International Telecommunication Union

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

Series G

Supplement 41

(05/2005)

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

Design guidelines for optical fibre submarine cable systems

ITU-T G-series Recommendations – Supplement 41

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Supplement 41 to ITU-T G-series Recommendations

Design guidelines for optical fibre submarine cable systems

Summary

This supplement describes design considerations for repeatered, repeaterless and optically amplified systems supporting SDH and OTN signals in optical submarine cable systems. In particular, this supplement focuses on the specific matters relevant to the optical fibre submarine cable systems.

This supplement also describes a common way of thinking of the requirements for designing the optical fibre submarine cable systems and aims of consolidating and expanding on materials related to several Recommendations, including G.971, G.972, G.973, G.974, G.975, G.975.1, G.976 and G.977.

Source

Supplement 41 to ITU-T G-series Recommendations was agreed on 27 May 2005 by ITU-T Study Group 15 (2005-2008).

FOREWORD

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1 Scope

This supplement describes design considerations for repeatered, repeaterless and optically amplified systems supporting SDH and OTN signals in optical submarine cable systems. In particular, this supplement focuses on the specific matters relevant to the optical fibre submarine cable systems.

This supplement also describes a common way of thinking of the requirements for designing the optical fibre submarine cable systems and aims at consolidating and expanding on materials related to several Recommendations, including G.971, G.972, G.973, G.974, G.975, G.975.1, G.976 and G.977.

This supplement should also allow a reader to better understand the specifications in the fibre, components, and system interface Recommendations currently developed respectively in Questions 5, 7 and 8 of ITU-T Study Group 15. This supplement should not prevent technical development relevant to the optical fibre cable systems technologies.

2 References

2.1 General references

The following ITU-T Recommendations and other references are quoted in this supplement.

– ITU-T Recommendation G.650.1 (2004), *Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable.*

– ITU-T Recommendation G.650.2 (2005), *Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable*.

– ITU-T Recommendation G.652 (2005), *Characteristics of a single-mode optical fibre and cable*.

– ITU-T Recommendation G.653 (2003), *Characteristics of a dispersion-shifted single-mode optical fibre and cable*.

– ITU-T Recommendation G.654 (2004), *Characteristics of a cut-off shifted single-mode optical fibre and cable*.

– ITU-T Recommendation G.655 (2003), *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable*.

– ITU-T Recommendation G.656 (2004), *Characteristics of a fibre and cable with non-zero dispersion for wideband optical transport*.

– ITU-T Recommendation G.661 (1998), *Definition and test methods for the relevant generic parameters of optical amplifier devices and subsystems*.

– ITU-T Recommendation G.663 (2000), *Application related aspects of optical amplifier devices and subsystems*.

– ITU-T Recommendation G.671 (2005), *Transmission characteristics of optical components and subsystems*.

– ITU-T Recommendation G.691 (2003), *Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers*.

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

– ITU-T Recommendation G.693 (2005), O*ptical interfaces for intra-office systems*.

– ITU-T Recommendation G.694.1 (2002), S*pectral grids for WDM applications: DWDM frequency grid*.

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

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

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

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

– ITU-T Recommendation G.957 (1999), *Optical interfaces for equipments and systems relating to the synchronous digital hierarchy*.

– ITU-T Recommendation G.959.1 (2003), *Optical transport network physical layer interfaces*.

– ITU-T Recommendation G.971 (2004), *General features of optical fibre submarine cable systems*.

– ITU-T Recommendation G.972 (2004), *Definition of terms relevant to optical fibre submarine cable systems*.

– ITU-T Recommendation G.973 (2003), *Characteristics of repeaterless optical fibre submarine cable systems*.

– ITU-T Recommendation G.974 (2004), *Characteristics of regenerative optical fibre submarine cable systems*.

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

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

– ITU-T Recommendation G.976 (2004), *Test methods applicable to optical fibre submarine cable systems*.

– ITU-T Recommendation G.977 (2004), *Characteristics of optically amplified optical fibre submarine cable systems*.

– ITU-T G-series Recommendations – Supplement 39 (2003), *Optical system design and engineering considerations*.

– IEC/TR 61282-3 (2002), *Fibre optic communication system design guides – Part 3: Calculation of polarization mode dispersion*.

– IEC/TR 62380 (2004), *Reliability data handbook – Universal model for reliability prediction of electronics components, PCBs and equipment*.

2.2 References in clauses 6, 7 and 9

[1] ZSAKANY (J.C.), MARSHALL (N.W.), ROBERTS (J.M.), ROSS (D.G.): The Application of Undersea Cable Systems in Globe Networking, *AT&T Technical Journal*, Vol. 74, No.1, pp.8-15, January/February 1995.

[2] O'MAHONY (M.J.), SPIRIT (D.M.): High Capacity Optical Transmission Explained, *John Wiley & Sons*, 1995.

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3 Terms and definitions

Formal definitions are found in the primary Recommendations.

4 Abbreviations and acronyms

This supplement uses the following abbreviations:

3R	Regeneration of power, shape, and timing
ASE	Amplified Spontaneous Emission
BER	Bit-Error Ratio
BOL	Beginning of Life
BU	Branching Unit
COTDR	Coherent Optical Time Domain Reflectometry
CSF	Cut-off Shifted single mode Fibre
CWDM	Coarse Wavelength Division Multiplexing
DGD	Differential Group Delay
DLS	Digital Line Section
DPSK	Differential Phase Shift Keying
DSF	Dispersion Shifted single mode Fibre
DWDM	Dense Wavelength Division Multiplexing
DWDMS	Dense Wavelength Division Multiplexing System
EDF	Erbium Doped Fibre
EOL	End of Life
ER	Extinction Ratio
FEC	Forward Error Correction

FIT	Failure In Time
FWM	Four-Wave Mixing
IrDI	Inter-Domain Interface
LOC	Line Optical Channel
MPI-R	Multi-Path Interface at the Receiver
MPI-S	Multi-Path Interface at the Source
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NDSF	Non-Dispersion Shifted single mode Fibre
NF	Noise Figure
NRZ	Non Return to Zero
NZDSF	Non-Zero Dispersion Shifted single mode Fibre
OA	Optical Amplifier
OD	Optical Demultiplexer
OFA	Optical Fibre Amplifier
OM	Optical Multiplexer
OOK	On-Off Keying
OSNR	Optical Signal-to-Noise Ratio
OSR	Optical Submarine Repeater
OTDR	Optical Time Domain Reflectometry
OTN	Optical Transport Network
PDG	Polarization-Dependent Gain
PDL	Polarization-Dependent Loss
PFE	Power Feeding Equipment
PHB	Polarization Hole Burning
PMD	Polarization Mode Dispersion
R	Single channel optical interface point at the Receiver
RX	(optical) Receiver
RZ	Return to Zero
S	Single channel optical interface at the Source
SDH	Synchronous Digital Hierarchy
SOP	State of Polarization
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
SWS	Single Wavelength System
TS	Terminal Station
TTE	Terminal Transmission Equipment

TX (optical) Transmitter

WDM Wavelength Division Multiplexing

WDMS Wavelength Division Multiplexing System

XPM Cross-Phase Modulation

5 Parameters of system elements

5.1 Transmitter parameters

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

5.1.1 System operating wavelength range

The operating wavelength ranges for single-channel SDH systems up to 10 Gbit/s are given in ITU-T Recs G.691 and G.957. The operating wavelength ranges for single-channel and multi-channel IrDIs up to 40 Gbit/s are defined in ITU-T Rec. G.959.1. Other applications may use different wavelength bands and ranges within bands as defined in this supplement.

5.1.2 Spectral characteristics

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

5.1.3 Maximum spectral width of SLM sources

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

5.1.4 Maximum spectral width of MLM sources

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

5.1.5 Chirp

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

5.1.6 Side-mode suppression ratio

The side-mode suppression ratio of a single longitudinal mode optical source is defined in ITU-T Recs G.957, G.691 and G.959.1. Values are given for SDH and OTN IrDI systems up to 40 Gbit/s.

5.1.7 Maximum spectral power density

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

5.1.8 Maximum mean channel output power

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

5.1.9 Minimum mean channel output power

This property of a multi-channel optical signal is specified and defined in ITU-T Rec. G.959.1.

5.1.10 Central frequency

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

5.1.11 Channel spacing

Channel spacing is defined in ITU-T Rec. G.694.1 for DWDM as well as ITU-T Rec. G.694.2 for CWDM. A complete classification of WDM systems is in ITU-T Rec. G.671.

5.1.12 Maximum central frequency deviation

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

5.1.13 Minimum extinction ratio

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

5.1.14 Eye pattern mask

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

5.1.15 Polarization

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

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

This value gives the ratio of optical signal power relative to optical noise power of an optical transmitter in a given bandwidth coupled into the transmission path.

5.2 Submarine cable parameters

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

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

The relevant specifications as well as implementation related aspects of the optical fibre submarine cables are given in ITU-T Recs G.973, G.974 as well as G.977 respectively.

5.2.1 Classification of the submarine cable

5.2.1.1 Classification based on application

An underwater optical fibre cable can be:

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

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

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

5.2.1.2 Classification based on cable protection

The optical fibre submarine cable should provide protection against the environmental hazards at its depth of utilization: protection against marine life, fish-bite and abrasion, and armours against aggression and ship activities. Different types of protected cable are defined in ITU-T Rec. G.972, in particular:

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

5.2.1.3 Classification based on fibre protection by the cable structure

The strength of the cable structure together with that of the fibre determine the overall cable mechanical behaviour. They should be designed so as to guarantee the system design life, taking into account the cumulative effect of load applied to the cable during laying, recovery and repair, as well as any permanent load or residual elongation applied to the installed cable.

Two generic types of cable structure are commonly used to protect the optical fibres:

- The tight cable structure, where the fibres are strongly maintained in the cable, so that the fibre elongation is essentially equal to that of the cable;
- The loose cable structure, where the fibres are free to move inside the cable, so that the fibre elongation is lower than that of the cable, staying zero until the cable elongation reaches a given value.

5.2.2 Transmission parameters of fibre in a submarine cable

Generally, the transmission characteristics of the fibres before cabling (installation in the cable) will be similar to, or the same as, those specified in ITU-T Recs G.652, G.653, G.654, G.655 and G.656. Types of fibre are chosen to optimize the system overall cost and performance.

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

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

The main parameters that characterize an optical fibre are:

- the attenuation coefficient at all the operating wavelengths expressed in dB/km;
- the chromatic dispersion coefficient at all the operating wavelengths in ps/nm.km;
- the zero dispersion wavelength λ_0 in nm;
- the dispersion slope around the operating wavelengths in ps/nm^2.km;
- the non-linear refractive index n_2 in m^2/W;

- the effective area A_{eff} in μm^2;
- the non-linear coefficient n_2/A_{eff} in W^{-1};
- the ensemble average polarization mode dispersion (PMD) in ps/(km)^{½}.

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

- Non-Dispersion Shifted single mode Fibre (NDSF) defined in ITU-T Rec. G.652.
- Dispersion Shifted single mode Fibre (DSF) defined in ITU-T Rec. G.653.
- Cut-off Shifted single mode Fibre (CSF) defined in ITU-T Rec. G.654.
- Non-Zero Dispersion Shifted single mode Fibre (NZDSF) defined in ITU-T Recs G.655 and G.656.
- Dispersion Compensation single mode Fibre (DCF).
- Negative dispersion slope fibre.
- Very large effective area fibre.

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

5.2.2.1 Fibre loss

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

5.2.2.2 Fibre non-linearity

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

5.2.2.3 Polarization Mode Dispersion (PMD)

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

5.2.2.4 Chromatic dispersion

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

5.2.3 Fibre mechanical parameters

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

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

5.2.4 Cable mechanical parameters

The cable, with the cable jointing boxes, the cable couplers, and the cable transitions, should be handled with safety by cable ships during laying and repair operation; it should withstand multiple passages over the bow of a cable ship.

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

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

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

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

5.2.5 Cable electrical parameters

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

5.2.6 Factory length of the submarine cable

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

5.2.7 Physical parameters of the submarine cable

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

5.2.8 Repair cable

Repair cable is used when submarine cable is broken or damaged. The repair cable should be in accordance with the cable to be repaired as for optical characteristics, electronic characteristics, and mechanical characteristics.

5.3 Submarine repeater parameters

For submarine repeaters parameters, refer to ITU-T Recs G.974 and G.977.

5.3.1 Repeater types

There are three types of repeaters:

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

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

5.3.2 Parameters of the optical repeater with 3R electrical regeneration

5.3.2.1 Optical parameters

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

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

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

5.3.2.2 Jitter parameters

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

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

5.3.3 Parameters of the optical repeater with EDF amplification

5.3.3.1 Optical parameters

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

- Small Signal Gain (SSG);
- Nominal Gain (NG);
- Noise Figure (NF);
- Nominal Signal Output Power (NSOP);
- Nominal Signal Input Power (NSIP);
- Compression Factor (CF);

- Minimum repeater mean input power (dBm);
- Minimum repeater mean output power (dBm);
- Jitter performance;
- Phase shifter performance.

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

- Gain Flatness (GF).

5.3.3.2 Polarization effects

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

5.3.4 Parameters of the optical repeater with Raman amplification

For further study.

5.3.5 Mechanical parameters of repeater

5.3.5.1 Repeater housing

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

Technical design considerations of the repeater housing are as follows:

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

5.3.5.2 The internal unit

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

5.3.5.3 Corrosion protection

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

5.3.5.4 Water pressure resistance

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

5.3.5.5 High-voltage insulation

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

5.3.5.6 Thermal management

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

5.3.5.7 Repeater housing sealing

The repeater must be provided with a protection against water and gas ingress, both directly from the surrounding sea and from axial cable leakage resulting from a cable break close to the repeater.

5.3.5.8 Ambient atmosphere control

Reliability and proper operation of components may require a controlled internal atmosphere regarding relative humidity or any expected gas that may be generated inside the repeater.

5.3.6 Electrical parameters of repeater

5.3.6.1 Power modules

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

5.3.6.2 Surge protection

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

5.4 Cable joint parameters

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

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

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

5.4.1 Optical parameters

5.4.1.1 Splice loss

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

5.4.2 Mechanical parameters

5.4.2.1 Strength

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

5.4.2.2 Tensile strength

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

5.4.2.3 Corrosion protection

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

5.4.2.4 Water pressure resistance

The joint must be designed to support large pressure strengths.

5.4.2.5 Joint sealing

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

5.4.2.6 Bend characteristic

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

5.4.3 Electrical parameters

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

5.4.3.1 High-voltage insulation

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

5.4.4 Physical parameters

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

5.5 Receivers parameters

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

5.5.1 Sensitivity

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

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

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

5.5.2 Overload

Receiver overload definition and values for SDH single-channel systems up to 10 Gbit/s are defined in ITU-T Recs G.957 and G.691. Overload definition and values for SDH and OTN IrDI receivers up to 40 Gbit/s are defined in ITU-T Rec. G.959.1.

5.5.3 Minimum mean channel input power

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

5.5.4 Maximum mean channel input power

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

5.5.5 Optical path penalty

Optical path penalty definition and values for SDH single-channel systems up to 10 Gbit/s are defined in ITU-T Recs G.957 and G.691. Path penalty definition and values for both single and multi-channel OTN IrDI receivers up to 10 Gbit/s are defined in ITU-T Rec. G.959.1. Path penalty definitions and values for single-channel SDH and OTN IrDI receivers up to 40 Gbit/s are also defined in ITU-T Rec. G.959.1.

5.5.6 Maximum channel input power difference

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

5.5.7 Minimum OSNR at receiver input

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

6 Optical network topology

The types of optical network topology for optical fibre submarine cable systems are point-to-point, star, branched star, trunk and branch, festoon, ring and branched ring. This clause is based on information given in [1].

6.1 Point to point

This configuration (Figure 6-1) consists of direct submarine link between two Terminal Transmission Equipments (TTE) located in two different Terminal Stations (TS).

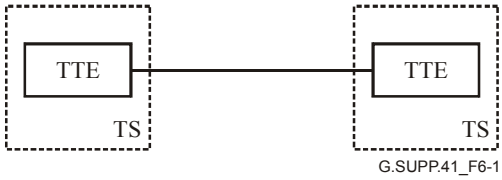


Figure 6-1 – Topology of point to point

6.2 Star

This configuration (Figure 6-2) consists of a main terminal station (TS) that links several other TSs with separate cables. In the basic star configuration, traffic is directly transmitted from TTEs of the main TS to the TTE of the other TSs independently. Therefore, the star network requires a separate cable for each TS that leads to a relatively costly configuration, particularly when TSs are geographically distant.

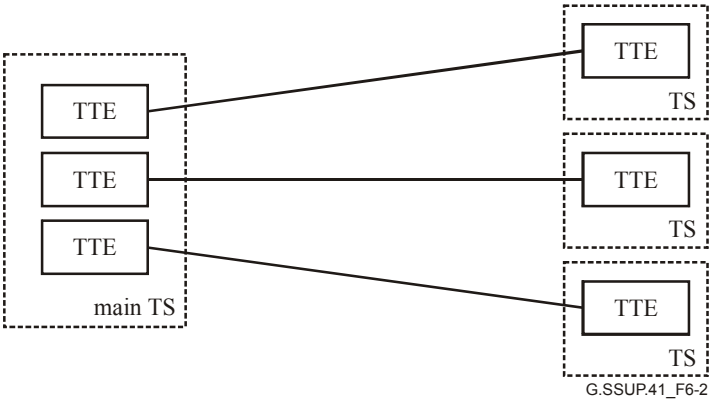


Figure 6-2 – Topology of star

6.3 Branched star

This configuration (Figure 6-3) provides the same capacity as the basic star, except that the splitting of traffic is done underwater, minimizing the cost of separate cable between remotely located TSs. Splitting of traffic is accomplished with a branching unit (BU) that interconnects the fibres of a single trunk cable with separate fibres inside two or more branches.

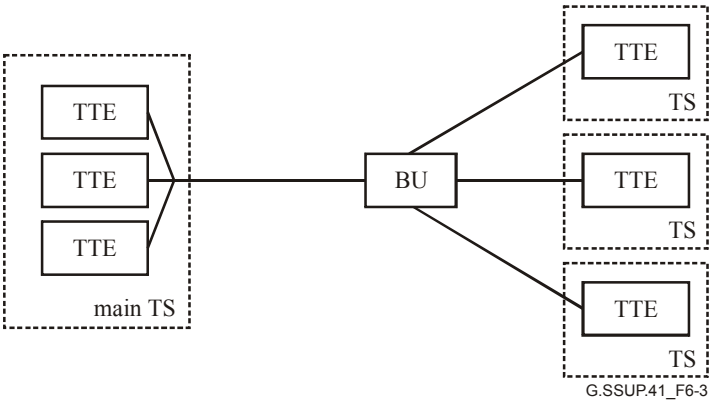


Figure 6-3 – Topology of branched star

6.4 Trunk and branch

This configuration (Figure 6-4) connects several TSs including TTEs to a single trunk cable by means of branching units that allow the extraction of a part of the traffic in the direction of the TSs of the branches.

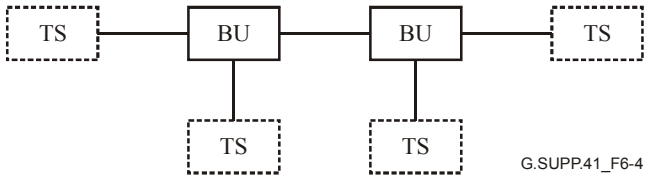


Figure 6-4 – Topology of trunk and branch

6.5 Festoon

The festoon (Figure 6-5) is basically a series of loops between major coastal landing points, and it is often deployed – though not always – as a repeaterless system. In anticipation of a future increased capacity requirement, these repeaterless applications are typically engineered with higher-fibre-count cables than those required for initial service. Thus, in the case of a need of additional capacity, terminal equipments are the only additional investments required. The architecture of a festoon frequently mirrors that of a typical, land-based installation. Such architecture may often be used as a supplemental, diverse route to an existing land-based system. This configuration is an increasingly popular alternative to a land-based system, especially when the continental terrain provides difficult installation and maintenance challenges.

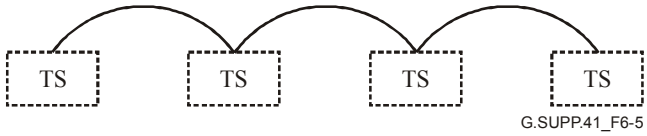


Figure 6-5 – Topology of a festoon

6.6 Ring

The ring configuration (Figure 6-6) is essentially a set of connected, point-to-point cables having twice the requisite transmission capacity. In case any single failure occurs within the ring, such as a cable cut, traffic is routed around the ring – away from the inoperable segment – and on to its original destination. Shore-based transmission equipment provides automatic failure detection and switchover control for the entire ring without dropping a call.

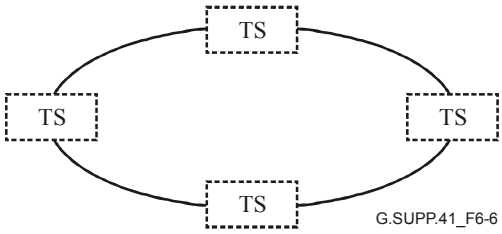


Figure 6-6 – Topology of a ring

6.7 Branched ring

This configuration (Figure 6-7) extends the basic capability of the ring in a cost-effective manner with the addition of a branching unit. The branched-ring structure retains the self-healing nature of the ring. The branched ring, then, can be thought of as a merger between the trunk-and-branch and the ring, retaining most of the benefits of each. This configuration can be made in a number of ways, including hook-up through other networks. With proper planning, a network can be installed as a trunk-and-branch arrangement and upgraded later to a branched ring.

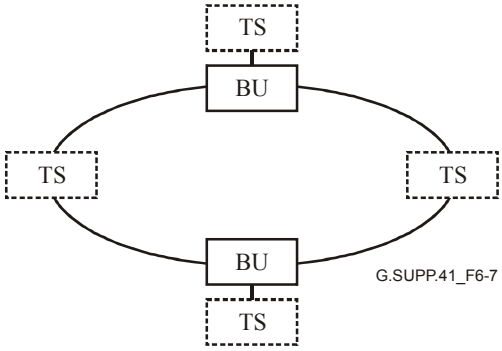


Figure 6-7 – Topology of a branched ring

7 System design considerations

7.1 Optical power budget

Optical power budget, as defined in ITU-T Rec. G.976, is a contractual performance budget which guarantees the system performance to be better than the minimum required BER performance defined in ITU-T Recs G.826 and/or G.828.

The optical power budget starts from a simple linear quality factor (Q factor) which only takes into account degradation due to the ASE noise of amplifiers (*mean Q*). Then, the optical power budget allocates the penalties/impairments for all types of degradation (due to the transmission, due to terminal equipments, etc.). The degradation is estimated using a combination of theoretical analysis, computer simulations and direct measurements on experimental test-beds.

For each submarine Digital Line Section, it is recommended to establish two distinct power budgets, one at the Beginning of Life (BOL) and another one at the End Of Life (EOL):

- The BOL power budget provides the worst-case digital line section performance which will be measured during the commissioning.
- The EOL power budget provides the estimated worst-case digital line section performance at the end of system life and includes margins for ageing, internal failures and specified repair margins.

The EOL margin is the difference between the worst Q factor estimated at the end of system life and the minimum Q factor needed to satisfy the required transmission performance. In addition, the optical power budget should clearly show the minimum Q factor required to obtain the specified error performance of the system and include margin improvement provided by the use of FEC (if applicable). (See Figure 7-1.)

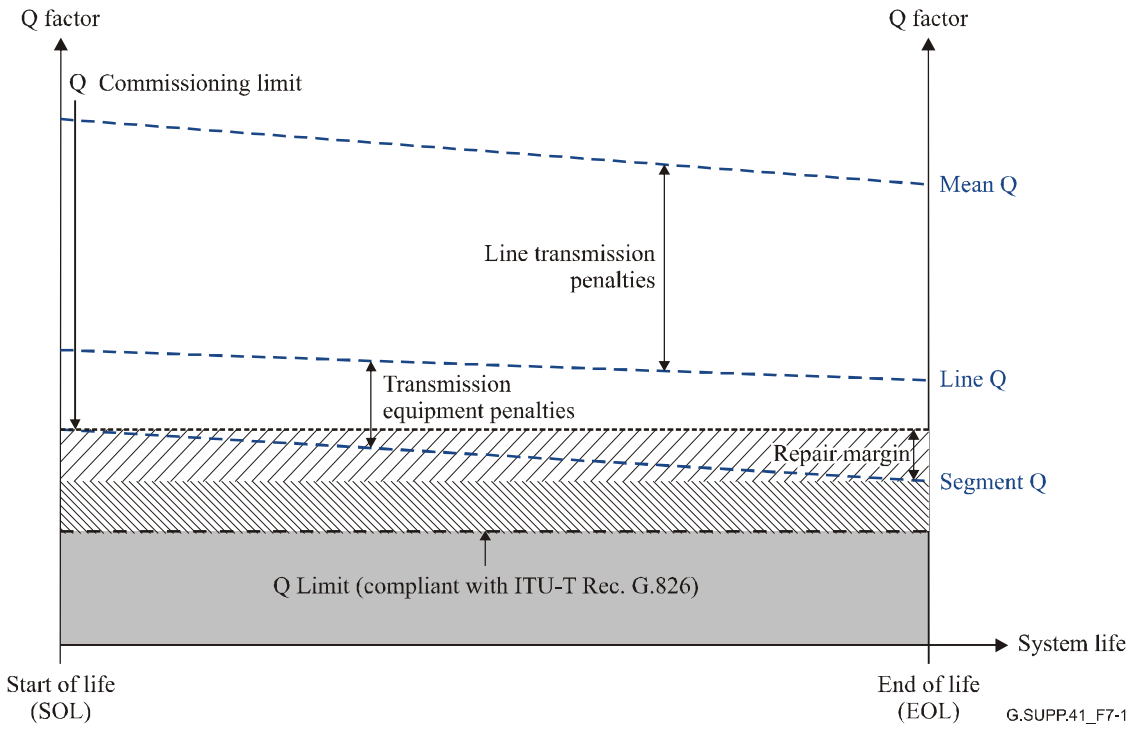


Figure 7-1 – Power Budget structure example

7.1.1 Quality factor (Q factor)

The Optical Power Budget table of a submarine Digital Line Section uses Q factors as described in Annex A/G.977 and is expressed in decibels. The following text is based on Supplement 39 to ITU-T G-series Recommendations and it is reproduced here for the benefit of the reader.

The Q factor is the signal-to-noise ratio at the decision circuit in voltage or current units, and is defined by:

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

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

Since practical Q factor estimation techniques make measurements in the upper and lower regions of the received "eye" in order to infer the quality of the signal at the optimum decision threshold, Q can be considered as only a qualitative indicator of the actual BER.

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

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

where:

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

A commonly used approximation for this function is:

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

for $Q > 3$ (Gaussian assumption).

An alternative expression that gives accurate values over the whole range of Q [2] is given in:

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

A graph showing these two approximations for Q-values lower or equal to 5 is given in Figure 7-2.

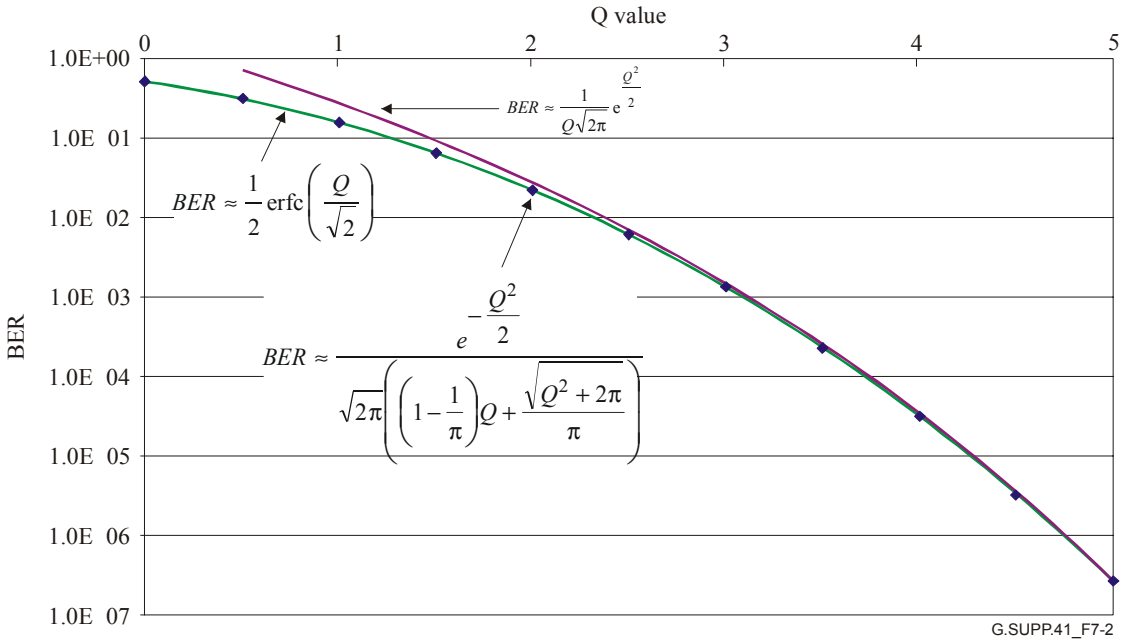


Figure 7-2 – Approximations relating BER and Q

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

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

The performances of a submarine Digital Line Section should be characterized by the measurement of its Q factor or by a direct BER measurement that should meet the contractual Q factor commissioning limits indicated in the Optical Power Budget.

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

7.1.2 Relevant parameters for Optical Power Budget

According to ITU-T Rec. G.977, it is recommended that the Optical Power Budget takes into account, as a minimum, the impairments arising from the following effects and considerations:

- Optical noise accumulation (see 7.1.3) → Mean Q factor calculation.
- Propagation impairments (see 7.1.4) → Line Q factor calculation.
  - Propagation impairments due to the combined effects of chromatic dispersion and non-linear effects (self-phase modulation, cross-phase modulation, four-wave mixing effects between line optical channels, stimulated Raman scattering, etc.) (see 7.1.4.1);
  - Propagation impairments due to optical polarization effects such as Polarization Mode Dispersion (PMD), Polarization Dependent Loss (PDL), Polarization Dependent Gain (PDG). As these impairments fluctuate with time, a distinct provision should be taken for performance variations with time (see 7.1.4.2);
  - Impairments due to the non-flatness of the cumulative gain curve on the whole segment (see 7.1.4.3);
  - Non optimal pre-emphasis impairment (see 7.1.4.4);
  - Impairments due to the misalignment of the wavelength(s) of the submarine Digital Line Section (see 7.1.4.5);
  - Impairments due to the supervision (see 7.1.4.6);
  - Manufacturing and environmental impairments (see 7.1.4.7).
- Impairments to take into account non-ideal characteristics of the terminal transmission equipment (related to back-to-back Q factor performances of the terminal transmission equipment) (see 7.1.5) → Segment Q factor calculation.
- Specifically for EOL power budget, some additional margins should be added (see 7.1.6) → Segment margin.
  - Margins due to specified repair operations (repair splices, additional loss and change in dispersion map due to extra cable length after repair, etc.) (see 7.1.6.1);
  - Margins due to cable and component ageing (see 7.1.6.2);
  - Margins due to the foreseen failures of some components, such as pump laser failures (see 7.1.6.3).

Cross-Phase Modulation and Four-Wave Mixing between optical channels, Stimulated Raman Scattering, non-flatness of the cumulative gain curve and non-optimal relative powers of optical channels are impairments especially applicable to WDM and DWDM systems as they deal with simultaneous propagation of several optical signals on the same fibre.

7.1.3 Optical noise accumulation

7.1.3.1 Optical signal-to-noise ratio calculation

In a system including a cascaded optical amplifier chain, ASE noise accumulates from the contribution of each Optical Amplifier. The Optical Signal-to-Noise Ratio (OSNR) decreases after having passed through each Optical Amplifier. Thus, OSNR is a useful parameter for monitoring and characterizing Optical Amplifier performance. Figure 7-3 depicts a multi-channel system we use as a benchmark (N span, N – 1 line amplifiers).

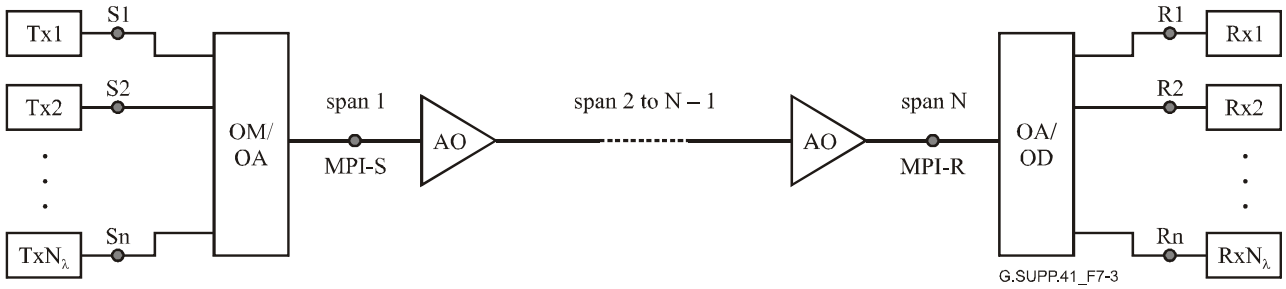


Figure 7-3 – Representation of optical line system interfaces (a multi-channel N-span system)

Two different ways exist for OSNR calculation:

i) simple noise accumulation with constant signal power; or

ii) noise accumulation with total output power constant.

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

In this clause, we will develop item i): signal power is kept unchanged.

For the system shown in Figure 7-3, the following main assumptions are made:

- All Optical Amplifiers contained in the chain have the same Noise Figure (NF).
- Losses of all spans are equal.
- Total output powers of all in-line amplifiers are the same.

In this case, the OSNR at the input of the receivers (point R_i in Figure 7-3, i = 1, … n) can be approximated by:

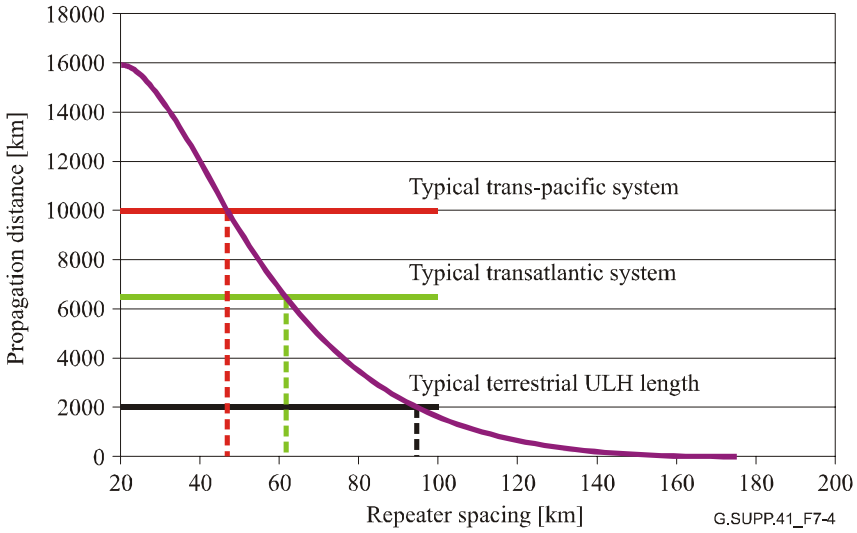
$$OSNR = \frac{P_{out}}{N_\lambda \cdot N_{amp} \cdot NF - \frac{1}{G} \cdot G \cdot h\nu \cdot B_r} \tag{7-7}$$

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

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

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

where the gain G equal to $e^{\alpha L}$, with L the span length. As a consequence, for a given OSNR, the total length achievable is a function of the span length. Figure 7-4 shows an example of typical span lengths for usual submarine and terrestrial systems.



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

Figure 7-4 – Example of repeater spacing required to achieve typical submarine and terrestrial transmission distances

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

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

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

In the case of unrepeated systems with Remote amplification and a single booster amplifier at the transmitter, Equation 7-7 can be modified to:

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

where L is the total cable length in km, α its total loss in km^{-1}, P_{Trans} the output power of the transmitter (point MPI-S in Figure 7-3), NF_1 and NF_2 the noise figures of the remote amplifier and the booster amplifier and G_1 the gain of the remote amplifier.

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

7.1.3.2 Q-factor calculation

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

$$Q_{lin} = \frac{\frac{2M.OSNR.(1-ER)}{1+ER}\sqrt{\frac{B_r}{B_e}}}{\sqrt{1+\frac{4M.ER.OSNR}{1+ER}}+\sqrt{1+\frac{4M.OSNR}{1+ER}}} \tag{7-11}$$

where *OSNR* is the Optical Signal-to-Noise Ratio expressed in the optical bandwidth B_r, *ER* is the transmitter Extinction Ratio expressed in linear units, B_e is the receiver electrical bandwidth in Hz,

B_r is the receiver optical bandwidth in Hz, and M is a coefficient relating to the modulation format ($M = 1$ for NRZ, $M \sim 1.4$ for RZ [3]). Note that the coefficient M also depends on the Extinction Ratio parameter.

7.1.4 Propagation impairments

Propagation impairments cause some additional penalties in comparison to the *Mean Q* value calculated with simple ASE noise accumulation considerations. They have to be deducted from the *Mean Q* factor to obtain the *Line Q* value (see Figure 7-1).

7.1.4.1 Propagation impairments due to non-linear effects

Non-linear interactions between the signal and the transmission medium begin to appear when the optical signal power density becomes high. It should be noted that high optical signal power is necessary in order to get acceptable OSNR value without reducing the span lengths. Consequently, fibre non-linearity has received an important consideration both in high-capacity systems and in long routes without electronic regeneration and particularly in the case of long optically amplified submarine links. Two types of non-linearities are generally distinguished: those which relate to the fibre's intensity dependent index of refraction known as the Kerr effect (self-phase modulation, cross-phase modulation and four-wave mixing) and those which are linked to scattering effects (stimulated Raman mainly). Several parameters influence the severity of these non-linear effects, including the fibre dispersion characteristics, the effective area and non-linear refractive index of fibres, the number and spacing of channels in WDM systems as well as the signal intensity and data rate. These non-linear effects are described in the Appendix II/G.663. A review of the main non-linear effects is presented in 7.1.4.1.1, 7.1.4.1.2, 7.1.4.1.3 and 7.1.4.1.4.

7.1.4.1.1 Self-Phase Modulation (SPM)

The following text is based on II.3.1/G.663 and it is reproduced here for the benefit of the reader. Since fibre's refractive index depends on the optical signal intensity, the temporal variation of the optical signal intensity induces a modulation of its own phase. This effect is called Self-Phase Modulation (SPM).

In optical transmission systems, Self-Phase Modulation gradually broadens the signal spectrum because of phase change due to optical intensity change (see Figure 7-5). In the presence of spectral broadening caused by SPM, the signal experiences a greater temporal broadening while propagating along the fibre, due to the effects of chromatic dispersion, in the normal dispersion region of the fibre (i.e., below the zero-dispersion wavelength). Conversely, in the anomalous dispersion region, the chromatic dispersion and SPM can compensate each other, giving less temporal broadening. The well-known soliton propagation is based on this phenomenon.

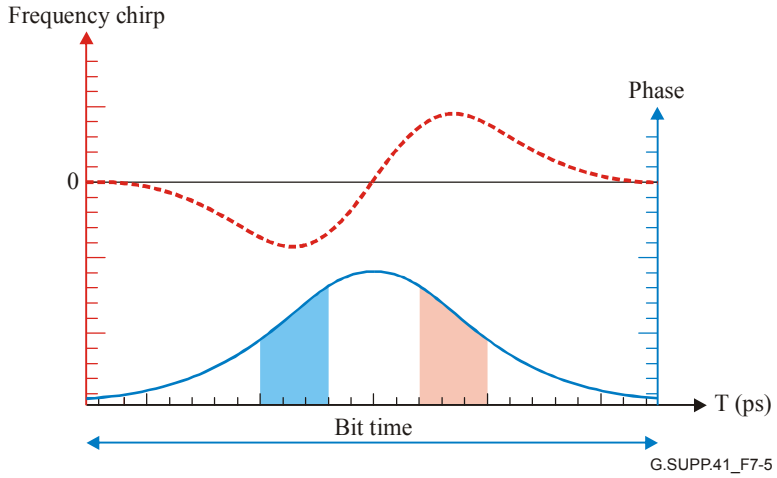


Figure 7-5 – Temporal variation of the phase shift and the frequency chirp induced by SPM [4]

Generally, the effects of SPM are significant only in systems exhibiting high cumulative dispersion or very long reaches like optically amplified submarine systems. Systems operating in the normal dispersion regime which are dispersion-limited may not tolerate the additional effects due to SPM. In WDM systems with very small channel spacing, the spectral broadening induced by SPM may also create interference between adjacent channels. The effect of SPM may also induce degradation when combined with narrowband optical filtering. Since SPM is essentially a single-channel effect, it is not influenced by the greater channel counts. The distortion penalty of SPM is increased by larger launched channel powers. It is also increased by a higher channel bit rate, since signals with higher bit rates have higher rising/falling bit slopes.

The effects of SPM may be mitigated by operating at wavelengths above the zero-dispersion wavelength of ITU-T Rec. G.655 fibre. Fibres with attributes of increased fibre effective area, or decreased non-linear refractive index, also reduce the SPM penalty. For all fibre designs, SPM effects may be reduced by decreasing the launched channel powers, though system design trends call for larger powers to allow longer span distances.

7.1.4.1.2 Cross Phase Modulation (XPM)

The following text is based on II.3.3/G.663 and it is reproduced here for the benefit of the reader. In multichannel systems, Cross-Phase Modulation (XPM) will gradually broaden the signal spectrum when the temporal optical intensity evolution results in changes in phase due to interactions between adjacent channels. The amount of spectral broadening introduced by XPM is related to the channel spacing and fibre chromatic dispersion, since the dispersion-induced differential group velocities will cause the interacting pulses to separate as they propagate down the fibre. Once spectral broadening is introduced by XPM, the signal experiences a greater temporal broadening as it propagates along the length of the fibre due to the effects of chromatic dispersion.

The systems penalty from XPM is increased by smaller channel spacing. As noted for SPM, the change in signal phase is related to the change in fibre refractive index, which in turn is related to the channel power. Larger average launched powers lead to larger phase shifts, which when combined with dispersion effects lead to a larger system penalty.

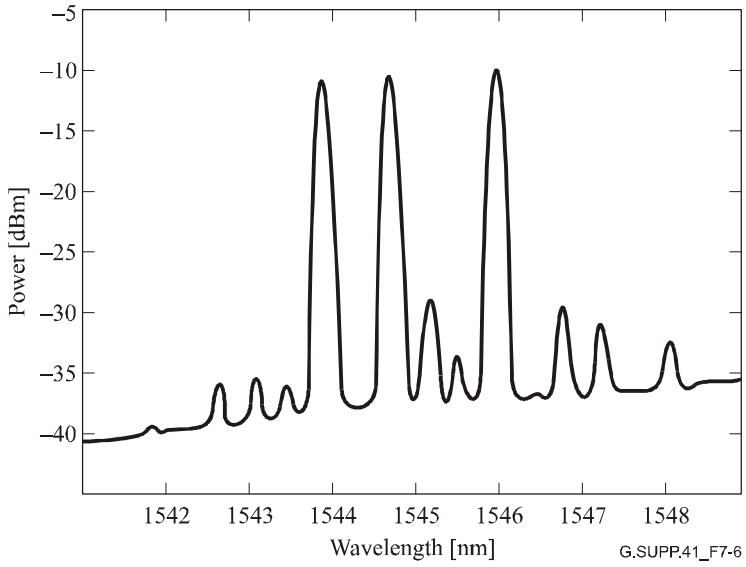
The impairments from XPM are more significant in ITU-T Rec. G.652 fibre systems, relative to ITU-T Recs G.653 and G.655 fibre systems. The broadening due to XPM may result in interference between adjacent channels in WDM systems.

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

7.1.4.1.3 Four-Wave Mixing (FWM)

The following text is based on II.3.5/G.663 and it is reproduced here for the benefit of the reader. Four-Wave Mixing (FWM), also called four-photon mixing, occurs when the interaction of two or three optical waves at different wavelengths generates new optical waves, called mixing products or sidebands, at other wavelengths. This interaction occurs mainly between signals in WDM systems.

In the case of two signals, the intensity modulation at their beat frequency modulates the fibre refractive index and produces a phase modulation at a difference frequency. The phase modulation creates two sidebands at frequencies given by this difference. In the case of three signals, more and stronger mixing products are produced (see Figure 7-6) which will fall directly on adjacent signal channels when the channel spacing are equal in frequency. Two optical waves propagating along a fibre produce FWM with high efficiency if the phase matching condition is achieved between sidebands and initial signals.



NOTE – D = –0.2 ps/nm.km at the central channel when 3-mW channels are used [5].

Figure 7-6 – Optical power spectrum measured at the output of 25-km length of dispersion shifted

The generation of FWM sidebands can result in significant depletion of the signal power. Furthermore, when the mixing products fall directly on signal channels, they cause parametric interference which manifests as amplitude gain or loss in the signal pulse, depending on the phase interaction of the signal and sideband.

Parametric interference causes closure of the eye pattern at the receiver output, thereby degrading Bit-Error Ratio (BER) performance. Multichannel systems are trending towards greater channel counts, which increase the number of possible mixing products falling on signal channels.

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

7.1.4.1.4 Stimulated Raman Scattering (SRS)

The following text is based on II.3.7/G.663 and it is reproduced here for the benefit of the reader. Stimulated Raman scattering is a broadband effect which involves the interaction of light and the vibrational modes of silica molecules. SRS causes a signal wavelength to behave as a Raman pump for longer wavelengths, either other signal channels or spontaneously scattered Raman-shifted light. In any case, the shorter wavelength signal is attenuated by this process, which amplifies the longer wavelength signal.

Stimulated Raman Scattering (SRS) impacts mainly WDM systems with large bandwidth. The shorter wavelength signals in WDM systems can suffer degraded signal-to-noise performance because a portion of their power is transferred to longer wavelength channels through SRS. This results in total system capacity limitations based on the total number of channels, channel spacing, average input power and overall system length.

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

7.1.4.1.5 Influence of non-linear effects

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

Usually, the influence of non-linear effects on WDM systems is evaluated by means of numerical simulation tools based on Split Step Fourier method [4]. Results are most of the time validated by experimental tools like recirculating loop [6] or test bed.

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

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

- Type of fibre used for the transmission;
- Scheme of dispersion compensation;
- Span length;
- In line optical output power;
- Channel spacing.

7.1.4.1.6 Conclusions

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

7.1.4.2 Propagation impairments due to optical polarization effects

The following text is based on II.4.1/G.663 and it is reproduced here for the benefit of the reader. It is well known that optical components and subsystems are more or less sensitive to the polarization state of the optical signal. These polarization effects can be separated in 3 parts:

- the PMD: Polarization Mode Dispersion;
- the PDL: Polarization Dependent Loss;
- the PDG: Polarization Dependent Gain.

They are described in detail in ITU-T Recs G.663, G.671, G.650.2 and in IEC 61282-3.

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

7.1.4.2.1 Polarization Mode Dispersion (PMD)

The optical fibre birefringence, due to the non-uniform geometrical properties occurring during the manufacturing process, induces a modification of the propagation time which depends on the state of polarization (SOP). The Polarization Mode Dispersion value is the average Differential Group Delay (DGD) time between two orthogonally polarized modes, which causes pulse spreading in optical transmission systems. The following text is based on Supplement 39 to ITU-T G-series Recommendations and it is reproduced here for the benefit of the reader.

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

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

where:

$DGD\max_{link}$ is the maximum DGD of the link (ps);

$DGD\max_{F}$ is the maximum DGD obtained after concatenated optical fibre cable (ps);

S is the Maxwell adjustment factor (see Table 7-1);

PMD_{Ci} is the PMD value of the ith component (ps).

Equation 7-12 assumes that the statistics of the instantaneous DGD can be approximated by a Maxwell distribution, the probability of the instantaneous DGD exceeding $DGD\max_{link}$ being controlled by the value of the Maxwell adjustment factor taken from Table 7-1.

Table 7-1 – DGD means and probabilities referred to ITU-T Rec. G.959.1

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

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

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

PMD power penalty

As explained in Supplement 39 to ITU-T G-series Recommendations, the power penalty induced by DGD at the receive point R (see Figure 7-3) is a function of the relative power of the two orthogonal polarization modes. This gap varies in time because the relative alignment of the main states of polarization in the optical fibre cable and the polarization of the source varies. The maximum link DGD is set to allow no more than a given first-order power penalty in the worst-case power splitting ratio (equal power in both modes). The worst-case first-order power penalty is also affected by the transmission format, NRZ or RZ.

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

The RZ case is for further study.

7.1.4.2.2 Polarization-Dependent Loss (PDL)

The Polarization-Dependent Loss is defined in the ITU-T Rec. G.671 as the maximum variation of insertion loss due to a variation of the state of polarization (SOP) over all SOPs. In amplified systems, one mode of amplifier control is to operate at constant signal power. Both the signal and noise are affected by polarization-dependent losses. However, because the noise is unpolarized, the signal and noise are affected differently. The noise can be resolved into a component parallel to the signal and a component orthogonal to the signal. It can be shown that the combined effect of PDL and optical amplification is always to increase the component of the noise orthogonal to the signal. Furthermore, the magnitude of the orthogonal noise component changes with time as the signal polarization changes due to polarization mode dispersion. This leads to a reduction in the OSNR and the Q value at the receiver. Furthermore, the fluctuations time lead to fading of the OSNR and Q value at the receiver, both of which lead to an impairment in system performance.

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

7.1.4.2.3 Polarization-Dependent Gain (PDG)

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

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

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

7.1.4.4 Non-optimal pre-emphasis impairment

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

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

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

Thus, channel power pre-emphasis allows equalizing system transmission performance of all channels. Nevertheless, the power level of each channel being different, the propagation in an optical fibre will induce additional penalties (see Figure 7-7).

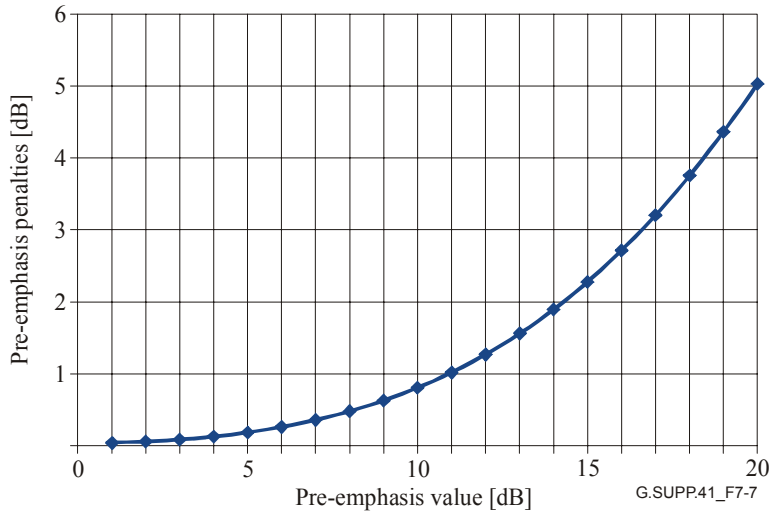


Figure 7-7 – Example of penalties induced by the pre-emphasis adjustment

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

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

7.1.4.6 Impairments due to supervision

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

7.1.4.7 Manufacturing and environmental impairments

During the manufacturing process, we cannot guarantee that all the equipment manufactured behaves in exactly the same manner or, in other words, exhibits the same performance. Therefore, some impairment should be allocated to take into account the transmission performance variation

resulting from these differences. This item also concerns the variation of environmental conditions that can occur in the system (temperature and pressure for example).

7.1.5 Impairments due to the terminal transmission equipment imperfections

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

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

7.1.6 System margins

A submarine system has a design life of 25 years. This design life requires some additional margins to be satisfied.

7.1.6.1 Impairments due to repair operations

After the submarine line lay, a cable repair requires at each time to add some extra cable. This additional cable leads to a span loss enhancement and consequently to a Q-factor degradation.

The repair operation margin is evaluated by estimating the total number of repairs required during the system life. Usually the following scenario is used:

- Land cable repair: 1 repair every 4 km with a minimum of 2 repairs;
- Shallow water repair: 1 repair every 15 km with a minimum of 5 repairs;
- Deep water repair: 1 repair every 1000 km.

Each repair will add a cable section in direct proportion to the depth of water at the repair position. Usually, the increase in length is between 1.5 and 2.5 times the depth of water.

To calculate the margin required for repair operations, the total additional cable length is evaluated in the worst case when all estimated repairs are added. Another Q-factor is calculated with the sum of the total initial line length and the maximum extra cable added by repairs. The difference between this Q-factor and the Mean Q corresponds to the repairs allocation margin.

7.1.6.2 Impairments due to equipments ageing

The impairment due to the equipments ageing is mainly due to the fibre. As a matter of fact, its attenuation will slowly increase due to physical effects related to the environment. Two of them are usually taken into account:

- Hydrogen effects in the fibre: The degradation is usually approximated by an additional loss after 25 years of around 0.003 dB/km.
- Radiation effects: Optical fibres are loss-sensitive to high energy radiation (gamma rays) whose origins may be related to sediments, sea water or artificial sources (waste site). The loss increase is estimated to be lower than 0.002 dB/km after 25 years.

In the same way as for repair operation (see 7.1.6.1), a Q factor is calculated with these additional losses and compared to the mean Q value in order to obtain the margin value required for equipments ageing.

7.1.6.3 Impairments due to the foreseen faults of some components

Due to the cost and complexity of marine operations to replace or repair submerged equipment, the most sensitive components are redundant in order to avoid interventions as much as possible. The major faults to take into account are the repeater pump failures. Pump redundancy avoids an output

power shutdown in the case of a pump failure but such an incident will always induce an output power and noise figure degradation leading to a Q factor decrease.

The additional margin required to take this into account depends on the reliability of the pump and the redundancy setup.

7.1.6.4 Unallocated margin

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

7.1.7 Conclusion

Optical Power Budget tables describe how the System Performance will be met. A template of the recommended Optical Power Budget table is available in Annex A/G.977.

In submarine systems using Optical Amplifiers (ITU-T Recs G.973 and G.977), regeneration occurs only in the terminal transmission equipment at the submarine electro-optic interface. Between the emission and the reception, the channels will suffer impairments due for example to optical noise accumulation, propagation (fibre non-linearities, chromatic dispersion, etc.). Therefore, it is recommended to establish the optical Power Budget at the submarine Digital Line Section level. As some systems may accommodate several submarine Digital Line Sections with different impairments, it is further recommended that an optical Power Budget be established for each submarine Digital Line Section.

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

Additionally, in the case where the design of a multi-landing point system has been optimized for the longest submarine Digital Line Section in terms of Optical Signal-to-Noise Ratio degradation and repeater spacing, extra margins may be available for the shorter ones. Those extra margins, usually called unallocated Supplier/segment margins, should be clearly reported in the Power Budget tables.

The Supplier should provide sufficient information in order to support the validity of the Power Budget tables, in particular but is not limited to:

- the overall transmission distance and the span length values;
- the number of transmitted wavelengths;
- the Extinction Ratio at the transmitter;
- the nominal repeater output power value;
- the nominal Noise Figure value;
- the optical and electrical bandwidth values at the receiver;
- the back-to-back Q specification for the terminal;
- the Forward Error Correcting code characteristics (including BER before FEC and BER after FEC curves).

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

7.2 Dispersion considerations

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

7.2.1 Pulse spreading due to chromatic dispersion

Chromatic dispersion in a single-mode fibre is a combination of material dispersion and waveguide dispersion, and it contributes to pulse broadening and distortion in a digital signal. The main cause is the presence of different wavelengths in the optical spectrum of the source. Each wavelength has a different phase delay and group delay along the fibre, so the output pulse is distorted in time.

7.2.2 Chromatic dispersion mapping

As explained in ITU-T Rec. G.973 in the case of a single-channel system and in ITU-T Rec. G.977 for WDM system, the dispersion map is the principal tool for describing the chromatic dispersion characteristics of a system. Cumulative dispersion is defined as the dispersion measured between the output of the terminal transmitter and any other point in the optical path. The dispersion map is the plot of local chromatic dispersion, for a given operating wavelength, as a function of distance from the optical transmitter to the optical receiver. The dispersion map will depend mainly on the type of system (SWS or WDMS).

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

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

For a WDMS at 10 Gbit/s with large number of LOC (Figure 7-8), the fibres typically with large chromatic dispersion are used along the link for all the sections. One portion of the section is typically positive dispersion with positive slope (normally with very large effective area) and the remaining portion is negative dispersion with negative slope (normally very small effective area).

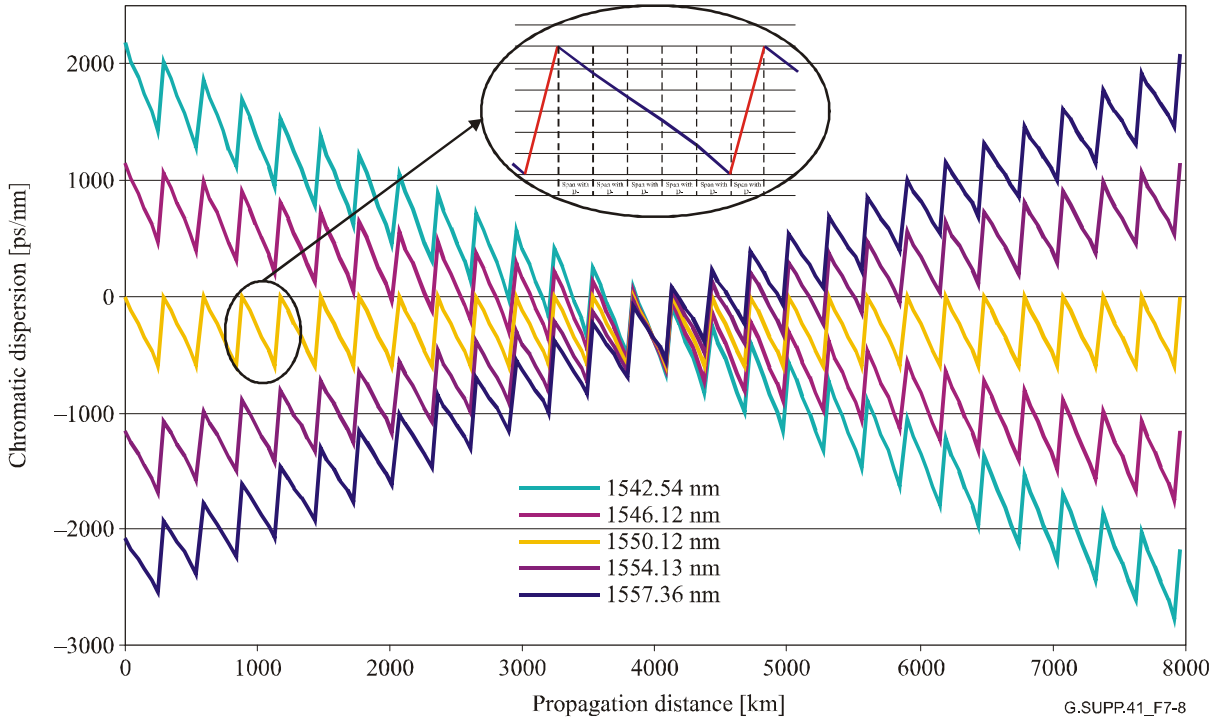


Figure 7-8 – Typical chromatic dispersion map for a submarine WDM System with 163 spans designed for 40 wavelengths centred around 1550.12-nm WDM System

7.2.3 Dispersion management implementation

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

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

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

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

8 Forward error correction

This clause is for further study.

9 Reliability consideration

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

Failures occurring during the system life may be due to internal faults (shunt fault, fibre loss increase, repeater failures, card failures, etc.) or external aggressions (e.g., anchors and fishing activities for wet plant and misoperation for dry plant).

9.1 Reliability requirement

Reliability is defined as the probability for a component or a subsystem to perform a required function under specific conditions for a given period of time. This can be expressed through different figures:

– Failure In Time (FIT): Number of failures per hour for 10^9 devices. This value is temperature-dependent and has to be recorded at the operating temperature. In a statistical viewpoint, this definition is equivalent to: number of failures per device for 10^9 hours.

– Mean Time Between Failures (MTBF): Expected time between 2 consecutive failures.

It should be noted that these statistical figures have no meaning for an individual device and only provide performance probabilities rather than absolute expectations.

At first, the overall reliability constraint is used to estimate the reliability allowed for each subsystem and then for each component. Required reliability of a component for a given system life is then translated into failure rate (FIT) or MTBF.

For a system or a subsystem, the following figures are defined:

– Mean Time To Repair (MTTR): Expected time needed to repair a failure.

– Outage = MTTR/MTBF: Amount of time usually expressed in minutes per year whenever the network is not available to perform his function.

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

9.2 Internal fault

In order to achieve the reliability target in the submarine systems (minimizing internal faults) and to establish a maintenance policy applicable during the entire system life, the failure root causes should be identified at component, sub-system and system levels. Therefore, the reliability of all components used within the system must be demonstrated for the period of contractual system life (generally 25 years). Predicted reliability is often based on ITU-T Rec. G.911, IEC 62380, MIL-HDBK-217 [7], Telcordia SR 332 [8] and component's suppliers data.

9.2.1 Failure rate analysis

9.2.1.1 Infant mortality

At the beginning of life working condition, units or components used in submarine systems exhibit a high failure rate which is decreasing with time. This short period is called the infant mortality time (infant mortality: usually one or two years). It is mainly due to the non-ideal manufacturing process (defective raw materials, improper operations, contaminated environment, power surge, ineffective inspection or inadequate shipping and handling). It should be noted that the infant mortality relates to an entire batch of devices and cannot reflect the behaviour of a single device. In that particular case the single device will either fail or pass a test, whereas the failure rate of a number of units will follow a decreasing curve.

9.2.1.2 Random failure

The period next to the infant mortality is characterized by a lower failure rate. This period is called the useful life because the failure rate is almost constant until the beginning of the last phase (wear-out period). Constant failures obey to random processes and are generally not detectable even with highly controlled process.

9.2.1.3 Ageing

The last period occurs when systems and associated components begin to wear out during use. Failures may result from ageing, material fatigue, excessive wearout, environmental corrosion, undesirable environment or cumulative damage.

The failure's rate behaviour is conventionally described as a bathtub curve during the life of the system as shown in Figure 9-1.

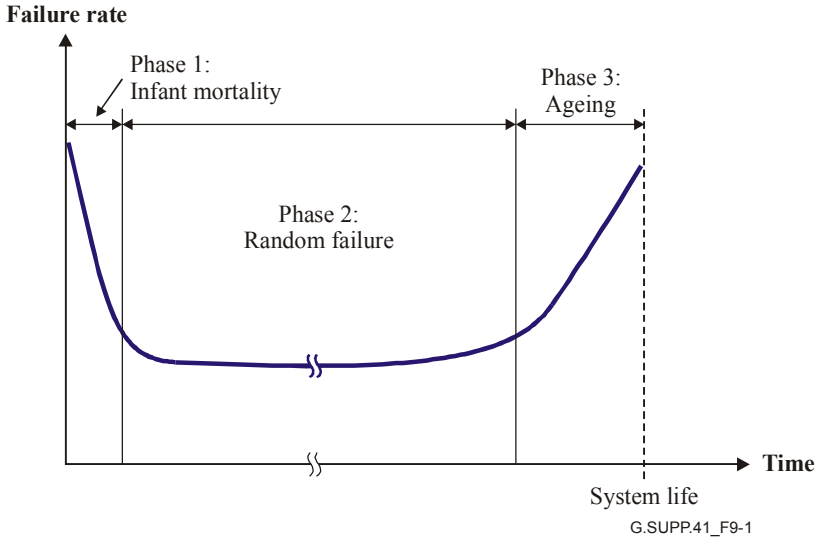


Figure 9-1 – Typical failure's rate behaviour during the life of a system

9.2.2 Wet plant reliability

The wet plant is more critical than the dry plant in terms of reliability because the MTTR is greater. Typical MTTR values give around 2 weeks for the wet plant repair instead of 2 hours for the dry plant. From a reliability point of view, this is why the FIT for laser pumps used within the repeaters is a sensitive issue for the system. For example, typical FITs for amplifiers in terrestrial networks are within 1000 to 10 000 compared to submarine amplifiers, that are within 10 to 100 (around 2 orders of magnitude lower).

Designing ultra reliable submarine systems means that the probability of a wear-out failure occurring during the system life must be quasi non-existent and the probability of random failure must be minimized as much as possible.

Repeaters are the most critical equipment as they contain electronic, optical and opto-electronic components. In addition to that, one must keep in mind that any internal damage, whatever the cause is, may directly impact the transmission quality. Consequently, careful precautions must be taken to prevent and reduce the risk of failure. In particular, an optical failure occurring on a specific fibre must not affect the system performances of the other fibres. The tests required before and during the cable installation are detailed in the ITU-T Rec. G.976.

i) General requirements

Low FITs are obtained through the use of heavily screened components, close control of raw materials, robust and simple design, careful manufacturing process and thorough quality control.

It is quickly apparent that a test condition is required to accelerate the time to failure in a predictable and understandable way. It should also be recognized that a system includes a variety of different manufacturing processes and assembly procedures and each one should be tested. Each failure should be attributed to a single failure mechanism and should not be correlated to a potential interaction between the device under test and the test procedure itself. For both economical purpose and technical feasibility, the reliability requirements make necessary the use of accelerated tests.

ii) Redundancy

In order to achieve the required reliability and to reduce accordingly the FIT of the subsystems, redundant configurations are generally used. For example, redundant pump laser configurations are usually employed to ensure that the amplifier reliability target is met.

9.2.3 Example of reliability calculation

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

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

The FIT value (defined for 10^9 devices) that is considered in Equation 9-1 is equal for all four pumps. The value 21.9×10^{-5} in Equation 9-1 comes from:

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

Figure 9-2 shows the number of pumps failed during the 25 of the system lifetime for a typical transatlantic cable (150 repeaters) with 1 fibre pair only. The typical FIT for a submarine laser pump is assumed to be 25. The number of pumps failed is estimated by the product between p and the total number of pumps.

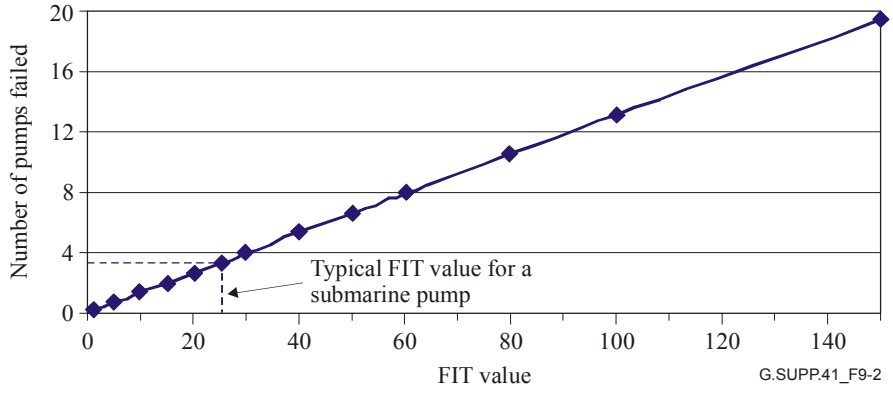


Figure 9-2 – Estimated number of pumps failed in the 25 years for a typical transatlantic link composed of 1 fibre pair and 150 repeaters containing four pumps each

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

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

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

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

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

The estimated number of pumps failed is $N.p$ (Figure 9-2) and the variance $Np(1-p)$. This probability law obeys to the Binomial Law and the probability to have exactly n pumps failed during the system life is:

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

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

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

With the same typical system as the one used in Figure 9-2 and using Equation 9-4, this probability leads to MTBF value between the first and second failure into the same repeater represented in Figure 9-3. The MTBR obtained for a typical FIT equal to 25 is more than 1500 years!

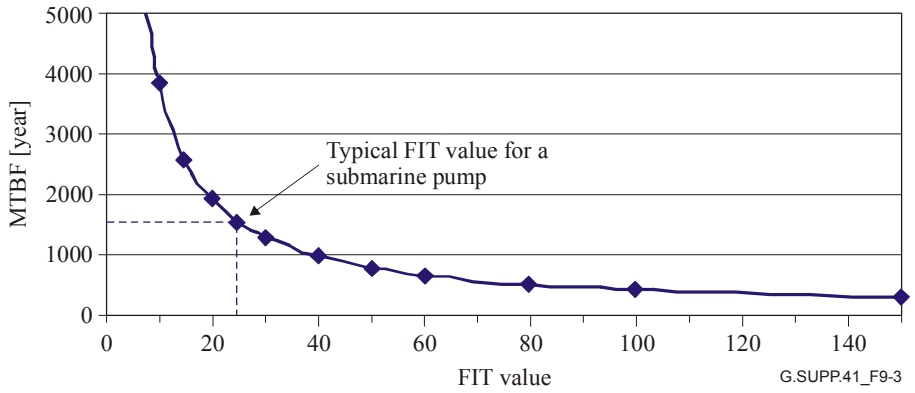


Figure 9-3 – MTBF for a second pump failure in the same repeater in a typical transatlantic link composed by 1 fibre pair and 150 repeaters with four redundant pumps each

9.3 External fault

External faults usually occur in the cable sections. As a matter of fact, the main causes of failure are aggressions such as bottom fishing, fishing trawlers, ocean currents, geological events (earthquakes and volcanoes) and thermal failures due to overload. Nearly 90 percent of the failures are caused by fishing activities and ship anchors damage. To protect the cable against these various factors, the wet plant can be buried in the shallow water except in rocky area where seabed conditions do not allow burial. Additionally, the cable route is selected to avoid as much as possible geological hazards.

In case of failure in the wet plant marine operations are necessary and a cable ship is mobilized for the repair. The section of damaged cable is cut, recovered and replaced with spares on board. The Mean Time To Repair (MTTR) is estimated to be from 1 to 3 weeks depending on the fault location, the sea depth, the ship availability, the damage root cause, and the weather that can dramatically slow down the marine operations.

In order to minimize the impact on traffic of such faults, the overall network availability is increased through route diversity when possible (see clause 6 for details on the submarine network

topologies). In the event of a fault in the wet plant leading to a loss of transmission, the traffic is usually rerouted onto a protection path.

9.4 Fault localization

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

As detailed in ITU-T Rec. G.976, some tests may be performed in service and others out of service from the terminal station depending on the facility that is used (repeater supervisory or external means such as OTDR, coherent OTDR, resistance or capacitance measurements on the conductor, etc. These tests are used to find and to identify the type of fault with the best accuracy. Generally, OTDR is employed to check the quality of the cable that is located between the TTE and the first submerged repeater and COTDR for the long distance repeated systems fault location.

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

10 Upgradability considerations

This clause is for further study.

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Printed in Switzerland
Geneva, 2005