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

Digital sections and digital line system – Optical fibre submarine cable systems

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Transverse compatible dense wavelength division multiplexing applications for repeatered optical fibre submarine cable systems

Recommendation ITU-T G.977.1

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Recommendation ITU-T G.977.1

Transverse compatible dense wavelength division multiplexing applications for repeatered optical fibre submarine cable systems

Summary

Recommendation ITU-T G.977.1 provides physical layer specifications for dense wavelength division multiplexing (DWDM) applications on dispersion-unmanaged repeatered optical fibre submarine cable systems. Transverse compatible applications for DWDM applications for repeatered optical fibre submarine cable systems are described for point-to-point, multichannel line systems with optically pumped amplifiers. The primary purpose is to enable multiple vendors to design DWDM transmission equipment for submarine fibre links that are compliant with this Recommendation.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T G.977.1	2020-10-29	15	11.1002/1000/14511

Keywords

DWDM, repeatered optical fibre submarine cable system, transverse compatibility.

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

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ITU draws attention to the possibility that the practice or implementation of this Recommendation 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 Recommendation development process.

As of the date of approval of this Recommendation, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. 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/.

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Recommendation ITU-T G.977.1

Transverse compatible dense wavelength division multiplexing applications for repeatered optical fibre submarine cable systems

1 Scope

This Recommendation specifies a physical layer for dense wavelength division multiplexing (DWDM) applications in point-to-point repeatered optical fibre submarine cable systems. The goal is to enable transversally compatible applications.

The primary purpose is to enable multiple vendors to provide terminal equipment for submarine fibre links that are compliant with this Recommendation.

This Recommendation includes a generic reference model for physical layer applications. The specifications take into account parameters such as maximum attenuation, fibre types, wavelength ranges, maximum chromatic dispersion (CD), minimum local CD coefficient, maximum differential group delay (DGD) and effective area.

This Recommendation focuses on repeatered optical fibre submarine cable systems without CD management.

This Recommendation presumes that the optical tributary signals transported within optical channels are digital.

This Recommendation covers a multiple-link partial transverse compatible repeatered optical fibre submarine cable system, where all the submerged plant is provided by a single vendor for all fibre pairs, while the terminal equipment at either end of the link may be provided by a different vendor. A full transverse compatible system, where different types of submerged equipment are provided by different vendors from its terminating equipment, lies outside the scope of this Recommendation.

2 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.654] Recommendation ITU-T G.654 (2020), *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), *Definition and test methods for the relevant generic parameters of optical amplifier devices and subsystems*.

[ITU-T G.671] Recommendation ITU-T G.671 (2019), *Transmission characteristics of optical components and subsystems.*

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

[ITU-T G.694.1] Recommendation ITU-T G.694.1 (2020), *Spectral grids for WDM applications: DWDM frequency grid.*

[ITU-T G.696.1] Recommendation ITU-T G.696.1 (2010), *Longitudinally compatible intra-domain DWDM applications*.

[ITU-T G.697] Recommendation ITU-T G.697 (2016), *Optical monitoring for dense wavelength division multiplexing systems*.

[ITU-T G.780] Recommendation ITU-T G.780/Y.1351 (2010), *Terms and definitions for synchronous digital hierarchy (SDH) networks*.

[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 (2020), *General features of optical fibre submarine cable systems*.

[ITU-T G.972] Recommendation ITU-T G.972 (2020), *Definition of terms relevant to optical fibre submarine cable 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.979] Recommendation ITU-T G.979 (2016), *Characteristics of monitoring systems for optical submarine cable systems*.

3 Terms and definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

3.1.1 branching unit (BU) [ITU-T G.977].

3.1.2 cable terminating equipment (CTE) [ITU-T G.972].

3.1.3 client class [b-ITU-T G.696.1].

3.1.4 dense wavelength division multiplexing (DWDM) [ITU-T G.972].

3.1.5 dense wavelength division multiplexing system (DWDMS) [ITU-T G.972].

3.1.6 digital line section (DLS) [ITU-T G.977].

3.1.7 dispersion compensating single-mode fibre (DCF) [ITU-T G.972].

3.1.8 electrical command response (ECR) [ITU-T G.972].

3.1.9 forward amplified spontaneous emission (ASE) power level [ITU-T G.661].

3.1.10 gain equalizer [ITU-T G.977].

3.1.11 interoperable cable portion [ITU-T G.972].

3.1.12 land repeater [ITU-T G.972].

3.1.13 line optical channel (LOC) [ITU-T G.977].

3.1.14 maintenance controller [ITU-T G.972].

3.1.15 monitoring equipment (ME) [ITU-T G.972].

3.1.16 noise figure (NF) [ITU-T G.661].

3.1.17 optical coupling junction (OCJ) [ITU-T G.972].

3.1.18 optical signal-to-noise ratio (OSNR) [ITU-T G.661].

3.1.19 optical submarine repeater (OSR) [ITU-T G.972].

3.1.20 optical transport hierarchy (OTH) [ITU-T G.972].

3.1.21 polarization dependent loss (PDL) [ITU-T G.671].

3.1.22 polarization mode dispersion (PMD) [ITU-T G.650.2].

3.1.23 power feeding equipment (PFE) [ITU-T G.972].

3.1.24 submarine electro-optic interface (SEOI) [ITU-T G.977].

3.1.25 synchronous digital hierarchy (SDH) [b-ITU-T G.780].

3.1.26 terminal portion [ITU-T G.972].

3.1.27 tilt equalizer [ITU-T G.977].

3.1.28 maximum total output power [ITU-T G.661].

3.1.29 wavelength division multiplexing (WDM) [ITU-T G.972].

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.2.1 generalized optical signal to noise ratio (GOSNR): A measurement of the total noise contributions due to linear noise and fibre nonlinearity.

3.2.2 multichannel receive main path interface reference point (MPI-R_M): A (multichannel) reference point on the optical fibre just before the optical network element transport interface input optical connector.

NOTE – Paraphrased from [ITU-T G.959.1].

3.2.3 multichannel source main path interface reference point (MPI-S_M): A (multichannel) reference point on the optical fibre just after the optical network element transport interface output optical connector.

NOTE – Paraphrased from [ITU-T G.959.1].

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

ASE Amplified Spontaneous Emission

AWGN Additive White Gaussian Noise

BOL Beginning Of Life

BU Branching Unit

CD	Chromatic Dispersion
CTE	Cable Terminating Equipment
DCF	Dispersion Compensating single-mode Fibre
DGD	Differential Group Delay
DLS	Digital Line Section
DWDM	Dense Wavelength Division Multiplexing
DWDMS	Dense Wavelength Division Multiplexing System
ECR	Electrical Command Response
EOL	End Of Life
GAWBS	Guided Acousto-optic Wave Brillouin Scattering
GOSNR	Generalized Optical Signal to Noise Ratio
GSNR	Generalized Signal to Noise Ratio
IPI	Interoperable Path Interface
LOC	Line Optical Channel
ME	Monitoring Equipment
MPI	Main Path Interface
MUX	Multiplexer
NF	Noise Figure
NLI	Nonlinear Interference
OA	Optical Amplifier
OCJ	Optical Coupling Junction
OSR	Optical Submarine Repeater
OTH	Optical Transport Hierarchy
PDF	Positive Dispersion single-mode Fibre
PDL	Polarization Dependent Loss
PFE	Power Feeding Equipment
PMD	Polarization Mode Dispersion
PoP	Point of Presence
QAM	Quadrature Amplitude Modulation
QPSK	Quaternary Phase Shift Keying
ROADM	Reconfigurable Optical Add Drop Multiplexer
Rx	Receive
SDH	Synchronous Digital Hierarchy
SEOI	Submarine Electro-Optic Interface
SHB	Spectral Hole Burning
SNR	Signal-to-Noise Ratio
SoP	State of Polarization

SPM	Self-Phase Modulation
TOP	Total Output Power
TPND	Transponder
TTE	Terminal Transmission Equipment
TVSP	Time-Varying System Penalty
Tx	Transmit
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch
XPM	cross-Phase Modulation

5 Conventions

This clause is intentionally left blank.

6 Classification of optical interfaces

6.1 Applications

This Recommendation addresses transversally compatible DWDM application in a point-to-point repeatered optical fibre submarine cable system.

6.2 Reference configurations

For the purpose of this Recommendation, the relevant reference points applicable to the DWDM application for point-to-point repeatered optical fibre submarine cable systems are shown in Figure 6-1.

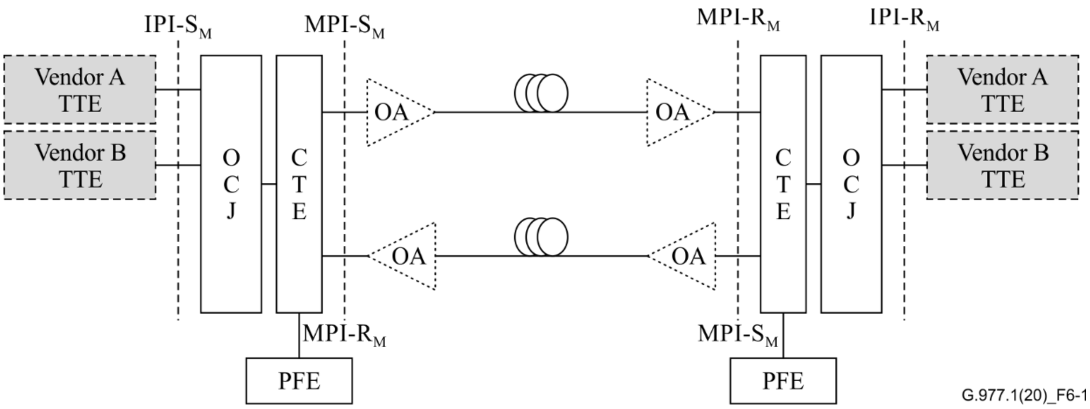

Figure 6-1 – Reference configuration for a dense wavelength division multiplexing system
CTE: cable terminating equipment; OA: optical amplifier

The reference points main path interface-S$_M$ (MPI-S$_M$) and MPI-R$_M$ in Figure 6-1 are defined in clauses 3.2.1 and 3.2.2, respectively.

The reference points interoperable path interface-S$_M$ (IPI-S$_M$) and IPI-R$_M$ in Figure 6-1 are specified as follows:

– IPI-S$_M$ is a (multichannel) interoperable reference point on the optical terminal just before the optical coupling junction;

– IPI-R_M is a (multichannel) interoperable reference point on the optical terminal just after the optical coupling junction.

6.3 Optical coupling junction

An optical coupling junction (OCJ) is any optical coupling that may exist as a passive or active optical interface. Transversal compatibility is ensured before the OCJ at the transmit site and after the OCJ at the receive site. The OCJ also serves as a coupling interface for any submarine cable monitoring and control equipment.

7 Repeatered-span partial transverse compatibility

The applications covered by this Recommendation are multi-span black-box multiple-link transverse compatible systems.

The systems are deemed to be multiple-link partial transverse compatible when all submerged plant is provided by a single vendor for all fibre pairs, while the terminal equipment at either end of the link is provided by a different vendor. Both ends for each single link are terminated by equipment from the same manufacturer. A repeatered-span partial transverse compatible system is illustrated in Figure 7-1.

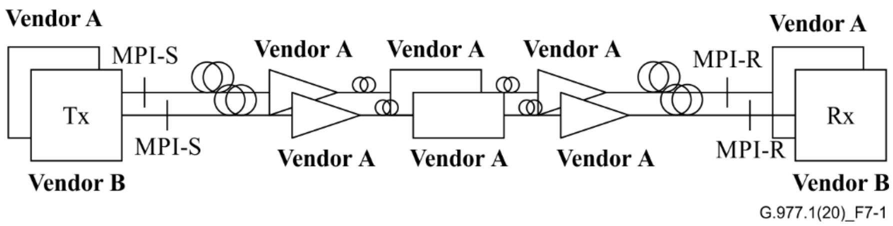

Figure 7-1 – Repeatered-span multiple-link partial transverse compatibility

A specification of the system interfaces and boundaries of a repeatered partial transverse compatible system can also be found in [ITU-T G.971].

8 Parameters

8.1 Span loss

The span loss from MPI-S_M to MPI-R_M is specified for an operating wavelength region, which includes loss caused by splices, connectors, optical attenuators and other passive or active optical devices (if used) as well as fibre loss. These losses are averaged across all spans.

The attenuation coefficient of each ITU-T G.652, ITU-T G.653, ITU-T G.654, ITU-T G.655 and ITU-T G.656 fibre is specified in the corresponding Recommendations. It should be noted that a submarine transmission system may contain attenuation values outside this range.

8.2 Fibre types

In submarine systems, several types of optical fibres may be used to construct an optical path. These are specified in [ITU-T G.652], [ITU-T G.653], [ITU-T G.654], [ITU-T G.655] and [ITU-T G.656]. The following fibre type is considered for transversal compatibility in a repeatered digital line section (DLS):

– positive dispersion single-mode fibre (PDF) compliant with [ITU-T G.652] and [ITU-T G.654].

Depending on the system specifications, various combinations of fibre types may be used to ensure a point of presence (PoP) to PoP connection. Each DLS, however, is assumed to only contain PDF. Further information on fibre types can be found in [ITU-T G.978].

8.3 Wavelength ranges

The operating wavelength range consists of one or more of the wavelength bands, as specified in [b-ITU-T G-Sup.41].

8.4 Maximum chromatic dispersion

This parameter defines the maximum value of the optical path CD from MPI-S_M to MPI-R_M in the operating wavelength region. The CD (which is expressed in picoseconds per nanometre) of an optical path must be stated to ensure acceptable system operation. CD can be calculated as the product of the CD coefficient of each fibre (picoseconds per nanometre·per kilometre) and its length (kilometres). It is noted that, for submarine systems, the optical path can consist of several types of fibres with different CD coefficients.

The CD coefficient of each ITU-T G.652, ITU-T G.653, ITU-T G.654, ITU-T G.655 and ITU-T G.656 fibre is specified in the corresponding Recommendations.

Further information regarding CD impairment can be found in [b-ITU-T G-Sup.39].

9 Characteristics and performance of the system

9.1 Optical loading specification

The end-to-end specifications of the system are derived by pre-loading an unpolarized DWDM channel power profile at the transmit (Tx) end. The optical power loading can exist in the form of carved amplified spontaneous emission (ASE) or traffic-carrying channels. The specifications of the cable system are derived from the receive (Rx) end spectrum where effects such as power deviations may be visible. Thus, each specification is referenced to a transmit and receive channel measurement with respect to the channel's frequency.

The centre frequency of the reference channel is typically given in terahertz. The frequency may not necessarily align with an ITU-T G.694.1 50 GHz frequency grid, but may be provisioned on an arbitrary frequency grid. Guidance for the line specifications is provided in Table A.1 for one or all loading channels. An example of a loading configuration on the transmit site is shown in Figure 9-1.

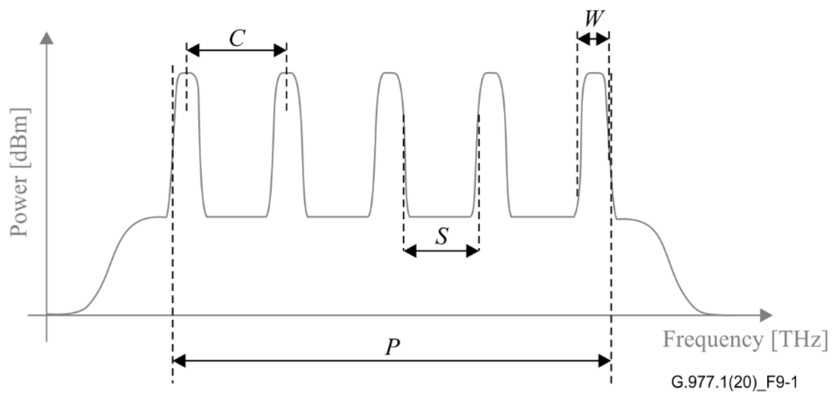

Figure 9-1 – An example transmit spectrum

C: channel grid spacing; *S*: edge-to-edge channel spacing; *W*: channel width; *P*: passband

9.1.1 Channel grid spacing

The centre-to-centre frequency spacing C of the channels used to load the submarine cable system is the channel grid spacing. The frequency spacing in gigahertz may not necessarily align with an ITU-T G.694.1 frequency grid.

9.1.2 Average power per channel

The power of a reference channel is typically given in decibels relative to 1 mW. [ITU-T G.692] specifies the reference channel power. The power per channel at the Tx end should be constant across all channels in the spectrum as a requirement for flat launch. The power per channel P may be calculated using the repeater total output power (TOP) and the number of channels in the spectrum N:

$$P\ [\text{dBm}] = \text{TOP}[\text{dBm}] - 10\log_{10}(N)$$

9.1.3 Gain deviation and slope of tilt

Gain deviation is determined by the maximum decibel difference, for a reference channel, between the receive power and the transmit power. A positive gain deviation may require a traffic-carrying channel to be underlaunched, whereas a negative gain deviation may require a traffic-carrying channel to be pre-emphasized. Figure 9-2 shows an example of a transmit and receive spectrum with loading channels. The power per channel for both sites is also plotted and the difference between the Rx and Tx channel powers results in the gain deviation. Typically, the worst case positive or negative gain deviation is specified.

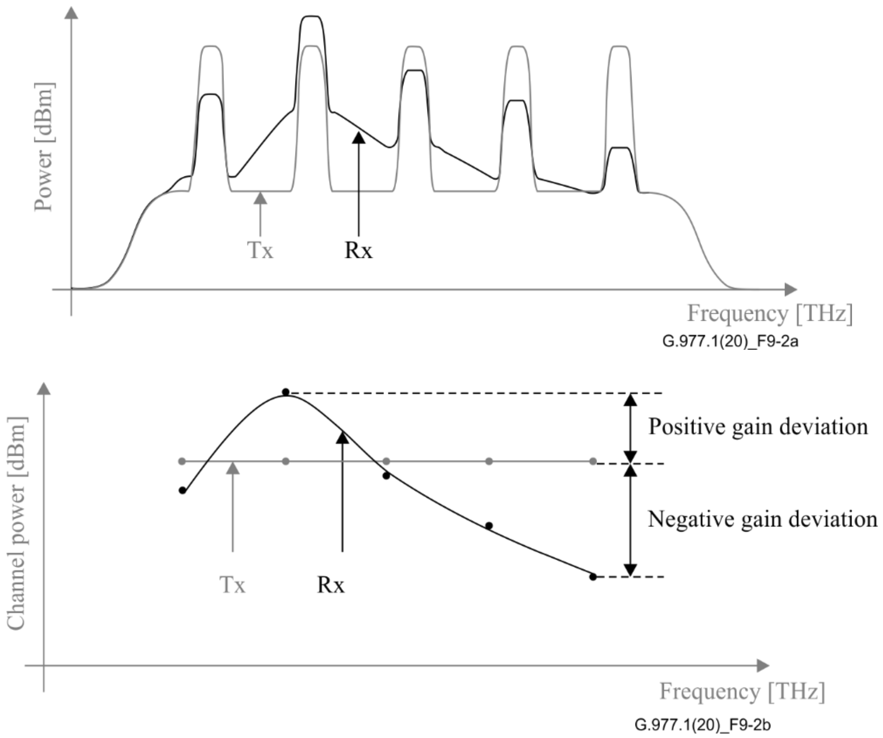

Figure 9-2 – a) An example of transmit (Tx) and receive (Rx) spectra. b) A measure of gain deviation where each point represents the integrated channel power of the Tx and Rx

When multiple positive and negative gain deviations occur, it is sometimes useful to note the slope of tilt in the spectrum. Figure 9-3 is an example of the gain deviations represented in the presence of end-to-end tilt in the system.

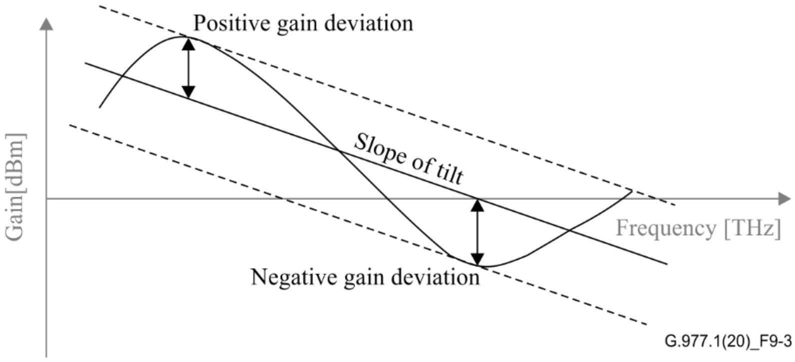

Figure 9-3 – An example of the gain deviation spectrum illustrating the slope of tilt

9.1.4 Optical signal-to-noise ratio

As described in [b-ITU-T G-Sup.39] and [b-ITU-T G-Sup.41], the optical signal-to-noise ratio (OSNR) is determined by the ratio of total signal power to noise power. Measurements of the OSNR should follow the guidance of [ITU-T G.697] and the signal bandwidth W used in the calculation should be stated. OSNR is specified between IPI-S_M and IPI-R_M.

9.1.5 Signal-to-noise ratio

OSNR is a signal-to-noise ratio (SNR) where both signal and noise power are referenced to the same optical bandwidth. For the measurement of ASE channels:

$$\mathrm{SNR}_{\mathrm{ASE}} = \frac{B_{\mathrm{o}}}{C}\mathrm{OSNR}_{\mathrm{ASE}}$$

where B_o is the optical bandwidth (typically 12.5 GHz or 0.1 nm at 1 550 nm); and C the carrier spacing in gigahertz. Similarly, any other noise impairment, such as nonlinear interference (NLI), modem implementation or modem-line implementation, can be expressed as either an SNR or OSNR by scaling to the signal baud or equivalent bandwidth B_e in gigahertz:

$$\mathrm{SNR} = \frac{B_{\mathrm{o}}}{B_{\mathrm{e}}}\mathrm{OSNR}$$

9.1.6 Generalized droop

The generalized droop model aims to account for the aggregation of multiple sources of Gaussian noise (or signal distortions modelled as a Gaussian noise) under the constraint of fixed total power. Rather than simply summing independently assessed variances from different sources of additive white Gaussian noise (AWGN), it accounts for the overall induced signal depletion (or droop) as well as the mutually induced noise droop terms through an autoregressive process. If each source of noise is modelled as generating signal droop with respect to total power, then the overall signal droop due to combined sources of noise is the product of individual droops.

The signal droop is the ratio between total power (per channel) and signal power [b-Bononi]. The effect of signal power depletion on the SNR can be expressed through the product rule for inverse droop [b-Antona]:

$$1 + \frac{1}{\mathrm{SNR}} = \left(1 + \frac{1}{\mathrm{SNR}_1}\right)\left(1 + \frac{1}{\mathrm{SNR}_2}\right)\cdots\left(1 + \frac{1}{\mathrm{SNR}_N}\right)$$

where SNR_1 to SNR_N denote the contribution of each impairment. Here the SNR terms are expressed per channel in the relevant noise bandwidth, i.e.,

– channel spacing to derive SNR out of a cascade of constant power EDFAs;
– channel bandwidth in order to aggregate guided acousto-optic wave Brillouin scattering (GAWBS), nonlinear noise, ASE, crosstalk, etc.

9.1.7 Linear signal-to-noise ratio

The linear SNR or SNR_{ASE} describes the total linear noise contributions of the interoperable cable portion. The linear impairments described here are due to ASE.

The effect of droop (clause 9.1.6) on the SNR_{ASE} can be expressed through the product rule for inverse droop [b-Antona]:

$$1 + \frac{1}{\mathrm{SNR_{ASE}}} = \prod_{n=1}^{N} \left(1 + \frac{1}{\mathrm{SNR}_n}\right)$$

Where SNR_n denotes the ASE contribution of each EDFA.

9.1.8 Nonlinear signal-to-noise ratio

The nonlinear SNR or SNR_{NLI} describes the total noise contributions from NLI in the optical fibre due to Kerr nonlinearity. Nonlinear impairments may include, but are not limited to self-phase modulation (SPM) and cross-phase modulation (XPM).

9.1.9 Guided acousto-optic wave Brillouin scattering signal-to-noise ratio

The GAWBS SNR or SNR_{GAWBS} is the contribution from the acoustic modes of the transmission fibre scattering light in the forward direction with a frequency shift that is determined by the acoustic mode oscillation frequency [b-Bolshtyanksy].

9.1.10 Modem signal-to-noise ratio

SNR_{MODEM} is the total noise arising from the specific modem technology used. SNR_{MODEM} is the submarine electro-optic interface (SEOI) back-to-back implementation using an identical coupling configuration that is also used for propagation.

9.1.11 Other signal-to-noise ratio impairments

SNR_i are all other modem and line impairments. The interaction of modem and line impairments may include but is not limited to dispersion penalties, laser linewidth interactions, and polarization dependent loss (PDL).

9.1.12 Generalized optical signal-to-noise ratio

The generalized optical signal-to-noise ratio (GOSNR) is the total noise contributions due to linear noise and fibre nonlinearity. That is,

$$\frac{1}{\mathrm{GOSNR}} = \frac{1}{\mathrm{OSNR_{ASE}}} + \frac{1}{\mathrm{OSNR_{NLI}}} + \frac{1}{\mathrm{OSNR_{GAWBS}}}$$

where $\mathrm{OSNR_{NLI}}$ is the OSNR due to fibre nonlinearity; and $\mathrm{OSNR_{GAWBS}}$ is the OSNR due to GAWBS. The GOSNR measurement should adequately remove all transponder distortion and implementation noises; these should be stated if any. GOSNR can alternatively be represented as a generalized signal to noise ratio (GSNR):

$$\frac{1}{\mathrm{GSNR}} = \frac{1}{\mathrm{SNR_{ASE}}} + \frac{1}{\mathrm{SNR_{NLI}}} + \frac{1}{\mathrm{SNR_{GAWBS}}}$$

To account for droop impairments (clause 9.1.6), the generalized droop formula may be used [b-Bononi]:

$$1 + \frac{1}{\mathrm{GSNR}} = \left(1 + \frac{1}{\mathrm{SNR_{ASE}}}\right) \cdot \left(1 + \frac{1}{\mathrm{SNR_{NLI}}}\right) \cdot \left(1 + \frac{1}{\mathrm{SNR_{GAWBS}}}\right)$$

To simplify measurements with coherent modems, a GSNR or GOSNR is confined to dual polarization quaternary phase shift keying (QPSK) and 16-quadrature amplitude modulation (16-QAM) modulation formats [b-Hartling].

9.1.13 Total signal-to-noise ratio

The total SNR (in linear units) of a CD uncompensated submarine cable system can be represented as a superposition of all noise contributions [b-Hartling]:

$$\frac{1}{\mathrm{SNR_{TOT}}} = \frac{1}{\mathrm{GSNR}} + \frac{1}{\mathrm{SNR_{MODEM}}} + \frac{1}{\mathrm{SNR}_i}$$

The combined GSNR and SNR_i quantity is known as the external signal-to noise ratio, $\mathrm{SNR_{EXT}}$:

$$\frac{1}{\mathrm{SNR_{EXT}}} = \frac{1}{\mathrm{GSNR}} + \frac{1}{\mathrm{SNR}_i}$$

9.2 System specifications

In transversely compatible point-to-point systems, the system specifications should be provided for the land segment(s) and sea segment independently between the IPI-S_M and IPI-R_M.

9.2.1 Span length

A span is the distance between consecutive repeaters. The nominal length of the spans in the submarine cable is given in kilometres.

9.2.2 Span loss

Span loss is the average loss per span in decibels at the reference channel frequency.

9.2.3 Accumulated chromatic dispersion

The total accumulated CD in picoseconds per nanometre is typically quoted at the minimum channel frequency within the passband. The accumulated CD should include terrestrial and submarine segments.

9.2.4 Passband

The passband determines the operating frequency range that supports traffic-carrying channels. The passband is typically measured over the received spectrum. In the presence of optical channels, the passband P is defined at the −3 dB edge of the first blue (Start) and last red (Stop) channel's specified power, see Figure 9-1.

9.2.5 Mean polarization mode dispersion

Small departures from perfect cylindrical symmetry in the fibre core lead to birefringence affecting the mode indices of orthogonally polarized signals. The mean polarization mode dispersion (PMD) may be expressed as the average over all spans of the DLS given in picoseconds per root kilometre [b-ITU-T G-Sup.41].

9.2.6 Mean polarization dependent loss

Mean PDL is the average variation of insertion loss over all states of polarization (SoPs). The average PDL over all spans of the DLS is given in decibels.

9.2.7 Number of repeaters

The total number of repeaters for the DLS should be separated between terrestrial and submarine segments.

9.3 Optical submarine repeater specification

Optical submarine repeater (OSR) definitions are given in [ITU-T G.977]. Specifications are provided for each DLS. Specifications should include the total number of repeaters, total output powers, noise figures and information about cable monitoring channel frequencies and channel bandwidths.

9.3.1 Total output power

Each OSR contains a specified total output power in decibels relative to 1 mW. The average total output power is given for the OSRs in the submarine portion if all OSRs are identically configured.

9.3.2 Repeater noise figure

The noise figure of an OSR in decibels quantifies the decrease of the SNR at the output of an OSR [ITU-T G.661]. It may be specified at a channel frequency and OSR gain. The average noise figure across the band is given for the OSRs in the submarine portion if all OSRs are identically configured.

9.3.3 In-band monitoring channels

In-band monitoring channel(s), with a centre frequency in terahertz, are used for fault location analysis as given in [ITU-T G.977] and [ITU-T G.976].

9.3.4 In-band monitoring channel passband

Each in-band monitoring channel is allocated a spectral width in gigahertz as shown in Figure 9-4. The spectral width defines the passband associated with the monitoring channel.

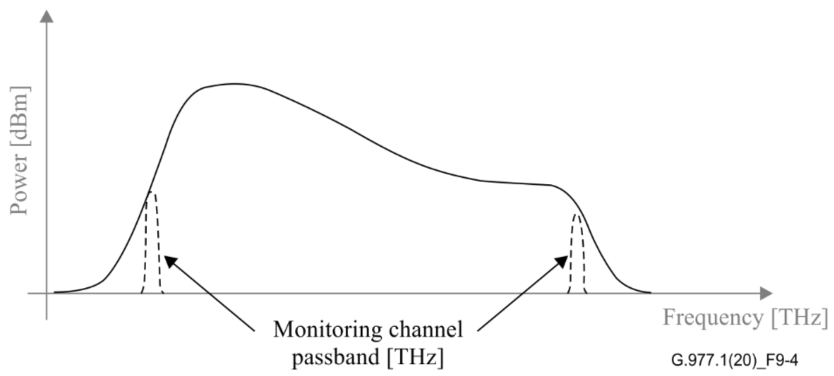

Figure 9-4 – An example of the in-band monitoring channel passbands

9.4 Branching unit specification

Branching unit (BU) and ROADM-BU definitions are given in [ITU-T G.977]. Specifications of number of BUs, losses and span locations are key parameters for the DLS.

9.4.1 Number of branching units

BUs offer fibre add or drop functions described in [b-ITU-T G-Sup.41]. The total number of BUs is counted between the landing points in a submarine cable system.

9.4.2 Branching unit loss

Each BU contains an insertion loss in decibels. The loss is specified independently of span loss.

9.4.3 Branching unit span locations

BUs exist in specific spans of a submarine cable system. The locations are nominal specifications and are subject to change during installation.

9.5 Equalizer specification

Equalizers can exist in several forms intended to shape or tilt the gain of the system. The number of gain or tilt equalizers should also be provided including their span periodicity.

9.5.1 Number of gain equalizers

The total number of active or passive gain equalizers is used to modify the optical gain evolution.

9.5.2 Gain equalizer losses

Each gain equalizer contains an insertion loss in decibels. The loss is specified independently of span loss.

9.5.3 Gain equalizer span periodicity

Gain equalizers are typically distributed equally in a submarine cable system. The locations are specified by their span periodicity. It should be noted that these are nominal specifications and are subject to change.

9.5.4 Number of tilt equalizers

The total number of tilt equalizers is used to shape the slope of the spectrum to maintain a uniform power evolution across the channels.

9.6 Fibre specification

Fibre specifications are given in [ITU-T G.978].

9.6.1 Fibre effective area

The effective area in square micrometres of the single-mode fibre [ITU-T G.650.2] is considered in the submarine cable system. If multiple fibre types exist, the effective area for each fibre should be stated.

9.6.2 Fibre chromatic dispersion

CD is the wavelength dependency of group velocity so that all spectral components of an optical signal propagate at different velocities [b-ITU-T G-Sup.41]. The CD coefficient of the fibre used in the submarine cable system is given in picoseconds per nanometre per kilometre. The CD is referenced at a reference channel frequency. If multiple fibre types exist, the dispersion for each fibre should be stated.

9.6.3 Fibre loss

The average optical fibre attenuation or loss is given in decibels per kilometre at the reference channel frequency. If multiple fibre types exist, the loss for each fibre should be stated.

9.6.4 Fibre chromatic dispersion slope

The derivative with respect to wavelength of the fibre CD is the fibre CD slope in picoseconds per square nanometre per kilometre. If multiple fibre types exist, the dispersion slope for each fibre should be stated.

9.6.5 Fibre nonlinear coefficient

The strength of optical nonlinearity induces a performance degradation on traffic-carrying channels. The Kerr effect of the fibre can be quantified with the nonlinear index n_2 in square metres per watt. The nonlinear coefficient of the fibre, in reciprocal watts is given by $\gamma = n_2/A_{eff}$, where A_{eff} is the effective area in square metres. If multiple fibre types exist, the nonlinear coefficient for each fibre should be stated.

NOTE – Measurement methods for the fibre nonlinear coefficient γ are found in [b-IEC TR 62285].

9.7 Repair guidance

[b-ITU-T G-Sup.41] recommends repair guidance.

9.7.1 Deep water

[ITU-T G.972] defines deep water.

9.7.2 Deep water repairs

The recommend guidelines for budgeting deep water repairs are one repair every 1 000 km over the lifetime of a submarine cable [b-ITU-T G-Sup.41].

9.7.3 Shallow water

[ITU-T G.972] defines shallow water.

9.7.4 Shallow water repairs

The recommend guidelines for budgeting shallow water repairs are one repair every 15 km with a minimum of five repairs over the lifetime of a submarine cable [b-ITU-T G-Sup.41].

9.7.5 Optical signal-to-noise ratio allocation for repairs

The total OSNR degradation due to allocation of deep water and shallow repairs is stated in decibels per 0.1 nm or decibels per 12.5 GHz.

10 Optical safety considerations

While this Recommendation relates to the fibre infrastructure and does not specify the characteristics of the optical transmission systems operating over it, such systems may well operate at relatively high optical power levels. Information on optical safety considerations can be found in [b-ITU-T G.664], [b-IEC 60825-1], and [b-IEC 60825-2].

Annex A

Specification of transversally compatible dense wavelength division multiplexing applications for repeatered optical fibre submarine cable systems

(This annex forms an integral part of this Recommendation.)

A.1 Introduction

This annex outlines optical specifications and technical descriptions for the characterization of a transversally compatible submarine cable system. The information provided in this annex is intended as a guide.

A.2 Key SNR performance parameters

The key measurement parameter for the interoperable cable portion is the GSNR. The GSNR on an undersea cable requires three conditions to be met:

1) the transmission line is well modelled and aligned to the Gaussian noise model;

2) the coherent optical transponders employed have a translation from Q^2 to $\mathrm{SNR}_{\mathrm{TOT}}$ and vice versa;

3) the optical transponder conforms to the following specifications:
   - modulation format: dual polarization QPSK or dual polarization 16-QAM,
   - carrier spacing for adjacent channels: ≤1.15x baud,
   - spectral shaping: root raised cosine with ≤0.1 roll-off,
   - nonlinearity compensation: disabled.

Measurements must be conducted across the usable bandwidth of the spectrum. In general, due to the frequency dependency of amplifier noise figures, scattering effects, gain shape, nonlinearity, etc., optical signals experience frequency-dependent performance variations as they propagate. This relationship with frequency also varies notably with different input power profiles, due to the power limited nature of the subsea repeater, and the frequency-dependent nature of spectral hole burning (SHB). Thus, $\mathrm{SNR}_{\mathrm{ASE}}$, $\mathrm{SNR}_{\mathrm{EXT}}$, and $\mathrm{SNR}_{\mathrm{TOT}}$ will always vary across an optical spectrum; consequently the input power profile must be carefully chosen to represent conditions of traffic-carrying channels.

Populating the entire spectrum with test transponders to conduct the $\mathrm{SNR}_{\mathrm{EXT}}$ measurement may be impractical. A minimum of three test transponders and ASE as power holders for the remainder of the optical spectrum is recommended. The ASE power holders can be continuous or channelized. The advantage of channelized ASEs is that they can also be used to measure the $\mathrm{SNR}_{\mathrm{ASE}}$. Figure A.2-1 shows the measurement configuration for an $\mathrm{SNR}_{\mathrm{EXT}}$ measurement.

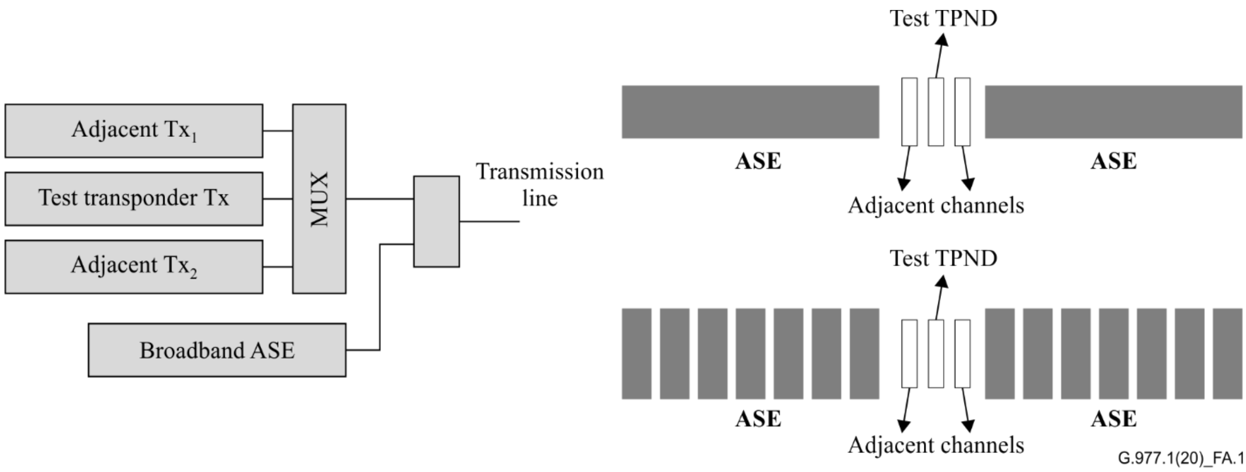

Figure A.1 – Configuration of the channel plan used to measure SNR_{EXT} or GSNR

Figure A.2-2 is an illustration of the different SNR contributions. The left plot represents the back-to-back performance of the test transponder (Test TPND), while the right plot represents the propagated performance curve. The total SNR_{TOT} is a conversion from Q assuming condition 2 whereby the design of the modem permits a translation between the two quantities. For example, a QPSK modem satisfies the relationship $Q = \sqrt{\mathrm{EC} \cdot \mathrm{SNR_{TOT}}}$ [b-ITU-T G-Sup.41] and 16-QAM satisfies $Q = \sqrt{2}\mathrm{erfc}^{-1}\left[\frac{3}{4}\mathrm{erfc}\left(\sqrt{2 \cdot \mathrm{EC} \cdot \mathrm{SNR_{TOT}}/5}\right)\right]$.

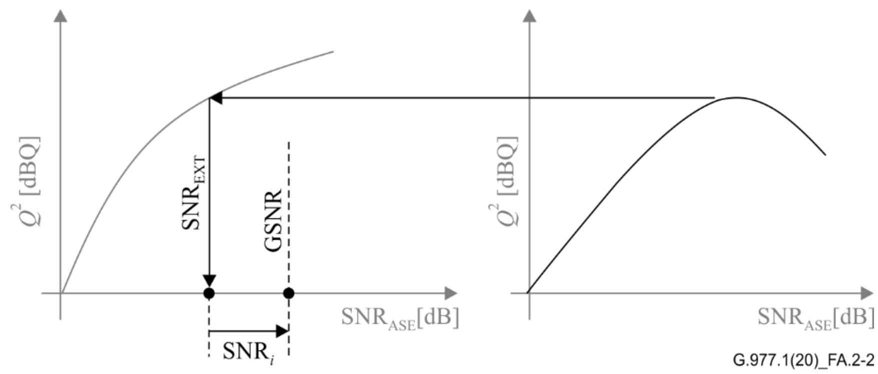

Figure – A.2 – Measurement of Q^2, SNR_{EXT} and GSNR

Standardized techniques for the measurement of SNR_i, are still under study. Current methods typically utilize simulated or laboratory-based measurements to estimate SNR_i.. GSNR is found by the difference in reciprocals of SNR_{EXT} and SNR_i as described in clause 9.1.12:

$$\frac{1}{\mathrm{GSNR}} = \frac{1}{\mathrm{SNR_{EXT}}} - \frac{1}{\mathrm{SNR}_i}$$

A.3 Key design specifications

There are many optical specifications that may be considered in the design phase that cannot be directly measured on system commissioning. Effective area of fibre, fibre loss, repeater noise figure, per repeater gain profile, etc., cannot be directly measured via end-to-end system commissioning, but are each one of several parameters that contribute to the measurable parameters, such as OSNR and GSNR. As such, a set of optical parameters that describe the key parameters that contribute to overall optical performance should be specified and agreed during the system design phase. This set of parameters is often requested and provided in the form of a key parameter table. A particularly important use for these parameters, is that they should provide, at a minimum, the key values required for a terminal transmission equipment (TTE) provider to model and estimate system capacity. A proposed key parameter table for modelling estimation in advance of cable commissioning is Table A.1.

Assumptions and any relevant information for all parameters should be provided, such as cable systems that utilize more than one wavelength band as specified in clause 8.3 should state any wavelength dependence. Cable systems incorporating any terrestrial or land segments should have their parameters stated based on [ITU-T G.696.1] and [b-ITU-T G-Sup.39].

Table A.1 – Key parameter table

DLS	**Site A to site B**
Fibre pair number	**Z**
1 Commissioning parameters	
1.1 SNR_{ASE} [dB] (under agreed equalization conditions)	
1.2 GSNR [dB] (under agreed equalization conditions)	
1.3 Slope of tilt [dB THz^{-1}] (under agreed equalization conditions)	
1.4 Max gain deviation [dB] (under agreed equalization conditions)	
2 System specification	
2.1 System length [km]	
2.2 Nominal span length [km]	
2.3 Span loss [dB]	
2.4 Accumulated chromatic dispersion [ps nm^{-1}]	
2.5 Mean PMD [ps $km^{-½}$]	
2.6 Mean PDL [dB]	
2.7 Number of repeaters	
3 Repeater specification	
3.1 Repeater TOP [dBm]	
3.2 Repeater noise figure [dB]	
3.3 Repeater gain [dB]	
3.4 Data passband [GHz]	
4 Fibre specification	
4.1 Fibre effective area [μm^2]	
4.2 Fibre chromatic dispersion coefficient @ 1 550 nm [ps /nm^{-1} km^{-1}]	
4.3 Fibre loss (cabled) [dB km^{-1}]	
4.4 Fibre chromatic dispersion slope @ 1 550 nm [ps /nm^{-2} km^{-1}]	
4.5 Fibre nonlinear coefficient [W^{-1}]	
5 Repair and aging assumptions (BOL to EOL*)*	
5.1 Total SNR_{ASE} penalty for repairs and aging [dB]	

Table A.1 – Key parameter table

DLS	**Site A to Site B**
Final system design details	
Branching unit loss [dB]	
Shape equalizer insertion loss [dB]	
Tilt equalizer loss [dB]	

A description of each parameter is as follows:

1) Commissioning parameters determine the design parameters to be validated.

Row 1.1 The average SNR_{ASE} of the channels as specified in [b-ITU-T G-Sup.41] and clause 9.1.7. The SNR_{ASE} stated may be different to row A of the power budget table [ITU-T G.977] due to pre-emphasis.

Row 1.2 The average GSNR of the channels as described in clause 9.1.12.

Row 1.3 The slope of tilt determines by how many decibels per terahertz the spectrum is tilted. An example of slope of tilt is shown in clause 9.1.3.

Row 1.4 The gain deviation determines the maximum difference of the power of a channel at the receiver relative to the transmitter in decibels.

2) System specifications determine the end-to-end propagation characteristics.

Row 2.1 System length is total end-to-end propagation length of the interoperable cable portion.

Row 2.2 Nominal span length is the span length in kilometres. Individual span lengths may be requested.

Row 2.3 Nominal span loss is the total loss per span in decibels at the reference channel frequency. Losses on a per span basis may be requested.

Row 2.4 The total accumulated CD in picoseconds per nanometre as defined in [b-ITU-T G-Sup.39] is quoted at the reference channel frequency.

Row 2.5 Mean PMD is the average polarization mode dispersion over all spans of the DLS in picoseconds per root kilometre [b-ITU-T G-Sup.41].

Row 2.6 Mean PDL is the average value over all spans of the DLS in decibels [b-ITU-T G-Sup.41].

Row 2.7 The total number of repeaters for the DLS.

3) Repeater specifications include OSR characteristics as given in [ITU-T G.977].

Row 3.1 The average total output power of the repeaters in decibels relative to 1 mW.

Row 3.2 The average noise figure of the repeaters in decibels.

Row 3.3 The average optical gain of the repeaters in decibels.

Row 3.4 The data passband determines the operating wavelength range [ITU-T G.671] that supports traffic-carrying channels. The passband is typically measured over the received spectrum in terahertz. The passband is defined at the −3 dB edge in the first blue (Start) and last red (Stop) channel at a specified power per channel (see Figure 9-1).

4) Fibre specifications of the spans are manufacturer parameters.

Row 4.1 Average fibre effective area across all spans in square micrometres [ITU-T G.650.2]. If different fibre types exist, effective areas for each type should be specified.

Row 4.2 Fibre CD coefficient at the reference wavelength should be specified for the different fibre types in picoseconds per nanometre per kilometre.

Row 4.3 Fibre loss at the reference wavelength should be specified for the different fibre types in decibels per kilometre.

Row 4.4 The fibre CD slope is the rate of change or derivative of the fibre CD in row 4.2 with respect to wavelength.

Row 4.5 The fibre nonlinear coefficient should be specified at the reference frequency for the different fibre types in reciprocal watts.

5) Repair guidance as given in [ITU-T G.977] and [b-ITU-T G-Sup.41] may be different depending on the repair margins of the system. These specifications should be stated.

Row 5.1 Total SNR_{ASE} penalty allocated for the life of the system.

A.4 Key measurement specifications

The final commissioning of a system will reveal significantly more detail than can be defined in advance with respect to frequency dependence of parameters like SNR_{ASE}, SNR_{EXT} and GSNR. As such, there is value in this detail that is desired for TTE vendors to model the capacity potential of a system. Additionally, more detailed information is relevant in ongoing monitoring of a system, for identification of system changes as a result of aging, failures, or repairs, to enable informed decisions on system maintenance. The additional recommended information, beyond that specified in the key parameters table, should be collected at system commissioning for the purposes of system modelling and ongoing system monitoring. The number of channels tested should be agreed between supplier and operator. An example of the information to be collected is shown in Table A.2; values of whose parameters should be agreed between the operator and supplier.

Table A.2 – Key measurement specifications

DLS	**Site A to Site B**
Fibre pair number	**Z**
	Measured
Measured performance parameters and key inputs (flat Tx)	
Number of channels	Provided as attachment. Include all measurement conditions & calculations.
Tx power [dBm] per channel vs frequency	
Rx power [dBm] per channel vs frequency	
SNR_{ASE} [dB] vs frequency	
Gain [dB] vs frequency	
Measured performance parameters and key inputs (equalized)	
Number of channels	Provided as attachment. Include all measurement conditions and calculations.
Tx power [dBm] per channel vs frequency	
Rx power [dBm] per channel vs frequency	
SNR_{ASE} [dB] vs frequency	
GSNR [dB] vs frequency	

Collection of additional information may be desired based on specific system features, such as guard bands introduced by wavelength selective switch (WSS) reconfigurable optical add drop multiplexers (ROADMs) in various configurations. These should be addressed on a case-by-case basis.

There are also certain system characteristics that may be measured by a modem today, such as accumulated CD, PMD, PDL and time-varying system penalties (TVSPs), some of which require a statistical distribution of data to calculate, thus necessitating a stability test. A third party test measurement tool can also be used to characterize these elements.

A.5 Commissioning specifications

The commissioning specifications determine the commissioning targets in terms of SNR_{ASE} and GSNR. The interoperable cable budget begins with the nominal design, accounting for penalties to achieve the realizable GSNR of the submarine portion. SNR_{ASE} and GSNR may be defined within the channel spacing (C).

$$\mathrm{SNR}_{\mathrm{ASE}} = \frac{B_0}{C}\mathrm{OSNR}_{\mathrm{ASE}}$$

where B_0 is the optical bandwidth (typically 12.5 GHz or 0.1 nm at 1 550 nm) and C is the carrier spacing in gigahertz. Similarly, GOSNR can be scaled to GSNR.

See Table A.3.

Table A.3 – Interoperable cable budget

		SNR_{ASE} dB	**GSNR dB**
1	Design (submarine portion)		
2.1	Guided acousto-optic wave Brillouin scattering (GAWBS)		
2.2	Impairment due to ROADM (submarine portion)		
2.3	Impairment due to terrestrial extension or unrepeatered branch		
2.4	Generalized droop		
3	**Nominal (system)**		
4	Manufacturing margin		
5	**Flat launch average system**		
6	Pre-emphasis margin		
7	**BOL average system** (under agreed equalization conditions)		
8	BOL worst case		
9	Aging and repairs		
10	**EOL average system** (under agreed equalization conditions)		
11	EOL worst case		

A description of each parameter is as follows.

Row 1: The design SNR_{ASE} and GSNR of the submarine portion, averaged across the band.

Row 2.1: The GSNR impairment due to GAWBS as described in clause 9.1.9.

Row 2.2: SNR_{ASE} impairment from any ROADMs in the submarine portion.

Row 2.3: Impairments arising from the terrestrial extensions or any unrepeatered branch. This accounts for the GSNR when defined for a DLS and not solely the submarine portion.

Row 2.4: Droop impairments in SNR_{ASE} due to noise accumulation from the EDFAs with fixed output power. The droop impairment in GSNR is determined by the generalized droop formula. See clause 9.1.6.

Row 3: The nominal SNR_{ASE} and GSNR on row 3 for the system uses rows 1 to 2.4 in the generalized droop formula in clause 9.1.12.

Row 4: The manufacturing margin provides allocation for normal product fluctuations due to the manufacturing process, marine operations and environmental conditions.

Row 5: This is the system average SNR_{ASE} under flat launch conditions at beginning-of-life (BOL). Row 5 SNR_{ASE} is given by subtracting row 4 from row 3.

Row 6: Represents the SNR_{ASE} impairment from using transmitter pre-emphasis to equalize performance using the agreed upon equalization scheme.

Row 7: Represents the average SNR_{ASE} after equalization has been applied. The row 7 SNR_{ASE} is calculated by subtracting row 6 from row 5. This represents the commissioning limit for the average equalized performance at BOL. The row 7 GSNR is deduced using the generalized droop formula with the row 3 GSNR and row 7 $SNR_{ASE.}$

Row 8: This is the allowance for spectral variation of performance across the band. The values correspond to the worst case SNR_{ASE} and GSNR across the band after equalization.

Row 9: Represents the SNR_{ASE} penalty due to aging and repairs of the interoperable cable portion.

Row 10: Represents the average SNR_{ASE} after equalization has been applied under end-of-life (EOL) conditions. Row 10 SNR_{ASE} is calculated by subtracting row 9 from row 7. The row 10 GSNR is deduced using the generalized droop formula with the row 7 GSNR and row 10 $SNR_{ASE.}$

Row 11: This is the allowance for spectral variation of performance across the band. The values correspond to the worst case SNR_{ASE} and GSNR across the band after equalization under EOL conditions.

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