idealized conditions are rarely present in real systems and the correlation between the *Q*-factor of an optical signal and the BER measured after regeneration is influenced by the different receiver characteristics (noise bandwidth, impulse response, etc.) in the regenerator compared to that of the *Q*-factor meter.

NOTE – The above description of *Q*-factor measurement is for up to 10 Gbit/s NRZ or RZ signals. *Q*-factor measurement may not apply to 40 Gbit/s or 100 Gbit/s signals with advanced modulation formats and this is for further study.

An additional factor that has a serious effect on the validity of a *Q*-factor measurement at any point in an optical path is the residual dispersion present at that point. Figure III.9 is a block diagram for a simple five-span transmission system incorporating dispersion compensation modules (DCMs) in the line amplifiers. In such a system, while the end points labelled E and F usually have nominally zero residual dispersion, *Q*-factor measurements at intermediate points of the optical path are only possible with proper dispersion compensation at those points.

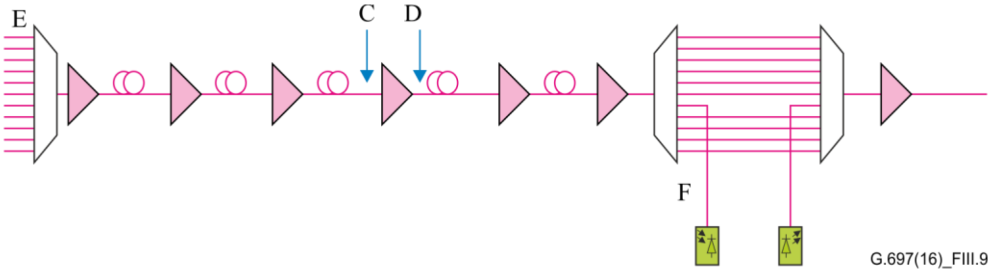

Figure III.9 – Five-span transmission system incorporating dispersion compensation modules in the line amplifiers

Figure III.10 shows the residual dispersion versus distance for a system where the dispersion of each nominally 80 km span is compensated by an 80 km DCM embedded in each line amplifier, and an additional DCM within the receiving preamplifier. In this case, for example, the *Q*-factor measured at point C (the input to the third line amplifier) is quite different to the *Q*-factor at point D (the output of the same amplifier) due to the large difference in residual dispersion of the two points.

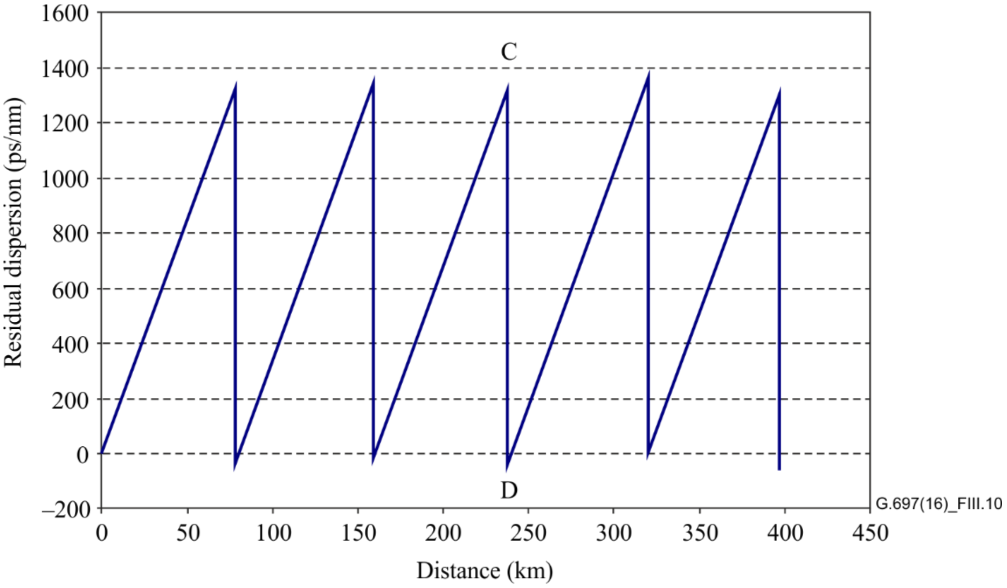

Figure III.10 – Residual dispersion versus distance for a simple system

A solution to the dispersion map, illustrated in Figure III.10, is to only measure the *Q*-factor at the amplifier outputs (e.g., point D).

The residual dispersion map in Figure III.10 is for a wavelength where the fibre dispersion is reasonably accurately compensated for by the DCM. In long-haul systems that cover a large wavelength range, however, the fact that the slope of the fibre dispersion with wavelength typically does not exactly match the inverse of the slope of the DCM dispersion with wavelength means that the residual dispersion map is different over the range of channel wavelengths. This is illustrated in Figure III.11 where the residual dispersion maps of the extreme wavelength channels are also shown.

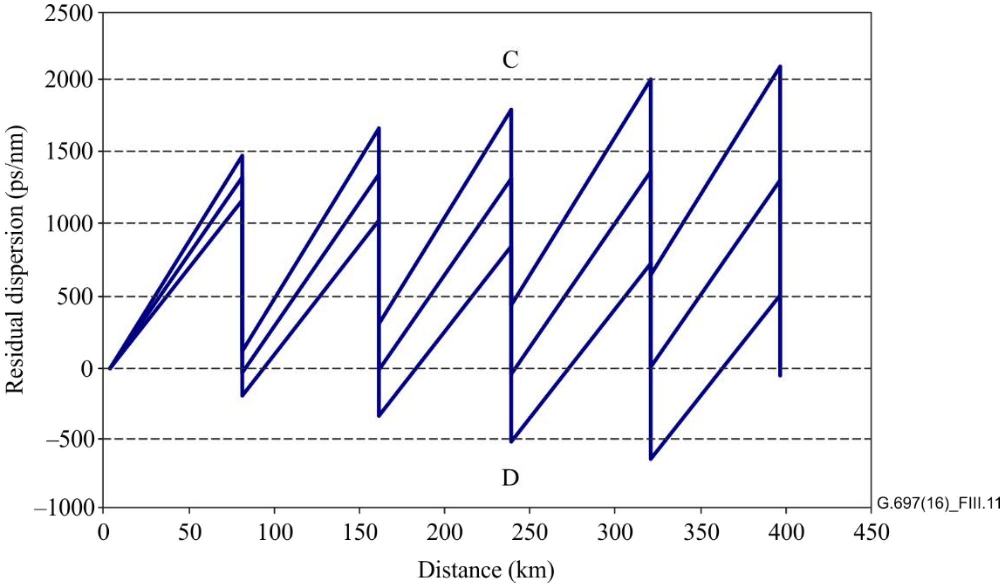

Figure III.11 – Residual dispersion versus distance for a simple system with a wide wavelength range

In the case of a more complex dispersion map, as illustrated in Figure III.12, where there are DCMs in the transmitter and the receiver as well as embedded in the line amplifiers, the points with zero dispersion do not now necessarily coincide with the output of line amplifiers. Here, additional compensation devices in the measuring equipment would be required for *Q*-factor measurement to be valid at these monitoring points.

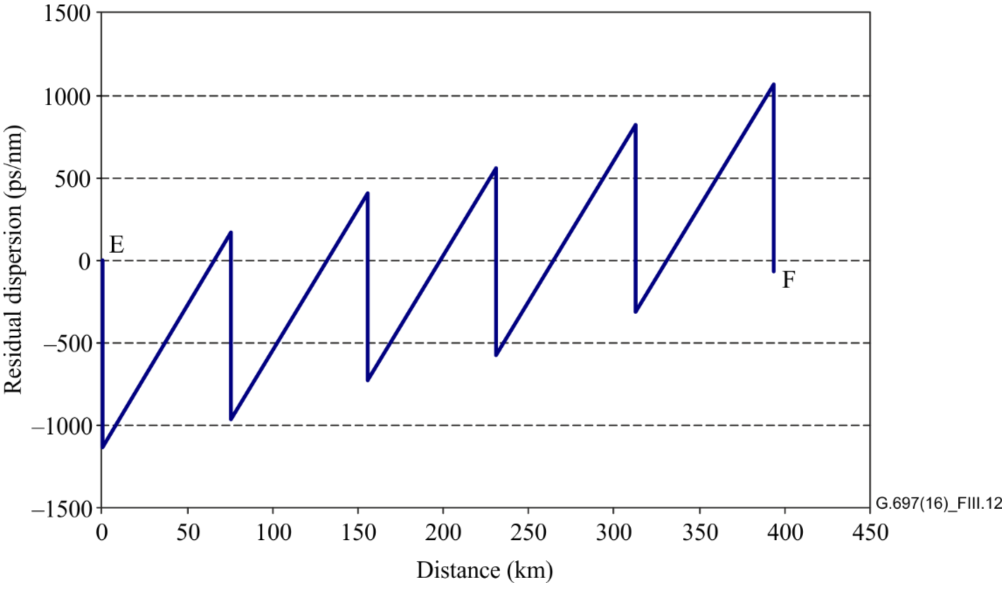

Figure III.12 – Residual dispersion versus distance for a more complex system

Appendix IV

Possible positions for suitable monitoring equipment and their relative functions in several optical network elements

(This appendix does not form an integral part of this Recommendation.)

IV.1 Introduction

While OM is implemented (and in service) in many current optical transmission systems, there are significant differences between the OM deployments between them. This is due to the presence of different transmission and control system designs, the size of the network and different strategies for impairment management in the various systems. For this reason, a general requirement as to which parameter value with which particular accuracy is a reliable indicator of the operational condition of such a system cannot be generalized.

The choice of which option to deploy depends upon the specific characteristics of the ONE, in particular for a DWDM system, whose characteristics include length, number of spans, number of channels and inaccessibility of the sites, as well as cost/benefit considerations. Particular consideration is required because, as the number of monitoring points grows, there is an increasing consumption of signal power with a consequent reduction of the DWDM system reach.

As a conclusion, it is underlined that the possible positions for suitable monitoring points and their relative functions in several ONEs which are shown in this appendix should be considered as examples and not as requirements. These examples are of interest because they can show what is feasible from the technological point of view and what network operators could need.

A general model for possible monitoring positions in an ONE is shown in Figure IV.1.

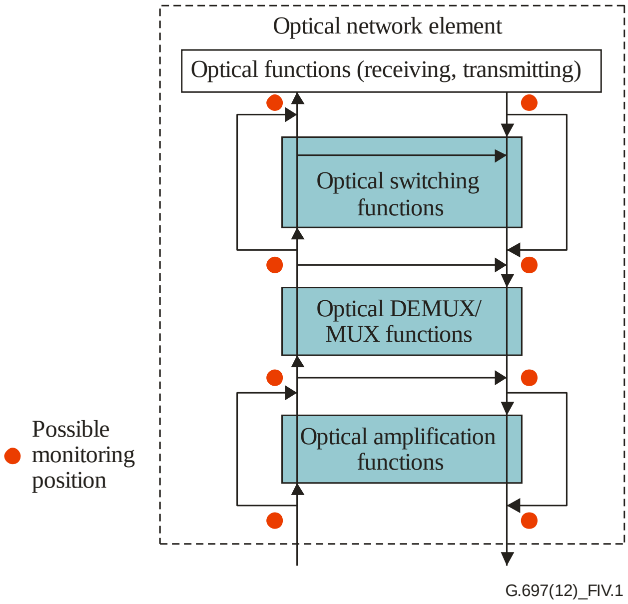

Figure IV.1 – Example of embedded monitoring equipment positioning inside an optical network element

IV.2 Embedded monitoring points

IV.2.1 Dense wavelength division multiplexing line segment

An example of positioning of EME in a long-distance DWDM line segment with optical channels operating at 10 Gbit/s, 40 Gbit/s or 100 Gbit/s is shown in Figure IV.2.

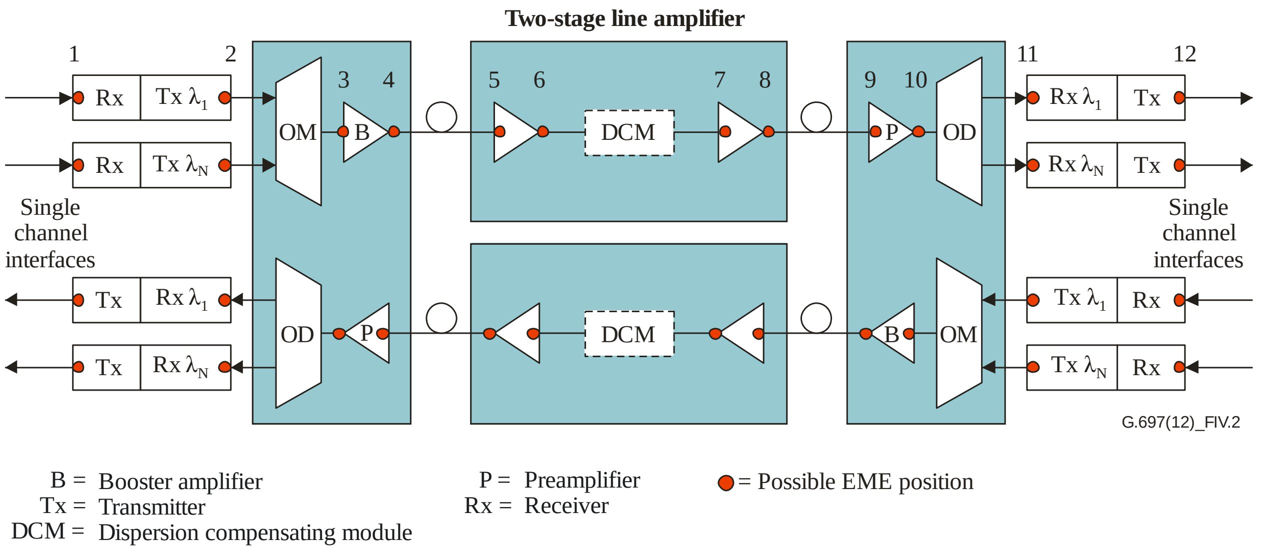

Figure IV.2 – Example of embedded monitoring equipment positioning inside a long-distance dense wavelength division multiplexing line segment

The optical parameters listed in clause 10 can be measured in the various monitoring points of Figure IV.2 according to Table IV.1.

Table IV.1 – Possible monitoring in a dense wavelength division multiplexing line segment

Monitoring parameters	Embedded monitoring equipment position
a) Total power at input of various stages of optical amplification	3, 5, 7, 9
b) Total power at output of various stages of optical amplification	4, 6, 8, 10
c) Channel input power	1, 11
d) Channel output power	2, 12
e) Channel power at the output of various stages of optical amplification	4, 6, 8, 10
f) Channel OSNR at the output of various stages of optical amplification	4, 6, 8, 10
g) Channel wavelength	2
NOTE – This table lists possible monitoring positions. The appropriate choice of monitoring depends on the particular system (see clause IV.1).	

IV.2.2 Reconfigurable optical add-drop multiplexers

An example of positioning of embedded monitoring equipment in a ROADM is shown in Figure IV.3.

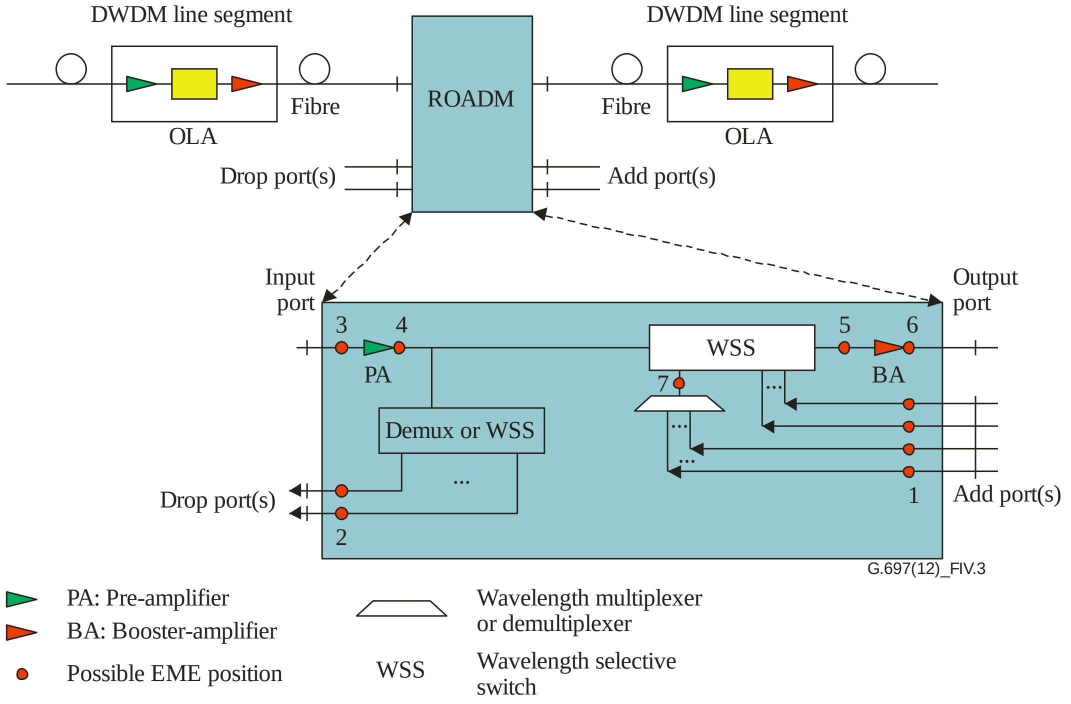

Figure IV.3 – Example of embedded monitoring equipment positioning inside a reconfigurable optical add-drop multiplexer

The optical parameters listed in clause 10 can be measured in the various EMEs of Figure IV.3 according to Table IV.2.

Table IV.2 – Possible monitoring in an example reconfigurable optical add-drop multiplexer

Monitoring parameters	Embedded monitoring equipment position
a) Total power at input of various stages of optical amplification	3, 5
b) Total power at output of various stages of optical amplification	4, 6
c) Channel input power	1
d) Channel output power	2
e) Channel power at the output of various stages of optical amplification	4, 6
f) Channel OSNR at the output of various stages of optical amplification	4, 6
g) Channel wavelength	1
h) Total power	7
NOTE – This table lists possible monitoring positions. The appropriate choice of monitoring depends on the particular system (see clause IV.1).	

The position and the function of the EMEs inside the WSS are for further study.

IV.3 External monitoring points

IV.3.1 Dense wavelength division multiplexing line segment

An example of positioning of EMPs in a long-distance DWDM line segment with optical channels operating at 10 Gbit/s, 40 Gbit/s or 100 Gbit/s is shown in Figure IV.4.

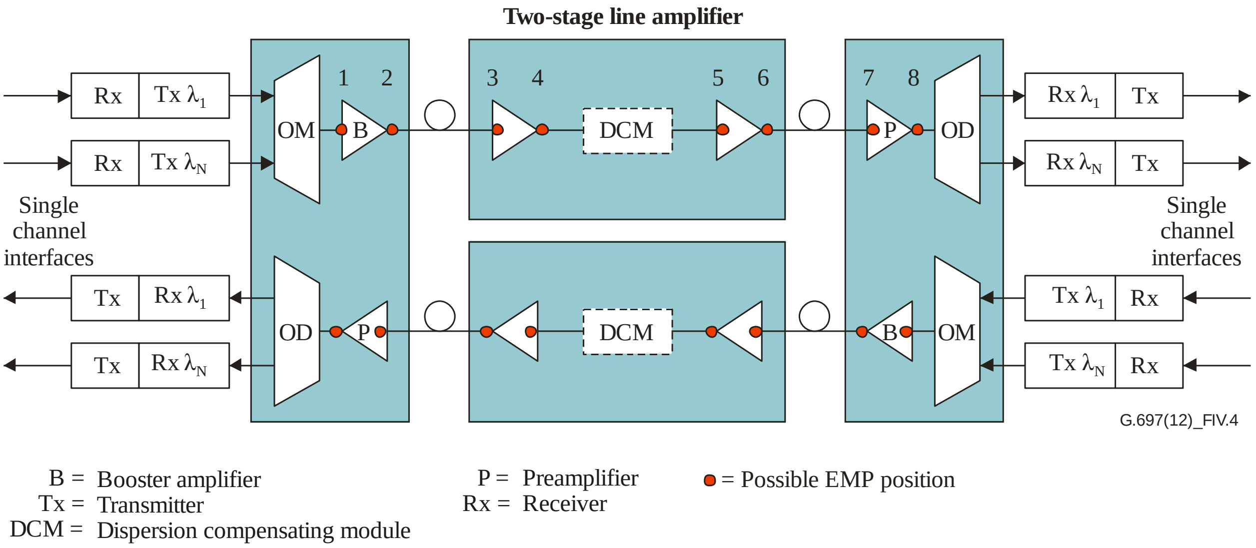

Figure IV.4 – Example of external monitoring point positioning inside a long-distance dense wavelength division multiplexing line segment

All of the optical parameters listed in clause 8 can be measured in the various monitoring points of Figure IV.4 with suitable external measurement equipment. The appropriate choice of which monitoring points are provided depends on the particular system (see clause IV.1).

IV.3.2 Reconfigurable optical add-drop multiplexers

An example of positioning of EMPs in a ROADM is shown in Figure IV.5.

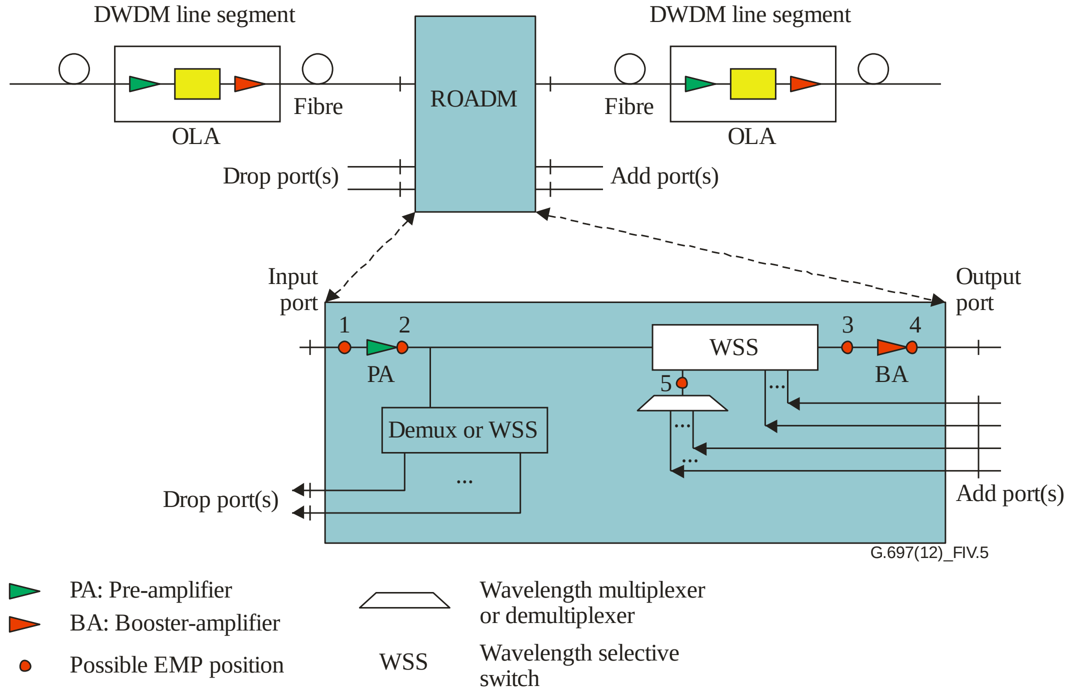

Figure IV.5 – Example of external monitoring point positioning inside an example reconfigurable optical add-drop multiplexer

All of the optical parameters listed in clause 10 can be measured in the various monitoring points of Figure IV.5 with suitable external measurement equipment. The appropriate choice of which monitoring points are provided depends on the particular system (see clause IV.1).

Appendix V

Parameter encoding

(This appendix does not form an integral part of this Recommendation.)

This appendix contains a possible encoding scheme for the communication of information relating to optical parameters. The use of this information, how it is communicated, whether information for any particular parameter is included and whether the value for any parameter is obtained by measurement, measurement prior to system installation or purely provisioned, is outside the scope of this appendix.

V.1 Wavelength ID (32 bits)

This field contains the wavelength label and is composed of four sub-fields:

- **Grid** (3 bits, 0 to 2): The value for grid is set to 1 for the ITU-T DWDM grid as defined in [b-ITU-T G.694.1], set to 2 for the ITU-T coarse wavelength division multiplexing (CWDM) grid as defined in [b-ITU-T G.694.2]. The values of 0 and 3 to 7 are reserved for future use.
- **Channel spacing** (4 bits, 3 to 6): The channel spacing encoding when Grid is set to "1" (DWDM) is shown in Table V.1 and the channel spacing encoding when Grid is set to "2" (CWDM) is shown in Table V.2

Table V.1 – Dense wavelength division multiplexing channel spacing encoding

Channel spacing (GHz)	Value
100	1
50	2
25	3
12.5	4
Flexible grid	5
Reserved for future use	0, 6 to 15

For channel spacings greater than 100 GHz, there is more than one possible choice of grid (see [b-ITU-T G.694.1]), so the appropriate element of the 100 GHz spaced grid should be encoded.

Table V.2 – Coarse wavelength division multiplexing channel spacing encoding

Channel spacing (nm)	Value
20	1
Reserved for future use	0, 2 to 15

- *n* (16 bits, 7 to 22): The value used to compute the frequency as shown below: When the grid is "1", frequency (THz) = 193.1 THz + n × channel spacing (THz) For the case where the channel spacing value is set to "5", a channel spacing of 6.25 GHz should be used in the above formula. When the grid is "2", wavelength (nm) = 1 471 nm + n × channel spacing (nm) n is encoded as a 16-bit two's complement number.
- *m* (9 bits, 23 to 31): When the grid is "1" and the channel spacing value is set to "5" this is the value used to compute the slot width as: slot width (GHz) = 12.5 GHz × m (see [b-ITU-T G.694.1]) otherwise set to 0; m is encoded as a 9-bit unsigned integer.

As an example, the encoding of the 193.85 THz element (approximately 1 546.518 nm) from the 50 GHz spaced grid in [b-ITU-T G.694.1] would be grid = 1, channel spacing = 2, *n* = 15, Reserved = 0. This results in an encoding of 000000000 0000000000001111 0010 001 or 0x00000791.

V.2 Parameter ID source (8 bits)

This field defines the source of the parameter ID lookup table. The value "1" corresponds to this Recommendation, all other values are reserved for future use.

V.3 Parameter ID (8 bits)

When the parameter ID source is equal to "1", the parameter encoding shown in Table V.3 applies. For all other values of the parameter ID source, the parameter encoding is given in the document referred to in V.2.

Table V.3 – Parameter ID encoding

Value	Parameter	Unit	Notes
1	Total power	dBm	
2	Channel power	dBm	
3	Frequency deviation from nominal	GHz	For DWDM channels
4	Wavelength deviation from nominal	nm	For CWDM channels
5	OSNR	dB (0.1 nm)	Referred to a 0.1 nm noise bandwidth
6	Q	–	Linear *Q*
7	Polarization mode dispersion (PMD)	ps	Mean differential group delay (DGD). This parameter is normally only measured at time of installation
8	Residual dispersion	ps/nm	This parameter is normally only measured at time of installation

All other values of the parameter ID are reserved for future use.

V.4 Value of parameters (32 bits)

The parameter value is encoded as a 32-bit floating-point number according to [b-IEEE 754]. The 32-bit number is divided into a sign (1 bit), an exponent (8 bits) and a mantissa (23 bits). The parameter value is then:

$$\text{Value} = (-1)^{\text{sign}} \times 2^{(\text{exponent} - 127)} \times (\text{number between 1.0 and 2.0 derived from mantissa})$$

For details see [b-IEEE 754].

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