Chapter 2
A Tutorial on Physical-Layer Impairments in Optical Networks

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1 Introduction

Exploiting the wavelength domain in order to utilise the abundant fiber spectrum has been one of the cornerstones of optical communications. By transmitting different channels on different wavelengths, one could multiply the transmitted capacity without the need of advanced multiplexing subsystems. The history of the WDM technique began once laser and receiver technology became widely available at room temperature; hence, the transmission of two signals simultaneously, one at the 1.3 μm and one at the 1.55 μm, was possible in the 1980s. Meanwhile the advent of fiber amplifiers in the late 1980s together with improved optical subsystems alleviated the need for a number of optoelectronic regenerators and brought about the breakthrough of the WDM technology in mid-1990s resulting in optical networks that soon looked like the one shown in Fig. 2.1. Each signal modulates one of the tens of wavelengths which are now multiplexed passively onto the same fiber. Many optical channels can now share the same optical components (fibers, amplifiers etc.), leading to an enormous cost reduction. Further enhancement of the overall capacity was achieved by technology improvements that could bring WDM channels closer. The next generation of WDM systems was based on higher channel bit rates per wavelength. 40 Gb/s made techno-economic sense only when efficient modulation formats combined with high-speed digital signal processing could actually replace adequately their 10Gb/s counterparts.

Nevertheless optical communications have been aiming at cost reduction through efficient utilisation of common resources. By looking into the history of optical communication systems [1, 2], both experimentally achieved and commercially available, it is evident that there are two ways that their capacity has been

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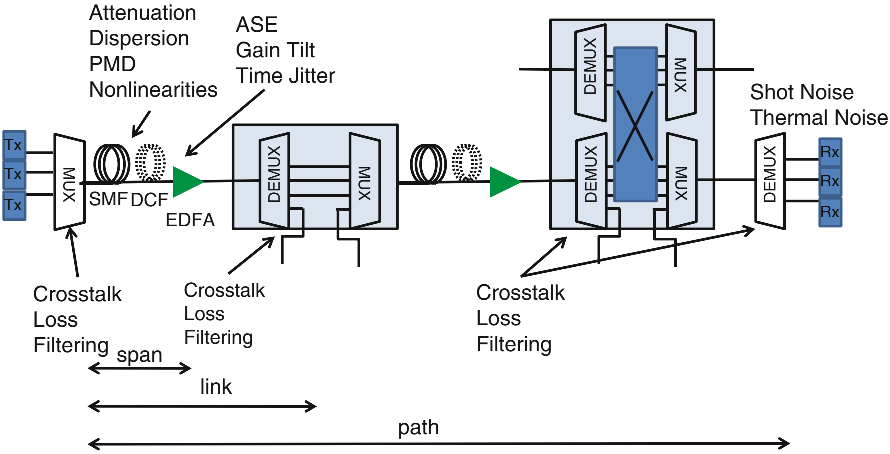

Fig. 2.1 WDM system that comprises a number of dispersion compensated and amplified spans and also ROADMs and OXCs. The figure indicates the impairments and their place to the system that will be thoroughly discussed in this chapter

evolved throughout the years: the one concerns efficient *multiplexing* and the other concerns efficient data *modulation* for spectral efficiency. Meanwhile optical networking has been based on the notion of *statistical multiplexing* for temporally efficient resource sharing.

2 Wavelength Division Multiplexing Transmission Systems

Multiplication of the transported capacity over a single fiber has been historically achieved through packing of individually transmitted channels into the same medium, with the least possible impact on each signal transmission, that is, multiplexing. We can then assume that the overall capacity of a wavelength domain multiplexed system is determined by the useable bandwidth, the spectral efficiency hence the number of channels and the bit rate per channel. Meanwhile the overall transmission reach is an important parameter for the overall cost of an optical WDM system. Evidently there is a trade-off between the above parameters in order to achieve the highest possible capacity together with the longest possible span. Achieving a high capacity times length product (B × L) has been the main target of all different WDM system designs and is being compromised by all the physical degradations that are discussed in this chapter.

The maximum usable bandwidth in a WDM system is usually determined by the amplifier bandwidth and/or the demultiplexer bandwidth. In the most advanced WDM transmission systems in order to maximise the B × L product, both the C and L transmission bands are ulitised with EDFAs, but a further upgrade using, for instance, Raman amplifiers is suggested extending useable fiber bandwidth to the long-wavelength window of the fiber. The impressive achieved capacity of above

64 Tbit/s that has been reported in [3] is of the order of magnitude of the fiber raw bandwidth available in the spectral region between 1.3 μm and 1.7 μm. Recently other "domains" have been utilised in order to extend the multiplexing factor of WDM systems. Polarisation [4], code division [5] and spatial division multiplexing [6] have all been proposed as means to achieve orthogonal multiplexing of signals, with the latter being possibly the record capacity achieved so far in a single fiber. Recently due to its superior scalability, frequency domain has been also used, and coherent Orthogonal Frequency Division Multiplexing is well positioned to be an attractive choice for >100 Gb/s transmission [7]. Since then, there has been extensive innovation towards developing various forms of optical OFDM. Combination of all these multiplexing techniques with WDM is the trend in contemporary hero experiments that seek to achieve record B × L [1–3, 5–10].

Meanwhile the main way to increase the capacity of a WDM transmission system is the utilisation of the bandwidth more efficiently with spectrally efficient modulation formats. The idea is that other than modulating the amplitude of the complex signal A, as in *amplitude-shift keying* (ASK) modulation formats, one can let the phase, or its time derivative, carry the information, as in *phase-shift keying* (PSK) and *frequency-shift keying* (FSK), respectively [4]. PSK has better tolerance to noise at the receiver than ASK formats; however, *coherent receivers* required for phase detection became readily available only recently when digital signal processing allowed their advent. Quadrature modulation doubles the number of transmitted bits per symbol. Differential PSK modulation formats where the phase of a bit is modulated with respect to that of the previous one relaxed the need of complex receivers. Furthermore, a combination of more than one signal characteristics can be modulated, for example, the amplitude *and* the phase of the signal to represent different information symbols, as in *amplitude and phase-shift keying* (APSK). With respect to the number of states, one refers to *binary transmission* if only two states are allowed for A, representing two symbols 0 and 1, whereas in *M-ary transmission*, M states are allowed for A, representing M symbols. Although $\log_2 M$ times information is carried by symbols in M-ary transmission, which translates into higher spectral efficiency, transmitter and receiver complexity is higher and tolerance to noise decreases, like in duobinary or quaternary formats [4].

In [1–3] all hero experiments with respect to their overall capacity and spectral efficiency until 2010 are reviewed. Since then, the list has grown significantly mainly due to the advent of the new multiplexing techniques [6–10]. If we define spectral efficiency as the ratio of information rate per channel over the channel spacing, a bandwidth efficiency of 1 bit/s/Hz has been achieved in an 80 × 107 Gb/s system [1] or in a 16 × 112 Gbit/s system [2] up to 9.3 bit/s/Hz reported in [11]. In [12] 1.28 Tbit/s in a single-channel experiment has been reported. In [13] aggregate transmitted capacity of 25.6 Tbit/s has been reported in 2007, 64 Tbit/s in 2011 [3] and 102.3 Tbit/s [10] and 305Tbit/s in [6] in 2012. The transmission lengths are also impressive with 10.608 km reported in the experiment of [9]. All those experiments that combine advanced modulation formats with advanced communication techniques like coherent detection manage also to enhance the length of the B × L as they might exhibit improved robustness to the fiber impairments and achieve increased receiver sensitivity [14]. In this chapter we seek to understand the signal degradations that arise when a multiwavelength high-bit-rate channel propagates into a system like the one shown in Fig. 2.1.

3 Wavelength Switched Optical Networks

WDM technology has been the key enabler in the evolution of optical networks from high-capacity point-to-point links towards flexible meshed optical networks with dynamic resource allocation utilising two-way reservations. Different ways have been used to describe optical networks. The concept of reconfigurable optical networks is not new – in fact, it has been around for at least two decades [15, 16]. In WSON, transportation from a source node to the destination node is completed in a transparent way by setting up a lightpath that comprises a number of spans (Fig. 2.1). This network supports an optical layer utilising multi-degree reconfigurable optical add/drop (ROADM) and cross-connect nodes (OXC) and provides traffic allocation, routing and management of the optical bandwidth. ROADMs although have emerged in the market before 2000 due to the downturn of telecommunications market following that year have only managed to be part of the major vendors portfolio around the globe only in 2002. Long-haul DWDM networks have nearly all been constructed with ROADMs in the last years. Hence, other than the transmission links, the principal building blocks of optical networks are those optical nodes shown in Fig. 2.1. To support flexible path provisioning and network resilience, OXCs utilise a switch fabric to enable routing of any incoming wavelength channel to the appropriate output port. Similarly ROADMs utilise switch fabrics in order to add/drop locally a number of wavelengths out of the WDM comb. First-generation ROADMs were of degree two and supported ring or line architectures. Currently ROADMs support high-degree nodes, and hence, they are featured as colourless and directionless. Colourless means that add/drop ports are not wavelength specific, and directionless feature enables any transponder to be connected to any degree.

Several designs have been proposed for robust ROADMs and OXCs based on different switching technologies and different architectures [17–22]. In Fig. 2.2 a ROADM and a OXC in a typical configuration are shown [23, 24]. Depending on the switching technology used, OXC designs are commonly divided into opaque and transparent [23]. Opaque OXCs incorporate either an electrical switch fabric or optical ones with OEO interfaces. They support sub-wavelength switching granularities and offer inherent regeneration, wavelength conversion and bit-level monitoring; multi-casting is possible if required. Switching times however are limited to ~ μsec if electronic switching is used. In opaque OXCs with an optical switch fabric, signal monitoring and regeneration can still be implemented but with added complexity, bit-rate limitation and increased power consumption. The complexity and power consumption are related to the processing that takes place in the

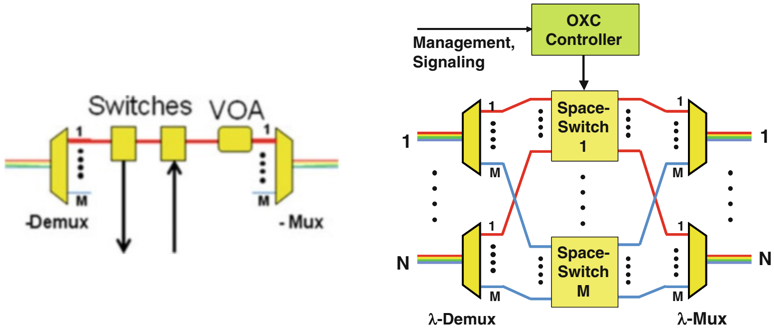

Fig. 2.2 A typical configuration of a ROADM [17] and an OXC architecture [16]. For the wavelength selective OXC architecture, the switching fabric is segmented, so following the wavelength demultiplexing stage, the incoming wavelength channels are directed to discrete switches each supporting a single wavelength

transponders. In [18] optoelectronic conversion is used as the means to perform regeneration without the implications of electronic signal processing.

For transparent OXCs a variety of optical switch fabrics have been developed [25, 26] that exhibit different physical performance. Switching time is a very significant feature and sets the switching time of the node.

When discussing physical impairments in optical networks, it is imperative to discuss them in the context of the switch architecture. To build a high-port-count node, the simplest solution is based on a central switch fabric, like the crossbar switch. However today, guided-wave technology can achieve small to moderate port counts (less than about 128 × 128) with moderate to high insertion loss and rapid switching speeds. Free-space technologies are more likely to achieve larger port counts (256 and higher) with low loss and slower switching speeds [19, 26]. Hence large crossbar switches are not a feasible architecture beyond a certain port count. Therefore, various multistage optical switch structures have been suggested like the three-stage Clos, the wavelength selective switch (WSS) and the λ-S-λ architectures [27].

4 Physical Impairments in Optical Networks

A typical WDM optical network path is illustrated in Fig. 2.1 with the physical representation of transmitter and receiver equipment, the transmission system that comprises the fiber spans and amplifiers, and also switching equipment like a ROADM and OXC. The figure indicates the place, where different degradation mechanisms occur that are going to be discussed in this chapter. The optical signals are generated by the modulation of N electronic signals on different wavelengths which are in turn multiplexed on the same fiber using a passive multiplexer.

They are then copropagating into the same fiber spans where they suffer different linear and nonlinear effects. Each fiber span is assumed to comprise a transmission fiber together with a dispersion compensating element and an optical amplifier to compensate for the span losses. Evidently different WDM designs exist. After propagating over a series of transmission spans and periodically spaced amplifiers, the WDM channels may be separated again in order to be switched at an OXC or dropped locally at a ROADM where it will be received by the receiver.

The following most important degradation mechanisms can be identified:

- Transmitter (Tx) and receiver (Rx)-related impairments
- Transmission-related impairments that are either linear effects (dispersion, polarisation mode dispersion) or nonlinear ones (Kerr effect related and scattering effects)
- Amplifier-related noise (amplified spontaneous emission generated in optical amplifiers)
- ROADM- and OXC-related distortion, that is, crosstalk (in multiplexers and switches) and nonideal filter characteristics and filter concatenation

In this chapter we will seek to understand the physical impairments that occur in such systems and give some analysis in most cases of how they can be computed and what impact they seem to have on the B × L product of an optical network.

4.1 Optical Signal Generation and Detection

Transmitters and receivers in WDM systems may induce their own impairments. The type and significance of transmitter/receiver impairments are related to the modulation format and type of detection [4, 28, 29].

Transmitters comprise optical source and modulators. Single-mode lasers with very low-side-mode suppression ratio are desirable as they can be spectrally spaced too closely combined with modulators with high extinction ratio that do not degrade the receiver sensitivity [4]. Furthermore phase noise could be detrimental, especially in PSK modulation formats.

Receivers on the other hand inherently induce shot noise and thermal noise during optical signal detection [4, 29] while depending on the detection technique beat noise may manifest itself due to the local oscillator. All these terms are discussed in the next chapter and are shortly defined as follows:

- Shot noise is related to the quantum nature of photons in the sense that random fluctuations of photons during the duration of a bit are translated into fluctuation of photocurrent electrons. The variance of this noise term is directly related to the receiver power; hence, it may be variable according to the signal modulation and/or according to the local oscillator amplitude.
- Thermal noise is associated with the random move of electrons in the electronic part of the receiver due to finite temperature.

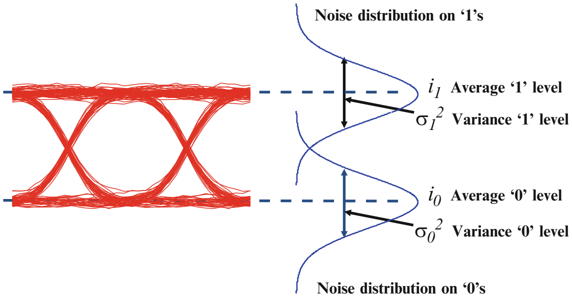

Fig. 2.3 Fluctuating signal received by the decision circuit and Gaussian probability densities of 1 and 0 together with the corresponding eye diagram

- Beat noise in coherent systems refers to the "beating" of more than one optical field at the photodetector.

Evidently the relative strength of the above factors strongly is associated on the receiver design, signal power and detection scheme. Furthermore their relative values with respect to the other system noise terms are important when designing a high-capacity WDM system.

4.2 Eye Diagram, Q Factor and BER

In any communication system, noise and distortion in the signal result in errors in the recovered signal. Here, we will briefly explain some of the main figures utilised in order to compare performance of different systems in optical communications. The ultimate measure of a system's performance in digital communications is the bit error rate (BER). This is defined as probability of faulty detected bits. BER calculations in a system are usually modelled by Monte Carlo simulations, Gaussian approximation or a deterministic approach [30]. The impairments discussed in this chapter are assumed to have Gaussian distribution.

Figure 2.3 shows schematically the fluctuating signal received by the decision circuit at the receiver. The corresponding "eye diagram" is illustrated which represents a repetitively sampled signal, superimposed in a way to provide representation of the noise behaviour. Characteristic degradations occur to the eye diagram that indicates imperfect transmission.

If i_D is the decision threshold, i_1 the photocurrent when the signal bit is "one", i_0 the photocurrent when the signal bit is "zero" and σ_0 and σ_1 are the photocurrent variances for 0 and 1 bits, the formula that describes the BER for an ASK signal after detection is therefore given by [29]:

$$\mathrm{BER} = \frac{1}{2}\frac{1}{2}\mathrm{erfc}\left(\frac{1}{\sqrt{2}}\frac{i_1 - i_D}{\sigma_1}\right) + \frac{1}{2}\frac{1}{2}\mathrm{erfc}\left(\frac{1}{\sqrt{2}}\frac{i_D - i_0}{\sigma_0}\right) \tag{2.1}$$

The optimum threshold is that for which the BER is minimised, and it is approximately:

$$i_D = \frac{\sigma_0 i_1 + \sigma_1 i_0}{\sigma_1 + \sigma_0}$$

by substituting this into (2.1) we get:

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right)$$

where Q is the Q factor defined as:

$$Q = \frac{|i_1 - i_0|}{\sigma_1 + \sigma_0} \tag{2.2}$$

It is evident that the Q factor gives an indication of the signal power level with respect to the noise induced. Even in the case of a simple system in the power level falls to a level that is of the order to the noise, the Q factor is affected and the signal is irreversibly destroyed; hence, it cannot be detected.

The BER improves, when the Q factor increases and takes values lower than 10^{-12} for $Q > 7$. For a typical communication system, the minimum acceptable BER would be 10^{-9} ($Q \sim 6$). The presence of Forward Error Correction (FEC) however allows for a better margin. With the introduction of FEC in optical communication systems in the mid-1990s, transmission experiments started to include a coding overhead (typically 7 % increase of the bit rate), to allow the operation of the system at a higher BER value. This is typically 10^{-5} so that at the output of a hard decision FEC module, the BER is less than 10^{-12} but can reach values as high as 10^{-3} depending on the codes, overheads and system under investigation.

For a given system, the receiver sensitivity typically corresponds to the average optical power for which a BER $= 10^{-9}$, or any other prespecified BER value. Equation (2.2) can assist in the determination of receiver sensitivity, for a back-to-back system, where only receiver-induced noise is affecting system performance. In order to calculate the receiver sensitivity, in a direct detection ASK system, we assume that $P_0 = 0$ (no power is carried on the 0 bits). The power carried on signal bit *one* is $P_1 = \mathrm{i}_1/R_{\mathrm{D}},$ where R_{D} is the receiver responsivity. The average received power will be $P_{\mathrm{s}} = (P_1 + P_0)/2 = P_1/2$. The RMS noise currents σ_1 and σ_0 include contributions from shot noise and thermal noise from the receiver and thus can be written as

$$\sigma_0 = \sigma_{\mathrm{T}} \quad \text{and} \quad \sigma_1 = \sqrt{\sigma_{\mathrm{T}}^2 + \sigma_{\mathrm{s}}^2}$$

If we neglect the dark current for the PIN receiver with Δf being the bandwidth of the receiver, we get the following expression from which P_s can be calculated:

$$Q = \frac{i_1}{\sqrt{\sigma_s^2 + \sigma_T^2} + \sigma_T} = \frac{R_D P_1}{\sqrt{2qR_D P_1 \Delta f + \sigma_T^2} + \sigma_T} \tag{2.3}$$

In binary phase modulation (BPSK) systems with coherent detection, a local oscillator (laser) is mixed with the detected signal before the photodiode. Typically a differential receiver is employed where the mixed signal is fed into two photodiodes out of phase and their outputs subtracted. The result is that the direct detection terms of the local oscillator (P_{LO}) and signal (P_s) are cancelled leaving only the mixing terms. Therefore, we have

$$\begin{aligned} i_1 &= 2R_D\sqrt{P_{LO}P_s} \\ i_0 &= -2R_D\sqrt{P_{LO}P_s} = -i_1 \end{aligned}$$

and

$$i_D = 0$$

Similarly, the RMS noise currents are equal for both transmitted symbols, and we have

$$\sigma_1 = \sigma_0 = \sqrt{\sigma_T^2 + \sigma_s^2}$$

for an unamplified back-to-back system. The shot noise term is now dominated by P_{LO} that is typically higher than the received signal P_s, so we have

$$\sigma_s^2 \approx 2qR_D P_{LO} \Delta f$$

The outcome of this analysis is that we can calculate the Q factor for the back-to-back coherent binary phase modulation receiver as

$$Q = \frac{2R_D P_{LO} P_s}{\sqrt{\sigma_T^2 + 2qR_D P_{LO} \Delta f}} \tag{2.4}$$

For quaternary (QPSK) modulated systems, there are two receivers, one for the in phase and one of the quadrature orthogonal components, with the above analysis holding for each one of them.

Now, the impact of the transmission channel on the signal degradation is manifested via the increase in the power required by the receiver to achieve the same BER. All the effects that will be discussed in the remaining of this chapter degrade either the relative levels of i_1 and i_0, for example, effects like dispersion that act as intersymbol interference effects, or they increase the noise terms in the Q factor, hence degrading receiver sensitivity. To give an example of how the impact of the transmission channel on the signal Q factor degradation can be modelled analytically, let us assume a dispersion-compensated amplified WDM system that operates at 10 Gb/s with direct detection ASK signals like the one described in [31]. Here, one can argue that cross-phase modulation (XPM), four-wave mixing (FWM) and amplifier noise are the significant effects. All these effects can be modelled as Gaussian random variables. If we assume that all the above effects are included into the current fluctuations at the receiver, the standard deviation of the latter will be given by

$$\begin{aligned}\sigma_0 &= \sqrt{\sigma_{\mathrm{T}}^2 + \sigma_{\mathrm{sp-sp}}^2}\\ \sigma_1 &= \sqrt{\sigma_{\mathrm{T}}^2 + \sigma_{\mathrm{S}}^2 + \sigma_{\mathrm{s-sp}}^2 + \sigma_{\mathrm{sp-sp}}^2 + \sigma_{\mathrm{XPM}}^2 + \sigma_{\mathrm{FWM}}^2}\end{aligned} \tag{2.5}$$

where σ_{T} is the thermal and σ_{S} the shot noise of the receiver. The ASE-related spontaneous-spontaneous $\sigma_{\text{sp-sp}}$ noise and signal-spontaneous $\sigma_{\text{s-sp}}$ noise are calculated as in [32] for the whole amplifier chain and are explained in the second part of this chapter. σ_{XPM} and σ_{FWM} are the standard deviations of the XPM and FWM generated fluctuations, respectively, and are explained in the second part of the chapter. Correspondingly if coherently detected phase modulation is deployed, the standard deviation terms above should be appropriately modified with the inclusion of P_{LO}.

4.3 Optical Signal Propagation Through Optical Fibers and Amplifiers

4.3.1 Attenuation and Losses

In their quest to achieve a high capacity times length product, telecommunication transmission systems have introduced optical fiber as the main transmission medium, especially in long-haul systems. This is because attenuation in optical fiber is of the order of 0.36 dB/km at 1300 nm and 0.2 dB/km at 1550 nm. The effects that comprise the attenuation are mainly absorption, Rayleigh scattering and loss due to geometric effects. Absorption consists of intrinsic IR and UV absorption, natural property of the glass itself, that contributes to the absorption of very short and very long wavelengths [33, 34]. Meanwhile, impurities are a major source of loss due to manufacturing procedures in fibers. Two types of impurities are particularly bothersome to minimise in glass: metal ions and OH ions; these are important impurities as they create a peak at the attenuation. Finally, Rayleigh scattering acts as a theoretical boundary as it is the scattering by the small inhomogeneities in the material.

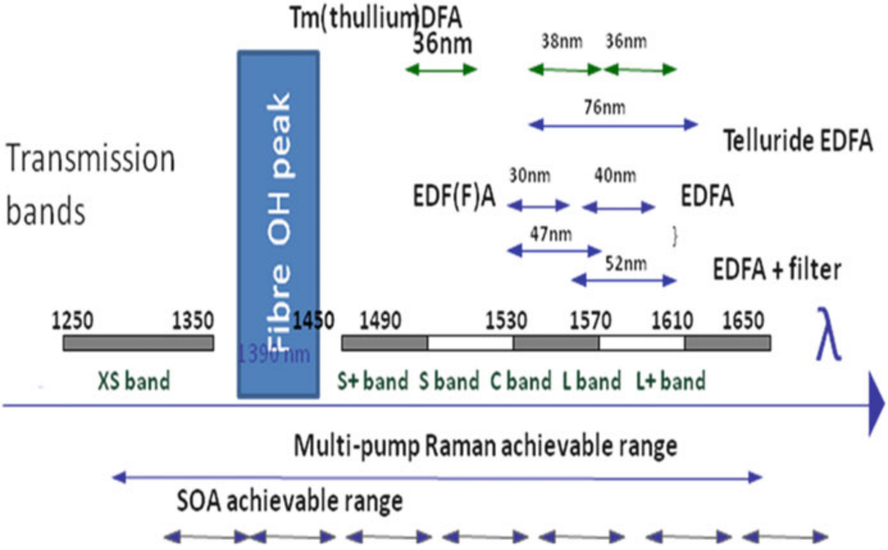

Fig. 2.4 WDM transmission bands with respect to the wavelength and different amplifier technologies that cover those wavelengths [35, 36]

4.3.2 Amplifiers

After having propagated through substantially long distances as well as through different optical networking elements, the signal power falls well beyond the levels that can be detected by the receiver. The advent of the optical amplifier and specifically the EDFA made the compensation of losses feasible simultaneously for a number of WDM channels, as long as these wavelengths were all confined in the gain bandwidth of the device. All optical signals are then optically amplified without the need of separate power consuming optoelectronic conversion. Different optical amplifiers have been proposed in the literature and have been developed with different characteristics as far as the operation principle, the material and operational characteristics are concerned. More specifically in order to achieve the widest useable bandwidth possible, different technologies may be devised as can be seen in Fig. 2.4.

Here we will discuss some general concepts of optical amplifications. In most cases it is based on the principle of stimulated emission, as in the case of laser. Without the use of optical feedback, however, only population inversion is required in gain medium for optical amplification to occur. Inserted photons are amplified by the gain medium along the length of the amplifier depending on the wavelength and the input signal power. Meanwhile spontaneously emitted photons of various wavelength, phase and direction are travelling along the amplifier and invoke amplification in the same amplifying medium. Hence, amplified photons exit the device together with amplified spontaneous emission (ASE) that acts as noise to the signal.

In most cases amplifiers are modelled ignoring the influence of noise, and in many cases they can be modelled as gain element that compensates exactly the losses from previous spans. This approximation is valid when strong saturation conditions are applied. An amplifier model that accounts for the self-saturating effects needs to be used as in [37]:

$$G = \frac{P_{\mathrm{sat}} \mathrm{productlog}\left(\frac{e^{\frac{P_{\mathrm{in}}}{P_{\mathrm{sat}}}} G_{\mathrm{ss}} P_{\mathrm{in}}}{P_{\mathrm{sat}}} \right) + Bhf\mathrm{NF}}{P_{\mathrm{in}} + Bhf\mathrm{NF}} \tag{2.6}$$

where P_{sat} is the saturation power of the amplifier, P_{in} is the input power, B is the bandwidth, f the frequency, NF the noise figure of the amplifier and the function productlog(x) is the solution of the differential equation $dy/dx = y/(x(1 + y))$.

In order to understand the effect of ASE on the Q factor, we have to assume an NRZ ASK signal. If we assume that the OSNR is measured in a specific $\Delta\nu_1$ optical bandwidth, then we can write [29]

$$\mathrm{OSNR} = \frac{P_{\mathrm{ave}}}{S_{\mathrm{v}} \triangle v_1} \tag{2.7}$$

where S_{v} is the power spectral density of the ASE. $\Delta\nu_{\mathrm{opt}}$ is the optical filter bandwidth after the amplifier, and $P_{\mathrm{sp}} = \Delta\nu_{\mathrm{opt}}\, S_{\mathrm{v}}$ is the spontaneous emission noise power that enters the receiver. It is evident that when the signal propagates through a number of concatenated amplifiers, the spontaneous emission will build up together with the signal, and the overall OSNR will degrade.

At a direct detection receiver, the ASE-induced current noise has its origin in the beating of the signal electric field with the spontaneous emission noise but also of the beating of the spontaneous emission with itself. So the total variance of the current fluctuations is now going to have four terms [32]:

$$\sigma^2 = \sigma_{\mathrm{T}}^2 + \sigma_{\mathrm{s}}^2 + \sigma_{\mathrm{s-sp}}^2 + \sigma_{\mathrm{s-sp}}^2 \tag{2.8}$$

Correspondingly in (2.4) the ASE-related terms are the following:

$$\begin{aligned} \sigma_{\mathrm{s}}^2 &= 2qR(P_1 + P_{\mathrm{sp}})\Delta f \\ \sigma_{\mathrm{s-sp}}^2 &= 4R^2 P_1 S_{\mathrm{v}} \Delta f \\ \sigma_{\mathrm{sp-sp}}^2 &= 4R^2 S_v^2 \Delta f \Delta v_{\mathrm{opt}} \end{aligned}$$

Evidently P_1 accounts for the amplified power of 1, so both P_1 and S_{V} account for G [29]. By using the equations above, the Q factor can be calculated in (2.5). Note that the gain is assumed equal for the whole WDM comb although in reality gain tilting may affect the design of a WDM system. Furthermore ASE can also induce time jitter in a bit sequence by shifting the optical pulses from their original time position randomly.

The modulation format plays an important role in the propagation of the signal through a chain of optical amplifiers or a generally amplified system. Although in order to compare different modulation formats directly one has to make several assumptions about the optical filtering and electronic hardware implementations that sometimes lead to nonoptimal solutions for specific cases, it is generally well recognised that RZ formats perform well among OOK modulation formats also due to the higher peak power. Especially RZ AMI exhibits an enhanced performance [14]. Among the PSK formats DPSK shows as expected a very good performance, if balanced detection is used, which allows in principle to double the noise-limited transmission distance. Evidently all the above concern a typical amplifier that reamplifies only the amplitude of the signal. Phase-sensitive amplifiers (PSA) have been reported [38] and may have a sub-quantum-limited noise figure with respect to the conventional erbium-doped fiber amplifier that has an associated inherent minimum noise figure of approximately 3 dB. All the above should be taken into account when/if advanced modulation formats are considered.

4.4 Dispersion

4.4.1 Chromatic Dispersion

Dispersion of light propagating into a fiber is the phenomenon where the group velocity of a propagating pulse depends on the wavelength. Typically pulses propagating in a single-mode fiber are hardly monochromatic; hence, chromatic dispersion broadens the pulse duration while causing intersymbol interference [4, 28, 29]. Although dispersion may severely affect the performance of a system based on single-mode fiber, it is a linear phenomenon; hence, it can be compensated completely if the reverse dispersion is applied. Mathematically, chromatic dispersion is defined either by the second derivative of the propagation constant β which is denoted as β_2 or by the so-called group velocity dispersion (GVD) coefficient normally denoted by D. Two are the components of the dispersion in a fiber:

Material dispersion: The silica dielectric constant, and, therefore, the refractive index, depends on the transmitted frequency.

Waveguide dispersion: The effective propagation constant related to the waveguiding nature of the fiber depends on the wavelength even if the core and cladding indices are constant.

Evidently to optimise the transmission of a multichannel WDM signal over a long fiber length is not a trivial task. The interplay of dispersion and nonlinearities plays an important role. Dispersion management has been introduced into systems that require high local dispersion for the sake of nonlinearities and negligible total accumulated dispersion (dispersion × length). The details of a transmission system with dispersion management are shown in Fig. 2.1, where special dispersion-compensating fiber modules are utilised for each fiber span that retain high local values for the reduction of the effect of nonlinearities and overall dispersion remains zero. Different dispersion management schemes exist [4]. Besides the best choice of the amplifier and compensation module spans, the maximum and minimum powers and the exact dispersion map are important. As it is cost-efficient to co-place amplifiers and dispersion compensator system, the intra-amplifier spacing dictates the cost. Although the longer the spacing the lower the cost, the effect on the total span length achievable should also be considered.

With respect to the demands on dispersion management, the single-channel bit rate is essential. It is noted that the impact of dispersion measured as an eye-opening penalty increases with the bit rate and specifically scales quadratically. For 2.5 Gb/s per channel, no dispersion compensation is needed, and the signals have only to be amplified after some fiber span. For 10 Gb/s per channel long-haul systems, dispersion management is necessary, but fixed though properly adjusted compensators over the whole WDM bandwidth are sufficient. Furthermore, today advanced digital signal processing can be performed to complement the system tolerance to dispersion at those rates. For 40 Gb/s and above tuneable per channel, compensators have to complement the fixed compensators in order to address residual and time-varying dispersion and or advanced equalisation techniques.

Meanwhile the effect of modulation format has to be taken under consideration as spectrally narrow formats may yield significantly better dispersion tolerance. Duobinary and DQPSK formats have shown especially high-dispersion tolerance; however, the effect has to be discussed in relation to other system characteristics like, for example, filtering and/or fiber nonlinearity. As mentioned above it is the combination of format and bit rate that dictates the optimum dispersion compensation scheme. For a typical NRZ-ASK WDM transmission system, full dispersion compensation by optical means can be assumed to be feasible for the whole WDM comb.

4.4.2 Polarisation Mode Dispersion

Other than chromatic dispersion high-bit-rate transmission systems suffer from polarisation mode dispersion (PMD). The effect is related to the birefringent nature of the fiber and the two polarisations of light that copropagate in. So, when an optical pulse is injected in a fiber, at the end of the fiber, the pulse is split up in two pulses which have orthogonal polarisations and a delay against each other. At the receiver the two pulses are taken as a single broadened pulse, and this effect is called PMD [39]. For 10 Gb/s systems, PMD compensation is not necessary. For long-haul systems with 40 Gb/s and above, some compensation of PMD is necessary. Whereas dispersion compensation can be achieved using fixed, passive schemes, polarisation mitigation has to be adjusted to the actual state of PMD, and it has to be tuneable.

PMD affects the eye opening hence the Q factor of the channels in a statistical way. The effect is obviously related to the modulation format other than the channel bit rate. As in the case of chromatic dispersion, the tolerance of a specific format to the effect is related to the waveform and the filter; hence, direct comparison is out of the scope of this chapter. As a rule, however, one could assume that the first-order PMD sensitivity scales linearly with the symbol duration; hence, DQPSK is expected to be more tolerant than binary modulation formats although RZ formats are more resilient than NRZ due to their resilience to intersymbol interference [14].

Because of the possibly rare manifestation of the phenomenon instead of worst system design, specific margins are allowed in the operation of a system with predefined outage probability. To give an example, let us assume a system with k spans of SMF and DCF fiber and specific PMD. For a given fiber, the DGD is a random variable with a Maxwellian distribution. Following the analysis in [40], the distribution of the eye-opening penalty is derived using the statistics of the PMD vector which results in the pdf of the first- and higher-order PMD. As a result the pdf of the PMD-affected Q factor can be calculated. Now due to the statistical nature of the effect, the lowest acceptable achieved Q factor can be calculated for a specific outage probability (OP) derived by integration of the pdf (Q). By setting the outage probability equal to 0.00018, the achieved Q as a function of the Q factor without PMD (Q_{wopmd}) can be derived: $Q = Q_{\mathrm{wopmd}}\mathrm{OP}^{(\log 10/10\mathrm{n})}$ where $n = 16/\mathrm{m}$ and $m = \mathrm{A}\pi\mathrm{k}(\mathrm{DB})^2$ where D is related to the lengths and dispersion parameters of the single-mode fiber and the dispersion-shifted fiber of the span.

4.4.3 Nonlinear Effects

Nonlinear effects in optical fibers are related to the Kerr effect and scattering effects. The first is related to the variation of the fiber refractive index with incident optical power. In multichannel WDM transmission systems the optical power confined in the core of the fiber induces changes to the refractive index and hence to the phase change of the electromagnetic fields. Scattering effects are of two types Raman and Brillouin and can be generally overcome in WDM systems so will only be discussed for the sake of completeness.

Fiber nonlinearities are summarised in Fig. 2.5 after [14]. They are further divided in two large categories depending whether they occur as consequence of the interaction of the pulses of the same WDM channel or between the one channel and the ASE noise (intra-channel nonlinearities) or as a result of the interactions of two or more WDM channels (interchannel nonlinearities).

As far as the signal–signal interaction is concerned, effects like cross-phase modulation (XPM) and four-wave mixing (FWM) occur between WDM channels but also between individual pulses and lead to the phenomena of intra-channel XPM (IXPM) and intra-channel FWM (IFWM). The nonlinear interaction of a channel or a pulse with itself is referred to as self-phase modulation (SPM) which is a single-channel effect. Regarding signal noise interactions the dominant optical source of noise in a transmission line is typically the ASE generated by optical amplification.

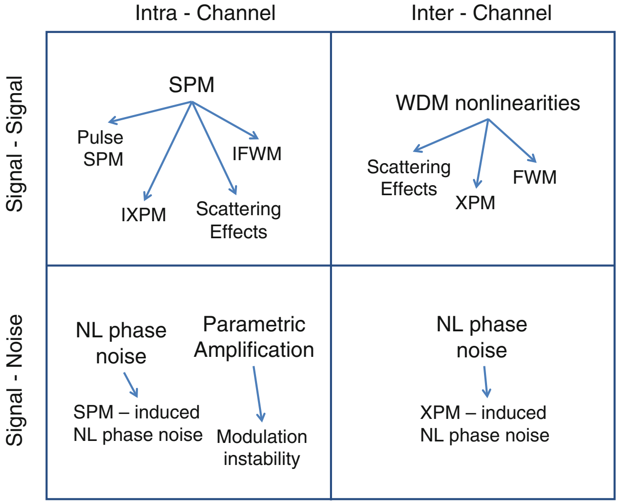

Fig. 2.5 Classification of fiber nonlinearities after [14]. SPM is self-phase modulation, XPM is cross-phase modulation, and FWM is the four-wave mixing. NL describes nonlinear. The I in front indicates the effect intra-channel

The dominant form of nonlinear signal–noise interactions manifests itself in noise-induced nonlinear distortions of specific signal characteristics (e.g. amplitude, timing, phase or frequency [41]). An example of signal–noise nonlinear interaction that affects PSK formats is nonlinear phase noise, which is sometimes referred to as the Gordon–Mollenauer effect [42].

The significance of each type of nonlinearities is related to the per-channel bit rate. In [14] the effects are thoroughly discussed, and it is argued that interchannel effects play important role at WDM systems where per-channel bit rates are of 10 Gb/s and below, whereas intra-channel nonlinearities affect systems most strongly when bit rates are above 10 Gb/s. The exact impact of each type of fiber nonlinearity also depends on the local fiber dispersion. Evidently lower dispersion fibers have stronger interchannel effects than fibers with high local dispersion.

Furthermore the modulation formats play a very important role, and we will discuss in each section the significance of the modulation format. Although a detailed understanding of the limitations that fiber nonlinearities have on advanced modulation formats is still a research topic, some numerical and experimental investigations suggest the types of nonlinear effects that are typically limiting transmission: Intensity-modulated formats are limited by all nonlinear effects but only above 40 Gb/s intra-channel effects start getting significant. For PSK formats, at 2.5 and 10 Gb/s, the main limitations come from nonlinear phase noise. At 40 Gb/s and above, intra-channel nonlinearities dominate, although nonlinear phase noise can become a limitation at low OSNR.

Since the effects of fiber nonlinearity depend on many system parameters, the comparison of modulation formats with respect to their resilience to such nonlinear phenomena may depend on the system design and operating conditions. Hence when describing the impact of nonlinearities on an advanced modulation format, system characteristics should be specified.

Additional comparisons of various advanced modulation formats for nonlinear transmission can be found in [43–45].

Interchannel Effects

XPM

At the same time the intensity modulation of one channel effectively modulates the optical phase of all other WDM channels. The additional spectral components that may appear due to this induced phase modulation will generally lead to pulse distortion when operating in high-dispersion regime. Depending on the operating conditions, however, it has been widely accepted that higher dispersion can lead to an averaging of the effect, as each channel is affected by the impact of many pulses travelling with different speed.

XPM is an important source of performance degradation in multichannel WDM systems. In the following paragraph the analysis presented in [31] is adopted. By treating XPM as noise inducing effect, one can utilise equation (2.5) to analyse the XPM-induced Q factor degradation. In Fig. 2.6 we have modelled a transmission system that comprises 20 spans like in Fig. 2.1. 40 WDM channels modulated with ASK-NRZ copropagate with 1 mW of power per channel and 50 GHz channel spacing. The rest of the system parameters are modelled as in [32]. One of the curves shows the Q factor calculated with XPM as the only nonlinear effect included. Evidently XPM severely affects the Q factor of the specific system. Furthermore the effect on different channels implies that some are more severely affected than others which adds an extra degree of complexity in the optical network physical design. It is evident that XPM can be a limiting factor in a high-bit-rate WDM system with small channel spacing; however, it can be neglected if 100 GHz spacing is used.

Four-Wave Mixing

In a nonlinear medium where more than one electromagnetic wave propagate, mixing effects arise when the beating of two waves at their difference frequency drives material excitations. The coherent output to a new frequency is then the result of diffraction of the third wave from this material excitation. FWM is one of these phenomena which is severe in WDM systems with uniform channel spacing as the new products fall on neighbouring channels.

Performance degradation is caused in two ways:

- The generation of new components at different frequencies represents a loss of signal energy.

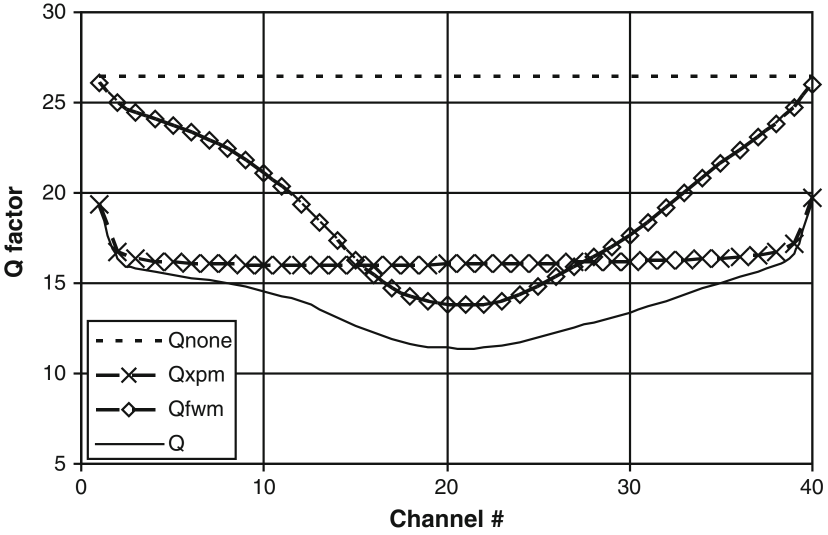

Fig. 2.6 Example of Q factor calculation with (solid line Q) and without nonlinear effects (dashed line Q_{none}) after [31] and [32]. Equation (2.5) is used to include XPM effects as in [46] and FWM effects as in [47]. All figures include ASE-related effects through (2.9)

- In WDM system using equally spaced channels the new components fall on frequencies allocated to other channels, causing severe crosstalk.

In a WDM system with N channels with equal channel spacing, the total time averaged FWM power generated at channel k at the end of the Mth link, assuming that the same input power per channel for all channels, can be calculated as in [47]. Like all nonlinearities, a moderate power level per channel is one possible solution for FWM. If fiber with uniform dispersion characteristics for all WDM channels is used, FWM may be tolerable for a WDM system. If the system is such that one channel falls exactly at zero dispersion wavelength, then only unequal channel spacing could be used to mitigate FWM as the products will fall out of the band of the signals. By assuming that FWM is a degradation-inducing effect that can be described as Gaussian noise, one can use equation 2.5 in order to model the effect of the FWM on the Q factor. In Fig. 2.6 we have modelled a transmission system that comprises 20 spans similar to the one in Fig. 2.1. One of the curves shows the value of the Q factor that is calculated when FWM is the only nonlinear effect included. It is obvious that FWM significantly affects the performance of some channels under the specific conditions.

Scattering Effects: Stimulated Raman and Stimulated Brillouin Scattering

Brillouin scattering is related to the Brownian motion of fiber molecules. Part of the light travelling through the fiber is backscattered by the proper component of the acoustic noise. This backscattered light, called Stokes wave, interferes with the propagating light that acts as a pump. A stationary wave is induced, and a coherent acoustic wave is created that stimulates the Brillouin scattering, which in turn reinforces the acoustic wave. This feedback process is called stimulated Brillouin scattering (SBS). The SBS process can be summarised as an energy transfer from the pump wave to the Stokes wave; however, in source linewidths like today's WDM networks, it is not considered a limitation.

Stimulated Raman scattering (SRS) is a nonlinear effect appearing in systems also involving high-power sources. Light in the fiber interacts with molecular vibrations, and scattered light is generated at a wavelength longer than the incident light. Another signal co- or contra-propagating in the fiber will undergo amplification providing its wavelength correspond to the up-conversion. In wide WDM systems loss of energy and crosstalk between channels take place.

SRS may limit the performance of a WDM system by depleting the lower wavelength channels while adding crosstalk to the higher wavelength ones. In [31] an exact analytical solution for SRS is given, and equation (2.5) can be used to describe the effect of SRS in the Q factor of a WDM system.

In [4] it is argued that for a 40-channel WDM system with 100 GHz channel spacing, the SRS-related penalty can be reduced below 0.5 if the power per channel drops below 3 mW. Hence in today's networks by keeping moderate power levels, one can reduce the effect of this phenomenon.

Intra-channel Effects

SPM

As far as the SPM is concerned, which is a major single-channel nonlinear effect that affects all systems, the modulation of the signal power gives rise to a temporal variation of the optical phase of its signal channel which combined with the local dispersion may lead to pulse spreading not to mention the distortion in phase-modulated signals. It is actually the interplay between SPM and fiber dispersion that makes SPM an especially important nonlinear effect since it distorts the received waveform, degrades receiver sensitivity and limits transmission distance and/or optical amplifier output power.

In [48] the SPM is treated like a phenomenon that leads to frequency chirping of optical pulses. The SPM-induced chirp depends both on the variation of power and the pulse shape; hence, analytical treatment is not straightforward. In general spectral broadening of the pulse induced increases the signal bandwidth considerably and limits the performance of the system.

Other Intra-channel Effects

Due to the high fiber dispersion in dispersion managed systems, pulses within each channel tend to overlap during a significant part of transmission span, and as a result they interact through the fiber nonlinearity.

Together with SPM all pulses generated a contribution to the nonlinear phase shift that depend now on the power of the pulses and is called IXPM. Similarly to the XPM this effect causes different data pulses to experience time shifts causing time jitter. However, since locations where real acceleration of pulses may take place are related to the dispersion, IXPM can be reduced by launch position optimisation [49].

In a similar fashion IFWM is the result of a sum of three different pulses in the time domain that overlap due to the dispersion broadening, and a fourth pulse is generated. This will lead to a ghost pulse on a zero bit or amplitude jitter on a "one" bit. Different methods have been proposed for the suppression of IFWM leading to higher complexity receivers and transmitters. Utilising alternate polarisation among neighbouring bits reduces IFWM efficiency [4]. Sub-channel multiplexing in time domain with slightly different wavelengths has been suggested as means to detune the IFWM product out of the signal band.

4.5 OXC and ROADM Physical Impairments

Each OXC and ROADM introduces physical impairments that, similarly to other effects described so far, also limit the abundant fiber bandwidth in several ways. Hence, although transparency is a great asset for optical networks, in some cases the term has been misleading as the real offered transparency depends on many different system characteristics. Let us assume that by transparent, we characterise a system where no electronic processing takes place. The combination of transparency and fast reconfigurability gives the OXCs and ROADMs great flexibility.

The OXC and ROADM systems affect the physical performance in three different ways: introducing loss to the system, introducing crosstalk terms and imperfect filtering characteristics. In order to investigate the physical performance of such an optical networking element, the scalability versus cascadeability performance of such a switch should be evaluated. This is the physical performance of the element and how it is compromised by the increase in the number of wavelengths and fibers and the number of concatenated nodes.

Like all physical elements, OXCs and ROADMs introduce loss to the propagating signals which can be seen as an aggregate loss of all the elements that comprise the system (see Fig. 2.1), that is, multiplexers, demultiplexers and switch fabrics together with other required components like filters or attenuators. The main degradation source, however, is the loss of the switch fabric, mainly due to the high number of the devices that are required when high-port node architectures are designed. Insertion loss depends on the switching technology, the switch architecture and its size. Switch fabrics with large loss require power-consuming transceivers and demand more optical amplifiers to compensate for loss. Both can be really complex and power consuming when advanced modulation formats are utilised.

However, there is more into optimising the loss performance of an OXC than having low insertion loss. The variation of loss among different paths across the fabric must also be as low as possible. For example, this is one of the main disadvantages that may arise in multistage architectures. Although semiconductor optical amplifiers (SOAs) have been proposed as gates (on/off switches) also because of their induced gain, they still affect the OSNR of the bypass signals. It is also desirable that the performance of the optical switch be wavelength and polarisation independent. Polarisation-dependent loss (PDL) and polarisation mode dispersion (PMD) should be as low as possible.

However, the main physical-layer impairment introduced by the optical elements is crosstalk. Crosstalk terms arise due to the imperfect gating of signals or at demultiplexers, multiplexers and filters. It originates from the possible power leakage of imperfect devices but also due to the limited extinction ratio of the switches and can be either at the same wavelength with the interfering signal or at different wavelengths. The higher the extinction ratio of the switching device, the better it is. Residual optical power coming from a device when it is at the off state can be the source of crosstalk in a switching system. Crosstalk terms at the same wavelength as the main signal produce interferometric noise, which significantly compromises system operation. The phase noise in the interfering terms is converted to intensity noise when they, are converted to electrical form by a square law detector. These current fluctuations manifest themselves as relative intensity noise (RIN) and add to those resulting from shot noise and thermal noise in equations (2.5). In [50] an analytical treatment of the RIN is reported. As a result of this extra parameter, the Q factor is now reduced in the presence of intensity noise, and in order to maintain the same Q factor, the received power must be increased. Crosstalk terms that are at different wavelength appear as power addition crosstalk which is also expected to reduce the Q factor.

Other than the residual power that is due to imperfect filtering, filter shapes dictate specific performance to optical signals that propagates through them. In optical networks optical signals propagate through a number of mux/demux and transparent OXCs. The concatenation of filters narrows the overall optical bandwidth of the devices, and the propagating signal may be affected by passband misalignments. This evidently is true for advanced modulation formats for which careful filter design considerations are sought. Hence for some modulation formats, tight filtering is optimum as ASE is suppressed (e.g. duobinary ASK formats), while others (NRZ) which are susceptible to ISI may not be ideal following considerable concatenation of filters.

5 Conclusions

Wavelength Switched Optical Networks (WSONs) have arisen as a natural continuation of the success of WDM systems. Although the introduction of fiber in the 1970s was to demonstrate the delivery of a humble capacity of 6 Mbps, it was clear that the optical channel could offer much more than that. However, at the time it seemed that attenuation was the only factor that could limit the promising prospects of the newly developed transmission medium. Since then, optical communication history has proven that physical impairments are numerous and always related to the context of the achievable B × L. Today that achievable capacities reach the available raw fiber bandwidths and spectral efficiency is starting to become the main issue, cross-channel effects that were discussed in the context of WDM seemed already as a trivial design issue, and intra-channel effects are taking over as the bothersome obstacles in system development. Meanwhile crosstalk and filtering effects that arise from the optical networking elements are adding some complexity to the optimisation of the physical layer. In the context of this chapter we discussed all the impairments that impact the performance of the system and are related to the transmitter and receiver, the fiber nonlinear effects and linear effects, the amplifier-induced noise and the ROADM filtering and crosstalk effects. However, it was made clear that the significance of the various impairments strongly depends on multiplexing scheme, modulation format and detection mode, while their interplay between linear and nonlinear impairments complicates things. So in low-bit-rate amplitude modulation, FWM and XPM are the main nonlinear impairments; however, as data rates increase and formats become more spectrally efficient, intra-channel effects dominate. For low-bit-rate phase-modulated formats, the main limitations on nonlinear transmission generally come from nonlinear phase noise. At 40 Gb/s and above, intra-channel nonlinearities dominate.

However, exact conclusions on relative impairment impact are system design specific. This is one of the main reasons behind the versatility of methods for combating linear physical impairments has not been an easy task. Advances in optical enabling technologies, such as dispersion compensation modules, and in high-speed electronics, such as feedforward equalisers, have made possible the design of spectrally efficient high-capacity transmission system where impairments are mitigated via well-studied digital communication and signal processing techniques like modulation, coding and equalisation. Specifically as data rates move beyond 100 Gb/s per channel, modulation formats and line coding are used to mitigate linear and nonlinear impairments explained in the chapter while achieving high spectral efficiencies in optical network environments. Meanwhile multi-level modulation is being applied as means to apply electronic pre- and post-processing by using lower rate digital electronics hardware.

At the same time optical component technology has been researched as means to convey the abundant fiber bandwidth to other functionalities in the network which up to now have been occupied by electronic technology. Optical subsystems are appealing as alternatives to electronic counterparts only when substituting many components with one subsystem for efficient resource sharing (fiber, amplifier, dispersion compensation). As a result, optical technology is more attractive as a genuinely cost effective and recently energy efficient suggestion albeit unsuitable for the intelligent manipulation and processing of bits. Towards this direction the focus of optical intelligence today has moved from devising optical bit-rate tailored subsystems like 2R regenerators towards impairment resilient modulation formats, for example. Combating physical-layer impairments with optical means while utilising the available bandwidth efficiently seems to be the next cost-efficiency achievement of optical technology that will probably win over the progressive advancement of electronic processing.

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