Mitigation of Fiber Nonlinear Effects in 1.28 Tbps DQPSK Modulated DWDM System

Tomáš Huszaník, Ján Turán, Ľuboš Ovseník

***Abstract*—The main limitation factor of high capacity multichannel DWDM (Dense Wavelength Division Multiplexing) systems are fiber nonlinear effects. The optical signal is severely degraded due to fiber nonlinear effects also known as Kerr fiber nonlinearity. Nonlinear effects under investigation are self-phase modulation (SPM) and cross-phase modulation (XPM). There are several methods to compensate these nonlinear distorts, some less or more effective. Nonlinear distort due to SPM and XPM can be effectively mitigated through implementation of optical DQPSK modulation over commonly used intensity modulation known as OOK (On-Off Keying). This paper presents a numerical simulation model of 1.28 Tbps DWDM system with optical DQPSK modulation. We present several scenarios and methods to mitigate fiber nonlinear effects including Fractional Fourier Transform (FrFT). Linear and nonlinear effects are considered together, so we implement the inline FrFT module in the optical domain which causes a time-frequency plane rotation to mitigate combined linear and nonlinear effects. The performance of proposed 1.28 Tbps DQPSK modulated DWDM system is evaluated in term of bit error rate (BER) and Q factor value.**

***Index Terms*—chromatic dispersion, DQPSK, DWDM, FrFT, nonlinear effects.**

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I. Introduction

THE exponential increase in transmission capacity triggered the era of fast and reliable data transfer techniques through fiber optical networks. This has led to the exploration of new options in the field of spectrally efficient systems suitable for extremely high data rates. Consequently, there is a gradual transition from existing systems with a 10 Gbps transmission rate to 40 Gbps optical transmission systems. However, with the increase in network transmission capacity, the demand for optical signal performance is also increased to ensure acceptable bit error rate (BER) in the receiver. Increasing transmission power, however, leads to distortion of the transmitted signal due to the non-linear Kerr effect or interference between adjacent channels. These are the main limitations that set the upper limit of the maximum effective SNR (signal to noise ratio) of the optical link and limit the performance of the entire system. On the other hand, linear effects, such as chromatic dispersion (CD), spontaneous photon emission, fiber optic loss, or channel overlapping through long stretches of fiber are also important factors when designing the DWDM system. Despite the relatively reliable and efficient modulation formats (intensity modulation), the spectral efficiency of the DWDM system is heavily influenced by linear and nonlinear effects such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM). Nonlinear effects affect not only the backbone networks but also access fiber optic networks and their capacity and transmission range itself. In designing high-speed multi-channel optical transmission, therefore, the impact of linear and nonlinear transmission degrading phenomena has required a great deal of attention from research teams. The influence of nonlinear effects such as XPM and FWM can be controlled in conventional optical communication systems by residual local optical fiber dispersion or by setting the channel spacing to a sufficiently large value. The chromatic dispersion, as a linear effect, can be effectively compensated either periodically along the fiber or on the receiver side [1]-[3].

The current generation of fiber optical networks relies mainly on basic optical modulation techniques such as NRZ-OOK or optical phase modulation (OPM). However, with the increasing transmission rates and capacity basic modulation formats are no more suitable for such transmission. From the study of nonlinear effects, it has been found that the generation of nonlinear effects SPM, XPM and FWM can be minimized if the transmitted signal has some special characteristics. A narrow bandwidth modulation format can increase spectral efficiency and chromatic dispersion resistance. Conversely, the modulation format with constant optical performance may be less prone to SPM and XPM. A multilevel modulation format can capture more information than a binary signal, and thanks to the longer symbol duration, reduce degradation due to chromatic and polarization dispersion. In addition, long-haul transmission is an important factor influencing the occurrence of nonlinear phenomena, as well as the amplification of the optical signal often performed by an erbium doped fiber amplifier (EDFA) or semiconductor optical amplifier (SOA), which also introduces noise into the system and under certain circumstances (the length of doped fiber, the degree of amplification) the nonlinear SPM and XPM effects can build up in the optical fiber. The main difference between doped fiber amplifier and semiconductor one is the in the energy delivery, as in the case of EDFA a laser pump is used. For SOA, the power is supplied by an electric excitation field.

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T. Huszaník, J. Turán and Ľ. Ovseník are with the Faculty of Electrical Engineering and Informatics, Technical University of Košice, Košice, Slovakia (email: tomas.huszanik@tuke.sk, jan.turan@tuke.sk, lubos.ovsenik@tuke.sk).

The principle of amplifying light is based on the recombination of electrons and holes at the p-n transition. SOAs are produced as chips that are placed in a closed housing capable of maintaining a constant temperature. Therefore, via advanced optical modulation formats and optimization of fiber optical transmission path we can mitigate fiber nonlinear effects [2], [3].

In this paper we present the structure of DWDM system with 32 wavelength channels and capacity of 1.28 Tbps (40 Gbps per channel). Each channel is DQPSK (Differential Quadrature Phase Shift Keying) modulated. Using the simulation tool OptiSystem™ we investigate the nonlinear effects in proposed 1.28 Tbps DQPSK modulated DWDM system. We present several ways to mitigate fiber nonlinear effects in high capacity DWDM system including Fractional Fourier Transform (FrFT) which will be further described in this paper.

The structure of the paper is organized as follows: in the second chapter we discuss related works, the third chapter is dedicated to the brief overview of FrFT and its implementation to the optical DQPSK transmitter, the fourth chapter include the description of mathematical simulation model of DWDM system, followed by results analysis and discussion in the chapter five.

II. Related Works

Several researchers have contributed their effort to investigate the influence of fiber nonlinear effects on signal transmission in high speed DWDM networks. Sajgalikova et al. compared the different numerical modeling of optical degradation mechanisms in [4]. The fiber nonlinear effects were also investigated by Karar [5]. The self-phase modulations dependence on chromatic dispersion was investigated by Ivaniga et al. [6]. He proved SPM influence in DWDM system with AWG multiplexer and demultiplexer. Zhang et al. [7] studied the impact of fiber nonlinearity on PMD (Polarization Mode Dispersion) penalty in DWDM systems back in 2005. They determined the PMD-induced Q factor penalty in 80 channel DWDM system with transmission rate of 10.67 Gbps. Nain et al. provides the mathematical description of nonlinear Kerr effects in [8]. He also provides the experimental results of SPM, XPM and FWM at 5 Gbps and 10 Gbps over 100 km transmission distance. In [9], Ivaniga et al. performed the simulation of 8 and 16 channel DWDM system. They simulated the two scenarios in which the transmission power was increased. The main contribution of that paper was the monitoring of SPM under two different coding methods – NRZ (Non-Return to Zero) and Miller coding. The influence of FWM in DWDM system with AWG with NRZ and BRZ (Bipolar Return to Zero) was investigated by Ivaniga et al. [10]. Authors put their effort into investigation of FWM influence on Ultra-DWDM system (with channel spacing of 12.5 GHz). Authors of this manuscript published the paper [11] in which they propose a 40 Gbps 16 channel DWDM system with 2-DPSK (Differential Phase Shift Keying) modulation and counter directional EDFA. Authors estimate the optimal parameters of counter directional EDFA such as the optimal length of erbium doped fiber, pump power and pump central wavelength. Lavrinovica et al. [12] also estimated EDFA performance in 40 Gbps DWDM system. Since nonlinear effects, most significantly SPM, are chromatic dispersion dependent, several authors contributed to this area. Spolitis et al. compared several passive chromatic dispersion compensation techniques in 16 channel DWDM in [13]. The study of fiber nonlinear effects controlled by different optical modulation formats in 10 Gbps DWDM systems are provided in [14] by Huszaník et al. The same authors also contributed on investigation of optical IQ modulation in 4 channel DWDM system with the presence of optical fiber nonlinearities [15]. Authors provide comparative analysis of three possible configurations of optical IQ modulator and evaluate its performance in high spectral DWDM system. Optical QPSK was also investigated by Fady El-Nahal [16]. Optical modulation formats for DWDM systems were intensively studied by Kahn [17], Kaur [18], Jawla [19] and Faisal [20]. In 2014, Mohaparta et al. [21] studied digital modulation formats within and beyond 400 Gbps in both DWDM and CWDM (Coarse Wavelength Division Multiplexing). In this paper, authors team, describe the influence of bit rate on different digital modulations.

III. Overview of Fractional Fourier Transform in fiber optical networks

The main limitation factors of current long-haul fiber optical communication networks are nonlinear effects and chromatic dispersion. Nonlinear effects, especially SPM, are in a very close relationship to CD. The combined effect of CD and Kerr nonlinear effects correspond to time-frequency distortion of transmitted optical pulses. CD affects the amplitude and the width of the optical spectra of transmitted optical pulse. Nonlinear effects such as SPM and XPM do not have influence on the pulse envelope. This contribution of CD and nonlinear effects result in the time-frequency distortion. The correction of transmission affected by time-frequency distortion can be done by introducing a transformation that corrects the time-frequency rotation. This correction can be done by utilizing Fractional Fourier Transform (FrFT) [22]-[23].

FrFT is based on conventional Fourier transform. Fourier transform (FT) is widely used in various fields. It enables to transform signal from time domain to frequency domain. The concept of conventional Fourier transform is very well known. The functions *f* and *F* are Fourier transform pair if [22]:

$$f(x) = \int_{-\infty}^{\infty} F(v)e^{(i2\pi vx)}dv, \quad (1)$$

$$F(v) = \int_{-\infty}^{\infty} f(x)e^{(-i2\pi vx)}dx. \quad (2)$$

The fractional Fourier transform is the general form of conventional Fourier transform. Fractional Fourier transform can be defined as [22]:

$$X_\phi(u) = \int_{-\infty}^{\infty} x(t)K_\phi(t,u)dt, \quad (3)$$

$$X_\phi(u) = \sqrt{\frac{1 - j\cot\phi}{2\pi}} \cdot \exp\left(j\frac{u^2}{2}\cot\phi\right) \int_{-\infty}^{\infty} x(t)\exp\left(j\frac{t^2}{2}\cot\phi - jut\csc\phi\right) dt. \quad (4)$$

In the equation (4), $\phi=p(\pi/2)$, p is the order of FrFT. If $\phi=\pi/2$, FrFT corresponds to the conventional FT. FrFT with parameter ϕ can be seen as an angle of rotation in the time-frequency plane (Fig. 1) [22]-[23].

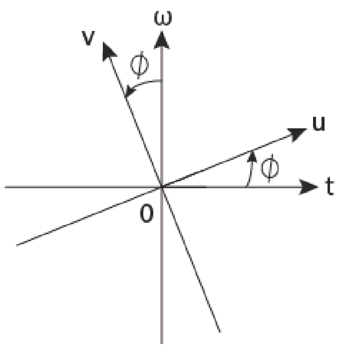

Fig. 1. Time-frequency plane rotation

So, the FrFT is performed as a rotation operation on the time frequency distribution. If the rotation is $\phi=0$, there will be no change when applying FrFT and $\phi=\pi/2$ equals to FT [23].

The FrFT module consists of two optical phase modulators and a dispersive optical medium as shown on Fig. 2. The two optical phase modulators are driven by periodic parabolic electric signal and the dispersive medium (optical fiber) which can act like a filter which performs an approximated operation of convolution [22], [23].

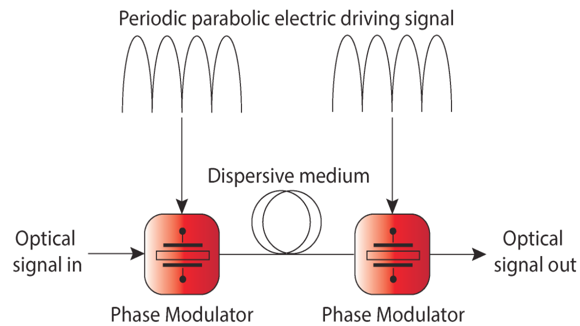

Fig. 2. The structure of FrFT module

IV. Description of Proposed Simulation Model

The simulation model of 1.28 Tbps DQPSK modulated DWDM system was created within the OptiSystem™ environment. OptiSystem™ is an innovative software package for simulating optical communication systems. It enables to design, test and optimize virtually any type of optical connection in the physical layer of a wide range of optical networks, from analogue video transmission to intercontinental bone fiber optical networks. The simulation is based on Time-Domain Split-Step method (TDSS).

The block scheme of a simulation model is shown on Fig. 3. It consists of three parts: transmitting section, optical fiber section and receiving section. The global parameters of a simulation model are: bit rate – 40 Gbps, time window – 6.4e-09, sample rate – 1.024e+13 Hz, sequence length – 256 bits.

Transmitting section is formed of 32 wavelength channels placed in C-band in the range of (193.0 – 196.1) THz with the

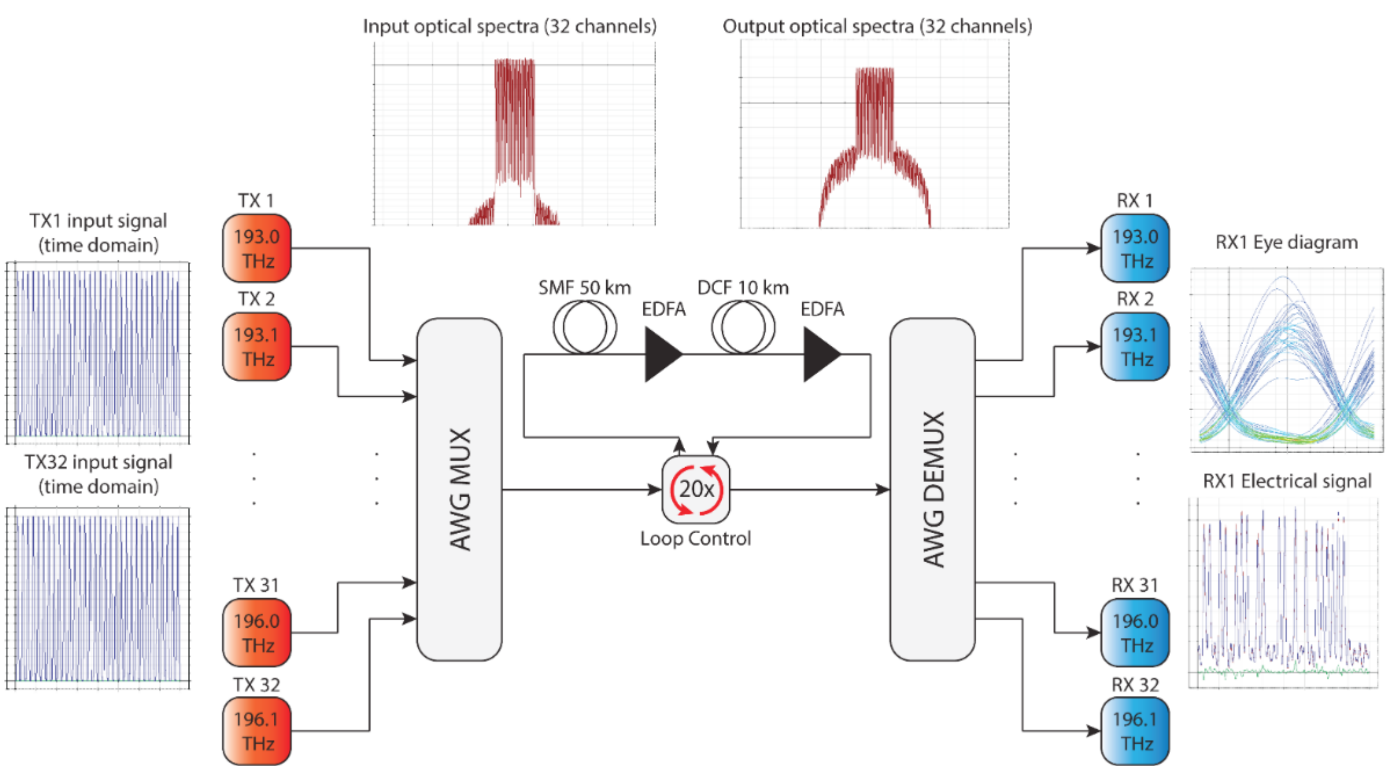

Fig. 3. Simulation model of 1.28 Tbps DQPSK modulated DWDM system

channel spacing of 100 GHz. Each transmitter utilizes optical DQPSK modulator with 40 Gbps bit rate. The block scheme of optical transmitter with DQPSK modulator is on Fig. 4. Optical DQPSK modulator is formed of pseudorandom binary sequence (PRBS) generator generaring pseudorandom bit sequence with 40 Gbps bit rate (per channel). Data are then precoder by 4-DPSK (Differential Phase Shift Keying) precoder and then electrically modulated via NRZ modulator drivers. NRZ signal is then modulated by two $LiNbO_3$ Mach-Zehnder (MZ) modulators. In one of the arms, there is an optical phase shifter to create orthogonal signal to the other arm of the modulator structure and thus create I (In phase) and Q (Quadrature) signal component. Optical carrier is generated by continuous wave (CW) laser.

The induced phase difference between two arms of the IQ modulator is expressed by following equation:

$$\Delta\varphi_I(t) = \frac{u_I(t)}{V_\pi}\pi \cdot \Delta\varphi_Q(t) = \frac{u_I(t)}{V_\pi}\pi, \tag{5}$$

where $\Delta\varphi_I(t)$ and $\Delta\varphi_Q(t)$ are phases of I and Q arms, $u_I(t)$ is the voltage applied on the arms of $LiNbO_3$ MZ modulators and V_π is the driving amplitude for switching bias voltage. The transfer function of an IQ (DQPSK) modulator is:

$$\frac{E_{out}(t)}{E_{in}(t)} = \frac{1}{2}cos\left(\frac{\Delta\varphi_I(t)}{2}\right) + j\frac{1}{2}cos\left(\frac{\Delta\varphi_Q(t)}{2}\right). \tag{6}$$

Then, the amplitude modulation $A_{IQM}(t)$ (3) and phase modulation $\varphi_{IQM}(t)$ (4) of DQPSK modulator is:

$$A_{IQM}(t) = \left|\frac{E_{out}(t)}{E_{in}(t)}\right| = \frac{1}{2}\sqrt{cos^2\left(\frac{u_I(t)}{V_\pi}\pi\right) + cos^2\left(\frac{u_Q(t)}{V_\pi}\pi\right)}, \tag{7}$$

$$\varphi_{IQM}(t) = arg\left[cos^2\left(\frac{u_I(t)}{V_\pi}\pi\right) \cdot cos^2\left(\frac{u_Q(t)}{V_\pi}\pi\right)\right]. \tag{8}$$

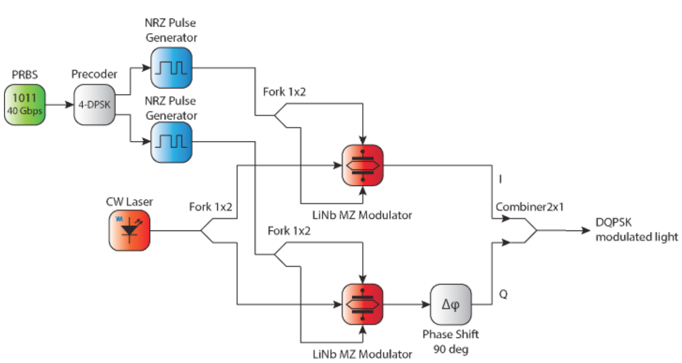

Fig. 4. The block model of optical DQPSK transmitter

The structure of optical DQPSK transmitter is modified with FrFT module to mitigate the influence of fiber nonlinear effects. In general, the FrFT module consists of two optical phase modulators driven by periodic parabolic electric signal and dispersive medium. However, OptiSystem™ does not allow to use an arbitrary waveform generator for generating periodic parabolic electric signal. To produce periodic parabolic signal, we used the sine pulse generator with the binary NOT and binary OR components. PRBS generates the stream of binary ones and zeros, which does not produce periodic parabolic signal by connecting the sine pulse generator. However, by using binary NOT and binary OR components as shown on Fig. 5, the sine pulse generator is driven by binary ones only so the periodic parabolic signal can be produced. The dispersive medium (SMF) is 0.1 km long. All 32 wavelength channels are multiplexed by AWG (Arrayed Waveguide Grating) multiplexer and then transmitted through the optical fiber section. The insertion loss of an AWG is 5.5 dB.

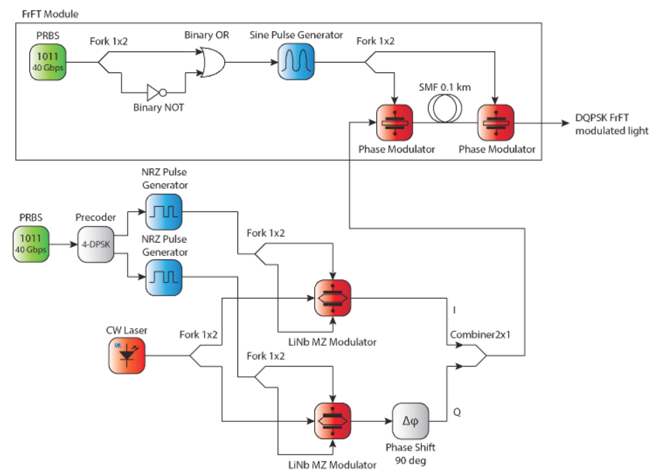

Fig. 5. The block model of optical DQPSK transmitter with FrFT

Optical distribution path (seen on Fig. 3) is formed of a loop component with number of loops 20. Each loop consists of 50 km of highly nonlinear optical fiber (HNLF), two in-line erbium doped fiber amplifiers (EDFAs) and dispersion compensation fiber (DCF). An SMF has attenuation of 0.22 dB/km, chromatic dispersion is set to 17 ps/km-nm^2, nonlinear refractive index is n_2 = 2.6e-20 m^2/W and effective cross section area of the fiber is A_{eff} = 80 μm^2. Induced chromatic dispersion is fully compensated in dispersion compensation fiber. DCF is an optical fiber that has opposite value of dispersion to the main transmission fiber, in this case, the value of chromatic dispersion of DCF is -80 ps/km-nm^2, n_2 is 2.6e-20 m^2/W and A_{eff} is 30 μm^2. The length of DCF is 10 km. In each loop, there are two EDFAs. The first one, in-line EDFA having the noise figure of 6 dB and output power 20 dB is used to compensate the power loss of the SMF. The second EDFA is used to compensate the power loss of DCF and its output power is 5 dB and noise figure is 6 dB.

The signal is demultiplexed using AWG demultiplexer. The block scheme of optical DQPSK receiver is illustrated on Fig. 6. The receiver is formed of one-bit delay line with double balanced photodiode. Data are precoded differentially at the transmitter. That means, that at the receiver side, we can compare and restore the phase of current transmitted symbol with the phase of previously transmitted symbol. The phase difference between current and previous symbol may be 0, π/2, -π/2 or π. The signals detected by two photodiodes (I and Q) are multiplied and regenerated. Receiver sensitivity is -30 dBm.

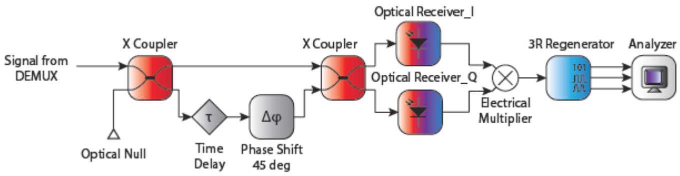

Fig. 6. The block model of optical DQPSK receiver

The received signal is analyzed in electrical domain and compared to the originally transmitted signal. Analyzer component is used to generate the eye diagram. From the eye diagram we extract bit error rate (BER) and Q factor. The calculation of BER and Q factor is based upon these equations [2]:

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}, \tag{9}$$

In the equation (9), I_1 is the mean value and σ_1 is the deviation of the pulse 1, I_0 is the mean value and σ_0 is the deviation of pulse 0. The relationship between the BER and the Q factor itself can be determined by a linear combination of probabilities that the receiver is decrypting the incorrect symbol [2]:

$$BER = \frac{1}{2}[P(1|0) + P(0|1)], \tag{10}$$

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{1}{\sqrt{2\pi}Q} exp\left(-\frac{Q^2}{2}\right). \tag{11}$$

V. Simulation Results and Discussion

The proposed simulation model of 1.28 Tbps DQPSK modulated DWDM system is evaluated in three different scenarios. In all scenarios we consider the fiber nonlinear effects. The objective is to investigate the impact of intensity fluctuations of channel 1 (193.0 THz) on the phase of the signal in channel 2 (193.1 THz). In all simulation scenarios we consider the case without nonlinear effects and chromatic dispersion, the case with nonlinear effects and chromatic dispersion and the case in which we add FrFT module to the DQPSK modulator structure while considering nonlinear effects and chromatic dispersion.

A. Scenario 1

In the first scenario, we set the simulation model to 20 loops. Each loop consists of 50 km of SMF and 10 km of DCF. The performance of the DWDM system is evaluated independently in each loop. The aim of this scenario is to evaluate the influence of fiber nonlinear effects depending on the transmission distance. Fig. 7 shows the optical spectra of 32 wavelength channels transmitted on 250 km and 500 km. Chromatic dispersion cumulated by transmission through the SMF is compensated at the end of each loop by dispersion compensation fiber. From the given spectra we can see that the impact of FWM is weak and thus is neglected. However, the influence of SPM and XPM due to chromatic dispersion is considerably higher. The signal spectra distort as the transmission distance is increased. It is caused due to the in-line amplification. The contribution of SPM and XPM is increasing after each loop. As a consequence, the quality of the received signal, measured by BER and Q factor, is decreasing at each loop.

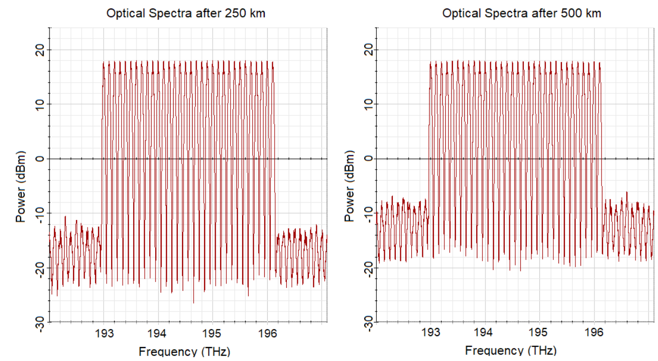

Fig. 7. Optical signal spectra after 250 km and 500 km

Fig. 8 shows the eye diagrams of received signals distorted by nonlinear effects after 550 km and 800 km. The BER values are 3.26e-12 at 550 km and 1.37e-06 at 800 km. In general, the minimum required value of BER is 1e-10. When we do not take nonlinear effects on account, the maximum reach of the proposed DWDM system is over 1000 km. However, due to nonlinear effects the reach is reduced almost by half – 600 km with nonlinear effects and 750 km with nonlinear effects with FrFT module DQPSK transmitter.

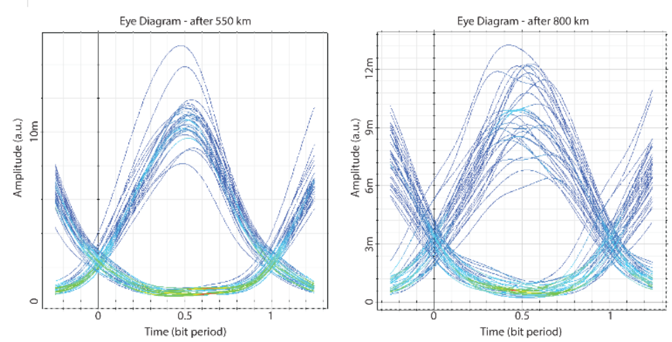

Fig. 8. Eye diagrams of received signals after 550 km and 800 km

The dependence between optical fiber length and BER is illustrated on Fig. 9. There were three calculations made. The first calculation (blue line) does not take nonlinear effects into equation. Thus, the performance of the DWDM system is influenced only by linear effects – attenuation, chromatic dispersion and optical noise and induced by EDFAs. In the second calculation (red line) we consider nonlinear effects, while the nonlinear refractive index n_2 = 2.6e-20 m^2/W. The maximum acceptable reach is 600 km which is 400 km difference to the case without nonlinear effects. The reason of 400 km drop is the nonlinear interaction in SMF. The nonlinear interaction depends on the length and the cross-section area of the optical fiber. The influence of nonlinear effects increases, the longer the length of the fiber connection. However, as the signal spreads along the line, its performance decreases due to the fiber attenuation. So most nonlinear effects occur at the beginning of the optical path and gradually fade away as the signal propagates through the optical fiber. By utilizing FrFT into optical DQPSK modulator, there is a slight improvement in the performance and the transmission distance has been extended to 750 km (yellow line). Above the 750 km, the transmission quality is no more sufficient for today's standards.

Values of Q factor are provided in Table I. The threshold in Table I. is calculated from equation (11): for 1e-10 BER, the Q-factor is 6.36.

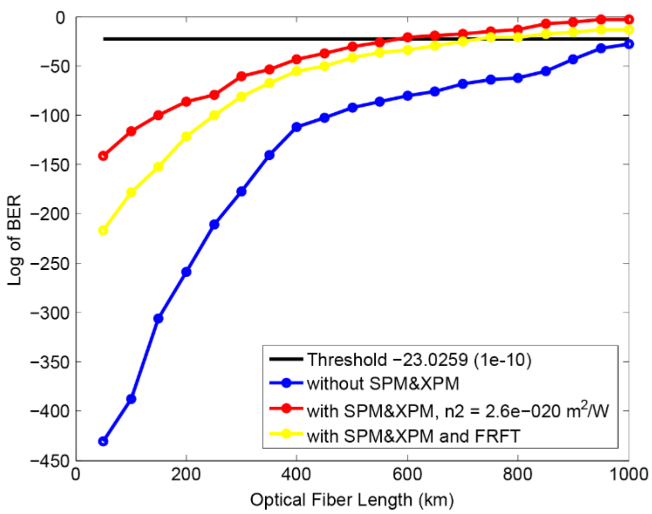

Fig. 9. System performance comparison of three different scenarios

TABLE I
VALUES OF Q FACTOR

Transmission distance (km)	Q factor		
	No SPM&XPM	With SPM&XPM	With SPM&XPM + FrFT
50	29.20	16.61	20.65
100	27.70	15.02	18.68
150	24.56	13.90	17.23
200	22.57	12.84	15.33
250	20.33	12.30	13.88
300	18.63	10.71	12.44
350	16.56	10.05	11.30
400	14.70	8.95	10.20
450	14.06	8.24	9.71
500	13.32	7.38	8.81
550	12.87	6.87	8.23
600	12.37	6.03	7.85
650	12.02	5.78	7.26
700	11.41	5.46	6.76
750	11.05	4.92	6.08
800	10.82	4.69	5.98
850	10.24	3.32	5.41
900	8.97	2.80	5.12
950	7.68	1.54	4.72
1000	7.06	1.54	4.73
Threshold		6.36	

B. Scenario 2

A common way to avoid the creation of fiber nonlinear effects is to keep launch powers low. The main goal is to keep propagation linear. Kerr nonlinear effects, SPM and XPM, are power sensitive. The phase shift difference due to SPM, when propagating single channel over optical fiber is [1]:

$$\Delta\varphi = -2\pi n_1 \frac{L}{\lambda A} P, \tag{12}$$

where n_1 is fiber core refractive index, L is the length of the optical fiber, A is the cross-section area of the optical fiber, λ is the wavelength of transmitted signal and P is the power of transmitted signal. SPM and XPM are very similar depending on the refractive index of the optical fiber from the optical signal intensity. However, for XPM, the total phase shift of the transmitted optical pulse in one channel is affected by the properties of the adjacent channels. The refractive index of the optical fiber is also determined by the total intensity of all transmitted channels. Cross-phase modulation actually causes fluctuations in power at a certain wavelength to phase fluctuations at other channels. The result of XPM may be an excessive displacement of the spectral line and the impulse shape deformation. So, in 32 channel DWDM system is the phase shift of the i-channel through the XPM expressed by following equation [1]:

$$\phi_{nl}^{i} = k_{nl} L_e \left(P_i + 2 \sum_{n=i+1}^{32} P_n \right). \tag{13}$$

In the equation (13), k_{nl} is the nonlinear propagation coefficient, L_e is the effective length of the fiber and P is the power. The first part of the equation (13) represents the contribution of the SPM and the second part the contribution of the XPM. The second part of equation (13) also expresses the non-linear sensitivity, and indicates that XPM is two times more efficient than the SPM at given energy.

To evaluate the influence of the launch power on the nonlinear effects, we swept the output power of CW laser of each channel in the range of -10 – 12 dBm. To mitigate nonlinear effects, the launch power must be low. However, it is impractical for long-haul links. With higher launch levels we can transmit further and the detection is more efficient. To fully evaluate the launch power dependence on nonlinear effects we opted for 550 km long transmission (11 loops). Fig. 10 shows the eye diagrams of received signals after 550 km with 10 dBm launch power. BER of received channel is 3.76e-81 without consideration of nonlinear effects and 1.67e-07 with nonlinear effects.

For low launch levels (-10 – 0 dBm) we get BER values above the threshold for all three cases. The signal is not well detectable for the receiver. The lowest possible launch level, for

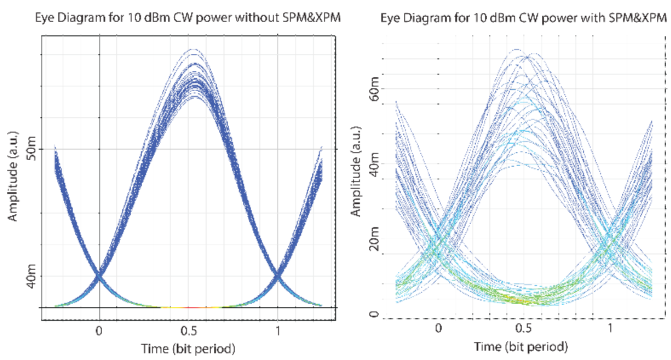

Fig. 10. Eye diagrams of received signals for 10 dBm CW power without and with nonlinear effects

which the performance of the proposed DWDM is acceptable is -3 dBm. In the case without nonlinear effects, BER values increase as the launch power increases. However, SPM and XPM cause severe signal distortion as the launch power increases. This distortion is cause primarily due to phase interaction between adjacent channels induced by XPM. The optimal launch power of the case with nonlinear effects is 5 dBm according to this experiment. The BER in this case is 5.37e-20. As we increase launch power even further, the effect of SPM and XPM increases. The slight correction of the transmission affected by phase shift caused by SPM and XPM and time-frequency distortion respectively can be mitigated by utilization of FrFT. We can see slight improvement of BER in this case – BER 8.51e-22 for 5dBm. Values of calculated Q factor are in Table II.

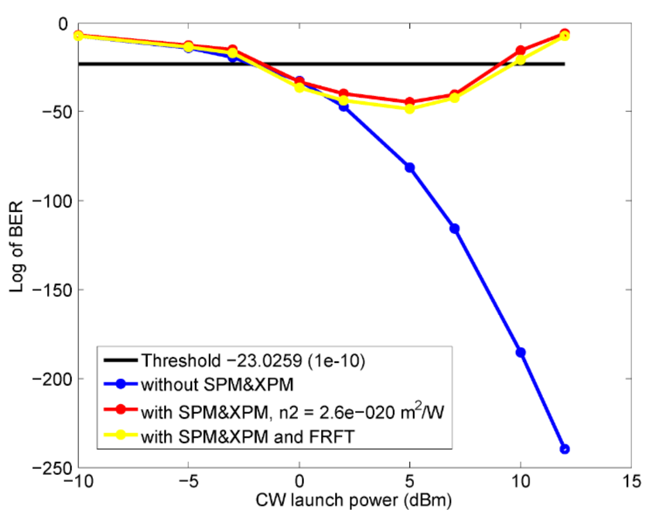

Fig. 11. CW launch power sweep vs BER of three different scenarios

C. Scenario 3

Since SPM occurs in a close association with chromatic dispersion, it is important to take SPM into account in high-speed systems which are particularly limited in chromatic dispersion. In systems with a transmission rate above 10 Gbps and in systems with high power SPM significantly increases the effects of chromatic dispersion, i.e. overlapping of the transmitted optical pulses. Deployment of appropriate dispersion compensating

TABLE II
VALUES OF Q FACTOR FOR DIFFERENT VALUES OF CW LAUNCH POWER

CW Launch power (dBm)	Q factor		
	No SPM&XPM	With SPM&X-PM	With SPM&X-PM + FrFT
-10	3.16	3.10	3,27
-5	4.78	4.47	4.66
-3	5.75	5.03	5.38
0	7.68	7.76	8.17
2	9.35	8.55	9.00
5	12.48	9.08	9.52
7	14.97	8.63	8.85
10	19.04	5.10	5.98
12	21.70	2.74	3.28
Threshold		6.36	

modules in the fiber link limits the signal degradation. In the third scenario we present the way of mitigating nonlinear effects through the chromatic dispersion compensation. There are three possible configurations of DCF compensation technique shown on Fig. 12.

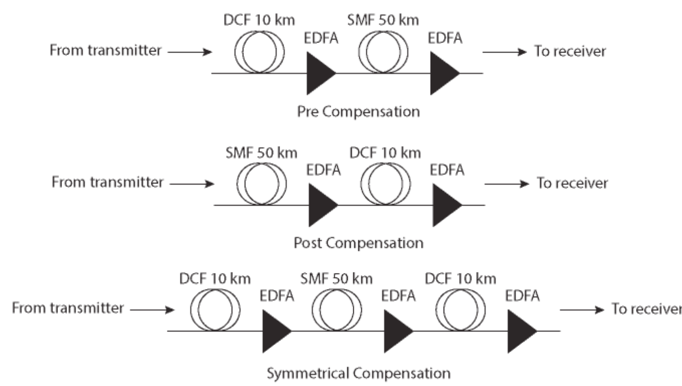

Fig. 12. Schematic of three simulation setups

To simplify calculations, we do not consider nonlinear effects in DCF, since its length is shorter and its nonlinear contribution will be negligible. The nonlinear effects and the resulting distortions occur only in SMF. The simulation setup of this scenario is: length of transmission path – 550 km (11 loops), CW launch power 5 dBm. The most effective DCF compensation techniques are post-compensation and symmetrical compensation. The BER of the DWDM system without CD compensation is above the threshold (-23.0259 / 1e-10). The values of BER and Q factor for different DCF configurations are provided in Table III.

VI. CONCLUSION

This paper successfully demonstrates the 1.28 Tbps DQPSK modulated DWDM system in the presence of optical fiber nonlinearities. Using the OptiSystem™ the simulation model has been established to estimate the transmission performance of the proposed system in relation to mitigation of fiber nonlinear

TABLE III
VALUES OF Q FACTOR AND BER FOR DIFFERENT CD COMPENSATION TECHNIQUES

DCF setup	550 km, CW power – 5 dBm	
	Q factor	BER
No compensation	5.58	1.02e-09
Pre-compensation	7.81	8.25e-15
Post-compensation	9.04	5.37e-20
Symmetrical compensation	9.30	4.56e-21

effects. We show that spectrally efficient DQPSK modulated optical signal is robust against the nonlinear effects such as SPM and XPM and linear effect of chromatic dispersion. The higher capacity can be achieved by utilization of optical DQPSK modulation format but the influence of nonlinear effects is still not negligible. The maximum reach of DWDM is limited by nonlinear effects and the power must be kept low enough no to generate nonlinearities. FrFT has been applied on the tested channel in all cases and it is noted that there are improvements in the performance. Nonlinear effects can be mitigated by utilization of FrFT to the optical transmitter. The right choice of launch power along with CD compensation technique can significantly reduce the nonlinear distort due to SPM and XPM.

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REFERENCES

[1] R. Ramaswami, K. N. Sivarajan, G. H. Sasaki. *Optical Networks*, 2010. 928p. ISBN 978-0-12-374092-2.

[2] J. M. Simmons, *Optical Network Design and Planning*, 2014, 529 p. ISSN: 1935-3847, DOI: 10.1007/978-3-319-05227-4.

[3] S. P. Singh and N. Singh, "Nonlinear Effects in Optical Fibers: Origin, Management and Applications," *Progress In Electromagnetics Research*, vol. 73, pp. 249-275, 2007. DOI:10.2528/PIER07040201.

[4] J. Sajgalikova, M. Dado, J. Litvik, "Comparison of Numerical Modelling of Degradation Mechanisms in Single Mode Optical Fibre Using MATLAB and VPIphotonics," *Advances in Electrical and Electronic Engineering,* vol. 13, no. 3, pp. 268-272, 2015. DOI: 10.15598/aeee.v13i3.1330.

[5] A. S. Karar, S. Gazor, Y. Gao, J. C. Cartledge, M. O'Sullivan, C. Laperle, A. Borowiec, K. Roberts, "Polynomial Pulses for Mitigating Fiber Nonlinearity in Coherent Optical Fiber Communications," in *IEEE Photonics Technology Letters*, vol. 27, no. 15, pp. 1653-1655, 2015. DOI: 10.1109/LPT.2015.2433834.

[6] T. Ivaniga, J. Turán, Ľ. Ovseník, "Verification of the SPM Impact in DWDM System Using AWG Multiplexer / Demultiplexer," *Acta Electrotechnica et Informatica*, Vol. 17, No. 1, 2017, 17–22, DOI:10.15546/aeei-2017-0003.

[7] G. Zhang, J. T. Stango, X. Zhang, X. Chongjin, "Impact of fiber nonlinearity on PMD penalty in DWDM transmission systems," *IEEE Photonics Technology Letters*, vol. 17, no. 2, pp. 501-503, 2005. DOI: 10.1109/LPT.2004.839010.

[8] H. Nain, U. Jadon, V. Mishra, "Performance investigation of Kerr effects on to WDM fiber optical networks," *IEEE International Conference on Recent Trends in Electronics, Information and Communication Technology*, 2016, pp. 2018-2022, DOI: 10.1109/RTEICT.2016.7808193.

[9] T. Ivaniga, Ľ. Ovseník, J. Turán, "Influence of self-phase modulation on 8 and 16-channel DWDM system with NRZ and miller coding," *Carpathian Journal of Electronic and Computer Engineering,* vol. 8, no. 1, pp. 17-22, 2015.

[10] P. Ivaniga, T. Ivaniga, J. Turán, Ľ. Ovseník, M. Márton, D. Solus, J. Oravec, T. Huszaník. "The Influence of FWM with AWG Multiplexor in DWDM System," *Przeglad Elektrotechniczny*, vol. 2018, no. 4, pp. 113-117, 2018. DOI:10.15199/48.2018.04.28.

[11] O. Kováč, J. Mihalík, I. Gladišová, "Convolution implementation with a novel approach of DGHM multiwavelet image transform," *Journal of Electrical Engineering*, vol.68, no.6, pp. 455-462, 2017. DOI: 10.1515/jee-2017-0080.

[12] I. Lavrinovica, J. Porins, G. Ivanovs, "Estimation of EDFA Performance in 40 Gbit/s 8 channel DWDM Transmission System," *PIERS Proceedings*, pp. 502-505, Prague, Czech Republic, 2015.

[13] V. Spolitis, V. Bobrovs, P. Gavars, G. Ivanovs, "Comparison of passive chromatic dispersion compensation techniques for long reach dense WDM-PON system," *Elektronika ir Elektrotechnika*, vol. 122, no. 6, pp. 65–70, 2012.

[14] O. Kováč, P. Lukács, I. Gladišová, "Textures classification based on DWT," *Proc. 28th Int. Conf. Radioelektronika, RADIOELEKTRONIKA 2018*, Prague; Czech Republic; 19-20 April 2018; pp. 1-5. DOI: 10.1109/RADIOELEK.2018.8376379.

[15] T. Huszaník, J. Turán, Ľ. Ovseník, "Comparative analysis of optical IQ modulation in four-channel DWDM system in the presence of fiber nonlinearities," *Proceedings of the 2018 19th International Carpathian Control Conference, ICCC 2018*, pp. 468-473, 2018. DOI:10.1109/CarpathianCC.2018.8399675.

[16] Fady El-Nahal, "Coherent Quadrature Phase Shift Keying (QPSK) Optical Communication Systems", *Optoelectronics letters*, Vol. 14, No. 5, pp: 372-375, 2018.

[17] J. Kahn, K. P. Ho. "Spectral Efficiency Limits and Modulation/Detection Techniques for DWDM Systems," *IEEE. Journal of Selected Topics in Quantum Electronics*, vol. 10, no. 2, pp. 259-272, 2004. ISSN: 1558-4542. DOI: 10.1109/JSTQE.2004.826575.

[18] A. Kaur, S. Dewra. "Comparative Analysis of Different Modulation Techniques in Coherent Optical Communication System," *International Journal of Innovative Research in Computer and Communication Engineering,* vol. 3, issue 8, pp. 7193 – 7200, August 2015. ISSN: 2320-9801.

[19] S. Jawla, R. K. Singh. "Different Modulation Formats Used In Optical Communication System," *IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)*, vol. 8, no. 4, pp. 15-18, 2013. e-ISSN: 2278-2834, p-ISSN: 2278-8735.

[20] M. Faisal, T. Faruque, M. A. R. Khan, "Post mitigation performance comparison of RZ-DPSK and CSRZ-DPSK DWDM systems," *8th International Conference on Electrical and Computer Engineering*, Dhaka, pp. 433-436, 2014. DOI: 10.1109/ICECE.2014.7026971.

[21] S. K. Mohapatra, R. R. Choudhury, R. Bhojray, P. Das. "Performance analysis and monitoring of various advanced digital modulation and multiplexing techniques of F.O.C within and beyond 400 GB/s," *International Journal of Computer Networks & Communications (IJCNC)*, vol.6, no.2, pp. 159 – 181, India, 2014. ISSN: 0974-9322.

[22] B. T. Krishna, "Fractional Fourier transform: a survey," *Proceedings of the International Conference on Advances in Computing, Communications and Informatics (ICACCI '12)*, Chennai, India, 2012, pp. 751-757. DOI: http://dx.doi.org/10.1145/2345396.234551.

[23] A. Yang, L. Xiang, X. Chen, "A FrFT based method for measuring chromatic dispersion and SPM in optical fibers," *Optical Fiber Technology,* vol. 34, pp. 59-64, 2017. DOI: 10.1016/j.yofte.2017.01.002.