Simulation and Analysis of the Signal Transmission in the Optical Transmission Medium

Rastislav Róka and Filip Čertík
Institute of Telecommunications, Slovak University of Technology in Bratislava, Ilkovičova 3, Bratislava, Slovakia

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Abstract: This paper presents a possible way for simulating a signal transmission in the optical transmission medium. A main attention is focused on characteristics and analysis of linear and nonlinear effects that influence optical signals transmitting in the environment of optical fibers. Simultaneously, functional blocks created in the Matlab Simulink programming environment for particular effects are presented in the proposed simulation model. At the same time, the paper present a simulation of the optical transmission system that can include various modulation and encoding techniques utilized for the signal transmission. In addition, a comparison of results from the proposed simulation model with measurements on real optical transmission paths is introduced.

1 INTRODUCTION

Nowadays, an interest in the signal transmission through optical fibers rapidly increases due to the transmission bandwidth. Constructing new optical transmission paths can be time consuming, expensive and sometimes not available solution. In the electric domain, utilizing new advanced signal processing can lead to increasing of the transmission capacity. Such solutions can be easily integrated. With increasing of modulation rates, linear and nonlinear influences on the transmitted optical signal are growing and by this way additional bit errors in information signals are generating. Therefore, it is important to design and simulate the influence on advanced signal processing techniques in the optical transmission system with respect to its linear and nonlinear effects. The simulation gives transmission boundaries of each advanced signal processing techniques for the designed optical system and allows comparing all the solutions for the optical system before deployment. The simulation allows increasing the data rate and the transmission range of deployed optical transmission system using advanced signal processing techniques and allows designing a new optical transmission system with different optical fibers.

In (Ahmed, 2007), an optical link simulator was designed like a platform on which the transmission and optimization of communication systems could be carried out. The simulator has been developed under the Simulink environment in the form of modules.

In (Del Río Bellisco, 2004), a software tool developed for simulating of optical communication systems was presented. The simulation allows determination of the spectral and frequency responses of particular blocks and the whole system. The tool has been developed using the Matlab programming environment.

The accurate determination of fiber nonlinearities is an important issue in the design of optical communication systems. In (Batagejl, 2002), the need of knowing fiber non-linear coefficients in global optical networks was presented.

First, basic characteristics of the optical fiber are introduced. The paper presents created simulation blocks in detail for each environmental effect in the optical transmission medium. The analysis of effects is shown on the transmission of noncoherent OOK modulated signals via the standard single-mode fiber. In the final part, the comparison of results from simulation models with measured parameters from the Ciena system is introduced.

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2 ANALYSIS OF THE OPTICAL TRANSSMISION MEDIUM

Each optical fiber represents a transmission system, which is frequency dependent. Pulse propagation inside this transmission system can be described by the nonlinear Schrödinger equation (NLSE), which is derivate from Maxwell equations. From the NLSE equation we can expresses effects in optical fibers that can be classified as:

a) linear effects, which are wavelength depended,

b) nonlinear effects, which are intensity depended.

2.1 Linear Effects

Major impairments of optical signals transmitted via optical fiber are mainly caused by linear effects - the dispersion and the attenuation. The attenuation limits power of optical signals and represents transmission losses. In practical way, it is a power loss that depends on a length of the transmission path. Total signal attenuation *a* [dB] is defined for a particular wavelength, which is defined by

$$a[dB] = 10\log_{10}\frac{P_i}{P_0} \tag{1}$$

where P_i is the input power and P_0 is the output power.

The attenuation of optical fibers is mainly caused by material absorption losses, radiation scattering and by bending losses (Saleh and Teich, 1991). Nowadays, optical transmission systems are able to minimize impact of the attenuation by deploying regenerators or all optical amplifiers like Raman or EDFA amplifiers increasing the optical system range. The attenuation block is a part of the Stimulated Raman and Brillouin scattering block shown in fig.10.

Another source of linear effects represents the dispersion that causes broadening of optical pulses in time and phase shifting of signals at the fiber end. There are three dispersion types:

- *modal dispersion,*
- *chromatic dispersion,*
- *polarization mode dispersion.*

The mode dispersion occurs in multi-mode fibers due to unequal propagation constants of different modes. The paper focused on the single-mode fiber SMF and long-haul transmission systems, so the modal dispersion is not considered (Binh, 2010).

The chromatic dispersion CD is caused by a different time of the spreading wave through the fiber for different wavelengths and it depends on the spectral width of the pulse. The CD influences the transmission signal by broadening the optical pulse in time and by phase shifting the signal phase (Keiser, 2003). To characterize the CD effect, the group velocity delay *GVD* parameter is measured. The *GVD* represents the amount of the optical pulse broadening. The relation between the phase shift and the optical pulse broadening cause by CD is given by two equations

$$t = \frac{1}{2\pi}\frac{d\varphi}{df_m} \tag{2}$$

$$GVD = \frac{1}{2\pi}\frac{d^2\varphi}{df_m^2} \tag{3}$$

where t is a time, φ represents phase and f_m represents modulation frequency.

The CD effect simulation is based on equations (2) and (3). The CD block generates *GVD* values that broaden a propagating transmission signal and change its phase. The CD block is shown in fig.1 and consists of the GVD generator that adjusts the variable integer delay using constant amplitude representing the *GVD*. The delayed signal is created with boundaries of the broadening. Both signals are merged in the CD block, where a phase shift and a power decrease are calculated. The output signal is driven to the Complex phase shift block, where a signal is shifted.

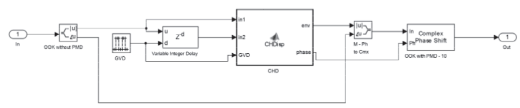

Figure 1: The CD block.

Another dispersion that occurs in the single-mode fiber is called the polarization mode dispersion PMD. The PMD is a random phenomenon that can be only statistically evaluated. The light mode transferred via the single mode optical fiber consists of two modes on different polarization planes which result from propagations principle states of polarization PSP. In ideal optical fibers, two polarization modes would propagate with the same velocity. But in a reality, the optical fiber is nonsymmetrical and imperfect and causes different velocity of these two polarization modes. This effect is also called the birefringence and it is equal to differences Δn between relative refractive indexes for ordinary n_0 and extraordinary n_e rays given by the equation

$$\Delta n = n_e - n_0 \tag{4}$$

The group-delay difference between slow and fast polarization modes is called the differential group delay *DGD* measured in picoseconds. The *DGD* between two orthogonal states of polarization SOP causes the PMD. As a pulse propagates through a light-wave transmission system with the PMD, the pulse splits into fast and slow modes, and therefore becomes broadened and changing the phase of propagating pulse (Jamaludin, 2005).

The PMD effect simulation is similar to the CD simulation. The PMD block is shown in fig.2 and is based on equations (2) and (3). The difference is that the PMD block uses the Random number generator generating *DGD* values with the Gaussian distribution. The PMD effect is negligible in comparison with the CD and therefore we must compensate the CD effect to highlight the PMD effect on the transmitted signal. When the CD is compensated, the high data rate signal can be transmitted, where the PMD with its stochastically behavior becomes more relevant and represents boundaries for the transmission rate.

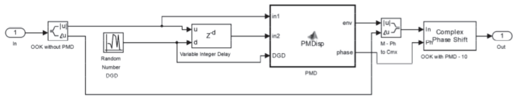

Figure 2: The PMD block.

2.2 Nonlinear Effects

These nonlinear effects play an important role in the long haul optical signal transmission. We can classify nonlinear effects by following way:

- *Kerr nonlinearities* are self-induced effects, where the phase velocity of the pulse depending on the pulse's own intensity. The Kerr effect describes a change in the fiber refractive index due to electrical perturbations. Due to the Kerr effect, we are able to describe FWM, SPM and XPM effects,
- *Scattering nonlinearities* occur due to a photon inelastic scattering to lower energy photons. The pulse energy is transferred to another wave with a different wavelength.

2.2.1 The Four-wave Mixing Effect

The four-wave mixing FWM effect represents a parametric interaction among waves satisfying a particular phase relationship called the phase matching. This nonlinear effect occurs only in systems that carry more wavelengths through the optical fiber and it is classified as a third-order distortion phenomenon. The interaction between waves generate the fourth wave that with angular frequency ω_k given by

$$\omega_k = \omega_1 \pm \omega_2 \pm \omega_3 \tag{5}$$

The nonlinear interaction generates new frequency components of the material polarization vector, which can interfere with input fields if a phase matching condition is obtain. The most frequency components fall away from our original bandwidth or near it. Frequency components that directly overlap with bandwidth will cause an interference with original waves (Singh, 2007). The power of new generated waves can be obtain by solving coupled propagation equations of four interacting waves, which leads to equation (6) that mainly depends on the power of neighbor channels, the channel spacing and on the dispersion.

$$A_k^2 = 4\eta\gamma^2 d_e^2 L_e^2 A_1^2 A_2^2 A_3^2\, e^{-\alpha l} \tag{6}$$

where factor η is the FWM efficiency, γ is the nonlinear coefficient, $L_e$is the effective length, $A_1^2(z)$, $A_2^2(z)$, $A_3^2(z)$ are powers of input waves, l is the fiber length, α is the attenuation and d_e the so-called degeneracy factor (equal to 3 if the degenerative FWM is considered, 6 otherwise).

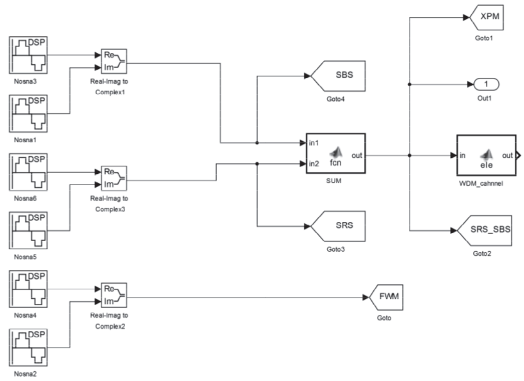

Figure 3: The block scheme for generating additional wavelength channels.

The block design for the FWM effect requires the WDM technology and thus the generation of additional wavelength channels. The data signal generation of additional wavelength channels is shown in fig.3. The additional neighbor channels are mixed in the WDM block and driven to the FWM block, which is shown in fig.4. The block scheme first verifies the phase matching conditions and then mixes the neighbor signals using the equation (6) if phase conditions are satisfied.

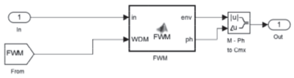

Figure 4: The FWM block.

2.2.2 Self-phase and Cross-phase Modulation Effects

The self-phase modulation SPM and the cross-phase modulation XPM effects have an important impact on high data speed communication systems that use the dense wavelength division multiplexing DWDM. The SPM effect occurs due to Kerr effect in which the refractive index of optical fiber increases with the optical intensity decreasing the propagation speed and thus inducts the nonlinear phase shift. The XPM effect is very similar to the SPM in which the intensity from different wavelength channels changes the signal phase and thus the XPM occurs only in WDM systems. In fact, the XPM converts power fluctuations in a particular wavelength channel to phase fluctuations in other co-propagating channels (Iannone, 1998). Both, SPM and XPM effects results to spectral broadening and distortion of the pulse shape, where spectral broadening can be described by equation (7) and phase shift by equation (8).

$$\omega' = \omega_0 + \frac{d\varphi}{dt} \tag{7}$$

where ω' is the signal frequency influenced with the SPM effect, ω_0 is the initial signal frequency

$$\Delta\varphi_i = \frac{2\pi \overline{n_2} z}{\lambda} \left[I_i(t) + 2 \sum_{i \neq j} I_j(t) \right] \tag{8}$$

where the first term in bracket represents the SPM effect and the second term represents XPM effect.

In the equation (8), the factor 2 has its origin in a form of the nonlinear susceptibility and represents the XPM twice as effective as the SPM for the same power amount. The XPM effect affects the signal only the interacting signals superimpose in time (Yasser, 2012). The XPM effect can decrease a system performance even greater than the XPM effect, especially in case of 100 channel systems.

The design of the SPM and XPM block is shown in fig.5, where the SPM&XPM block calculates the amount of spectral broadening using the equation (8). Both outputs are driven to the Frequency Shifting block, where the signal is spectrally broaden.

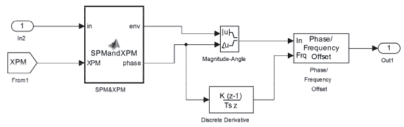

Figure 5: The SPM & XPM block.

2.2.3 Stimulated Raman and Stimulated Brillouin Scattering Effects

The Stimulated Brillouin Scattering SBS and Stimulated Raman Scattering SRS effects influence the intensity of the transmitted signal. In the SBS case, the acoustic wave changes the frequency of several photons that results to interference with a transmitted signal. This frequency shifted wave is propagating only in the opposite direction as the transmitted signal and the power can be described by

$$-\frac{dI_s}{dz} = +g_B I_p I_s - \alpha_s I_s \tag{9}$$

where the I_p is a pump signal, I_s represent transmitted signal intensity, g_R is stimulated Raman gain coefficient and α_s and α_p are losses of signals.
The SRS effect is similar to the SBS, were the spectral width is wide and interferes with several transmitted signals. The SRS effect propagates in both directions (Cotter, 1993). Both stimulated scattering effects represent a noise in optical transmission systems. The power of the frequency shifted wave can be described by

$$-\frac{dI_s}{dz} = +g_R I_p I_s - \alpha_s I_s \tag{10}$$

where the I_p is a pump signal, I_s represent transmitted signal intensity, g_R is stimulated Raman gain coefficient and α_s and α_p are losses of signals.
The SRS&SBS block can be designed by adding additional signal channels using a combination of two equations. The equations include the transmitted signal attenuation coefficients and therefore we can design the common SRS&SBS and attenuation block. The final block is shown in fig.6. Assuming the SM fiber, the SRS downshifts the neighbor signals by about 13,2 THz with the Raman band around 5 THz and the SBS downshifts about 11 GHz with the Brillouin band less than 20 MHz.

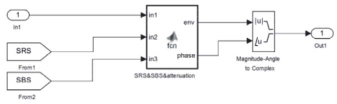

Figure 6: The SRS, SBS and attenuation block.

2.2.4 Modelling of Transmission Signals Influenced Bynonlinear Effects

Following figures are displaying graphical presentations of transmitted signals that are influenced by nonlinear effects in the optical transmission medium. The comparison of signals without and with the CD influence is shown in fig.7. The PMD influence on a transmitted signal is shown in fig.8. The FWM influence on the amplitude of a transmitted signal is shown in fig.9. The fig.10 shows the signal phase shift due to phase modulation effects. The SRS and SBS influences on a transmitted signal with the attenuation are shown in fig.11.

3 SIMULATION OF THE OPTICAL TRANSMISSION SYSTEM

The presented simulation model comes out from the simulation model for optical communications introduced in (Róka, 2012) (Róka and Čertík, 2014). A modeling is performed in the Matlab Simulink 2014. The simulation model presents an influence of linear and nonlinear effects at the signal transmission in the optical transmission media. To verify simulation model, we have prepared a comparison of two optical transmission paths measured in cooperation with the company Orange Slovakia. The optical path_1 consists of the 59.2 km standard SM fiber (ITU-T G.652) with the 10 Gb/s

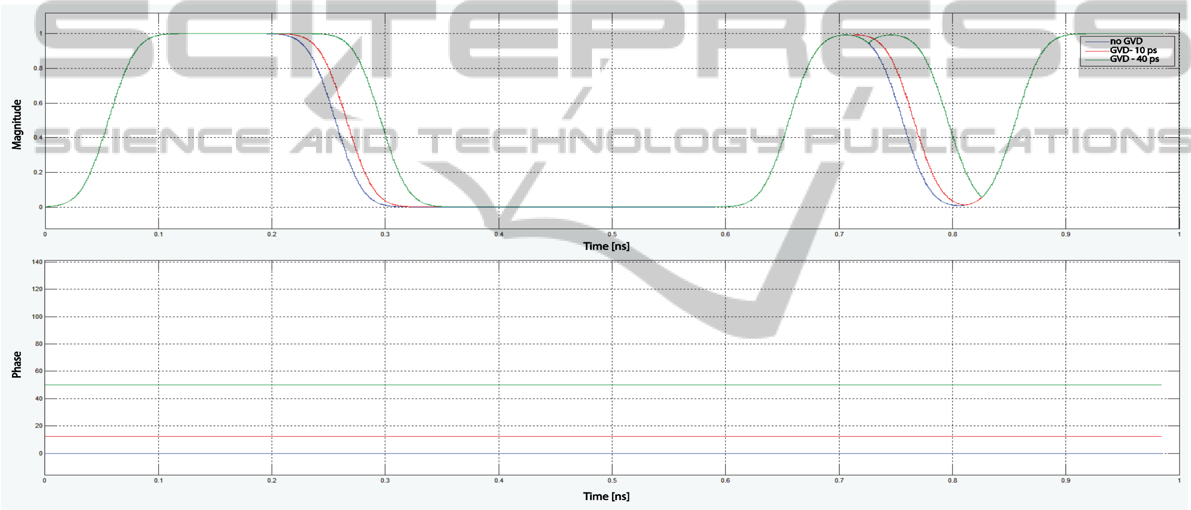

Figure 7: The CD influence on a transmitted signal.

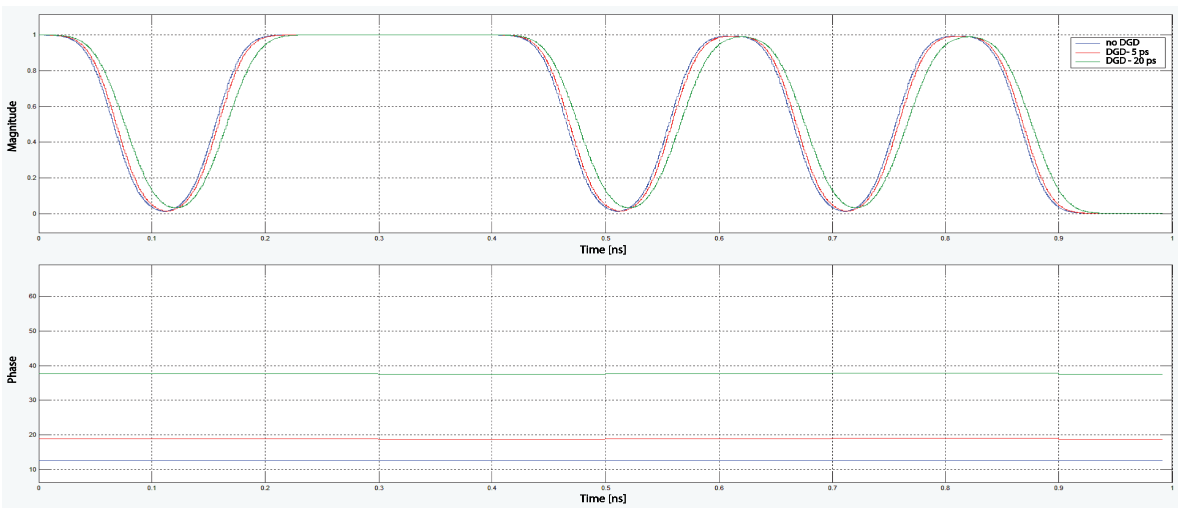

Figure 8: The PMD influence on a transmitted signal.

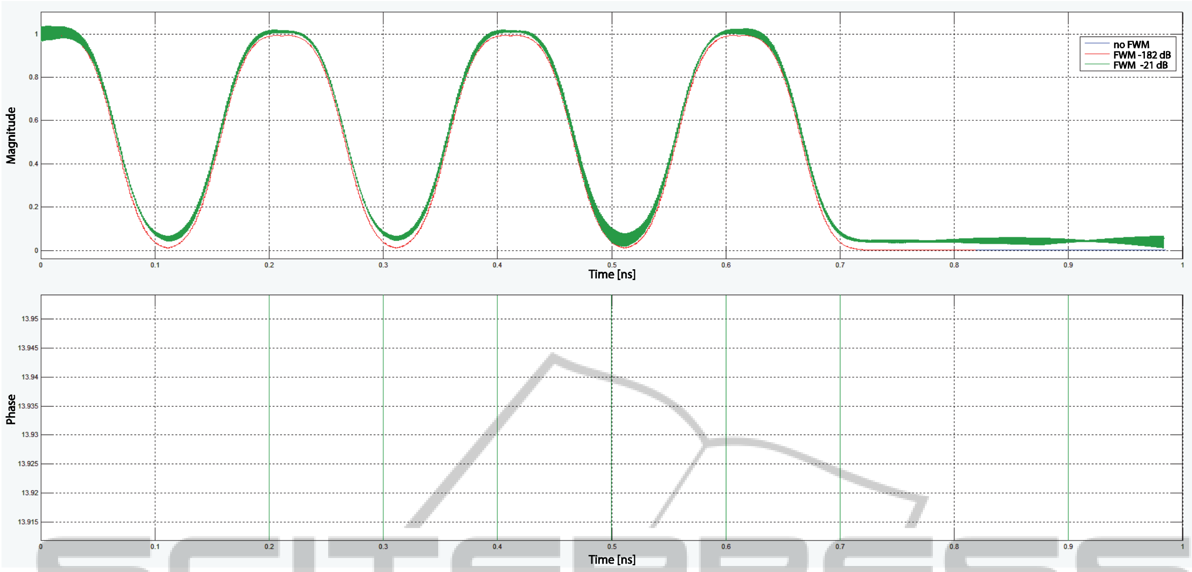

Figure 9: The FWM influence on a transmitted signal.

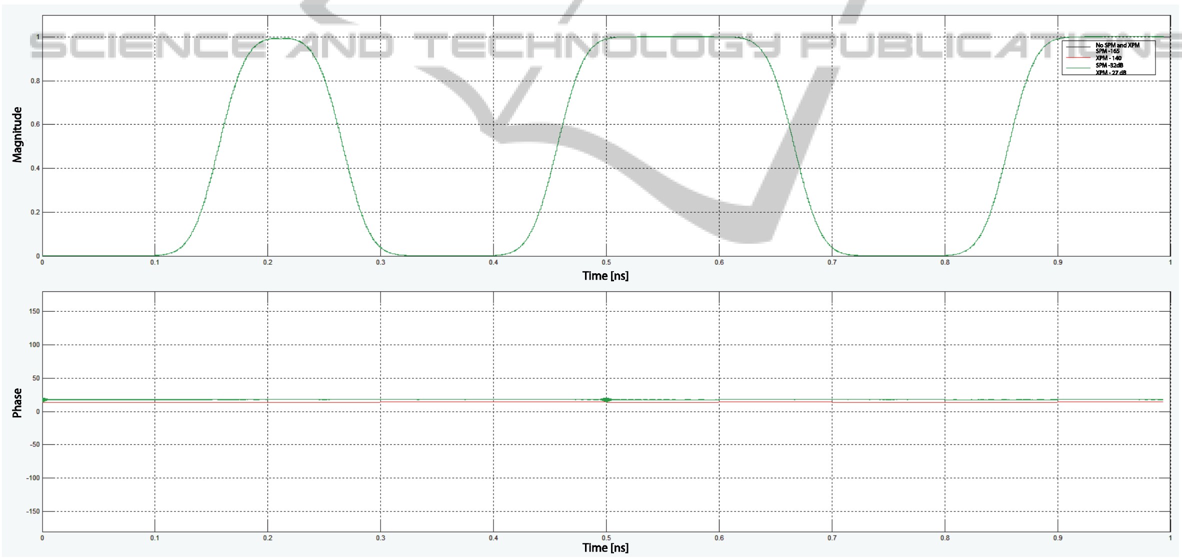

Figure 10: The SPM and XPM influences on a transmitted signal with the phase shift.

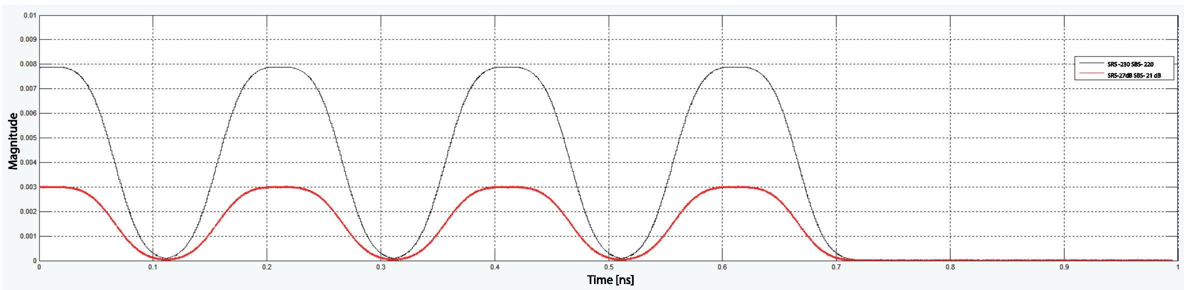

Figure 11: The SRS and SBS influences on a transmitted signal with the generated noise.

noncoherent OOK modulated signal using 80 channels. The optical path_2 consists of 170,7 km standard SM (ITU-T G.652) fiber with 10 Gb/s noncoherent OOK modulated signal using 80 channels. We examine the transmitted signal with the frequency 193,4 THz. The path_1 is using only one the erbium doped fiber amplifier EDFA at the fiber end, while the path_2 is using additional 3 EDFA amplifiers every 40 km. The simulation model for the path_1 is shown in fig.12 and the simulation model for the path_2 is shown in fig 13.

For describing the signal transmission in the optical transmission medium, we can calculate a bit error rate parameter BER. The BER calculation for each simulation model is done by comparing input and output bits. The simulation results for the optical path_1 and optical path_2 shows the BER parameter higher than 10^{-12} satisfying the transmission condition. Both simulation models use the Reed-Solomon Coding RS (255.239) that can enhance the system BER parameter.

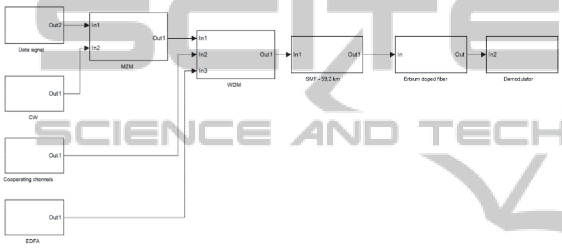

Figure 12: The optical path_1 simulation model.

Table 1: The comparison of the optical path_1 parameters.

Parameters	Measured	Simulated
Rx power (dBm)	-13,2	-13,4
OSNR	25,9	24,3
PMD (ps)	1,06	1,25
SPM (dB)	0,87	1,22
XPM (dB)	-57,59	-60,5
FWM (dB)	N/A	-124,3
Q	7,99	8,1
BER	$>10^{-15}$	$>10^{-12}$

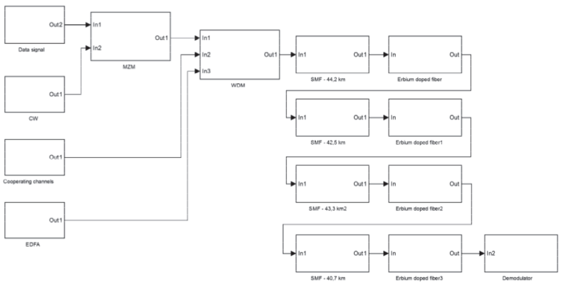

Figure 13: The optical path_2 simulation model.

Table 2: The comparison of the optical path_2 parameters.

Parameters	Measured	Simulated
Rx power (dBm)	-13,69	-12,3
OSNR	21,07	20,9
PMD (ps)	1,74	1,83
SPM (dB)	1,03	1,1
XPM (dB)	-42,02	-40,5
FWM (dB)	N/A	-112
Q	6,27	6,2
BER	$>10^{-15}$	$>10^{-12}$

4 CONCLUSIONS

This contribution analyses linear and nonlinear effects in the optical transmission medium. Using created specific blocks in the Matlab Simulink, we can simulate the influence of each optical fiber effects on transmitted signals utilizing WDM optical systems. We present results of the simulation for the noncoherent OOK modulation signal transmission in two different optical paths. Finally, we compare analyzed results acquired from created simulation models with measured parameters from the real optical transmission paths.

5 FUTURE WORK

In future analysis, we can design a new combination of high-bit rate coherent modulation formats, such as QPSK, 8PSK, 16QAM and FSK, with different encoding techniques, such as BCH, LDPC, for analyzing and implementing in any optical transmission systems.

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