Evaluation of Nonlinear Effect Impact on Optical Signal Transmission over Combined WDM System

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Abstract— The authors have investigated the impact of nonlinear distortions to optical signal transmission over proposed configuration of combined wavelength division multiplexed (WDM) fiber-optic transmission system (FOTS). In chosen model of ultra-dense combined WDM system optical signals are transmitted with two different per channel bitrates (i.e., 10 and 40 Gbit/s) and three different optical signal modulation formats are used for the encoding of transmitted data body (i.e., non-return to zero encoded on-off keying or NRZ-OOK, orthogonal polarization shift keying or 2-POLSK and NRZ encoded differential phase shift keying or NRZ-DPSK) and in addition "non ITU-T" defined minimum and equal frequency intervals are used for the channels separation.

1. INTRODUCTION

The transmission throughput over the existing wavelength division multiplexed (WDM) fiber-optic transmission systems (FOTS) can be increased in the following manner: using higher per channel bitrates, narrower channel spacing or wider amplifier bandwidth [1–3]. So, the increase of "for WDM-suitable" band utilization (or increase of spectral efficiency) allows to reduce the number of channel required for the transmission of the same data body as compared with relatively spectrally inefficient WDM systems (i.e., SE < 0.2 bit/s/Hz) [4]. As well as allows postpone the shortage of "for WDM-suitable" band and avoid the deployment of new optical fibers [7]. That is why the method of increase of transmissions SE has some characteristics that are adequate for future needs and requirements of continuous traffic growth.

Obviously, it is necessary to evaluate the impact of all fiber nonlinearities to optical signal transmission over the purposed model of combined-WDM system designed for the future optical transport networks. Hence, two different nonlinear impacts are analyzed in this paper: optical signal self-phase modulation (SPM) and cross-phase modulation (XPM), while four waves mixing (FWM) and scattering process are planned for further research efforts.

This impact occurs from the increased power levels coupled to the optical fiber as well as due to variations of fiber's dispersion coefficient [8, 9]. Note that data in investigated combined-WDM systems are encoding by manipulation with optical signal's freedom degrees such as intensity, phase and state of polarization. In accordance with each freedom degree and respecting previous researches (e.g., [4, 10]) the most applicable modulation format has been chosen: non-return to zero encoded on-off keying (NRZ-OOK), NRZ encoded differential phase shift keying (NRZ-DPSK) and orthogonal binary polarization shift keying (2-POLSK). The similar combined or hybrid WDM systems currently are starting to appear as the result of upgrade of existing transport infrastructure [2, 5].

2. NUMERICAL ANALYSIS AND MATHEMATICAL MODEL

In this paper, the impact of nonlinear optical effects (NOE, SPM and XPM particularly) on optical signal transmission have been mainly analyzed for the 9-channel combined-WDM systems that complies with the following scheme of configuration: [1st ($f_c = 193.025$ THz), 4th and 7th channels: NRZ-OOK, $R = 10$ Gbit/s] — [2nd ($f_c = 193.100$ THz), 5th and 8th channels: 2-POLSK, $R = 40$ Gbit/s] — [3rd ($f_c = 193.175$ THz), 5th and 9th channels: $R = 40$ Gbit/s].

The detailed configuration and the main blocks of simulation model in RSoft Design Group, Inc. software OptSim 5.2 is shown on Fig. 1. The basic system's configuration such as the modulation format distribution among the channel as well as the basic parameters of transmitting and receiving units such as optical filter type, bandwidth and order have been obtained in [10] but the minimum and equal channel spacing value acceptable for signal detection on the other fiber end with appropriate error probability below the maximum permissible threshold have been obtained in [4]. The investigated configuration represents the "worst case scenario" since have a higher average BER value for signals detected as compared with the rest of possible configurations [4, 10]. Optical signal booster and pre-amplifier have been placed after the multiplexer and before the demultiplexer, respectively, for achieving the expressions of the fiber nonlinearities. The part of

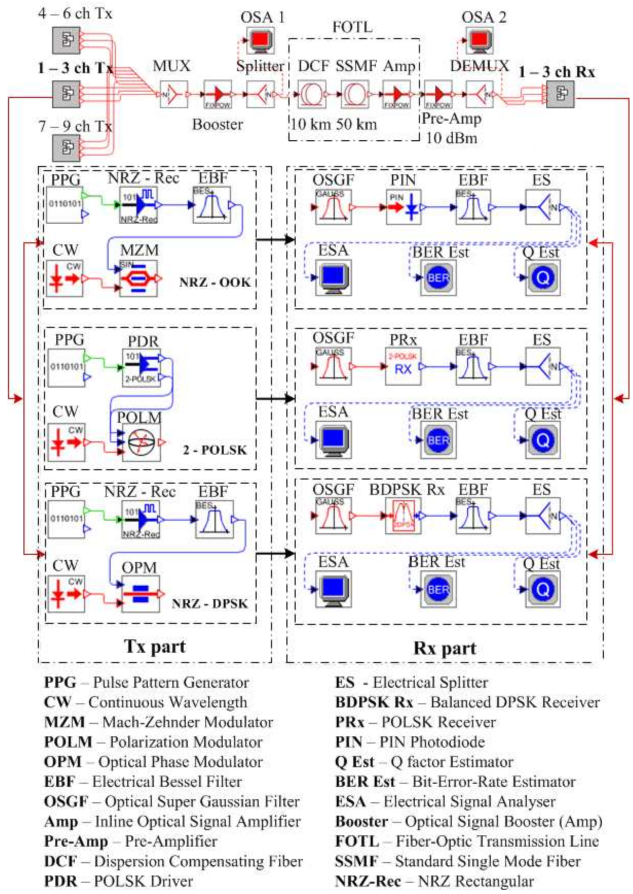


Figure 1: The configuration of simulation scheme in OptSim 5.2 used for the evaluation of self-phase modulation impact on optical signal transmission over the ultra-dense WDM system with combined data rates and signal formats; the blocks of transmitting and receiving units for NRZ-OOK, 2-POLSK and NRZ-DPSK signal formats.

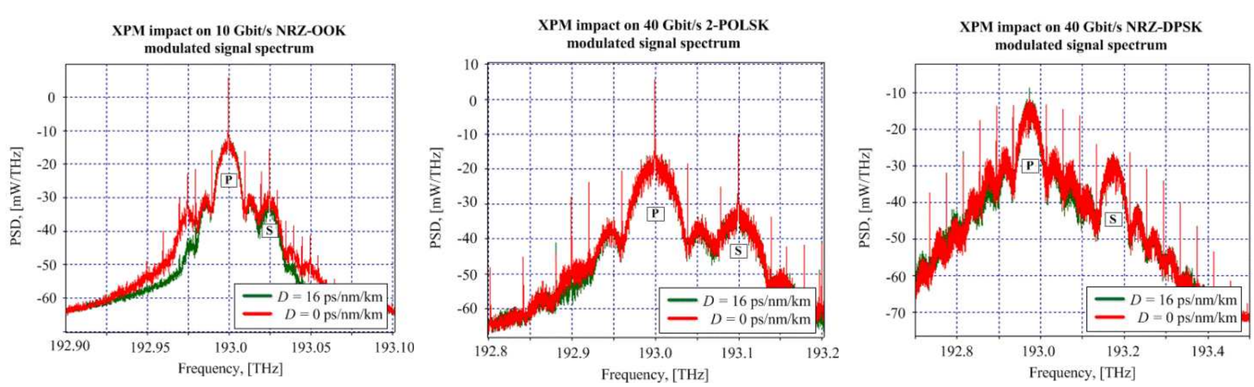
fiber-optic transmission line consists of chromatic dispersion (CD) compensation module (DCM) based on DCF, standard single mode fiber (SSMF, ITU-T Recommendation G. 652) and inline fixed output power EDFA. The fixed output power level was changed exactly for the booster and inline amplifier, whereas it remained unchanged and equal to 10 dBm for pre-amplifier. During the simulations we have analyzed the NOE while others impacts such as amplified spontaneous emission (ASE) noise and other fibers nonlinearities (e.g., FWM, Brillouin scattering and Raman crosstalk) are being ignored. The 10 km of DCF (dispersion coefficient at 1550 nm is -80 ps/nm/km, its core effective area is $20 \cdot 10^{-12}\,\mathrm{m}^2$ and fiber non-linearity coefficient is 5.071/W/km) compensates CD that optical signal will accumulated during the transmission over 50 km of SSMF (dispersion coefficient at 1550 nm is 16 ps/nm/km, its core effective area is $80 \cdot 10^{-12}\,\mathrm{m}^2$ and fiber non-linearity coefficient is 1.271 /W/km). In further researches the number of such FOTL can be increased for the evaluation of system performance after the transmission over several such sectors (using the principle of iteration loops already described in [10]).

3. RESULTS AND DISCUSSIONS

This research revealed the maximum output power level of EDFA at which the BER values for the single channel as well as multichannel FOTS are still fulfill the requirements addressed to the maximum permissible error probability for signal detection. As well as it is analyzed the influence of fiber's first order dispersion coefficient variations to optical signal distortions (and increment of detected signals BER value) rose due to SPM and XPM. Before the analyze such impact to signal transmission over the spectrally efficient multichannel WDM FOTS with combined data rates and signal formats, let is evaluate their impact on single channel FOTS performance.

WDM system detailed described in previous section, the NRZ-OOK modulated optical signals with 10 Gbit/s per channel bitrate are transmitted in the first system's channel. If such signals are transmitted in single channel FOTS, the BER value of detected signals exceed the maximum permissible threshold of 10^{-12} if the booster and inline optical amplifier's fixed output power level is larger than 18 dBm. Note that the central wavelength value of each channel in single channel FOTS are as similar as in 3-channel combined-WDM FOTS and the configuration of FOTL units remains unchanged. The similar effect of BER value improvement in combined-WDM system in comparison with traditional systems with one modulation format has been described in [11]. FOTL structure was modified as compared with depicted in Fig. 1 in order to analyze the influence of SSMF first order dispersion coefficient variations to the changes of signals' BER values due to XPM. In addition, 10 Gbit/s NRZ-OOK, 40 Gbit/s 2-POLSK and 40 Gbit/s NRZ-DPSK modulated signals were transmitted not over one span of SMF but two in order to become more evident changes on detected signal spectrum.

Instead of dealing with one channel FOTS as it was for SPM, here we placed two channels. One of them is so-called pump channel but the second one is the probe channel containing informative signal. For 10 Gbit/s NRZ-OOK signal, channel spacing between pump and signal channel is 25 GHz, 100 GHz for 40 Gbit/s 2-POLSK and 200 GHz for 40 Gbit/s NRZ-DPSK (see Fig. 2). 10 Gbit/s NRZ-OOK signal spectrums sufficiently changes and its left part broadens if SMF dispersion coefficient is close to 0 ps/nm/km (see Fig. 2(a)). As for the 40 Gbit/s 2-POLSK and NRZ-DPSK signals, the spectrum distortions are almost no noticeable (see Figs. 2 (b)–(c)). 40 Gbit/s 2-POLSK channel power increases but by less than 0.1 dBm if dispersion coefficient is around 0 ps/nm/km as compared with the power levels at $D = 16$ ps/nm/km/. Whereas, for 40 Gbit/s NRZ-DPSK channel, it is almost constant (see Fig. 3). Such power level variations of filtered channel lead to some evidence changes in detected informative signals Q-factor values (see Fig. 4). For 40 Gbit/s 2-POLSK channel, it decreases by 0.8 dB whereas, 40 Gbit/s NRZ-DPSK channels experiences some Q-factor increase, if a value of dispersion coefficient is close to 0 ps/nm/km. In contrast, power level of filtered informative 10 Gbit/s NRZ-OOK channel increases sufficiently (by more than 1 dB), if dispersion coefficient changes from 16 to 0 ps/nm/km. Q-factor value decreases as it is shown in Fig. 4. The gradual increase of the fixed output power levels of booster and inline optical amplifiers allows obtaining in system's channel detected signal BER correlation diagram for each channel. As can be seen in Fig. 5, the first channel's BER value is sufficiently below the 10^{-12} even if power levels of optical amplifiers are larger than 25 dBm. In this case, the 1st channel's BER $= 5 \cdot 10^{-23}$ and the detected eye diagram evidences only about small amount of "1" amplitude jitter. The third channel's BER exceeds the maximum acceptable error probability of 10^{-16} only at 19 dBm. At 18 dBm the BER for this channel is equal to $1 \cdot 10^{-19}$ and the detected eye diagram evidences about some noticeable timing jitter that reduces the eye opening. As for the second system's channel where 2-POLSK modulated signals are transmitted with 40 Gbit/s per channel bitrate, then its BER values obtained for such power level range of booster and inline optical amplifier are exceeding the maximum permissible threshold of 10^{-16}. At 4 dBm its value is equal to $3 \cdot 10^{-7}$. As can be seen from the eye diagram obtained for this channel, it is very noisy with lot of an amount of amplitude jitter. The eye opening width is not enough for securing of signal detection with appropriate error probability below the maximum acceptable threshold.Variations of BER values of 40 Gbit/s 2-POLSK channel is non-essential depending on fiber's dispersion coefficient (see green



(a) (b) (c)

Figure 2: XSPM and XPM impact on modulated signal spectrum: (a) 10 Gbit/s NRZ-OOK; (b) 40 Gbit/s 2-POLSK; (c) 40 Gbit/s NRZ-DPSK, where P is the pump signal and S is probe or informative signal.

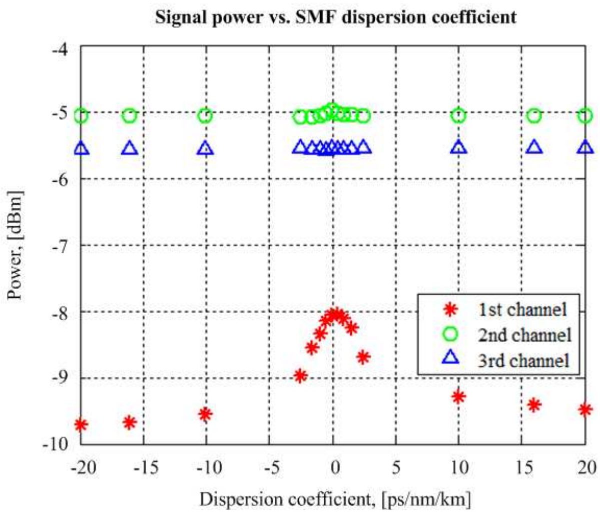


Figure 3: Filtered informative signal power in function of SMF dispersion coefficient.

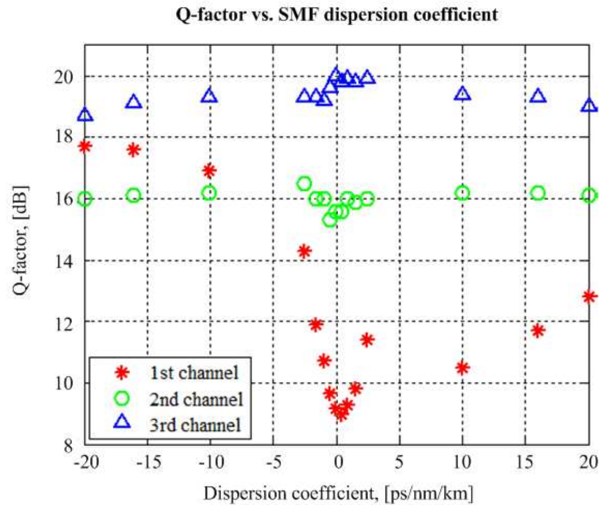


Figure 4: Detected informative signal Q-factor value in function of SMF dispersion coefficient.

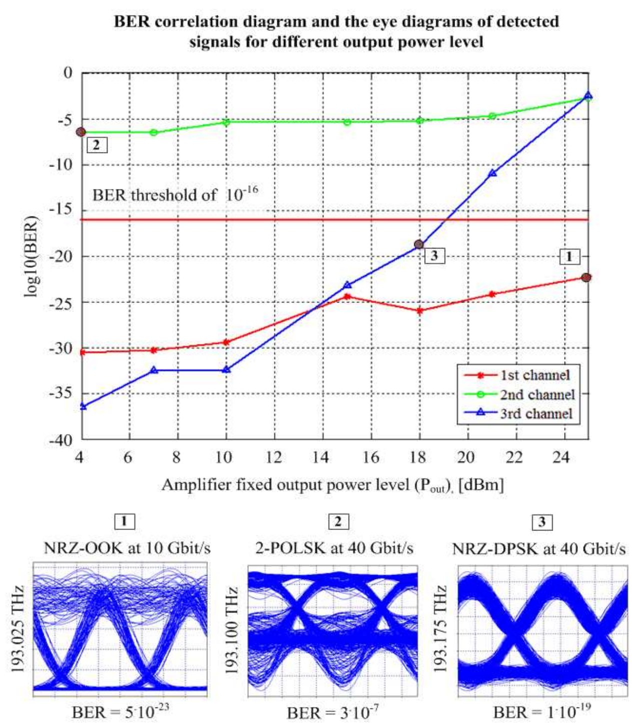


Figure 5: BER correlation diagram for the central systems channels (i.e., those with number 1–3) that represents BER as a function on the output power level of optical signal amplifiers (booster and inline amplifier) and the eye diagrams of each channel for the maximum tolerable amplifiers' output power levels.

curve in Fig. 5) and these values in all investigated range sufficiently exceed defined threshold. They vary around the value of 10^{-6}, so in such spectrally efficient combined-WDM system some FEC technique must be used.

4. CONCLUSIONS

As for the spectrally efficient combined-WDM system in which 75 GHz non ITU-T defined but equal frequency intervals are used for channel separation, then transmission in the first channel (10 Gbit/s NRZ-OOK) does not fail even at 25 dBm of amplifiers output power levels. In the third channel (40 Gbit/s NRZ-DPSK) it fails only at 18 dBm, whereas in the second channel (40 Gbit/s 2-POLSK) fails already at 4 dBm and in this channel detected signals cannot be performed with appropriate error probability below 10^{-16}. Similar "bad" performance of 40 Gbit/s 2-POLSK channel is observed after the evaluation of dispersion coefficient influence to the detected BER values. To sum up, comparing the performance of two 40 Gbit/s channels we have to conclude that 2-POLSK modulated signals are more susceptible to the impact of fiber nonlinearities (i.e., SPM particularly) in such ultra-dense combined transmission mode than NRZ-DPSK signals. As result, transmission fails in this 2-POLSK channel and some FEC technique must be used to secure signal detection with appropriately low BER.

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