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Investigation of Differently Modulated Optical Signals Transmission in HDWDM Systems

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Abstract: The authors' developed combined system model can be considered under the concept of next generation optical network (NGON) as a model for the future design of backbone networks. Such solution can be topical in the result of different telecom operators' optical networks convergence. In this case a necessity to transmit differently modulated signals over a single optical fiber even with different bit rates may occur. This research is performed with OptSim 5.2 simulation software that numerically solves nonlinear Schrödinger equation. The authors have revealed the optimal parameter configuration for developed combined transmission systems and obtained in system's channels detected signals bit-error-rate (BER) correlation diagrams. They represent BER as a function from different system's parameters such as channel output power level, optical amplifier fixed output power level and system's channels allotment in C-band of ITU-T (Telecommunication Standardization Sector of the International Telecommunications Union) recommended spectral grid. As well as these obtained BER values were compared with the results for similar system, where instead of standard single mode fiber (according ITU-T Rec. G.652 D) optical signals are transmitted over non-zero dispersion shifted fiber (ITU-T Rec. G. 655).

Key words: Wavelength division multiplexing (WDM), modulation formats, bit-error-rate.

1. Introduction

Within the last few years strongly arises demand of transmission systems' channels information throughput. This trend is observed mainly due to rising number of worldwide internet user and data volume itself that is requested per user [1-3]. New information services including data, online and broadband services, such as online video conferences and video on demand, and their rapid advance in modern information age only contributes to this trend of increase of demand for information capacity [4]. In order to satisfy and secure appropriate quality of service (QoS) and service level agreement (SLA) required bandwidth for one channel currently is being doubled within two year period [5].

Wavelength division multiplexing (WDM) technology for fiber optic transmission systems has been developed and introduced in order to make use of approximately 60 THz bandwidth that is offered by silica optical fibers [1, 3, 6]. In recent years total information carrying capacity of transmission systems was increased for the account of channels number, channel spacing and per channel bit rates. However in this case must take into the account total amount of optical power coupled into a fiber. Coupled power increase resulting in additional transmission impairments caused by nonlinear optical effects (NOE) and its combination with linear distortion mechanisms [2]. Generally it leads to distorted transmission in some channels of fiber optic transmission system (FOTS) or even to complete failure of system's channels. It means that informative signals cannot be detected on the other end of the fiber with a required

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error probability. This reduces system's total carrying capacity and channel's data throughput. Consequently, another system's total transmission capacity increment solution must be found out.

Currently one of the most intensively studied system's total transmission capacity increment solutions is the increasing of system's channel spectral efficiency. Actually it is more efficient utilization of available bandwidth. It means that more informative bits are transmitted using one hertz from available frequency band. It ensures that a smaller number of channels must be used to transmit the same amount of informative bits. Channel's spectral efficiency can be increased in three different ways. The first one, the reduction of used system's channel spacing. This means that a larger number of transmission channels can be allocated in available frequency band. The second one, the increase of per channel bit rate maintaining previously used channel spacing values for separation of transmission channels. And finally the third one is the combination of pervious two ways.

Obviously that it is easier to achieve a larger channel's spectral efficiency if for optical signal modulation and coding some of novel modulation formats are used. This novel (or advanced) modulation formats provide narrower optical signals spectrum or multilevel encoding schemes that ensure more bits per one symbol than it is in traditional modulation formats, for example, on-off keying (OOK) with non-return to zero (NRZ) encoding format (NRZ-OOK) [7-8]. Maximal spectral efficiency, which can be obtained with traditional OOK modulation formats, is about 0.4 bit/s/Hz [7]. It has been reported in Ref. [9-11] that using such novel modulation formats as quadrature amplitude modulation (16-QAM particularly) and orthogonal frequency-division multiplexing(OFDM) together with polarization division multiplexing (PDM) technique it can be achieved SE larger than 6 bit/s/Hz and even reaches 7 bit/s/Hz.

Our study object of this paper is optimal combined WDM system configuration that provides lowest in system's channels detected signals BER values. This developed combined WDM system's model is offered for the future design of backbone optical networks and can be considered under the concept of NGON. Chosen optical signal modulations formats and per channel bit rates, according to authors' thoughts, are the most appropriate and probable at this moment. It was concluded after careful evaluation of current state of optical telecommunication networks, their possible and the most likely development strategy and trends in the future [2, 12-13]. The paper is organized as follows: Section 2 developed combined high density WDM (HDWDM) system model is described as well as simulation scheme and strategy is revealed; section 3 describes the method of measurements and here authors evaluate accuracy of the results obtained by simulations; in section 4, results of this research are discussed and section 5 contains main conclusions.

2. Simulation Model and Schemes

Previously in Ref. [2] as combined FOTS model have been offered three-channel WDM system (see Fig. 1), where three different modulation formats are used for optical carrier signal modulation: differential phase shift keying (DPSK) with non-return-to-zero encoding (NRZ-DPSK), orthogonal binary polarization shift keying (2-POLSK) and on-off keying with NRZ encoding (NRZ-OOK).

In addition in Ref. [2] have been detected that if in such combined system 50, 75 or 100 GHz channel spacing are used for channel separation, then the obtained channels' BER values corresponding to BER values, which are obtained for systems, where only one

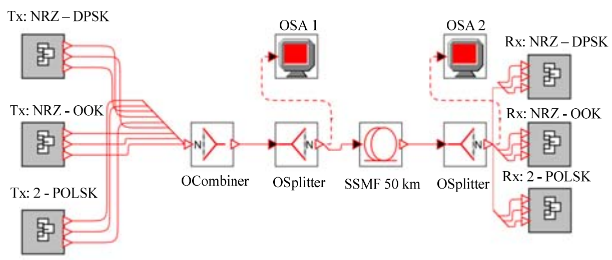

Fig. 1 Purposed model of three-channel combined WDM system.

these formats is used for the optical signal modulation. It's approximately equal to: 10^{-17} for NRZ-DPSK channel, 10^{-25} for NRZ-OOK channel and 10^{-40} for 2-POLSK. While if in three-channel WDM system with 10 Gbit/s per channel bit rate less than 50 GHz channel spacing is used for channel separation then become evident combined transmission features. And in this case obtained BER value for detected signals in combined WDM system depends not only from modulation format, which is used of optical signal modulation in given channel, but also form modulation formats in adjacent channels.

To identify channel that is a source of larger amount of interchannel crosstalk noise than the rest of system's channels six combined systems were investigated. These systems differ from each other only with modulation formats distribution among channels. This distribution scheme is as follows: [NRZ-DPSK (1, 2, 3, 3, 2, 1)]-[NRZ-OOK (2, 1, 1, 2, 3, 3)]-[2-POLSK (3, 3, 2, 1, 2)]. This configuration represents modulation format and channel's number where one on these formats is used. The system's channels central frequencies are anchored to 193.1 THz according to ITU-T Recommendation G.694.1 and the first channel's central frequency is equal to 193.075 THz, the second—193.100 THz and the third—193.125 THz. After this crosstalk source have been detected simulation model were updated in order to find out the optimal modulation format distribution, which provides the lowest in system's channels detected signals' BER values. For this purpose existing transmission systems model were updated to nine-channel WDM system. These channels are grouped by three and these groups have identical transmitter and receiver blocks configuration but with different channels' central wavelengths. It was specially done to take into account linear and nonlinear crosstalk influences to optical signal transmission which are experience central's group channel (1^{st}-3^{rd}) from adjacent groups (4^{th}-6^{th} and 7^{th}-9^{th}). For system's further analysis we will use only channels number 1-3, but 4-6 and 7-9 are used as sources of interchannel crosstalk (see Fig. 2).

Then NRZ-DPSK, 2-POLSK and NRZ-OOK modulated optical signals are combined, optically preamplified with fixed output power erbium-doped fiber amplifier (EDFA) and send over 50 km of single mode optical fiber. There are two different types of single mode fiber used in this research: standard single mode fiber or SSMF (according to ITU-T Recommendation G.652 D) and non-zero dispersion shifted fiber or NZ-DSF (according to ITU-T Recommendation G.655). Then optical signals are filtered with Super Gaussian optical filters, converted to electrical signals and then electrically filtered using Bessel electrical filters. Fiber span length was chosen equal to 50 km in order to avoid increase of amplified spontaneous emission (ASE) noise. Larger amplifier spacing would require gain greater than 10 dB, but this in a prohibitive leads to growth of ASE noise [14].

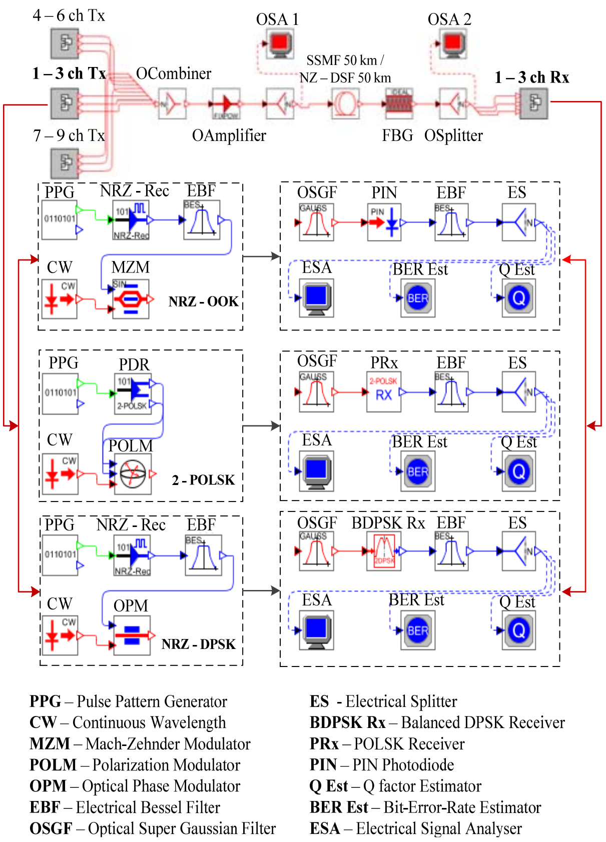

Fig. 2 Developed combined WDM system model and its block scheme in OptSim software.

In addition for evaluation of system performance and its further analyze such measurements as detected signals eye diagrams and system's output optical spectrum in the beginning and in the end of optical link were obtained.

3. Measurement Technique and Accuracy

This research is based on powerful and accepted mathematical simulation software OptSim 5.2. It solves complex differential nonlinear Schrödinger equation (NLSE) using split-step Fourier method (SSFM). This equation describes optical signal propagation over the fiber and can be written as Eq. (1) [3]:

$$\frac{\partial}{\partial z}\cdot A+\frac{\alpha^{l}}{2}\cdot A+j\cdot\frac{\beta_2}{2}\cdot\frac{\partial^2}{\partial t^2}\cdot A-\frac{\beta_3}{6}\frac{\partial^3}{\partial t^3}\cdot A= \\ =j\cdot\gamma\cdot|A|^2\cdot A \qquad (1)$$

where *A(t, z)* is complex optical field; *z*—fiber length, [km]; α^l is linear attenuation coefficient of an optical fiber, [km^{-1}]; β_2 is the second order parameter of chromatic dispersion, [ps^2/nm]; β_3 is the third order parameter of chromatic dispersion, [ps^3/nm]; γ is nonlinear coefficient, [W^{-1}·km^{-1}]; *t*—time, [s]. NLSE takes into the account linear and nonlinear affects and they influence to optical signal distortions. The principle of split-step method is better illustrated by (1), which can be written as follows [3, 15]:

$$\frac{\partial}{\partial z}\cdot A(t,z)=\left(\widehat{D}+\widehat{N}\right)\cdot A(t,z) \qquad (2)$$

$\widehat{D}$ is linear operator responsible for linear effects such as dispersion and attenuation [3]:

$$\widehat{D}=-\frac{\alpha^l}{2}-j\cdot\frac{\beta_2}{2}\cdot\frac{\partial^2}{\partial t^2}+\frac{\beta_3}{6}\cdot\frac{\partial^3}{\partial t^3} \qquad (3)$$

$\widehat{N}$ is nonlinear operator, which takes into account Kerr and other nonlinear effects (NOEs) [3]:

$$\widehat{N}=j\cdot\gamma\cdot|A|^2\cdot A \qquad (4)$$

In general split-step method is based on assumption that linear and nonlinear effects affect optical signals independently. This statement can be considered as true if we assume that all fiber length *z* is being divided into sufficiently small spans *Δz*, and only then these linear and nonlinear effects by turns are taken into account for each $\frac{\Delta z}{2}$ segment.

There are two basic algorithms for realization of SSFM: Time domain split step (TDSS) and frequency domain split step (FDSS). These two algorithms differ only with an approach that is being used for calculation of linear operator $\widehat{D}$. While in both cases nonlinear operator $\widehat{N}$ is being calculated in time domain [15].

Operator $\widehat{D}$ is being fully characterized by its impulse response *h(t)* and it is mathematically correct to calculate its influence to *A(t, z)* optical field using products of mathematical convolution. In TDSS case it can be written as follows [15]:

$$A_L[n]=A[n]*h[n]=\sum_{k=-\infty}^{\infty}A[k]\cdot h[n-k] \qquad (5)$$

This algorithm calculates this convolution in time domain and precisely obtains time delay values between signals with different wavelength. In OptSim software this TDSS algorithm is realized using finite impulse reaction (FIR) filters. This sophisticated technique provides complete control of an overall mistake that may occur during all process of calculating. By contrast FDSS calculates $\widehat{D}$ in frequency domain but firstly for this algorithm is necessary to calculate fast Fourier transformation (FFT) from *A[n]* signal samples and from *h(t)* impulse reaction. Then it is necessary to use invers FFT (FFT^{-1}) to convert obtained data array to time sample domain. FDSS algorithm can be mathematically described using following equation [15]:

$$A_L^{'}[n]=A[n]\otimes h[n]= \\ =FFT^{-1}\{FFT(A[n])\times FFT(h[n])\} \qquad (6)$$

As one can see, then in this case circular convolution is used for obtaining signal sample array $A_L^{'}[n]$. This array may contain fewer samples than it is necessary to obtain actual convolution products—$A_L[n]$ sample array. Hence this algorithm is easier to implement than TDSS and it requires less computation time and resources but serious errors may occur during calculation [3].

Eq. (2) can be solved assuming that $\widehat{D}$ and $\widehat{N}$ operators are independent and fiber span Δz length is small enough (5-100 m depending on the simulation accuracy requirements). Then optical signal after propagation over Δz span can be described in the following manner [15]:

$$A(t, z+\Delta z) \cong \exp\left[\frac{\Delta z}{2}\cdot\widehat{D}\right]\cdot\exp\left\{\Delta z\cdot\widehat{N}\left[A\left(t, z+\frac{\Delta z}{2}\right)\right]\right\}\cdot\exp\left(\frac{\Delta z}{2}\cdot\widehat{D}\right)\cdot A(t,z) \quad (7)$$

For the evaluation of system performance will be used such parameter as Q-factor and BER value. Q = 7.03 (16.94 dB) corresponds to the commonly used reference for BER of 10^{-12}.

Q-factor uncertainty range (see Fig. 3) and BER confidence interval magnitude depends on the total number of simulated bits N_{total} [15]:

$$\mathrm{dev}[Q^*] \equiv \sigma_Q \cong \frac{Q}{\sqrt{2\cdot N_{total}}} \quad (8)$$

where Q is Q-factor value that can be calculated using following Eq. (9) [3, 15]:

$$Q = \frac{|\mu_1-\mu_0|}{\sigma_1+\sigma_0} \quad (9)$$

where $\mu_{1,0}$ and $\sigma_{1,0}$ are the mean and the standard deviation of the received signal, when a logical "1" and "0" is transmitted, and $\pi \approx 3.14$ [3, 15].

$$\mathrm{BER} = \frac{1}{2}\cdot\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right) \quad (10)$$

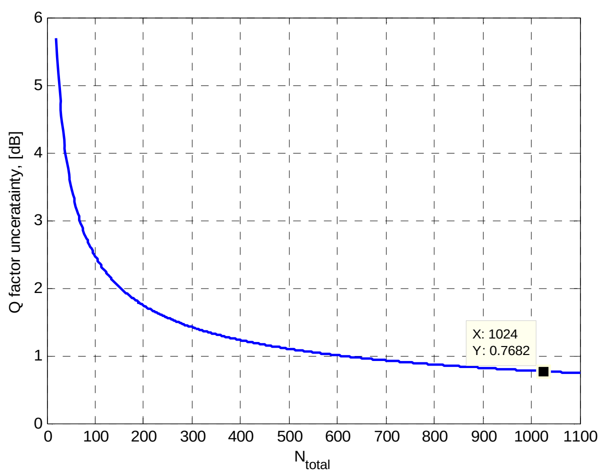

Fig. 3 Q-factor uncertainty as a function form total number of simulated bits.

Using Eq. (8) Q-factor uncertainty range can be expressed as Ref. [15]:

$$\mathrm{range} = 20\cdot\log_{10}\left(\frac{1+\sqrt{\frac{2}{N_{total}}}}{1-\sqrt{\frac{2}{N_{total}}}}\right) \quad (11)$$

As one can see from Fig. 3 Q-factor uncertainty range for 1,024 simulated bits that is used in our schemes is equal to 0.77 dB.

Q-factor and BER value 95% ($\pm 2\sigma_Q$) confidence intervals for 16.94 dB nominal value can be obtained using Eq. (8) and Eq. (10) assuming that we are dealing with Gaussian distribution. For 1,024 of simulated bits these intervals are

$$Q_{\text{for } 16.94\text{ dB}} \in [16.55; 17.31], [\mathrm{dB}] \quad (12)$$

$$\log 10\{\mathrm{BER}_{\text{for } 10^{-12}}\} \in [-12.97; -11.04] \quad (13)$$

As an example we will give BER 95 % confidence interval as a function from the number of simulated bits for 10^{-12} nominal. This value will be used as reference for transmission channel with 10 Gbit/s per channel bitrate (see Fig. 4).

As one can see, when simulating 1,024 bits at BER = 10^{-12}, the confidence interval magnitude is less than ±1 order. It points to the conclusion that OptSim simulation software allows obtaining sufficiently accurate preliminary results and there is no point to increase the total number of simulated bits, because obtained results accuracy does not improve sufficiently.

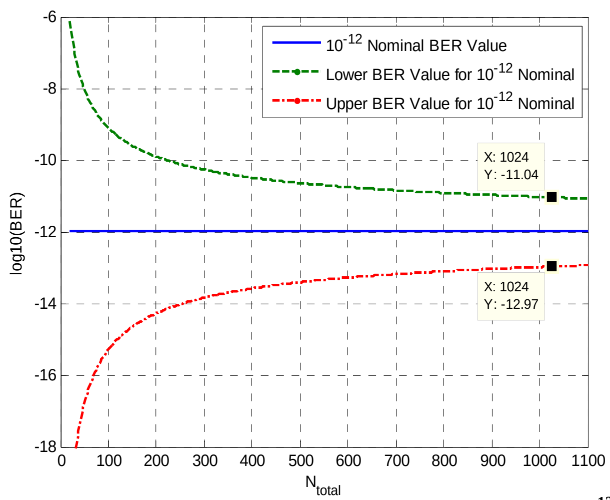

Fig. 4 BER value 95% confidence intervals for 10^{-12} nominal.

4. Results and Discussion

The aim of this paper was to investigate optimal configuration for combined WDM systems where differently modulated optical signals are transmitted. To achieve this goal several objectives must be solved.

Firstly it is necessary to identify channel in [1st: NRZ-DPSK, 10 Gbit/s, 193.075 THz]-[2nd: 2-POLSK, 10 Gbit/s, 193.100 THz]-[3rd: NRZ-OOK, 10 Gbit/s, 193.125 THz] combined WDM FOTS that is a source of larger amount of interchannel crosstalk noise than the rest of channels.

For this purpose six different systems were studied. These systems differ from each other only with modulation formats that are used in each particular system's channels. These systems have following configurations:

[NRZ-DPSK]-[NRZ-OOK]-[2-POLSK];
[NRZ-OOK]-[NRZ-DPSK]-[2-POLSK];
[NRZ-OOK]-[2-POLSK]-[NRZ-DPSK];
[2-POLSK]-[NRZ-OOK]-[NRZ-DPSK];
[2-POLSK]-[NRZ-DPSK]-[NRZ-OOK];
[NRZ-DPSK]-[2-POLSK]-[NRZ-OOK].

In each systems channel were determined signals BER values that further were used for system's performance analyze. The obtained results are summarized below (see Table 1). Using these results for each configuration system's average detected signals BER values were calculated. As one can see, sufficiently smaller BER value is for the third combined system configuration then it is for the rest of possible configuration. The third configuration is as follows: [1st: NRZ-OOK\193.075 THz]-[2nd: 2-POLSK\193.100 THz]-[3rd: NRZ-DPSK\193.125 THz]. After careful analysis of these obtained results it was found that investigated combined system channel, where for optical signals modulation NRZ-DPSK modulation format is used, is a source of larger amount of interchannel crosstalk than channels, where NRZ-OOK or 2-POLSK format is used. This was concluded based on obtained NRZ-OOK and 2-POLSK channels BER results for different system's configurations. This become evident if we analyze obtained BER values for the fourth, fifth and sixth system.

Table 1 BER values for different combined systems channels.

f (THz)	1st system	2nd system	3rd system
193.075	3×10^{-24}	2×10^{-8}	1×10^{-40}
193.100	9×10^{-12}	9×10^{-25}	1×10^{-18}
193.125	1×10^{-40}	1×10^{-13}	3×10^{-27}
Average	3×10^{-12}	7×10^{-9}	5×10^{-19}
f (THz)	**4th systems**	**5th system**	**6th system**
193.075	1×10^{-40}	1×10^{-21}	4×10^{-27}
193.100	2×10^{-8}	6×10^{-25}	8×10^{-14}
193.125	3×10^{-25}	6×10^{-12}	1×10^{-40}
Average	5×10^{-9}	2×10^{-12}	3×10^{-14}

Firstly let's focus to the fifth system's BER values. As one can see from this configuration scheme then in this case NRZ-DPSK modulated optical signals are transmitted in central system's channel. As a result detected signals BER values in adjacent channels are sufficiently higher than they are in cases, when NRZ-OOK or 2-POLSK modulated optical signals are located further from NRZ-DPSK channel as it is in the sixth system. Comparing BER results obtained for 2-POLSK modulated signals in the fourth and sixth system (1×10^{-40} and 9×10^{-14} respectively), we can conclude that in combined system detected signals BER value decreases if channel, where these signals are transmitted, is located further from NRZ-DPSK channel.

To assess NRZ-DPSK channel created crosstalk impact to optical signals transmission in all others combined system's channels previously studied three-channel combined systems model (see Fig. 1) was modified and supplemented with 2 × 3 channels that have appropriate system's configuration (see Fig. 2). As before, in system channels detected signals BER values were obtained for six different combined system configurations (see Table 2).

As well as using these data two different channels average BER values were calculated: system's average BER that takes into account all system channels (1st-9th); central group channels' average BER that takes into account only channels number one to three.

Table 2 BER values for different 9-channel combined systems' channels.

No.	f (THz)	1st system	2nd system	3rd system
4	193.000	5×10^{-23}	2×10^{-11}	1×10^{-40}
5	193.025	5×10^{-11}	4×10^{-24}	1×10^{-11}
6	193.050	1×10^{-13}	3×10^{-16}	9×10^{-24}
1	193.075	4×10^{-22}	2×10^{-8}	1×10^{-10}
2	193.100	5×10^{-10}	2×10^{-23}	4×10^{-15}
3	193.125	3×10^{-16}	3×10^{-13}	4×10^{-23}
7	193.150	4×10^{-24}	8×10^{-8}	1×10^{-11}
8	193.175	7×10^{-9}	2×10^{-23}	4×10^{-17}
9	193.200	1×10^{-40}	1×10^{-14}	4×10^{-29}
Average (1st-3rd)		2×10^{-10}	7×10^{-9}	4×10^{-11}
Average (1st-9th)		9×10^{-10}	1×10^{-8}	2×10^{-11}
No.	f (THz)	4th systems	5th system	6th system
4	193.000	1×10^{-40}	3×10^{-31}	9×10^{-27}
5	193.025	3×10^{-11}	2×10^{-23}	6×10^{-15}
6	193.050	3×10^{-24}	2×10^{-11}	3×10^{-11}
1	193.075	1×10^{-11}	2×10^{-15}	4×10^{-23}
2	193.100	1×10^{-8}	3×10^{-26}	1×10^{-14}
3	193.125	4×10^{-22}	3×10^{-10}	5×10^{-10}
7	193.150	1×10^{-12}	2×10^{-15}	3×10^{-22}
8	193.175	3×10^{-8}	5×10^{-24}	2×10^{-13}
9	193.200	1×10^{-23}	3×10^{-12}	1×10^{-40}
Average (1st-3rd)		3×10^{-9}	9×10^{-11}	2×10^{-10}
Average (1st-9th)		4×10^{-9}	3×10^{-11}	5×10^{-11}

As one can see from obtained data (see Table 2), then the lowest average BER values for 1st till 3rd and 1st till 9th channel are for the third combined system configuration and they are equal to $BER_{1st\text{-}3rd} = 4 \times 10^{-11}$ and $BER_{1st\text{-}9th} = 2 \times 10^{-11}$ respectively. But the highest BER values are for the second configuration and they are equal to $BER_{1st\text{-}3rd} = 7 \times 10^{-9}$ and $BER_{1st\text{-}9th} = 1 \times 10^{-8}$. So, BER difference between the best and worst case scenario, corresponding to [(NRZ-OOK)\193.075 THz]-[(2-POLSK)\193.100 THz]-[(NRZ-DPSK)\193.125 THz] and [(NRZ-OOK)\193.075 THz]-[(NRZ-DPSK)\193.100 THz]-[(2-POLSK)\193.125 THz] configuration respectively, is approximately three orders (see Figs. 5-6).

In these both cases channel with highest detected signal error probability is the first one, where by the way NRZ-OOK modulated optical signals are transmitted. Comparing BER values obtained for NRZ-OOK and 2-POLSK modulated optical signals

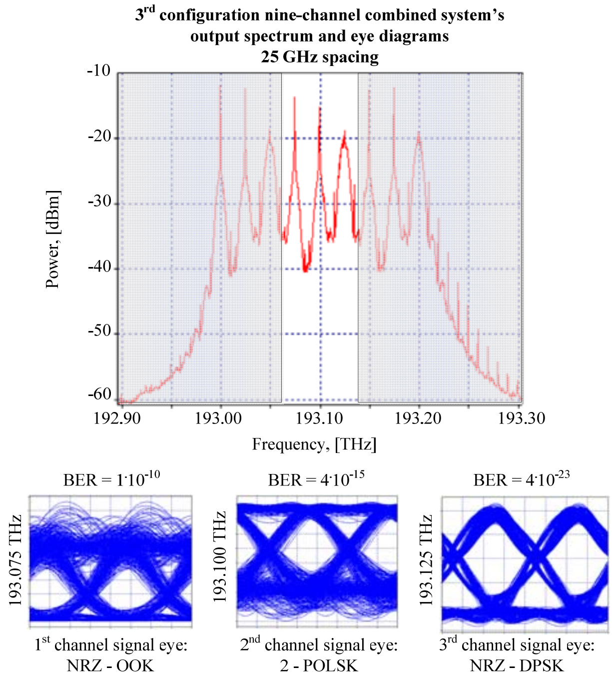

Fig. 5 Nine-channel combined system's with the third configuration output spectrum and eye diagrams in case of 10 Gbit/s per channel bitrates and 25 GHz channel spacing.

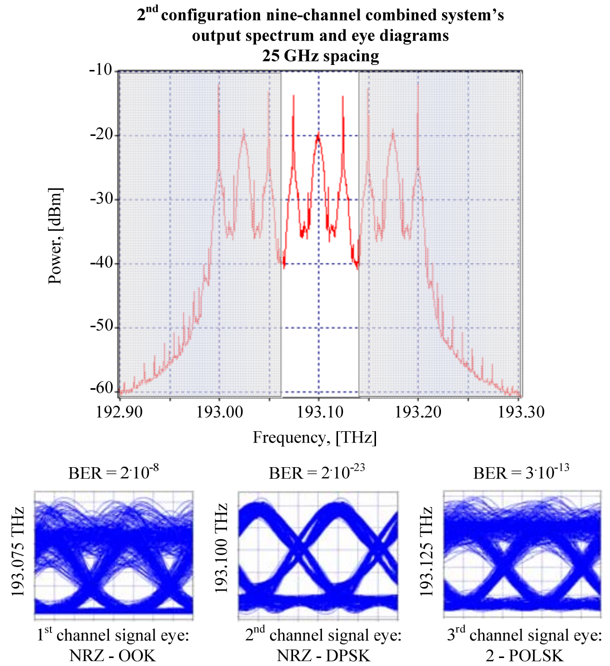

Fig. 6 Nine-channel combined system's with the second configuration output spectrum and eye diagrams in case of 10 Gbit/s per channel bitrates and 25 GHz channel spacing.

for these two systems configuration, we have to conclude that these values differ by no more than two orders (1×10^{-10} and 2×10^{-8} in NRZ-OOK case and 4

× 10^{-15} and 3 × 10^{-13} for 2-POLSK channels). As for NRZ-DPSK channel then the resulting BER values differences in both cases are not significant: 4 × 10^{-23} and 2 × 10^{-23} (see the 1st channel in Fig. 5 and the 2nd channel in Fig. 6).

As a result, for further research of optimal combined system configuration will be used as a starting point nine-channel combined WDM system with the third configuration.

Previously it has been detected that channel, where NRZ-DPSK modulated optical signals are transmitted, is larger amount of interchannel crosstalk source than NRZ-OOK or 2-POLSK channels. So, to reduce that type of noise it has been decided to decrease optical power level radiated by distributed feedback lasers (DFB) in continuous wavelength (CW) regime that are used in these channels. Using OptSim Scan Parameter simulation regime in system's channel detected signals BER value as function from NRZ-DPSK channel laser output power level was obtained (see Fig. 7).

As previously, using these BER results for each system channel average BER value for central channels were calculated. It revealed that in system channels detected signals average BER values are below 10^{-12} if NRZ-DPSK channels' lasers output power level is in the range from 3.5 to 4.5 dBm. The lowest average channels' BER value is reached if these lasers output power is equal to 3.5 dBm. In this case $BER_{1st\text{-}3rd}$ = 3 × 10^{-18} and the worst channel is the second one (2-POLSK) and its BER_{2nd} = 1 × 10^{-17} (see Fig. 7).

Assuming that we are dealing with one sector of ultra-long haul backbone optical network, it was decided to supplement this model of combined WDM system with additional optical element—fixed output power optical amplifier. It allowed take into an account ASE noise arising from EDFA which is the most widely used optical amplifier. To find out optimal amplifier output power level, that provides minimal channels' BER values, BER correlation diagram for each were obtained. It represents in systems channels detected signals BER values as a function from amplifier fixed output power level (see Fig. 8). Let us note that, in this case NRZ-DPSK channel laser output power level remains unchanged as it was in initial combined WDM system model in Ref. [2].

As one can see from Fig. 8, then BER value for the system's first channel varies around 10^{-11} value, for the second channel around 10^{-16} and for the third—10^{-24}. Knowing that the worst combined system's channel is the second one, where 2-POLSK modulated optical signals are transmitted, then was decided to choose amplifier output power level that provides minimal BER value exactly in this channel.

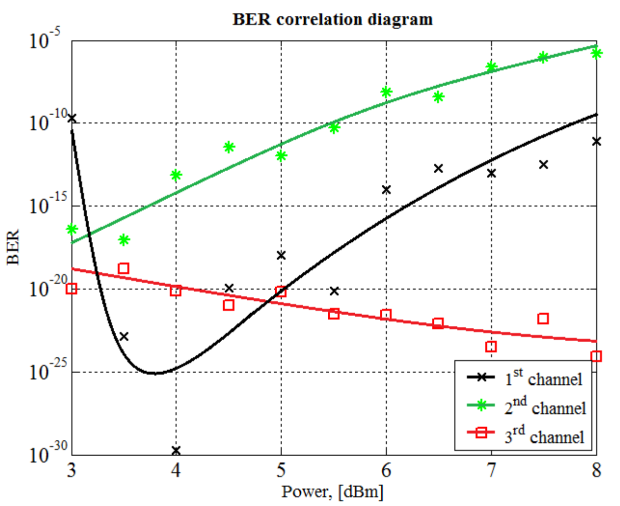

Fig. 7 BER as a function from NRZ-DPSK channel laser radiated output power level.

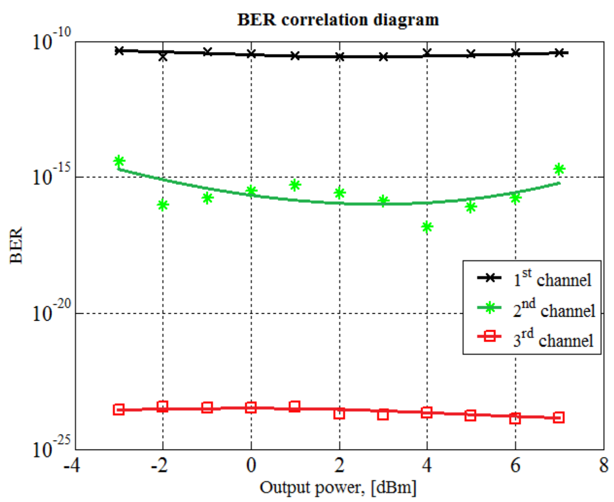

Fig. 8 BER as a function form optical amplifier fixed output power level.

Consequently, optical amplifier fixed output power level equal to 4 dBm was chosen. This level provides in the second system's channel detected signals $BER_{2nd} = 1 \times 10^{-17}$.

If both these optimal parameters are used in combined system model configuration, then in system channels detected signals BER values are well below the maximal acceptable BER threshold 10^{-12}, that is defined for 10 Gbit/s per channel bitrate (see Table 3). Channels BER values for revealed optimal system configuration were obtained for two types of single mode fiber. The first fiber was standard single mode fiber (SSMF) according to ITU-T Recommendation G.652 D and the second was non-zero dispersion shifted fiber (NZ-DSF) according to ITU-T Recommendation G.655.

For these two cases BER results as well as detected signals eye diagrams were compared one to another (see Fig. 9).

To summarize results that was reported in Table 3, as well as in Fig. 9, must be stated the fact that in system channels detected signals BER values decreased significantly comparing to initial unoptimized system.

BER value for the first system channel sufficiently dropped from 1×10^{-10} to 5×10^{-26} if SSMF is used and to 9×10^{-20} if NZ-DSF is used. Exactly for this first channel, where NRZ-OOK modulated optical signals are transmitted, experiencing the most radical BER value improvement comparing to 2-POLSK and NRZ-DPSK channels. In these channels detected signal BER values do not improve so noticeably (see eye diagrams in Figs. 5 and 9). The second channel's BER value decreases from 4×10^{-15} to 7×10^{-19} for SSMF and to 6×10^{-21} for NZ-DSF, but the third channel's BER value variation is not essential from 4×10^{-23} to 6×10^{-22} if SSMF is used. But if in this system instead of SSMF NZ-DSF is used then it is possible to obtain lower BER values for NRZ-DPSK channels. In this channel detected signals BER value decreases to 1×10^{-40}.

Table 3 BER value for different system configurations.

System description	1st	2nd	3rd
Initial	1×10^{-10}	4×10^{-15}	4×10^{-23}
$P_{NRZ\text{-}DPSK} = 3.5$ dBm	1×10^{-23}	1×10^{-17}	2×10^{-19}
FIXPOWER = 4 dBm	4×10^{-11}	1×10^{-17}	2×10^{-24}
Optimal and SSMF	5×10^{-26}	7×10^{-19}	6×10^{-22}
Optimal and NZ-DSF	9×10^{-20}	6×10^{-21}	1×10^{-40}

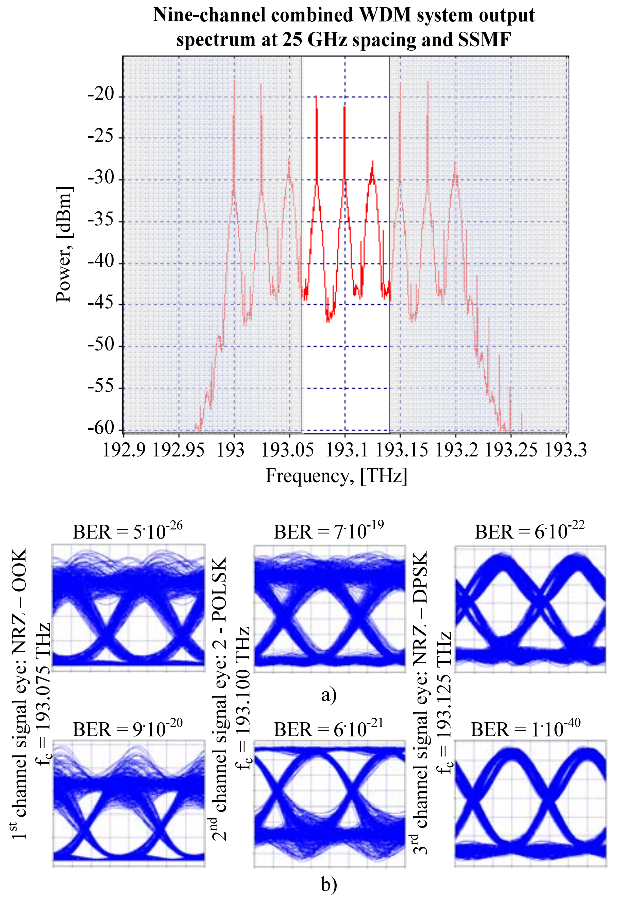

Fig. 9 Optimal configuration nine-channel combined WDM system output optical spectrum and eye diagrams: (a) SSMF; (b) NZ-DSF.

In addition, coherence between detected signals BER values and channels' central frequency position in C-band (191.6-195.9 THz) was investigated. As well as, for each system channel the worst and the best position in C-band, that provides the highest and the lowest possible signals BER values, respectively, for previously found optimal combined system's configuration, was revealed (see Table 4). As previously, this research was held for two types of optical fiber: SSMF (G.652 D) and NZ-DSF (G.655).

Table 4 Best and worst channels positions in C-band and their BER values.

No.	Fiber	B/W	f_c (THz)	BER
1st	SSMF (G.652 D)	Best	195.725	8×10^{-26}
		Worst	192.350	2×10^{-16}
2nd		Best	193.950	3×10^{-31}
		Worst	192.150	2×10^{-20}
3rd		Best	195.100	8×10^{-25}
		Worst	192.400	7×10^{-19}
1st	NZ-DSF (G.655)	Best	193.475	1×10^{-39}
		Worst	193.925	5×10^{-26}
2nd		Best	191.925	2×10^{-23}
		Worst	195.750	3×10^{-14}
3rd		Best	C-band	1×10^{-40}
		Worst		

It showed that depending on channel central frequency the first channel's BER value varies around nominal value of 10^{-20} if SSMF is used and around 10^{-30} if NZ-DSF. But BER values obtained for the second channel and NZ-DSF are for several orders worse comparing to transmission over SSMF. They vary around 10^{-20} and 10^{-25}, respectively.

In addition, as one can see from Table 4, then BER value obtained for NZ-DSF and the worst case of 2nd channel central frequency is approximately for six orders larger comparing to the worst case of SSMF. These let us conclude that 2-POLSK modulated signals are not suitable for transmission over NZ-DSF fiber in [NRZ-OOK]-[2-POLSK]-[NRZ-DPSK] combined WDM systems and they are sufficiently distorted at appropriate channel central frequency. As result system's average BER value is significantly higher than it might be in case of SSMF (see Table 5). In same time the lowest 1st-3rd channels average BER value is gained with NZ-DSF and it is about two orders lower than in case of SSMF. As for the third channel, then in case of SSMF and different channel central frequencies obtained BER values vary somewhere around 10^{-23}. Whereas in case of NZ-DSF these values remain constant and approximately equal to 10^{-40} in all C-band. It allows to judge about NRZ-DPSK modulated optical signals transmission suitability over NZ-DSF single mode optical fiber.

Table 5 Minimal and maximal in system's 1st-3rd channel detected signals BER values.

Characteristics	BER	2nd channel f_c (THz)	1st-3rd channel
MIN average BER/ SSMF	3×10^{-23}	195.750	8×10^{-26}
			2×10^{-24}
			8×10^{-23}
MAx average BER/ SSMF	6×10^{-17}	192.375	2×10^{-16}
			7×10^{-28}
			7×10^{-19}
MIN average BER/ NZ-DSF	5×10^{-25}	192.825	1×10^{-31}
			1×10^{-24}
			1×10^{-40}
MAx average BER/ NZ-DSF	1×10^{-14}	195.750	1×10^{-27}
			3×10^{-14}
			1×10^{-40}

Let is note, that Corning LEAF non-zero dispersion shifted fiber characteristics and parameters were used in OptSim in order to obtain mathematical model of a NZ-DSF. This fiber is the world's most widely deployed NZ-DSF and is specially optimized for high-speed and high capacity long-haul and metro networks [16].

5. Conclusions

The most appropriate realization of high-density combined WDM fiber optic transmission system configuration for differently modulated optical signals has been investigated. As a model of combined WDM systems have been offered WDM system, where three different optical signal modulation formats are used. This model has following initial configuration: [1st: NRZ-DPSK, 10 Gbit/s, 193.075 THz]-[2nd: NRZ-OOK, 10 Gbit/s, 193.100 THz]-[3rd: 2-POLSK, 10 Gbit/s, 193.125 THz]. In this paper obtained results are summarized below as recommendations and conclusions for the future design of backbone optical networks.

Channels, where NRZ-DPSK modulated optical signals are transmitted, are sources of larger interchannel crosstalk noise comparing to NRZ-OOK or 2-POLSK signals. Consequently, in these channels detected signals BER value decreases if channel, where these signals are transmitted, is located further from

NRZ-DPSK channels. It is possible to minimize NRZ-DPSK created signals crosstalk by reduction the output power of lasers that are used in these channels or by the use of optimal modulation format allocation for particular transmission channel.

Optimal modulation format allocation for particular channel is [(NRZ-OOK)\193.075 THz]-[(2-POLSK)\ 193.100 THz]-[(NRZ-DPSK)\193.125 THz]. It provides in system channels detected signals average BER values not higher than 2×10^{-11}. Whereas [(NRZ-OOK)\193.075 THz]-[(NRZ-DPSK)\193.100 THz]-[(2-POLSK)\193.125 THz] that is the worst possible modulation formats distribution provides BER values not higher than 1×10^{-8}. In these both cases NRZ-OOK modulated signals are the most distorted and as result channels, where in this way modulated optical signals are transmitted, are the worsts combined systems' channels with highest BER values. As well as, detected signals BER values in case of these two combined system's configurations differ for NRZ-OOK and 2-POLSK signals no more than by two orders (1×10^{-10} and 2×10^{-8} ; 4×10^{-15} and 3×10^{-13} respectively) and for NRZ – DPSK this difference is not significant (4×10^{-23} and 2×10^{-23}).

Lasers output power level in the range from 3.5 to 4.5 dBm, that are used in channel, where NRZ-DPSK modulated signals are transmitted, provides average BER value well below necessary threshold of 10^{-12}. If these lasers output power is equal to 3.5 dBm, then the lowest average BER value is obtained and it's approximately equal to 10^{-18}. In this case the worst system's channel is the second (2-POLSK) and it's BER = 10^{-17}. To simulate ASE noise arising from EDFA combined system model was supplemented with fixed output power optical amplifier. Based on obtained channel BER correlation diagrams, this power level was chosen equal to 4 dBm. It provides the lowest possible BER values for 2-POLSK signals detected in the second system's channel (around 10^{-18}) that is the worst channel in developed combined system if SSMF is used. But if optical signals are transmitted over NZ-DSF, then the worst system channel is the first one where NRZ-OOK modulation format is used and its BER varies around 10^{-19}.

Investigating coherence between BER values and channels' central frequencies position in C-band, it have been stated several facts. Firstly, obtained channels central frequency values for each system channel the worst and the best position in C-band, that provide the highest and the lowest possible detected signals BER values, respectively (see Table 4). Secondly, 2-POLSK modulated signals are not suitable for transmission over NZ-DSF fiber in investigated combined WDM system, because these signals are sufficiently distorted at appropriate channel central frequency. If combined system's channels are allocated around nominal of 195.750 THz, then obtained average detected signals BER value is about 10^{-14} and it is the worst possible case. Whereas the lowest possible average BER value (5×10^{-25}) can be reached anchored combined systems channels frequency grid to 192.825 THz. Thirdly, NRZ-DPSK modulated optical signals are well suitable for transmission over NZ-DSF. As result, in these channels detected signals BER values are not higher than 10^{-40} regardless to channel central frequency positioning in C-band.

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