Physical limits of the applicability of 10 and 40 Gbps speed DWDM systems

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Due to the growing transmission demands and the technical evolution, the use of DWDM systems that have more and more channels for the transmission of bundles of higher and higher speeds is spreading. In case of the application of 10 Gbps, but especially 40 Gbps systems, the dispersion characteristics of the optical fibres come to the focus of attention. Due to the high optical levels that can be provided with optical amplifiers, non-linear phenomena in the optical fibres can be observed. The imperfection of the passive optical devices used for the multiplexing/de-multiplexing of the wavelengths causes channel cross-talks. The aforementioned phenomena are in close relation with the high-speed transmission and they have to be taken into account when designing, installing and operating such systems. In general, the problems of the physical layer appear much more in case of high speed multiplex wavelength transmissions than as it used to be in case of known lower speed systems.

1. Introduction

The current DWDM connections enable transmitting of 40-160 channels each of 10 Gbps, but the development of the 40 Gbps devices, too, has entered the phase, in which the first multi wavelength systems, transmitting traffic of industrial scale on 40 Gbps bundles, have appeared.

In the time of the early single channel, single mode optical systems, the optical fibre seemed to be almost an ideal transmitting medium. The distance that could be bridged over was only limited by the optical attenuation, while till the appearance of the 2.5 Gbps systems, in systems using single mode fibre the impact of the chromatic dispersion was also negligible. The applied laser sources could be quite simply directly modulated, preserving normal signal shape and good extinction ratio. At the applied optical outputs of maximum few milliwatt, the optical fibre behaved fully linearly, noise or cross-talk had not to be expected on the line. With the high speed (>10 Gbps) multi wavelength systems, we have got far from the aforesaid almost ideal status.

2. Physical limits of the optical transmission

In the optical fibre transmission systems – with the exception of the analogue cable television applications – we transmit digital signals. Often these signals are multiplex signals bundled with a certain time division multiplexing (TDM) method. In spite of the aforesaid, we can state that on optical level the transmission is performed in a fully analogue way. For the optical transmission of the digital information "pre-multiplexed" by TDM there is an intensity modulation applied on the optical carrier. We do not call this modulation method as amplitude modulation, because the optical carrier is not a single-frequency carrying wave, but usually a spectrum of several MHz bandwidth. The intensity modulation can be simply performed with the help of switching on/off the driving current of the semiconductor laser used as light source, or using an external modulator. On the reception side, a very simple direct detection is taking place and there is no need to create the carrier; the original digital signal is included in the change of the current of the receiver's photo detector. No special coding is required for the transmitting of the signal; scrambled NRZ or RZ coded signals can be transmitted.

Notwithstanding, the NRZ coding is not the best coding method from the point of view of the transmission, at least for two reasons: first, the radiated carrier does not carry information and it unnecessarily loads the optical amplifiers, secondly, it is quite sensitive to the Polarisation Modus Dispersion (PMD). The RZ coding is more favourable from the point of view of PMD, through the carrier is radiated in this case, too. There exist other modulation methods favourable from many aspects and some of them are close to being introduced in the practical use. Due to space limits this article does not allow us to describe these methods.

The characteristics of the transmission medium, the applied light sources, the passive and active devices installed on the transmission path and the features of the optical receiver fundamentally influence the high speed transmission. The maximum length of the optical section is limited first of all by the attenuation of the optical fibre and the passive elements inserted within the transmission path. Besides the attenuation, the signal distortion caused by the dispersions, the noise produced by the optical amplifiers, the interferences caused by the crosstalks, the signal shape distortions,
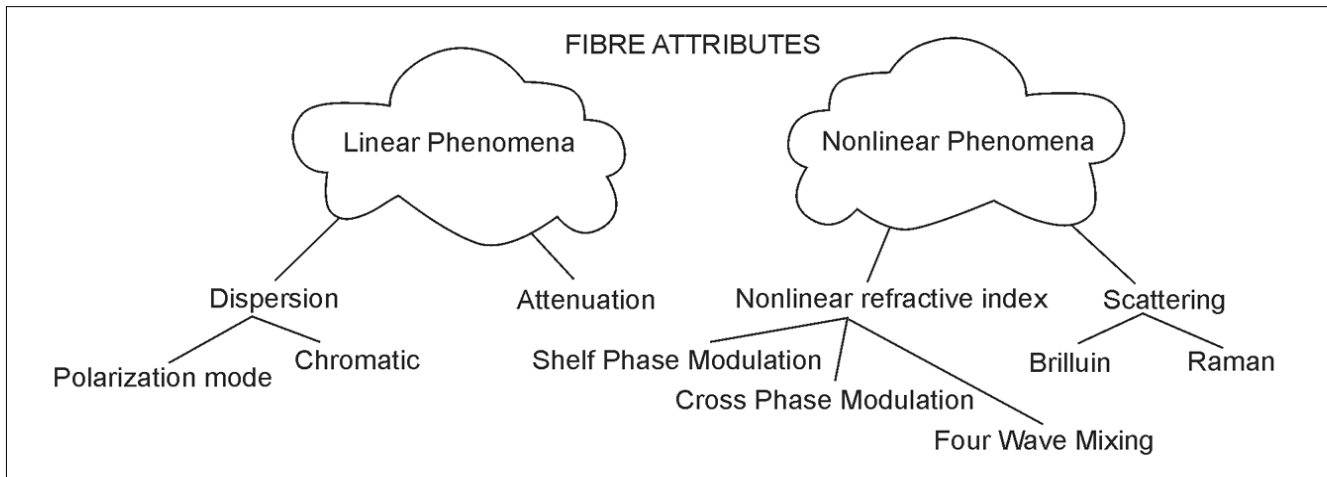
Figure 1. Characteristics of an optical fibre

noises and the jitter developing due to the non-linear characteristics occurring in the fibre altogether further limit the section that can be bridged over at an acceptable bit error rate. The application of a redundant error correction coding (Forward Error Correction, FEC) provides protection to a certain extent against the errors occurring on the line section. Activating FEC, a noise gain of 4...6 dB can be achieved.

In the followings we give an overview of factors that influence the high speed transmission on the physical level. The phenomena that on any way influence the propagation of the light pulse in the optical fibre are grouped into two categories and illustrated in *Figure1*.

2.1. The transmission medium

A basic element of DWDM systems is the optical fibre itself. ITU-T has standardized, in its recommendations, several types of single mode optical fibres that basically differ from each other in respect of their dispersion characteristics.

In the last one and the half decades most of the networks were built from single mode optical fibre cables described in ITU-T Recommendation G.652. This type of fibre is often called as "standard" single mode fibre (SSMF). The SSMF is optimised for 1310 nm wavelength, which means that the fibre has 0,3...0,5 dB/km attenuation and its chromatic dispersion value is low enough in this spectrum.

Shifted dispersion fibres (G.653) have appeared mostly for the application in long distance connections. The dispersion characteristics of these fibres are optimised for the lower attenuation 1550 nm wavelength. Thus, with the higher performance of the fibre the section distances could be further extended. At the same time, this type of fibres has explicit disadvantages from the point of view of high speed DWDM. Because of the smaller diameter of the mode field, the non-linear phenomena occur in an increased degree. In this context, it is an additional disadvantage that in the transmission range, the chromatic dispersion becomes zero and the dispersion coefficient reverses its sign.

Later, further fibre types have appeared having better parameters that match better to the needs of broadband and high speed DWDM transmission. Their common characteristic feature is that their dispersion parameters are optimised for the 1550 nm environmental conditions and that thanks to their relatively bigger and efficient diameter they tolerate higher output levels without increasing of the disadvantageous non-linear phenomena. The characteristics of these types of optical fibres are described in Recommendation G.655. The manufacturers differentiate the fibre types by different fancy names.

2.1.1. Linear characteristics

The most important transmission attributes of the optical fibres are the wavelength dependent attenuation, the chromatic and the polarization mode dispersion.

The attenuation of the silicon-based single-mode fibres arises from three factors: the absorption, the scattering and the wave guiding losses *(Figure 2)*.

• Absorption may be of intrinsic nature, which is caused by the electron transients falling into the UV range and the photons of the IR range; or may be generated by contaminations, caused by temporary metallic components, or the vibrations of H_2 and OH ions; and finally caused by problems due to inhomogeneity of the material.

Figure 2.
Components of the attenuation of an optical fibre
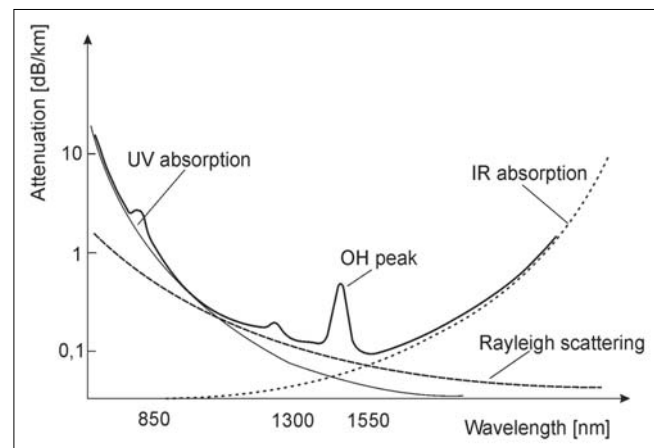
• A considerable part of dispersion losses is caused by Rayleigh-scattering, which is an inherent material characteristic of non-crystalline substances. Light dispersion may occur also on macroscopic defects of the material, such as blisters, cracks and other inhomogeneities, or the interfacial unevennesses of the core-shelf plane.

• Waveguiding losses may arise from macrobanding (losses originating from the curve of the waveguide) or from microbanding (losses caused by perturbation).

The size of the attenuation influences basically the signal transmission, but with the application of optical amplifiers the attenuation problem can easily be eliminated.

The light pulse components having various wavelengths propagate in the optical fibre at different velocities due to the wavelength dependency of the refractive index of the silicon oxide. This phenomenon is called chromatic dispersion (CD). The CD develops as the common result of several effects. From these factors, the waveguide dispersion can be influenced by shaping the profile of the optical fibre's refractive index *(Figure 3)*. This offers the possibility of producing optical fibres with different dispersion characteristics.
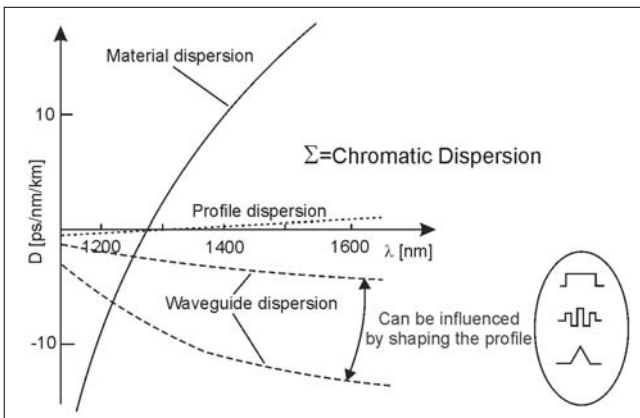

Figure 3. Chromatic dispersion

Due to chromatic dispersion the individual components of the light pulse coupled into the fibre arrive at different points of time at the place of reception and cause the broadening of the original pulse *(Figure 4)*.

If the broadening is so big that it leads to the overlapping of the subsequent pulses, it results in bit errors
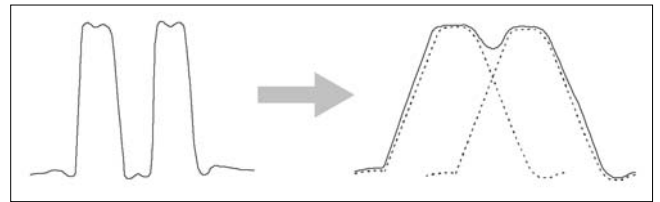

Figure 4.
The chromatic dispersion effect:
pulse broadening and overlapping

in the transmission. The higher the transmission speed is, the more the chromatic dispersion affects the transmission quality, because the overlapping of the adjacent pulses takes place earlier due to the shortened bit time, and also the spectrum of the laser transmitter broadens much more due to the effect of the higher modulation frequency. As a result of these jointly occurring phenomena the dispersion-sensitivity increases nearly quadratically with the bit rate. A 40 Gbps system is more sensitive to dispersion by approximately 16 times than a 10 Gbps system and 256 times more sensitive than a 2.5 Gbps system.

The extent of the pulse broadening depends on the spectral characteristics of the transmitter. Application of narrow light sources, with a few MHz spectrum may be advantageous, but from other points of view (for instance Brillouin scattering) the application of them is definitely disadvantageous. The extent of pulse broadening can be calculated with the following formula:

$$t_H = \delta\lambda * L * D,$$

where $\delta\lambda$ is the spectrum width of the light source, L is the length of the link and D is the chromatic dispersion coefficient of the optical fibre.

Figure 5. shows a (10 Gbps) STM-64 signal shape spreading on a G.652 optical fibre, after concatenation of 5, 50 and 100 km length optical fibres. The receiver is a standard SDH reference receiver. The pulse broadening can be seen well and also that the noise has significantly increased due to the optical amplifier used at the measurement of the 100 km fibre length.

In spite of its isotropic material and circular cross section the optical fibre has slight birefringence. The birefringence introduced to the fibre is caused by the non-circularity, surface unevennesses developed during manufacturing, longitudinal and crosswise power

Figure 5.
STM-64 signal shape degradation due to chromatic dispersion on an inserted 5, 50 and 100 km length SSMF at 1550 nm
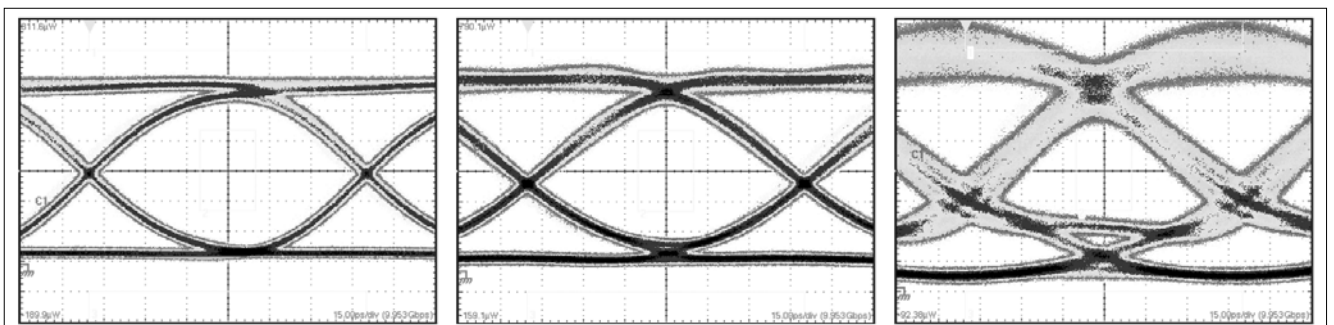
impacts during installation, longitudinal twisting or bending. The polarization mode dispersion attributable to the group delay difference of the two polarization components of the HE_{11} dominant modus of the light. The difference in the group delays belonging to the different polarization planes is called Differential Group Delay, DGD.

The polarization mode dispersion is the rms value of the differential group delay. Additional higher order PMD effects come to this first order DGD, such as: polarization-dependent chromatic dispersion, skewing of the dominant polarization planes, etc. Similarly to chromatic dispersion, the adverse impact of PMD to transmission appears as broadening of the transmitted pulse and pulse overlapping arising due to broadening.
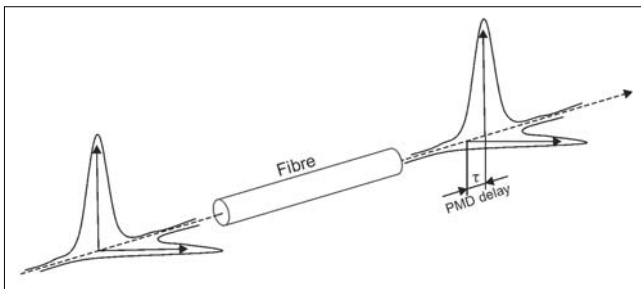

Figure 6. The PMD effect

The value of the PMD is proportionate with the square root of the cable length. The value of polarization mode dispersion permitted to a system is usually quoted in 1/10 of the periodic time typical for the given transmission system. For example, for a 10 Gbps system we allow maximum 10 ps. If the PMD coefficient of our cable is 0,5 ps/√km, then the maximum permitted section length (limited by the PMD effect) is $L = (10/0,5)^2 = 400$ km. The effect of PMD can be compensated by adequate techniques.

2.1.2. Non-linearities

The output optical power of the "traditional" optical systems exceeded the +3...5 dBm value only rarely. The application of optical amplifiers made it possible to achieve higher, even +20 dBm (100 mW) output levels. Thus, with the amplifiers applied periodically along the transmission link there can be high signal level sustained, and the system's sensitivity to the noise developing in the receiver decreases significantly. At the same time, due to the higher power level, the increased number of channels in the WDM systems we leave the range where the optical fibre shows linear behaviour with a good approximation. The non-linear characteristics of the fibre originate from the fact that the light – due to the enormous spectral density of order of magnitude of 100 MW/m² occurring in the core – enters into interaction with the glass fibre. Non-linearities can be grouped basically into two different categories:

Effects that arise because of the changing of the refractive index caused by high field strength belong to the first category. These are the followings:

– Self Phase Modulation, SPM,
– Cross Phase Modulation, XPM and
– Four Wave Mixing, FWM.

Scattering type phenomena belong to the second category. These are the followings:
– Stimulated Brillouin Scattering, SBS and
– Stimulated Raman Scattering, SRS.

Effects occurring due to the change of the refractive index

The refractive index of the optical fibre, even if to a small extent, depends on the intensity of the light. At the peaks of the pulses of the modulated light signal the refractive index changes (Kerr effect). The extent of the change is:

$$n = n_0 + n_2 |E|^2,$$

where n is the changed refractive index, n_0 is the original value of the refractive index, n_2 is the refractive index coefficient that depends on the non-linear field strength, E is the field strength. The approximate value of n_2 is $-2,2 \times 10^{-20}$ m²/W, which practically does not depend on the type of the fibre. The increase of the refractive index can be expressed with a more practical formula as:

$$n = n_0 + \frac{n_2}{A_{eff}} P,$$

where P is the power launched into the fibre, A_{eff} is the effective area of the optical fibre.

The change in the refractive index results in phase modulation and the latter changes the signal spectrum. The Self Phase Modulation (SPM), in case of negative chromatic dispersion, introduces the broadening of the light pulse, while in case of positive dispersion, it reduces the pulse. The spectral broadening caused by Self Phase Modulation may cause in multi-channel systems interference among the adjacent channels. Zero, or near to zero positive chromatic dispersion environment reduces the effect of this phenomenon. High bit rate, negative dispersion and several concatenated sections further increase the effect of SPM. In case of 10 or 40 Gbps systems, the effect of this phenomenon can be detected already at power levels above 10 mW. With the proper setting of the dispersion values of the fibre sections the degrading effect of SPM is more or less manageable in case of homogeneous optical links not longer than 1000 km.

Cross Phase Modulation (XPM) is caused by the signals of other systems working on other wavelengths of the WDM system that also cause changes in the refractive index and induce undesired phase couplings among the carrier waves. Cross Phase Modulation and Self Phase Modulation are always together at present. The effect of XPM is, of course, more intensive in case of DWDM systems with short channel distances. Higher optical powers lead to the broadening of the spectrum of the transmitter and cause timing jitter in the received signal. The chromatic dispersion appearing due to spectral broadening further worsens the situation on long-haul systems. Therefore, efforts shall be made for the optimal setting of chromatic dispersion of the links.

The recommended compensation settings can be calculated with the following empirical formula:

$$D_{PRE} = \frac{-D_{SMF}}{\alpha} \ln\left[\frac{2}{1+e^{-\alpha L}}\right],$$

where D_{PRE} is the recommended compensation value, α is the per km attenuation of the fibre, D_{SMF} is the dispersion and L is the length of the link. In practical systems the compensation value is set to -200 ps/nm, which means the over-compensation of the link. In general it can be stated that the XPM effect is not significant in case of 100 GHz or larger channel distances and at less than 5 mW launched power.

Four-Wave Mixing (FWM) is the most dangerous non-linear phenomenon in WDM systems. Exceeding the critical power, due to the undesired phase couplings mixing products occur, the wavelengths of which fall on operating wavelengths in case of equal channel spacing.

In case of wavelengths ω_1 and ω_2 the created mixing products are: $2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$. In a system consisting of N channels the number (n_λ) of the developed "ghost" wavelengths is expressed as:

$$n_\lambda = N^2\left(\frac{N-1}{2}\right),$$

where N is the number of wavelengths applied in the given system. So thus, for instance, in a 32-channel DWDM system, there appear more than 15 thousand (!) mixing products. Four-Wave Mixing develops already on 10 km fibre lengths on wavelengths or in the vicinity of wavelengths, the chromatic dispersion value of which is zero. Thus, FWM is especially critical in case of low effective area, dispersion shifted G.653 fibres.

In this case the non-desired effect can only be reduced with carefully chosen, non-equal channel spacing. Mixing products – taking into account also the products generated by the noise of optical amplifiers – appear as noise in the given channel and cause the closure of the eye pattern and finally degrade the system's BER performance.

The effects of scattering type phenomena

Stimulated Brillouin Scattering (SBS) is attributable to the macroscopic interaction between the light and the density waves of the fibre's material (acoustic photons). Due to Brillouin scattering the power launched into the fibre at 1550 nm is partly reflected on a frequency shifted by appr. 11 GHz. Thus, the phenomenon is especially harmful if extremely low channel spacing is applied. The extent of backward scattering is independent of the number of channels applied in the system, but it very much limits the power that can be launched into the fibre, especially in case of transmitters with low spectral width. The power level that causes at least 1 dB degradation in the optical signal-to-noise ratio can be calculated using the following relation:

$$P_{th} = 21\frac{KA_{eff}}{gL_{eff}} \cdot \frac{\Delta v_p + \Delta v_B}{\Delta v_B},$$

where P_{th} denotes the threshold power, g denotes the Brillouin gain coefficient (constant) ($\sim 4 \times 10^{-9}$ cm/W), A_{eff} is the fibre effective area, K is a constant determined by the degree of freedom of the fibre's polarization statuses (in case of G.652 fibres, $K=2$), Δv_B and Δv_p represent the Brillouin bandwidth and the spectral width of the pumping light. L_{eff} denotes the effective fibre length, which can be defined with the formula:

$$L_{eff} = \frac{1 - e^{(-\alpha L)}}{\alpha},$$

where α is the fibre attenuation per length unit and L is the fibre length.

In case of sources having spectral width of $\frac{\Delta v_p}{\Delta v_B} \ll 1$, which is smaller than the Brillouin bandwidth, the critical (threshold) power can be calculated using the following relation:

$$P_{th} = 21\frac{KA_{eff}}{gL_{eff}}.$$

In the practice SBS phenomenon occurs already at power levels of approximately 80 mW (+19 dBm). Its effect can be reduced with some per cents low frequency (30...100 kHz) amplitude modulation applied on the carrier wave.

Stimulated Raman Scattering (SRS) occurs as the interaction of light and the SiO_2 molecules of the fibre which involves the high frequency vibration of the adjacent nucleuses (optical photon). The induced radiation has the same direction as the normal light propagation and its wavelength is shifted typically by 100 nm towards the lower wavelengths. The induced radiation has a spectral width of 50...60 nm.

In *Table 1 (on the next page)*, we provide a summary of the optical characteristics discussed before, the physical phenomena and their effects on digital transmission and the methods for the elimination or compensation of these effects.

3. Q-factor measurement methods

In intensity modulated digital optical transmission systems the information is represented by two possible signal levels. In real systems, different mean noise values are added to the two signal levels. It means that different electrical signal/noise ratios can be attributed to the two signal levels. When we would like to determine the occurrence probability of the bit errors of the transmission, we have to reckon with two various signal-to-noise ratios. The two signal-to-noise ratio values can be merged in one transmission quality parameter, and it is the Q-factor.

The Q-factor is interpretable as a signal-to-noise ratio at the input point of the decision circuit of the optical receiver. The Q-factor and the optical signal/noise ratio can be arranged together in the case only, if we take into account only the ASE noise generation of the optical amplifiers. In the reality – as we could see it before – there are several other effects influencing the quality

of the optical signal, thus the Q-factor and the optical signal/noise ratio can be calculated into each other with certain inaccuracy only.

To determine the relationship between BER and the eye opening it is necessary to determine statistically the amplitude noise. If there is no Inter Symbol Interference (ISI) present, the noise is statistically independent from the signal content and if the dominant amplitude noise is of Gaussian distribution, the Q-factor can be expressed by the following equation:

$$Q = \frac{(\mu_1 - \mu_0)}{(\sigma_1 + \sigma_0)},$$

where μ_1 and μ_0 represent the low and high average levels of the amplitude function, σ_1 and σ_0 represent the Gaussian distribution values of white noise _(see Fig. 7)_.
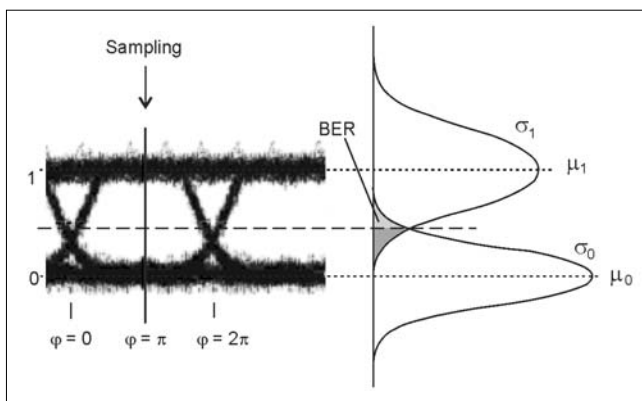

Figure 7.
Noise distribution, mean value and distribution
of logical 1 and 0 levels

Analysing the probability curves, we can see that there are two possibilities for the occurrence of a wrong decision: to detect "0" instead of "1" and vice versa, to detect "1" instead of "0". The bit error rate is proportional to the sub-curve area belonging to the opposite logical level stretching over the decision threshold (grey area on Figure 7).

The decision threshold is in its optimal place (i.e. the probability of wrong decisions is the lowest), if the amount of the sub-curve areas belonging to the other logical level on the right and the left side is the minimum. This value is at the crossing point of the two bell-shaped curves, if they are fully identical. In real systems, however, the bell-shaped curves belonging to the two logical levels are always different from each other.

The optimal decision level is at:

$$\mu = \frac{\sigma_0\mu_1 + \sigma_1\mu_0}{\sigma_1 + \sigma_0}.$$

It can be seen from the eye pattern that the occurrence probability of the logical levels depends on the place of detection, too. Taking the width of the eye pattern as 2π, the optimal sampling phase is at the place where $\varphi = \pi$.

Relationship between BER value and Q-factor:

$$BER = \frac{1}{4}erfc\left(\frac{\mu - \mu_0}{\sqrt{2}\sigma_0}\right) + \frac{1}{4}erfc\left(\frac{\mu_1 - \mu}{\sqrt{2}\sigma_1}\right),$$

where _erfc_ is the supplementary error function, integrated from _x_ up to ∞, and μ is the decision threshold.

Table 1. Summary of non-linearities

Interference effect	Cause	Critical per channel power	Effect	Compensation
Attenuation/noise	Material absorption/circuit elements	Independent from power	Decreased power, BER	Shorter section, optical fibre with lower attenuation
CD	Wavelength-dependent group propagation velocity	Independent from power	Decreased power, BER, increased spectrum width	Insertion of dispersion with opposed sign
PMD	Random change of refractive index	Independent from power	Decreased power, BER, signal shape degeneration	Compensation of optical or electrical PMD
FWM	Signal interference	10 mW	Side-bands, BER	Accurate CD setting, irregular channel distribution
SPM/XPM	Intensity-dependent refractive index	10 mW	Spectral broadening, BER, channel crosstalk	Accurate CD setting
SRS	Interaction of photons and fibre molecules	1 mW	Power depletion, OSNR, crosstalk, BER	Conceptual power level planning
SBS	Interaction of photons and the fibre's density waves	5 mW	Power, OSNR depletion, signal instability, crosstalk, BER	Source with larger spectrum width

Figure 8.
Relationship between Q-factor and BER

Figure 9.
Synchronous double threshold method for Q-factor measurement

ITU recommends the following formula for the approximation of the *erfc* function:

$$BER(Q) = \frac{1}{2} \times \left[2 \times e^{-\left(\frac{Q}{\sqrt{2}}\right)^2} \times \right.$$

$$\left. \times \frac{a0 + a1 \times \frac{Q}{\sqrt{2}} + a2 \times \left(\frac{Q}{\sqrt{2}}\right)^2}{\left[b0 + b1 \times \frac{Q}{\sqrt{2}} + b2 \times \left(\frac{Q}{\sqrt{2}}\right)^2 + b3 \times \left(\frac{Q}{\sqrt{2}}\right)^3 \right] \times \sqrt{\partial}} \right],$$

where

a0 = 1.69071595	b0 = 1.90764542
a1 = 1.45117156	b1 = 3.79485940
a2 = 0.50003230	b2 = 2.90845448
	b3 = 1.00000000

At values $Q > 1,5$ the approximation provides a good accuracy and is simply programmable.

There are several known methods available for the determination of the Q-factor. The so called "synchronous double threshold" may be one of the most advan-

Figure 10.
Measurement results and extrapolation

tageous methods. In an arrangement illustrated in *Figure 9*, the signal is split into two parts and sent to two different decision circuits.

The decision level of one of the decision circuits is set fixed to the optimum value, while the threshold value of the other decision circuit is adjustable. The clock signal which corresponds to the ever current bit rate and with the help of which the optimal decision position of the decision circuits can be set, is provided by a PLL circuit.

Comparing the decision results of the two comparator branches (EXOR, EXCLUSIVE-OR) conclusions can be drawn for the BER value. The result is illustrated in a diagram as shown in *Figure 10*. The vertical axis shows the bit error ratio, while the horizontal axis shows the decision levels. The method allows measurement with acceptable accuracy of bit error ratios in the range between 10^{-4} and 10^{-8}. Applying a regression function, a good extrapolation to the smaller BER values can be done from the diagram.

By this method, in an indirect way, i.e. by calculating the Q-factor, it becomes possible to determine approximately the BER value of the transmission system, independently from the transmitted protocol and the bit contents. In case of extent Inter Symbol Interference (ISI) and non-Gaussian noise distribution, we have to reckon with measurement inaccuracy and be more care-

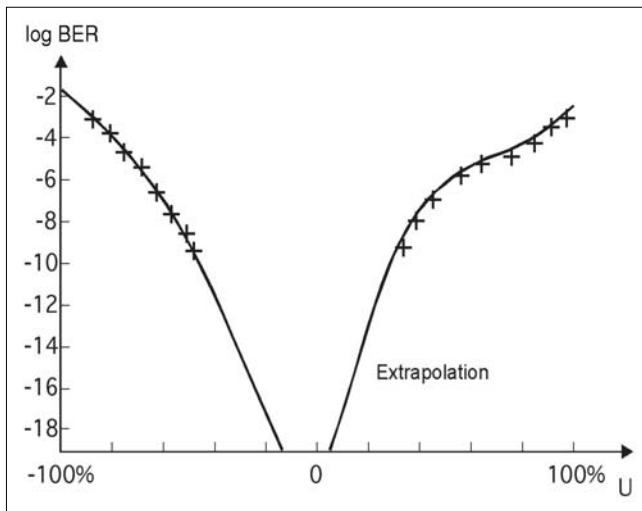Figure 11. Non-Gaussian noise distribution

Figure 12. Degenerated Q curves in case of non-Gaussian noise distribution

ful at the applying of regression lines. It may be useful to control the eventual inter symbol interferences and the noise distribution on the eye pattern displayed on a digital oscilloscope.

For instance, in case of non-Gauss noise _(see Fig. 11 and 12)_, the adjustment of the regression line should only be done for the BER range below 10^{-8}.

3.1. Application possibilities for Q-factor measurement

The Q-factor method, of course, is not applicable for detecting errors occurring in the receiver. At the same time, it is an excellent tool for the indication of the various degradations of the optical transmitter, while with the help of it the proper adjustment of the chromatic dispersion compensation, the proper setting of which is very important in case of high speed systems, can be very well controlled, along with the eventual noise increase in the optical amplifiers, or non-linearity effects occurring at higher number of channels, or at higher optical levels.

The Q-factor measurement and assessment on the basis of it requires further considerations in case of non NRZ or RZ coding or in case of non intensity modulation (see [6]).

Following the installation of transmission systems one of the most important thing to do is to perform the appropriate control measurements regarding system performance. The BER (bit error ratio) test is one of the most important control tests. According to the specification

requirements we expect the systems to be within the BER range of $10^{-12}...10^{-13}$. It is quite time consuming to perform the BER test measurements. For instance, in case of a 10 Gbps system to measure statistically correctly a 10^{-13} bit error ratio takes at least 28 hours. One can imagine how long testing times would be required in case of putting into operation a DWDM system with several parallel channels. In such cases, the Q-factor measurement, performed in a few minutes, provides quite accurate approximation of the bit error rate characteristics of the optical signal. Thanks to the very quick measurement that can be performed with the Q-factor method, the malfunctioning network parts or components can be easily identified and separated in difficult cases.

The Q-factor measurements do not fully substitute the BER measurements performed with bit error ratio measuring instruments for the estimation of the system's performance capabilities. Nevertheless, it can help that long lasting tests take place only, when according to the Q-factor tests the system seems to be faultless or error free. Thus, one can save plenty of time and trouble. Last, but not least the number of 10...40 Gbps bit error rate measuring tools which are very expensive, can be reduced with the purchasing of some less costly instruments applicable for Q-factor measurement.

Figure 13 and Figure 14 show the measurement results of a Hungarian DWDM line section of 420 km length. As it can be drawn from Figure 13, the BER value is of 2×10^{-5}. Measuring the Q-factor at several points of the line section, it could be detected that the laser transmitter installed at the beginning of the section was not working properly. Having it replaced, the Q-factor and BER values have improved significantly (see Figure 14).

Another exciting application field of Q-factor measurement is the optimized setting of the levels and dispersion compensation of the optical systems.

_Figure 13.
Q-factor measurement results of
a defective STM-64 line section_
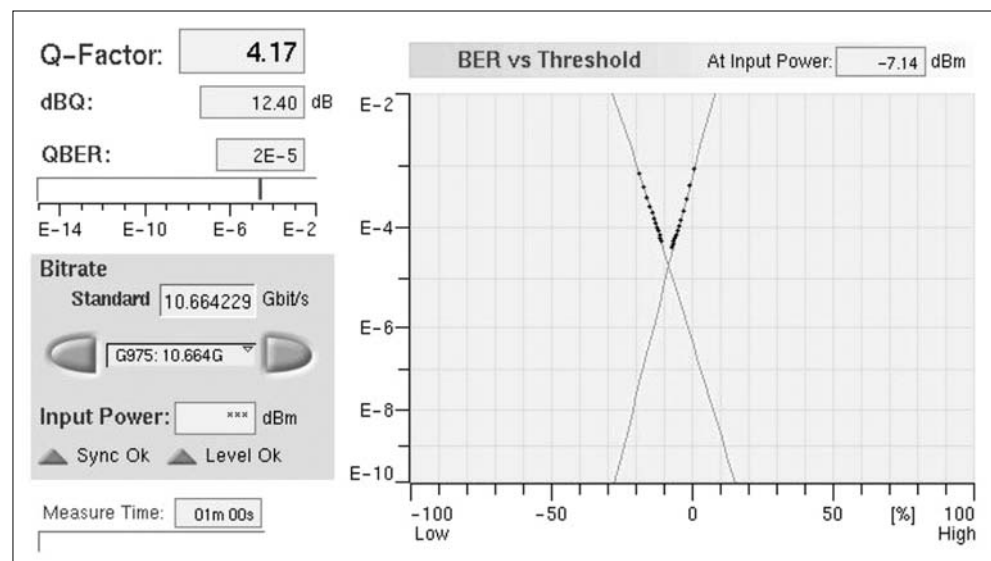
The Q factor measurement offers the possibility of fast controlling after the changing of the compensation and levelling parameters, enabling the settings considered to be optimal from the point of view of the optical signals.

The great advantage of the Q-factor measurement technique is that it allows monitoring of the living system under operation, connecting the measuring device to the measuring points of it. This method can improve the efficiency of the fault detection and maintenance activities. Under operation testing and monitoring may be very useful also for the follow-up of particular maintenance activities or in SLA complaint investigations.

4. Summary

The physical layer of the network basically influences the quality of the high speed multi-wave optical systems. Practically there is analogue signal transmission taking place in the physical layer. In the design, planning and dimensioning of high speed DWDM networks, there are several parameters to be taken into consideration that were less important in the past. Typically such parameters are the non-linear characteristics of the optical fibres, the noise of the optical amplifiers, the exact synthesis of the system and the dispersion compensation. From the point of view of the performance of the systems, the perfect and coordinated functioning of the physical layer is essentially important. The 10...40 Gbps systems set new challenges from planning/designing and operations point of view.

The Q-factor measuring method supports well the operations and maintenance of the physical layer. Sending a feedback on experience gained by the tests for the planning and incorporation of them into the planning process may beneficially promote the accuracy of the planning work.

Figure 14.
Q-factor measurement results after fault correction
on line section illustrated on Figure 13
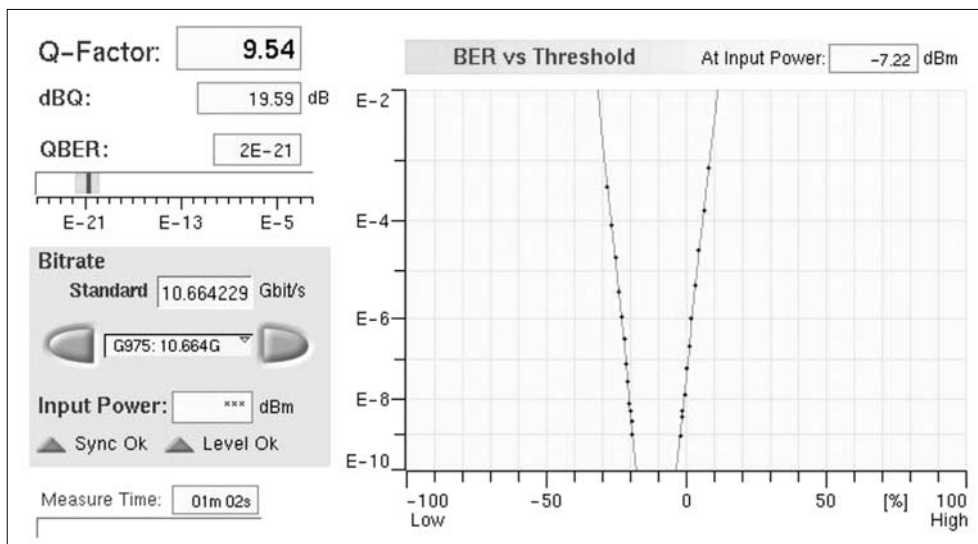
Last but not least, the planning or the optimization of the systems has economic/financial aspects, too: the quality of the transmission is manageable, the network will not be unnecessarily oversized, or, for example the number of the optical amplifiers, and along with that the investment costs can be reduced, or investment savings can be achieved.

References

[1] Ines Brunn:
    Dense Division Multiplexing, Pocket Guide;
    Acterna Eningen GmBH.
[2] Vitus Zeller:
    Q factors basics, Pocket Guide;
    Acterna Eningen GmBH.
[3] Jan-Pierre Laude:
    DWDM fundamentals, components and applications;
    Artech House Inc. 2002.
[4] Hanik, N.:
    Netze mit optischem Frequenzmultiplex;
    Der Fernmelder Ingenieur, 1997/06.
[5] Jeszenői P.:
    DWDM rendszerek alkalmazhatósága
    meglévő optikai hálózaton; Előadások gyűjteménye –
    13. Távk. és informatikai hálózatok kiáll. és szemin.
[6] G. Bosco, P. Poggiolini:
    On the Accuracy of the Q-parameter to Assess BER
    in the Numerical Simulation of Optical DPSK
    Systems; ECOC 2003 Proceedings.
[7] Maxim I.C.:
    Optical Receiver Performance Evaluation;
    Application Note HFAN-03.0.2 (Rev. 0, 03/03).
[8] Marcuse, D., Chraplyvy, A.R., Tkach, R.W.:
    "Dependence of cross-phase modulation on
    channel number in fiber WDM systems,"
    IEEE Journal of Lightwave Technology,
    Volume 12, Number 5, p.885, May 1994.
[9] ITU-T Rec. O.201:
    Q-factor test equipment to estimate the transmission
    performance of optical channels.