Investigation of Spectrally Efficient Transmission for Differently Modulated Optical Signals in Mixed Data Rates WDM Systems

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Abstract — **The authors have studied the possibilities to obtain the maximum spectral efficiency for a combined wavelength division multiplexing (WDM) system by minimizing the channel spacing. The fiber optic transmission systems under study can be considered in the context of next generation optical networks and is offered as a model for designing the future backbone networks. In the case of different telecom operators' optical networks merging, in the nearest future the necessity may arise to transmit variously modulated optical signals over a single optical fiber (even with different per channel bitrates). In this paper the authors show an optimal combined WDM system configuration that provides the least bit-error-rate values for the signals detected in system's channels. It is found that the minimal channel spacing for differently modulated optical signals in the investigated mixed data rates WDM system is 75 GHz if these signals are transmitted with 10 Gbit/s and 40 Gbit/s per channel bitrates. It is revealed that such a system's average spectral efficiency depends also on a combined system's configuration in the case of channel separation with equal frequency intervals.**

Keywords - wavelength division multiplexing (WDM); modulation formats; spectral efficiency; channel spacing; bit-error-rate.

I. INTRODUCTION

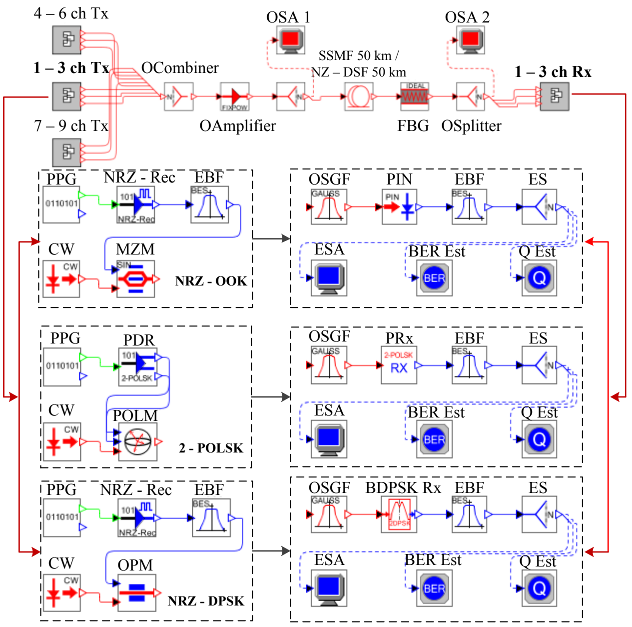
One of the major problems that will probably intensify within the next two or five years is capacity shortage in transmission systems. This trend is due to a rising number of worldwide internet users and the data volume itself requested per one user. As a result, the demand for transmission capacity and information throughout has risen steeply during the last few years [1, 2]. Besides, the expansion and variety of new online and broadband services as well as their rapid advance contribute to this continuous growth in the internet traffic. The existing transmission systems 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 [3, 4]. Currently, to ensure the needed carrying capacity of a transmission system and the data throughput of each individual channel the required bandwidth of backbone fiber optic transmission system (FOTS) networks is doubled every two years [5].

Since cost reductions and increased flexibility are and will be the main drivers for the evolution of all optical transport networks [6], currently one of the most intensively studied solutions for raising the system's total transmission capacity is improvement of its spectral efficiency (SE) through more effective use of approximately 60 THz bandwidth offered by silica optical fibers. In addition, the capacity rise strategy based on the use of already deployed infrastructure is among the most cost-effective ones. More efficient use of the channel bandwidth means that a greater number of informative bits can be transmitted employing one hertz it, i.e. 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). Obviously, the SE in WDM systems with traditional modulation formats (e.g., on-off keying with non-return to zero encoding (NRZ – OOK)) is much lower as compared with the systems where advanced modulation formats (together with additional multiplexing techniques) are employed for optical signal modulation. The maximum SE which can be obtained with traditional on-off keying (OOK) modulation formats is ~ 0.4 bit/s/Hz [7]. By contrast, in [8, 9, 10] it is reported that the use of such novel modulation formats as 16 – QAM (quadrature amplitude modulation) and orthogonal frequency-division multiplexing (OFDM) together with polarization division multiplexing (PDM) technique allows achieving SE>6 bit/s/Hz (and even 7 bit/s/Hz). The object of our study is the minimum allowable channel spacing in combined WDM systems that can ensure the optical signal detection with acceptable error probability and the maximum SE of channels. The offered model of this system can be considered in the context of next generation optical networks and is intended for designing the future backbone optical networks. Configuration of the WDM system was chosen based on evaluation of the current state of optical networks, the most probable trends in their development strategy, etc. [11, 12]. In the authors' opinion and respecting the principle of continuity and flexibility, the chosen optical signal modulation formats and per channel bitrates are the most appropriate and fitted for realization of a combined WDM system at the moment.

II. NUMERICAL ANALYSIS AND MODEL

A. Simulation scheme

In the paper, 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). A similar combined FOTS model and reasons for selecting these modulation formats have already been described by the authors in [2]. 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 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 (4^{th} - 6^{th} and 7^{th} – 9^{th}). 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 (see Fig. 1).



PPG – Pulse Pattern Generator
CW – Continuous Wavelength
MZM – Mach-Zehnder Modulator
POLM – Polarization Modulator
OPM – Optical Phase Modulator
EBF – Electrical Bessel Filter
OSGF – Optical Super Gaussian Filter
ES - Electrical Splitter
BDPSK Rx – Balanced DPSK Receiver
PRx – POLSK Receiver
PIN – PIN Photodiode
Q Est – Q factor Estimator
BER Est – Bit-Error-Rate Estimator
ESA – Electrical Signal Analyser

Figure 1. Simulation scheme of a developed nine-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.

Then the NRZ – OOK, 2 – POLSK and NRZ – DPSK modulated optical signals from transmitters are combined, optically preamplified by an erbium-doped fiber amplifier (EDFA) with optimal fixed output power and sent over 50 km of a standard single mode optical fiber (SSMF, according to ITU – T Recommendation G.652 D). The combined WDM system model was supplemented with EDFA to take into account amplified spontaneous emission (ASE) noise assuming that we are dealing with one sector of an ultra-long haul backbone optical network. The fiber length was chosen equal to 50 km in order to avoid a prohibitive growth in the ASE noise which occurs if the gain of EDFA exceeds 10 dB [2].

The optimal EDFA fixed output power level and the optimal power level radiated by distributed feedback (DFB) lasers in the continuous wavelength (CW) mode (which are used in the channels where NRZ – DPSK modulated optical signals are transmitted) were reported in [13] to be equal to 4 dBm and 3.5 dBm, respectively. The optimal value of these parameters ensures the lowest possible average BER of the detected signals in [1^{st} channel: NRZ – OOK, B = 10 Gbit/s, f_c = 193.075 THz] – [2^{nd} channel: 2 – POLSK, B = 10 Gbit/s, f_c = 193.100 THz] – [3^{rd} channel: NRZ – DPSK, B = 10 Gbit/s, f_c = 193.125 THz] combined system. For chromatic dispersion (CD) compensation in the case of 40 Gbit/s per channel bitrates a dispersion post-compensation module (DCM) is placed at the other fiber end before the optical power splitter. The used DCM is based on the chirped fiber Bragg grating (FBG) technology. This module compensates the CD level accumulated by a signal during its transmission over the whole optical fiber length. Then the optical signals are filtered with Super Gaussian optical filters, converted to electrical signals, filtered by Bessel electrical filters and, finally, detected.

Using this simulation scheme and the developed combined WDM system's model the minimum allowable channel spacing and spectral efficiency were found for every system with the following configuration: [1^{st}: NRZ – OOK (10 or 40 Gbit/s)] – [2^{nd}: 2 – POLSK (10 or 40 Gbit/s)] – [3^{rd}: NRZ – DPSK (10 or 40 Gbit/s)]. For performance evaluation the eye diagrams of detected signals and the system's output optical spectrum were obtained and further analyzed.

B. Simulation 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 [5]:

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

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, [$W^{-1}\cdot km^{-1}$]; t is the time, [s].

Solution for this equation is obtained using time domain split-step algorithm. The optical signal after propagation over Δz fiber span will then be described as follows [5, 14]:

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

where $\widehat{D}$, $\widehat{N}$ are linear and nonlinear operators [5, 14]:

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

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

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 [14]. The BER confidence interval depends on the total number of simulated bits [14]. As an example, we will assume a 95 % confidence interval for the BER as a function of the total number of simulated bits (N_{total}) at a 10^{-12} nominal (see Fig. 2).

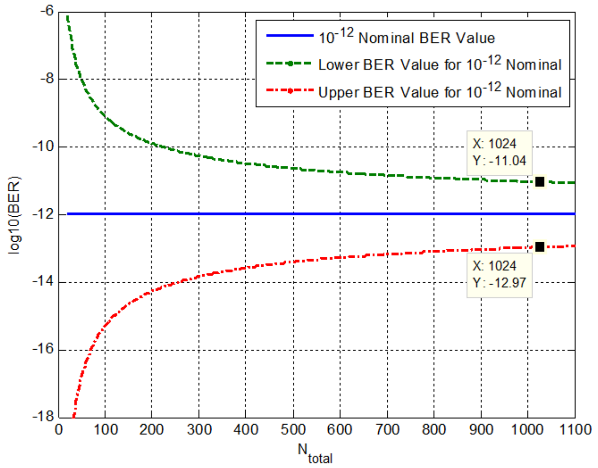


Figure 2. The 95 % confidence interval for a nominal BER=10^{-12}.

The 95 % confidence intervals for 1024 simulated bits and nominals of 10^{-12} and 10^{-16} (assuming the Gaussian distribution) are:

$$\lg\{BER_{for\ 10^{-12}}\} \in [-12.97; -11.04], \quad (5)$$

$$\lg\{BER_{for\ 10^{-16}}\} \in [-17.26; -14.64]. \quad (6)$$

As is seen from (5) and (6), the confidence interval for 1024 simulated bits and the nominal of BER = 10^{-12} is less than ±1 order, while for the nominal of BER = 10^{-16} it is less than ±2 orders. This evidences that OptSim software allows obtaining sufficiently accurate preliminary results.

III. Results and Discussion

According to the above mentioned combined WDM system configuration [1st channel: NRZ – OOK (10, 40 Gbit/s)] – [2nd channel: 2 – POLSK (10, 40 Gbit/s), 193.100 THz] – [3rd channel: NRZ – DPSK (10, 40 Gbit/s)], the minimum allowable channel spacing was studied for all eight possible mixed data rates of the system. These systems differ from each other only with per channel bitrates, whereas the distribution of modulation formats among the channels and the transmitting and receiving part configuration remain unchanged. The configuration of each investigated combined system will be clarified in further discussion of results obtained. The investigation of the minimum allowable channel spacing was carried out in order to achieve better utilization of the available frequency band and larger system channels' spectral efficiency. It should be noted that in this research minimum and equal channel spacing was set for each system. The channel spacing values were chosen based on the establishment principle of ITU – T Recommendation G.694.1.

Before analyzing the minimum channel spacing we will turn to combined WDM systems where optical signals are transmitted with equal per channel bitrates (only 10 Gbit/s or 40 Gbit/s). Previously it was mentioned that the optimal configuration of combined WDM system had been developed based on 10 Gbit/s per channel bitrate. Therefore it is of importance to find the minimum channel spacing exactly for this system.

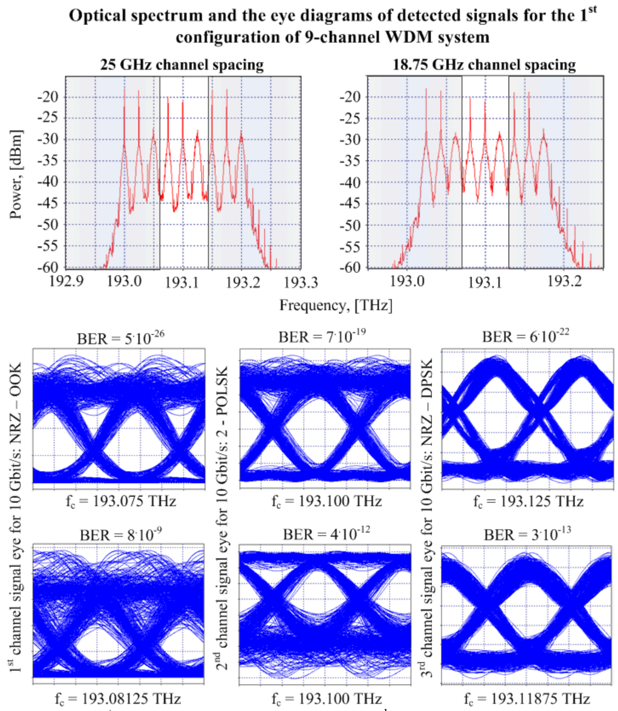


Figure 3. [1st: NRZ – OOK (10 Gbit/s)] – [2nd: 2 – POLSK (10 Gbit/s)] – [3rd: NRZ – DPSK (10 Gbit/s)] combined system's output spectrum and the eye diagrams of detected signals.

As could be seen from Fig. 3, if for channel separation in the [1st: NRZ – OOK (10 Gbit/s)] – [2nd: 2 – POLSK (10 Gbit/s)] – [3rd: NRZ – DPSK (10 Gbit/s)] combined system 25 GHz intervals are used, then the system's channel can easily be separated one from another using optical filters. As a result, linear and nonlinear crosstalk influence on the signal transmission will be negligible. In such a system's channels the eye diagrams of detected signals have "eyes" open enough, with noise and timing jitter influences being insignificant. As a consequence, the channels' BER values are sufficiently below maximum threshold (BER = 10^{-12}, see Fig. 3). In this case the system's worst channel is the second one, where 2 – POLSK modulated signals are transmitted (BER=$7 \cdot 10^{-19}$). The channel spacing reduction to 18.75 GHz leads to the transmission quality worsening. As is seen in the eye diagrams, the signal detection with an acceptable error probability is disturbed by high level noise due to inefficient separation of transmission channels. This is confirmed by the system's output optical spectrum for the 18.75 GHz channel spacing. Indeed, at such small channel spacing the system's channels are located so close together that they cannot be filtered even with efficient wavelength filters. As a result, BER of detected signals for the first and second system's channel is larger than the previously defined threshold. In this case the system's worst channel is the first one (NRZ-OOK), where the BER value is larger than 10^{-9}. Only in the third system's channel the received optical signals can be detected with the BER smaller than 10^{-12}.

If in all channels of a combined WDM system the optical signals are transmitted with 40 Gbit/s per channel bitrate, the minimum channel spacing is 100 GHz, which ensures that the BER values are lower than the maximum threshold (BER = 10^{-16}, see Fig. 4). In this case the worst system's channel with BER = $1 \cdot 10^{-14}$ is the first one (NRZ-OOK). Transmission in these channels are considerably distorted by adjacent NRZ-DPSK channels which are the sources of stronger interchannel crosstalk as compared with the NRZ – OOK or 2 – POLSK channels (see [13]). The best system's channel in this case is the channel where NRZ – DPSK modulated signals are transmitted with BER = 10^{-40} (see Fig. 4).

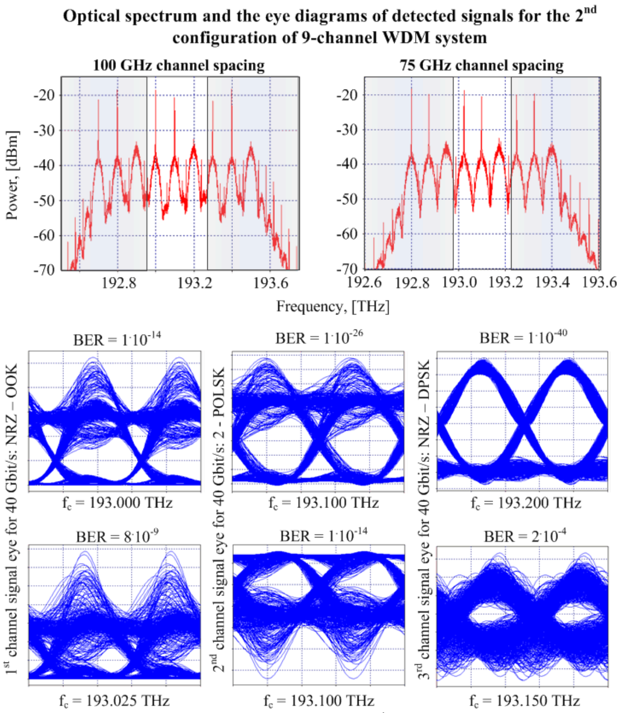


Figure 4. [1st: NRZ – OOK (40 Gbit/s)] – [2nd: 2 – POLSK (40 Gbit/s)] – [3rd: NRZ – DPSK (40 Gbit/s)] combined system's output spectrum and the eye diagrams of detected signals.

Channel spacing reduction to 75 GHz leads to inefficient filtering of channels, and, as a result, significant growth in the BER of detected signals. In this case the best system's channel is the third one, since its BER value at a 75 GHz channel spacing still corresponds to the maximum tolerated, i.e. BER<10^{-16} and is not larger than 10^{-40}. Transmission in this channel degrades only at a 50 GHz channel spacing; as a result, the third channel "eye" is almost closed and its BER value ($2 \cdot 10^{-4}$) is considerably larger than the previously defined maximum allowable threshold as compared with the first and second channel eye diagrams whose eyes almost closes already at 75 GHz (see Fig. 4). This is indicative of significant noise level and timing jitter of the detected signals.

In further discussion, we will analyze the channel spacing for 10 and 40 Gbit/s mixed data rate combined WDM systems. For convenience sake they were divided into two groups. The first one is combined WDM systems where only in one channel the optical signals are transmitted at 40 Gbit/s, while in the remaining two channels the per channel bitrate is 10 Gbit/s. The second group comprises the systems where in two channels the optical signals are transmitted at 40 Gbit/s, and only in one channel – with 10 Gbit/s.

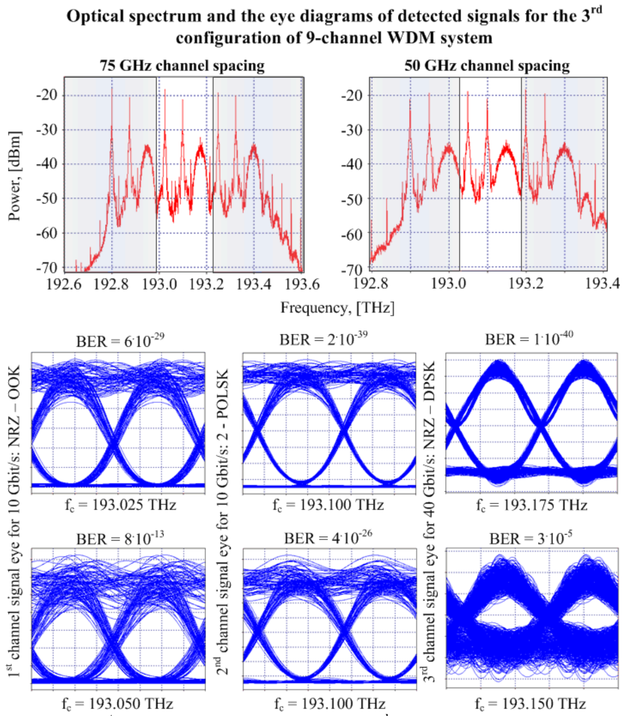


Figure 5. [1st: NRZ – OOK (10 Gbit/s)] – [2nd: 2 – POLSK (10 Gbit/s)] – [3rd: NRZ – DPSK (40 Gbit/s)] combined system's output spectrum and the eye diagrams of detected signals.

It was found that the third system's configuration: [1st: NRZ – OOK (10 Gbit/s)] – [2nd: 2 – POLSK (10 Gbit/s)] – [3rd: NRZ – DPSK (40 Gbit/s)] ensures the detected signal BER values that are the highest in a system's channels as compared with the fourth and the fifth configurations: [1st: NRZ – OOK (10 Gbit/s)] – [2nd: 2 – POLSK (40 Gbit/s)] – [3rd: NRZ – DPSK (10 Gbit/s)] and [1st: NRZ – OOK (40 Gbit/s)] – [2nd: 2 – POLSK (10 Gbit/s)] – [3rd: NRZ – DPSK (10 Gbit/s)], respectively. For these two configurations the detected signal BER values do not exceed 10^{-40} for all system channels if 75 GHz channel spacing is used. The third system's worst channel is the first one, where the 10 Gbit/s NRZ – OOK modulated signals are transmitted. At 75 GHz interval it's BER = $6 \cdot 10^{-29}$ (see Fig. 5).

If we reduce channel spacing to 50 GHz, the BER values for the system's first and second channels still fit maximum acceptable threshold (BER = 10^{-12}) which was previously defined for 10 Gbit/s. The highest BER value for these two channels is for the first one and it is equal to $8 \cdot 10^{-13}$. As for the worst system's channel at 50 GHz spacing, it is the third one. Its BER value far exceeds the maximum acceptable error probability of 10^{-16} and is equal to $3\cdot10^{-5}$. The fourth system's worst channel at 50 GHz is the second one, with BER = $4\cdot10^{-6}$. However, the best is the third channel, whose transmission does not fail even at 25 GHz (in this case BER=$8\cdot10^{-14}$). Transmission in the first channel of the 5th system fails at 50 GHz. Its BER for this channel spacing is equal to $1\cdot10^{-3}$, and the eye on the corresponding diagram is completely closed. However, transmission in the 5th system's second and third channel fails only at 25 GHz spacing (BER = $2\cdot10^{-7}$ and $2\cdot10^{-8}$, respectively).

The best configuration of a combined WDM system where optical signals are transmitted with 40 Gbit/s in two channels is the sixth one. It provides the lowest average BER value for the detected signals as compared with the seventh and the eight configurations: [1st: NRZ – OOK (40 Gbit/s)] – [2nd: 2 – POLSK (10 Gbit/s)] – [3rd: NRZ – DPSK (40 Gbit/s)] and [1st: NRZ – OOK (10 Gbit/s)] – [2nd: 2 – POLSK (40 Gbit/s)] – [3rd: NRZ – DPSK (40 Gbit/s)].

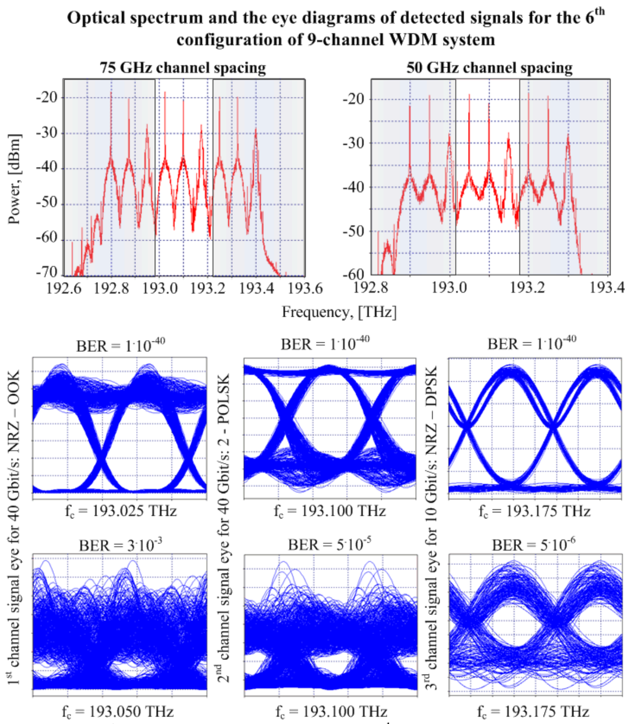


Figure 6. [1st: NRZ – OOK (40 Gbit/s)] – [2nd: 2 – POLSK (40 Gbit/s)] – [3rd: NRZ – DPSK (10 Gbit/s)] combined system's output spectrum and the eye diagrams of detected signals.

If for the channel separation a combined 6th configuration WDM system the 75 GHz intervals are used, the channels' 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 (see Fig. 6). In this case the NRZ – OOK and 2 – POLSK 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 $3\cdot10^{-3}$ and 5.10^{-5}, respectively. This value for the NRZ – DPSK channel exceeds the threshold of BER=10^{-12} only at 25 GHz interval and it is equal to $5\cdot10^{-6}$. Transmission fails in the 7th system's first and third channels at 50 GHz spacing, but the second channel's BER for such interval is still below 10^{-16} and equal to $3\cdot10^{-20}$. In contrast, the 8th system's transmission fails in all channels if 50 GHz intervals are used. The best channel at such spacing is the first one and its BER is equal to $2\cdot10^{-12}$.

In addition, for each configuration of the studied combined WDM systems the channels' average spectral efficiency was calculated. Assuming that we operate with discrete noiseless channels and all the sent information is received unchanged at the other end (i.e. BER →0), the system's average spectral efficiency (SE, [bit/s/Hz]) can be calculated by the following formula:

$$SE = \frac{\sum_{i=1}^{N} B_i}{N \cdot \Delta f}, \quad (7)$$

where N is a number of channels in a WDM system, [1]; B is the bitrate per channel, [10, 40 Gbit/s]; Δf is the channel spacing, [GHz].

As the result, the following values for spectral efficiency have been obtained: 0.40 bit/s/Hz for the 1st, 2nd, 3rd, 6th, 7th and 8th system's configurations, and 0.27 bit/s/Hz for the 3rd, 4th and 5th ones.

IV. Conclusions

The efficiency of transmission in mixed data rate WDM systems has been investigated for differently modulated optical signals. As the model of a developed combined WDM system meant for the future design of backbone optical networks a system of the following configuration is offered: [1st channel: NRZ – OOK (10 or 40 Gbit/s)] – [2nd channel: 2 – POLSK (10 or 40 Gbit/s)] – [3rd channel: NRZ – DPSK (10 or 40 Gbit/s)]. According to this configuration the minimum allowable channel spacing and the channels average spectral efficiency for eight different combined systems have been obtained and analyzed. These systems differ from each other in per channel bitrates. The minimum channel spacing that ensures the BER value of detected signals below the maximum threshold of 10^{-12} for 10 Gbit/s per channel bitrate and 10^{-16} for 40 Gbit/s is:

- 25 GHz if per channel bitrate (B) in each system's channel is equal to 10 Gbit/s;
- 75 GHz if at least in one system's channel B = 40 Gbit/s;
- 100 GHz if optical signals are transmitted with 40 Gbit/s per channel bitrate.

Based on these data, the channel's average spectral efficiency for each combined system's configuration has been estimated. It is equal to:

- 0.27 bit/s/Hz if only in one of the three channels of the system B = 40 Gbit/s;
- 0.40 bit/s/Hz if in all system's channels optical signals are transmitted with equal per channel bitrate (10 or 40 Gbit/s) or at least in two of the three channels that form the central group of a system's channels B = 40 Gbit/s.

An important point is that the channels' average spectral efficiency for each combined system's configuration was obtained for equal channel spacing. Significantly higher spectral efficiency could be achieved if for the channel separation in such mixed data rate WDM systems unequal intervals were taken.

Acknowledgment

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