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Conference Article

Modelling and Performance Analysis of Modulation Formats and Dispersion Compensation Schemes in a High-Speed Optical Communication Network

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Abstract

The main subject of study and analysis in this paper is the single-channel optical communication network. A comparative analysis and evaluation of network performance is presented for different possible scenarios: 10 to 40 Gbps network bandwidth, NRZ and two RZ based formats for optical signal modulation, as well as applying symmetrical dispersion compensation scheme (DCS), and pre- or post-compensation scheme. In the performance analysis, the optimal input power of the optical signal is determined by evaluating the signal parameters and the obtained BER characteristics for the different operating scenarios.

Keywords: NRZ; RZ; CSRZ; Dispersion compensation; Optical power level, Single channel.

1. Introduction

The optical signal modulation process in optical access networks has a direct impact on the quality of service and the system performance. The efficiency and performance of the optical transmission network are evaluated and analyzed on the basis of the obtained values of the BER and the Q-factor. Their values can be optimized by using the appropriate encoding of the optical signals. Three modulation formats are taken into account in this paper: NRZ (Non-Return to Zero), RZ (Return to Zero) and one of the RZ-based formats, which is called CSRZ (Carrier-Suppressed Return to Zero) [1].

The theory of signal modulation is well known [2], however considering their characteristics, the main challenge is to formulate recommendations and scenarios for their appropriate use according to transmission line parameters in the design process. In the similar way, the task with choosing the appropriate dispersion compensation schemes (DCS) is also important: pre-compensation, post-compensation or symmetrical compensation scheme [3].

Simulation models are proposed to investigate the network performance. They are developed for optimization purposes in the design processes of high-speed single-channel optical communication networks. The main objective is to find a complex solution in terms of ensuring the given distance transmission [4], high Q-factor [5], lower value of BER, appropriate time and frequency domain (spectral) characteristics, as well as the of optical energy balance and energy budget in the line [6], considering some important physical limitations, characteristics of the components in the system, the nonlinear effects and the effects of attenuation and dispersion in the fiber, the total number of amplifying spans [7], the selected dispersion compensation scheme and the inserted noise influence. The proposed models could be successfully used in the planning and design of high-speed single channel optical communication networks and it is an extension of [8].

2. Implementation of the simulation model

2.1. Implementation of a main simulation model

The main simulation model of a high-speed optical communication network is implemented in the Optiwave Optisystem environment, and it includes:

- an optical transmitter with modulator – this is a macro block that contains an optical transmitter (at center wavelength of 1,55 μm) and an external modulator – RZ, NRZ or CSRZ;
- an optical transmission line with optical amplification and dispersion compensation – this core part of the model consists of 10 amplifying sections at 50 km length each, giving a total transmission line length of 500 km. Each of the amplifying sections includes EDFA amplifiers to compensate the signal attenuation along the line as well as 10 km long dispersion compensation fiber (DCF).
- an optical receiver that consists of a photodetector and filters;
- blocks for measuring signal parameters (optical power and OSNR) and blocks for visualization of signal characteristics (optical spectrum, time diagram, eye-diagram and BER characteristics) – they are located at the input, output and at different control points of the optical transmission line.

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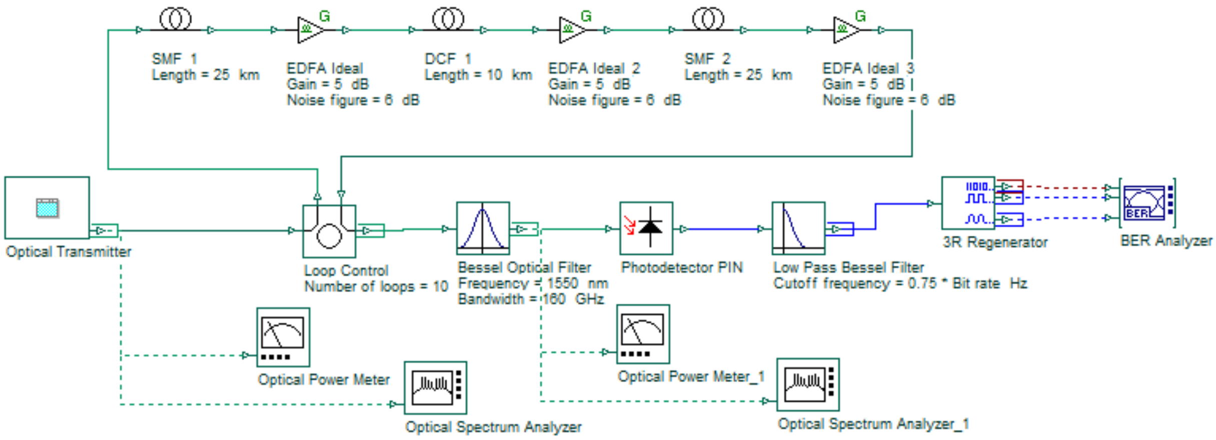

Fig. 1. Proposed model for simulation of single-channel optical communication line with symmetrical DCS

The developed model with symmetrical dispersion compensation is shown as an example in Fig. 1.

2.2. Modeling of optical transmitters with modulators

The first scenario involves an laser source, which is externally modulated by NRZ pulse generator and the Mach-Zehnder modulator. The signal can be assumed to have the NRZ pulse shape, where each mark in the pseudorandom bit sequence corresponds to the equivalent base band pulse $s_{NRZ}(t)$.The energy contained in one mark will be:

$$E_{NRZ} = \int_{-\infty}^{+\infty} \left| s_{NRZ}(t) \right|^2 \quad (1)$$

The second scenario involves an laser source, which is with external NRZ modulation – Fig. 2. The parameters of the NRZ generator are: rise time = 0,15 bit and fall time = 0,25 bit.

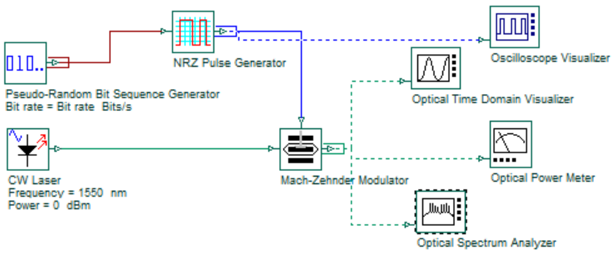

Fig 2. Model of externally NRZ modulated optical transmitter

The RZ modulated signal $s_{RZ}(t)$ (second scenario) is obtained by using the NRZ pulse generator and Mach-Zehnder modulator. The optical pulse in this case is narrower than the period of bits. The modulation frequency will be equal to the data rate and duty cycle of 50%. The phase of the signal depends on the modulation voltages $V_1(t)$ and $V_2(t)$: π is the modulating voltage required for a phase shift of π, changing the modulator transmission from the maximum to minimum value [6]. The modulating voltage $V_{RZ}(t)$ will be:

$$V_{RZ}(t) = \frac{V_{RF}}{2} + \frac{V_{RF}}{2}\cos\left(\frac{2\pi t}{T_b}\right), \quad (2)$$

where T_b is the bit duration, and V_{RF} – radiofrequency voltage.

The optical transmitter model with RZ modulation is shown in Fig. 3. In order to obtain a 50% duty cycle, the RZ impulse generator setting parameters should be as follows: duty cycle = 0,5 bit, rise time = 0,05 bit and fall time = 0,05 bit.

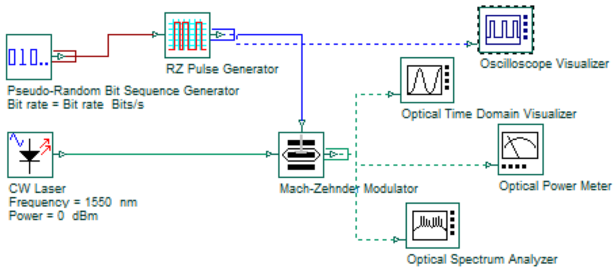

Fig 3. Model of externally RZ modulated optical transmitter

A 65% duty cycle will be obtained when the modulation frequency is half the data rate. This format is called carrier suppressed return to zero format (CSRZ). The modulating voltage $V_{CSRZ}(t)$ will be:

$$V_{CSRZ}(t) = V_{RF} + V_{RF}\cos\left(\frac{\pi t}{T_b}\right). \quad (3)$$

The model of optical transmitter with CSRZ modulation is shown in Fig. 4. Initially, the electrical input binary signal is NRZ encoded in a NRZ pulse generator block whose parameters are: rise time = 0,01 bit and fall time = 0,01 bit. The first modulator was implemented using a LiNb Mach-Zehnder Modulator block. A single sinusoidal signal generator controls the second LiNb Mach-Zehnder Modulator. The generator frequency is equal to B/2 (where B is the line bandwidth) and the signal phase is –90º.

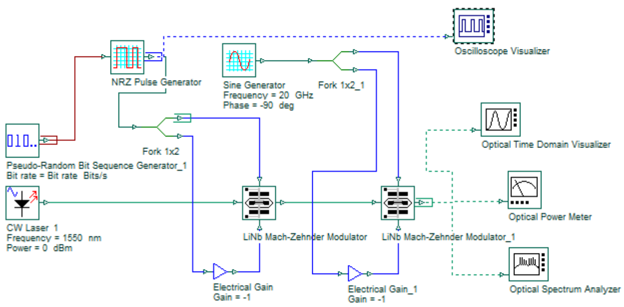

Fig 4. Model of externally CSRZ modulated optical transmitter

2.3. Modeling the optical transmission line

The transmission channel model is shown on Fig. 5. It consists of 10 amplifying sections (50 km each) with a total length of 500 km.

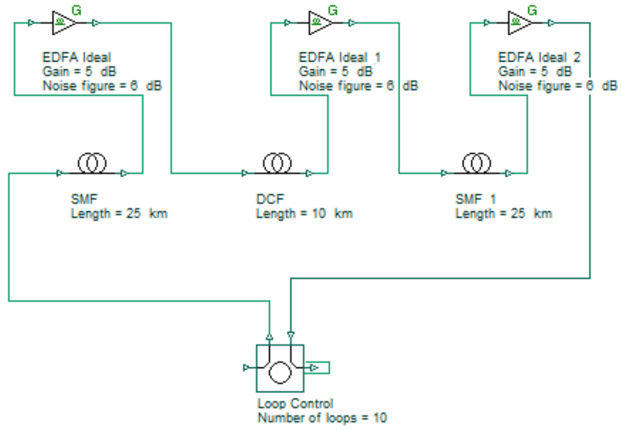

Fig 5. Transmission channel model with symmetrical DCS

The required number of 10 amplifying sections is achieved by using the loop control block. Each amplifying section consists of: two standard single mode optical fibers (SMF) 25 km in length each, i.e. overall length of the amplifying section 50 km; DCF fiber of 10 km length; three EDFA (Erbium-Doped Fiber Amplifier) optical amplifiers to compensate the signal attenuation along the optical fibers in each amplifying section.

To design a model with dispersion pre-compensation scheme (pre-DCF), a 10 km long DCF fiber is placed ahead of the standard SMF fiber with length of 50 km.

For dispersion post-compensation scheme (post-DCF), the DCF fiber is placed after the standard SMF fiber with length of 50 km.

Two EDFA amplifiers are used for pre-DCF and post-DCF dispersion compensation.

2.4. Modeling the optical receiver

The optical receiver model is shown in Fig. 6.

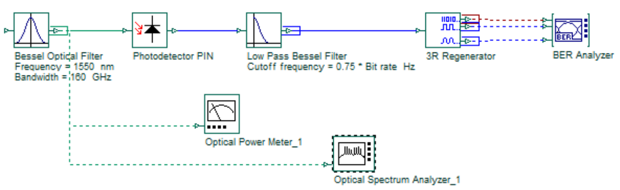

Fig 6. Optical receiver model

At the input of the optical receiver, the optical signal enters in the Bessel optical filter for primary band-pass filtration to remove the nonlinear distortion products. The filter bandwidth is 4 x Bit rate = 4 x 40 Gbps = 160 GHz. Then follows the detection and transformation of the optical signal into electrical, which is carried out in a block Photodetector PIN. The electrical signal is subjected to fine filtering in the low-pass Bessel 4th row filter with cutoff frequency equal to 0,75 x Bit rate [9].

2.5. Simulation conditions and criteria

A series of iterations were performed to determine the optimal value of a particular parameter, which in this case is the value of the input optical power P_{TX} (introduced by the optical transmitter). The iterations are performed at fixed values of the other parameters: given signal modulation type and DCS scheme. The optimal parameter value is determined on the basis of a test criterion.

The secondary objective of the research is to conduct a comparative analysis of the behavior of the optical transmission line and to assess the quality of the transmitted signals when different optical modulations are used and to give recommendations for their optimal use.

The main criteria for assessing the quality of transmitted optical signals are:

- maximum allowable BER: BER $\leq 1.10^{-13}$;
- Q-factor value: Q > 6;
- optical signal-to-noise-ratio: OSNR > 12.

3. Results

The BER characteristics (BER versus P_{TX}), which are obtained after the set of iterations performed, are shown in Figs. 7, 8 and 9 (for the three different modulation formats).

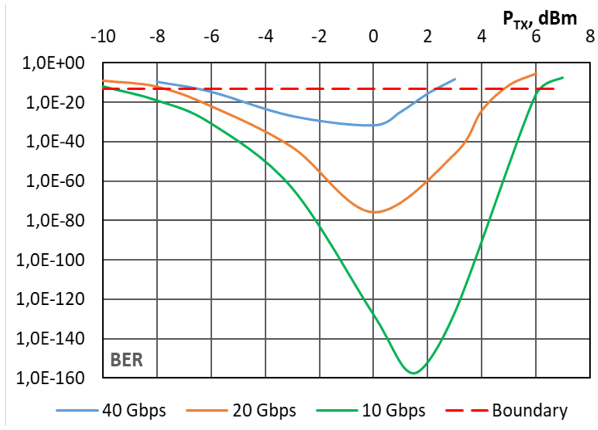

Fig 7. BER characteristics for NRZ modulated optical signal

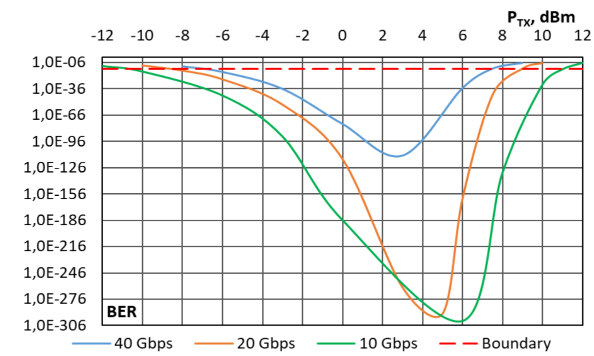

Fig 8. BER characteristics for RZ modulated optical signal

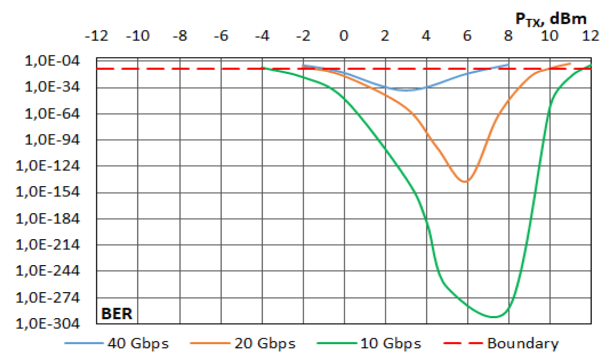

Fig 9. BER characteristics for CSRZ modulated optical signal

The graphical dependencies show the results of the comparative analysis. They are obtained at three different transmission rates – 10, 20 and 40 Gbps. The dotted red line corresponds to the BER threshold, which is assumed to be 1.10^{-13} (i.e. Q-factor will be higher than 6).

The NRZ and CSRZ modulated optical lead to a large dependence of BER on the transmission rate, which is evident from the Figs. 7 to 9. For RZ case at 10 and 20 Gbps the situation is different – the minimum BER is slightly different. The optimum power of the transmitter reduces with the increasing of transmission rate. The results show that the RZ and CSRZ modulation formats are highly recommended at 10 Gbps channels. At higher transmission speeds (20 or 40 Gbps), RZ modulation has a higher performance, while the BER characteristics of CSRZ are close to those of NRZ modulated signals.

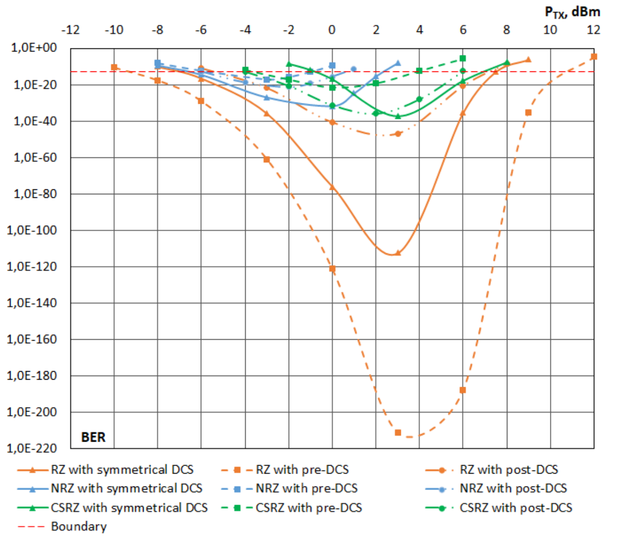

Fig 10. Comparative analysis of BER characteristics for different dispersion compensation schemes at 40 Gbps

A comparative analysis of the three main types of dispersion compensation schemes is shown in Fig. 10. As can be seen from Fig. 11 best results are obtained with RZ modulation with pre-DCS.

4. Conclusions

The obtained results shows that RZ modulation with pre-DCS allows a reduction of 1/3 of the number of optical amplifiers, since in the case of a pre-DCS in one amplification section only 2 EDFA amplifiers are used instead of three.

The BER characteristics of RZ modulation are significantly influenced by the compensation scheme used. For NRZ and CSRZ modulation formats, a better solution is to use symmetrical dispersion compensation. For all three types of modulation, the compensation scheme affects to a certain extent the value of the optimum transmitter power P_{TX}.

The dispersion compensation scheme affects most strongly when RZ modulation is used. Through the models presented, the most appropriate compensation scheme can be chosen, which will lead to more optimal optical line parameters and reduction of the investment.

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