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Impact of the Optical Fiber Nonlinear Phenomenon on the 16-channel DWDM OC-768 Long-haul Link

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Abstract. With the onset of the optical fiber in the backbone networks, new challenges have come for the constructors of these networks. The SDH (Synchronous Digital Hierarchy) technology, which has gradually replaced the PDH technology (Plesiochronous Digital Hierarchy), has also contributed to the booming of the optical network communications. On the basis of the SDH technology, synchronous optical networks, known as SONET, have emerged. The SONET OC-768 technology is the latest SONET variant of the synchronous optical network. Its main usage has been found in long-distance transmissions with a transfer rate of up to 40 Gbps. The major limitation factor of the fiber communication systems is the nonlinear phenomenon. In this paper we investigate the impact of the fiber nonlinear phenomenon on the 16-channel DWDM (Dense Wavelength Division Multiplex) OC-768 system in the OptSim simulation environment.

Keywords: DWDM, FWM, nonlinear phenomena, OC-768, SDH, SBS, SPM, SRS

Vpliv vlakenskih nelinearnih pojavov na 16-kanalno medkrajevno zvezo z zgoščenim valovnodolžinskim multipleksiranjem pri optičnem nosilcu OC-768

Z uporabo optičnih vlaken v hrbteničnih omrežjih prihajajo novi izzivi pri njihovi gradnji. K naglemu razvoju optičnih komunikacij pripomore tudi sinhrona digitalna hierarhija (SDH), ki postopoma zamenjuje plesiohrono digitalno hierarhijo (PDH). Na podlagi tehnologije SDH so nastala sinhrona optična omrežja, imenovana SONET. Zadnja verzija sinhronega optičnega omrežja je tehnologija SONET OC-768. Njena glavna uporaba je v prenosu na dolge razdalje s hitrostjo prenosa do 40 Gb/s. Poglavitna omejitev pri optičnih komunikacijah so vlakenski nelinearni pojavi. V prispevku obravnavamo vpliv vlakenskih nelinearnih pojavov na 16-kanalno medkrajevno zvezo z zgoščenim valovnodolžinskim multipleksiranjem pri optičnem nosilcu OC-768.

1 INTRODUCTION

The SONET abbreviation refers to a standardized synchronous optical network that synchronously transfers multiple-bit streams through an optical fiber using a highly coherent light source (laser or LED). The sychronous transmission method has been developed to replace the plesiochronous digital hierarchy system.

There is no considerable difference between the SONET and other technologies. The SONET-supporting hardware is designed to provide better configuration options and reliable services to users. To reach long distances, regenerators or optical amplifiers can be used. SONET also supports the use of a dense wavelength division multiplex (DWDM), coarse wavelength division multiplex (CWDM) and optical add drop multiplexer (OADM) systems. SONET supports a simultaneous transmission of multiple data streams. In packet-oriented networks, the data packet typically consists of two parts: a data header and payload. During transmission, the data header is transmitted first and then the payload is transmitted. However, there is a slight change in SONET. The header is called overhead and does not translate to a useful load. Instead, it interconnects with a useful load during the transfer process. The transfer alternates between the overhead and payload until the transmission process is complete [1].

At present, the fastest SONET for the optical data transmission applicable in real systems is OC-768. OC-768 supports up to a 40 Gbps transmission via an optical fiber. OC-768 has been developed to meet the ever-increasing bandwidth requirements. Multiplexing with DWDM is used to transmit multiple wavelength channels [2].

The history of OC-768 dates back to the early 21st century, when it was originally designed as a network line with a transmission rate of 39,813 Gbps. Already in 2008, this technology was deployed by AT&T on their IP/MPLS network with a total fiber length of 128,000 km. This technology is also successfully deployed on the TAT-14/SeaGrit

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transatlantic cable system supporting 16 wavelength channels [1][2].

The aim of this paper is to investigate the impact of the nonlinear phenomenon on the OC-768 link supporting 16 wavelength channels using the OptSim simulation environment.

The structure of this paper is as follows: chapter 2 describes the nonlinear phenomenon, chapter 3 presents a simulation model of a 16-channel DWDM OC-768 optical link developed to the impact of the fiber nonlinear phenomenon and chapter 4 provides and discusses the results.

2 Related work

This paper is based on a continuous research already published by various authors. The impact of the nonlinear phenomenon on a 16-channel DWDM system with an arrayed waveguide grating is investigated by Ivaniga et al [3]. They show an effective way of reducing the nonlinear phenomenon using the Bipolar Return to Zero (BRZ) encoding technique. Huszaník et al [4] also investigate the impact of high spectral optical modulation techniques with transmission rate of 20 Gbps in DWDM systems and present how the nonlinear phenomenon responds to different signal shapes using optical IQ modulation techniques. The nonlinear changes in different WDM systems with different dispersion levels and input signal powers are presented by Bobrovs et al [5]. Other interesting topics releated to the fiber nonlinear phenomenon are discussed in [6-9].

3 Overview of the fiber nonlinear phenomenon

The two types of the fiber nonlinear phenomenon are generally distinguished. The first type is based on the interaction between the transmitted light waves and molecular vibrations (phonons) in the transfer medium. This category of nonlinear effects includes the stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). The second type of the nonlinear phenomenon arises from the dependence of the refractive index of the optical fiber on the intensity of the signal in the optical fiber. This group of the nonlinear phenomenon, includes a self-phase modulation (SPM) and four-wave mixing (FWM). The nonlinear phenomenon is the main limitation factor for the high-speed and long-haul optical communication systems. The way in which they affect the transmitted signal in the optical fibers may vary depending on the length of the fiber, signal level, amount of the noise present in a channel, etc. [1][10].

3.1 Stimulated Raman Scattering

The principle of the stimulated Raman scattering (SRS) is based on the fact that the bound radiation in the fiber generates vibrations at the molecular level and consequently loses some of its energy. From the point of view of the quantum mechanics this process can be described as scattering of a photon to a new photon and the so-called optical phonon (vibrational state). SRS is the result of an interaction between the optical radiation and high-frequency vibrational components of the optical fiber material. SRS creates a lateral vacuum which is displaced by 100 nm and spreads in a straight line. SRS limits the properties of the multichannel WDM systems, because it reduces the signal energy on lower wavelengths and increases the energy level on signals with higher wavelengths. The optical power threshold for SRS of a standard single mode fiber is about 0.5 W. The energy transfer between two different frequencies is most likely to occur when they are spaced approximately 13 THz in the frequency domain (see Fig. 1) [1].

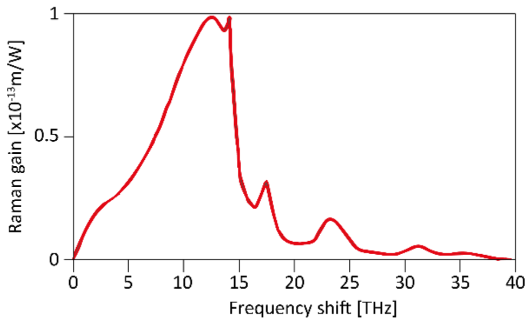

Figure 1. Raman gain.

3.2 Stimulated Brillouin Scattering

The stimulated Brillouin Scattering (SBS) is considered to be the dominant nonlinear phenomenon in the optical fiber. The basic principle is similar to SRS, the main difference between SRS and SBS is that the phonon in SBS is acoustic, which results in other features of the SBS phenomenon. The origin of the acoustic wave depends on the effect of thermal phonons as a result of the thermal oscillations of the crystalline lattice of the fiber core material and is induced by the input wave that generates this wave by the electrostrictive process. The acoustic wave changes the local refractive index and at this point the photon is separated from the propagation signal. The photon then propagates in the opposite direction, against the original wave or radiation source. This backward-scattered wave is frequency-shifted downward (wavelength increase), a frequency change is about 11 GHz, which is less compared to SRS. This backward-scattered wave affects the broadcast source stability and the source noise ratio. The optical power threshold for SBS is the lowest among the nonlinear phenomenon and ranges from a couple of mWs [10-13].

3.3 Self-Phase Modulation

A self-phase modulation (SPM) is a nonlinear phenomenon that is caused by an interaction between an optical substrate and light transmitted through the optical fiber. This interaction results in a change in the refractive index caused by the optical Kerr effect, which causes the phase of the transmitted optical signal to shift [10][11]. This phase shift can be described by the following equation:

$$\Delta\varphi = -2\pi n_1 \frac{L}{\lambda_0 A} P, \quad (1)$$

where n_1 is the refractive index of the optical fiber core, λ_0 is the wavelength of the carrier, L is the length of the optical fiber, A is the cross-sectional area of the optical medium, and P is the power of the transmitted signal [14]. The intensity of the transmitted optical signal depends on the change in the refractive index profile due to the Kerr effect:

$$n(I) = n_0 + n_2(I), \quad (2)$$

where n_0 is the fiber core refractive index and n_2 is the nonlinear refractive index. The intensity of the optical signal I can be expressed as:

$$I(t) = I_0 \cdot \exp\left(\frac{-t}{\tau}\right). \quad (3)$$

Further, the phase of the transmitted signal is a time variable according to the formula:

$$\varphi(t) = \omega_0(t) - \frac{2\pi}{\lambda_0 n(I) L'} \quad (4)$$

where ω_0 is the frequency of the carrier optical wave, λ_0 is the wavelength of the carrier, n is the fiber refractive index, and L is the length of the optical fiber. The frequency change due to SPM is illustrated in Fig. 2 [15].

As seen from this graphical dependence, the signal frequency is almost linear in the center of the graph. At the leading edge of the signal, the frequency decreases and the refractive index of the optical fiber increases due to the increase in the signal intensity. At the rising edge, when the signal intensity decreases, the frequency of the signal increases as the optical fiber refractive index decreases. This frequency change in the transmitted signal is called frequency chirping. These

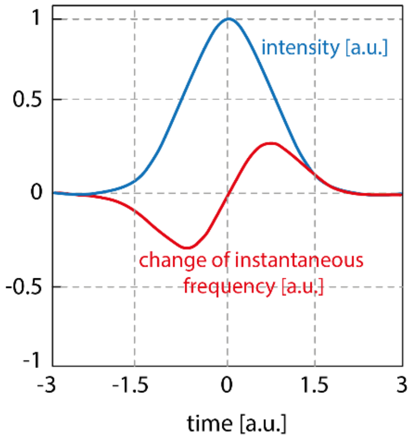

Figure 2. Change in the frequency due to SPM.

changes in the frequency cause a chromatic dispersion.SPM and chromatic dispersion occur in a close relationship and are more or less dependent on each other. For example, if a nonlinear SPM dominates compared to the chromatic dispersion, it is possible to reduce overlapping of the transmitted optical impulses caused by the chromatic dispersion. The transmitted signal appears stable, hence there is no overlapping of impulses when the effect of the SMP and chromatic dispersion is equivalent. On the other hand, the SPM impact will modulate the amplitude of the transmitted signal if the chromatic dispersion is negligible compared to SPM [1][15-18].

3.4 Four Wave Mixing

The nonlinear phenomenon of four a wave-mixing (FWM) is a modification of the Kerr effect. FWM should be considered especially when designing the DWDM systems. FWM is based on the assumption that several wavelengths of light are transmitted through one optical fiber. FWM then causes the occurrence of at least one new light wave, called idler. However, the wavelength of this new wave does not match the wavelengths of signals that have been coupled to the optical fiber [12]. The FWM example of is shown in Fig. 3.

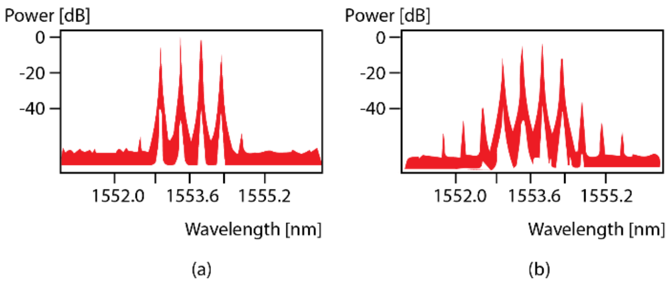

Figure 3. Optical spectra of four wavelength channels (a) without FWM and (b) with FWM.

FWM occurs when at least three signals of different wavelengths are propagated in a single optical fiber. Thus, when propagating three signals of frequencies f_i, f_j and f_k, there is an interaction that induces a new signal with the frequency of f_{ijk}:

$$f_{ijk} = f_i + f_j - f_k \qquad (i, j \neq k) \tag{5}$$

The new signal generated by the FWM phenomenon affects total transmission power *P(L)* in relation to optical fiber length *L*:

$$P(L) = \frac{1024\pi^6}{n^4\lambda^2c^2}(D_X) \cdot \frac{P_i(0)P_j(0)P_k(0)}{A_{ef}^2} e^{-\alpha L} \cdot \frac{(1-e^{-\alpha L})^2}{\alpha^2}\eta\,, \tag{6}$$

where P_i, P_j and P_k are the output powers of the optical signals, f_i, f_j and f_k are the channel frequencies, P is the power of the newly generated signal of the f_{ijk} frequency, n is the refractive index of the optical fiber, λ is the carrier wavelength, c is the velocity of light in the vacuum, A_{ef} is the coefficient determining the effective area of the core of the optical fiber, α is the loss coefficient, L is the length of the fiber, D is the degradation factor and X is the nonlinear susceptibility [1].

4 Simulation Model of the 16-DWDM OC-768 Long-Haul Link

The 16-channel DWDM OC-768 long haul link is designed in the OptSim programming environment. OptSim allows the design and simulation of the optical fiber communication systems as well as wireless-optic communication systems. The simulation in OptSim is based on the block theory. Each component or subsystem in the network is represented by one block. The simulation runs independently in each block. The simulation in OptSim runs under ideal conditions. However, the designer may opt to include undesirable linear and nonlinear phenomena in the simulation. OptSim allows to simulate in detail the degradation mechanisms of the nonlinear phenomena such as SRS, SBS, SPM and FWM [13-15].

The block diagram of the 16-DWDM OC-768 long-haul link optical communication system is shown in Fig. 4. The 16-DWDM OC-768 long-haul link consists of a transmitting part, optical distribution network and receiving part. The transmitting part consists of 16 2-DPSK (Differential Phase Shift Keying) wavelength channels. It is formed of a coherent light source with a central emission wavelength of 1550 nm. Channel spacing is set to 100 GHz according to ITU-T G.694.1. A pseudo-random sequence generator PRBS generates a pseudo-random sequence of a bit rate of 40 Gbps. The pseudo-random sequence is then modulated by an electric NRZ modulator. The NRZ-modulated data are modulated on an optical carrier using an optical phase modulator (OPM).

The optical distribution network is made up of a repeater (marked as a loop in the block scheme) whose task is to repeat the transmission several times over a given optical path. The optical path itself consists of 50 km of a single-mode optical fiber (SMF) with the attenuation of 0.2 dB/km and with a nonlinearity coefficient of $n_2 = 2.43\text{e-}20$ m^2/W. In this case, the nonlinear phenomenon of SPM, SRS, SBS and the phenomenon of chromatic dispersion is considered. Next, there is an erbium doped fiber amplifier (EDFA) which amplifies the signal by 10 dB and adds 6 dB of the optical noise. The next in the chain is an optical

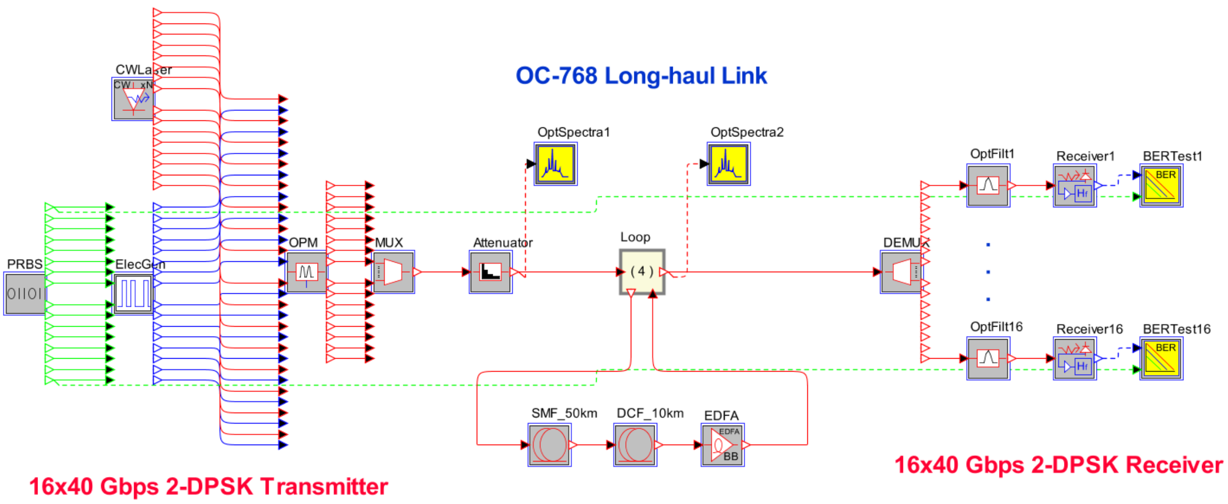

Figure 4. Simulation model of the 16-DWDM OC-768 long-haul link.

fiber that compensates the chromatic dispersion (DCF). The length of DCF is 10 km. DCF is an optical fiber having the opposite dispersion as the fiber used in the transmission system. It eliminates the dispersion caused by the transfer fibers. The optical distribution network thus consists of 60 km of the optical path in one span. There are 4 spans, so the overall length of the optical path is 4x60 km.

The receiving part consists of a bandpass optical filter, PIN-based photoconductor and electric low-pass filter. The received signal is analyzed for the transmission error probability (BER). The aim of the simulation is to investigate the impact of the nonlinear phenomena on the transmission quality.

5 RESULTS AND DISCUSSION

The proposed model of a 16-DWDM OC-768 long-haul link is tested for the optical noise level of 6 dB. To evaluate the quality of the transmitted signal, the eye diagram of the received signals is used. The eye diagram is a display from which important parameters regarding to the quality of the transmitted signal relative to the one originally transmitted can be immediately determined. An important parameter is the eye openness. It determines the signal-to-noise ratio. The more open the eye, the greater the signal-to-noise ratio and the less likely the occurrence of an error. The quality of the received signal without considering the optical noise is higher than when it is considered. The highest acceptable BER for the high-speed optical communication systems is 1e-012, which corresponds to 16.94 dB OSNR (Optical Signal-to-Noise Ratio).

In the first run, a simulation with four spans (240 km of the fiber) is done. The signal level is set to 0 dBm (1 mW) with a constant level of the noise of 6 dB. The optical spectra after the 2nd (120 km) and the 4th span (240 km) is provided in Fig. 5 and Fig. 6. Without considering the nonlinear phenomenon, these two spectra should be the same except for the power level. Fig. 6 shows a slight frequency chirp and creation of new spectral components in sidebands due to nonlinearity phenomena.

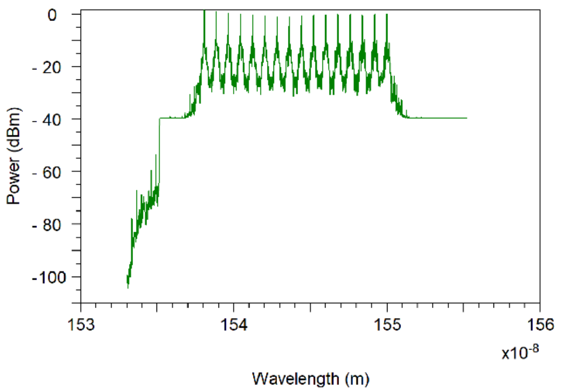

Figure 5. Output optical spectra after the 2nd span.

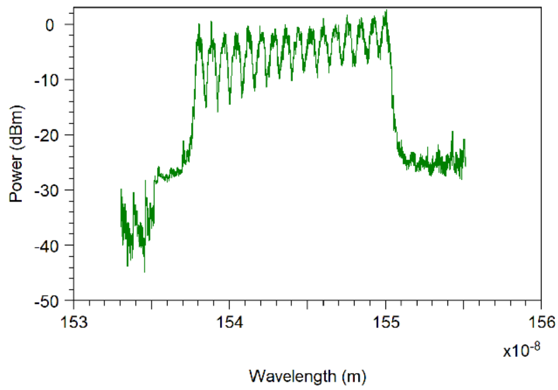

Figure 6. Output optical spectra after the 4th span.

In the second run, the transmission performance on an increased length of the optical path is tested. In this run, the number of spans from 1 to 10 (60 – 600 km of optical path) is varied. Using such setup, the maximal distance over which a signal can be transmitted considering the nonlinear phenomena is determined. For the simplicity, only channel 4 (15476 nm) is analyzed. The eye diagram of channel 4 after the 6th span is shown in Fig. 7.

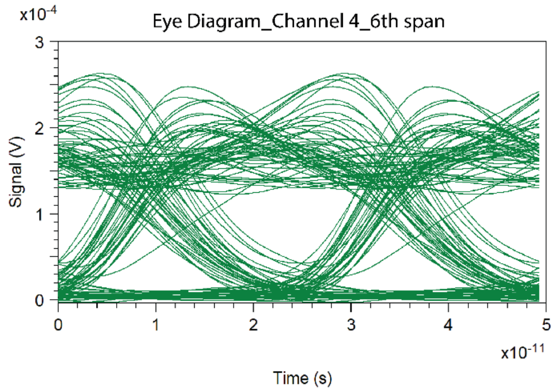

Figure 7. Eye diagram of channel 4 after the 6th span (360 km).

The dependence between the number of spans and BER is shown in Fig. 8. As seen in Fig. 8 the BER value increases almost linearly with the increasing value of the span. This is due to the nonlinear phenomenon. It is important to realize the fact that each span consists not only of 60 km of the fiber but also of EDFA amplifying signal by 10 dB at each span. The chart in Fig. 8 shows the nonlinearity caused by the in-line and its impact on the overall performance. Notice that this chart is for channel 4 only. The measured BER and OSNR values are shown in Table 1.

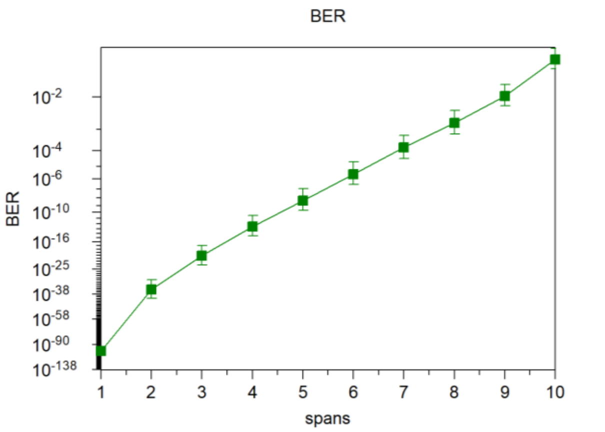

Figure 8. Number of spans vs BER.

Table 1. BER and OSNR values for multiple spans.

Spans	BER	OSNR (dB)
1 (60 km)	1.825e-078	25.444
2 (120 km)	8.532e-036	21.892
3 (180 km)	8.526e-021	19.350
4 (240 km)	3.304e-013	17.131
5 (300 km)	4.797e-009	15.175
6 (360 km)	2.559e-006	13.179
7 (420 km)	1.466e-004	11.177
8 (480 km)	1.746e-003	9.309
9 (540 km)	1.052e-002	7.261
10 (600 km)	4.666e-002	4.497

In the third run is considered the dependence between the EDFA gain and BER. The aim is to show that the nonlinear phenomenon is evoked by an increase in the EDFA gain. As concluded in chapter 2, the nonlinear phenomenon depends on the signal intensity. The increase in the intensity value changes the refractive index of the optical fiber resulting in a frequency chirp. Such frequency chirp may cause a crosstalk between the adjacent channels. The crosstalk can be easily reduced by enlarging the channel spacing which reduces the number of channels in the same bandwidth. The dependence between the EDFA gain and BER of the received channel 4 is shown in Fig. 9. As seen, for the gain levels of 1-7 dB, the BER value is 1.000e+000. By amplifying the signal to 9 dB BER is 2.395e-010. By increasing the EDFA gain a more nonlinear phenomenon is induced and BER drops back to 1.000e+000. This shows that the nonlinear phenomenon, most noticeably SPM and FWM, is power sensitive. For the low gain values (1-7 dB) signal is too weak to be detected and the nonlinearities do not significantly affect the transmission. The optimal gain value is between 9 and 10 dB. However, by exceeding this threshold, SPM and FWM are induced and BER increases rapidly.

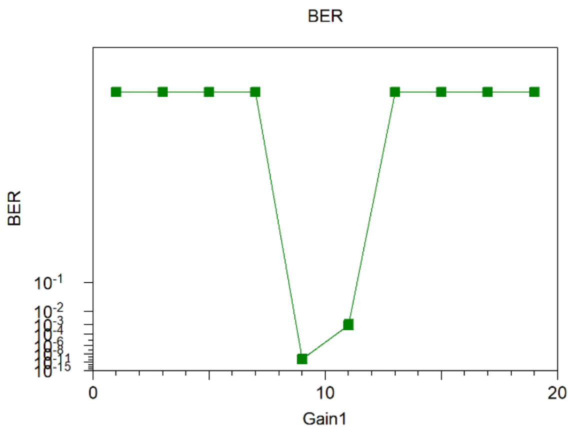

Figure 9. EDFA gain (dB) vs BER.

Fig. 10 shows the eye diagram of the received channel 4 for 13 dB of the EDFA gain. Though the eye seems to be open enough, the BER value is 1.000e+000. However, the thicker lines of the eye denote a high optical noise contribution.

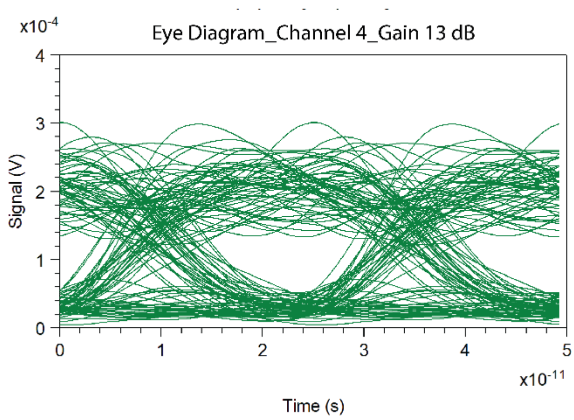

Figure 10. Eye diagram of the channel 4 with a 13 dB EDFA gain.

Table 2. BER and OSNR values for different gain levels.

EDFA Gain (dB)	BER	OSNR (dB)
1	1.000e+000	0.000
3	1.000e+000	0.000
5	1.000e+000	0.000
7	1.000e+000	0.000
9	2.395e-010	15.884
11	9.807e-004	9.8161
13	1.000e+000	0.000
15	1.000e+000	0.000
17	1.000e+000	0.000
19	1.000e+000	0.000

In the last run, the impact of differrent noise figure values induced by EDFA on the occurence of the nonlinear phenomenon is simulated. For the relatively low noise levels, from 3 to 9 dB, the eye diagrams are quite open and the lines are smoother. Fig. 11 shows the eye diagram of received channel 4 for a 3 dB noise. The BER value is 1.164e-013. Fig. 12 shows that by increasing the noise figure, the BER value exponentionally increases and that OSNR decreases. The BER and OSNR values are recorded in Table 3.

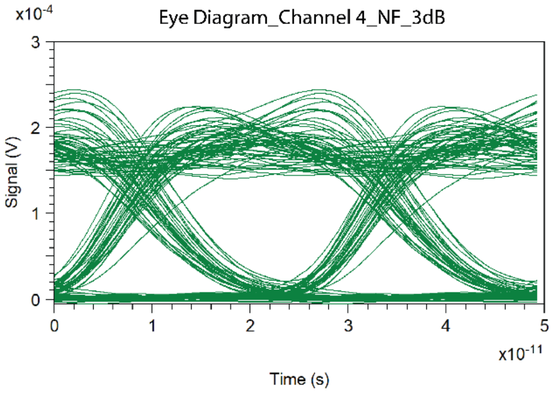

Figure 11. Eye diagram of channel 4 with a 3dB noise.

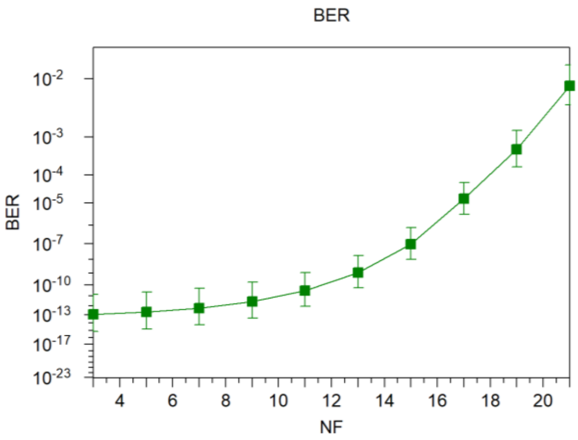

Figure 12. Noise figure (dB) vs BER.

Table 3. The BER and OSNR values for different noise levels.

Noise Figure (dB)	BER	OSNR (dB)
3	1.164e-013	17 .300
5	2.151e-013	17.202
7	5.725e-013	17.040
9	2.830e-012	16.762
11	3.286e-011	16.298
13	1.117e-009	15.534
15	9.655e-008	14.330
17	1.483e-005	12.415
19	5.176e-004	10.320
21	8.020e-003	7.633

Judging from the above results, it can be assumed that the fiber nonlinear phenomenon in the 16-channel DWDM OC-768 long-haul link depends on the transmission distance, transmission power level and the optical noise level present in the optical fiber. A careful selection of these parameters reduces an unwanted signal degradation caused by the nonlinear phenomenon.

6 Conclusion

This paper provides results of a study of the nonlinear phenomenon in a 16-channel DWDM OC-768 long-haul link. 16-channel DWDM OC-768 link with transmission speed of 40 Gbps and total length of optical fiber of 240 km was designed using OptSim simulation software. The results show that the nonlinear phenomenon affect the transmission over OC-768 optical link most notably with the increasing length of the optical fiber and the increasing amount of a noise in the channel. Because the majority of the nonlinear phenomenon is power sensitive (most notably SPM and FWM) by the selection of the right power level, the overall impact of these effects can be reduced. As presented in chapter 4, the optimum gain level of the in-lines EDFA is in the range of 9-11 dB for which the signal degradation caused by the nonlinear phenomena is the smallest.

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