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Performance Analysis of High-Speed Single Channel Transmission in Optical Communication Line

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Abstract

This paper studies and analyzes the performance of a high-speed single-channel optical communication network. The study is performed using a developed simulation model. The analysis is conducted for three different commonly used modulation formats – NRZ, RZ and CSRZ and at three different bit rates in the optical transmission channel - at 10, 20 and 40 Gbps. A set of simulations provides an optimal solution for the optical transmitter power level, as well as the energy and spectral characteristics. The system is analysed and evaluated in terms of BER, Q-factor, eye-opening factor and optical signal spectrum.

Keywords: Optical power level, optical modulation format, high-speed transmission, single channel, optical Q-factor.

1. Introduction

Modern optical communication networks are characterized by high bandwidth requirements, high utilization capabilities and network expansion. High-speed single-channel optical communication lines are mainly used in access networks. These networks deliver interactive and multimedia services to end users by penetrating the fiber to the subscriber's home. In these networks, it is necessary to satisfy the demand for high bandwidth and support the broadband services. For this reason, the basic requirement is to find the optimal solution in different scenarios, such as the length of the optical lines, the type of modulations used, the different types of fibers and the dispersion compensation schemes.

The modulation format is intended to provide the necessary transmission quality and spectral efficiency. The BER characteristics and the Q-factor are used as basic parameters for analyzing the performance of the optical access network. It is important to improve these parameters as much as possible. In this particular case, the impact of the modulation format is analyzed. Three different advanced modulation formats were considered – NRZ, RZ and CSRZ [1]. The BER value determines the amount of erroneous received bits in the optical receiver's decision circuit. Q-factor determines the quality of the transmitted signal and is directly related to the optical signal-to-noise ratio (OSNR). A higher value of Q-factor determines a better value of SNR (OSNR) and, respectively, a lower value of the probability of bit errors (i.e. BER) [2]. It is important that the value of the Q-factor be equal to or greater than 6, which defines the maximum BER of 1.10^{-9}. For that reason, in this paper it is assumed BER = 1.10^{-13} as a boundary condition to ensure a guaranteed quality of signal reception. The value of BER can be calculated by the following equation:

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

The main limitation to high-speed single channel optical communication systems over the single-mode fiber (SMF) at 1550 nm and the reasons for them are well known. The system supported data rate can be calculated using the analytical dependencies in [3].

There are various advanced modulation formats which are widely used in optical communication lines [4]. In our present work the performance comparison of RZ and NRZ modulation formats been made for optical channel transmission at different distances and different value of power level [5]. This paper focuses on the realization and comparative study of three simulation models of a high-speed single channel optical communication line. Three types of modulation formats are taken into account: NRZ, RZ and CSRZ.

The simulation models proposed in the paper are used to investigate the optical communication line performance and to propose an approach for finding the optimal solution in terms of allowable value of BER (i.e. of Q-factor) as well as good spectral characteristics and energy budget of the system for different bandwidth and modulation formats.

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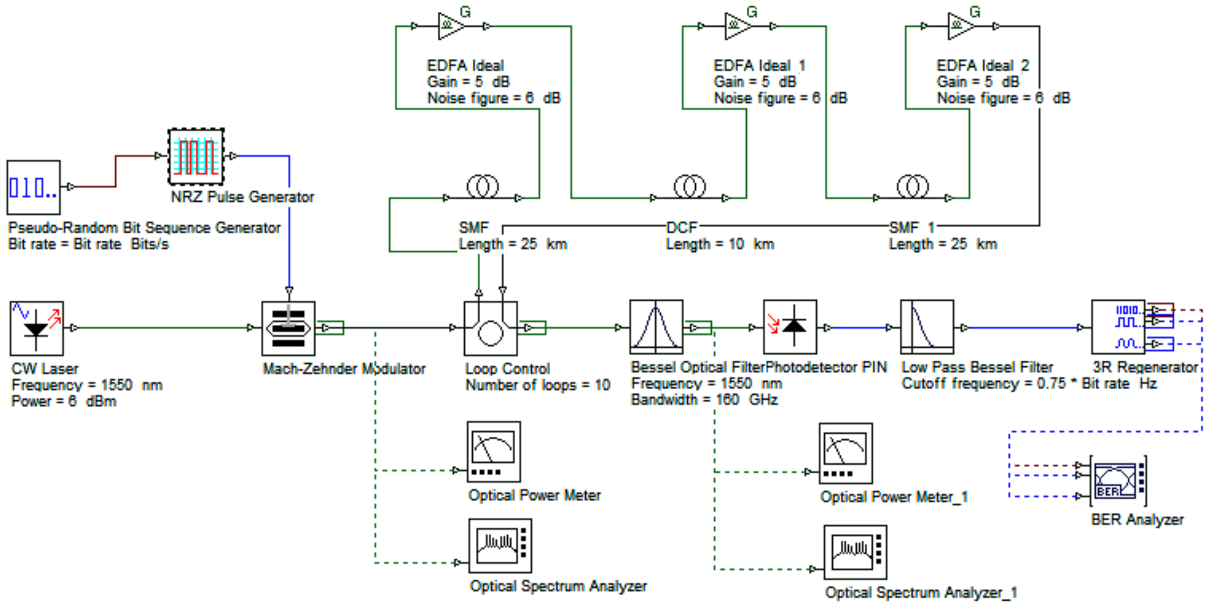


Fig. 1. Simulation model of high-speed single channel optical transmission line

2. Simulation model implementation and description

It is used Optiwave OptiSystem as a modeling software, which is a comprehensive software package for planning, designing, testing and simulation of the optical links at the physical layer of modern optical networks

For the purpose of the present study, a simulation models is developed, which is graphically represented in Fig. 1. The model implements a high-speed single-channel optical communication line. The model consists of standard single mode fiber, external modulated optical transmitter an optical receiver as well. The optical transmission line is with total length of 500 km (formed by 10 amplifying sections) and symmetrical dispersion compensation scheme (using DCF fiber) – Fig. 1.

It is used an optical transmitter with external modulation and center wavelength of 1.55 µm. For the first model, the NRZ modulator is used, as it is shown in Fig. 1.

In the second model is applied RZ modulator in the optical transmitter. It consists of RZ pulse generator instead of RZ pulse generator – Fig. 2

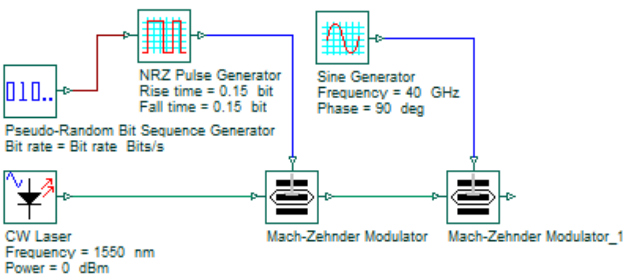


Fig 2. Optical transmitter model implemented with RZ modulation

The third model includes a CSRZ modulator. It uses one NRZ pulse generator and two LiNb Mach-Zehnder modulators – Fig. 3. The electrical input signal initially is NRZ encoded in the first NRZ pulse generator. The first modulator includes a LiNb Mach-Zehnder Modulator. The secondary LiNb Mach-Zehnder Modulator is controlled by a sine wave generator at signal frequency B/2 (B is the line bandwidth) and phase –90°.

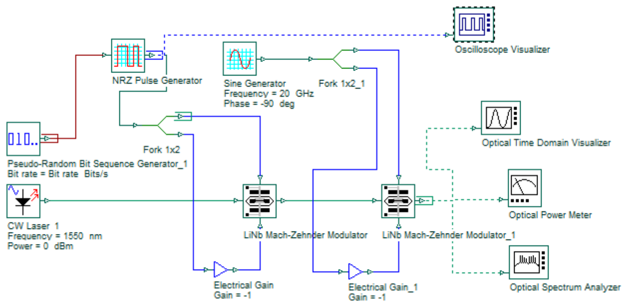


Fig 3. Optical transmitter model implemented with CSRZ modulation

The transmission channel consists of a number of optical spans (amplifying sections). The "Loop control" block performs a 10x multiplication of the optical span which defines a total line length of 500 km. Dispersion compensation is included in the optical spans. The dispersion compensating fiber (DCF) is not included in the total length of the line. EDFA amplifier is placed after each standard single-mode fiber. The EDFA’s gain is set to appropriate value to compensate the losses of the preceding fiber. The EDFA’s noise figure (NF) is set to be 6 dB and it is constant.

3. Results

Optical communication system performance evaluation is conducted under the following conditions:

- three different bit rates: 10 Gbps, 20 Gbps and 40 Gbps;
- three different modulation formats: NRZ, RZ and CSRZ.

Using a set of visualizers at different control pints of the model, the parameters of the signal and its characteristics are obtained and evaluated.

The graphical dependencies of BER characteristics (BER vs. optical transmitted power P_{TX}) are shown in Figs. 4 to 6 Each figure presents a comparative analysis for each transmission rate value (at 10, 20 and 40 Gbps) when different modulation formats (NRZ, RZ and CSRZ) are applied. The dotted red line represents the boundary condition for BER (assumed to be 1.10^{-13}, i.e. Q-factor higher than 6).

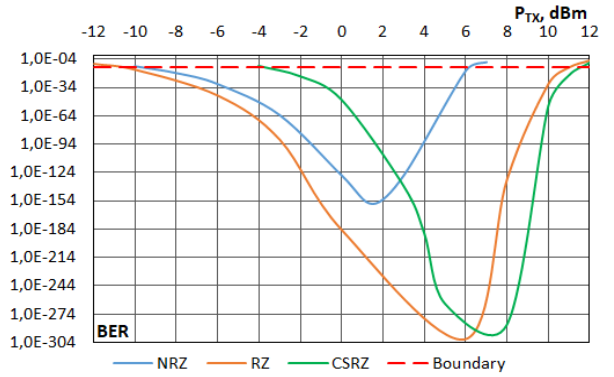


Fig 4. BER = $f(P_{TX})$ at 10 Gbps

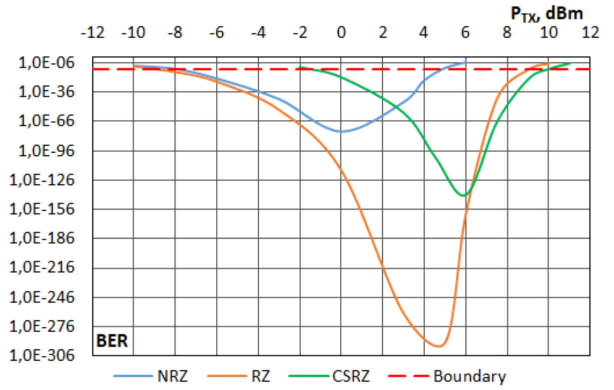


Fig 5. BER = $f(P_{TX})$ at 20 Gbps

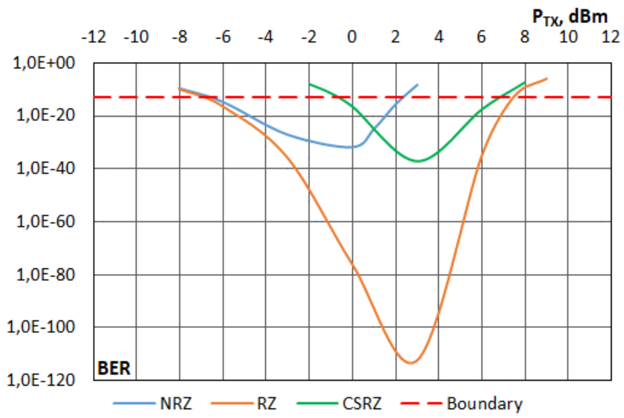
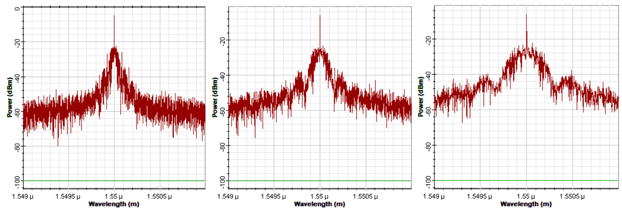


Fig 6. BER = $f(P_{TX})$ at 40 Gbps

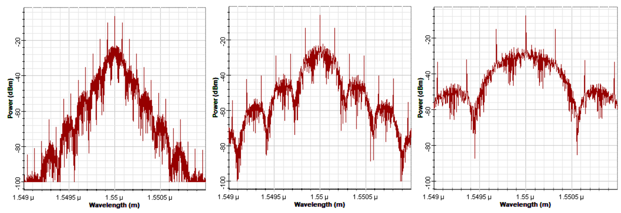
The results show that at higher transmission rates the RZ modulation has a better performance. This means that for lower transmission rates it is preferable to use RZ or CSRZ modulation. In addition, it can be seen that the BER characteristics (in terms of BER value) of CSRZ modulated are close to those of NRZ. On the other hand, it is clear that the main drawback of RZ and CSRZ modulated signal is the presence of significant side lobes in the optical spectrum characteristics, which can be seen from Figs. 7 to 9.

Fig. 10 shows the corresponding eye-diagrams and Q-factor of the optical signal in optimum condition of transmission (i.e. maximum obtained Q-factor).



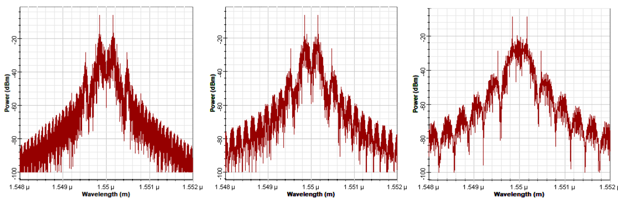
a) b) c)

Fig 7. Optical spectrum diagram of received optical signals for NRZ modulation format at (a) 10Gbps (b) 20Gbps and (c) 40Gbps



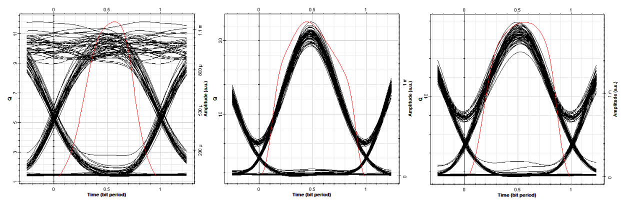
a) b) c)

Fig 8. Optical spectrum diagram of received optical signals for RZ modulation format at (a) 10Gbps (b) 20Gbps and (c) 40Gbps



a) b) c)

Fig 9. Optical spectrum diagram of received optical signals for CSRZ modulation format at (a) 10Gbps (b) 20Gbps and (c) 40Gbps



a) b) c)

Fig 10. Eye patterns of received optical signals with (a) NRZ- (b) RZ- and (c) CSRZ-modulation format at 40 Gbps

The obtained optimal parameters from the comparative analysis of results are presented for convenience in Table 1.

Table 1. Analysis of the optical signal parameters for RZ, NRZ and CSRZ modulation and symmetrical DCS

Modulation format	Parameter	Bit rate		
		10 Gbps	20 Gbps	40 Gbps
NRZ	P_{TX}, dBm	0	0	1,5
	Min. BER	$2{,}07.10^{-32}$	$1{,}09.10^{-76}$	$2{,}09.10^{-158}$
	Max. Q	11,79	18,47	26,78
RZ	P_{TX}, dBm	3	5	6
	Min. BER	$4{,}65.10^{-113}$	$4{,}54.10^{-293}$	$2{,}71.10^{-301}$
	Max. Q	22,56	35,56	37,69
CSRZ	P_{TX}, dBm	3	6	8
	Min. BER	$7{,}32.10^{-38}$	$1{,}86.10^{-141}$	$4{,}44.10^{-286}$
	Max. Q	12,81	25,29	36,12

4. Conclusions

For 10- and 20-Gbps-systems, the RZ- and CSRZ-modulated signals are affected to a greater extent by dispersion and dispersion slope, as well as by self-phase modulation. RZ modulated signals result in better performance of the system than NRZ signals, because of their greater tolerance to influence of nonlinear effects. NRZ could be a better option for 40-Gbps-systems because of it has narrower wave spectrum and therefore tolerates residual dispersion better.

At lower power levels of optical transmitter the performance of the system is improved with increasing the power to a certain optimum value. However, at higher optical transmitter power levels the nonlinear distortions are dominant and have a greater impact.

Since the RZ pulses are shorter, they will have a higher group velocity, which will lead to better performance with respect to reducing the effect of intra-channel nonlinearities. Because this type of distortionc are dependent on the optical pulse width, all signals with RZ-based modulation formats (RZ, CSRZ) will have the same behaviour and performance.

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