CHAPTER 7

OPTICAL SYSTEMS DESIGN

Introduction

This chapter describes design and engineering criteria for single-channel and multichannel digital optical line systems supporting PDH, SDH and OTN signals in intra-office, inter-office, and long-haul terrestrial networks. Two cases will be considered: optical systems without optical line-amplifiers (clause 1) and with optical line-amplifiers (clause 2).

The forward error correction impact on optical system design is dealt with in clause 3. Some reliability considerations for submarine optical systems are in clause 4.

The general concepts outlined in this Chapter can be also applied to the optical systems deployed in optical access networks (see Chapter 9).

1 "Worst case" design for systems without line amplifiers

(For further information see Supplement 39 to the ITU-T G-series of Recommendations).

For "worst-case" system design, optical systems in client networks (PDH, SDH and OTN) are specified by optical and electrical system parameters with maximum and minimum values at the end-of-life within Recommendations ITU-T G.957, ITU-T G.691, ITU-T G.692, ITU-T G.693, ITU-T G.695, ITU-T G.698.1 and ITU-T G.959.1.

Optical systems design is mainly based on the power budget. An optical power budget is a performance budget, which guarantees the system performance to be better than the minimum required BER performance objective derived from Recommendations ITU-T G.826 and ITU-T G.828.

1.1 Relevant parameters for power budget

Power budgets of *single-channel* (TDM) optical systems are given in Recommendations ITU-T G.957, ITU-T G.691, ITU-T G.693 and ITU-T G.959.1 and those for *multichannel* optical systems (WDM) in Recommendations ITU-T G.695, ITU-T G.698.1 and ITU-T G.959.1. The majority of optical systems without line amplifiers are single-channel systems.

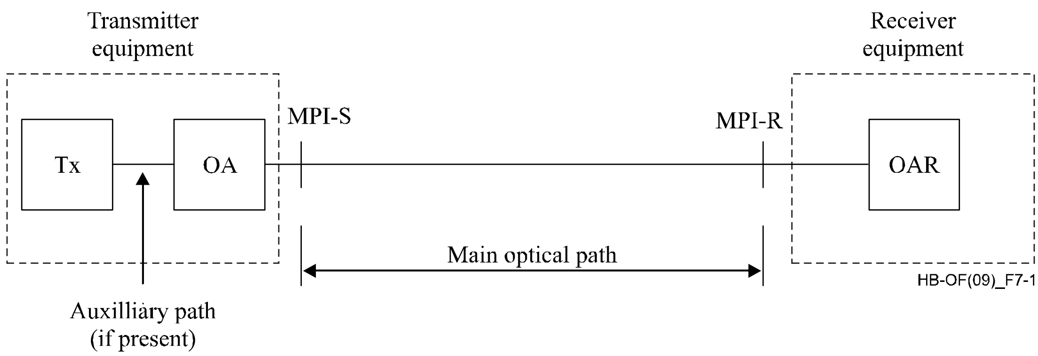
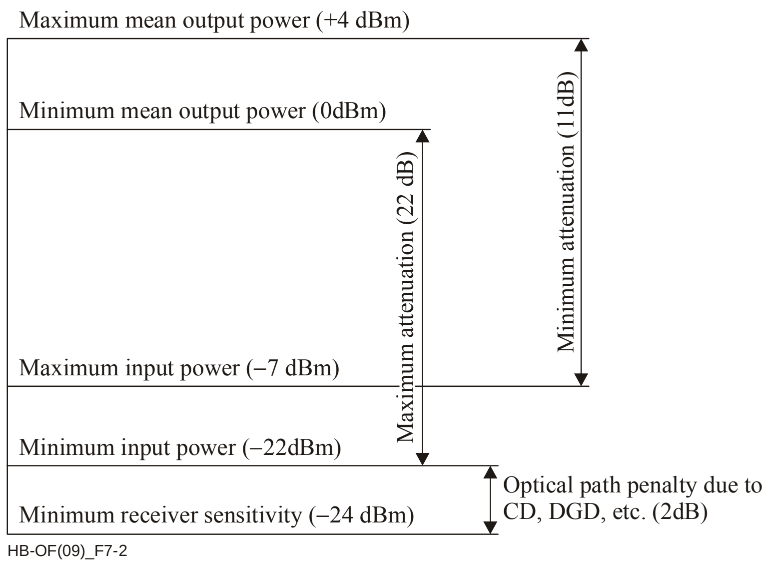


Figure 7-1 – A single-channel, single-span optical system

For a single-channel and single-span optical system, as in Figure 7-1, the following optical parameters are considered in a "worst-case" approach:

- maximum mean output power;
- minimum mean output power;
- maximum attenuation;
- minimum attenuation;
- maximum chromatic dispersion;
- minimum chromatic dispersion;
- maximum differential group delay (DGD);
- maximum mean (channel) input power;
- minimum receiver sensitivity;
- maximum optical path penalty.

An example of power budget for a single-channel and single span system operating at 10 Gbit/s on 80 km without optical amplifier and with a BER objective of 10^{-12} is shown in Figure 7-2.



Note – This corresponds to application code P1L1-2D2 of Recommendation ITU-T G.959.1

Figure 7-2 – Example of power budget for a single-channel single-span 10G system operating on 80 km with a BER objective of 10^{-12}

This example reproduces the values of the application code P1L1-2D2 of Recommendation ITU-T G.959.1. This figure shows that:

i) the difference between the maximum mean output power and the maximum mean (channel) input power gives the minimum attenuation;

ii) the difference between the minimum mean output power and the minimum mean (channel) input power gives the maximum attenuation;

iii) the minimum average optical power at the receiver must be greater than the minimum receiver sensitivity by the value of the optical path penalty;

iv) the minimum receiver sensitivity takes into account transmitter extinction ratio, transmitter eye closure, optical return loss at point MPI-S, receiver connector degradation, measurement tolerances and aging effects;

v) the maximum optical path penalty contains power penalties associated with the optical path (like chromatic fibre dispersion, polarization-mode dispersion related DGD and reflections).

The definitions of all these parameters are given in Chapter 6. In particular the minimum *receiver sensitivity* is defined (for the worst-case and end-of-life) as the minimum acceptable value of mean received optical power at point MPI-R to achieve a BER of 1×10^{-12}. Worst-case transmitter extinction ratio, transmitter eye closure, optical return loss at point MPI-S, receiver connector degradation, measurement tolerances and aging effect cause the worst-case condition for the receiver sensitivity.

Optical systems that would otherwise be limited in transmission length by optical fibre attenuation can be operated with the use of optical (booster-, or/and pre-) amplifiers (see Chapter 5 and Recommendations ITU-T G.661, ITU-T G.662 and ITU-T G.663).

Optical systems that would otherwise be limited in transmission length by chromatic dispersion require certain dispersion accommodation (DA) processes, discussed in Recommendation ITU-T G.691, to overcome fibre length limitation.

The following clauses show the limits that are to be put to the parameters, which mainly contribute to the optical path penalty (chromatic dispersion, differential group delay, reflections) in order to ensure that the specified value (2 dB in the example of Figure 7-2) is complied with.

Recommendation ITU-T G.959.1 reports that a maximum path penalty of 1 dB for low-dispersion systems (systems on Recommendation ITU-T G.655 and ITU-T G.653 fibres), and of 2 dB for high-dispersion systems (systems on Recommendation ITU-T G.652 fibres), is allowed. The path penalties are not made proportional to the target distance to avoid operating systems with high penalties.

1.2 Chromatic dispersion penalty

Chromatic dispersion in a single-mode fibre is a combination of material dispersion and waveguide dispersion, and it contributes to pulse broadening and distortion in a digital signal (see Chapter 1). From the point of view of the transmitter, this is due to two causes.

One cause is the presence of different wavelengths in the optical spectrum of the source. Each wavelength has a different phase delay and group delay along the fibre, so the output pulse is distorted in time (see Recommendation ITU-T G.957).

The other cause is the modulation of the source, which itself has two effects.

One effect is that of the Fourier frequency content of the modulated signal. As bit rates increase, the modulation frequency width of the signal also increases and can be comparable to or can exceed the optical frequency width of the source (see Recommendation ITU-T G.663).

Another effect is that of chirp, which occurs when the source wavelength spectrum varies during the pulse.

1.2.1 Relation between maximum chromatic dispersion and power penalty

Based on calculations shown in Supplement 39 to the ITU-T G-series of Recommendations, Table 7-1 shows the *theoretical* values of the maximum chromatic dispersion for 1 or 2 dB penalty and for several NRZ bit rates.

Table 7-1 – Maximum theoretical allowable chromatic dispersion for a chirp-free narrow-linewidth source at 1 550 nm for several unchirped NRZ bit rates and power penalties

Unchirped NRZ bit rate (Gbit/s)	Maximum chromatic dispersion (ps/nm)	
	1-dB penalty	2-dB penalty
2.5	18 820	30 110
10	1 175	1 880
40	73.5	118

1.2.2 Relation between chromatic dispersion coefficient and link length

From the values of Table 7-1 and from the values of the chromatic dispersion coefficient of the ITU-T specified optical fibres it is possible obtain the *theoretical* length limitations for a chirp-free narrow-linewidth NRZ bit rates for a 1 dB penalty (Table 7-2).

Table 7-2 – Theoretical length limitations for a chirp-free narrow-linewidth source at 1 565 nm with 3 fibre types and 2 unchirped NRZ bit rates for a 1 dB penalty

Fibre type		G.652	G.653	G.655
Dispersion coefficient at 1 565 nm (ps/(nm · km))		19	3.5	10
Dispersion-limited length (km)	NRZ 10G	61	333	116
	NRZ 40G	3.8	20.8	7.3

Now it is possible to compare the dispersion limited lengths of Table 7-2 with the system application codes considered in the ITU-T Recommendations. In the 1 550 nm region these are: intra-office I (≤ 25 km), short-haul S (≤ 40 km), long-haul L (≤ 80 km) and very-long-haul V (≤ 120 km):

i) NRZ 10G systems with ITU-T G.653 fibre for I, S, L, and V applications or with ITU-T G.655 fibre for I, S, and L applications usually are not limited by chromatic dispersion;

ii) NRZ 10G systems with ITU-T G.652 fibre for L and V applications are limited by chromatic dispersion and require chromatic dispersion accommodation;

iii) NRZ 40G systems require dispersion accommodation for all fibre types and for I, S, L and V applications. For ITU-T G.652 fibre the NRZ 40G length limitation starts at a few km.

Active and/or passive dispersion accommodation techniques as given in clause 2.4 below and in Chapter 5, can be applied to overcome fibre length limitations due to chromatic dispersion, in order to respect the path penalty limit.

1.2.3 Relation between maximum chromatic dispersion and line code

The theoretical maximum chromatic dispersion for unchirped sources has been calculated in the previous examples for NRZ modulation format. Table 7-3 shows the theoretical maximum chromatic dispersion for several RZ formats at 40 Gbit/s.

Table 7-3 – Maximum theoretical allowable chromatic dispersion for a chirp-free narrow-linewidth source at 1 550 nm for several unchirped RZ 40 Gbit/s formats and a 2-dB power penalty

Format (unchirped)	Maximum chromatic dispersion (ps/nm)
NRZ	118
RZ(⅔)	78
RZ(½)	59
RZ(⅓)	39
NOTE – The value given above for RZ(⅔) is for conventional RZ modulation and not for carrier-suppressed RZ.	

1.3 DGD power penalty

As shown in Chapter 1, PMD leads to broadening of optical pulses because of random variations in the birefringence of an optical fibre along its length. This broadening is in addition to the chromatic dispersion induced pulse broadening. The use of chromatic dispersion accommodation can eliminate chromatic dispersion broadening, but does not affect the PMD induced broadening.

The differential group delay (DGD) is the difference in arrival times of the two polarization modes at a particular wavelength and time. For a link with a specific PMD coefficient, the DGD of the link varies randomly with time and wavelength as a Maxwell distribution that contains a single parameter, which is the product of the PMD coefficient of the link and the square root of the link length. The system impairment due to PMD at a specific time and wavelength depends on the DGD at that time and wavelength.

The power penalty induced by DGD at the receive point R is a function of the relative power of the two orthogonal polarization modes. This varies as the relative alignment of the principle states of polarization of the optical fibre cable, and the polarization of the source, varies. The maximum link DGD is set to allow no more than a given power penalty in the worst-case power splitting ratio (equal power in both modes). The worst-case power penalty is also affected by the transmission format, NRZ or RZ.

1.3.1 The statistical distribution of PMD

(For further information see Recommendation ITU-T G.691).

The differential group delay between the polarization states in a non-polarization preserving fibre is a random variable. It is often assumed to have a Maxwellian distribution with the following probability density function:

$$f(\Delta\tau) = 32 \frac{\Delta\tau^2}{\pi^2 < \Delta\tau >^3} \exp\left(\frac{4\Delta\tau^2}{\pi < \Delta\tau >^2}\right) \tag{7-1}$$

where:

$\Delta\tau$: DGD, and

$<\Delta\tau>$: mean DGD.

Figure 7-3 shows the probability density function $f(\Delta\tau)$.

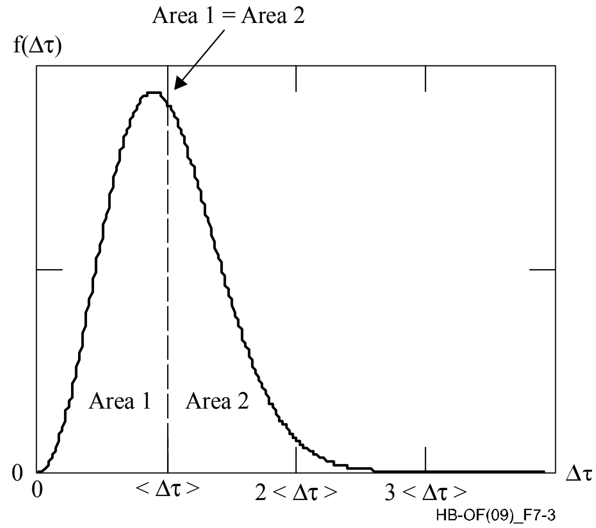


Figure 7-3 – The Maxwellian distribution function – Probability density function *f* (Δτ) vs differential group delay, Δτ

At a given instant, however, the system will experience a specific DGD, Δτ, that is some realization of the random distribution of DGD values, with the average given by the PMD of the link. A pulse train may thus suffer from a delay difference that is smaller or larger than the average PMD of the link.

Integrating this probability density function from $\Delta\tau_1$ to $+\infty$ gives the probability $P(\Delta\tau \geq \Delta\tau_1)$:

$$P(\Delta\tau \geq \Delta\tau_1) = \int_{\Delta\tau_1}^{\infty} f(\Delta\tau)d(\Delta\tau) \tag{7-2}$$

This probability $P(\Delta\tau \geq \Delta\tau_1)$ is depicted in Figure 7-4.

For example, if DGD is greater than 3 times the mean DGD, $\Delta\tau_1 = 3 <\Delta\tau>$, then it can be read from Figure 7-4 that $P(\Delta\tau \geq 3 <\Delta\tau>) \approx 4 \times 10^{-5}$.

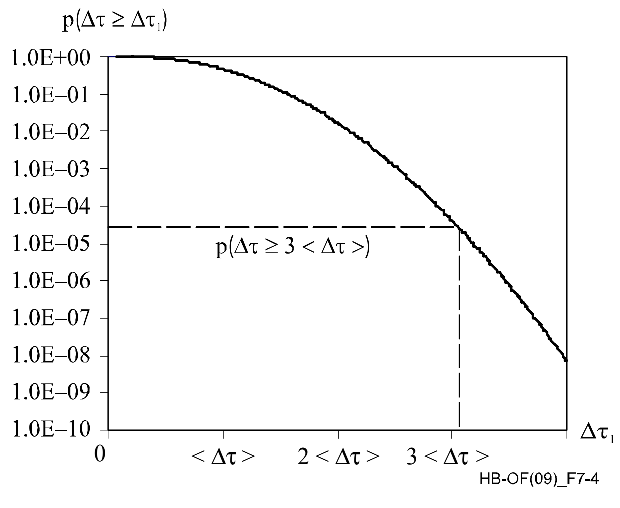


Figure 7-4 – Probability *P*(Δτ > Δτ1)

The DGD variations depend on the polarization states excited in the fibre, the strain in different parts of the fibre, temperature variations, etc. For links where the fibre is buried and undisturbed, this means that the DGD typically changes fairly slowly. However, if the link includes some aerial fibre or is disturbed the DGD can change on a sub-millisecond timescale.

1.3.2 The path penalty due to PMD

Now let us see the amount of total PMD in the link corresponding to a worst-case path penalty of 1 dB. The worst case is based on a DGD of 0.3 bit period in conjunction with the assumption that both principal states of polarization (PSP) carry the same optical power.

A Maxwellian distribution function is assumed for the DGD (see Figure 7-3). The connection between the DGD (being in direct coincidence with the PMD-induced signal pulse width broadening if the same optical power in both PSPs is assumed) and the corresponding path penalty is a receiver characteristic, and is illustrated in Figure 7-5.

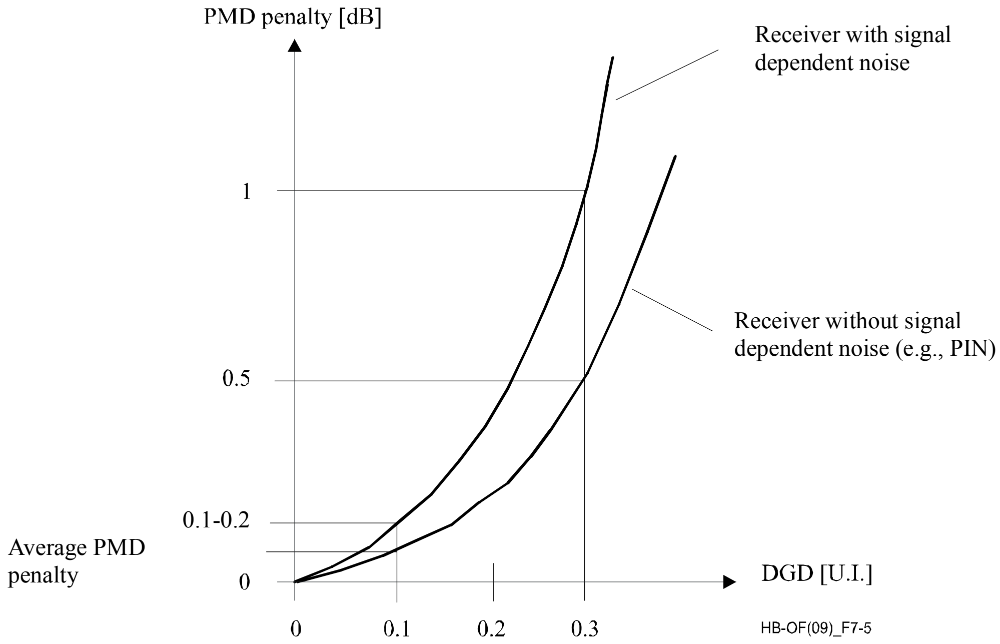


Figure 7-5 – Dependence of the receiver penalty on the actual DGD

With realistic assumptions and a well-designed receiver, it can be deduced that an actual DGD of 0.3 bit period (and 50% of optical power in both PSPs) will give a penalty of about 0.5 dB for a receiver with signal independent noise (PIN-receiver), and up to 1 dB for a receiver with signal dependent noise (APD or preamplifier).

For 10 Gbit/s NRZ applications in Recommendations ITU-T G.691 and ITU-T G.959.1, a 1-dB first-order penalty allowance corresponds to a 30 ps (about one third of the pulse width 100 ps) limit on DGD at point R.

If the PMD coefficient PMD_Q value (as specified in the ITU-T G.65 x-series of Recommendation) is not greater than 0.5 ps/km$^{1/2}$, this gives a total link length of 400 km, while with a maximum PMD coefficient PMD_Q = 0.2 ps/km$^{1/2}$, the total link length becomes 2 500 km. More details are given in § 2.3.

PMD compensation techniques may be used for links with excessive PMD (see Chapter 5). To establish the extent to which PMD compensation is required, a careful investigation of the outside plant may be needed.

1.4 Penalty due to reflections

Reflections are caused by refractive index discontinuities along the optical path. If not controlled, they can degrade system performance through their disturbing effect on the operation of the optical source or amplifier, or through multiple reflections which lead to interferometric noise at the receiver. Reflections from the optical path are controlled by specifying:

i) the minimum optical return loss of the cable plant at the source reference point (e.g. MPI-S), including any connectors; and

ii) the maximum discrete reflectance between source reference points (e.g. MPI-S) and receive reference points (e.g. MPI-R).

Reflectance denotes the reflection from any single discrete reflection point, whereas the optical return loss is the ratio of the incident optical power to the total returned optical power from the entire fibre, including both discrete reflections and distributed backscattering such as Rayleigh scattering.

1.4.1 Minimum optical return loss at MPI-S

Measurement methods for reflections are described in Recommendation ITU-T G.957. For the purpose of reflectance and return loss measurements, points MPI-S and MPI-R are assumed to coincide with the endface of each connector plug. It is recognized that this does not include the actual reflection performance of the respective connectors in the operational system. These reflections are assumed to have the nominal value of reflection for the specific type of connectors used.

The minimum optical return loss of the cable plant at MPI-S is usually limited to 24 dB, but for some interfaces it is 14 dB.

1.4.2 Maximum discrete reflectance between MPI-S and MPI-R

Optical reflectance is defined to be the ratio of the reflected optical power present at a point, to the optical power incident to that point. Control of reflections is discussed extensively in Recommendation ITU-T G.957. The maximum number of connectors or other discrete reflection points, which may be included in the optical path (e.g. for distribution frames, or WDM components), must be such as to allow the specified overall optical return loss to be achieved. If this cannot be done using connectors meeting the maximum discrete reflections cited here, then connectors having better reflection performance must be employed. Alternatively, the number of connectors must be reduced. It may also be necessary to limit the number of connectors or to use connectors having improved reflectance performance in order to avoid unacceptable impairments due to multiple reflections.

The maximum discrete reflectance between MPI-S and MPI-R is generally limited to –27 dB.

2 "Worst case" design for system with optical line amplifiers

(For further information see Supplements 39 and 41 to the ITU-T G-series of Recommendations).

For systems without line amplifiers as described above, the optical budget is based on optical power levels needed to give the required BER in the presence of the receiver electrical noise (see Figure 7-2). In contrast, for multichannel systems with line amplifiers the optical budget is based on OSNR (optical signal to noise ratio) that is needed to give the required BER.

For an optical system without line amplifiers the minimum average optical power at the receiver must be greater than the minimum receiver sensitivity by the value of the optical path penalty. (See § 1.1). For an optical system that includes line amplifiers, because the dominant noise component is ASE (amplifier spontaneous emission) generated in the line amplifiers rather than in the receiver, the equivalent relationship is that the minimum OSNR at the receiver must be greater than the minimum receiver OSNR tolerance by the value of the optical path OSNR penalty. In order to ensure that the electrical noise in the receiver is small compared to the optical noise, there are also constraints on the minimum optical power at the receiver input.

In typical submarine optical transmission systems the budget starts from a linear Quality Factor (Q-factor) which only takes into account degradation due to the ASE (amplifier spontaneous emission) of amplifiers. Then, the optical power budget allocates the penalties/impairments for all types of degradation (due to the optical path, due to terminal equipments, etc., …). The Q-factor, as described in Chapter 6, is related to the BER of the optical systems.

As an example a BER of 10^{-12} corresponds to $Q \approx 7.03$ ($\approx$ 17 dB).

The relation between the Q-factor written in terms of decibels and in linear values is the following:

$$Q \text{ (decibels)} = 20 \times \log_{10} Q \text{ (linear)} \tag{7-3}$$

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

The "worst case" approach adopted in the following clauses is suitable for a system with a small number of components providing reasonable margins to the system. However, for a system with a large number of components, for example a multi-span, multichannel system, the margins obtained from deterministic (worst-case) designs may become unreasonably large. In that situation, network operators, as well as manufacturers, should consider the use of statistical design, which is described in Annex A.

2.1 Relevant parameters for Optical Power Budget

Power budgets of *multi-channel* and multi-span optical systems have been given in Recommendation ITU-T G.698.2. The majority of optical systems with line amplifiers are multichannel systems. The scheme of such a system is in Figure 7-6.

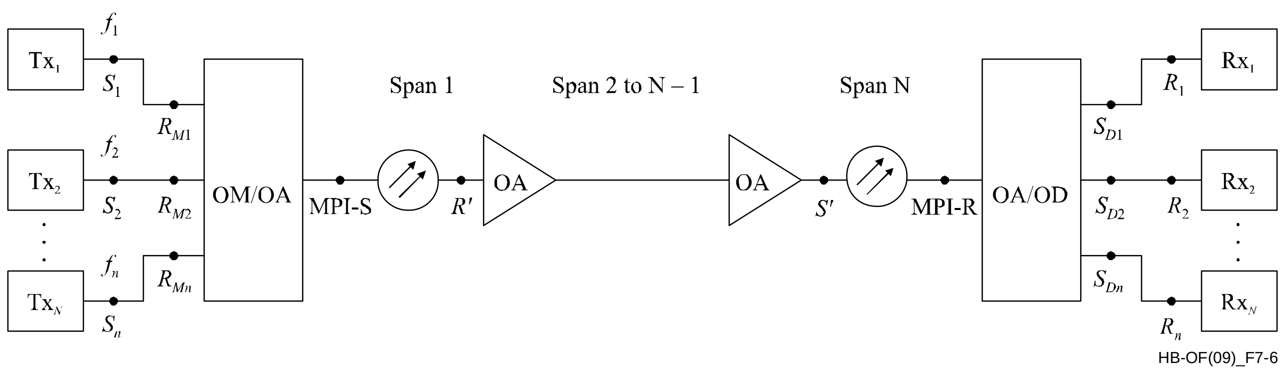
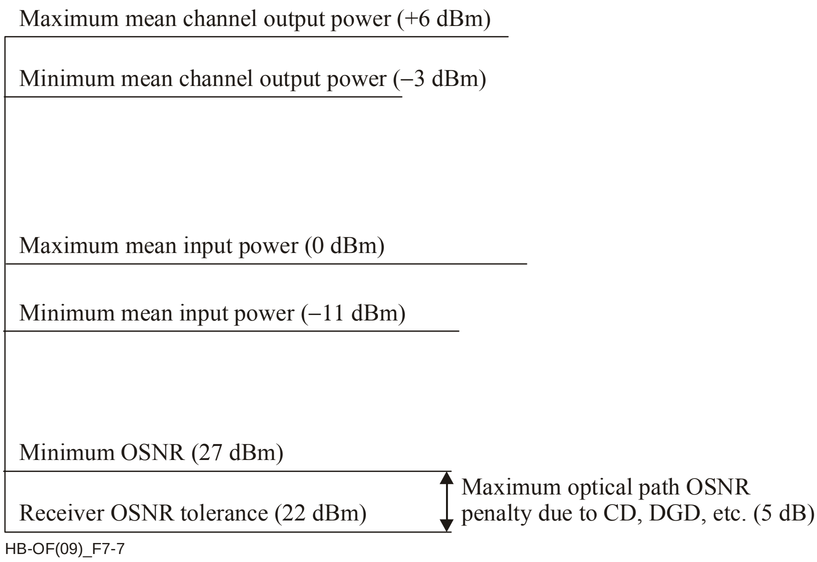


Figure 7-6 – Representation of a multichannel multi-span optical system with the relevant interfaces

An example of a power budget for a multi-channel system with 4-5 spans and with channels operating at 10 Gbit/s with 3-4 optical line amplifiers and with a BER objective of 10^{-12} is shown in Figure 7-7. In this power budget, as an example, are also shown the values of the application code DN100C-2A2(C) of Recommendation ITU-T G.698.2.



Note – This corresponds to application code DN100C-2°2(C) of Rec. ITU-T G.698.2.

Figure 7-7 – Example of power budget for a multi-channel system with 4-5 spans and with a BER objective of 10^{-12}

For this class of systems the following optical parameters are considered:

- maximum mean channel output power;
- minimum mean channel output power;
- maximum mean channel input power;
- minimum mean channel input power;
- minimum OSNR;
- receiver OSNR tolerance;
- maximum optical path OSNR penalty.

The maximum mean channel output power is given in order to limit the non linear effects and consequent penalties.

The minimum mean channel output power is given in order to ensure that there is a sufficiently high optical power at the input to the first optical amplifier in the link that it has an acceptable OSNR at its output.

The minimum OSNR takes into account the noise accumulation of all of the optical amplifiers in the link.

The maximum optical path OSNR penalty is defined as:

Lowest OSNR at R_S – Lowest OSNR at S_S

where:

– lowest OSNR at S_S is the lowest OSNR that meets the maximum BER of the application at point S_S i.e., *before* transmission through the link;

– lowest OSNR at R_S is the lowest OSNR that meets the maximum BER of the application at point R_S i.e., *after* transmission through the link.

This penalty contains the dispersion OSNR penalty, fibre non linearities penalty, interchannel crosstalk penalty, interferometric crosstalk penalty, reflection penalty from the optical path, PMD and polarization dependant loss (PDL) penalty.

It has to be noted that in this power budget there is not the minimum receiver sensitivity because with the use of a pre-amplifier the input level to the electrical receiver is always sufficient to guarantee a BER better than 10^{-12} due to electrical noise Recommendation ITU-T G.663. This means that multi-span optical systems are not limited by the receiver electrical noise.

A suitable margin should be allocated for future modifications of cable configurations and equipment parameters. An example of criteria adopted for the system margin referred to submarine systems is in Annex C.

If it is assumed that the link optical attenuation is compensated by means of optical amplifiers and the chromatic dispersion is compensated by means of chromatic dispersion compensators, then ASE noise and PMD become the most important impairments that limit the capacity and transmission distance of DWDM applications.

The following clauses discuss the fundamental limits for the transmission distance based on cascaded optical amplifiers (ASE noise) and fibre PMD. Moreover a description will be made of the other effects that limit the transmission distance by contributing to the value of the maximum optical path OSNR penalty (residual chromatic dispersion, optical non-linearity, etc.), in order to ensure that the specified value (5 dB in the example of Figure 7-7) is met.

2.2 Limit to the transmission distance due to optical signal to noise ratio

Optical systems that would otherwise be limited in transmission length by optical fibre attenuation can be operated with the use of optical (booster-, line- or/and pre-) amplifiers (see Chapter 5), as considered in the following.

The scheme of an optical system with line amplifiers has been shown in Figure 7-6.

In such a system with a cascaded optical amplifier chain, ASE noise accumulates from the contributions of all optical amplifiers. Therefore, the OSNR degrades after each optical amplifier. OSNR is useful for monitoring and characterizing optical amplifier performance. Equations to estimate the worst-case OSNR, when various simplifying assumptions are made, are given below.

Figure 7-6 depicts a multichannel N span reference system with a booster amplifier, $N - 1$ line amplifiers and a preamplifier. For this reference system, the following main assumptions are made:

i) all optical amplifiers in the chain including booster and preamplifier have the same noise figure;

ii) the losses (per channel) of all spans are equal;

iii) the output powers (per channel) of the booster and line amplifiers are the same.

In this case, the OSNR at the input of the receivers (point R_i in Figure 7-6, $I = 1, \ldots n$) can be approximated as:

$$OSNR = P_{out} - L - NF - 10\log\left(N + \frac{10^{\frac{G_{BA}}{10}}}{10^{\frac{L}{10}}}\right) - 10\log\left(h\nu\nu_r\right) \tag{7-4}$$

where:

P_{out}: output power (per channel) of the booster and line amplifiers (dBm),

L: span loss (dB) (which is assumed to be equal to the gain of the line amplifiers),

G_{BA}: gain of the optical booster amplifier (dB),

NF: signal-spontaneous noise figure of the optical amplifier (dB),

h: Planck's constant (in mJ · s to be consistent, with P_{out} (dBm)),

ν: optical frequency (Hz),

ν_r: reference bandwidth (Hz), typically 0.1 nm, and

$N - 1$: total number of line amplifiers.

The above equation takes into account the shot noise and the signal-spontaneous beat noise as the most dominant noise contributions.

Equation 7-4 indicates that the ASE noise is accumulated from all $N + 1$ amplifiers. It can be simplified in the following cases:

1) If the gain of the booster amplifier is approximately the same as that of the line amplifiers, i.e. $G_{BA} \approx L$, equation 7-4 can be simplified to:

$$OSNR = P_{out} - L - NF - 10\log(N+1) - 10\log(h\nu\nu_r) \tag{7-5}$$

2) The ASE noise from the booster amplifier can be ignored only if the span loss L is much greater than the booster gain $G_{BA.}$ In this case, equation 7-5 can be simplified to:

$$OSNR = P_{out} - L - NF - 10\log(N) - 10\log(h\nu\nu_r) \tag{7-6}$$

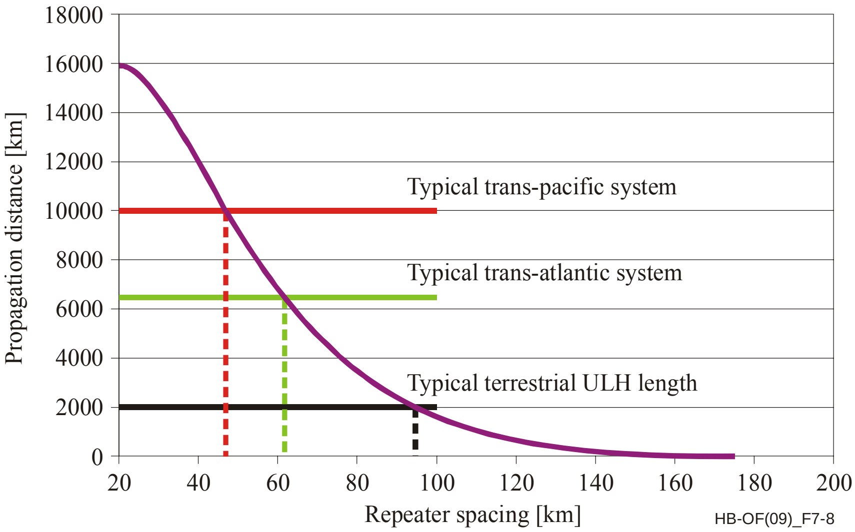
3) Equation 7-5 is also valid in the case of a single span with only a booster amplifier, (e.g. short-haul multichannel) in which case it can be modified to:

$$OSNR = P_{out} - G_{BA} - NF - 10\log(h\nu\nu_r) \tag{7-7}$$

4) In case of a single span with only a preamplifier, Equation 7-5 can be modified to:

$$OSNR = P_{out} - L - NF - 10\log(h\nu\nu_r) \tag{7-8}$$

From the above equations it is possible to evaluate the impact of multiple amplifiers. From equation 7-6 it is clear that OSNR can become quite small for large values of L (span length) and N (number of amplifiers in cascade). For a defined OSNR (necessary for achieving the BER objective) there is a relationship between the length of the link and the repeater spacing (Figure 7-8).



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

Figure 7-8 – Example of repeater spacing required to achieve typical submarine and terrestrial transmission distances

As the system length increases, the possible repeater spacing decreases, in order to maintain the OSNR objective. For links up to 2 000 km (terrestrial links) the repeater spacing can be 80-100 km, while, for transoceanic submarine links (6 000-8 000 km), the maximum repeater spacing is around 50 km. The output power from each of the amplifiers should be chosen to be high enough to maintain a good OSNR, while being low enough to avoid the impairments due to the fibre non linearities.

In practical transmission systems, the losses of the spans are not equal, so equations 7-4 to 7-8 can not be applied. In this case, a general equation to account for the OSNR of any end-to-end path through an optical network is given in equation 7-9.

$$OSNR_{out} = -10\log\left(10^{-\left(\frac{P_{in1}-NF_1-10\log(h\nu_r)}{10}\right)} + 10^{-\left(\frac{P_{in2}-NF_2-10\log(h\nu_r)}{10}\right)} + \ldots + 10^{-\left(\frac{P_{inN}-NF_N-10\log(h\nu_r)}{10}\right)}\right) \quad (7\text{-}9)$$

where:

P_{in1}, P_{in2} to P_{inN}: channel powers (dBm) at the inputs of the amplifiers,

NF_1, NF_2 to NF_N: noise figures (dB) of the amplifiers.

2.3 Limit to the transmission distance due to maximum differential group delay

The maximum differential group delay applies to the whole link between a transmitter and the corresponding receiver (Figure 7-6).

The equation below can be used to calculate the maximum DGD of a link (containing multiple components and fibre sections) with a defined probability of being exceeded:

$$DGD\max_{link} = \left[DGD\max_F^2 + S^2 \sum_i PMD_{Ci}^2 \right]^{1/2} \quad (7\text{-}10)$$

where:

$DGD\max_{link}$: maximum link DGD (ps),

$DGD\max_F$: maximum concatenated optical fibre cable DGD (ps),

S: Maxwell adjustment factor (see Table 7-4),

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

This equation assumes that the statistics of the instantaneous DGD are approximated by a Maxwell distribution, with the probability of the instantaneous DGD exceeding $DGD\max_{link}$ being controlled by the value of the Maxwell adjustment factor taken from Table 7-4.

Table 7-4 – S values and probabilities

Ratio of max. to mean (S)	Probability of exceeding max.	Ratio of max. to mean (S)	Probability of exceeding max.
3	4.2×10^{-5}	4	7.4×10^{-9}
3.2	9.2×10^{-6}	4.2	9.6×10^{-10}
3.4	1.8×10^{-6}	4.4	1.1×10^{-10}
3.6	3.2×10^{-7}	4.6	1.2×10^{-11}
3.8	5.1×10^{-8}		

Further details can be found in Recommendations ITU-T G.650.2 and ITU-T G.691. The value of $DGD\max_F$ (the maximum DGD due to the fibre part) can either be measured or, alternatively, an upper limit can be calculated for a given fibre length using the PMD_Q coefficient in the corresponding fibre Recommendation (see Chapter 1).

The DGD limits to ensure 1 dB penalty for the entire link are given in Table 7-5 for NRZ systems. These values are about one third of the pulse width. In the same table the value of the PMD (mean DGD) not to exceed for an outage probability with "five nines" (1×10^{-5} or 5 minutes/year) are given. These values have been obtained using the Maxwell adjustment factor 3.2 given in Table 7-4.

The total PMD of a fibre link, with total length L and a PMD coefficient for the individual cable sections PMD_Q, is given by $PMD = \sqrt{L} \cdot PMD_Q$. If the PMD coefficient PMD_Q value is not greater than 0.5 ps/km$^{1/2}$, this gives a total link length of 400 km for an optical channel at 10 Gbit/s and with a maximum PMD coefficient $PMD_Q = 0.2$ ps/km$^{1/2}$, the total link length becomes 2 500 km at 10 Gbit/s.

Examples of calculation of the maximum allowed length for an optical link are given in Annex B.

Table 7-5 – Maximum link differential group delay for NRZ

Client class	Units	Pulse width	DGD limit for 1 dB penalty	PMD (mean DGD) limit for an outage probability less than 1×10^{-5}
1.25G	ps	800	240	80
2.5G	ps	400	120	40
10G	ps	100	30	10
40G	ps	25	7.5	2.5

2.4 Penalty due to residual chromatic dispersion after accommodation

Optical amplifiers solve the attenuation problem but, at the same time, worsen the dispersion problem, since, in contrast with the electronic regenerators, an optical amplifier does not restore the amplified signal to its original state. As a result, dispersion-induced degradation of the transmitted signal accumulates over multiple amplifiers. As shown in clause 1.2.2, chromatic dispersion can strongly limit the maximum transmission distance of an optical system. In principle, the group velocity dispersion effects can be minimized using a narrow-linewidth lasers and operating close to the zero-dispersion wavelength of the fibre. However it is not always practical to operate near the zero-dispersion wavelength because of the effects on the non linearities (see § 2.7).

Dispersion accommodation attempts to solve this practical problem by cancelling the pulse broadening caused by the chromatic dispersion so that at the receiver the input signal can be restored. These methods can be classified as *active* methods (used at the transmitter or at the receiver) or as *passive* methods (use of dispersion compensating optical elements along the fibre link).

Some *active* dispersion accommodation techniques are reported in Recommendation ITU-T G.691, such as a prechirp applied in the optical transmitter to obtain pulse compression.

However the most widely used technique is the passive one. The *passive* chromatic dispersion accommodation technique, defined in Recommendation ITU-T G.691, can be used in a long-haul / multi-span high data rate transmission system. A passive dispersion compensator (PDC) can be composed of dispersion-compensating fibres (DCF) or fibre gratings. It can be applied in an optical transmitter with booster amplifier and/or an optical receiver with preamplifier as well as in the mid-stage of an optical line amplifier. The condition for perfect dispersion compensation is that:

$$D_1 \times L_1 = -D_2 \times L_2 \tag{7-11}$$

where:

D_1 and L_1 : dispersion coefficient and the length of the transmission fibre, while

D_2 and L_2 : dispersion coefficient and the length of the DCF.

The practical solution for a system with 10G channels is to add a DCF module (with 6-8 km of DCF) to optical amplifiers spaced at about 80 km. The DCF compensate the chromatic dispersion and the amplifier takes care of the transmission and DCF fibre attenuation. This simple scheme suffers from two problems. The DCF attenuation can be compensated by increasing the amplifier gain at the expense of enhanced ASE (amplified spontaneous emission) noise. Second, because of the small mode field diameter of the DCF, the non linear effects are considerably enhanced. The two problems can be solved by inserting the DCF within a two-stage amplifier (one pre-amplifier and another booster amplifier) (Figure 7-9).

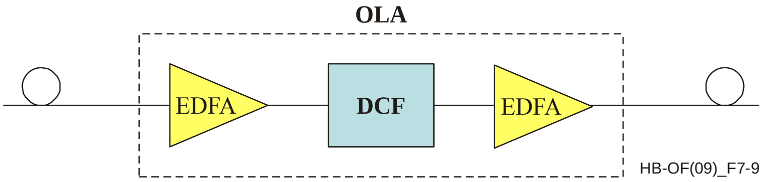


Figure 7-9 – Scheme for passive dispersion compensation for a line amplifier

In order to give a picture of the behaviour of the chromatic dispersion along a link, a dispersion map is used. A dispersion map is the plot of local chromatic dispersion, for a given operating wavelength, as a function of distance from the optical transmitter to the optical receiver. It plots the cumulative dispersion, i.e. the dispersion measured between the output of the terminal transmitter and any other point in the optical path.

In a DWDM system, the PDC can exactly compensate for the chromatic dispersion of one wavelength, but typically it cannot exactly compensate at the other wavelengths (Figure 7-10). The difference in residual dispersion between channels can be minimized in very long systems by applying dispersion compensation and dispersion slope compensation together. Since the chromatic dispersion in a fibre may vary with time/temperature, a high-speed system may need (in very long systems) to be compensated partly by PDC, and partly by dynamically adjusted adaptive compensation (see Chapter 5).

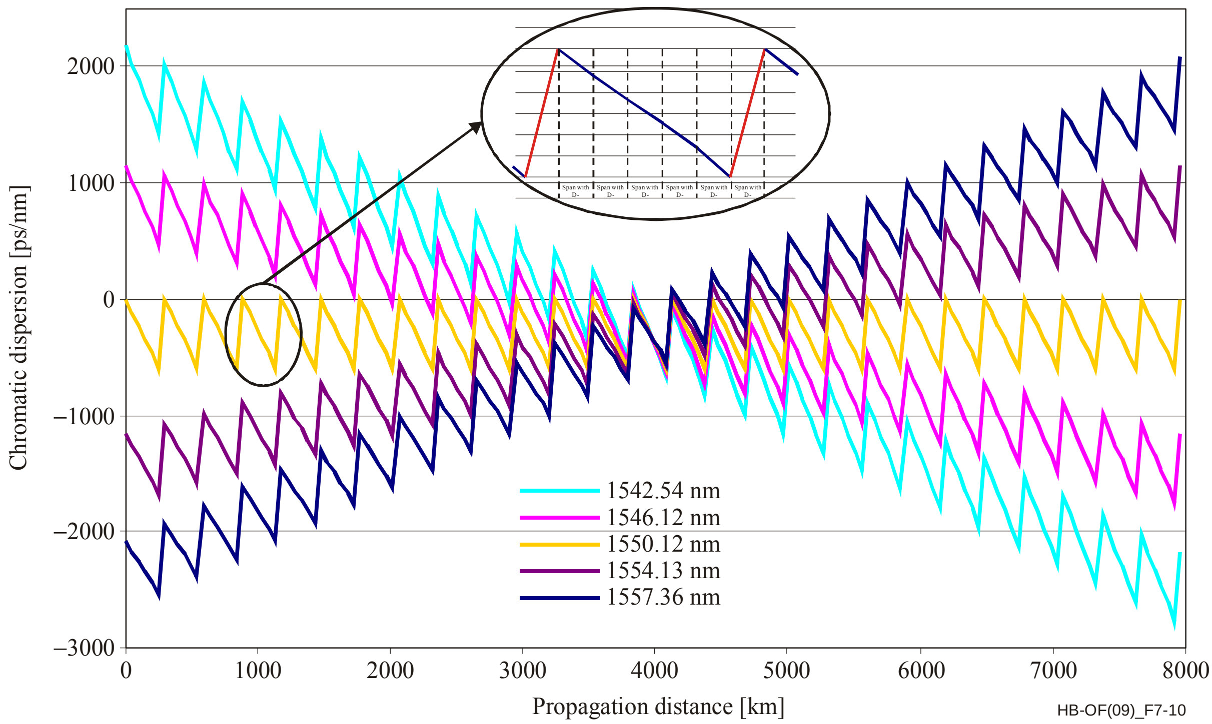


Figure 7-10 – Typical chromatic dispersion map for a submarine WDM system with 163 spans designed for 40 wavelengths centred around 1 550.12 nm

For acceptable operation of DWDM transmission systems over long distances with small channel spacing (e.g., 100 GHz), there is not only the limit for the maximum end-to-end dispersion value, but also a requirement for the local dispersion coefficient of the transmission fibre to have a minimum value, in order to avoid non-linear effects such as four wave mixing (FWM) and cross-phase modulation (XPM).

The value of local chromatic dispersion coefficient required to avoid significant penalties due to these effects depends on many factors of the transmission system design, such as the channel spacing, power level, link length, etc.

In conclusion, the design of the dispersion map for each optical section must be in accordance with the transmission requirements, mainly as a compromise between the limitation of non-linear effects and the pulse broadening.

2.5 Optical crosstalk penalty

(For further information see Supplement 39 to the ITU-T G-series of Recommendations).

One important issue in the design of DWDM systems is optical crosstalk. The system performance degrades whenever crosstalk leads to transfer of power from one channel to another. Optical crosstalk can occur in a perfectly *linear channel* because of the imperfect nature of various WDM components such as optical filters, demultiplexers and photonic cross-connects. Additionally, optical crosstalk can occur because of the *non linear effects* in optical fibres, a phenomenon referred to as nonlinear crosstalk as it depends on the nonlinear nature of the communication channel.

Linear inter-channel crosstalk is less of a problem, because of its incoherent nature, than the interferometric crosstalk that occurs during routing of DWDM systems from multiple nodes.

In the following linear crosstalk mechanisms will be considered as well as their impact on DWDM systems. Nonlinear crosstalk mechanisms will be described in § 2.7 dealing with non-linearities.

2.5.1 Definition of terms

Since the terms used to describe optical crosstalk and its effects are not entirely consistent across the industry, it is useful to briefly define them here (Table 7-6). Within ITU-T, there is a convention that the term "crosstalk" is reserved for description of system effects and that the properties of components use the term "isolation".

2.5.2 Inter-channel crosstalk penalty

A simple approach to calculating the crosstalk power penalty is based on the eye closure occurring as a result of the crosstalk.

The most commonly considered cause of the interchannel crosstalk is imperfect demultiplexing of a multichannel transmission signal into its individual channels prior to a set of single-channel receivers. This situation is depicted in Figure 7-11.

Here, a number of DWDM channels enter the common port of a demultiplexer. The worst case for any particular channel is for its power to be at the minimum and that of all of the other channels to be at the maximum. The maximum allowable difference between channels has been denoted as d (dB). When the channels emerge from the individual output ports, the disturbing channels have been attenuated with respect to the wanted channel by an amount equal to the Unidirectional Isolation I (dB).

The main parameter that governs the maximum level of optical crosstalk that can be tolerated in any given optical system is the inter-channel crosstalk penalty P_C. From this, and a small number of other parameters, it is necessary to be able to obtain the required isolation parameters of the demultiplexer.

Table 7-6 – Terms used

Parameter unit	Symbol	Defined in	Definition
System parameters			
Inter-channel crosstalk (dB)	C_C	ITU-T G.692	Ratio of total power in the disturbing channels to that in the wanted channel. (Wanted and disturbing channels at different wavelengths (k total)).
Interferometric crosstalk (dB)	C_I	–	Ratio of the disturbing power (not including ASE) to the wanted power within a single channel (wavelength). This parameter is also known as "Intra-channel crosstalk".
Inter-channel crosstalk penalty (dB)	P_C	–	Penalty assigned in the system budget to account for inter-channel crosstalk.
Interferometric crosstalk penalty (dB)	P_I	–	Penalty assigned in the system budget to account for interferometric crosstalk.
Channel power difference (dB)	D	ITU-T G.959.1	The maximum allowable power difference between channels entering a device.
Extinction ratio (linear used here)	*R*	ITU-T G.691	Ratio of power at the centre of a logical "1" to the power at the centre of a logical "0".
Eye-closure penalty (dB)	E	–	Receiver sensitivity penalty due to all eye-closure effects. This includes transmitter eye-closure and chromatic dispersion penalty.
Component parameters			
Insertion loss (dB)	IL	ITU-T G.671	The reduction in power from input to output port at the wanted channel wavelength.
Unidirectional Isolation (dB)	I	ITU-T G.671	The difference between the device loss at a disturbing channel wavelength and the loss at the wanted channel wavelength.
Adjacent channel isolation (dB)	I_A	ITU-T G.671	The isolation of the device at the wavelengths one channel above and below the wanted channel.
Non-adjacent channel isolation (dB)	I_{NA}	ITU-T G.671	The isolation of the device at the wavelengths of all disturbing channels except for the adjacent channels.

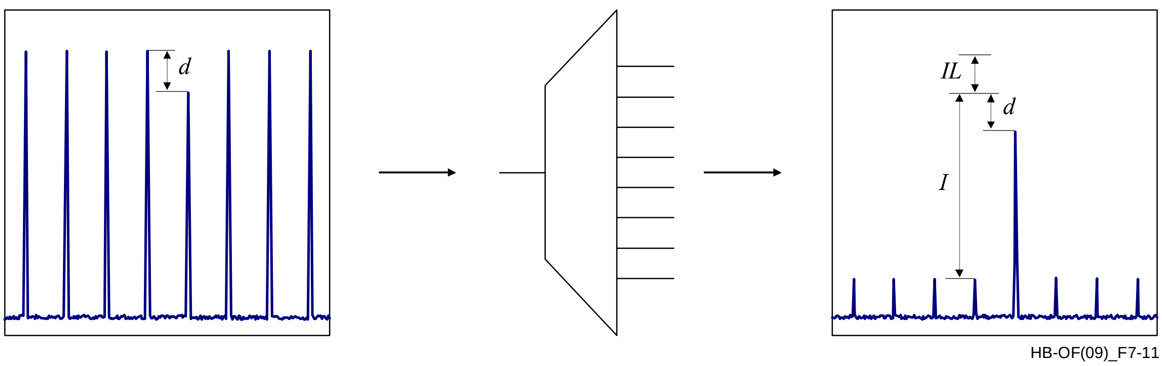


Figure 7-11 – Simple demultiplexer example

The induced optical penalty is plotted in Figure 7-12 against inter-channel crosstalk for different values of the extinction ratio (*r*), of the eye closure and of the DWDM channels which are the source of the crosstalk. The actual penalty incurred in a practical system lies somewhere below the highest curve.

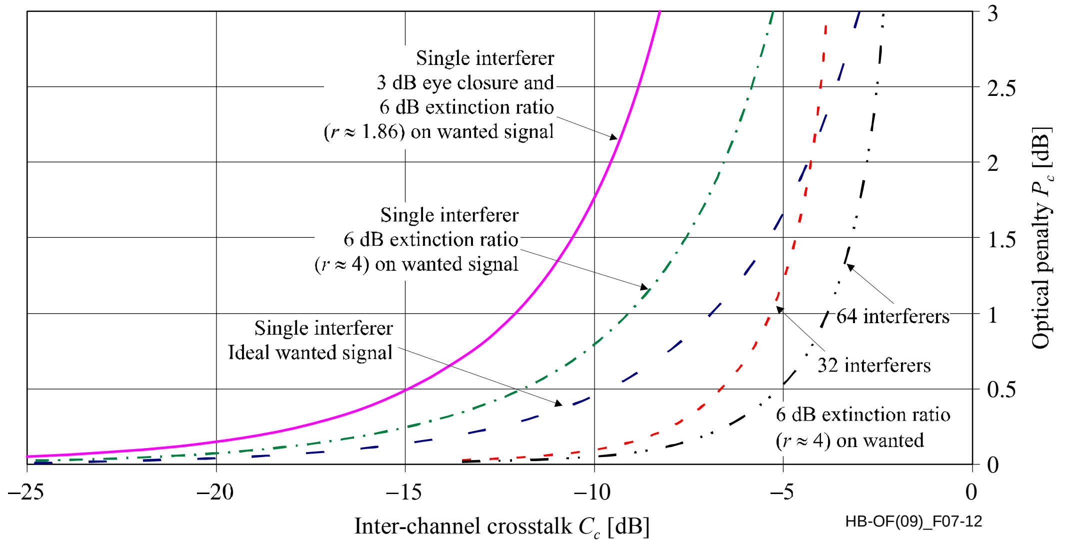


Figure 7-12 – Graph of optical penalty vs inter-channel crosstalk

The crosstalk penalty may also be dependent on the line code (RZ or NRZ) and the relative bit rates of the wanted and the number of the interferer signals.

As an example, a value of –16 dB is specified in Recommendation ITU-T G.698.2, which, according with the above figure, means a power penalty of about 0.5 dB.

2.5.3 Interferometric crosstalk penalty

Interferometric crosstalk results from DWDM components used for routing and switching along an optical network. The impact of the interferometric crosstalk on system performance should again be seen on the basis of the power penalty.

Interferometric crosstalk occurs when the disturbing channel and the wanted channel are at the same nominal wavelengths. Four examples of this are:

i) in an optical add-drop multiplexer where the wavelength in question is incompletely dropped before the new signal is added;

ii) in an optical multiplexer where one transmitter may be emitting power at the wavelength of another channel (e.g. due to inadequate side-mode suppression ratio); this is termed transmit-side crosstalk in Recommendation ITU-T G.692;

iii) in an optical cross-connect where lack of sufficient switch isolation causes light from more than one source fibre to reach the receiver;

iv) in any component or group of components where there is more than one path that the light can take to reach the receiver. This is called multi-path interference.

Interferometric crosstalk behaves differently from inter-channel crosstalk when the two optical signals are sufficiently close together that their beat frequency is within the electrical bandwidth of the receiver. In this case, it is the optical fields which interact to produce the crosstalk instead of the optical powers and, consequently, the levels of crosstalk required to produce a particular penalty are much smaller.

For a single interferer the crosstalk can be modelled as having a bounded probability density function (PDF). The interferometric crosstalk penalty for a wanted signal with 6-dB extinction ratio is plotted in Figure 7-13.

As an example, a value of –40 dB is specified in Recommendation ITU-T G.698.2, which, according with the above figure, means a power penalty of about 0.3 dB.

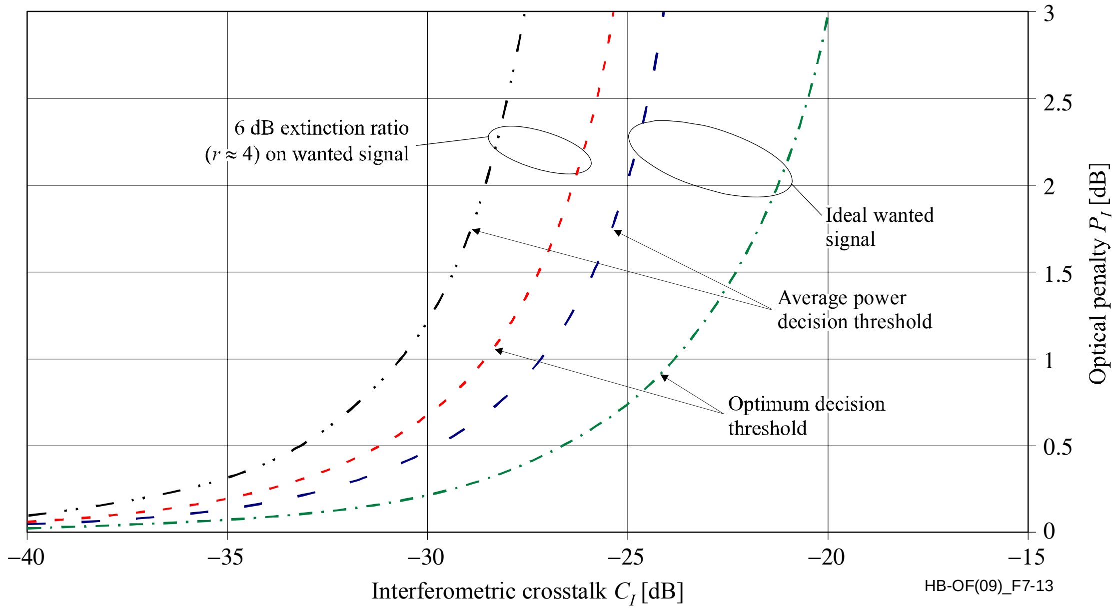


Figure 7-13 – Graph of optical penalty vs interferometric crosstalk for multiple interferers (Gaussian model)

2.6 Penalty due to reflections

The same considerations apply here as for clause 1.4 only changing the interface notation from single-channel (MPI-S) to multichannel (MPI-S_M) at the source reference point and (MPI-R) to (MPI-R_M) at the receiver reference point.

2.7 Penalty due to fibre non linearities

(For further information see Recommendations ITU-T G.650.3, ITU-T G.663 and Supplement 41 to the ITU-T G-series of Recommendations).

Non-linear interactions between the signal and the transmission medium (silica fibre) begin to appear as optical signal powers are increased to achieve longer span lengths at high bit rates. Consequently, non-linear fibre behaviour has emerged as an important consideration, both in high capacity systems and in long unregenerated routes. These non-linearities can be generally categorized as either *scattering effects* (stimulated Brillouin scattering and stimulated Raman scattering) or *effects related to the Kerr effect*, that is, the intensity dependence of the refractive index (particularly self-phase modulation in single-channel systems, cross-phase modulation and four wave mixing in multi-channel systems).

The influence of these non-linear phenomena increases with the optical input power. As a consequence, the system performance can be strongly degraded by such effects, if the fibre input optical power is very high. On the other side, the system performance is also degraded at low fibre optical input power, due to the low optical signal-to-noise ratio at the receiver. Therefore, a compromise should be found for a given system performance (BER) between the minimum input power level (to limit the noise) and the maximum output power threshold to limit the non-linearity effects.

Moreover a variety of parameters, in addition to the optical input power, influence the severity of these non-linear effects, including fibre dispersion characteristics, the effective area of the fibre, the non linear coefficient, the number and spacing of channels in multiple channel systems, overall unregenerated system length, the degree of longitudinal uniformity of the fibre characteristics, as well as source line width. A description of the influence of all these parameters on the non-linear phenomena is given in the following.

2.7.1 Stimulated Brillouin Scattering

In a lightwave communication system using an optical source with a narrow line width, significant optical power may be transferred from a forward-propagating signal to a backward-propagating signal when the stimulated Brillouin scattering (SBS) power rating of the optical fibre is exceeded. The scattered light is downshifted (or Brillouin-shifted) by approximately 11 GHz at 1 550 nm.

Of the single channel non-linear effects described here, SBS has the lowest threshold power. While studies have shown that the SBS threshold can vary between fibre types and even among individual fibres, it is typically in the order of 5 to 10 mW for externally modulated, narrow linewidth sources, but may be 20 to 30 mW for directly modulated lasers. The SBS threshold for a system deployed on ITU-T G.653 fibre is slightly lower than that for a system using ITU-T G.652 fibre, due to the smaller effective area of ITU-T G.653 fibre. This is generally true for all of the non-linear effects. The SBS threshold is sensitive to the source linewidth and power level. It is independent of the number of channels.

SBS effectively limits the amount of light that can be transmitted through a fibre path. Figure 7-14 shows this effect for a narrow-band source, where all of the signal power falls within the Brillouin bandwidth. The transmitted power becomes saturated and the backscattered power rapidly increases.

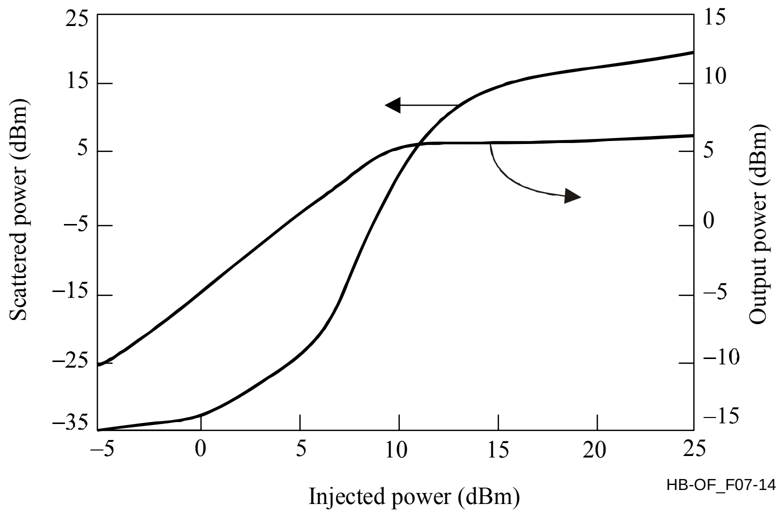


Figure 7-14 – Stimulated Brillouin scattering effect for narrow-band source

Stimulated Brillouin scattering impairments will not arise in systems where the source linewidth significantly exceeds the Brillouin bandwidth or where the signal power is below the threshold power.

Several possible definitions of SBS power rating are provided. The common concept among these, however, is that the input power at which SBS becomes important is in the regime where the backscatter power begins increasing rapidly. Because of the exponential increase in backscatter power, the range of input powers in this regime is rather narrow, so all definitions give similar (though not identical) results.

SBS does not present a practical limitation to the deployment of current long haul DWDM transmission systems because XPM (see clause 2.7.4) limits the performance at lower power levels than SBS.

2.7.2 Stimulated Raman scattering

Stimulated Raman scattering (SRS) causes a signal wavelength to behave as a Raman pump for longer wavelengths. In this case, the shorter wavelength signal is attenuated by this process, which amplifies the longer wavelength signal.

Stimulated Raman scattering can occur in both single- and multiple-channel systems. Signal powers in the order of 1W or more are needed to experience impairment from this phenomenon with only a single channel without line amplifiers. However, shorter wavelength signals in multiple-channel systems with channels spanning a wide wavelength range can suffer degraded signal-to-noise performance when a portion of their power is transferred to longer wavelength channels through SRS. This results in total system capacity limitations based on the total number of channels, channel spacing, average input power and overall system length. In particular, the threshold for the observation of a 1 dB penalty in a multi-channel system due to Raman gain in dispersion-unshifted fibre can be estimated to be:

$$P_{tot} \bullet \Delta\lambda \bullet L_{eff} < 40 \text{ mW} \bullet \text{nm} \bullet \text{Mn} \qquad (7\text{-}12)$$

where:

P_{tot}: combined power of all of the channels,

$\Delta\lambda$: optical spectrum over which the channels are distributed, and

L_{eff}: effective length (in units of 10^6 metres (Mm)).

The SRS threshold for a system deployed on ITU-T G.653 fibre is slightly lower than that for a system using ITU-T G.652 fibre, due to the smaller effective area of ITU-T G.653 fibre. SRS does not practically degrade single-channel systems; conversely it may limit the capability of WDM systems.

In single-channel systems, filters can be used to remove the unwanted spectrum. However, no practical techniques to eliminate the effects of SRS in multiple-channel systems have been reported. The effects of SRS may also be mitigated by reducing the input optical power. However, SRS does not present a practical limitation to the deployment of currently contemplated WDM systems because the SRS induced loss (and gain) values are modest for the power levels that are limited by XPM effects (see clause 2.7.4).

2.7.3 Self phase modulation

Because a fibre's refractive index depends on the optical intensity of the signal, the temporal variation of the optical intensity of the signal induces a modulation of its own phase. This effect is called self phase modulation (SPM). The fibre refractive index may be written as:

$$n = n_0 + \frac{n_2}{A_{eff}} P \qquad (7\text{-}13)$$

hence:

$$\frac{\partial n}{\partial t} = \frac{n_2}{A_{eff}} \frac{\partial P}{\partial t} \qquad (7\text{-}14)$$

where:

n_2: fibre nonlinear refractive index (m^2/W),

A_{eff}: fibre effective area, and

P: launched power.

In single wavelength systems, self phase modulation will gradually broaden the signal spectrum when changes in optical intensity result in changes in phase (Figure 7-15). Once spectral broadening is introduced by SPM, the signal experiences a greater temporal broadening as it propagates along the length of the fibre, due to the effects of chromatic dispersion, in the normal dispersion region of the fibre (i.e. below the zero-dispersion wavelength).

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

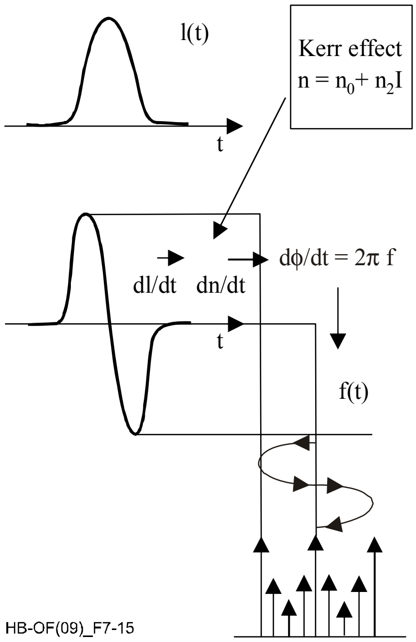


Figure 7-15 – Spectral broadening mechanism due to self phase modulation

The use of ITU-T G.653 fibre and the placement of the signal channel near the dispersion zero will reduce the impact of SPM. For systems less than approximately 1 000 km, SPM may be controlled through the implementation of dispersion compensation at appropriate intervals along the length of an ITU-T G.652 fibre system. The effects of SPM may be mitigated by operating at wavelengths above the zero-dispersion wavelength of ITU-T G.655 fibre. Fibres with attributes of increased fibre effective area, or decreased nonlinear refractive index, also reduce the SPM penalty. For all fibre designs, SPM effects may be reduced by decreasing the launched channel powers, though systems design trends call for larger powers to allow longer span distances.

2.7.4 Cross phase modulation

In multichannel systems, cross phase modulation (XPM) will gradually broaden the signal spectrum when changes in optical intensity result in changes in phase due to interactions between adjacent channels. The amount of spectral broadening introduced by XPM is related to the channel separation and fibre chromatic dispersion, since the dispersion-induced differential group velocities will cause the interacting pulses to separate as they propagate down the fibre. Once spectral broadening is introduced by XPM, the signal experiences a greater temporal broadening as it propagates along the length of the fibre due to the effects of chromatic dispersion.

The systems penalty from XPM is increased by smaller channel spacings and larger channel counts (though this saturates depending on distance). As noted for SPM, the change in signal phase is related to the change in fibre refractive index, which in turn is related to the channel power. Larger average launched powers lead to larger phase shifts, which when combined with dispersion effects lead to a larger system penalty.

The XPM penalty actually decreases for higher channel bit rates, since lower bit rate signals experience longer bit interactions or "walk-through". However, since higher bit rate receivers require higher OSNR for a given BER, these systems have to operate at higher power levels, which negates this effect.

The broadening due to XPM may result in interference between adjacent channels in multiple-channel systems. XPM can be controlled through appropriate selection of channel spacing. Studies have shown that only adjacent channels contribute significantly to XPM-induced signal distortion in multiple-channel systems. The Signal-to-Noise Ratio (SNR) of the centre channel of a three-channel system will approach that of a single-channel system as channel separation is increased. As a result, the effect of XPM can be rendered negligible with adequate spacing between the signal channels. Channel separations of 100 GHz were shown to be sufficient to reduce XPM effects in a simulation of a system with 5 mW of power/channel. Dispersion penalties due to XPM may also be controlled by the implementation of dispersion compensation at appropriate intervals along the length of the system. Fibres with attributes of increased fibre effective area, or decreased nonlinear refractive index, also reduce the XPM penalty.

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

2.7.5 Four-wave mixing

Four-wave mixing (FWM), also called four-photon mixing, occurs when the interaction of two or three optical waves at different wavelengths generates new optical waves, called mixing products or sidebands, at other wavelengths.

This interaction can occur between signals in multiple-channel systems, between OA ASE noise and a single channel, as well as between the main mode and side modes of a single channel. In the case of two signals, the intensity modulation at their beat frequency modulates the fibre refractive index and produces a phase modulation at a difference frequency. The phase modulation creates two sidebands at frequencies given by this difference. In the case of three signals, more and stronger mixing products are produced (Figure 7-16) which will fall directly on adjacent signal channels when the channel spacings are equal in frequency. Two optical waves propagating along a fibre produce FWM with high efficiency if the phase matching condition is achieved between sidebands and initial signals.

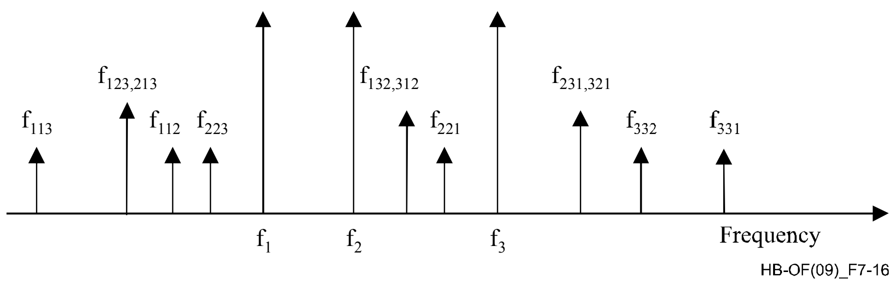


Figure 7-16 – Mixing products generated by four-wave mixing of three signals

Assuming that all channels have the same input power and equal channel spacing, the FWM efficiency, η, of a fibre can be expressed as the ratio of the FWM power to the per channel output power from the fibre and is proportional to:

$$\eta \propto \left[\frac{n_2 P}{A_{eff} D (\Delta\lambda)^2}\right]^2 \tag{7-15}$$

where:

- n_2: fibre nonlinear refractive index,
- P: channel input power,
- A_{eff}: fibre effective area,
- D: fibre chromatic dispersion coefficient, and
- $\Delta\lambda$: channel spacing.

Note that FWM efficiency is not influenced by increasing bit rate.

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

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

As seen by the equation (7-15), increased frequency spacing and local chromatic dispersion reduce the efficiency of the FWM process by destroying the phase matching between the interacting waves. However, systems are trending towards decreased frequency spacings, to allow more channels to occupy the same OA passband. Furthermore, as launched channel powers increase, the FWM efficiency (and hence system penalty) also increases.

Multichannel systems deployed in the 1 550 nm operating window over ITU-T G.652 fibre experience much less FWM impairment compared to systems deployed over ITU-T G.653 fibre, because ITU-T G.652 fibre has much more local chromatic dispersion, as well as larger fibre effective area. Conversely, the placement of a signal channel directly at or near the dispersion zero can result in a very significant buildup of FWM products over a relatively short fibre length (i.e. some hundreds of metres).

In the 1 550 nm zero dispersion region, four-wave mixing can create serious system impairment in multi-channel systems on ITU-T G.653 fibre, since the signal channels experience only a small value of local chromatic dispersion.

The non-zero dispersion shifted fibre, ITU-T G.655 fibre, has been developed to eliminate FWM effect in the C-Band. As a matter of fact this fibre has a small, but not zero, chromatic dispersion coefficient around 1 550 nm, to limit both the effect of the chromatic dispersion and the FWM effects. However, four-wave mixing may also impair multichannel systems, even on ITU-T G.655 fibre, depending on channel spacings of 50 GHz or less, fibre dispersion, and fibre nonlinear coefficient (proportional to the nonlinear refractive index divided by effective area).

As previously noted, chromatic dispersion may be used to suppress the generation of the FWM sidebands. Fibres with attributes of increased fibre effective area, or decreased nonlinear refractive index, also reduce the FWM efficiency. Uneven channel spacing Recommendation ITU-T G.692 may also be incorporated to mitigate the severity of the FWM impairment. Uneven channel spacing ensures that mixing products generated by three or more channels do not fall directly on other channel wavelengths. Reduction of the input power levels in ITU-T G.653 fibre systems could permit multiple channel operation, but might compromise the economic advantages of optical amplification.

2.7.6 Examples of maximum power threshold due to non-linear effects

Some factors that affect the maximum power threshold due to non-linear effects are the following:

i) Type of fibre used for the transmission

Fibres characterized by different non-linear coefficients and dispersion coefficients have very different behaviours regarding non-linear effects.

As an example, dispersion-compensating fibres (DCFs) have a small effective area and consequently a large non-linear coefficient. It has been verified with simulations that for optical input powers $P_{in} > 3$ dBm SPM starts degrading the system performance.

ITU-T G.652 fibres have a small non-linear coefficient and consequently SPM is in general negligible except at very high optical input powers (e.g. for $P_{in} > 8$ dBm, post-compensation scheme and amplifiers spacing of 100 km, SPM starts degrading the ideal linear of behaviour). Moreover, the high local dispersion typical of ITU-T G.652 fibres makes XPM and FWM effects quite negligible, assuming that the dispersion is exactly compensated.

ITU-T G.655 fibres have approximately the same behaviour as ITU-T G.652 fibres with respect to SPM, but, having a smaller dispersion coefficient, FWM is not negligible.

ii) Scheme of dispersion compensation

The following three schemes for dispersion compensation are characterized to different behaviour with respect to SPM have been considered:

– *Pre-compensation:* The dispersion compensating device is placed at the beginning of each span before the transmission fibre. This scheme is strongly subject to SPM. Simulation with amplifier spacing of 100 km, link length of 500 km, and amplifiers $NF = 6$ dB, showed that the maximum input power for $Q = 7$ is $P_{in} = 4$ dBm.

– *Post-compensation:* The dispersion compensating device is placed at the end of each span after the transmission fibre. Simulation with amplifier spacing of 100 km, link length of 500 km, and amplifiers $NF = 6$ dB, showed that the maximum input power for $Q = 7$ is $P_{in} = 13$ dBm.

– *Post-compensation + prechirp:* As post-compensation, but at the beginning of the link the pulse is pre-chirped. The optimum prechirp value, calculated by means of simulations, strongly reduces SPM effects.

iii) Span length

Due to fibre losses, the optical input power decays according to an exponential law during propagation in a span. On the other hand, the influence of non-linear effects depends on the optical power value. As a consequence, the maximum input power threshold due to non-linear effects has different values for systems that differ only in the amplifier spacing parameter.

For example, consider a 500-km link on ITU-T G.652 fibre with post-compensation and amplifiers $NF = 6$ dB. If the span length is 100 km, simulations show that the maximum input power for $Q = 7$ is $P_{in} = 13$ dBm. If the span length is 50 km, simulations show that the maximum input power for $Q = 7$ is $P_{in} = 8$ dBm.

In conclusion it is impossible to pick out a single value for the maximum optical input power to achieve a Q-factor greater than 7 (BER = 10^{-12}). This maximum input constraint may be used to identify the best performance region of a system and can be determined by means of preliminary simulations with the desired system parameters (type of fibre, dispersion compensation, amplifier spacing, channel spacing). Finally, notice that all suggestions reported here are based on the assumption of RZ modulation format, and they investigate neither the number of WDM channels nor their frequency spacing.

3 Forward error correction impact on optical system design

Forward error correction (FEC) is an important way of improving the performance of large-capacity long-haul optical transmission systems. With the use of FEC system design can accept relatively large BER (much more than 10^{-12}) in the optical transmission line (before decoding). FEC application may allow the optical parameters to be significantly relaxed and encourages the construction of large capacity long-haul optical transmission systems in a cost-effective manner.

FEC characteristics (in-band FEC, out-of-band FEC, coding Gain, net-coding gain) have been described in Chapter 6. Some FEC aspects related to system design are dealt with in the following.

FEC has been proven to be effective in OSNR-limited systems as well as in dispersion-limited systems. As for non-linear effects, reducing the output power leads to OSNR limitations, against which FEC is useful. FEC is less effective against PMD, however.

Candidates of optical parameter relaxation with FEC are described below.

3.1 Relaxation of transmitter and/or receiver characteristics

The maximum BER can be relaxed from 10^{-12} toward the values listed in the third row in Table 7-7.

Table 7-7 – Performance of standard FECs

Application	In-band FEC BCH (4359,4320)	Out-of-band FEC RS (255,239)
	SDH	OTN
BER_{in} for $BER_{out} = BER_{ref} = 10^{-12}$	2.9×10^{-6}	1.8×10^{-4}
Coding gain ($BER_{ref} = 10^{-12}$) (dB)	3.8	5.9
Net coding gain ($BER_{ref} = 10^{-12}$) (dB)	3.8	5.6
Code rate	1	239/255

This allows a reduced signal-to-noise ratio at the decision circuitry. Assuming a given OSNR in a reference system without FEC is sufficient to produce the required BER, the coding gain provided by adding FEC to the system can be used to relax component parameters in the transmitter and/or receiver. There are many parameters which could benefit from this such as the requirements for total launched power, eye mask, extinction ratio, electrical noise of a PIN receiver, noise figure of an optical pre-amplifier, isolation of demultiplex filters or, to some extent, the characteristic of the receiver transfer function determining the intersymbol interference and noise bandwidth before decision.

3.2 Reduction of output power levels to save pump power

Reducing the output power levels of transmitter and line amplifiers by the net coding gain (NCG) value leads to reduced OSNR at the end of an optical amplifier chain. The associated higher electrical noise and, therefore, higher BER is compensated by FEC. The same principle can be applied to a single-span application with an optically pre-amplified receiver. Deploying FEC in a single-span system without an optically pre-amplified receiver gives a transmitter output power saving of only half of the NCG value because, in this case, the system is limited by receiver electrical noise.

3.3 Reduction in power levels to avoid non-linearity

Reducing the output and input power levels of the optical amplifiers forces a system limited by non-linear effects to become OSNR limited, provided that the other parameters are unchanged. For example, after the power levels are decreased, the multichannel system parameters for ITU-T G.652 and G.655 fibre can also be applied to ITU-T G.653 fibre. Thus, a common system specification becomes possible that is valid for all fibre types.

3.4 Increase in maximum span attenuation

If the multi-span system is not chromatic dispersion limited (using ITU-T G.652 fibre with dispersion accommodation, ITU-T G.653 fibre, or ITU-T G.655 fibre), target span distance can be extended. The input power of each line amplifier can be decreased by the amount of the net coding gain. Therefore, the maximum span attenuation can be increased by the amount of the net coding gain (maximum case). The relaxation may eliminate unnecessary repeaters in a system with slightly larger loss than that specified.

In a single-span system without preamplifier, the increase of maximum path attenuation is half of the NCG value only because, in this case, the system is limited by receiver electrical noise.

3.5 Increase in maximum number of spans for a long-haul system

The total target distance of a long-haul system can be extended enormously by increasing the number of spans (and also line amplifiers) assuming that chromatic and polarization mode dispersion do not become limiting factors (i.e., the system remains OSNR limited). Providing that the attenuation of each span is the same and remains constant, the maximum number of spans can be increased by a factor given by the NCG value. In the case of standard out-of-band FEC, the target distance may be increased by a factor of almost 4. An example is given in Annex B.

3.6 Increase in channel count for high-capacity systems

If a multi-span system is limited by the output power of the optical amplifiers, the channel count can be increased by a factor given by the NCG value. In the case of standard out-of-band FEC, the channel count may be increased by a factor of almost 4. It should be noted, that this approach can be used as long as the reference system was not supported by non-linear effects which may change by reducing the channel power. For example, SPM cannot be used to compensate for chromatic dispersion if the channel power becomes less than the SPM threshold.

4 Reliability consideration (for submarine optical systems)

(For further information see Supplement 41 to the ITU-T G-series of Recommendations).

Submarine networks require reliable and robust fibre optical systems to avoid costly repairs in the wet plant. Failures occurring during the system life may be due to internal faults (shunt fault, fibre loss increase, repeater failures, card failures, etc.) or external aggressions (e.g. anchors and fishing activities for wet plant and misoperation for dry plant).

4.1 Reliability requirement

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

i) Failure rate (λ) generally expressed in FIT (Failure in time); 1 FIT represents 10^{-9} probability to fail during 1 hour of operation. This value tends to be temperature dependent and has to be recorded at the operating temperature;

ii) Mean time between failures (MTBF): expected time between 2 consecutive failures.

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

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

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

– Mean time to repair (MTTR): expected time needed to repair a failure,

– Outage = MTTR / MTBF: amount of time usually expressed in minutes per year when the network is not available to perform its function,

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

4.2 Internal fault

In order to achieve the reliability target in submarine systems (minimizing internal faults) and to establish a maintenance policy applicable during the entire system life, the failure root causes should be identified at component, sub-system and system levels.

4.2.1 Failure rate analysis

i) Infant mortality

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

ii) Random failure

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

iii) Ageing

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

The failure rate behaviour is conventionally described as a bathtub curve during the life of the system, as shown in Figure 7-17.

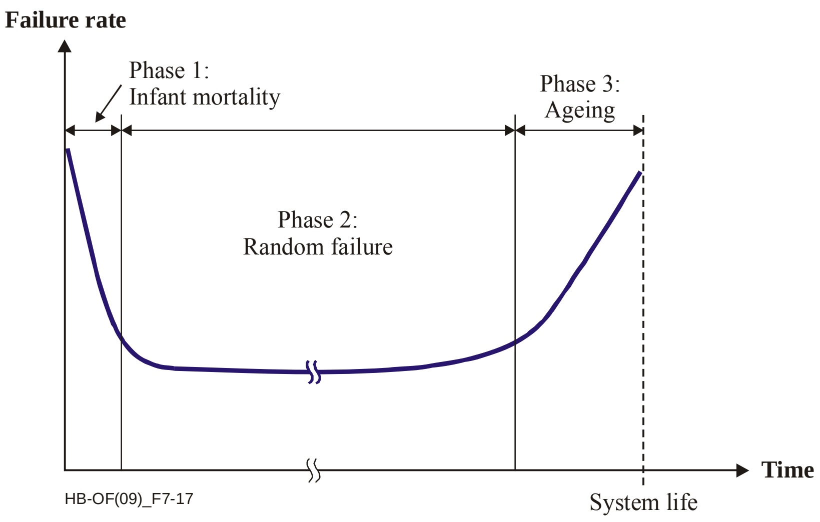


Figure 7-17 – Typical failure's rate behaviour during the life of a system

4.2.2 Submerged section reliability

The submerged section is more critical than the land section of a submarine system in terms of reliability because the MTTR is greater. Typical MTTR values give around 2 weeks (the intervention of a cableship is necessary) for the submerged section repair instead of 2 hours for the land section. From a reliability point of view, this is why the failure rate for laser pumps used within the repeaters is a sensitive issue for the system. For example, typical failure rates for amplifiers in terrestrial networks are within 1 000 to 10 000 FIT compared to submarine amplifiers, which are within 10 to 100 FIT (around 2 orders of magnitude lower).

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

Repeaters are critical equipment as they contain electronic, optical and opto-electronic components. Consequently careful precautions must be taken to prevent and reduce the risk of failure. In particular, an optical failure occurring on a specific fibre must not affect the system performances of the other fibres.

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

It is quickly apparent that a test condition is required to accelerate the time to failure in a predictable and understandable way. It should also be recognized that a system includes a variety of different manufacturing processes and assembly procedures and each one should be tested. For both economical purpose and technical feasibility, the reliability requirements make necessary the use of accelerated tests.

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

4.3 External fault

External faults usually occur in the cable sections. As a matter of fact, the main causes of failure are aggressions such as bottom fishing, fishing trawlers, ocean currents, geological events (earthquakes and volcanoes) and thermal failures due to overload. Nearly 90 percent of the failures are caused by fishing activities and damage from ship anchors. To protect the cable against these various factors, the wet plant can be buried in the shallow water except in rocky areas, where seabed conditions don’t allow burial. Additionally, the cable route is selected to avoid as much as possible geological hazards (See Chapter 4).

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

In order to minimize the impact on traffic of such faults, the overall network availability is increased through route diversity when possible. In the event of a fault in the wet plant leading to a loss of transmission, the traffic is usually rerouted onto a protection path.

Annex A

Statistical design for systems with line amplifiers

For a system with a small number of components, deterministic (or "worst case") design is useful, providing reasonable margins to the system. However, for a system with a large number of components, for example a multi-span, multichannel system, the margins obtained from deterministic designs may become unreasonably large. In that situation, network operators, as well as manufacturers, should consider the use of statistical design.

A.1 Generic methodology for the statistical design

System parameters (e.g. maximum attenuation or maximum chromatic dispersion of the link) are distinguished from element parameters (e.g. attenuation coefficient or dispersion coefficient of fibre bobbin product). System parameters are to be determined by the system design in which statistical properties of the element parameters are considered. Examples of the relationship between system and element parameters are shown in Table 7A-1.

Table 7A-1 – Relationship between system and element parameters

System parameter	Element parameter	Described in
Maximum attenuation	Fibre cable attenuation coefficient, transmitter output power, receiver sensitivity, power penalty, splice loss, connector loss	A.5 Statistical design of loss and gain
Maximum chromatic dispersion	Fibre dispersion coefficient, transmitter spectral width	A.6 Statistical design of chromatic dispersion
Maximum DGD	Cable PMD coefficient, power division between principal states of polarization, other elements in the link	A.7 Statistical design of DGD
Maximum output power	Cable attenuation coefficient, fibre zero-dispersion wavelength, fibre effective area, fibre non-linear coefficient, channel spacing	Not described

Supplement 39 to the ITU-T G-series of Recommendations proposes that only one system parameter in any particular system should be considered statistically. For example, in dispersion-limited systems, maximum chromatic dispersion is statistically considered, while the other system parameters are treated using the ordinary, worst-case design approach.

A.2 System outage probability

System outage probability is usually defined as the probability of BER exceeding 10^{-12}. However, since BER depends on many parameters (e.g. transmitter and receiver characteristics), it is difficult to refer to BER in generic statistical design. This clause, therefore, proposes to consider "system significance level" rather than "system outage probability", and to not refer to BER. Significance level is commonly used terminology in statistics for testing hypotheses.

Regarding each system parameter, system significance level is defined as the probability at which the system parameter will exceed a certain value *x*. Of course, system significance level is a function of *x*. For instance, system significance level of DGD is 4.2×10^{-5}, when *x* equals 3 times the average DGD value, as indicated in Recommendation ITU-T G.691. As another example, system significance level of maximum chromatic dispersion is 1.3×10^{-3}, when *x* equals the summation of the average value and 3σ (σ is standard deviation).

A.3 Probability threshold for system acceptance

Probability threshold for system acceptance (P_{th}) is defined as maximum affordable significance level of each system parameter. The probability threshold will depend on network operation scenario, and also the trade-off relationship between probability of exceeding the value and cost.

It should be noted that for some parameters considered here, P_{th} refers to the probability that the value is exceeded at the time the link is commissioned. For example, in the case of chromatic dispersion, a P_{th} value of 10^{-3} means it is expected that on average one in a thousand links will exceed the specified dispersion when commissioned. For other parameters, however, P_{th} refers to the probability that the value is exceeded at any particular time in the life of a link. An example of this is PMD where a P_{th} of 10^{-5} means that, at any instant, the probability of exceeding the maximum DGD is one in one hundred thousand.

Table 7A-2 contains some example values of P_{th} together with the equivalent values of the number of standard deviations away from the mean for Gaussian statistics and the equivalent maximum to mean ratio for the Maxwell distribution (PMD).

Table 7A-2 – Probability threshold for system acceptance

Probability threshold, P_{th}	Gaussian: Standard deviations away from the mean (σ)	Maxwell: Ratio of maximum to mean (S)
10^{-3}	3.1	2.5
10^{-5}	4.3	3.2
10^{-7}	5.2	3.7
10^{-9}	6.0	4.2

A.4 Design flow chart

The generic flow chart is depicted on the left-hand side of Figure 7A-1. An example of maximum chromatic dispersion is illustrated on the right-hand side of the same Figure.

A.5 Statistical design of loss

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

Link attributes are affected by factors other than optical fibre cables such as splices, connectors, and installation. For the purpose of link attribute values estimation, typical values of optical fibre links are provided in an appendix of each of the fibre and cable Recommendations.

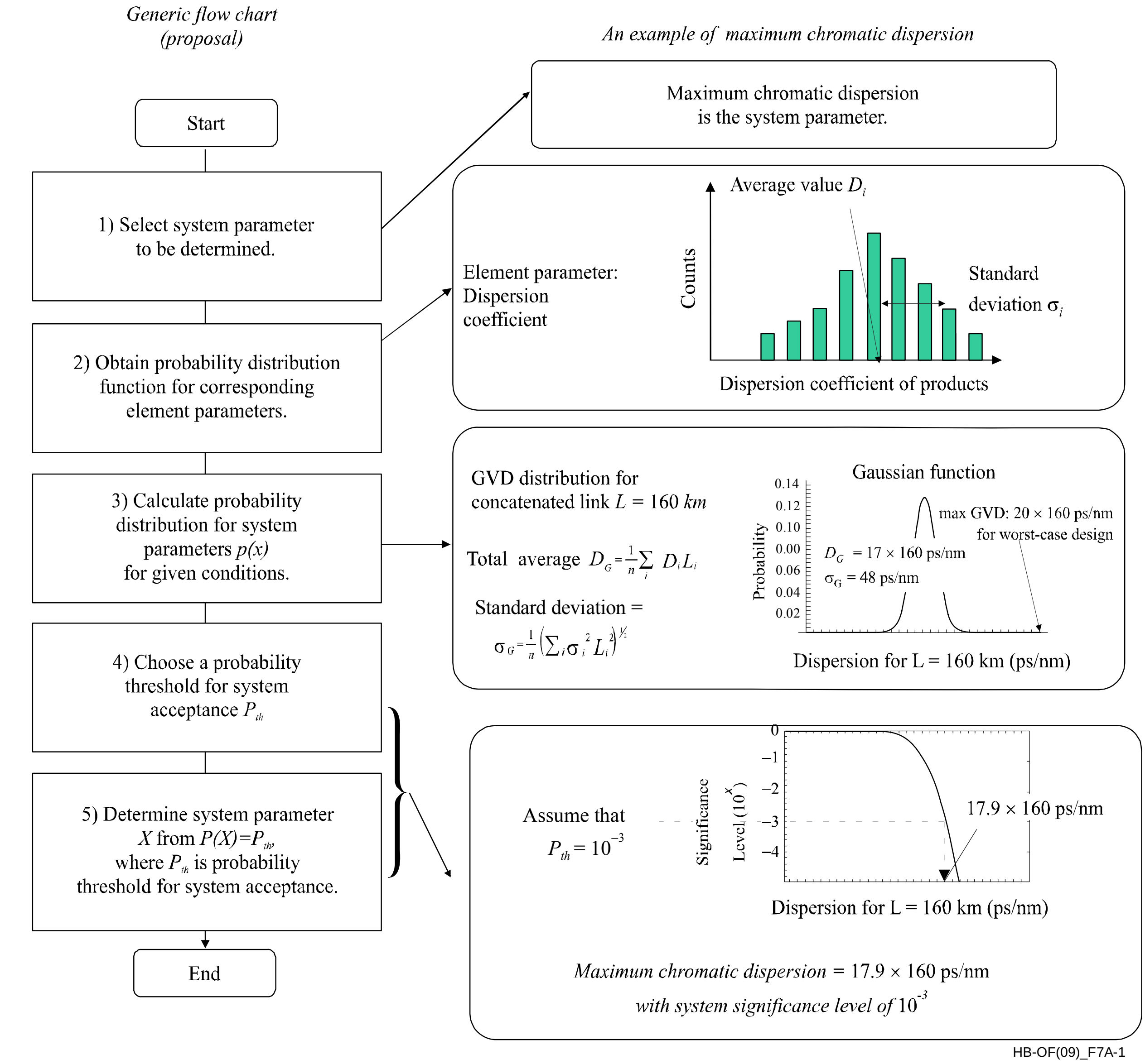


Figure 7A-1 – Generic flow chart and an example of maximum chromatic dispersion

1) Select the system parameter to be determined.

   In the example of Figure 7A-1, the system parameter is maximum chromatic dispersion.

2) Obtain the probability distribution function for corresponding element parameters.

   As can be seen in the histogram shown in the second right-hand box in Figure 7A-1, the average dispersion coefficient of fibre product i is assumed to be D_i, and standard deviation is σ_i.

3) Calculate the probability distribution for system parameter $p(x)$ for given conditions.

   In this example, the given condition is a fibre link length of 160 km. The statistical distribution of the system parameter is obtained as the concatenation of the distributions of several fibre bobbins. From the central limit theorem, the distribution of concatenated links has a Gaussian profile. In this example, the total average of chromatic dispersion is $17 \times 160 = 2\,720$ ps/nm, while standard deviation is 48 ps/nm. It should be noted that, by using the ordinary worst-case design, maximum chromatic dispersion is $20 \times 160 = 3\,200$ ps/nm.

4) Choose a value for P_{th}, the probability threshold for system acceptance.

   In this example, it is considered acceptable if one in a thousand links has a higher dispersion than the calculated value (P_{th} is 10^{-3}).

5) Determine system parameter X from equation $P(X) = P_{th}$, where P_{th} is the probability threshold for system acceptance.

In this example, maximum chromatic dispersion is determined to be $17.9 \times 160 = 2\,864$ ps/nm, assuming that P_{th} is 10^{-3}. Therefore, the dispersion requirement for the transmission system is relaxed by 336 ps/nm, compared to the worst-case system design.

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

$$A = \alpha L + \alpha_S x + a_C y \tag{7A-1}$$

where:

- α: typical attenuation coefficient of the fibre cables in a link,
- α_S: mean splice loss,
- x: number of splices in a link,
- α_C: mean loss of connectors,
- y: number of connectors in a link (if provided),
- L: link length.

A suitable margin should be allocated for future modifications of cable configurations (additional splices, extra cable lengths, ageing effects, temperature variations, etc.). The typical values found in an appendix of each of the fibre and cable Recommendations are for the attenuation coefficient of optical fibre links.

The combination of these attenuation contributors in combination with the system maximum attenuation value leads to a variation in the length of the spans. The span length is a targeted value for Recommendations such as ITU-T G.957 and ITU-T G.691, but may be exceeded up to the point where length is limited by chromatic dispersion.

The typical attenuation coefficient of the fibre, α, varies with wavelength, λ, due to a number of factors: Rayleigh scattering, water absorption, macrobending loss and microbending loss. For well-designed cables, the bending loss variation with wavelength can be negligible, but generally increases with wavelengths above 1 550 nm. For some cables, the microbending effect can, however, result in an elevated attenuation at higher wavelengths, which is called a bend edge. The Rayleigh scattering of ITU-T G.652 fibres is rather uniform across suppliers and time of manufacturing and follows a $1/\lambda^4$ relationship.

The peak water absorption wavelength is close to 1 383 nm and can be characterized roughly as a magnitude value multiplied with a distinctive curve around 1 383 nm. This peak can also be affected by hydrogen exposure and fibre hydrogen sensitivity. Over time, fibre manufacturers have learned to reduce the water absorption component, as well as the hydrogen sensitivity. Recommendation ITU-T Rec. G.652 includes two categories, ITU-T G.652.C and ITU-T G.652.D, for which the attenuation coefficient of the water peak in combination with hydrogen ageing is required to be less than or equal to the maximum value specified for the range 1 310 nm to 1 625 nm.

The attenuation values of some example ITU-T G.652 and ITU-T G.655 fibres are shown in Table 7A-3. The measurements included two 60 km lengths of 216 ITU-T G.655 fibres, and the same lengths of 55 ITU-T G.652 fibres.

The fitted attenuations values have been used to calculate attenuation statistics for both fibre types at the wavelengths covering the spectrum from 1 261 nm to 1 621 nm, which is the wavelength range of the CWDM systems (see Chapter 6). These calculations show that ITU-T G.655 fibres have on average 0.015-0.020 dB/km higher attenuation than ITU-T G.652 fibres in the wavelength range 1 261-1 341 nm, and 0.016-0.021 dB/km higher attenuation in the wavelength range 1 461-1 621 nm.

Figure 7A-2 illustrates the measurements of 308 links with ITU-T G.652 fibres, of 9 network operators, in the metro environment where the link length exceeded 20 km. These measurements have been made in the period of 2003 to 2005. (For further information see Recommendation ITU-T G.695 and the ITU-T G.65 x-series Recommendations).

Table 7A-3 – ITU-T G.655 and ITU-T G.652 fibre attenuation measurements

OTDR wavelength (nm)	ITU–T G.655 fibres				ITU–T G.652 fibres			
	Fitted attenuation (dB/km) Typical OH-model		Measured values (dB/km)		Fitted attenuation (dB/km) OH-model		Measured values (dB/km)	
	Average	Stdv	Average	Stdv	Average	Stdv	Average	Stdv
1241	0.443	0.007	0.439	0.007	0.423	0.009	0.42	0.011
1310	0.358	0.006	0.361	0.009	0.341	0.008	0.343	0.009
1383	0.412	0.042	0.413	0.043	0.51	0.227	0.508	0.224
1551	0.211	0.012	0.209	0.012	0.194	0.004	0.192	0.005
1621	0.227	0.016	0.23	0.017	0.207	0.006	0.209	0.006
1642	0.243	0.017	0.241	0.017	0.222	0.007	0.22	0.007
1650	0.25	0.017	–	–	0.229	0.008	–	–
1660	0.261	0.017	–	–	0.241	0.009	–	–
1670	0.274	0.017	–	–	0.254	0.011	–	–
1675	0.282	0.017	–	–	0.263	0.013	–	–

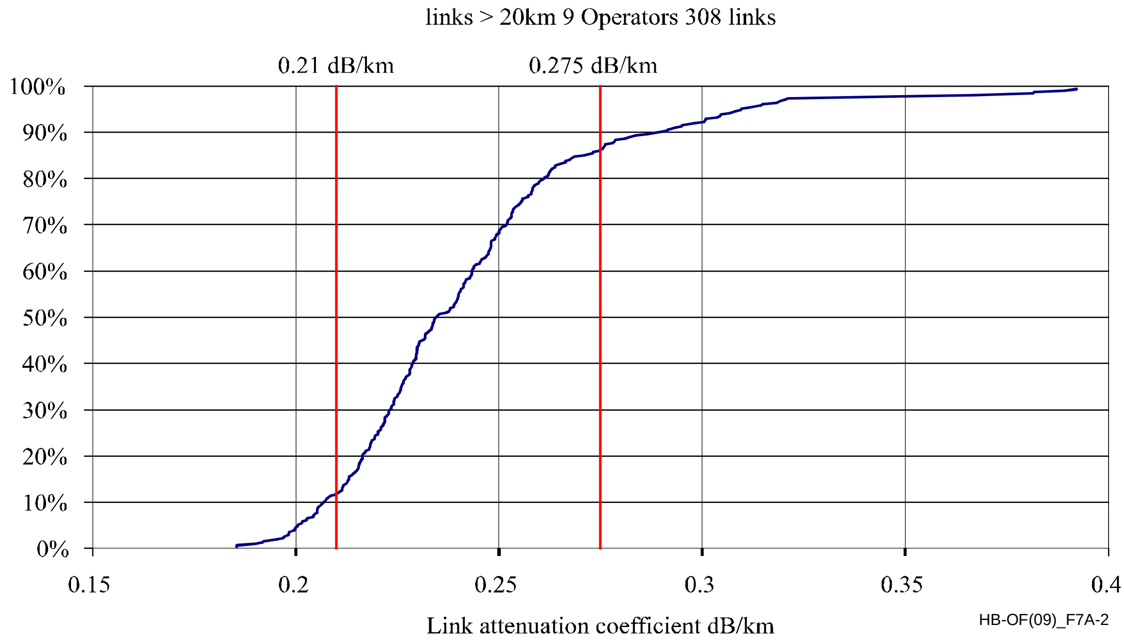


Figure 7A-2 – Probability of loss being met vs link 1 550 nm attenuation coefficient for links > 20 km

A.6 Statistical design of chromatic dispersion

When different components or fibres are combined, the chromatic dispersion of the combination is the total of the chromatic dispersion values of the individuals, on a wavelength-by-wavelength basis. The variation in the total dispersion of links will depend on the distributions of the products that are used in the links.

Some examples are given in the following for particular fibre and component types. These examples are not necessarily broadly representative.

The fibre chromatic dispersion coefficient, $D(\lambda)$, is measured as a function of wavelength λ.

The characterization methodology suitable for concatenation statistics for a single distribution, or for a combination of distributions, is to calculate the dispersion coefficient for each of the wavelengths in the range of the application – for each individual fibre segment. This creates a distribution of dispersion coefficient values for each wavelength. As an example, the distribution of a ITU-T G.655 fibre chromatic dispersion at 1 560 nm is shown in Figure 7A-3.

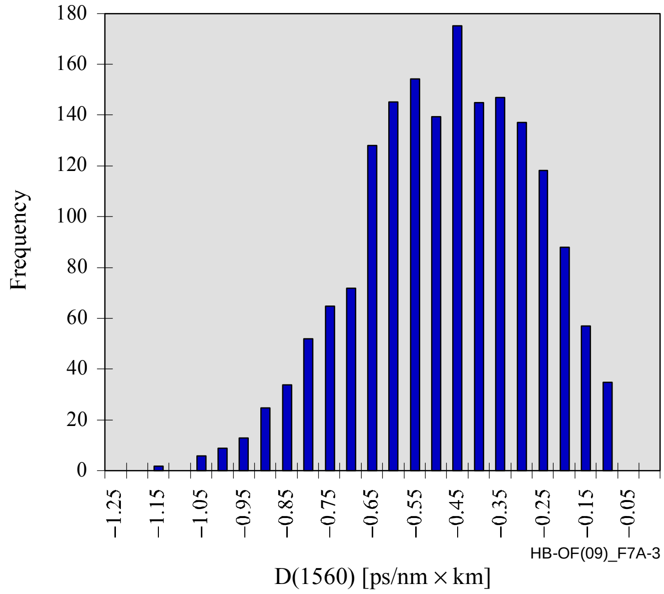


Figure 7A-3 – Histogram of dispersion coefficient values at 1 560 nm

As an application of the above method, the fibre statistics for chromatic dispersion coefficient (ps/nm · km) vs. wavelength (nm) are shown in Figures 7A-4 (dispersion values) and 7A-5 (standard deviation).

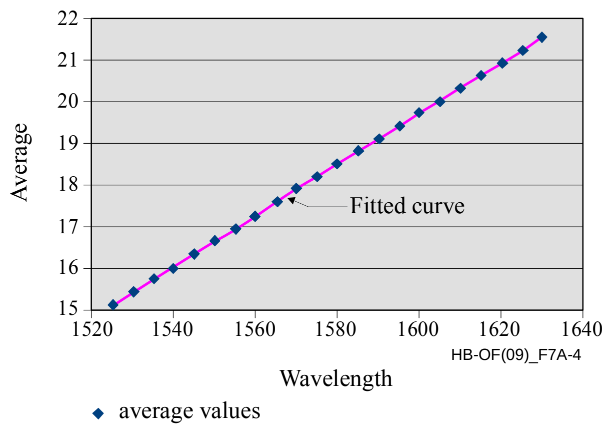


Figure 7A-4 – Average chromatic dispersion coefficient of G.652 fibre

The formula for the fitted line in Figure 7A-4 is:

$$\mu(\lambda) = -77.403 + 0.0607 \times \lambda \qquad \text{(ps/nm} \cdot \text{km)}$$

where λ is in nm.

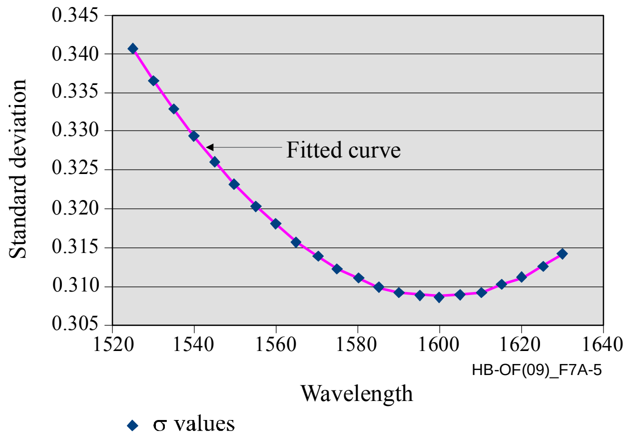


Figure 7A-5 – Standard deviation of chromatic dispersion coefficient of G.652 fibre

The formula for the fitted curve in Figure 7A-5 is:

$$\sigma(\lambda) = 15.013 - 18.384 \times 10^{-3} \times \lambda + 5.746 \times 10^{-6} \times \lambda^2 \qquad \text{(ps/nm} \cdot \text{km)}$$

In Figure 7A-6 and Figure 7A-7 the dispersion statistics of the DCFs (dispersion compensator fibres) are shown.

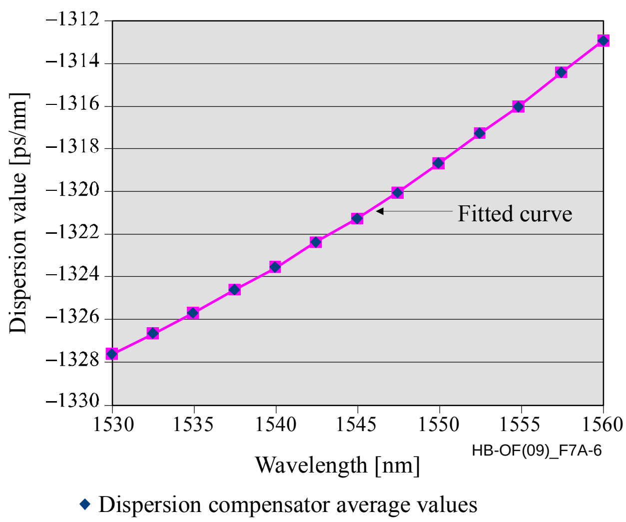


Figure 7A-6 – Dispersion compensator average values

The formula for the fitted curve in Figure 7A-6 is:

$$\mu(\lambda) = 8.010 \times 10^3 - 12.5698 \times \lambda + 4.227 \times 10^{-3} \times \lambda^2 \qquad \text{(ps/nm)}$$

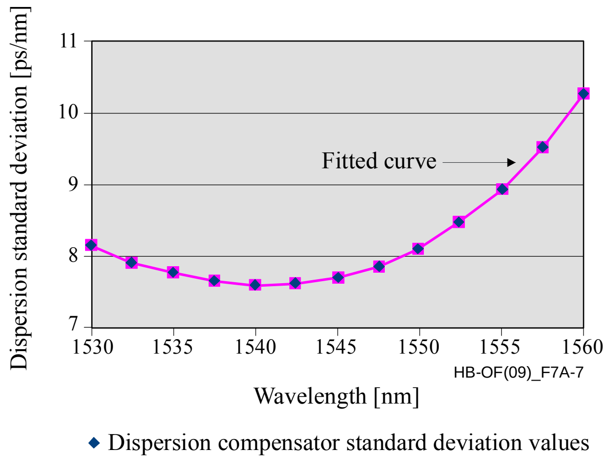


Figure 7A-7 – Dispersion compensator standard deviation values

The formula for the fitted curve in Figure 7A-7 is:

$$\sigma(\lambda) = 3.4612 \times 10^5 + 6.824 \times 10^2 \times \lambda - 0.4484 \times \lambda^2 + 9.818 \times 10^{-5} \times \lambda^3 \qquad \text{(ps/nm)}$$

Combining these statistics according to Supplement 39 of the ITU-T G-series of Recommendations, and using the link assumptions (400-km fibre, 10-km segments, 5 dispersion compensators), yields the results shown in Figure 7A-8.

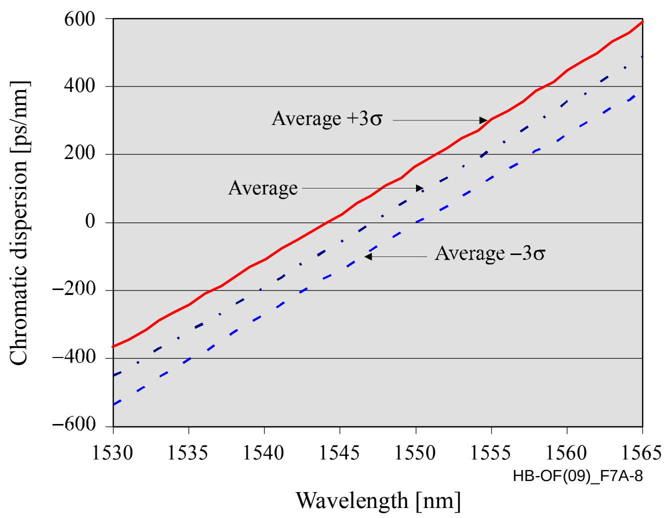


Figure 7A-8 – 3 σ limits for combined ITU-T G.652 fibre and compensators

For the C-band (1 530-1 565 nm) it appears from Figure 7A-8 that the chromatic dispersion of this compensated link is within ±600 ps/nm. In Recommendation ITU-T G.691, the limit for 10-Gbit/s transmission, with respect to chromatic dispersion alone, is indicated as approximately 1 000 ps/nm for transmitters and receivers that also conform to Recommendation ITU-T G.691.

A.7 Statistical design of DGD

The DGD varies randomly according to a Maxwell distribution characterized by the PMD value. As a consequence in § 7.2.3 DGD has already been dealt with the statistical approach.

Annex B

Example of design considerations for DWDM systems

This Annex presents some physical and technology limitations to the achievable link distances of DWDM optical transmission systems. For further in formation see Recommendation ITU-T G.696.1.

In § B.1, the fundamental limits due to ASE noise and PMD are discussed. This is followed in § B.2 with a discussion of other effects that limit the distances in practical systems and in § B.3, techniques to mitigate these effects are described. Finally, in § B.4, an example of the typical performance of currently available technology is given.

B.1 Enabling technologies and their limits

In this clause some of the fundamental constraints for the technological feasibility of DWDM applications are indicated.

It is assumed that the link optical attenuation is compensated for with optical amplifiers and the chromatic dispersion is compensated for with chromatic dispersion compensators.

ASE noise and PMD are the most important impairments that limit the capacity and transmission distance of DWDM applications.

The discussion in this § B.1 refers to NRZ line coding since this is commonly used in DWDM applications. Other line codings may give different results and might be more suitable in some cases (some alternatives to NRZ are discussed in § B.3).

B.1.1 ASE noise

The influence of ASE noise is essentially characterized by OSNR. As shown in § 2.2, the OSNR of a multichannel x span reference system with a booster amplifier, $x - 1$ line amplifiers and a pre-amplifier is given by:

$$\mathrm{OSNR} = P_{out} - L - NF_{eff} - 10 \cdot \log\left(x + \frac{10^{\frac{G_{BA}}{10}}}{10^{\frac{L}{10}}} \right) - 10 \cdot \log\left[\mathrm{h} \cdot \nu \cdot \nu_{\mathrm{r}}\right] \qquad \text{(7B-1)}$$

where:

- P_{out}: output power (per channel) of the booster and line amplifiers (dBm),
- L: span loss (dB) (which is assumed to be equal to the gain G_{LA} of the line amplifiers),
- G_{BA}: gain of the optical booster amplifier (dB),
- NF_{eff}: noise figure of the optical amplifier (dB),
- h: Planck's constant (in mJ * s to be consistent with P_{out} (dBm)),
- ν: optical frequency (Hz),
- ν_r: reference bandwidth (Hz, x – 1) is the total number of line amplifiers.

Equation 7B-1 takes into account the shot noise and the signal-spontaneous beat noise as the most dominant noise contributions. Other noise contributions might be considered in some cases.

This equation indicates that the ASE noise is accumulated from all $x + 1$ amplifiers.

For this reference system, the following main assumptions are made:

i) all optical amplifiers in the chain including booster and pre-amplifier have the same noise figure;

ii) the losses (per channel) of all spans are equal;

iii) the output powers (per channel) of the booster and line amps are the same.

For example, assuming the optical channel output power $P_{out} = 3$ dBm, the noise figure $NF_{eff} = 6.5$ dB, the reference bandwidth $\nu_r = 0.1$ nm and the span loss $L = 22$ dB, the solid curve shown in Figure 7B-1 is obtained.

For a 10 Gbit/s data rate, and assuming an OSNR limitation of 25 dB for a BER of 10^{-12} without FEC, a theoretical limiting distance of 5 spans is obtained.

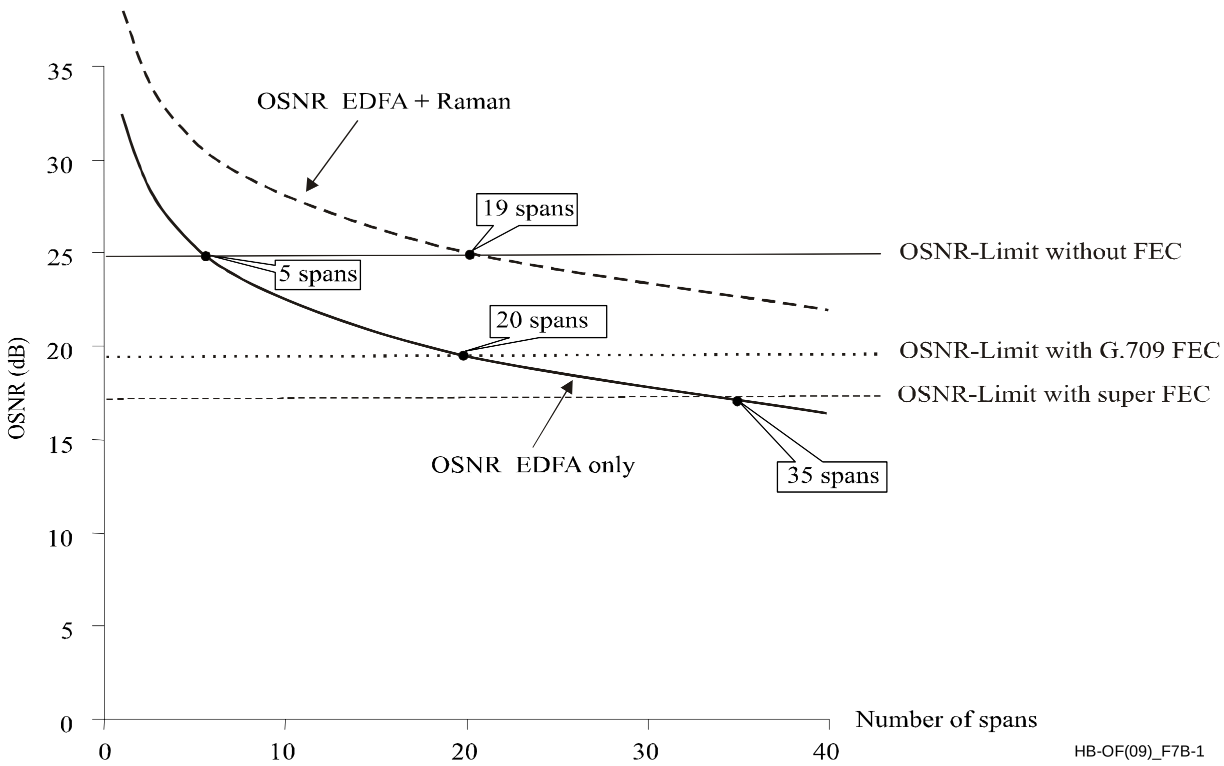


Figure 7B-1 – OSNR limits for a reference system, OSNR as a function of span number with and without Raman amplification

If one assumes the use of ITU-T G.709 FEC with a net coding gain of 5.6 dB, the limiting OSNR becomes 19.4 dB, which is reached at 20 spans.

Using stronger FEC, e.g. one of the schemes found in Recommendation ITU-T G.975.1, a net coding gain (NCG) of around 8 dB is feasible and the limiting OSNR becomes 17 dB, which is reached at 35 spans.

Distributed Raman amplification (DRA) is a further option to extend transmission distance. The OSNR improvement factor expected by DRA in backward pumping configuration can be calculated by the effective noise figure (NF_{eff}), which can be expressed by equation 7B-2.

$$NF_{eff} = 10 \cdot \log\left(\left(NF'_{LA} + \frac{P_{ASE,Raman}}{h \cdot \nu \cdot \nu_r}\right) \cdot \frac{1}{G'_{Raman}}\right) \quad (7B\text{-}2)$$

where:

NF'_{LA}: linear noise figure of the discrete line amplifier,

G'_{Raman}: linear gain of DRA,

$P_{ASE,Raman}$: ASE power resulting from DRA,

ν_r: reference bandwidth,

NF_{LA}: $10 \cdot \log (NF'_{LA})$ holds,

where:

NF_{LA}: noise figure of the discrete line amplifier (dB);

$P_{ASE,Raman}$ and $G_{Raman} = 10 \log \cdot (G'_{Raman})$ can be estimated analytically.

NF_{eff} as a function of Raman gain G_{Raman} is shown in Figure 7B-2.

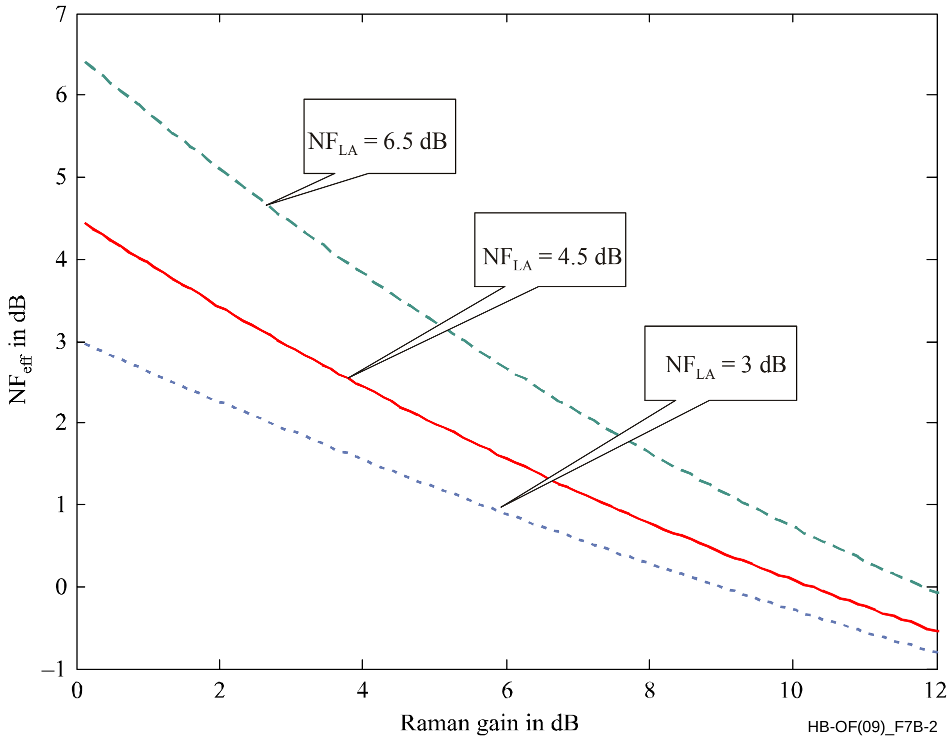


Figure 7B-2 – NF_{eff} as a function of Raman gain

Here, the following parameters are assumed: fibre length, 80 km; attenuation coefficient, 0.275 dB/km and 0.3 dB/km for signal and pump wavelength, respectively; effective area of fibre, 80 μm^2; and Raman gain coefficient, 3.1E-14.

The noise figures of the EDFA are 3 dB, 4.5 dB and 6.5 dB, respectively. The maximum transmission distance with Raman – EDFA combined amplifiers can be estimated by inserting NF_{eff} from equation 7B-2 in the OSNR equation 7B-1 and using $L = G_{Raman} + G_{LA}$ where again G_{LA} is the gain of the line amplifier in dB.

Assuming a Raman gain of approximately 9.3 dB and an EDFA noise figure of $NF_{LA} = 6.5$ dB, one obtains an effective noise figure of $NF_{eff} = 1$ dB, which gives the dashed curve shown in Figure 7B-1.

Now the theoretical limiting distance without FEC becomes 19 spans, and the addition of ITU-T G.709 FEC would allow a system with more than 40 spans.

B.1.2 PMD

The total PMD of a fibre link, with total length *L* and a PMD coefficient for the individual cable sections PMD_Q, is given by $PMD = \sqrt{\ } \cdot PMD_Q$. For a 10 Gbit/s NRZ interface, the total PMD should not exceed 10 ps (corresponding to an outage probability with "five nines" for a fibre induced maximum DGD = 30 ps). If the PMD coefficient PMD_Q value is not greater than 0.5 ps/km$^{1/2}$, this gives a total link length of 400 km; and with a maximum PMD coefficient $PMD_Q = 0.2$ ps/km$^{1/2}$, the total link length becomes 2 500 km, (Figure 7B-3).

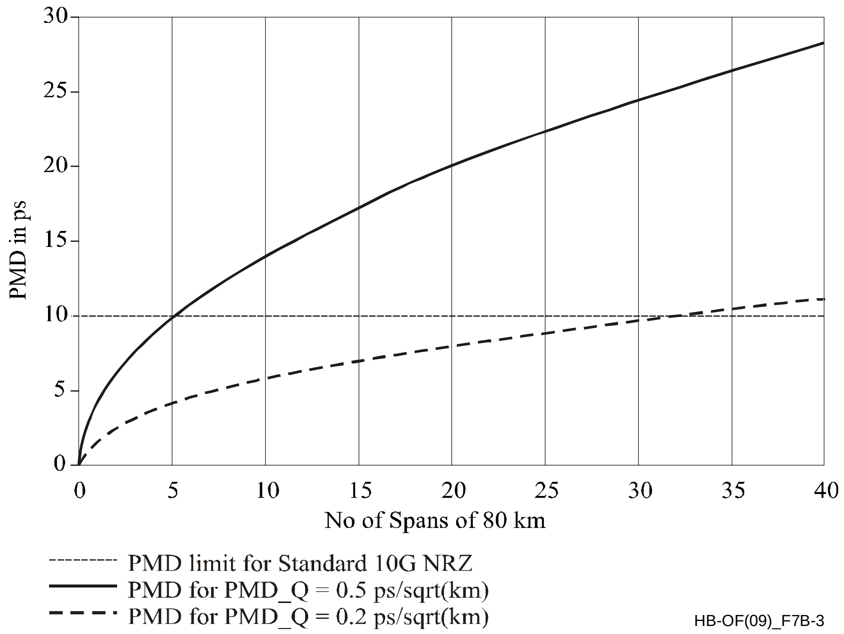


Figure 7B-3 – PMD vs distance for different PMD coefficients and PMD limit for 10 Gbit/s NRZ systems with 99.999% availability

Figure 7B-3 gives the guidance on maximum distance allowed according to the fibre's maximum PMD_Q for NRZ line coding based on its 1st-order DGD tolerance. This figure has not accounted for the PMD contribution from equipment.

A real system on a real fibre link should consider the PMD limit from the combined contribution of both fibre link and equipment which comprises all the nodes in a link.

In some circumstances, higher-order PMD should also be considered.

B.2 Other effects that limit transmission distance

The limiting link distances calculated in the previous clauses are the distances that might be achieved in ideal circumstances. There are, however, several effects in practical systems that reduce the maximum link length.

B.2.1 Accumulated gain ripples from EDFA cascading and tilt due to stimulated Raman effects

A real system in a real link needs to consider power divergence among channels due to accumulated gain ripple and stimulated Raman effects.

Technologies like gain flattening filters and dynamical gain/power equalization can be used to reduce the impact of such effects, but there will still be some impact, which will reduce the achievable distances to less than those shown in Figure 7B-1.

B.2.2 Non-uniform span length

The theoretical calculations above consider equal span lengths. For the discussion in this annex, a constant attenuation of 22 dB per span has been used. In real systems, the span lengths are usually not equal, actually depending on the real network topology and topographical constraints.

It is difficult to account for this "non-ideality" in a general manner, because, for the same system, longer spans mean an OSNR "debt" and shorter spans turn into an OSNR "credit".

The OSNR "debt" due to longer spans can be partially or completely compensated by increasing the output power of the amplifier preceding the span itself, provided that the increased power does not cause non-linear effects that cannot be tolerated without extra penalty.

Therefore, generally speaking, a link with longer spans may likely force the system to support a smaller number of spans, whereas a link with shorter spans may likely allow the system to support a larger number of spans. Given that this matter falls in the specific system design of the equipment vendor, it is simply mentioned here to give a more comprehensive view on these types of applications, without giving any details.

B.2.3 Optical non-linearity

Non-linear effects like self-phase modulation (SPM) and/or cross-phase modulation (XPM) accumulate over spans and become significant as the number of spans becomes large. Thus, non-linear penalty may not be ignored in a real link.

Higher channel power is good for OSNR, but is not necessarily good for BER. This is due to fibre non-linear effects.

Considering NRZ with average channel power of 3 dBm on ITU-T G.652 fibre (the same power assumed in Figure 7B-1), accumulated non-linear (SPM) phase, $\Phi_{NL} = \gamma P_{ch} L_{eff} N_{span}$ after 10 spans is close to 1 radian, and transmission is in a so-called "strong non-linear distortion" region where link distance may be non-linearity limited. Thus, the total link length could be much less than that predicted by Figure 7B-1, which is based on OSNR limits alone.

Some methods of mitigating these effects are discussed in § B.3.

B.2.4 Residual dispersion and dispersion tolerance

The curves in Figure 7B-1 assume that each channel in the WDM system is perfectly dispersion compensated. While dispersion compensation modules (DCMs) with an exactly inverse dispersion vs. wavelength slope to that of the fibre could be used, this is not usually the case and even then, higher order chromatic dispersion may need to be considered as the number of spans increases.

In addition to the mismatched slopes causing residual dispersion for some of the WDM channels, non-linear distortion can, if not mitigated, broaden the spectrum and thus reduce the dispersion tolerance after fibre transmission.

B.2.5 Accumulated PDL effects

Optical components such as WDM filters, VOAs or OAs exhibit finite polarization dependent loss (PDL) that may range from 0.1 to 0.3 dB per device or even more. PDL exerts stochastic intensity modulation on optical signals due to variations in the signal polarization with time. The induced power fluctuations are transformed at OAs under the effects of polarization dependent gain (PDG) into OSNR fluctuations.

In an extended long-haul system where many optical network elements are concatenated, the accumulated PDL can cause significant power fluctuation, which could degrade system performance and stability. However, the correlation between power fluctuations and OSNR variations may not necessarily be one-to-one. The power fluctuations may be too fast to be fully compensated by means of dynamic gain equalization.

B.3 Techniques used to mitigate impairments

There are several practical techniques which may improve the performance of a multi-span link, such as by choosing:

i) dynamic gain equalization;

ii) line coding;

iii) number of optical channels and their spacing;

iv) fibre types;

v) mixing different types of fibre within one span.

B.3.1 Dynamic gain equalization

In order to compensate for the gain tilt introduced by a long chain of amplifiers, the use of an integrated optical spectrum analyzer (OSA) or optical power monitor (OPM) and adjustable gain flattening filters can be used to ensure good equalization across all the channels of the DWDM aggregate signal.

B.3.2 Modulation format

Modulation formats other than NRZ can provide some advantages under certain circumstances.

As described in Supplement 39 to the ITU-T G-series of Recommendations, return to zero (RZ) line coded systems are significantly more tolerant to first-order PMD than NRZ systems. Also, modified RZ coding formats, such as phase-modulated RZ, can be additionally advantageous in terms of enhanced non-linear tolerance. These characteristics encourage the use of RZ line coding for very long link distances where PMD and non-linear effects are particularly significant.

On the other hand, RZ coding has (due to the broader bandwidth to be used) a potential drawback of being less spectrally efficient compared to NRZ (see Supplement 39 to the ITU-T G-series of Recommendations) and is usually more sensitive to residual chromatic dispersion than NRZ. For this reason, systems that adopt RZ modulation format require a more precise characterization and compensation of the dispersion associated with the link.

Line codes other than NRZ and RZ can also be applied to DWDM systems, each of them having benefits and drawbacks. In particular, for very long link lengths and ultra-high capacity DWDM signals, the choice of a particular line code depends on the individual optimal system design (see Supplement 39 to the ITU-T G-series of Recommendations).

B.3.3 Number of optical channels and their spacing

As a general trend, the maximum number of DWDM channels giving acceptable performance will tend to decrease with increasing link length and/or decreasing optical channel spacing, due to the increased impact of optical non-linearity.

B.3.4 Fibre types

One fibre type may have an advantage or disadvantage compared with another under certain conditions. In the C-band for example, ITU-T G.652 fibre has larger chromatic dispersion than ITU-T G.655 fibre or ITU-T G.653 fibre and, therefore, it may introduce less non-linear effects. However, Raman gain strongly depends on fibre type and ITU-T G.652 fibres, due to their large mode field diameters, show a smaller Raman gain for a given pump power than other fibres.

B.3.5 Mixing different types of fibre within one span

One technique that can be used to mitigate the effects of fibre non-linearity is to deliberately mix fibres with different characteristics within a single span. For example, a span containing alternating fibres with positive and negative dispersion results in a span with a high value of local dispersion (desirable to reduce the effects of XPM and four wave mixing) but a low net dispersion (which reduces the dispersion compensation requirements).

In cases where a link has different fibre types in different spans, the launch power may have to be different in each span depending on the fibre types of the first 20 km of each span, in order to minimize the non-linear distortion.

B.4 Practical example

From the preceding discussion, it is clear that the number of spans that can be practically achieved for a given channel spacing, operating wavelength region, bit rate and span loss depends upon many system design choices such as which FEC scheme to employ, whether to use dynamic gain equalization or whether to use Raman amplification, etc.

However, as an example of available technology, a system with the following attributes:

- Minimum channel spacing: 100 GHz;
- Operating wavelength region: C-band (1 530 to 1 565 nm);
- Client class: 10G;
- Span loss: 22 dB;
- ITU-T G.652 fibre type;
- ITU-T G.709 FEC,

can currently be cost effectively provided up to a maximum of about 15 spans.

Annex C

Example of margin calculation for the submarine systems

C.1 Systems margins

A submarine system typically has a design life of 25 years. It is subject to repair and ageing. The design life requires some provisional margins to be satisfied. These margins are called segment margins.

C.1.1 Impairments due to repair operations

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

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

– land cable repair: 1 repair every 4 km with a minimum of 2 repairs,

– shallow water repair: 1 repair every 15 km with a minimum of 5 repairs,

– deep water repair: 1 repair every 1 000 km.

During a repair operation, an additional length of spare cable must be added to the system in order to keep the tensile load carried by the cable below the required values. This extra-length of spare cable depends on the sea depth at the repair location. Usually a value between 1.5 and 2.5 times the sea depth is used. To calculate the margin required for repair operations, the total additional cable length is evaluated in the worst case when all estimated repairs are added. Another Q-factor is calculated, with the sum of the total initial line length and the maximum extra cable added by repairs. The difference between the two Q-factors corresponds to the repairs allocation margin.

C.1.2 Impairments due to equipments ageing

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

– Hydrogen effects in the fibre: the degradation is usually approximated by an additional loss after 25 years of around 0.003 dB/km.

– Radiation effects: optical fibres are loss sensitive to high energy radiation (gamma rays) whose origins may be related to sediments, sea water or artificial sources (waste site). The loss increase is estimated to be lower than 0.002 dB/km after 25 years.

A Q-factor is calculated with these additional losses and compared to the mean Q value in order to obtain the margin value required for equipments ageing.

C.1.3 Impairments due to the foreseen faults of some components

Due to the cost and complexity of marine operations to replace or repair submerged equipment, the most sensitive components are redundant, in order to avoid interventions as much as possible. The major faults to take into account are the repeater pump failures. Pump redundancy avoids an output power shutdown in the case of a pump failure but such an incident will always induce an output power and noise figure degradation leading to a Q-factor decrease.

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

C.1.4 Unallocated margin

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