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Investigation of Maximum Distance Reach for Spectrally Efficient WDM System with Mixed Data Rates and Signal Formats

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***Abstract*—The authors have investigated the maximum distance reach for wavelength division multiplexed (WDM) fiber optic transmission system (FOTS) where optical signals are transmitted with two different bitrate per channel (i.e. 10 and 40 Gbit/s) and for optical signal modulation three different modulation formats are used: NRZ-OOK, 2-POLSK and NRZ-DPSK. These chosen modulation formats encode information by manipulating with the different optical signal freedom degrees: amplitude, phase and state of polarization. The system's maximum distance reach was detected for the most spectrally efficient WDM system's configuration: [1st, 4th and 7th channels: NRZ-OOK, R= 10 Gbit/s] – [2nd, 5th and 8th channels: 2-POLSK, R=40 Gbit/s] – [3rd, 6th and 9th channels: NRZ-DPSK, R=40 Gbit/s]. It was done using iteration loops that consisted from chromatic dispersion compensation module, optical signal amplifier and one span of standard single mode fiber. One iteration loop corresponding to such configuration emulates one sector of fiber optic transmission line. It is found that the maximum distance reach depends on investigated system's average spectral efficiency and the length of SSMF span.**

***Index Terms*—Optical modulation, WDM, mixed, combined, HDWDM, optical fiber networks.**

I. Introduction

Within the next two or five years is capacity shortage in transmission systems will probably intensify not only due to the expansion and variety of new online and broadband services but also due to their rapid advance. This only contributes to the continuous growth in the internet traffic [1]. Using the existing transmission systems telecommunication service providers will be unable to secure appropriate quality of service (QoS) level and fulfill the service level agreements (SLA) if the internet traffic keeps doubling every year as it is now [2]. Such exponential traffic growth arises because of the rising number of worldwide internet users in African and Asian countries and due to the data volume itself requested per one user [3]. In recent years the most popular solution for this problem was relatively simple: the system's bandwidth required for securing the necessary carrying capacity was doubled every two years in backbone fiber optic transmission systems (FOTS) [4].

Approximately for the last two year on of the most intensively studied solution of total transmission capacity improvement possibilities in wavelength division multiplexed (WDM) system is the increase of its spectral efficiency. This solution is the most topical and cost effective since it allows maintaining the maximum of already deployed infrastructure. Cost reductions and increased flexibility are and will be the main drivers for the evolution of all optical transport networks [5]. This solution provides the opportunities to postpone bottleneck effect and secure that a greater number of informative can be transmitted using one hertz of available bandwidth. In WDM systems this bandwidth is limited not only with the bandwidth offered by standard single mode fiber (according to ITU-T Recommendation G.652.D), i.e. approximately 60 THz, but also with the bandwidth of optical components such as dispersion compensating module (DCM) [3].

The increase of channel's SE means that a smaller number of channels are required to transmit the same body of data comparing to the wavelength division multiplexing (WDM) systems with a low spectral efficiency (<0.2 bit/s/Hz). Apparently that high spectrally efficient transmission (SE>1 bit/s/Hz) over WDM system cannot be gained if traditional optical signal modulation formats, e.g. on-off keying with non-return to zero encoding scheme (i.e., NRZ-OOK) are applied. In [6] reported that the maximum SE for traditional OOK formats is not larger than 0.4 bit/s/Hz. By contrast, the usage of such advanced modulation and coding format as quadrature amplitude modulation (QAM) and coherent optical orthogonal frequency division multiplexing (CO-OFDM) allows achieving SE about 6 bit/s/Hz that was reported in [7], [8].

Our study object in this paper is the maximum distances reach for WDM system that complies with the following criteria: 1) not only traditional OOK but also novel modulation formats (e.g., orthogonal binary polarization shift keying or 2-POLSK) are used for optical signal modulation; 2) the minimum allowable and equal frequency intervals are used for channel separation to secure the maximum possible system's SE. This research will identify the number of sector of fiber optic transmission line over

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whom optical signals can be successfully transmitted and then detected with appropriate error probability. This information intensifies when it is necessary to choose system's further development strategy or for planning the improvement of already existing network infrastructure.

II. Numerical Method and Accuracy

This research is based on powerful and widely accepted mathematical simulation software OptSim 5.2 for solving the nonlinear Schrödinger equation which describes the optical signal propagation over a fiber [4]

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

where $A(t, z)$ is the optical field; z is the fiber length, [km]; α^l is the 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 a nonlinear coefficient, [W^{-1}·km^{-1}]; t is the time, [s].

In differential form 1 can be written as follows [4]

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

where $\widehat{D}$ is linear operator responsible for linear effects such as dispersion and attenuation [9]

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

where $\widehat{N}$ is nonlinear operator, which takes into account Kerr and other nonlinear effects (NOEs) [9]

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

Solution for this equation is obtained using time domain split-step algorithm assuming 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. The optical signal after propagation over Δz fiber span is described as follows [9]

$$A(t,z+\Delta z)\cong\exp\left[\frac{\Delta z}{2}\times\widehat{D}\right]\cdot\exp\left\{\Delta z\times\widehat{N}\left[A\left(t,z+\frac{\Delta z}{2}\right)\right]\right\}\times\exp\left(\frac{\Delta z}{2}\cdot\widehat{D}\right)\times A(t,z). \quad (5)$$

For the performance evaluation two commonly used references for BER value will be employed. The maximum permissible BER value for the signals transmitted at 10 Gbit/s and 40 Gbit/s per channel bitrate is 10^{-12} and 10^{-16}, respectively. Q-factor uncertainty is related to the total number of simulated bits N_{total} as it is shown in Fig. 1.

As one can see from Fig. 1 Q-factor uncertainty range for 1,024 simulated bits that is used in our schemes is equal to 0.77 dB. The BER confidence intervals for nominal thresholds of 10^{-12} and 10^{-16} can be obtained using the relationship between BER and Q-factor

$$\text{BER}=\frac{1}{2}\cdot\text{erfc}\left(\frac{Q}{\sqrt{2}}\right). \quad (6)$$

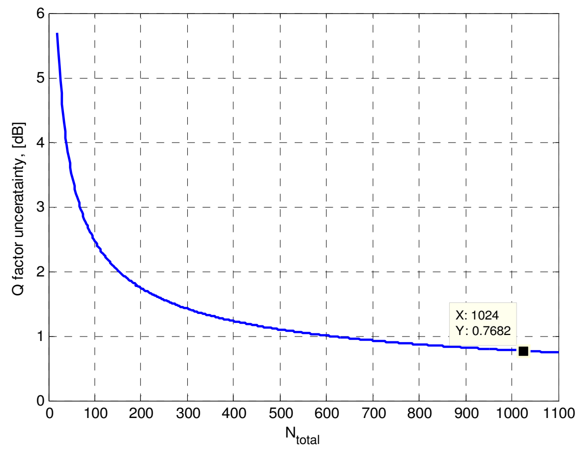


Fig. 1. Q-factor uncertainty as a function form total number of simulated bits [10].

For 1024 simulated bits and assuming that we are dealing with Gaussian noise distribution in PIN photodiode the BER confidence intervals are:

$$\lg\{\text{BER}_{\text{for }10^{-12}}\}\in[-12.97;-11.04], \quad (7)$$
$$\lg\{\text{BER}_{\text{for }10^{-16}}\}\in[-17.26;-14.64]. \quad (8)$$

So, the obtained BER confidence intervals evidence that this numerical algorithm and OptSim software allows obtaining sufficiently accurate results. The resulting BER error is less than ±2 orders.

III. Simulation Scheme

Previously in [1], [9] as a combined FOTS a 9-channel WDM system is considered in which three different modulation formats are used for optical carrier signal modulation. The first one is the NRZ-OOK, which is a modulation format traditionally employed in FOTS. The second one is the orthogonal binary polarization shift keying (2-POLSK), and the third – the differential phase shift keying with non-return to zero encoding (NRZ-DPSK). As one can see that in this system information is encoded by manipulating with all three optical signal's degree of freedom such as intensity (or amplitude), phase and state of polarization.

The system's channels are divided into three groups with identical configuration of the transmitter and receiver as well as distribution of modulation formats among the channels but with different central wavelengths of channels. For evaluation of such a combined system's performance the quality of optical signal transmission was analysed in all system's channels but represented quality criteria, e.g., eye diagrams and BER values only for the central group channels – i.e. those with number one to three. This was specially done to take into account linear and nonlinear crosstalk effects in the optical signal transmission to which the central group's channels (from the first to the third system's channel) are exposed from the channels of adjacent groups (4th - 6th and 7th – 9th). As mentioned above, for further analysis of system's performance we use channels 1-3, while 4-6 and 7-9 are taken only as sources of interchannel crosstalk (Fig. 2). So, in [1], [9] investigated systems have a following configuration: [1^{st}, 4^{th} and 7^{th} channels: NRZ-OOK, R= 10 or 40 Gbit/s)] – [2^{nd}, 5^{th} and 8^{th} channels: 2-POLSK, R=10 or 40 Gbit/s)] – [3^{rd}, 6^{th} and 9^{th} channel: NRZ-DPSK, R= 10 or 40 Gbit/s)]. The maximum distance reach will be investigated for spectrally efficient WDM system that corresponds to the following configuration: [1^{st}, 4^{th} and 7^{th} channels: NRZ – OOK, R=10 Gbit/s, f_c=193.025 THz] – [2^{nd}, 5^{th} and 8^{th} channels: 2 – POLSK, R=40 Gbit/s, f_c=193.100 THz] – [3^{rd}, 6^{th} and 9^{th} channels: NRZ – DPSK, R=40 Gbit/s, f_c=193.175 THz].

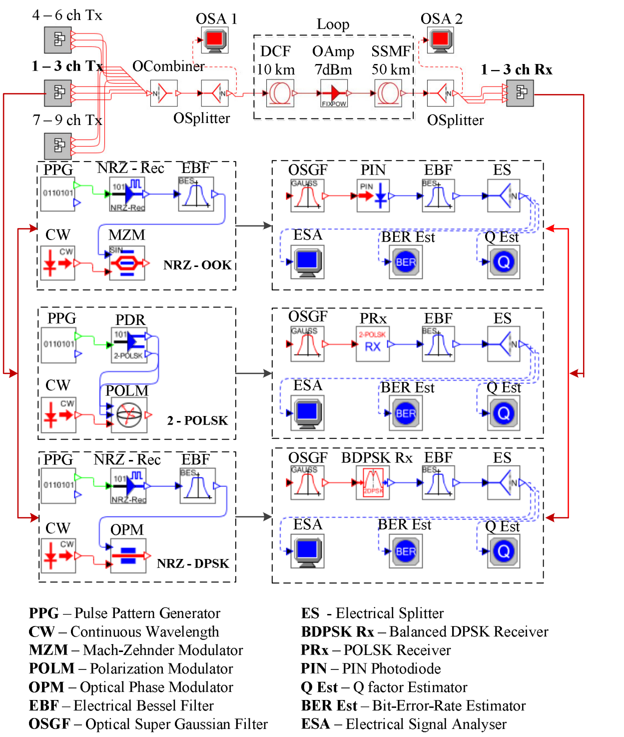


Fig. 2. Simulation scheme of developed 9-channel combined WDM system and block diagram of the channel transmitting and receiving units for NRZ-OOK, 2-POLSK and NRZ-DPSK optical signal modulation formats and the configuration of iteration loop.

Exactly this system was chosen for this research because it is the worst configuration of a combined WDM system where optical signals are transmitted with 40 Gbit/s in two channels. It provides the highest average BER value for the detected signals as compared with the [1^{st}, 4^{th} and 7^{th} channels: NRZ – OOK, R= 40 Gbit/s, f_c=193.025 THz] – [2^{nd}, 5^{th} and 8^{th} channels: 2 – POLSK, R=10 Gbit/s, f_c=193.100 THz] – [3^{rd}, 6^{th} and 9^{th} channels: NRZ – DPSK, R=40 Gbit/s, f_c=193.175 THz] or [1^{st}, 4^{th} and 7^{th} channels: NRZ – OOK, R=40 Gbit/s, f_c=193.025 THz] – [2^{nd}, 5^{th} and 8^{th} channels: 2 – POLSK, R=40 Gbit/s, f_c=193.100 THz] – [3^{rd}, 6^{th} and 9^{th} channels: NRZ – DPSK, R=10 Gbit/s, f_c=193.175 THz] system.

If for the channel separation 75 GHz frequency intervals are used, the worst system's channel is the first one and its BER value is sufficiently higher than 10^{-40} and is equal to $1\cdot10^{-23}$. As for the rest of the system's channels, their BER values are not higher than 10^{-40}. As could be seen from the system's output optical spectrum, the channels are located maximally close to each other, so further compaction would lead to the signal spectrum overlapping as it is shown for 50 GHz spacing (Fig. 3). In this case 2-POLSK and NRZ-DPSK channels are overlapping. As a result, the BER value for the signals detected in these channels is considerably higher than 10^{-16} and is equal to $4\cdot10^{-4}$ and $8\cdot10^{-5}$ (see the 5^{th} and 6^{th} eye in Fig. 3), respectively. Whereas NRZ-OOK channel's BER is $2\cdot10^{-12}$ at 50 GHz interval but it still is above the maximum tolerated error probability threshold of 10^{-12}.

Note that for chromatic dispersion (CD) compensation in this system fibre Bragg grating was used and EDFA fixed output power level was equal to 4 dBm according to optimal combined system configuration found out in [9].

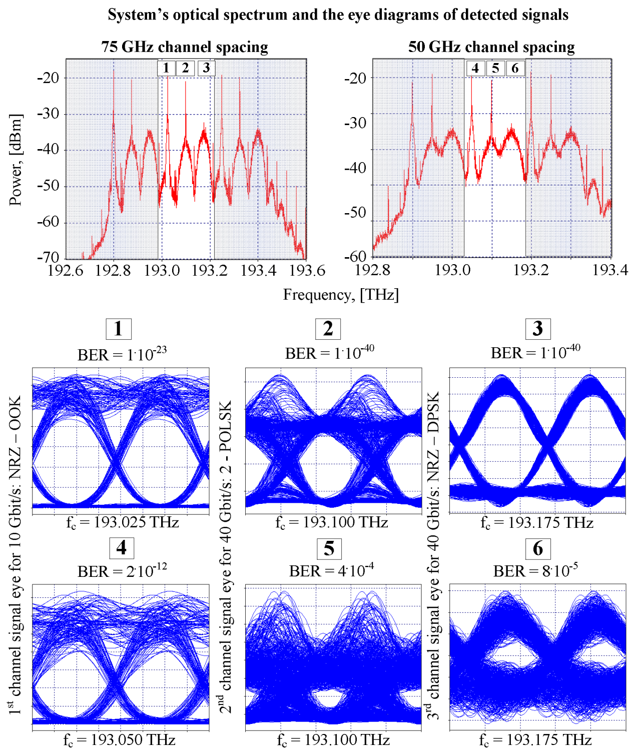


Fig. 3. Optical spectrum and the eye diagrams of detected signals for the [1^{st} channel: NRZ-OOK, R= 10 Gbit/s] – [2^{nd} channel: 2-POLSK, R= 40 Gbit/s] – [3^{rd} channel: NRZ – DPSK, R= 40 Gbit/s] 9-channel combined WDM systems at 75 and 50 GHz channel spacing values.

But in our investigated system for CD compensation 10 km of dispersion compensating fibre (DCF) is used and EDFA fixed output power level is attuned to 7 dBm to compensate the DCF insertion loss (Fig. 2). In addition, this EDFA power level secures the minimum BER value for the second system's channel. The similar CD compensation map is described in [11]. Standard single mode fibre (SSMF) length remains unchanged and is 50 km. 10 km of DCF, 7 dBm fixed output power level EDFA and 50 km span of SSMF forms the configuration of iteration loop (Fig. 2).

IV. RESULTS AND DISCUSSION

The aim of this research was to find out the maximum number of iteration loops for such configuration of WDM system to reach the maximum transmission distance with previously described permissible error probability. If optical signals are transmitted only over one loops then the worst system's channel is the second one (i.e. where 2-POLSK modulated signals are transmitted with 40 Gbit/s bitrate per channel, Fig. 4 (b)). Its BER is $8\cdot10^{-22}$ comparing with BER=$1\cdot10^{-40}$ which is detected in the similar system where

FBG instead of DCF is used for CD compensation (see the second eye in Fig. 3). The first channel's BER is $4\cdot10^{-31}$ (see Fig. 4 (a)) and it is for several orders lower than for initial system with FBG (i.e. BER=$1\cdot10^{-23}$, see the first eye in Fig. 3). By contrast, in both cases the BER values detected in the third system's channel are not larger than $1\cdot10^{-40}$ (Fig. 4 (a) and the third eye in Fig. 3). So, the changes in CD compensation map significantly affect 2-POLSK modulated optical signal transmission in our investigated combined WDM systems model. This may occur due to negative value of first order CD coefficient (-80 ps/nm/km) at the reference frequency (i.e. 193.1 THz) of used DCF.

If optical signals are transmitted over two iteration loops, the second channel's BER value is beyond the maximum permissible threshold of 10^{-16}. By contrast, the increases in BER value for the first and third system's channel are not sufficient ($4\cdot10^{-30}$ and $2\cdot10^{-38}$, respectively).

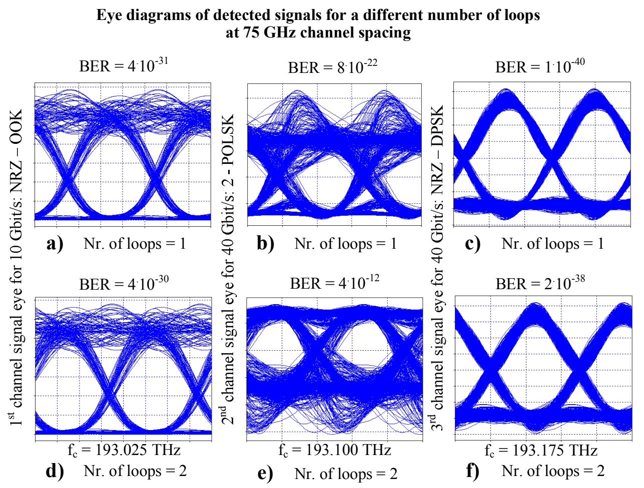


Fig. 4. In system's channels detected signals eye diagrams and BER values for a different number of iteration loops and 75 GHz channel spacing.

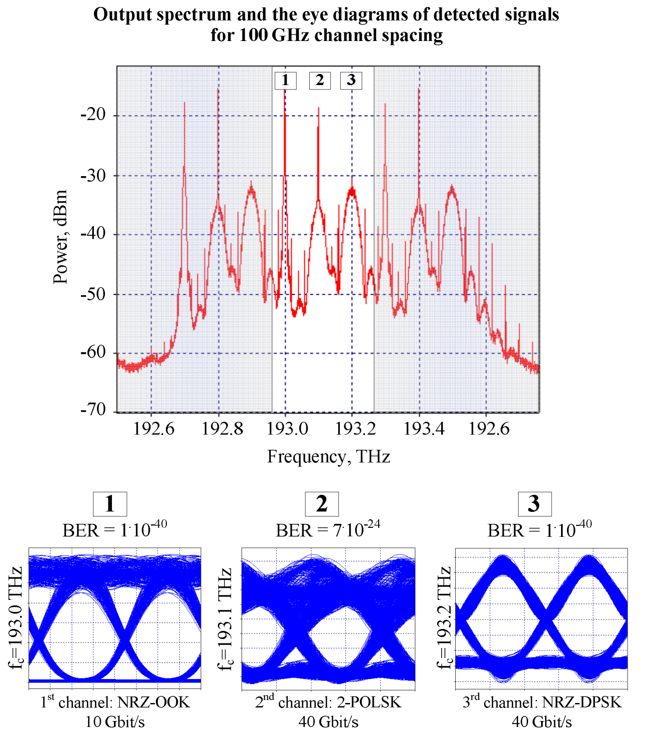


Fig. 5. Combined system's output spectrum, eye diagrams and BER values of detected signals if 100 GHz frequency intervals are used for channel separation.

To enlarge the maximum distance reach for investigated WDM system, it is necessary to increase the frequency intervals between the transmission channels. If we increase channel spacing from previous value of 75 GHz to 100 GHz value according to frequency grid suggested in ITU-T Recommendation G.694.1 then after the transmission over two loops in system's channel detected signals BER values do not exceed the maximum tolerated BER of 10^{-16} (Fig. 5). As one can see from it, the worst system's channel at this case is the second one (2-POLSK, 40 Gbit/s) and its BER is $7\cdot10^{-24}$ comparing with the first and third channels whom they are not larger than 10^{-40}. If we increase the number of iteration loops to three, then BER value of the second channel is already above the threshold of 10^{-16} and is equal to $2\cdot10^{-16}$ (Fig. 6 (b)). As for the rest system's channels for number of iteration loops equal to three, BER value for the first system's channel still do not exceed 10^{-40} but for the third one it increased up to $6\cdot10^{-28}$ (Fig. 6 (a) and (c)). So, at 100 GHz channel spacing and three iteration loops transmission fails only in the second system's channel.

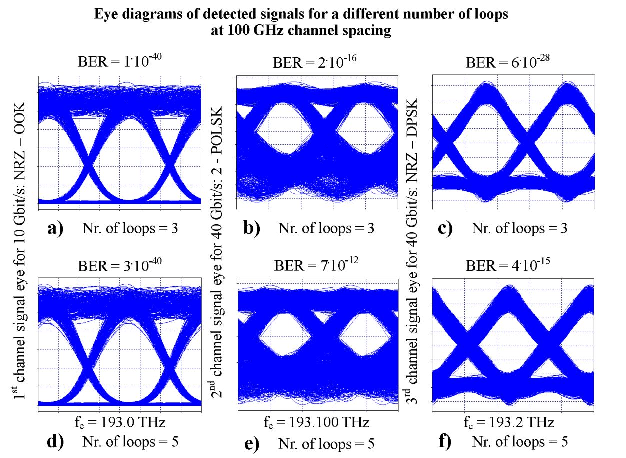
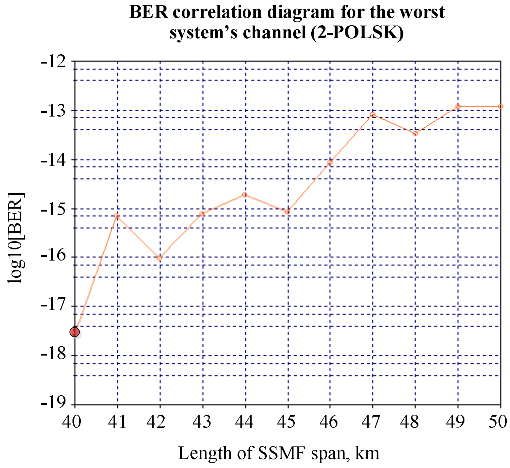


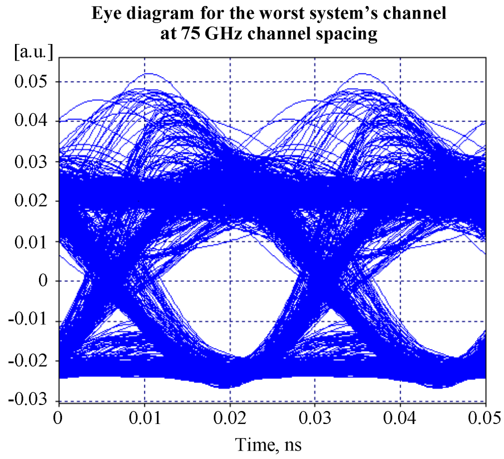
Fig. 6. In system's channels detected signals eye diagrams and BER values for a different number of iteration loops and 100 GHz channel spacing.

If we transmit optical signals over five iteration loops then signal detection in the second and third system's channel cannot be performed with the appropriate error probability. BER values in both channels exceed the maximum threshold of 10^{-16} and they are equal to $7\cdot10^{-12}$ and $4\cdot10^{-15}$, respectively.

Previously for the detection of the maximum number of loops we were dealing with SSMF span length equal to 50 km. By the reduction of this sector length, we can increase the number of loops maintaining the appropriate error probability for signal detection. As one can see from Fig. 7 (a) showing the BER correlation diagram for the signals detected in second system's channel (worst channel) after the two iteration loops then even if for channel separation 75 GHz intervals are used, its BER value are below the maximum threshold of 10^{-16} if used SSMF span length is equal to 40 km. In this case the worst system's channel (the second one) BER value is $3\cdot10^{-18}$ (Fig. 7 (b)), the first channel BER=$2\cdot10^{-31}$ and the third channel's BER is not greater than 10^{-40}. So, the maximum distance reach for this configuration of investigated WDM system (i.e., 75 GHz channel spacing and 40 km of SSMF span length) is two times greater than the length of SSMF span and is 80 km.



a)

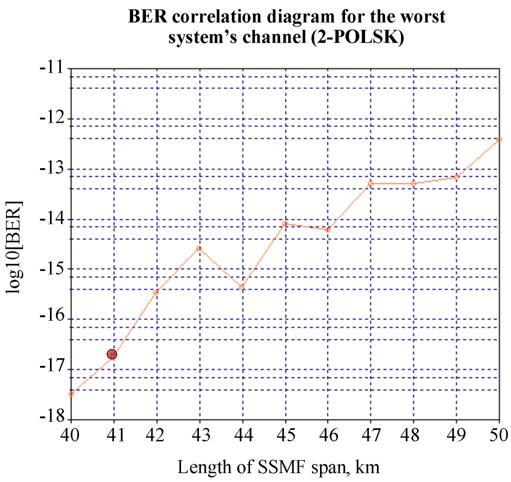


b)

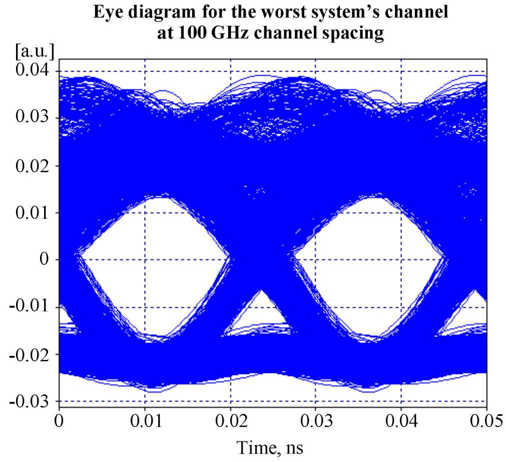
Fig. 7. Worst system's channel (2^{nd} channel: 2-POLSK, 40 Gbit/s): a) BER correlation diagram; b) detected signal eye diagram after two iteration loops consisted from 40 km of SSMF span length (BER=$3\cdot10^{-18}$) if for channel separation 75 GHz frequency intervals are used.

Optical signals can be detected with appropriate error probability if they are transmitted over four iteration loop consisted from SSMF span length not larger than 41 km (Fig. 8 (a)).

This refers to the investigated systems with 100 GHz channel spacing. In this case the worst system's channel is second one as well and its BER is $2\cdot10^{-17}$ (Fig. 8 (b)).



a)



b)

Fig. 8. Worst system's channel (2^{nd} channel: 2-POLSK, 40 Gbit/s): a) BER correlation diagram; b) detected signal eye diagram after four iteration loops consisted from 41 km of SSMF span length (BER=$2\cdot10^{-17}$) if for channel separation 100 GHz frequency intervals are used.

As for the rest of system's channels then the first channel BER is not larger than 10^{-40} but the third – $5\cdot10^{-25}$. If for such channel spacing we reduce the length of used SSMF to 40 km, then worst systems channel is the same as for the systems with 75 GHz channel spacing and is $3\cdot10^{-18}$, the first channel's BER is still not larger than 10^{-40} but the third – dropped to $6\cdot10^{-26}$.

So, the maximum distance reach for investigated WDM system with 100 GHz channel spacing is four times greater than length of SSMF span (i.e. 41 km) and is 164 km.

V. CONCLUSIONS

The maximum distance reach for spectrally efficient WDM system has been investigated in this paper. For this purpose WDM system with the following configuration was used: [1^{st}, 4^{th} and 7^{th} channels: NRZ-OOK, R= 10 Gbit/s, f_c=193.025 THz] – [2^{nd}, 5^{th} and 8^{th} channels: 2-POLSK, R=40 Gbit/s, f_c=193.100 THz] – [3^{rd}, 6^{th} and 9^{th} channels: NRZ-DPSK, R=40 Gbit/s, f_c=193.175 THz].

As one can see from this configuration, there are three different types of optical signal modulation used and optical signals are transmitted with two different bitrate per channel (i.e. 10 and 40 Gbit/s). If for channel separation 75 GHz frequency intervals are used, system's average spectral efficiency (SE) is equal to 0.40 bit/s/Hz. It is the worst case scenario and it provides the highest average BER value for the detected signals as compared with two other possible configurations (described above). So, we have investigated the maximum distance reach for the spectrally most efficient and the worst configuration of mixed data rate and signal formats WDM transmission system. The maximum distance reach was detected using iteration loops that consisted of DCM (i.e. 10 km of DCF), optical amplifier (i.e. +7dBm EDFA) and 50 km of SSMF span. One iteration loop corresponding to such configuration emulated one sector of fibre optic transmission line.

In our investigated WDM system optical signals can be successfully transmitted and then detected with appropriate error probability over:

– One iteration loop if 75 GHz frequency intervals are used for channel separation. In this case the system's average spectral efficiency is equal to 0.40bit/s/Hz and the system's maximum distance reach is equal to the length of SSMF span and is only 50 km;

– Two iteration loops if 100 GHz frequency intervals are used for channel separation. In this case the system's average spectral efficiency is equal to 0.30 bit/s/Hz and the system's maximum distance reach is two times greater than the length of SSMF span and is 100 km.

If we reduce length of the SSMF span to 40 km in WDM system with 75 GHz channel spacing that the maximum distance reach increases from one iteration loop to two loops and in this case it is 80 km. For investigated WDM system with 100 GHz channel spacing the maximum distance reach increases up to four iteration loops if we reduce the length of SSMF span to 41 km. In this case the maximum transmission distance is not larger than 164 km.

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