Impact of Environmental Influences on Multilevel Modulation Formats at the Signal Transmission in the Optical Transmission Medium

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Abstract: This paper is devoted to the analysis of environmental influences in the optical transmission medium and their impacts on multilevel modulation formats. An attention is focused on main features and characteristics of environmental negative influences of optical fibers. Consequently, principles for appropriate multilevel modulation formats are introduced together with block schemes representing their main functionalities. The created Simulink model for technologies and communications is verified for real conditions in the optical transmission medium. It can allow executing requested analysis for environmental influences on advanced multilevel modulation formats at the signal transmission. Finally, a comparison of considered multilevel modulations is introduced, using constellation diagrams, signal characteristics, eye diagrams and waterfall curves of individual signals.

Keywords: optical transmission medium, environmental influences, multilevel modulation formats

1. Introduction

Nowadays, users have increasingly higher demands on the transmission rate, due to the development of technologies that are becoming part of everyday life. As the solution, optical transmission fibers were proved remarkably improved properties over the metallic lines. The optical transmission systems are mainly used for long-haul and backbone networks, where the capacity of the system is a few THz. Currently, optical fibers are also used in metropolitan and access networks.

The optical fiber provides a transmission medium in which microwave signals that modulate optical carriers can be transmitted and distributed with high bandwidth and very low losses. The accurate determination of environmental influences of optical fibers is an important issue in the design of optical communication systems using advanced optical signal processing techniques. Besides analyzing their impact on optical waves at the signal transmission using an appropriate simulation model, acquired results should be verified and compared with results from measurements. The simulation allows determination of the spectral and frequency responses of particular blocks and the whole system [1], [2], [3]. A transmission of baseband signals would be ineffective. As the most preferred treatment, a signal modulation that transmits data (information) signals using another (modulation) signal is shown [4]. This paper deals with multilevel modulation formats, because they can be easily constructed and have good transmission capabilities in different variations. The first modulation scheme is the On-Off keying. The second considered modulation scheme is the Duobinary keying that appears very resistant to dispersion influences, therefore can be used in long distance paths. The third designed scheme is 16-QAM modulation used in the WDM system due to its narrow bandwidth. Then, impacts of environmental influences at the signal transmission in the optical transmission medium are analyzed for considered multilevel modulation formats.

2. The environment of optical fibers

2.1 Transmission parameters of the optical fiber

Basic transmission factors of the standard optical single-mode fiber utilized in telecommunications are following:

- linear effects
  - the attenuation,
  - dispersions (CD, PMD).
- nonlinear effects
  - Kerr nonlinearities (FWM, SPM, XPM, XPolM),
  - Scattering nonlinearities (SRS, SBS).

Linear effects represent a majority of losses at the optical signal transmission signal through the optical fiber. These linear effects are mainly caused by the attenuation and the dispersion. Nonlinear effects in the optical fiber may potentially have a significant impact on the performance of WDM optical communication systems [5]. These effects play an important role in a transmission of optical pulses through the optical fiber. *Kerr nonlinearities are* a self-induced effect in that the phase velocity of waves depends on the wave’s own intensity. The Kerr effect describes a change in the refractive index of the optical fiber due to an electrical perturbation. Due to the Kerr effect, we are able to describe effects of Four Wave Mixing (FWM), Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM). *Scattering nonlinearities* occur due to an inelastic photon scattering to the lower energy photon. We can say that energy of the light wave is transferred to another wave with different wavelengths. Stimulated Brillouin and Raman scattering effects appear in the optical fiber.

More detail information can be found in [6].

2.2 The attenuation

The most important parameter of optical fibers is the attenuation that represents a transmission loss. In practical way, it is a power loss that depends on a length of the transmission path. The attenuation leads to a reduction of the signal power as the signal propagates over some distance. When determining the maximum distance that a signal propagate for a given transmitter power and receiver sensitivity, the attenuation must be considered. The total signal attenuation a [dB] of the optical fiber along the fiber length L [km] defined for a particular wavelength can be expressed as

$$a[dB] = 10\log_{10}\frac{P_i}{P_0} \tag{1}$$

where P_i is the input power and P_0 is the output. The attenuation coefficient α [dB/km] of the optical fiber can be obtained by measuring the input and the output optical power levels.

2.3 Dispersions

The dispersion is a widening of the pulse duration as it travels through the optical fiber. We distinguished two basic dispersive forms - the intermodal dispersion and the chromatic dispersion. Both cause an optical signal distortion in multimode optical fibers, whereas a chromatic dispersion is the only cause of the optical signal distortion in single-mode fibers.

The chromatic dispersion CD represents a fact that different wavelengths travel at different speeds, even within the same mode. In a dispersive medium, the index of refraction $n(\lambda)$ is a function of the wavelength. Thus, certain wavelengths of the transmitted signal will propagate faster than other wavelengths. The CD dispersion is the result of material dispersion, waveguide dispersion and profile dispersion.

The chromatic dispersion is caused by different time of the spreading wave through fiber for a different wavelength and it depends on the spectral width of the pulse. As mentioned before, optical fiber represents the transmission system. Then the system has transfer function $H_0(\omega)$ given by equation (2). We assume that $|H_0(\omega)| = 1$ and we can expand phase into the Taylor series as is given by equation (3). If we consider first two coefficients, then we can write transfer function as given by equation (4).

$$\mathrm{H}_0(\omega) = |\mathrm{H}_0(\omega)|.e^{-j.\varphi(\omega)} \tag{2}$$

$$\varphi(\omega) = -\left[\varphi_0 + \frac{d\varphi}{d\omega}(\omega-\omega_0) + \frac{1}{2}\frac{d^2\varphi}{d\omega^2}(\omega-\omega_0)^2 + \frac{1}{6}\frac{d^3\varphi}{d\omega^3}(\omega-\omega_0)^3 \ldots\right] \tag{3}$$

$$\mathrm{H}_0(\omega) = e^{-j.\varphi_0}.e^{-j.\frac{d\varphi}{d\omega}(\omega-\omega_0)}.e^{-j.\frac{d^2\varphi}{d\omega^2}(\omega-\omega_0)^2} \tag{4}$$

where $H_0(\omega)$ is a transfer function, φ_0 is an initial phase of the system and ω_0 is an initial angular frequency

2.4 The Four Wave Mixing effect

The Four Wave Mixing FWM is a parametric interaction among waves satisfying a particular phase relationship called the phase matching. This nonlinear effect occurs only in systems that carry more wavelengths through the optical fiber and it is classified as a third-order distortion phenomenon. In this case, we are assuming that three linearly polarized monochromatic waves with angular frequencies ω_j (j = 1, 2, 3) are propagating.

The power of new generated waves can be obtain by solving coupled propagation equations of four interacting waves. We assume that the new generated FWM wave is mainly depended on three nearest waves of the light, so the power A_k^2 at the frequency $\omega_k = \omega_1 + \omega_2 - \omega_3$ is given by

$$A_k^2 = 4\eta\gamma^2 d_e^2 L_e^2 A_1^2 A_2^2 A_3^2\, e^{-\alpha l} \tag{5}$$

where factor η is the FWM efficiency, γ is the nonlinear coefficient, L_e is the effective length, $A_1^2(z)$, $A_2^2(z)$, $A_3^2(z)$ are powers of input waves, l is the fiber length, α is the attenuation and d_e the so-called degeneracy factor (equal to 3 if the degenerative FWM is considered, 6 otherwise).

2.5 The Self-Phase Modulation effect

The Self-Phase Modulation SPM has an important impact on high data speed communication systems that use the dense wavelength division multiplexing. The SPM effect occurs due to the Kerr effect in which the refractive index of optical fiber increases with the optical intensity decreasing the propagation speed and thus inducts the nonlinear phase shift.

This varying parameter n_r causes the SPM effect in which the signal phase propagating through the optical fiber changes with the distance and can be described by

$$\phi = \left(n_0 z + \phi_0\right) + \frac{2\pi}{\lambda}\overline{n_2} I(t) z \tag{6}$$

where Φ_0 represents the initial phase.

2.6 The Cross-Phase Modulation Effect XPM

The Cross-Phase modulation XPM is very similar to the SPM in which the intensity from different wavelength channels changes the signal phase and thus the XPM occurs only in WDM systems. In fact, the XPM converts power fluctuations in a particular wavelength channel to phase fluctuations in other co-propagating channels. The XPM effect results to spectral broadening and distortion of the pulse shape.

If we assume N signal having different carrier frequencies propagating in an optical fiber, the nonlinear signal phase depends on signal intensities at different frequencies. This phase shift can be described by expression

$$\Delta\phi_i = \frac{2\pi\overline{n_2}z}{\lambda}\left[I_i(t) + 2\sum_{i\neq j} I_j(t)\right] \tag{7}$$

where the first term in bracket represents the SPM effect and the second term represents XPM effect.

3. Principles of multilevel modulation formats

In multilevel modulation formats, the amplitude (signal strength) of the carrier wave is varied in proportion to the waveform being transmitted.

3.1 The On-Off keying

The On-Off keying (OOK) is a modulation scheme that consists only of two signal levels. The logic "1" is represented by transmitting of optical radiation and the logic "0" is represented by absence of the optical radiation. Example of the OOK wave can be seen in Fig. 1.

3.2 The Duobinary keying

The Duobinary modulation is a scheme for transmitting *R* [bits/sec] signal data rates using less than *R/2* [Hz] bandwidth. Nyguist's results show us that in order to transmit *R* [bits/sec] without the inter-symbol interference (ISI), the minimum bandwidth required of the transmitted pulse will be *R/2* [Hz]. This result means that duobinary pulses will be affected by the ISI, but in controlled limits. The duobinary can be described as combination of ASK and PSK [7], [8] [9]. A complete scheme of the duobinary transmitter circuits is shown in Fig. 2. The invertor output is sent to the differential precoder input that resolves cyclic decoding error in the receiver. The signal is sent out to the differential encoder, where is mapped on values [-1, 0, 1], where "-1" introduces bit with the amplitude 1 and phase $-\pi$. More detailed description of the Duobinary modulation scheme is presented in [10].

3.3 The 16-QAM modulation

The QAM (Quadrature Amplitude Modulation) is a technique that combines two modulation schemes (an amplitude shift keying and a phase shift keying). The QAM is a multilevel modulation that is able to transmit *n* bit by *m* symbols. The main advantage of this modulation is an ability to spare the bandwidth or to increase the bit rate. In this paper, we apply the 16-QAM modulation, because higher level modulations have high performance requirements for modeling and simulation.

Fig. 3 presents principles of the 16-QAM 16 modulator using the Quad parallel Mach-Zender modulator. This modulator consists of two QPSK (quadrature phase shift keying) modulators (QPSK 1, QPSK 2). Each QPSK modulator consists of the Dual parallel Mach – Zender modulator that is driven by two binary data sequences. The QPSK 2 is attenuated by 3dB to achieve a rectangular 16-QAM constellation. The QPSK 2 signal must be attenuated before coupling. The QPSK 1 sets a quadrant where the symbols of QPSK2 (smaller amplitude) are mapped [11].

The 16-QAM demodulation is divided in two steps. The first step is to determine quadrant, wherein the bits are detected. The first two bits of the four-bit code word are assigned by the received signal phase, the other two bits are assigned by their position on imaginary and real axis. In Fig. 4, a decoding rule and levels of the decision are presented for the 16-QAM modulation format. More detailed description of the 16-QAM modulation scheme is in [12].

4. Analysis of environmental influences at the signal transmission of multilevel modulation formats

The analysis is performed using the optical transmission path created in the Matlab Simulink 2014 environment. It consists from functional blocks implemented into the created model of the optical transmission path. In the simulation, it is used the fiber length $l = 80$ [km] and the working wavelength $\lambda = 1550$ [nm], that means the total attenuation is $a_{\text{total}} =$ 16,8 [dB] (i.e. $\alpha_{\text{specific}} = 0{,}21$ [dB/km]), other specific values are PMD = 10 [ps/$\sqrt{\text{km}}$] and CD = 10 [ps/(nm.km)]. More detailed information related to created block of environmental influences is published in [6], [13-16].

The transmission scheme contains next fundamental parts:

• Data signal	(green)
• Source of optical signal (CW)	(red)
• Mach-Zender modulator	(turquoise)
• Model of the optical transmission path	(orange)
• Mach-Zender demodulator	(blue)
• Block of the BER calculating	(yellow)
• Scopes and evaluation devices	(cyan)

Fig. 5 presents the complete block scheme prepared in the Matlab environment. This scheme is the same for all the modulation schemes, differences for each modulation scheme are present in blocks Data signal and Mach-Zender modulator.

The CW block represents a source of the carrier signal that is sent to the modulator. The CW block consists of several sine generators that generate signals at the same time, until a real source of optical emissions is not monochromatic (i.e. it has not only one carrier wave (λ), but there are more waves ($\Delta\lambda$)).

The Data signal block consists of the Bernoulli generator that produces information data stream. Next, there is a modulator block wherein data signal and continuous wave (split in constructive and destructive light waves) are connected. The output signal is combined in a complex form and sent to the Optical transmission path block. Then, the signal goes to a demodulator block that is adopted for each modulation scheme. The data stream from the demodulator goes to the Bit Error Calculation block, where bits are compared and the total error rate is calculated.

The Scopes and evaluation devices block contains constellation diagrams, eye diagrams and time scopes. These can be used for verifying the functionality of modeling blocks for presented modulation formats.

4.1 Impact on On-Off Keying signals

The data source in the OOK modulation scheme consists of the Bernoulli generator and the Gaussian filter that emulates a real shape of electrical signals. Next, the signal goes into the simple two-arm Mach-Zender modulator. After optical transmission path the signal is gained and compared whit level of decision in Mach-Zender demodulator. Finally, the BER block computes errors which occurred during the transmission. Examples of the OOK signal in different parts of the prepared model are shown in Fig. 6.

4.2 Impact on Duobinary keying signals

The block scheme of the data source present in the duobinary modulation is shown in Fig. 7. The signal is converted from binary to duobinary form as mentioned before. Examples of waveforms at the transformation from binary to duobinary are shown in Fig. 8. Then, the duobinary signal goes to the Mach-Zender modulator. In this case there is used the dual parallel Mach-Zender modulator that provides creating of the three-level signal. Fig. 9 shows examples of the output from the Mach-Zender modulator. After passing the optical transmission path, the signal is sent to the Mach-Zender demodulator block. The demodulator operates using two flag bits *E (k)* and *F (k)*. These two bits are associated with the XOR operation and negated what brings the originally transmitted signal. Figure 10 shows the demodulation process using the flag bits.

4.3 Impact on 16-QAM modulation signals

The data source in the 16-QAM modulation scheme consists of the 4 Bernoulli generators that are connected to the buffer. The buffer produces 4-bit code word. The block scheme of the 16-QAM data source is shown in Fig. 11. The data stream continues to the Mach-Zender modulator. In this scheme, there is used the Quad parallel MZM modulator. Each bit of code word controls one arm. The block scheme of the used 16-QAM modulator is shown in Fig. 12. The 16-QAM constellation diagram used in this scheme is demonstrated in Fig. 13. After passing the optical transmission path, the signal is sent to the Mach-Zender demodulator block. The demodulator operates in two steps. The first step is decoding first bit pair of the code word based on the phase of received signal. The second step is decoding second bit pair of the code word based on the signal level in real and imaginary axis. The decoding rule is mentioned before in this paper. The block scheme of the used 16-QAM demodulator is shown in Fig. 14.

5. Results of the analysis and a comparison of multilevel modulation formats

The eye diagrams and constellation diagrams for particular multilevel modulation formats are shown in Fig. 15-17. For the OOK keying, we can see the optical power in the In-phase amplitude part of the eye diagram. The Quadrature amplitude part has a value of zero because the OOK signal does not have any shifts in the imaginary axis as we can see in the constellation diagram.

For the Duobinary keying, we can see that the duobinary signal is a three level modulation format in the Scatter plot and in the In-phase amplitude parts of the eye diagram. The Duobinary as well as the OOK has no movement in the imaginary axis, therefore nothing is changed in the Quadrature amplitude part off the eye diagram.

For the 16-QAM 16 modulation, there are 4 shifts in the real and imaginary planes as is shown in the constellation diagram and in the eye diagram.

In Fig. 18, waterfall curves for considered OOK, Duobinary and 16-QAM modulation formats based on the presented simulation parameters are introduced. As can be seen, the Duobinary needs less E_b/N_0 than the OOK and 16-QAM for a successful transmission of payload with lower BER values. Bandwidth parameters for particular modulation formats are introduced in Table 1.

Table 1. Bandwidth parameters for multilevel modulation formats

Modulation format	$W_b/symbol$ [MHz]	bit/symbol	W_b/bit [MHz]	E_b/N_0 [dB] *at BER = 10^{-8}*
OOK	70,11	1	70,11	11,9
Duobinary	70,11	2	35,055	12,7
16-QAM	70,11	4	17,527	15,8

6. Conclusion

This paper analyzes environmental influences in the optical transmission medium and presents their impact on various multilevel modulation formats at the signal transmission over optical single-mode fibers. We focused on linear transmission factors – the attenuation and the dispersion - and on nonlinear effects – the four wave mixing, the self-phase modulation and the cross-phase modulation. Nonlinear effects in the optical fiber may potentially have a significant impact on the performance of WDM optical communication systems.

The analysis utilizes a model of the optical transmission path including functional schemes for the optical signal transmission utilized multilevel - OOK, Duobinary and 16-QAM - modulation schemes. These modulation formats are compared with each other using constellation diagrams, signal waveforms, eye diagrams and waterfall curves from a viewpoint of negative environmental effects in the optical transmission medium.

The Duobinary keying is more resistant to negative influences degrading the signal transmission than other modulations. Therefore, it can be used in optical transmission systems over long distances (about hundreds kilometers). The 16-QAM modulation format has better bandwidth utilization than other considered modulations. Account on that, it can be used in systems with higher number and denser spacing of wavelengths. The OOK keying in spite of worse bandwidth utilization and resistance to negative influences during the transmission is the cheapest solution compared these three modulation formats.

Thanks to the modeling and simulations, it is possible to find appropriate modulation and/or encoding techniques and consequently to execute advanced analysis of their utilization for deployment in the real optical transmission systems.

7. Acknowledgement

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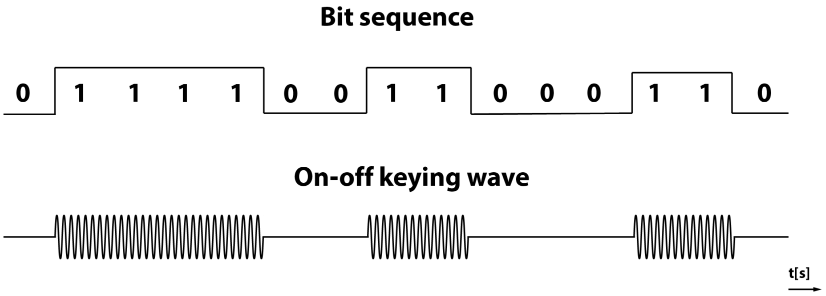
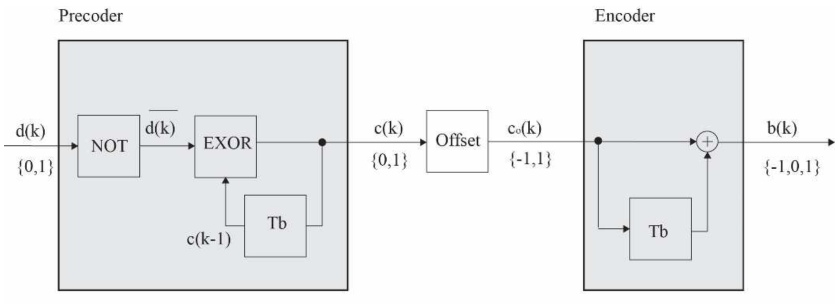


Figure 1. Examples of the On-off keying wave



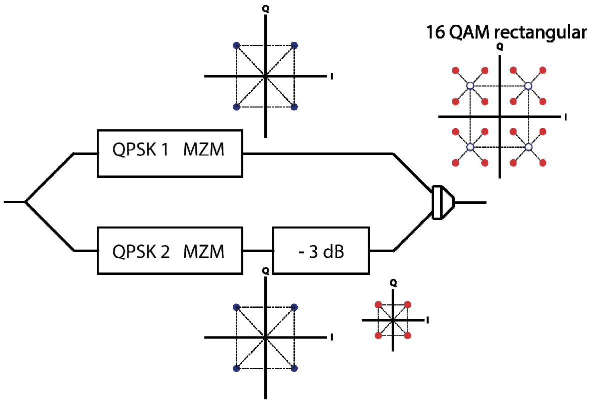


Figure 2. The complete scheme of Duobinary transmitter circuits **Figure 3.** Principles of the 16-QAM modulator

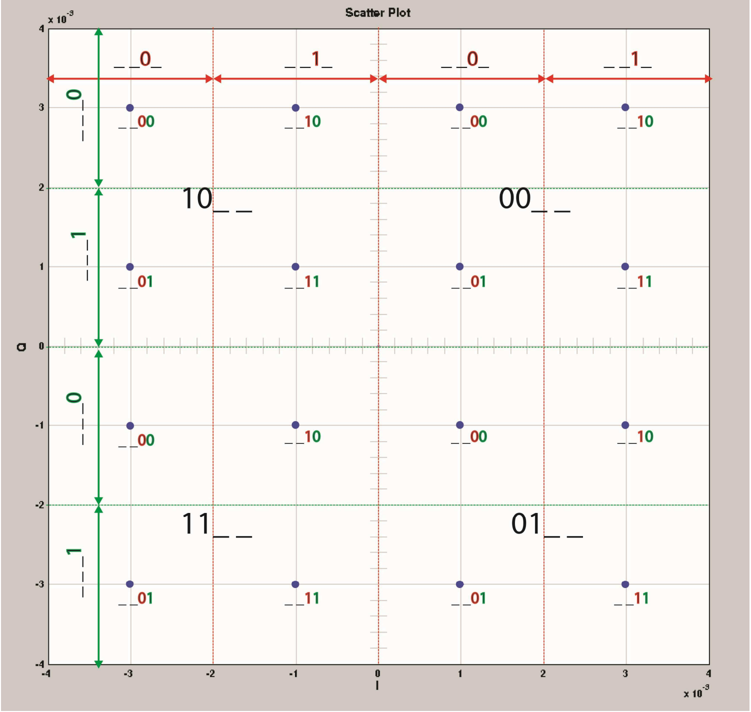


Figure 4. The decoding rule of the 16-QAM modulation format

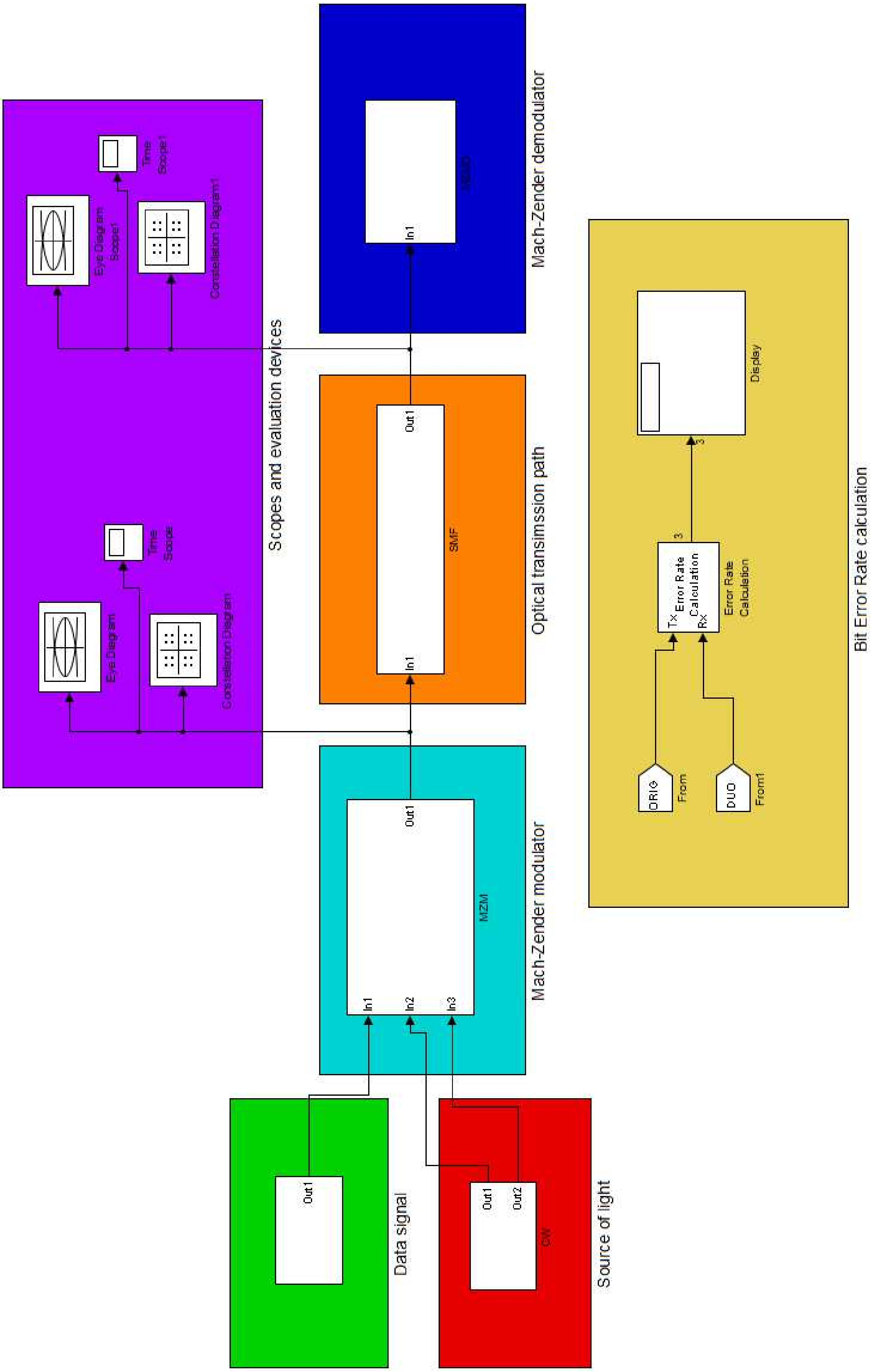


Figure 5. The block scheme for analyzing impacts of different environmental influences at the signal transmission in the optical transmission medium using the Matlab environment

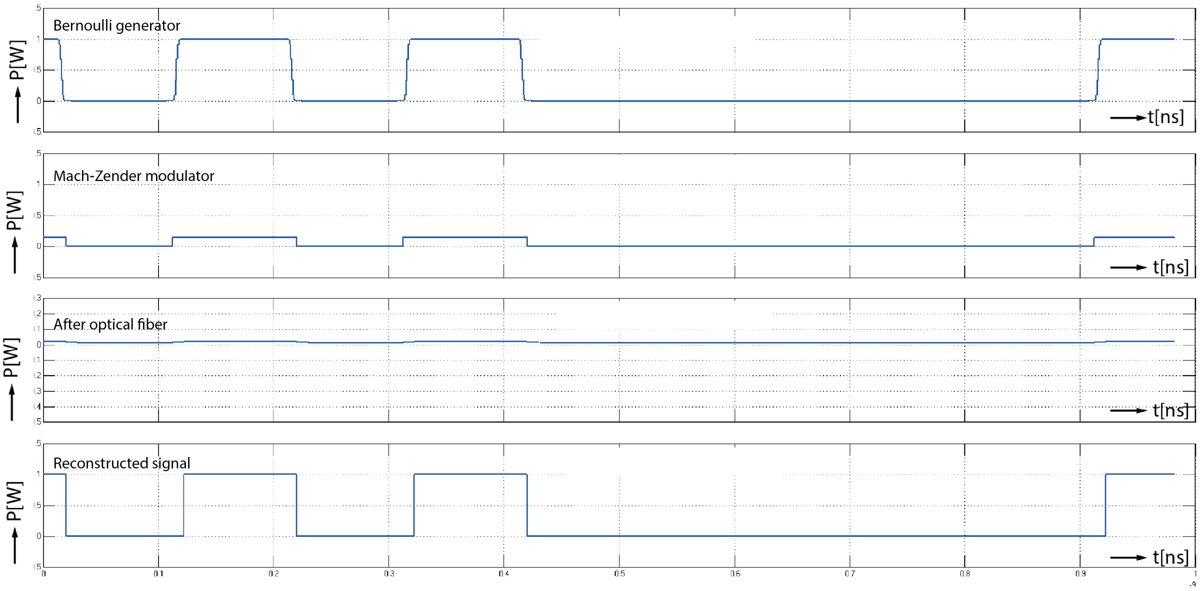


Figure 6. Examples of the OOK signal in different parts of the optical transmission system’s model

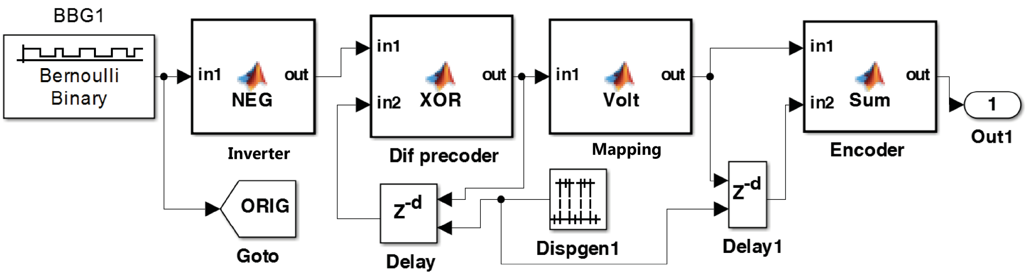


Figure 7. The block scheme of the Duobinary data source

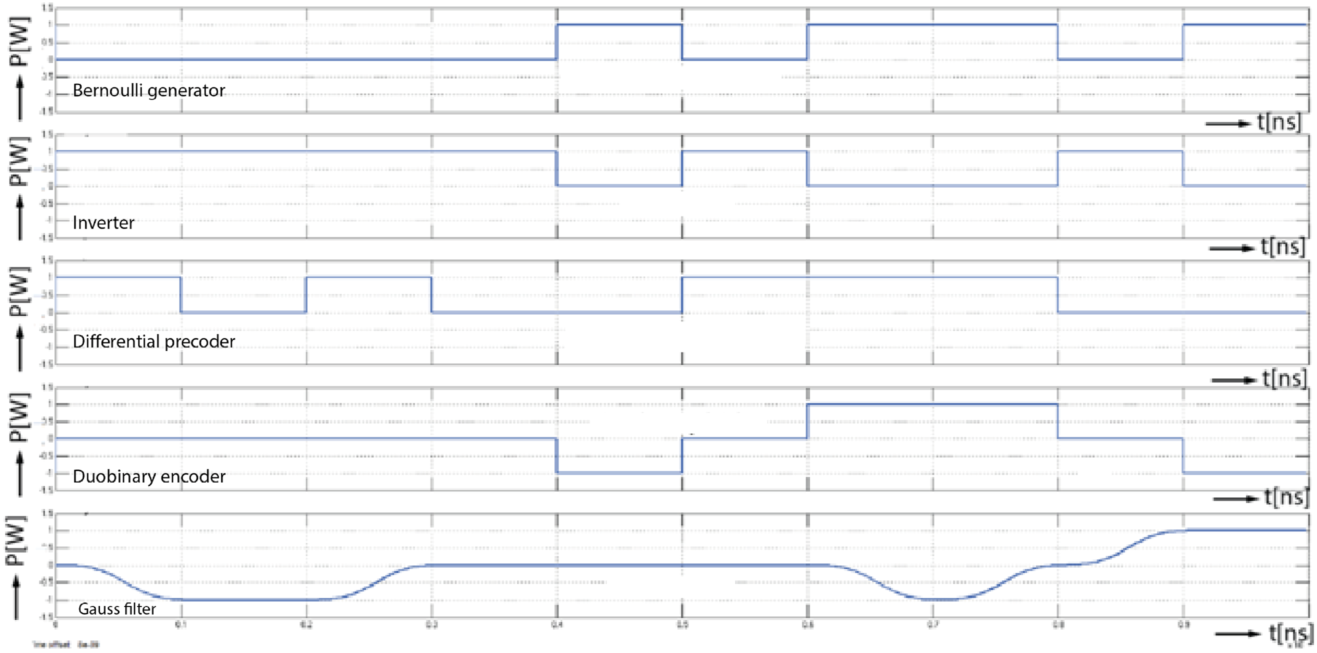


Figure 8. Examples of waveforms at the signal transformation from binary to Duobinary

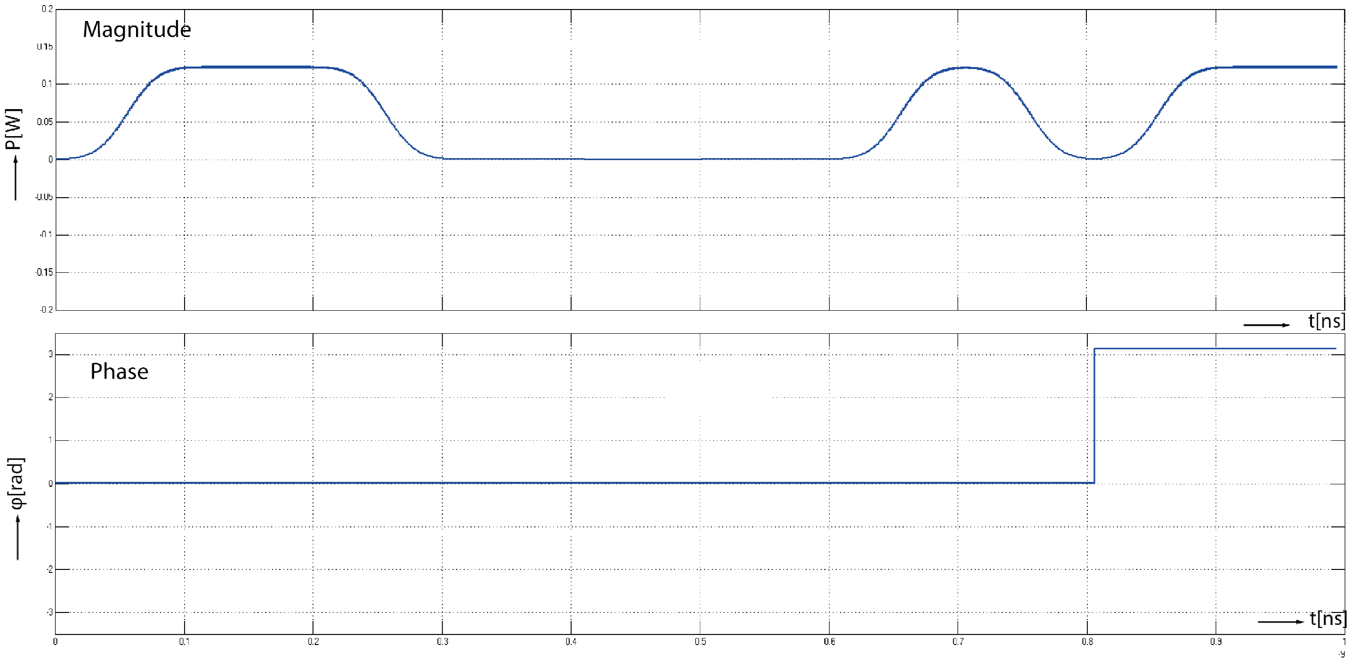


Figure 9. Examples of the output from the Mach-Zehnder modulator

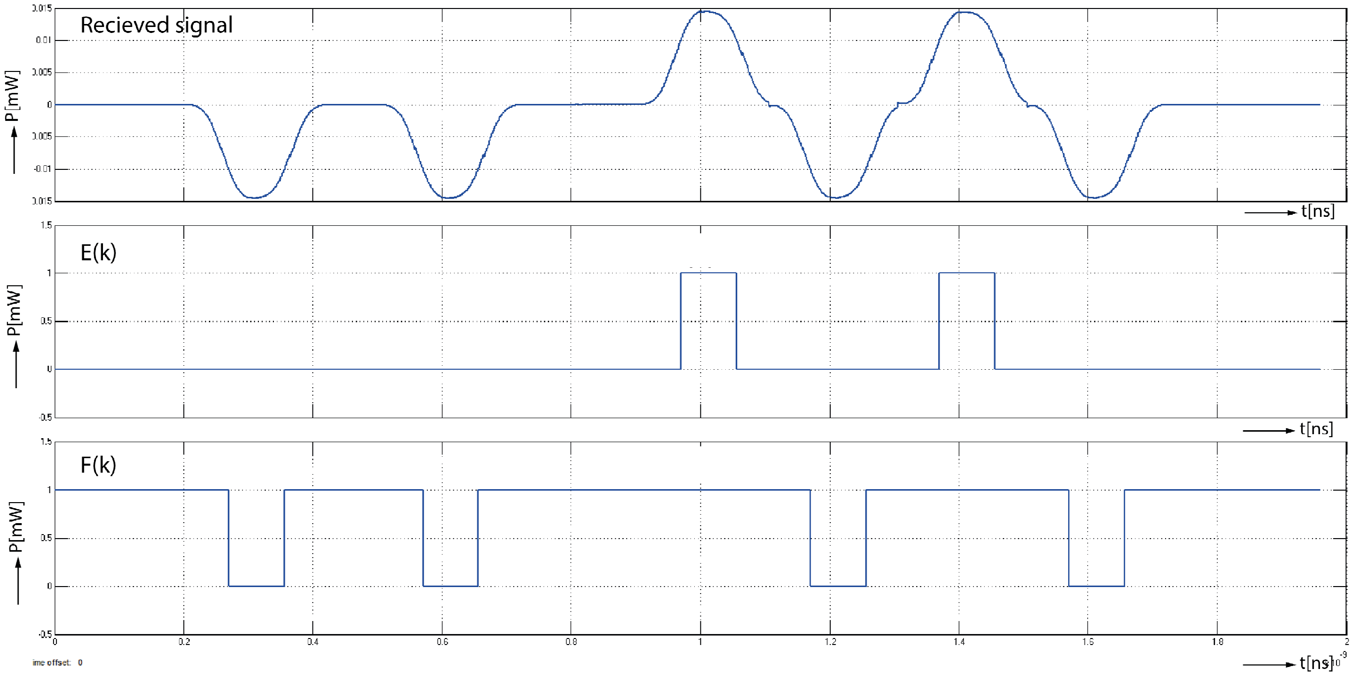


Figure 10. Examples of the output from the Mach-Zehnder demodulator

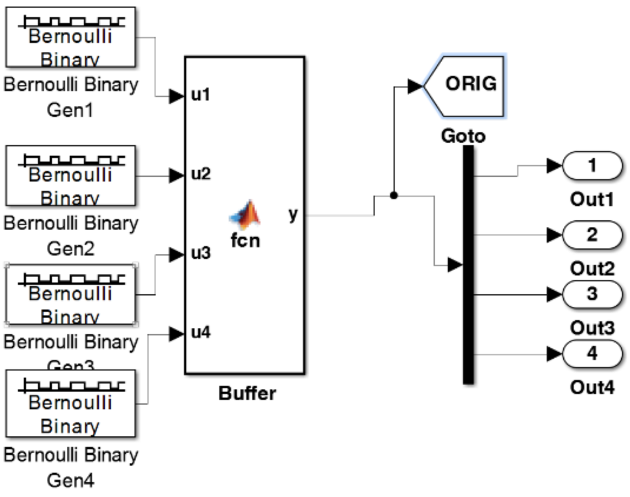


Figure 11. The block scheme of the 16-QAM data source

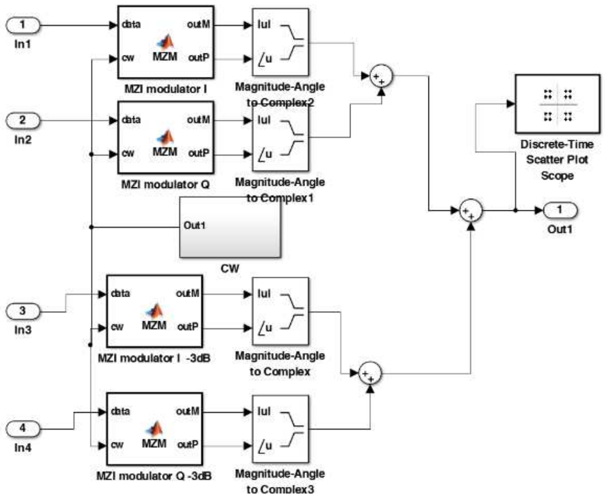


Figure 12. The block scheme of the 16-QAM modulator

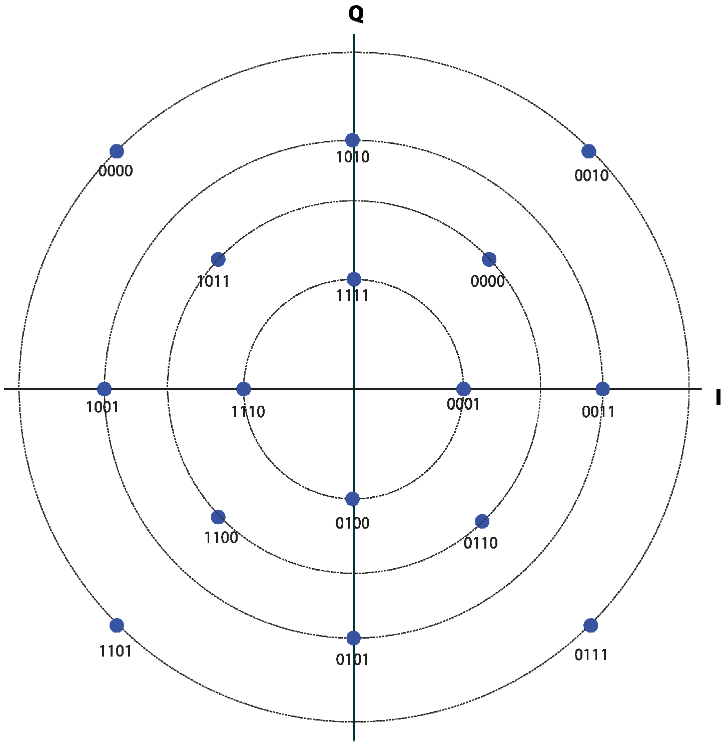


Figure 13. The rectangular 16-QAM constellation diagram

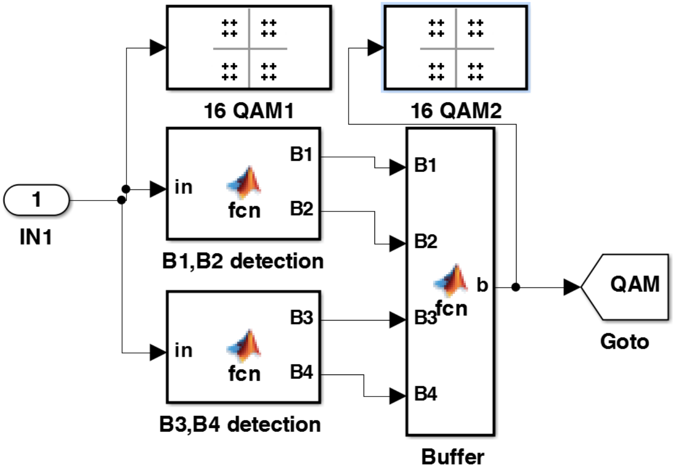


Figure 14. The block scheme of the 16-QAM demodulator

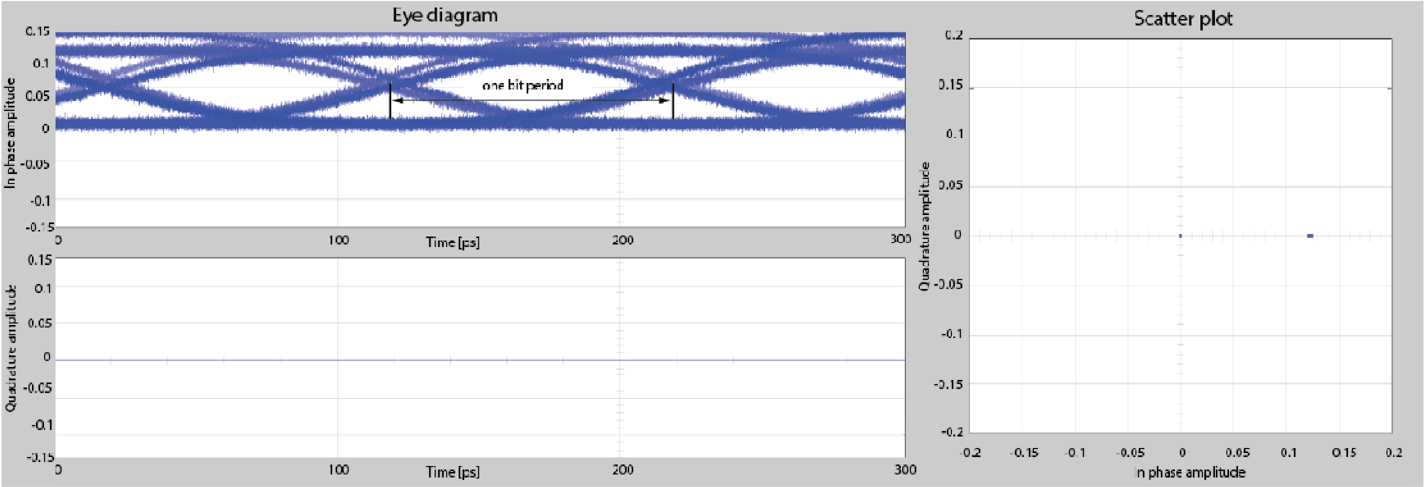


Figure 15. The constellation and eye diagrams presenting an impact of environmental influences at the OOK signal transmission in the optical transmission medium

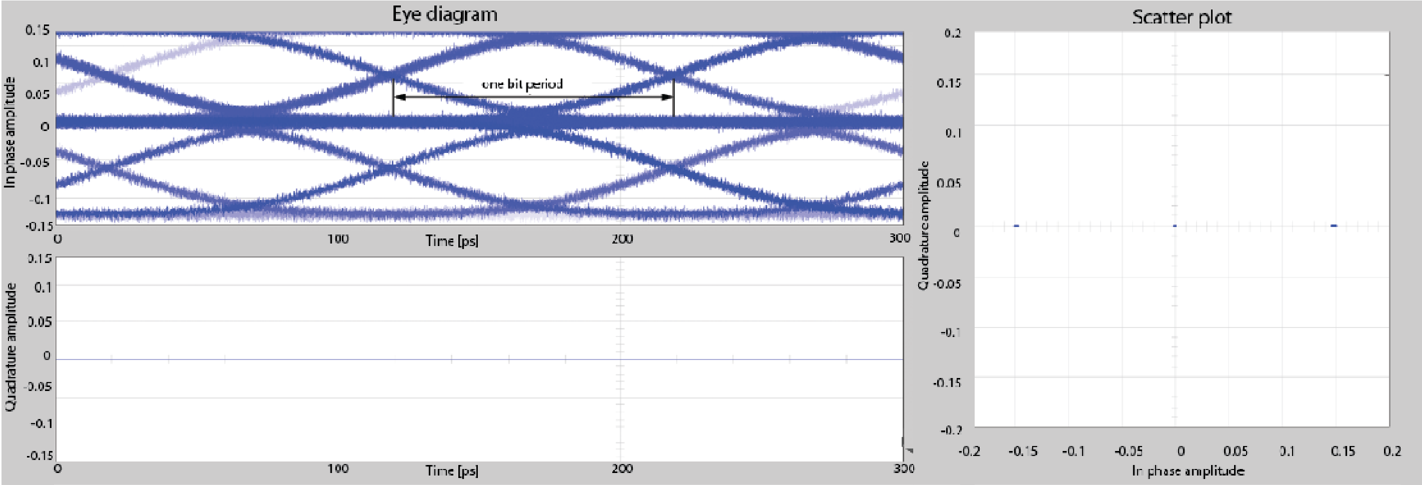


Figure 16. The constellation and eye diagrams presenting an impact of environmental influences at the Duobinary signal transmission in the optical transmission medium

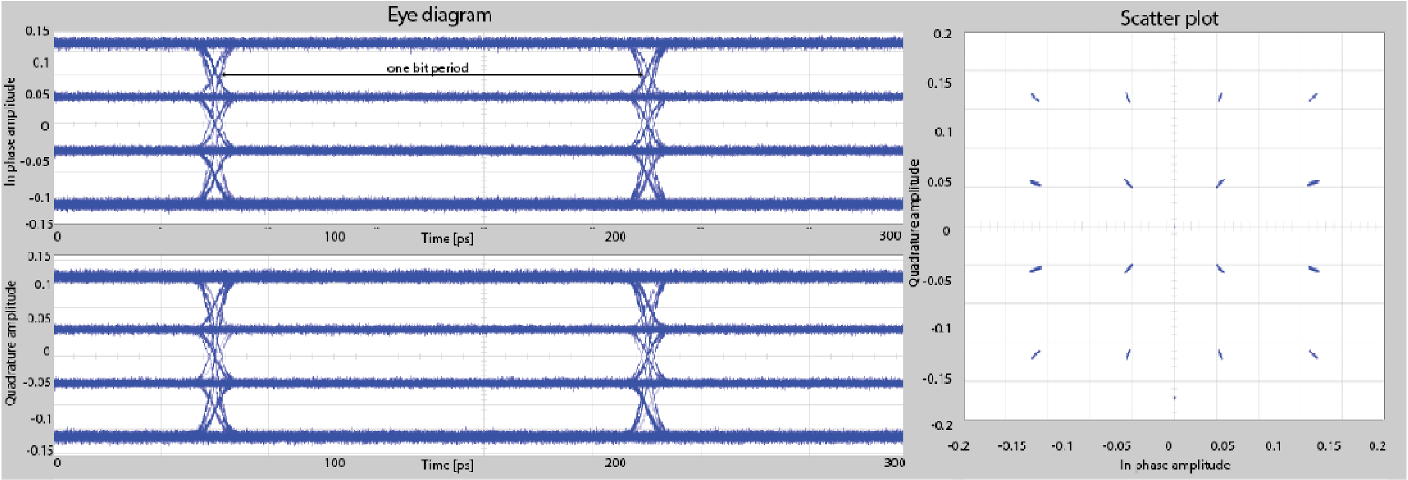


Figure 17. The constellation and eye diagrams presenting an impact of environmental influences at the 16-QAM signal transmission in the optical transmission medium

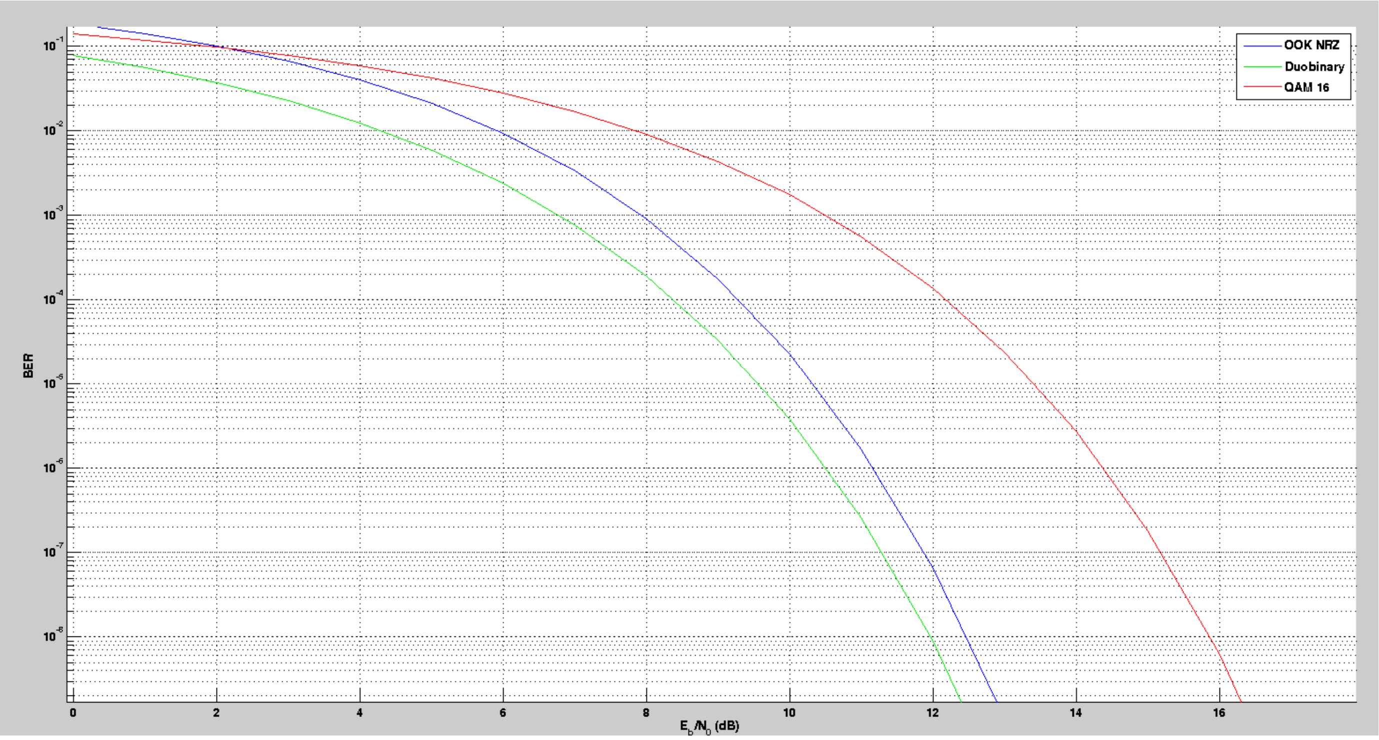


Figure 18. Waterfall curves at different E_b/N_0 values depending on environmental influences in the optical transmission medium for various multilevel modulation formats