Investigation of Spectrally Efficient Transmission in Mixed WDM Systems

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Abstract— The authors have investigated the minimal allowed channel spacing for developed mixed wavelength division multiplexing (WDM) systems in order to obtain the maximum spectral efficiency for system's channels. These fiber optic transmission systems can be considered under the concept of next generation optical networks and is offered as a model for the future design of backbone optical networks.

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 only contributes to this trend of increase of demand for information capacity [4]. The existing transmission systems will be unable to secure appropriate quality of service (QoS) level and fulfill service level agreements (SLA) if internet traffic keeps doubling every year as it is now [4, 5]. Currently to ensure the requested transmission system's carrying capacity and data throughput of each individual channel required bandwidth of backbone fiber optic transmission system (FOTS) networks is being doubled within a two year period [6, 7].

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. Channel's spectral efficiency can be increased in three different ways. The first one, the reduction of used system's channel spacing. 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 [8]. 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 [9, 10]. In a case of different telecom operators' optical networks convergence a necessity to transmit differently modulated optical signals over a single optical fiber even with different per channel bitrates may occur in the soon future. That is why our study object of this paper is the spectral efficiency of the developedmixed WDM system which model is offered for the future design of backbone optical networks and can be considered under the concept of next generation optical network (NGON) [2, 11, 12].

This paper is organized as follows: Section 2 describes the developed model of mixed data rates WDM systems; in the Section 3 authors reveal the accuracy of the obtained results; in Section 4 the results are discussed; Section 5 contains the main conclusions.

2. SIMULATION MODEL

In this paper, as mixed FOTS is offered 9-channel WDM system, where three different modulation formats are used for carrier signal modulation. The first one is the NRZ-OOK, which traditionally used modulation format for FOTS. The second one is the orthogonal binary polarization shift keying (2-POLSK) and the third one is the differential phase shift keying with non-return to zero encoding (NRZ-DPSK). System's channels are divided into three groups with identical configuration of transmitter and receiver as well as modulation formats distribution among channels but with only with different channels' central wavelengths. It was specially done to take into account linear and nonlinear crosstalk influences to optical signal transmission that are experience central's group channels (from the first to the third system channel) from channels of adjacent groups (4th–6th and 7th–9th. For system's performance further analysis we will use channels number 1–3, but 4–6 and 7–9 are used only as a sources of interchannel crosstalk (see Fig. 1).

Then NRZ-OOK, 2-POLSK and NRZ-DPSK modulated optical signals from transmitters are mixed, optically preamplified and send over 50 km of standard single mode optical fiber (SSMF according to ITU-T Recommendation G.652 D). Fiber span length was chosen equal to 50 km in order to avoid in a prohibitive growth of ASE noise which occurs if used EDFA gain is greater than 10 dB [2]. The optimal EDFA fixed output power level and the optimal power level radiated by distributed feedback (DFB) lasers in continuous wavelength (CW) regime, that are used in channels, where NRZ-DPSK modulated optical signals are transmitted, previously were obtained in [13] and is equal to 4 dBm and 3.5 dBm, respectively. For chromatic dispersion (CD) compensation in case of 40 Gbit/s per channel bitrates dispersion post compensation module (DCM) is placed on the other fiber end before optical power splitter. This module compensates CD level that is being accumulated by signal during transmission over whole optical fiber length. Then optical signals are filtered with Super Gaussian optical filters, converted to electrical signals, then filtered with Bessel electrical filters and then detected.

3. SIMULATION 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). For the evaluation of system performance will be used such parameter as BER value. 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. The BER confidence interval depends on the total number of simulated bits [14]. In our simulation we have simulated more than 1.024 bits and for such number of bits Q-factor uncertainty is less than 0.77 dB [14]. Using this value the 95% confidence intervals for 1024 simulated bits and nominals of 10^{-12} and 10^{-16} (assuming the Gaussian distribution) are:

$$\lg\{\mathrm{BER}_{\mathrm{for}10^{-12}}\} \in [-12.97; -11.04], \tag{1}$$

$$\lg\{\mathrm{BER}_{\mathrm{for}10^{-16}}\} \in [-17.26; -14.64]. \tag{2}$$

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

4. RESULTS AND DISCUSSIONS

According to the above mentioned configuration of mixed WDM system [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)], frequency plan of the channels' central wavelength allotment was studied for mixed per channel bitrates of the systems. In this research the investigation of maximum systems channels' spectral efficiency will be performed in order to achieve better utilization of the available frequency band. The channel spacing values were chosen based on the establishment principle of ITU-T Recommendation G.694.1.

Using the previously described configuration of developed mixed WDM system, six different systems with mixed data rates can be formed. All six studied WDM systems for convenience sake were divided into two groups. The first one contains 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.

It was found that the first 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 second and the third 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 first 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 $\mathrm{BER} = 6 \cdot 10^{-29}$ (see the 1st eye in Fig. 2(a)). If we reduce channel spacing to 50 GHz, the BER values for the system's first and second channels still fit maximum acceptable threshold of $\mathrm{BER} = 10^{-12}$ (see the 4th and 5th eye in Fig. 2(a)) which was previously defined for 10 Gbit/s. The highest BER value

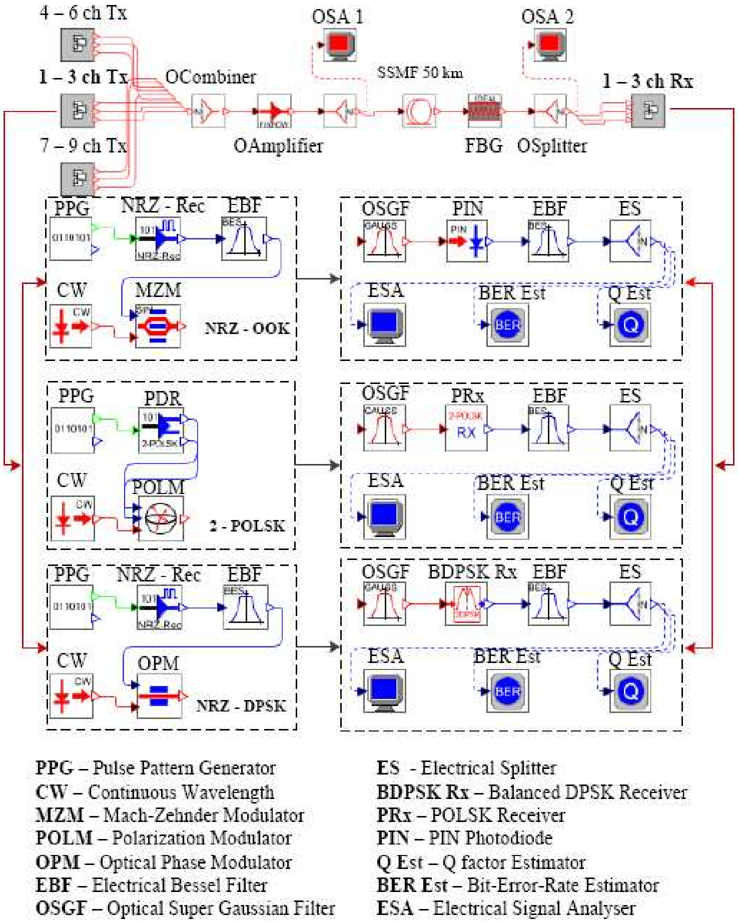


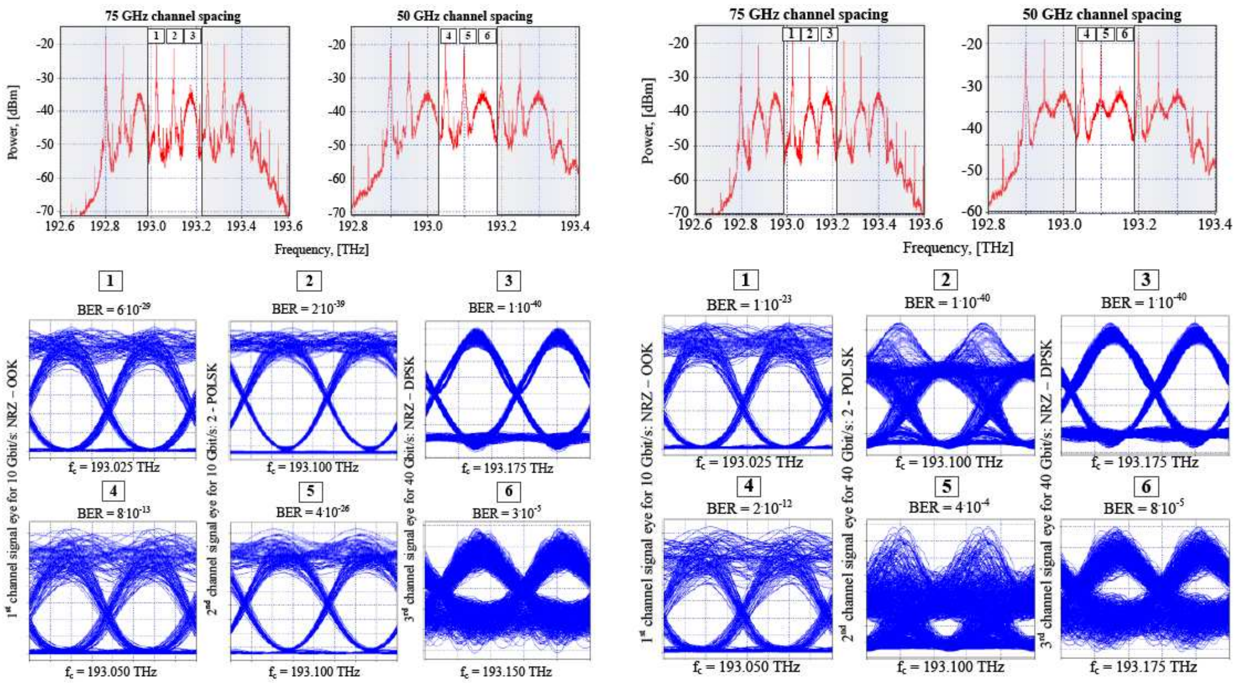
Figure 1: Developed 9-channel mixed WDM system simulation scheme and channels' transmitting and receiving parts block scheme for NRZ-OOK, 2-POLSK and NRZ-DPSK optical signals modulations formats.

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 $3 \cdot 10^{-5}$.

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

If for the channel separation in the 4th configuration of mixed WDM system the 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 $1 \cdot 10^{-23}$. 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 (see Fig. 2(b)). 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 $4 \cdot 10^{-4}$ and $8 \cdot 10^{-5}$ (see the 5th and 6th eye in Fig. 2(b)), respectively. Whereas NRZ-OOK channel's BER is $2 \cdot 10^{-12}$ at 50 GHz interval but it still is above the maximum tolerated error probability threshold of 10^{-12}.

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]) has been calculated for the each studied mixed WDM systems and is equal to: 0.40 bit/s/Hz for the 1st, 2nd and 3rd system's configurations, and 0.27 bit/s/Hz for the 4th, 5th and 6th ones.



(a) (b)

Figure 2: Optical spectrum and the eye diagrams of detected signals for the [1st: NRZ-OOK (10 Gbit/s)]-[2nd: 2-POLSK (40 Gbit/s)]-[3rd: NRZ-DPSK (40 Gbit/s)] 9-channel combined WDM systems at 75 and 50 GHz equal channel spacing: (a) [1st: NRZ-OOK (10 Gbit/s)]-[2nd: 2-POLSK (10 Gbit/s)]-[3rd: NRZ-DPSK (40 Gbit/s)]; (b) [1st: NRZ-OOK (10 Gbit/s)]-[2nd: 2-POLSK (40 Gbit/s)]-[3rd: NRZ-DPSK (40 Gbit/s)].

5. CONCLUSION

The authors have investigated the spectral efficiency of purposed mixed WDM system. This system's model is offered for the future design of the transport optical networks and complies with the following configuration: [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 and equal frequency intervals values between two adjacent channels have been obtained and analyzed for six different WDM systems with mixed per channel bitrates and signals' formats. It is found out that the minimum channel spacing to such WDM systems is not from ITU-T G.694.1. grid and is equal to 75 GHz if optical signals are transmitted with 10 and 40 Gbit/s per channel bitrates. As well as, such system's average spectral efficiency depends on the particular configuration of mixed system. SE is equal to: 0.27 bit/s/Hz if only in one of the three channels of the system $B = 40\,\text{Gbit/s}$; 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 $B = 40\,\text{Gbit/s}$.

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