CHAPTER 8

OPTICAL SYSTEMS APPLICATIONS

Introduction

This Chapter deals with the applications of the optical systems in the various parts of the Optical Transport Network with the exclusion of the optical access network which is described in Chapter 9.

Clauses 1, 2 and 3 cover general aspects of these applications. The other clauses are devoted to the various specific applications: intra-office (clause 4), metro access networks (clause 5), metro core networks (clause 6), backbone networks (clause 7) and submarine systems (clause 8).

At the end of the Chapter, a short reference is made in clause 9 to the wavelength switched optical networks (WSONs), considering that the present optical transport networks, with an ever decreasing number of O/E/O conversions within their boundaries, are evolving towards such optically transparent networks.

1 The Optical transport network

Optical networks are used to connect a large group of users spread over a geographical area. Optical networks can be subdivided in access networks, metropolitan access networks (or metropolitan networks), metropolitan core networks (or regional networks) and long-haul networks (or backbone networks) depending on the area they cover (Figure 8-1). All these types of networks can benefit in general from the optical transmission technologies and in particular of the WDM technologies.

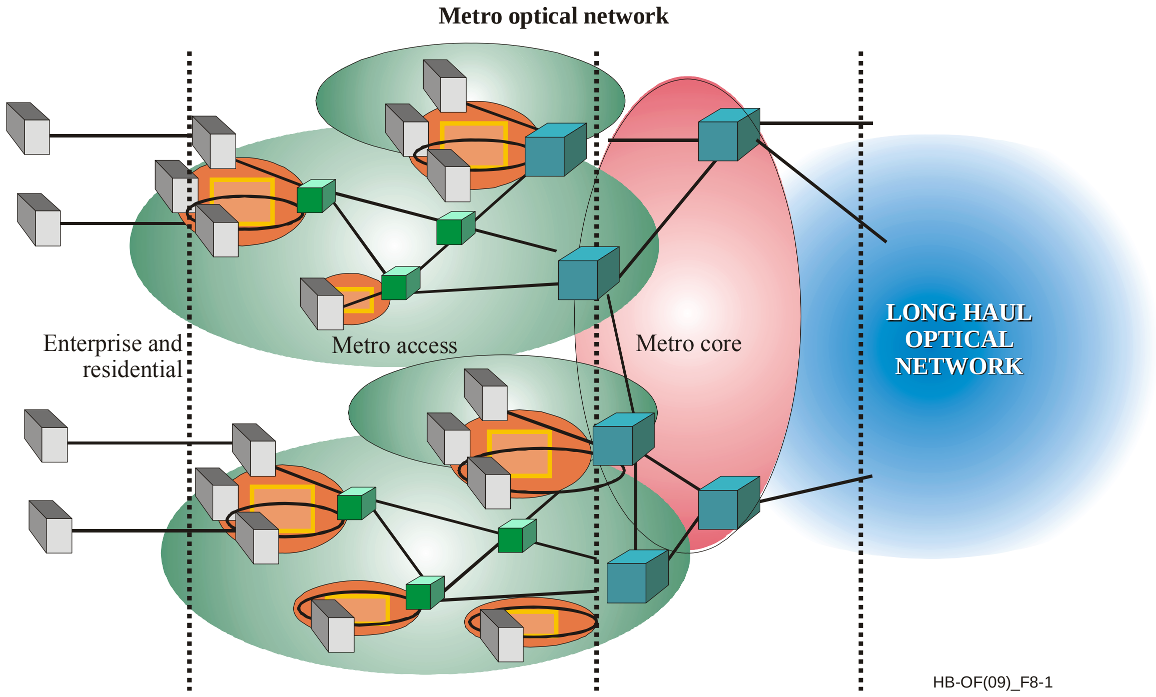


Figure 8-1 – Example of an optical network

An optical transport network (OTN) is composed of a set of optical network elements (ONEs) connected by optical fibre links, able to provide functionality of transport, multiplexing, routing, management, supervision and survivability of optical channels carrying client signals, according to the requirements given in Recommendation ITU-T G.872.

2 Optical network topologies

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

Recommendations ITU-T G.692, ITU-T G.693 and ITU-T G.959.1 currently concern point-to-point transmission systems, while Recommendations ITU-T G.695, ITU-T G.698.1 and ITU-T G.698.2 include more complex arrangements involving an optical add/drop function (bus structure). Recommendation ITU-T G.983.x and the ITU-T G.984 x-series of Recommendations cover a point-to-multipoint topology for optical access networks (see Chapter 9).

A point-to-multipoint topology is commonly used for access networks, while a ring topology is most practical for metro networks. Backbone nodes are usually interconnected by point-to-point WDM lines in a mesh topology.

In this clause, generic descriptions of typical examples of these network topologies are shown for the purpose of clarification.

2.1 Point-to-point links

The representation of a point-to-point DWDM link is shown in Figure 8-2. Light of *n* WDM channels is carried by one output fibre of a multichannel transmitter (M-Tx). This optical signal passes transmission sections with alternating fibre pieces and optical amplifiers before entering a multichannel receiver (M-Rx).

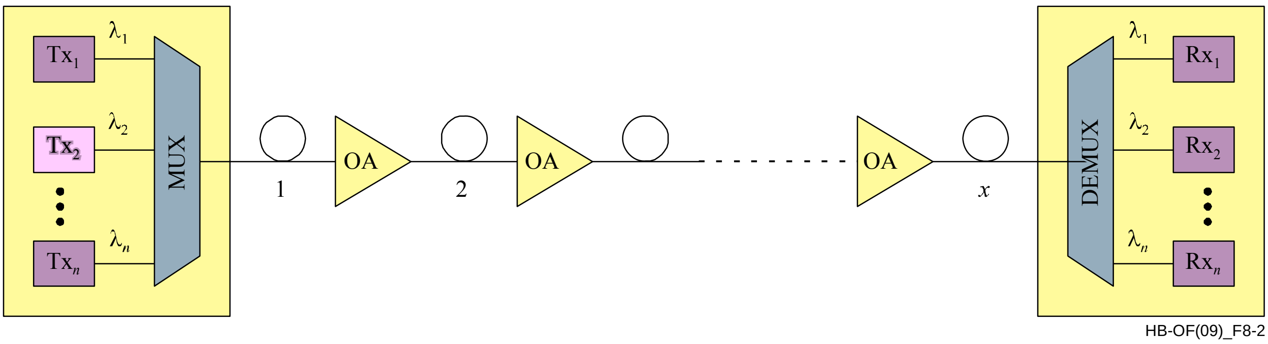


Figure 8-2 – Example of a WDM point-to-point link

Point-to-point links constitute the simplest kind of lightwave systems. Their role is to transport information available in the form of a digital bit stream, from one place to another. The link length may vary from a few kilometres to thousands of kilometres, depending on the specific application. For example, optical links are used to connect different equipment inside a building, or between two buildings placed a short distance apart. The low attenuation and wide bandwidth of optical fibres are not of primary importance for such links. Fibres are used mainly because of their other advantages, such as immunity to electromagnetic interference. The situation is different for lightwave systems, which are used for high speed transmission across continents with a link length of thousands of kilometres. Low attenuation and large bandwidths of optical fibres are important factors in transoceanic systems from the point of view of reducing the overall cost per unit transmission capacity.

When the link length exceeds a certain value, depending on the operating wavelength, it becomes necessary to compensate for fibre attenuation, as the signal would otherwise become too weak to be detected correctly. Fibre attenuation can be compensated by using optical amplifiers. Amplifiers are especially valuable for WDM systems as they can amplify many channels simultaneously.

Optical amplifiers solve the attenuation problem, but they add noise and worsen the impact of fibre dispersion and non-linearity because signal degradation continues to accumulate over multiple amplification sections. Indeed, periodically amplified systems are often limited by fibre dispersion, unless fibre compensation techniques are used. Most terrestrial systems employ dispersion compensation, but still place a 3R regenerator after a certain number of optical amplification sections in order to reset the accumulation of other impairments.

The spacing (L) between optical amplifiers (repeater spacing) is a major design parameter, because the system cost reduces as the repeater spacing increases. The BL product (where B is the signal bit rate) is often used as a measure of the system performance for point-to-point links. The achievable BL product depends on the signal wavelength, since both fibre attenuation and dispersion are wavelength dependent.

Point-to-point systems can be connected in a mesh structure.

2.2 Bus structures

The representation of a bus structure is shown in Figure 8-3.

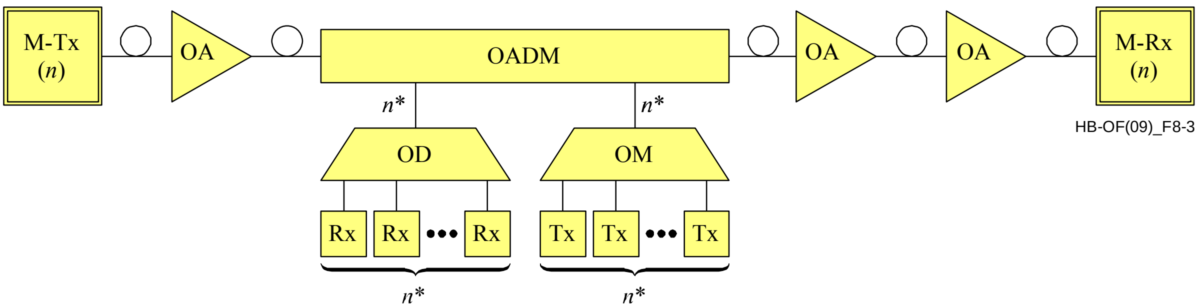


Figure 8-3 – Example of a bus structure with optical amplifiers and one OADM

A number (n) of WDM channels emitted from the M-Tx enters the OADM. A subset (n^*) of WDM channels is dropped and added by the OADM. The number n^* of dropped and added channels may range between 0 and n.

When $n^* = n$, all WDM channels are dropped and added. If $n^* = 0$, then no channel is added or dropped, i.e. the OADM is just a through-way network element. This scheme can be generalized by incorporating a sequence of optical amplifiers and optical add/drop multiplexers (OADMs).

2.3 Point-to-multipoint links

Optical networks using a passive coupler (optical branching component) are often called passive optical networks (PONs) because they avoid active switching. PONs have the potential for bringing optical fibres to the home (or to the curb). A PON structure is shown in Figure 8-4. For further information on the PONs see Chapter 9.

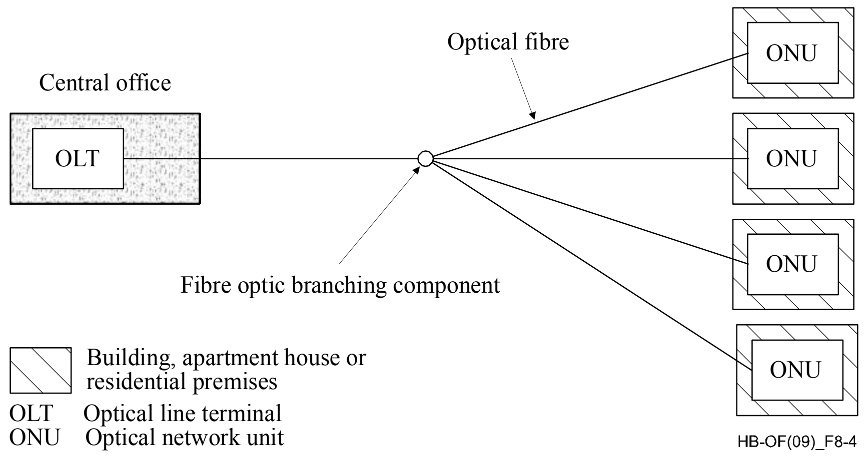


Figure 8-4 – Example of a point-to-multipoint structure

3 Classification of optical systems applications

In ITU-T Recommendations the optical systems are classified by their network application as:

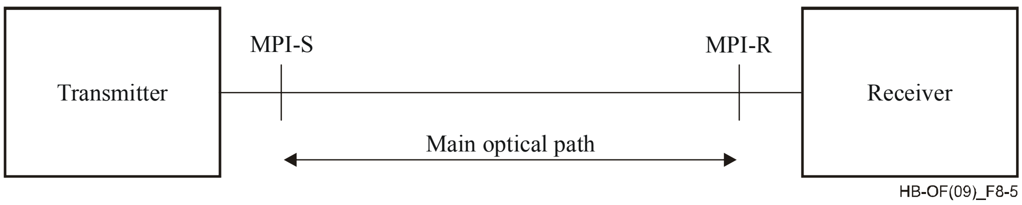
- intra-office systems;
- metro access (metro) systems;
- metro-core (regional) systems;
- long-haul (backbone) systems;
- repeaterless and repeatered submarine systems.

Moreover single-span systems are classified on the basis of their length as: intra-office (< 25 km), short-haul (40 km), long-haul (80 km), very long-haul (120 km) and ultra long-haul (160 km). The last three lengths are intended for system operating at 1 550 nm.

4 Intra-office systems

Intra-office systems are specified in Recommendations ITU-T G.693 and ITU-T G.959.1, which provide optical interface specifications to enable transverse (multivendor) compatibility of nominal 10 Gbit/s and 40 Gbit/s aggregate for link distances up to 2 km, per Recommendation ITU-T G.693 and up to 25 km, per Recommendation ITU-T G.959.1 over ITU-T G.652, ITU-T G.653 and ITU-T G.655 fibres.

Figure 8-5 illustrates a system of this type and shows the reference points used to specify optical interface parameters.



Note – The main optical path includes fibre and connectors, and may include other passive optical devices such as photonic cross-connects.

Figure 8-5 – Optical link example showing reference points

The black-box approach is used and, therefore, parameters are specified for the transmitter at point MPI-S, for the receiver at point MPI-R, and for the main optical path between points MPI-S and MPI-R.

The main optical path for some intra-office applications may include passive optical devices, e.g. photonic cross-connects (PXCs), which introduce significant attenuation.

For applications up to 2 km, total attenuation of the main optical path will, in general, be dominated by the loss of the passive optical devices rather than by fibre loss itself. In this case values of maximum attenuation may not be simply inferred from the target distances of applications.

Attenuation categories are used to distinguish among applications that have the same source, fibre type and target distance, and are intended for the same signal class, but have different values of maximum attenuation.

In particular, intra-office systems specified in Recommendation ITU-T G.693 refer to:

i) target distances: 0.6 km and 2 km (main optical path);

ii) highest class of optical tributary signal supported: NRZ 10G and NRZ 40G;

iii) maximum attenuation categories of the main optical path: 4 dB, 6 dB, 12 dB, 16 dB;

iv) source and fibre type: 1310 nm sources on ITU-T G.652 fibre, 1550 nm sources on ITU-T G.652 fibre, 1 550 nm sources on ITU-T G.653 fibre, 1550 nm sources on ITU-T G.655 fibre.

Some applications require FEC (forward error correction) bytes as specified in Recommendation ITU-T G.709 to be transmitted.

The application codes specified in Recommendation ITU-T G.693 are shown in Table 8-1 for single-channel systems. Those of Recommendation ITU-T G.959.1 for multichannel systems are in Table 8-2.

Table 8-1 – Application codes for single-channel systems specified in Recommendation ITU-T G.693

Target distance	**0.6 km**			**2 km**					
Attenuation category	4 dB	12 dB		4 dB	6 dB		12 dB		16 dB
Source nominal wavelength	1 310 nm	1 310 nm	1 550 nm	1 310 nm	1 310 nm	1 550 nm	1 310 nm	1 550 nm	1 550 nm
Type of fibre	ITU-T G.652	ITU-T G.652	ITU-T G.652 ITU-T G.653 ITU-T G.655	ITU-T G.652	ITU-T G.652	ITU-T G.652 ITU-T G.653 ITU-T G.655	ITU-T G.652	ITU-T G.652 ITU-T G.653 ITU-T G.655	ITU-T G.652 ITU-T G.653 ITU-T G.655
Application code signal class NRZ 10G	Yes	Yes	Yes	Yes	–	Yes	–	–	–
Application code signal class NRZ 40G	–	–	–	–	Yes	Yes	Yes	Yes	Yes

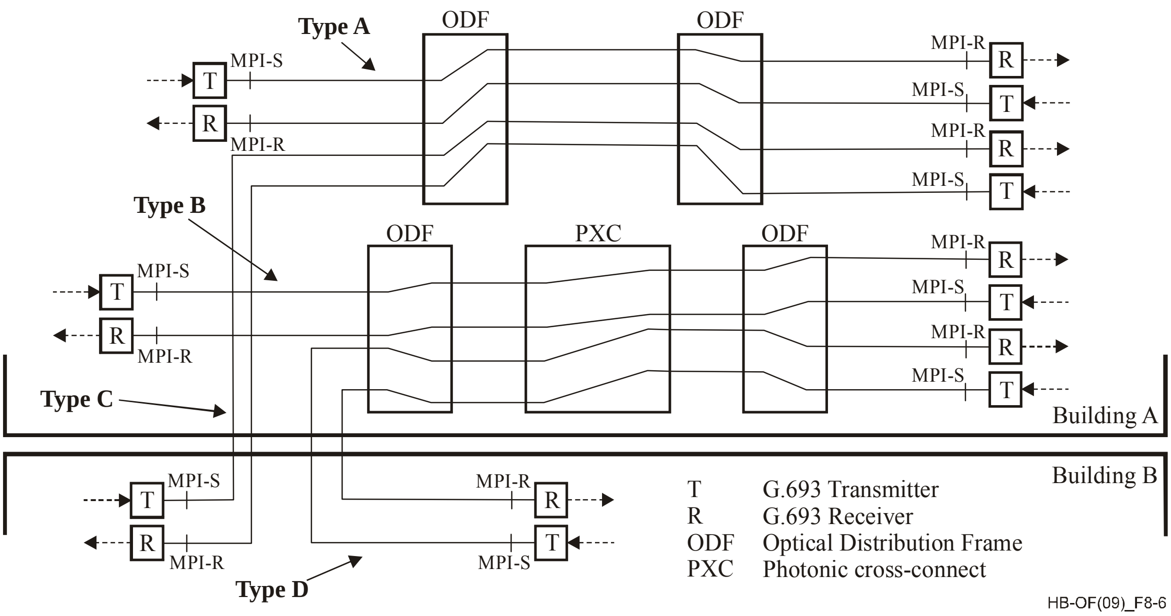
Note – "Yes" means that this application code is specified in Recommendation ITU-T G.693.

Table 8-2 – Application codes for multichannel systems specified in Recommendation ITU-T G.959.1

Application	Intra-office		
Source nominal wavelength (nm)	1550		
Type of fibre	G.652	G.653	G.655
Target distance (km)	20	2	20
Application code signal class NRZ 2.5G	–	–	–
Application code signal class NRZ 10G	Yes 16/32 channels	Yes 16 channels	Yes 16/32 channels

Note – "Yes" means that this application code is specified in Recommendation ITU-T G.959.1.

Figure 8-6 shows a system configuration with different combinations of attenuation category and target distance, corresponding to some ITU-T G.693 application codes.



Interface	Attenuation Category(s)	Target Distance
Type A	R (4 dB)	0.6km
Type B	M (12 dB)	0.6km
Type C	R (4 dB) or L (6 dB)	2km
Type D	M (12 dB) or H (16 dB)	2km

Figure 8-6 – Examples of system configurations using applications defined in Recommendation ITU-T G.693

The figure illustrates that, when selecting an application, attenuation category is determined by the devices in the main optical path, e.g. whether or not a PXC is included, while target distance is determined by the distance between the interconnected equipment.

Thus, for the choice of the most suitable application code, it is necessary to know the length of the intra office link, the bit rate of the signal, the type of fibre and the total loss of the network elements (e.g. ODF, PXC, connectors) placed in the link.

5 Metro access optical networks

CWDM or DWDM systems without line optical amplifiers are commonly used in metro access optical networks to cover distances up to about 80 km.

5.1 CWDM optical systems

Coarse wavelength division multiplexing (CWDM) systems are considered as a cheaper and simpler alternative to DWDM systems for metro access network applications. Since CWDM systems have wide channel spacing (20 nm), they do not require precise wavelength control for transmitter lasers. Thus, cost-effective non-cooled lasers as well as lower-cost passive components may be used for CWDM systems. On the other hand, the maximum number of optical channels in a CWDM system is lower than that of DWDM systems.

The specifications for CWDM systems in Recommendation ITU-T G.695 enable transversely (multi-vendor) compatible interfaces. Applications are defined using two different methods, one using multi channel interface parameters (black-box approach), and the other using single-channel interface parameters (black-link approach), (see Chapter 6). Both linear and ring structures as well as unidirectional and bidirectional applications are specified.

Figure 8-7 shows an example of a CWDM ring network including two or more OADMs. A set of reference points for a unidirectional ring "black-link" approach are described with single-channel connection (S_S and R_S) between transmitters (Tx) and receivers (Rx).

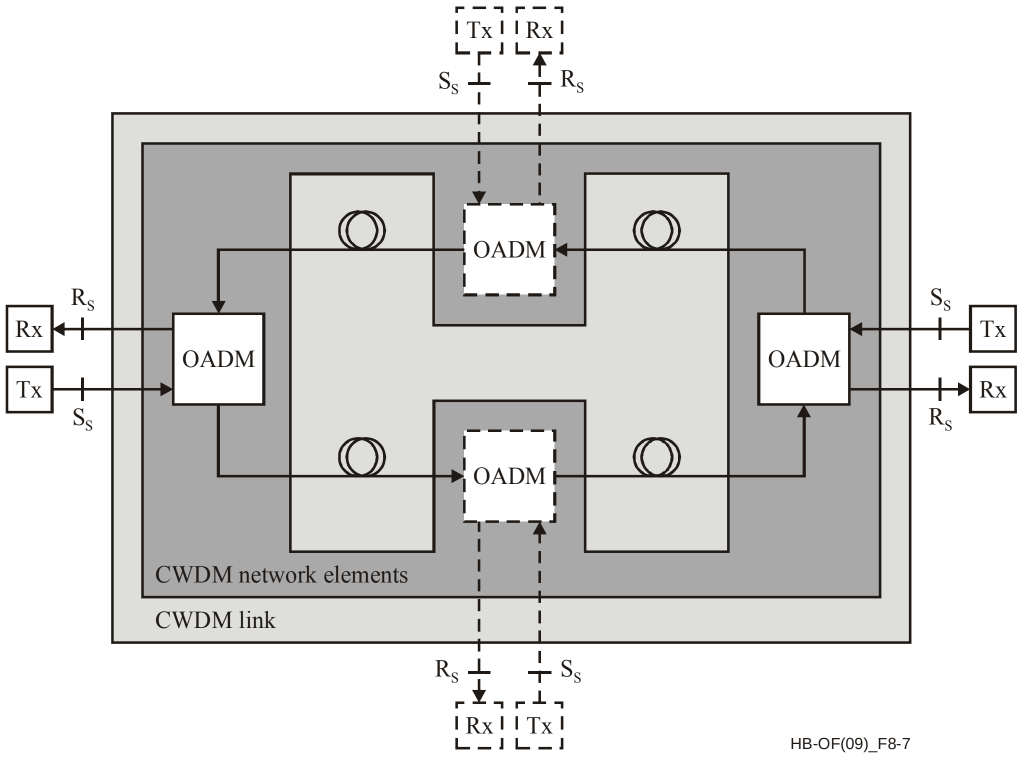


Figure 8-7 – Reference points for a unidirectional ring with "black-link" approach

Recommendation ITU-T G.695 defines optical interface parameter values without line amplifiers. In particular, Recommendation ITU-T G.695 describes CWDM optical line systems that include the following features:

i) target distances ranging from 20 km to 90 km;

ii) maximum number of channels up to 16 with a channel spacing of 20 nm, as specified in Recommendation ITU-T G.694.2 (see Chapter 6);

iii) single channel bit rate of NRZ 1.25 Gbit/s and 2.5 Gbit/s.

The specified application codes are shown in Table 8-3.

The maximum number of "express" OADMs in the link is constrained by several parameters, including maximum channel insertion loss, maximum optical multiplexer insertion loss, maximum optical demultiplexer insertion loss, numbers of connectors and their insertion loss, attenuation coefficient of the fibre, insertion loss of the OADM. An express OADM is one through which the wavelength of interest passes without being added or dropped.

As a matter of fact, the optical path from point S_S to R_S includes the optical path and a number of other network elements (NEs). In the case of ring black-link applications, the NEs include an OM, an OD and all of the OADMs that are traversed by the path from S_S to R_S being considered. The total insertion loss and the total chromatic dispersion of the CWDM network elements and of the optical path must not exceed the values specified for the optical path from point S_S to R_S.

The total loss of the path from S_S to R_S must be set between the minimum channel insertion loss and the maximum channel insertion loss described in the application code being used for the path. Therefore:

$$IL_{min} \le IL_{total} \le IL_{max}$$

where:

IL_{min}: minimum channel insertion loss for the application code,

IL_{max}: maximum channel insertion loss for the application code,

and:

$$IL_{total} = IL_{OM} + N_{OADM}\ IL_{OADM} + IL_{OD} + N_{con}\ IL_{con} + \alpha \bullet L$$

where:

IL_{OM}: OM insertion loss or OADM add loss at point S_S for the wavelength being used from S_S to R_S

N_{OADM}: number of express OADMs

IL_{OADM}: express OADM insertion loss for the wavelength being used from S_S to R_S

IL_{OD}: OD insertion loss or OADM drop loss at point R_S for the wavelength being used from S_S to R_S

N_{con}: number of connectors between S_S and R_S

IL_{con}: connector insertion loss

α: attenuation coefficient of the fibre (dB/km) for the wavelength being used from S_S to R_S

L: total length of fibre between S_S and R_S.

An express OADM is one through which the wavelength of interest passes without being added or dropped. The maximum number of express OADMs in a path between S_S and R_S is therefore given by:

$$N_{OADM} = \left\lfloor \frac{IL_{max} - IL_{OM} - IL_{OD} - N_{con} IL_{con} - \alpha L}{IL_{OADM}} \right\rfloor$$

where the square brackets express the floor function, which generates the largest integer less than or equal to the value of the expression in the brackets.

Table 8-3 – Application codes for CWDM systems specified in Recommendation ITU-T G.695

Application	4-channel unidirectional						4-channel bidirectional			8-channel unid.			12-channel unid.			16-channel unid.		
	Short-haul			Long-haul			Short-haul	Long-haul		Short-haul	Long-haul		Short-haul	Long-haul		Short-haul	Long-haul	
Type of fibre	ITU-T G.652	ITU-T G.653	ITU-T G.655	ITU-T G.652	ITU-T G.653	ITU-T G.655	ITU-T G.652	ITU-T G.652	ITU-T G.653	ITU-T G.652	ITU-T G.652	ITU-T G.653	ITU-T G.652	ITU-T G.652	ITU-T G.653	ITU-T G.652	ITU-T G.652	ITU-T G.653
Signal class NRZ 1.25G	–	–	–	–	–	–	–	Yes	Yes	–	Yes	Yes	–	Yes	–	–	–	–
Signal class NRZ 2.5G	Yes	Yes	Yes	Yes	Yes	Yes	–	Yes	Yes	Yes	Yes	Yes	–	Yes	–	Yes	Yes	–

Note – "Yes" means that an application code exists in Recommendation ITU-T G.695.

The evaluation of the maximum number of OADMs must be done for each S_S to R_S path in the network so that the maximum number of OADMs is not exceeded for any S_S to R_S path. This is quite simple for networks where all of the paths share a common hub (Figure 8-8), but becomes more complicated as the path topology becomes more complex (Figure 8-9).

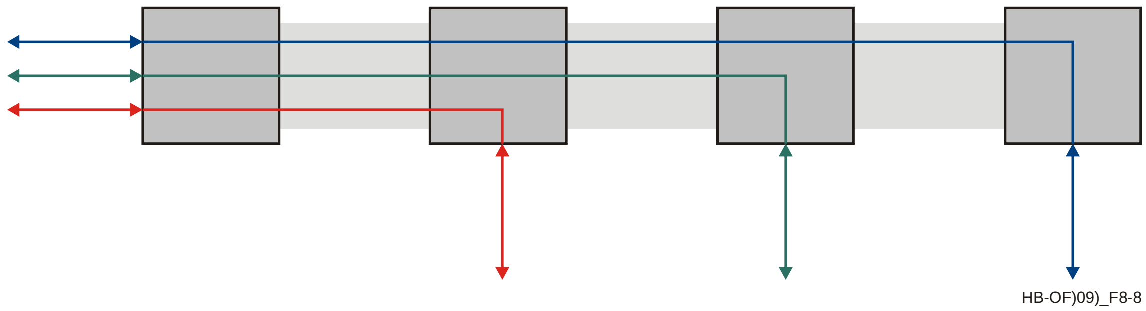


Figure 8-8 – Simple example of linear black-link topology

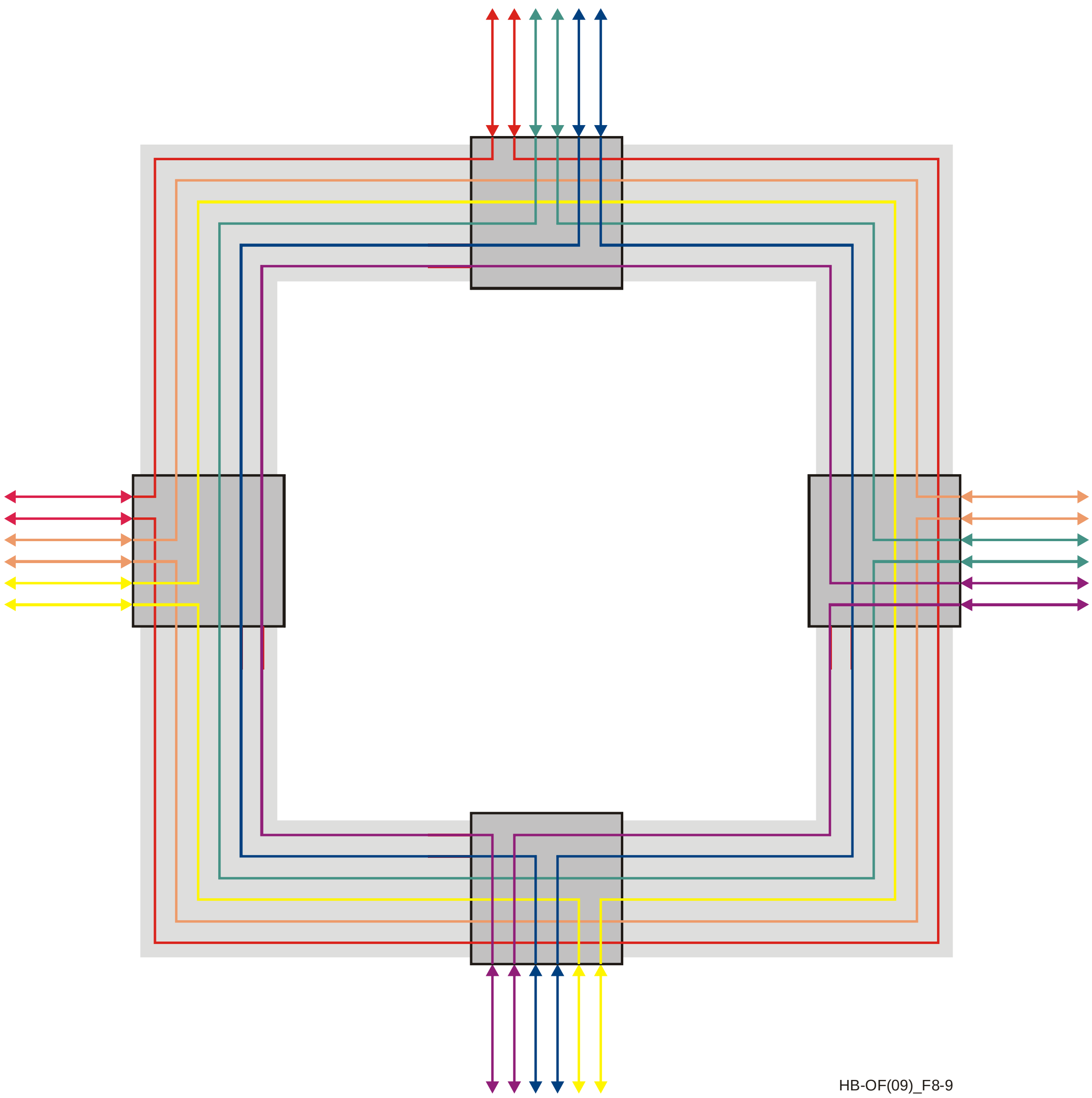


Figure 8-9 – Complex example of ring black-link topology

5.2 DWDM optical systems

DWDM systems for metro network applications are specified both with the black-box approach, in Recommendation ITU-T G.959.1, and with the black-link approach, in Recommendation ITU-T G.698.1.

5.2.1 Single-channel and DWDM optical systems (black-box approach)

Recommendation ITU-T G.959.1 provides transversely compatible optical interface specifications to enable multi-vendor interoperability with the black-box approach for links without line amplifiers.

This Recommendation provides the physical layer parameters and values for application codes corresponding both to the single-channel and multichannel interfaces with 3R regenerators on both sides of the interface as shown in Figure 8-10.

The reference points in Figure 8-10 are defined as follows:

– MPI-S is a (single channel) reference point just after each of the optical network element tributary interface output optical connectors;

– MPI-R is a (single channel) reference point on the optical fibre just before each of the optical network element tributary interface input optical connectors;

– MPI-S_M is a (multichannel) reference point on the optical fibre just after the optical network element transport interface output optical connector;

– MPI-R_M is a (multichannel) reference point on the optical fibre just before the optical network element transport interface input optical connector.

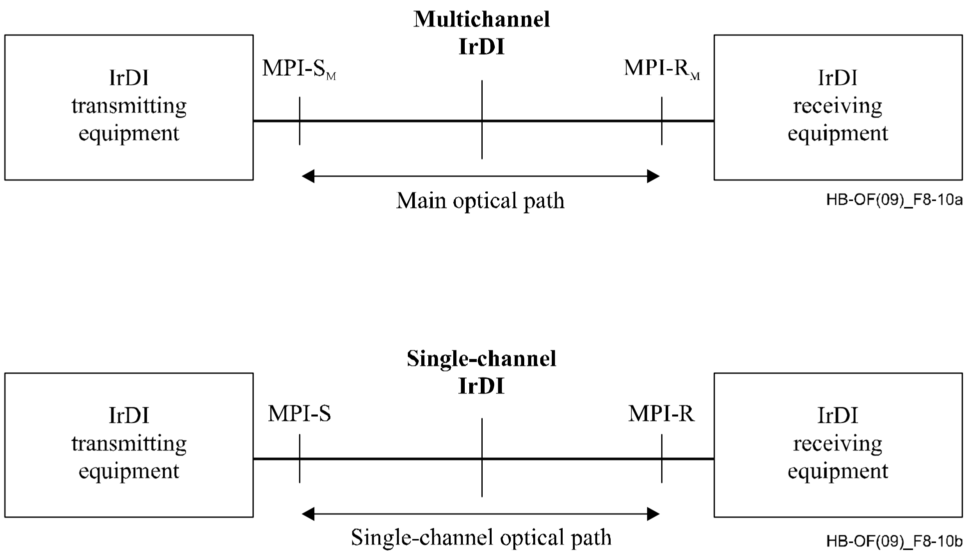


Figure 8-10 – Multichannel and single-channel IrDI reference configurations

The optical systems specified in Recommendation ITU-T G.959.1 cover:

i) target distances ranging from 20 km to 160 km;

ii) highest class of optical tributary signal supported: NRZ 2.5G, NRZ 10G and NRZ 40G;

iii) single and multi-channel applications;

iv) light sources and fibre types: 1 310 nm sources on ITU-T G.652 fibre, 1 550 nm sources on ITU-T G.652 fibre, 1 550 nm sources on ITU-T G.653 fibre, 1 550 nm sources on ITU-T G.655 fibre.

Some applications require FEC (forward error correction) bytes, as specified in Recommendation ITU-T G.709, to be transmitted to satisfy the target distance.

The specified application codes are shown in Tables 8-4 and 8-5.

The applications do not cover all possible combinations of distance category, optical tributary signal class, nominal source wavelength and fibre type. The applications included in Recommendation ITU-T G.959.1 are intended to satisfy a broad range of network requirements with low-cost implementations.

An example of these system interfaces with various clients is shown in Figure 8-11.

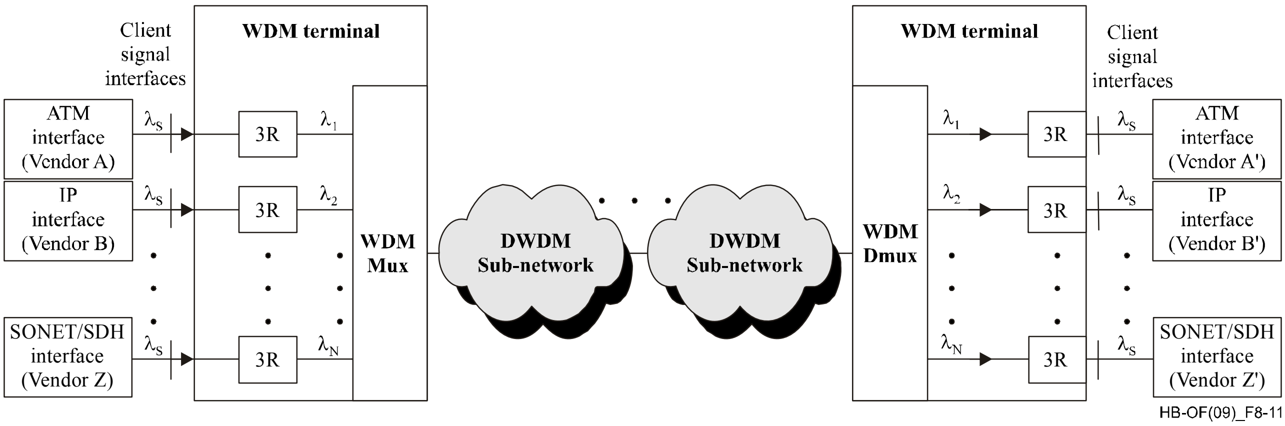


Figure 8-11 – Example of client signal interface with 3R regeneration

The interfaces specified in Recommendation ITU-T G.959.1 can be used for inter-domain and intra-domain connections. Inter-domain interfaces (IrDI) are intended to interconnect two different administrative domains. Such domains may consist of the equipment made by different vendors. The two administrative domains may also belong to different network operators. On the contrary, Intra-domain interfaces (IaDI) are those inside an administrative domain. Some examples of IrDI and of IaDI interfaces are shown in Figure 8-12.

As matter of fact, transverse (multivendor) compatibility is enabled for all IrDIs having exactly the same application code nWx-ytz. If a P16S1-2B2 interface of one vendor is implemented in domain A, it can be connected with a P16S1-2B2 interface of another vendor installed in domain B.

Interconnection between the interfaces with different application codes is a matter of joint engineering. Care must be taken, particularly with respect to critical parameters that must be matched, e.g. MPI-S_M output power, MPI-R_M power levels, maximum dispersion, minimum/maximum attenuation, etc. As an example, an interface P16S1-2B2 (booster amplifier power levels) in domain A should not be interconnected with an interface P16S1-2C2 (preamplifier power levels) in domain B without additional measures, e.g. adding an attenuator. In this example, the booster amplifier type interface output power may be +15 dBm and the minimum attenuation may be 0 dB. Thus, the input power to the preamplifier type interface may reach +15 dBm. Then, as the maximum receiver input power of the preamplifier type interface is +5 dBm, the receiver is overloaded by up to 10 dB. Care must also be taken to match the optical tributary signal bit rate and format.

Table 8-4 – Application codes for single-channel interfaces defined in Recommendation ITU-T G.959.1

Application	Short-haul				Long-haul				Very long-haul			Ultra long-haul		
Source nominal wavelength (nm)	1 310	1 550			1 310	1 550			1 550			1 550		
Type of fibre	ITU-T G.652	ITU-T G.652	ITU-T G.653	ITU-T G.655	ITU-T G.652	ITU-T G.652	ITU-T G.653	ITU-T G.655	ITU-T G.652	ITU-T G.653	ITU-T G.655	ITU-T G.652	ITU-T G.653	ITU-T G.655
Application code signal class NRZ 2.5G	Yes	Yes	–	–	Yes	Yes	–	–	–	–	–	Yes	Yes	Yes
Target distance for 2.5G (km)	20	40	–	–	40	80	–	–	–	–	–	160	160	160
Application code signal class NRZ 10G	Yes	Yes	Yes	Yes	Yes	Yes	–	–	Yes	–	Yes	–	–	–
Target distance for 10G (km)	20	40	40	40	40	80	–	–	120	–	120	–	–	–
Application code signal class NRZ 40G	Yes	Yes	Yes	Yes	–	Yes	Yes	Yes	–	–	–	–	–	–
Target distance for 40G (km)	20	40	40	40	–	80	80	80	–	–	–	–	–	–

Note – "Yes" means that an application code exists in Recommendation ITU-T G.959.1.

Table 8-5 – Application codes for multichannel interfaces defined in Recommendation ITU-T G.959.1

Application	Short-haul			Long-haul	
Source nominal wavelength (nm)	1550			1550	
Type of fibre	ITU-T G.652	ITU-T G.653	ITU-T G.655	ITU-T G.652	ITU-T G.655
Target distance (km)	40	40	40	80	80
Application code signal class NRZ 2.5G	Yes 16/32 channels	–	Yes 16/32 channels	Yes 16 channels	Yes 16 channels
Application code signal class NRZ 10G	Yes	Yes	Yes	Yes	Yes

Note – "Yes" means that an application code exists in Recommendation ITU-T G.959.1.

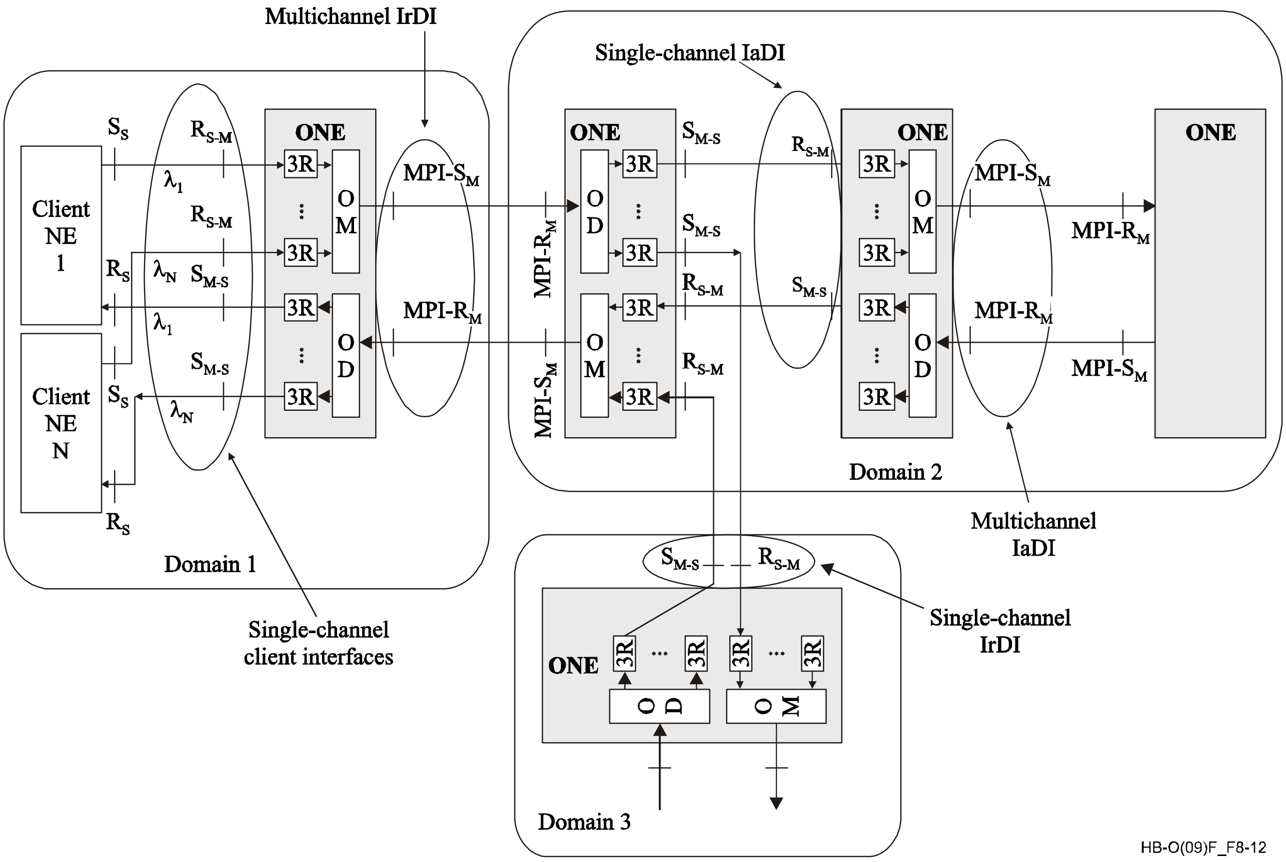


Figure 8-12 – Examples of multichannel and single-channel inter-domain and intra-domain interfaces

5.2.2 DWDM optical systems (black-link approach)

Optical interface specifications towards the realization of transversely compatible dense wavelength division multiplexing systems primarily intended for metro applications are also specified in Recommendation ITU-T G.698.1.

That Recommendation defines and provides values for single-channel optical interface parameters of physical point-to-point and ring DWDM applications (with transmission distance in the range of about 30 km to about 80 km) on single-mode optical fibres.

These DWDM systems with single-channel interfaces are primarily intended to be used in metropolitan area networks for a variety of clients, services and protocols.

The specification method in Recommendation ITU-T G.698.1 uses a "black-link" approach, which means that optical interface parameters for only (single-channel) optical tributary signals are specified. Additional specifications are provided for the black-link parameters such as maximum attenuation, chromatic dispersion, ripple and polarization mode dispersion. This approach enables transverse compatibility at the single-channel point using a direct wavelength-multiplexing configuration. However, it does not enable transverse compatibility at the multichannel points. In this approach, the OM and OD are treated as a single set of optical devices and OADMs can be included.

Figure 8-13 shows a set of reference points, for the *linear* "black-link" approach, for single-channel connection (S_S and R_S) between transmitters (Tx) and receivers (Rx). Here, the DWDM network elements include an OM and an OD, which are used as a pair with the opposing element, and may also include one or more OADMs.

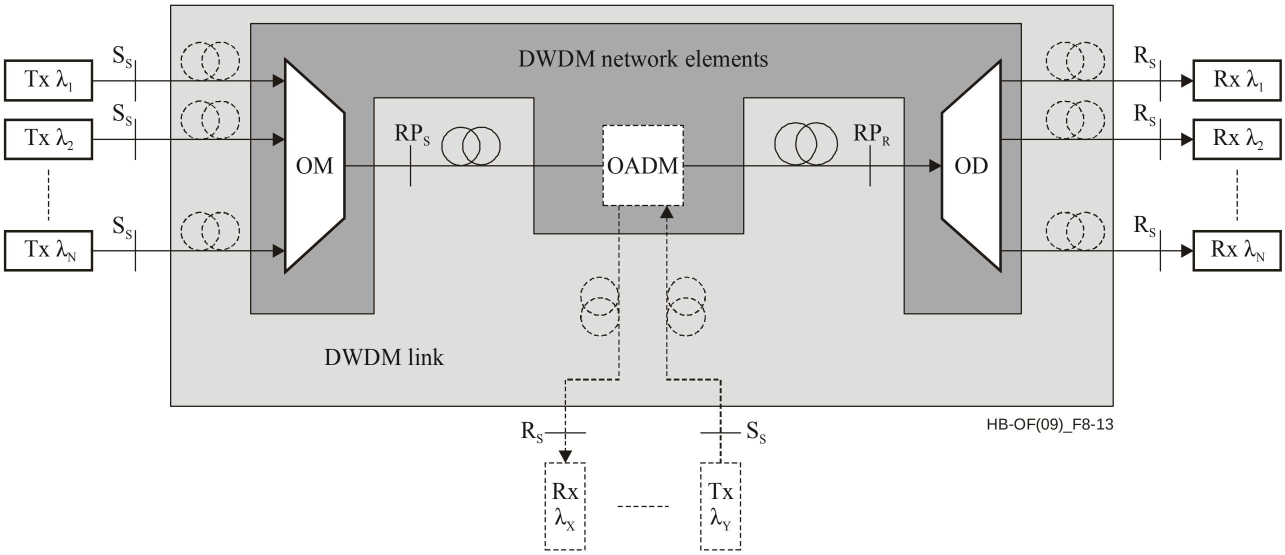


Figure 8-13 – Example of a linear configuration using black-link approach

As indicated in Figure 8-13, if the transmitter or receiver is located at a distance from the OM, OD or OADM, the fibre between point S_S or R_S and the DWDM network element is considered to be part of the black link.

Figure 8-14 shows a corresponding set of reference points for the *ring* "black-link" approach, for single-channel connection (S_S and R_S) between transmitters (Tx) and receivers (Rx). Here, the DWDM network elements include two or more OADMs connected in a ring.

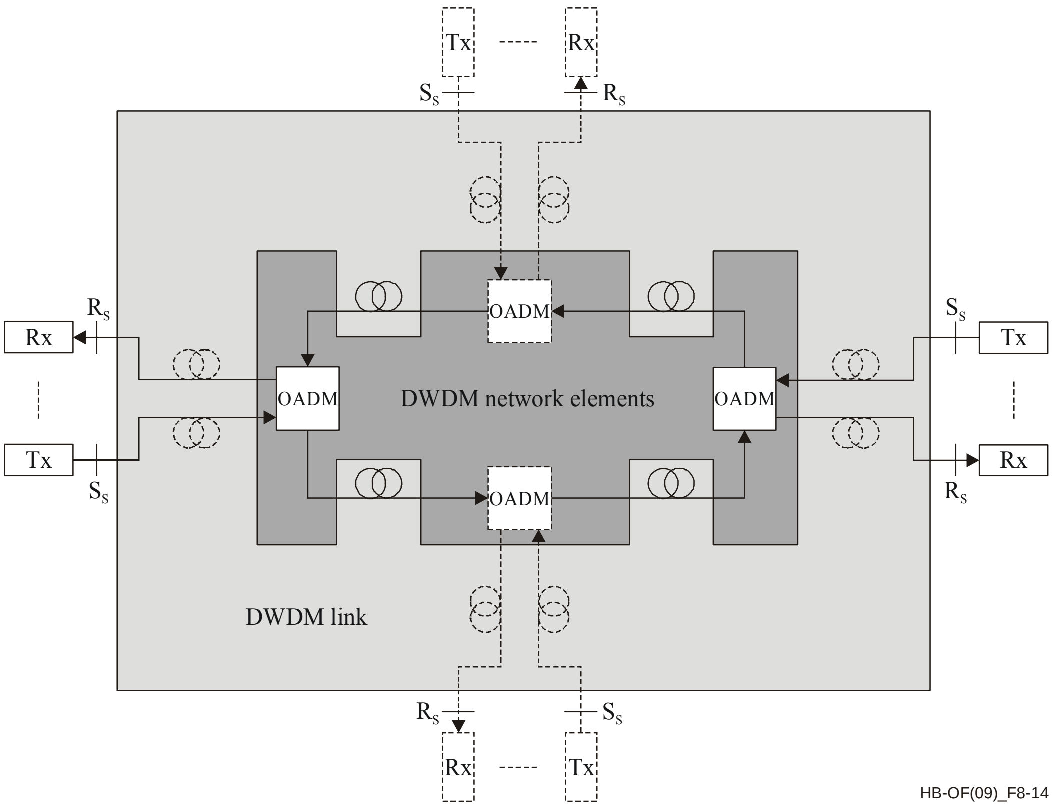


Figure 8-14 – Example of a ring configuration using black-link approach (without line optical amplifiers)

In this figure, single-channel reference points S_S and R_S are applied to systems for the "black-link" approach where every path from S_S to its corresponding R_S must comply with the parameter values of the application code.

All the reference models of Recommendation ITU-T G.698.1 do not include any optical amplifiers in the DWDM system.

DWDM systems described in Recommendation ITU-T G.698.1 include the following features:

i) channel frequency spacing: 100 GHz and above;

ii) signal channel bit rate: 2.5 Gbit/s and 10 Gbit/s.

The application codes of these types of systems are shown in Table 8-6, in which applications with and without forward error correction are listed.

Table 8-6 – Application codes for multichannel systems defined in Recommendation ITU-T G.698.1

Application	**Short-haul**		**Long-haul**		**Short-haul**		**Long-haul**	
Bit rate/ line coding	NRZ 2.5G	NRZ OTU1	NRZ 2.5G	NRZ OTU1	NRZ 10G	NRZ OTU2	NRZ 10G	NRZ OTU2
Fibre type	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655
Maximum channel insertion loss (dB)	16.5	19.5	25.5	28.5	18.5	21.5	24.5	27.5

The target distance is a function of the attenuation of the optical multiplexer and optical demultiplexer as well as the number of OADMs inserted in the system. The maximum number of OADMs that can be supported is constrained by the parameters which characterize the optical path between S_S and R_S (see, for example, Figure 8-13). In an Appendix to Recommendation ITU-T G.698.1, some formulas and calculations are given to determine the possible limitations and restrictions to the maximum number of OADMs, using the following parameters: maximum channel insertion loss, maximum ripple, maximum chromatic dispersion, reflections, maximum differential group delay and maximum interferometric crosstalk.

6 Metro core / regional optical networks

DWDM systems to be deployed in the metro core / regional networks can have lengths up to about 400 km. For these applications it is necessary to deploy DWDM systems with line optical amplifiers.

Optical parameter values for physical layer interfaces of DWDM systems primarily intended for metro applications including optical amplifiers are specified in Recommendation ITU-T G.698.2. Applications are defined using optical interface parameters at the single-channel connection points between optical transmitters and the optical multiplexer, as well as between optical receivers and the optical demultiplexer in the DWDM system (black-link approach). This means that optical interface parameters for only (single-channel) optical tributary signals are specified. This black-link approach uses a methodology which does not specify the details of the optical link, e.g. the maximum fibre length, explicitly. It enables transverse compatibility at the single-channel point using a direct wavelength-multiplexing configuration. However, it does not enable transverse compatibility at the multichannel points. The definition of single channel optical interfaces for DWDM systems enables the elimination of transponders, which would otherwise be needed in multi-vendor DWDM optical transmission networks. Chapter 6 of this Handbook shows two cases of interconnection between the DWDM line systems with transmitters and receivers: one with transponders (equipment non compliant) and one without transponder (equipment compliant).

Recommendation ITU-T G.698.2 provides the physical layer parameters and values for single-channel interfaces of DWDM multichannel optical systems in physical point-to-point and ring configurations. Figure 8-15 shows a ring application to illustrate the "black-link" approach together with the single channel reference points R_S and S_S. The arrangement of elements within the black-link is only an example, and Recommendation ITU-T G.698.2 does not intend to place constraints on the construction of such a black-link.

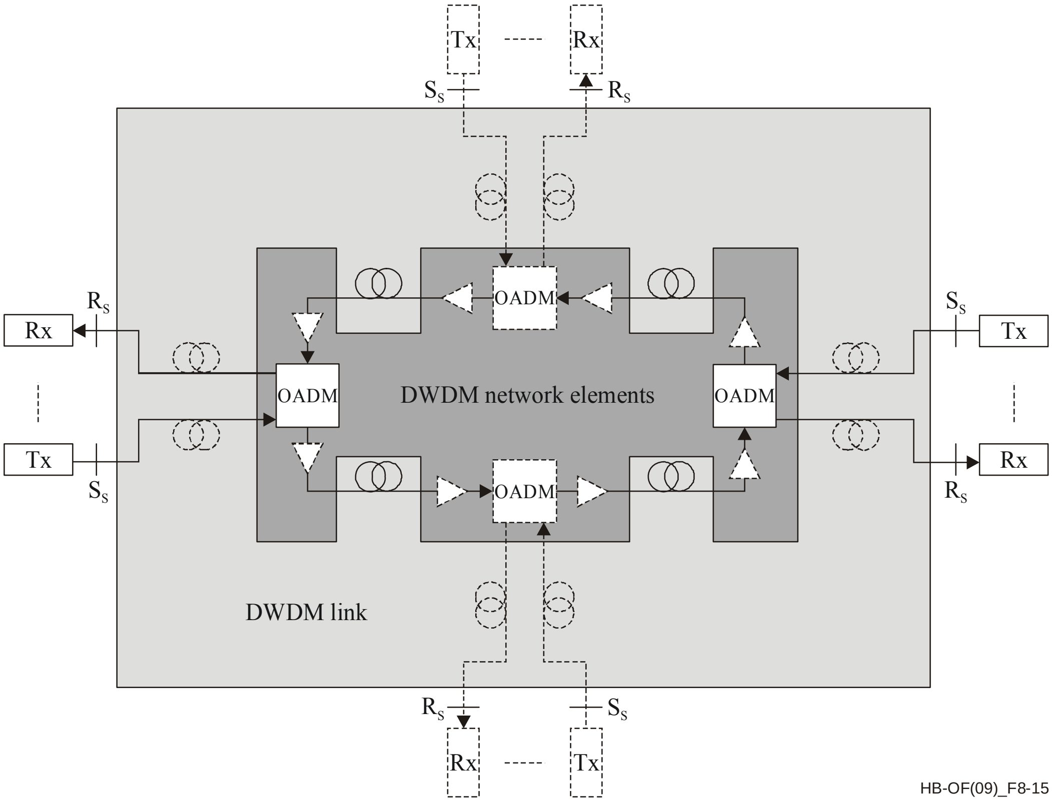


Figure 8-15 – Example of a ring configuration using black-link approach (with line optical amplifiers)

The current version of Recommendation ITU-T G.698.2 covers:

i) highest class of optical tributary signal: NRZ 2.5G and NRZ 10G;

ii) operating wavelength range: C-band, L-band;

iii) channel frequency spacing: 100 GHz;

iv) type of optical fibre: ITU-T G.652, ITU-TG.653 and ITU-T G.655 fibres;

v) black-link dispersion compensation regime: dispersion compensated (the black-link chromatic dispersion values are appropriate to a link that includes dispersion compensators between points S_S and R_S), dispersion un-compensated (the black-link chromatic dispersion values are appropriate to a link that does not include any dispersion compensators or is only partially compensated).

Some applications require FEC (forward error correction) bytes, as specified in Recommendation ITU-T G.709, to be transmitted.

Specifications are organized according to application codes, as shown in Table 8-7. These application codes are focused on features of the single-channel interfaces and do not define any elements or structure of the DWDM link.

Table 8-7 – Application codes defined in Recommendation ITU-T G.698.2

Bit rate/ line coding	**NRZ 2.5G with dispersion compensation**	**NRZ 2.5G without dispersion compensation**	**NRZ OTU1 with dispersion compensation**	**NRZ 10G with dispersion compensation**	**NRZ OTU2 with dispersion compensation**	**NRZ OTU2 without dispersion compensation**
Fibre type	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655	ITU-T G.652/ ITU-T G.653/ ITU-T G.655

For the choice of the most suitable application code it is necessary to know the signal channel bit-rate at the connection points, the type of the fibre available, the wavelength range the DWDM link was designed for, the requirements of the DWDM link on the spectral excursion of the transmitters (narrow or wide spectral excursion), the minimum OSNR supplied by the DWDM link and the range of the optical power at point R_S. The requirements of the DWDM link on the spectral excursion of the transmitters are related to the optical bandwidth of the wavelength multiplexers, de-multiplexer and OADMs as well as the total number of these devices cascaded in the black-link.

7 Backbone/long haul networks

DWDM systems to be deployed in the backbone networks may cover distances of more than 1 000 km. Recommendation ITU-T G.696.1 provides physical layer specifications for intra-domain (IaD) DWDM optical networking applications, in which optical line amplifiers are included depending on the distance the system should cover.

The goal is to enable longitudinally compatible applications inside an administrative domain. The primary purpose of that Recommendation is to enable multiple vendors to design DWDM transmission equipment for fibre links that are compliant with that Recommendation. The corresponding reference configuration is shown in Figure 8-16.

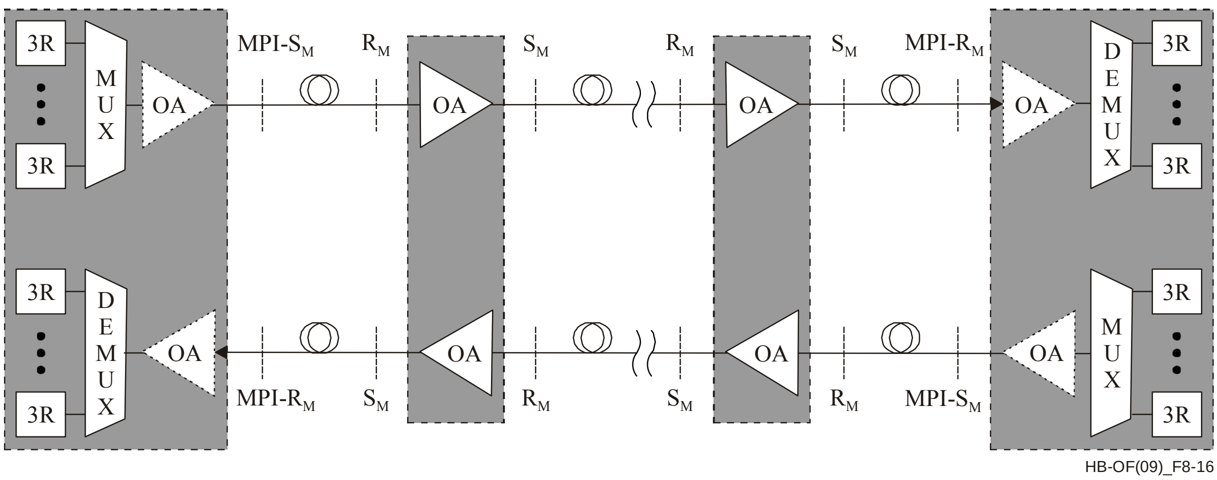


Figure 8-16 – Reference configuration for a multi-span DWDM system

Recommendation ITU-T G.696.1 specifies only longitudinally compatible applications because the specification of transversally compatible applications for DWDM systems with many line optical amplifiers (even if it gives more flexibility in the deployment of the systems) is very difficult and requires unacceptable margin.

This is due to the fact that the very long DWDM systems must be designed by a sophisticated optimization and considering compromise among a lot of different parameters and constraints which makes the coexistence in the same DWDM system of equipment from different manufacturers (as happens in transversally compatible applications) extremely difficult to standardize (see Chapter 7).

Recommendation ITU-T G.696.1 defines the generic term client class that refers to the client bit rate within an optical channel before additional FEC bytes have been added.

The specifications are organized according to application codes, which take into account parameters such as operating wavelength ranges of the optical amplifiers, combinations of channel counts, client classes, span distances, fibre types and system configurations. For these systems the application codes consist of two separable sections.

The application code notation is constructed as follows:

n . B – xWF(s)

where:

n: maximum number of channels supported by the application code,

B: client class: 1.25G, 2.5G, 10G, 40G,

x: number of spans within the application code,

W: letter indicating the span attenuation, such as:
S: indicating short-haul (up to 11 dB span attenuation),
L: indicating long-haul (up to 22 dB span attenuation),
V: indicating very long-haul (up to 33 dB span attenuation),

F: fibre type, such as ITU-T G.652.A, … ITU-T G.652.D denoted by “652A” … “652D” in the application code, respectively,

s: operating wavelength range in terms of spectral bands (see Chapter 6): O, E, S, C, L.

The first part “n . B” relates to the optical transmission system and the second part “xWF(s)” relates to the fibre infrastructure. Since this Recommendation covers longitudinally compatible systems, the parameters specified for intra-domain DWDM applications relate to the fibre infrastructure only, except for the system-related part of the application code affecting the fibre requirements. In case of a Raman amplified DWDM transmission system, a letter “R” shall be added at the end of the application code.

An example of a specific application could look like this:

40.10G-20L652A(C)R

This application indicates a 40-channel system with signal channels of the 10G payload class, 20 long-haul spans of ITU-T G.652A fibre which are suitable for use with Raman amplifiers. The C-band is used as the operating wavelength range.

Theoretical limits and design considerations for DWDM systems are indicated in an Appendix to Recommendation ITU-T G.696.1. In particular, ASE noise (characterized by OSNR) and PMD limits are illustrated by both general equations and specific examples based on reference systems with up 35 spans (2 800 km in length on the assumption of a mean value of 80 km per span). Moreover, there is an example showing the feasibility of a system with a maximum of about 15 span (1 200 km on the assumption of a mean value of 80 km per span).

Other effects that limit transmission distance are mentioned, as well, in the above-mentioned Appendix, such as accumulated gain ripples and stimulated Raman effects, non-uniform span length, optical non-linearity, residual dispersion, and accumulated PDL effects. Finally, a number of techniques used to mitigate impairments are summarized, including dynamic gain equalization, line coding (i.e. modulation format), number of optical channels and their spacing, fibre types, mixing different types of fibre within one span.

8 Repeaterless and repeatered optical fibre submarine systems

Optical fibre submarine cable systems are an important element of telecommunication networks because they allow the connection of terminal stations divided by a sea. These links can be of various lengths, starting from a few kilometres (for linking to islands just offshore) up to several thousands of kilometres (for linking different continents through the oceans). These very different applications require very different transmission capabilities.

Submarine systems are substantially different from terrestrial ones in many aspects, because the environmental conditions where they operate impose more severe requirements. There are essentially two basic requirements:

i) a very high reliability for the submerged plant, considering that each fault needs the intervention of a cable ship and each of these interventions lasts some days;

ii) a very long operational lifetime, considering the high costs of development, manufacturing and laying of a submarine link with the stringent reliability objectives noted above.

As a consequence all of the Recommendations on optical fibre, submarine cable systems deal not only with the electrical/optical characteristics, but also with the mechanical/reliability characteristics. Moreover, a detailed description is made of the tests to be carried out during the various phases of the realization from manufacturing to final acceptance.

There is another aspect that sets submarine systems apart from terrestrial ones and affects the manner in which Recommendations related to systems are written. Submarine systems, as terrestrial ones, are interconnected to terrestrial networks at the two terminal stations, and at these interfaces they have to be compliant with the SDH/OTN interfaces specified in Recommendations ITU-T G.707 and ITU-T G.709. In contrast to this, the situation of the submarine system itself (the connection between the two terminal stations) is different from that of the terrestrial systems for two main reasons:

i) the components of a terrestrial link often come from different vendors (fibres, cables, DWDM equipment, OADM, etc.), while the provision of a submarine link is usually made "turnkey" by a single vendor. This means that a single company supplies all that is necessary for the realization of the link between the two interfaces with the terrestrial networks;

ii) the installation of all of the submerged equipment required for the final capacity of the system (optical amplifiers, branching units, etc) is carried out at the time of the laying of the system.

These two differences have an impact on the way the specifications are written. For terrestrial systems, the applications specified are either longitudinally compatible or transversely compatible, in order to enable some level of multi-vendor interoperability. For submarine systems neither of these types of compatibility are generally very useful, because the equipment for all of the link and for all the optical fibres of the submarine cable are sourced from the same supplier at the time of the laying of the system. As a consequence, the Recommendations on submarine optical systems do not specify any particular application code with the values of the parameters at one particular interface, but they are focused on the identification of the parameters and of the characteristics of the submarine systems which should be carefully defined for each link. The specific values of these parameters for each system to be realized will be defined between the operator and the supplier, with the objective of achieving stringent quality objectives.

Based on the above general considerations, ITU has published several Recommendations which specifically deal with optical fibre submarine cable systems: Recommendations ITU-T G.971, ITU-T G.972, ITU-T G.973, ITU-T G.974, ITU-T G.975, ITU-T G.975.1, ITU-T G.976, ITU-T G.977 and ITU-T G.978.

8.1 Submarine systems topology

The types of topology for optical fibre submarine cable systems are in some way different from those applied for the terrestrial networks (see § 2). As shown in the following they are: point-to-point, star, branched star, trunk and branch, festoon, ring and branched ring.

8.1.1 Point to point

This configuration (Figure 8-17) consists of direct submarine link between two terminal transmission equipment (TTE) located in two different terminal stations (TS).

Figure 8-17 – Topology of point to point

8.1.2 Star

This configuration (Figure 8-18) consists of a main terminal station (TS) that links several other TSs with separate cables. In the basic star configuration, traffic is directly transmitted from TTE of the main TS to the TTE of the other TSs independently. Therefore, the star network requires a separate cable for each TS, which leads to a relatively costly configuration, particularly when TSs are geographically distant.

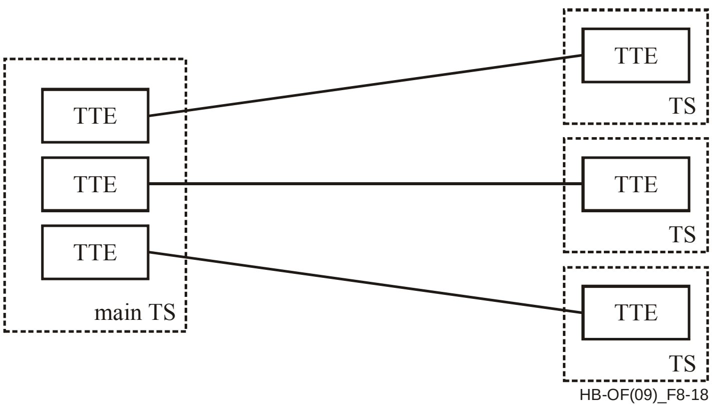


Figure 8-18 – Topology of star

8.1.3 Branched star

This configuration (Figure 8-19) provides the same capacity as the basic star, except that the splitting of traffic is done underwater, minimizing the cost of separate cable between remotely located TSs. Splitting of traffic is accomplished with a branching unit (BU) that interconnects the fibres of a single trunk cable with separate fibres inside two or more branches.

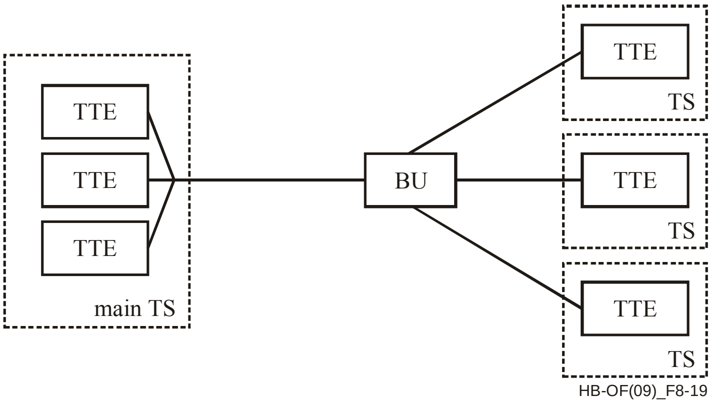


Figure 8-19 – Topology of branched star

8.1.4 Trunk and Branch

This configuration (Figure 8-20) connects several TSs including TTEs to a single trunk cable by means of branching units that allow the extraction of a part of the traffic in the direction of the TSs of the branches.

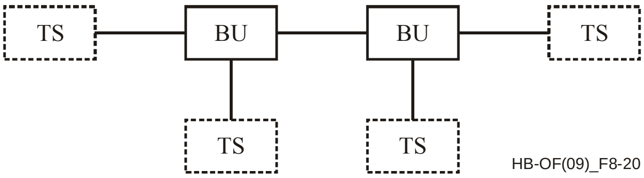


Figure 8-20 – Topology of trunk and branch

8.1.5 Festoon

The festoon (Figure 8-21) is basically a series of loops between major coastal landing points, and it is often deployed, though not always, as a repeaterless system. In anticipation of a future increased capacity requirement, these repeaterless applications are typically engineered with higher-fibre-count cables than those required for initial service. Thus, in the case of a need of additional capacity, terminal equipment is the only additional investment required. The architecture of a festoon frequently mirrors that of a typical, land-based installation. Such architecture may often be used as a supplemental, diverse route to an existing land-based system. This configuration is an increasingly popular alternative to a land-based system, especially when the continental terrain provides difficult installation and maintenance challenges.

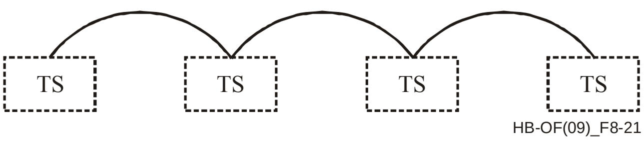


Figure 8-21 – Topology of a festoon

8.1.6 Ring

The ring configuration (Figure 8-22) is essentially a set of connected, point-to-point cables having twice the requisite transmission capacity.

In case any single failure occurs within the ring, such as a cable cut, traffic is routed around the ring, away from the inoperable segment, and on to its original destination. Shore-based transmission equipment provides automatic failure detection and switchover control for the entire ring without dropping a call.

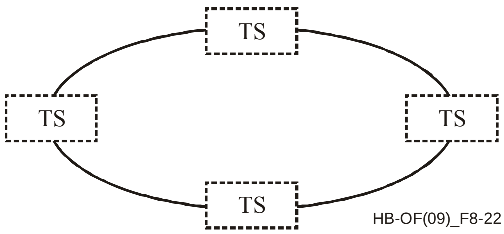


Figure 8-22 – Topology of a ring

8.1.7 Branched Ring

This configuration (Figure 8-23) extends the basic capability of the ring in a cost effective manner with the addition of a branching unit. The branched-ring structure retains the self-healing nature of the ring. The branched ring, then, can be thought of as a merger between the trunk-and-branch and the ring, retaining most of the benefits of each. This configuration can be made in a number of ways, including hook-up through other networks. With proper planning, a network can be installed as a trunk-and-branch arrangement and upgraded later to a branched ring.

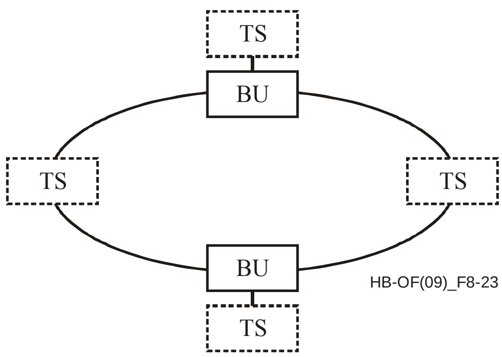


Figure 8-23 – Topology of a branched ring

8.2 Repeatered optical submarine systems

(For further information see Recommendation ITU-T G.977).

The use of the DWDM technique in combination with optical amplifiers, dispersion accommodation and FEC has completely changed the design of optical submarine systems. Starting from the first transatlantic optical cable system with a single-channel per fibre pair at 280 Mbit/s in 1988, the evolution of the technology has arrived at DWDM systems on transoceanic links with a capacity of 128 × 10 Gbit/s per fibre pair.

The characteristics of repeatered optical submarine systems using optical fibre amplifiers as line repeaters are dealt with in Recommendation ITU-T G.977. It refers to the system characteristics required to guarantee the performance, the reliability (usually 25 years, starting at the provisional acceptance date of the system) and the capacity upgradeability.

The following submerged equipment types are also defined:

i) Optical Submarine Repeaters;

ii) Branching Unit;

iii) Optical Submarine Equalizer.

Mechanical, electrical, and optical characteristics; supervisory and fault location facilities; and reliability considerations are detailed for all of them.

An example of repeatered/branched optical submarine system is shown in Figure 8-24.

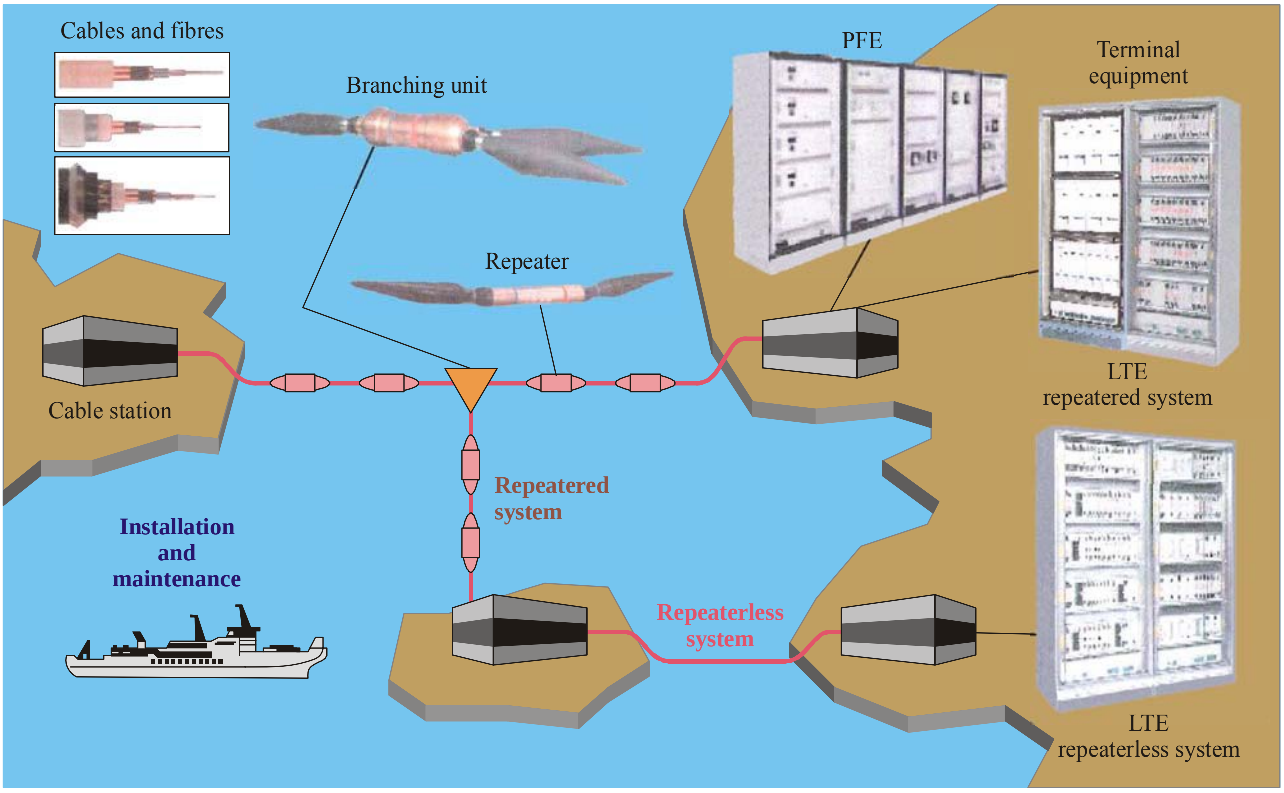


Figure 8-24 – Exampled of a repeatered / branched submarine system

8.2.1 System configuration

The configuration of a repeatered optical submarine system is in Figure 8-25 where:

- TTE (terminal transmission equipment) is the equipment terminating the optical submarine transmission line at the optical interface and connected to the system interface;
- CTE (cable terminating equipment) is the equipment providing the interface between the optical fibre from the TTE and the optical fibre cable, and the interface between the power feeding line from the PFE and the power feeding conductor from the optical fibre cable. The CTE is usually part of the PFE;
- BU (branching unit) is the equipment connecting more than two optical fibre submarine cable sections;
- PFE (power feeding equipment) is the equipment providing, through a power conductor in the optical fibre submarine cable, a stabilized constant electrical current for powering optical submarine repeaters and/or optical submarine branching units.

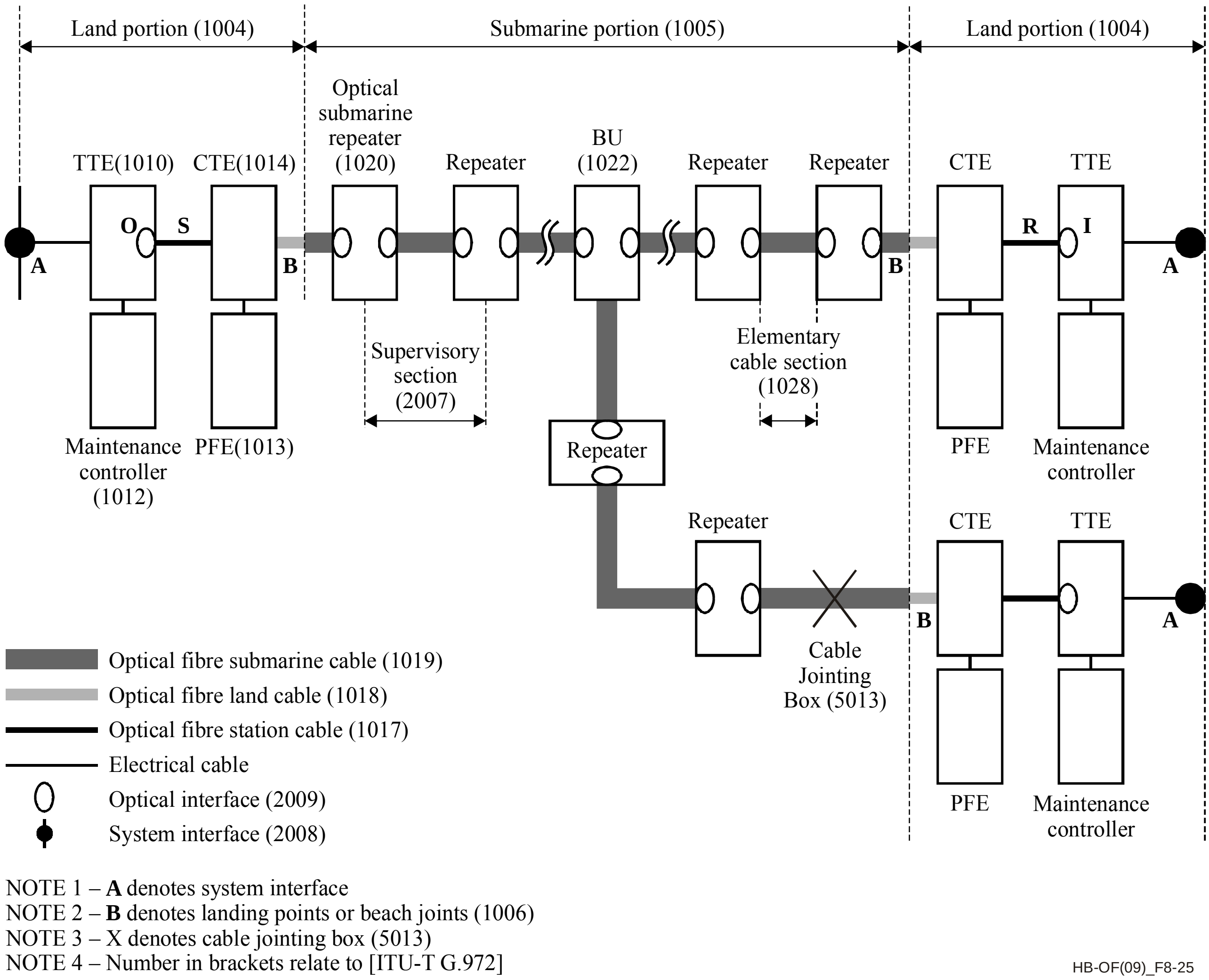


Figure 8-25 – Configuration of a repeatered optical fibre submarine cable systems

8.3 Repeaterless optical submarine systems

(For further information see Recommendation ITU-T G.973).

The purpose of a repeaterless optical fibre submarine cable system is to establish transmission links between two or more terminal stations located in a restricted geographical area. To reduce cost and complexity of this type of submarine system, no line optical amplifier is used. As a consequence, no power feeding equipment is necessary. As far as the branching unit devices are concerned, those considered in Recommendation ITU-T G.973 are the passive ones, thereby avoiding electronic components as well as supervisory and power feeding. Therefore, repeaterless optical submarine systems offer several advantages over the repeatered ones:

i) higher reliability because there are no submerged repeaters;

ii) lower cost because power feeding of the submerged repeaters and their supervision are not required;

iii) higher capacity because it is possible to lay submarine cables with a high number of fibres (e.g. 96 fibres) because there is not the constraint of the available space in the containers of the submerged repeaters;

iv) for these systems the principle "pay as you grow" applies because the first investment is only that related to the cable, while the terminal equipment can be installed/activated/paid for following the traffic demand.

The system performance and interface requirements of repeaterless optical fibre submarine cable systems are dealt with in Recommendation ITU-T G.973. It considers both single-channel systems and DWDM systems. A scheme of a multichannel system is illustrated in Figure 8-26.

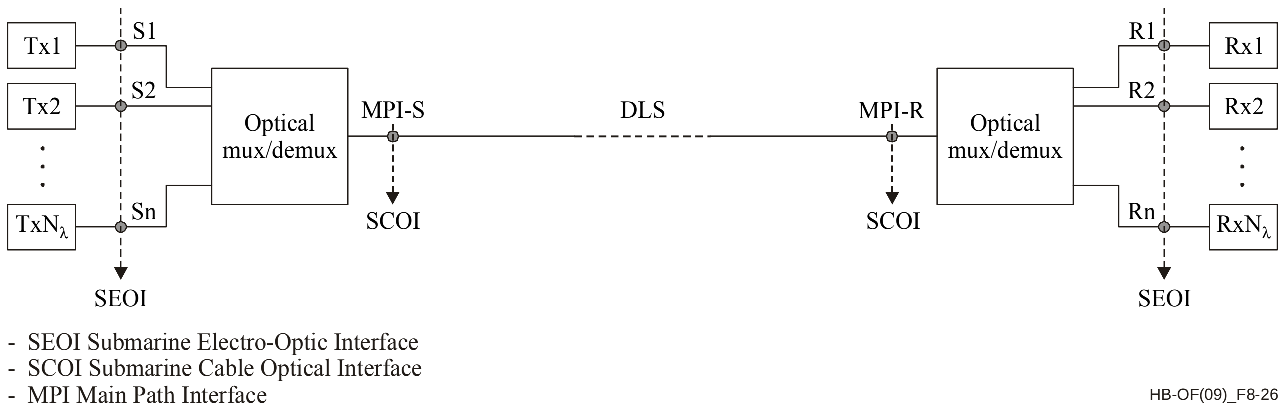


Figure 8-26 – Configuration of a repeaterless optical submarine system

The dispersion and nonlinear effects are of less concern for such systems than for transoceanic optical systems, but fibre attenuation becomes a major issue. The reason is easily appreciated, noting that a power budget of about 60 dB is necessary over a distance of about 300 km for transmitting about 30 channels at 10 Gbit/s. In order to realize such systems, it is necessary to use high performance FECs, Raman amplifiers and remote optically pumped amplifiers (ROPA), and specific types of fibres, which can also be different within the same link.

Recommendation ITU-T G.973 covers not only submarine systems with no optical amplifiers, but also submarine systems using discrete optical fibre amplifiers as power amplifiers, pre-amplifiers, Raman amplifiers and/or ROPA.

Optical amplifiers can be inserted in the system as power amplifiers just after the laser transmitter to increase the terminal output power, or as pre-amplifiers inserted just before the optical receiver to reduce the minimum optical signal power at the input of a composite receiver (pre-amplifier plus terminal receiver). In general, system enhancement can be achieved by power amplifier only, pre-amplifier only, or a combination of both.

Moreover, the application of remote optically pumped amplifiers (ROPA) and distributed Raman amplifiers (DRA) is also considered. A ROPA consists of a section of erbium-doped fibre (EDF) pumped from the terminal station at an appropriate wavelength, whereas the DRA use the fibre itself as an amplification medium and require the fibre pumped from the terminal station at appropriate wavelength. There is no electrical power propagation into the submarine portion. This technique can be employed at either the transmitter or the receiver side of a link although it is generally considered more efficient at the receive side. Generic characteristics of DRA are given in Chapter 5.

The possible system configurations are shown in Figure 8-27.

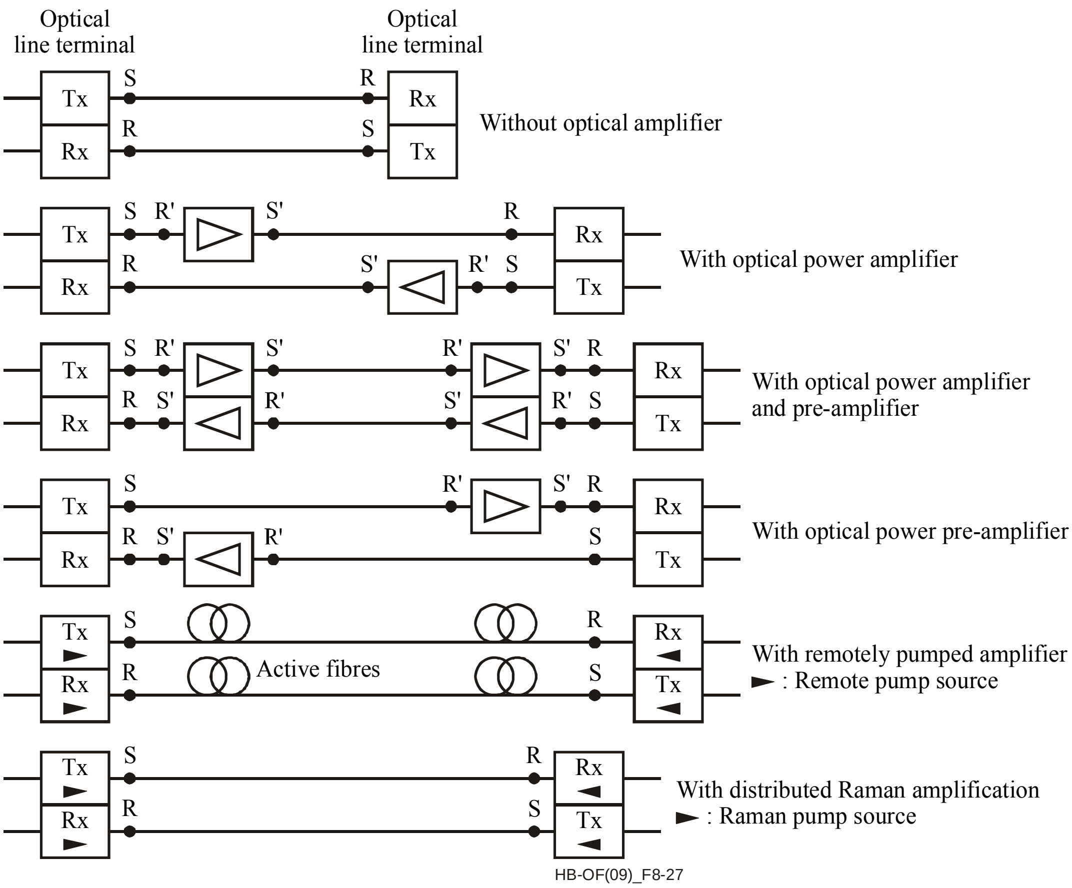


Figure 8-27 – Possible repeaterless system configurations

8.4 System reliability

The reliability of the submarine portion of an optical fibre submarine cable system is generally characterized by:

i) the expected number of repairs requiring intervention by a cableship and due to system component (e.g. splices, branching unit (BU), transitions, etc.) failures during the system design life. The usual requirements for the reliability of repeatered and repeaterless systems are less than three and one failure requiring cableship intervention, respectively, during the system design life:

ii) the system design life is the period of time over which the optical fibre submarine cable system is designed to be operational, in conformance with its performance specification. Usually, the system design life is a period of 25 years, starting at the provisional acceptance date of the system, i.e. the date following installation when the system is claimed to be compliant with the performance specification.

8.5 System upgradability

It may be advantageous to increase the transmission capacity by increasing the signal bit rate and/or the number of transmission channels. Such upgrading can be beneficial because the reuse of cables can be achieved cost-effectively over the equipment's long life, typically 25 years.

Bit-rate upgradeability demands that systems be constructed with cables optimized for the higher bit rate, while lower bit-rate TTE may be initially used. Even after upgrading, the bit rate of TTE output must comply with SDH/OTN specifications, to ensure compatibility with standard terrestrial equipment.

Upgradeability also demands that the initially installed cable be capable of carrying the maximum number of channels expected in the future.

Upgrading by increasing signal bit rate or by adding more channels is much different from many viewpoints of system design including the post-amplifier output power, pre-amplifier input power, power budget, signal-to-noise ratio, fibre chromatic dispersion, and fibre non-linearities. It is therefore recommended that the systems be designed properly, considering the possibility of future upgrades.

8.6 Optical Power Budget

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

The optical power budget starts from a simple linear quality factor (Q-factor) which only takes into account degradation due to the ASE noise of amplifiers (*mean Q*). Then, the optical power budget allocates the penalties/impairments for all types of degradation (due to the transmission, due to terminal equipment, etc., …). The degradation is estimated using a combination of theoretical analysis, computer simulations and direct measurements on experimental test-beds (see Chapter 7).

For each submarine system, it is recommended to establish two distinct power budgets, one at the beginning of life (BOL) and another one at the end of life (EOL) (Figure 8-28):

i) The BOL power budget provides the worst case digital line section performance which will be measured during the commissioning;

ii) The EOL power budget provides the estimated worst case digital line section performance at the end of system life and includes margins for ageing, internal failures and specified repair margins.

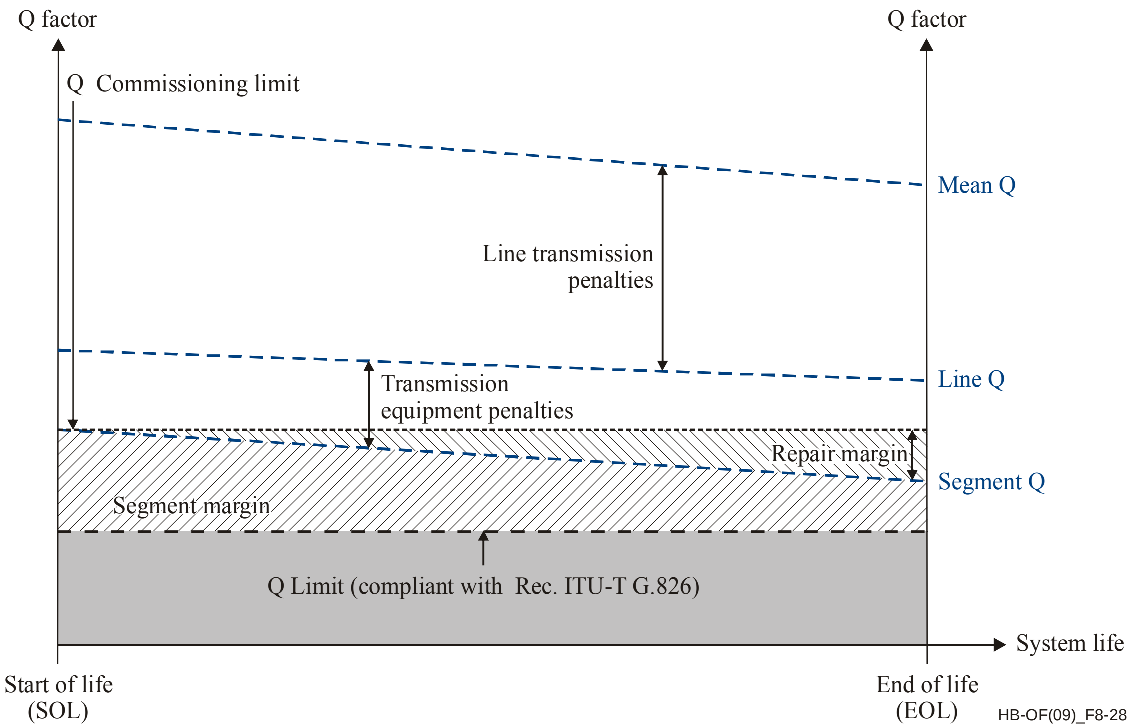


Figure 8-28 – Power budget structure example

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

The power budget tables should compute margins that should be considered as a minimum requirement for the system at BOL. In Recommendation ITU-T G.977 these margins should be expressed in terms of a Q-factor value. An example of a possible power budget template is shown in Table 8-8.

Table 8-8 – An example of a possible power budget template

	Parameter	**BOL Q (dB)**	**EOL Q (dB)**
1	Mean Q value (from a simple SNR calculation)		
1.1	Propagation impairments due to combined effects of chromatic dispersion, non-linear effect, four-wave mixing effects, stimulated Raman scattering effects, etc.		
1.2	Gain flatness impairment		
1.3	Non-optimal optical pre-emphasis impairment		
1.4	Wavelength tolerance impairment		
1.5	Mean PDL penalty		
1.6	Mean PDG penalty		
1.7	Mean PMD penalty		
1.8	Supervisory impairment		
1.9	Manufacturing and environmental impairment		
2	Time varying system performance (5 sigma rule)		
3	Line Q value (1 – (1.1 to 1.9) – 2)		
4	Specified TTE Q value (back-to-back)		
5	Segment Q value (computed from 3 and 4)		
5.1	BER corresponding to segment Q without FEC		
5.2	BER corresponding to segment Q with FEC		
5.3	Effective Segment Q value with FEC		
6	Q limit compliance with G.826 after FEC correction		
7	Repairs margins Components and fibre ageing penalty Pump(s) failure penalty Non-optimal decision threshold		
8	Segment margins		
9	Unallocated supplier margin		
10	Commissioning limits		

Table 8-8 should be completed as follows:

– Line 1 – Mean Q value (simple SNR calculation). (There exist different formulas: Simple noise accumulation with constant signal power or total output power and with/without extinction ratio, etc.) (see Chapter 7).

– Lines 1.1 to 1.9 give a non-exhaustive list of impairment sources that impact system performances. Those impairments have to be deducted from Line 1.

– Line 2 – Time varying system performance:

This defines an additional impairment due to polarization fluctuation phenomena that decrease the mean performances.

– Line 3 – Line Q value:

This line gives the line Q-factor. It is the result of this operation:

Line 3 = Line 1 – (line 1.1 to line 1.9) – line 2.

– Line 4 – Specified TTE Q value:

This line gives the specified LTE back-to-back Q factor at BOL and EOL.

– Line 5 – Segment Q value:

This line gives the segment Q-factor calculated from lines 3 and 4 using the following formula:

$$\frac{1}{Q^2 segment} = \frac{1}{Q^2 line} + \frac{1}{Q^2 TTEbacktoback}$$

– Line 5.1 – BER corresponding to segment Q without FEC:

Line 5 converted into bit error ratio (BER) before forward error correction.

– Line 5.2 – BER corresponding to segment Q with FEC:

BER after FEC correction.

– Line 5.3 – Effective segment Q value with FEC:

Line 5.2 converted into Q factor.

– Line 6 – Q limit for compliance with Recommendation ITU-T G.826 after correction:

Q-factor corresponding to the worst allowable bit error ratio before correction by FEC. For example, 11.2 dB corresponds to a BER of 2.4×10^{-4}. A BER of 2.4×10^{-4} is converted by the first generation FEC correction to a BER better than 10^{-11}. Therefore, a Q-factor of 11.2 dB covers all DLS lengths for the first generation FECs.

– Line 7 – Repairs, ageing and pump failures:

Line 7 is given by line 5 (BOL) minus line 5 (EOL).

– Line 8 – Segment margins:

Line 8 (EOL): the segment margins are usually 1 dB contractually at EOL.

Line 8 (BOL) is given by line 7 plus line 8 (EOL).

– Line 9 – Unallocated supplier margins:

Margin for other and unknown impairments.

– Line 10 – Commissioning limit:

This line gives the contractual commissioned Q limit for each DLS.

9 Wavelength switched optical networks (WSON)/all optical networks (AON)

(For further information see Recommendation ITU-T G.680).

A backbone network can extend to an entire geographical region (e.g. a country, which can have different dimensions such as USA or Italy) with a given topology (e.g. a mesh topology). The nodes in the network are connected through point-to-point DWDM links and they usually have 3R regeneration and switching made electronically (e.g. by digital cross-connects). Such transport networks are called "opaque" networks because they require optical-to-electronic conversion at the switching node. As a result, neither the bit rate nor the modulation format can be changed without changing the switching equipment.

An all optical network (AON) in which a DWDM signal can pass through multiple nodes (adding/dropping and/or switching the optical channels) is called optically "transparent". Transparent networks do not require optical-to-electronic conversion of all DWDM channels. The nodes in the transparent network may include optical add/drop channels through OADM or ROADM, and optical switching channels through PXC.

The present optical transport networks (OTN) are evolving towards all optical networks with an ever decreasing number of O/E/O conversions within their boundaries. The two main reasons for this evolution are the following:

i) DWDM systems are becoming capable of transporting optical signals for thousands of kilometres without electrical regeneration;

ii) Photonic cross-connects (PXC_S) and optical add/drop multiplexers ($OADM_S$) are becoming available with specifications suitable for their use in the telecommunication networks, including capacity, space requirements, power consumption, reliability and cost.

This evolution will lead to the deployment of an optically transparent domain that can be large enough to transparently transmit the signals in all the potential routes of the backbone network of a medium size country (optical paths up to around 2 000 km) (Figure 8-29).

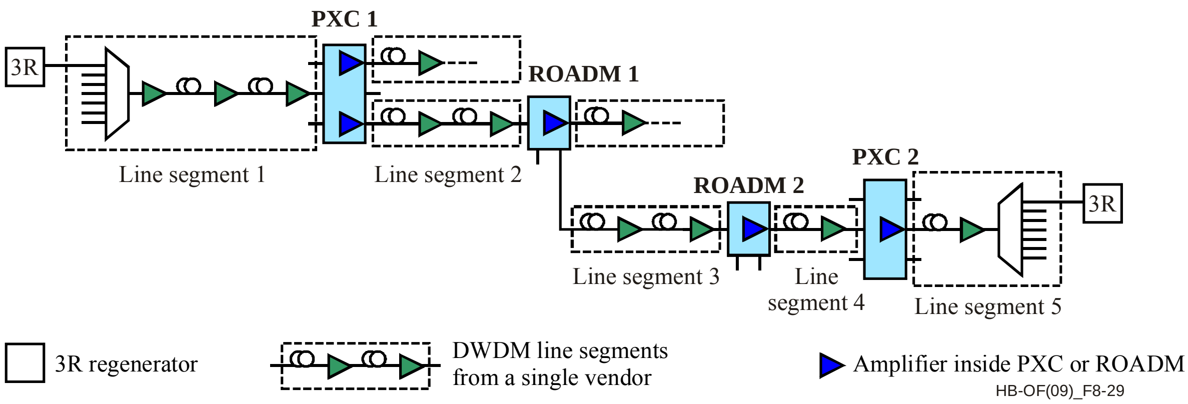


Figure 8-29 – Example of optical transmission system

Considering the OTN evolution described above, it is important to define a "degradation function" of optical network elements (ONE_S) such as photonic cross connects (PXC_S), optical add-drop multiplexers ($OADM_S$), etc. making up an optical network.

One application of the degradation functions is to enable, at the moment of the activation / rerouting of an optical channel, the calculation of the overall degradation of the chosen route on the basis of the "degradation function" of each ONE involved and to evaluate whether the overall degradation is compatible with the error performance objectives at the O/E/O 3R end-point. Figure 8-29 gives an example path. If this check gives a positive answer, the optical channel is activated. If the check is negative, it will be necessary either to find another route or to insert a 3R regeneration point at a suitable place along the route.

This calculation is done in terms of a list of parameters that characterize physical impairments (such as optical noise, chromatic dispersion etc.) and is intended to be independent from the network architecture that the devices are deployed in.

Recommendation ITU-T G.680 deals with this subject and covers a reference situation where the optical path between two consecutive electrical regenerators is composed of dense wavelength division multiplexing (DWDM) line segments from a single vendor and $OADM_S$ and PXC_S from other vendors as shown in Figure 8-30.

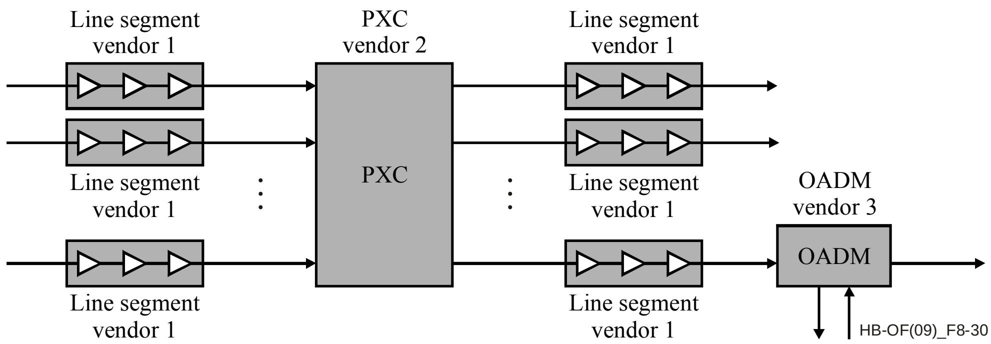


Figure 8-30 – Example of optical path with ONEs from different vendors

The information provided in Recommendation ITU-T G.680 (when taken together with the corresponding parameters from the DWDM line segments including any non-linear effects) enables the evaluation of the impact on line system performance of the combination of transfer parameters (OSNR, residual dispersion, PMD, PDL, channel ripple, transient phenomena, channel uniformity) related to the cascade of ONEs inserted in the optical path between the ingress and egress 3R electrical regenerators (Figure 8-29).

Recommendation ITU-T G.680 describes principles for calculating the effect of cascading multiple ONEs on the degradation of the optical signal quality for each parameter and for the combined effect of all of them. As an example, the impact of cascaded ONEs on line system OSNR and an example of calculation of this impact are given in the following. The impact of cascaded ONEs on the other parameter degradations, and the method of combining them, can be also found in Recommendation ITU-T G.680.

9.1 Impact of cascaded ONEs on line system OSNR

In the case that the ONEs considered contain optical amplifiers, the OSNR of the optical signals at the output or drop ports will be lower than the OSNR at the input or add ports. The magnitude of this reduction can be calculated using equation (8-1).

$$osnr_{out} = \frac{1}{\dfrac{1}{osnr_{in}} + \dfrac{1}{osnr_{one}}} \tag{8-1}$$

where:

$osnr_{out}$: linear OSNR at the output port of the ONE,

$osnr_{in}$: linear OSNR at the input port of the ONE,

$osnr_{one}$: linear OSNR that would appear at the output port of the ONE for a noise free input signal.

If the OSNR is defined in logarithmic terms (dB) and the equation for the OSNR due to the ONE being considered is substituted this equation becomes:

$$OSNR_{out} = -10\log\left(10^{-\left(\frac{OSNR_{in}}{10}\right)} + 10^{-\left(\frac{P_{in} - NF - 10\log\left(h\nu\nu_r\right)}{10}\right)}\right) \tag{8-2}$$

where:

$OSNR_{out}$: log OSNR (dB) at the output port of the ONE,

$OSNR_{in}$: log OSNR (dB) at the input port of the ONE,

P_{in}: channel power (dBm) at the input port of the ONE,

NF: noise figure (dB) of the relevant path through the ONE,

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

ν: optical frequency (Hz),

ν_r: reference bandwidth (Hz) (usually the frequency equivalent of 0.1 nm)

This equation can be generalized to account for the OSNR of any end to end path through an optical network (including the effect of the amplifiers in the WDM line segments). The resulting equation is Equation (8-3).

$$OSNR_{out} = -10\log\left(10^{-\left(\frac{P_{in1} - NF_1 - 10\log\left(h\nu\nu_r\right)}{10}\right)} + 10^{-\left(\frac{P_{in2} - NF_2 - 10\log\left(h\nu\nu_r\right)}{10}\right)} + \ldots + 10^{-\left(\frac{P_{inN} - NF_N - 10\log\left(h\nu\nu_r\right)}{10}\right)}\right) \tag{8-3}$$

where:

P_{in1}, P_{in2} to P_{inN}: channel powers (dBm) at the inputs of the amplifiers or ONEs on the relevant path through the network,

NF_1, NF_2 to NF_N: noise figures (dB) of the amplifiers or ONEs on the relevant path through the network.

The $OSNR_{out}$ value that is needed to meet the required system BER depends on many factors such as the bit rate, whether and what type of FEC is employed, the magnitude of any crosstalk or non-linear penalties in the DWDM line segments etc. and is outside the scope of reference situation considered within Recommendation ITU-T G.680.

An example calculation of the effect on OSNR of cascading multiple ONEs can be found in the next clause.

9.2 Example of calculation of the impact of cascaded ONEs on line system OSNR

In order to illustrate the effect of multiple ONEs on line system OSNR, an example system is shown in Figure 8-31.

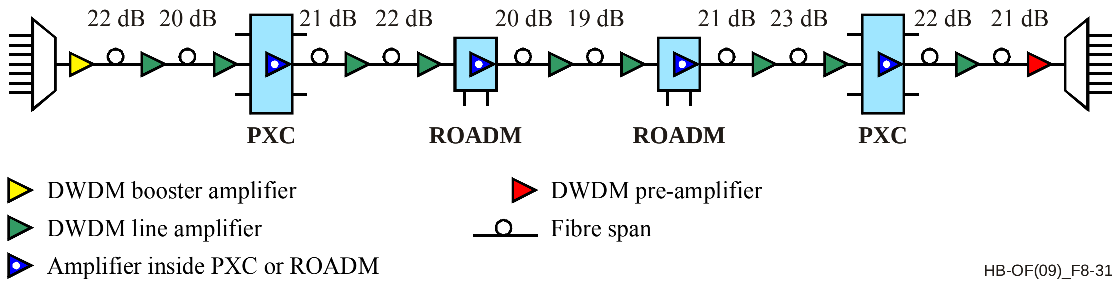


Figure 8-31 – Configuration of OSNR example system

This example also assumes:

- the channel signal-spontaneous noise figure for the ROADMs is 22 dB;
- the channel signal-spontaneous noise figure for the PXCs is 20 dB;
- the channel output power of all of the amplifiers is +1 dBm;
- the noise figures of the booster, line and pre-amplifiers are 7 dB;
- the gain of the booster amplifier is 10 dB.

Equation (8-3) can be applied to calculate the OSNR at the output of the demux for a channel wavelength of say 1 550.12 nm (193.4 THz). One element of this equation 10 log ($h\nu\nu_r$) for $\nu = 193.4$ THz and $\nu_r = 12.48$ GHz (0.1 nm) equals –58.0 dBm.

Equation (8-3) then becomes:

$$OSNR_{out} = -10\log\left(10^{-\left(\frac{-9-7+58}{10}\right)} + 10^{-\left(\frac{-21-7+58}{10}\right)} + 10^{-\left(\frac{-19-7+58}{10}\right)} + 10^{-\left(\frac{1-20+58}{10}\right)} + \ldots + 10^{-\left(\frac{-20-7+58}{10}\right)}\right)$$

Table 8-9 summarizes the values used for each term for P_{in} and NF and shows the resulting OSNR values at the output of each amplifier.

Table 8-9 – OSNR example summary

	Booster	**Line1**	**Line2**	**PXC1**	**Line3**	**Line4**	**OADM1**	**Line5**	**Line6**	**OADM2**	**Line7**	**Line8**	**PXC2**	**Line9**	**Pre1**
Pin (dBm)	–9	–21	–19	1	–20	–21	1	–19	–18	1	–20	–22	1	–21	–20
NF (dB)	7	7	7	20	7	7	22	7	7	22	7	7	20	7	7
Output OSNR	42.0	29.7	27.7	27.4	25.8	24.4	24.1	23.5	23.0	22.8	22.2	21.4	21.3	20.8	20.4

Hence, the OSNR at the output of the demux for the 1 550.12 nm channel would be 20.4 dB for this system.

The impact of cascaded ONEs on other parameter degradations and the method for combining them can be found in Recommendation ITU-T G.680.