

An effective integration of the PM 16-QAM modulation in enhanced metropolitan networks with the EDFA amplification

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This paper deals with the integration of polarization multiplexed 16-ary quadrature amplitude modulation format in optical metropolitan networks enhanced with the signal amplification. Before expensive experimental setup or practical testing and demonstration, we prefer creating of appropriate simulation platform for the optical transmission system. A novelty can be found in adjusting, optimizing and construction of the proposed optical system and functional parts for any modulation format used. So, such simulation platform is first introduced along with possibilities for numerical simulations of its optical components - laser and amplifier. By this way, essential noise tolerances for comparison with the data under real conditions are included. Subsequently, there are characterized implementations of terminal devices in detail with a possibility for upgrading to the dual-polarization mode operation. Finally, simulation results from the simulation platform are presented and a discussion about demands for effective exploitation of the polarization multiplexed 16-ary quadrature amplitude modulation in enhanced optical metropolitan networks concludes our contribution.

Keywords: PM 16-QAM modulation, simulation platform, optical metropolitan networks, DFB laser, EDFA amplification

1 Introduction

Although optical transmission systems have seen great progress in a fiber technology, the complete recovery of optical networks by new waveguides could not be realized due to financial difficulties, building permits, geographical locations, and other factors. For this reason, already existing optical networks are mainly used. At low transmission rates, single-mode fibers (SMF) exhibit low signal degradations, but these ones are rapidly growing at higher transmission rates. Requirements for higher transmission rates are growing due to demands for networking services (IPTV, cloud services, VOIP, 4 K video streaming, *etc*), global IP traffic will be nearly triple from 2018 to 2021 according to CISCO predictions [1]. Therefore, it is essential to develop modern optical transmission systems that allow increasing the overall network capacity, improving the optical signal to noise ratio (OSNR) and predictive compensating the polarization mode dispersion (PMD) and chromatic dispersion (CD). The overall network capacity can be extended through various approaches, including increasing of transmission rates, multiplexing of wavelength carriers and utilization of advanced modulation techniques [2]. Increasing of transmission rates is limited by the fact that some modulation formats have lower resistance to dispersions present in single-mode optical fibers thus they cannot be correctly detected in optical receivers due to the inter-symbol interference. Multilevel modulation techniques are more easily influenced by noise effects on the optical transmission path that

reduce the total transmission range. A multicarrier signal generation may be performed in the optical or electric domain. For orthogonal frequency division multiplex (OFDM) signals, subcarriers can be modulated by means of the binary phase shift keying (BPSK), the quadrature phase shift keying (QPSK) or multilevel electrical signals. Transceivers for these signals are technologically more complex and expensive [3]. The most complex solution has proved to be a combination of multiplexing and modulation techniques. For 100 Gb/s transmission rate, the PM QPSK modulation is suitable for applications in ultra-long-haul networks with the 1500 km maximum range [4]. For transmission rates beyond 100 Gb/s, this PM QPSK technique would not meet requirements set in the ITU-T G 694.1 recommendation for the 50 GHz grid, therefore a modulation technique capable transmitting more information bits in one symbol resulting in eventually narrower bandwidth spectrum should be used. The PM 16-QAM modulation can transmit eight information bits in one transmitted symbol [5]. After compliance some demands, this modulation format seems to be interesting for implementation in enhanced metropolitan networks. In a developing process, it is important to avoid expensive practical testing and demonstrations [6]. Therefore, it is necessary realize experimental efforts in an appropriate simulation platform for the optical transmission system that can accurately describe a behavior of optical components at the signal transmission under varying working conditions. This platform must be based on measured parameters acquired from real optical trans-

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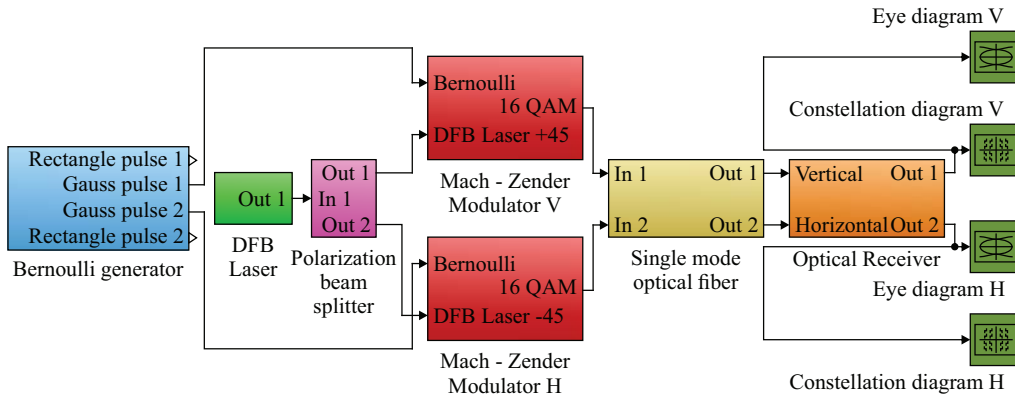


Fig. 1. The complete block scheme of the simulation platform for the optical transmission system

mission systems to predict performance and limitations of optical components more precisely. Commercial software has often many restrictions and they are not as adaptive as is needed for such experiments and simulations [7]. For the optical transmission system, therefore, we created our own simulation platform [8]-[11] in the Matlab Simulink programmable environment widely used by scientists, universities and research centers around the world for scientific and/or academic purposes. The paper is organized as follows a simulation platform for the optical transmission system is presented together with its relevant optical components in the section II. Closely, possibilities for numerical simulations of two newer blocks - the DFB laser and the EDFA amplifier - are introduced together with their main features in the simulation platform. The simulation of these optical devices is based on parameters extracted from real devices by measurements. The extraction of simulation data is more agile, and data can be processed through the Matlab environment. Also, real noise contributions are considered for simulated devices. In section 3, a way for exploitation and implementations of the PM 16-QAM modulations is introduced with more significant details. In the section 4, simulation results acquired from the simulation platform related to the PM 16-QAM modulation technique are displayed and a discussion with requirements for practical implementation of this modulation format in real optical transmission systems with the amplification is presented.

2 The simulation platform for the optical transmission system

The simulation platform consists of following functional blocks representing distinguished optical components

- Bernoulli generator (blue)
- DFB Laser (green)
- Polarization beam splitter (purple)
- Mach-Zehnder modulators (red)
- Single mode optical fiber (yellow)
- Optical receiver (orange)

- Measurement units - eye and constellation diagrams (dark green)

The simulation platform is performed in the Matlab R2017b Simulink software based on previous works [8]-[11]. In Fig. 1, there is presented a complete block scheme for the optical transmission system including main optical components. The Bernoulli generator block stands for a random data stream that is used to control arms of the Mach-Zehnder modulators (MZM). This data stream is shaped as a Gaussian wave to maintain a shape of real generated data signals. The DFB Laser block represents the continuous-wave light stream produced by a distributed feedback laser on that is modulated information data stream using MZM. The Polarization beam splitter block divides a signal from the DFB laser into two polarization planes that are entering MZM V and MZM H blocks. The Single mode optical fiber block represents the transmission medium of the SMF fiber including relevant environmental negative effects [12],[13]. The Optical Receiver block is represented by a preamplifier and the PIN diode with corresponding noise sources. The optical signal can be preamplified before the opto-electronic conversion by the erbium doped fiber amplifier (EDFA). Measurement units present Eye diagram and Constellation diagram blocks used for evaluating transmitted signals and for estimating BER values.

2.1 Possibilities for the DFB laser numerical simulations

The DFB Laser block simulates the inner dynamics of any semiconductor laser with a distributed feedback [14],[15]. The essential condition for its parameters is an extraction of values from real laser devices. These extracted values are used as input values for the laser rate equation system displayed in (1)-(3). Extracted values used in our simulation platform as well as the extraction methodology can be found in [15]

$$\frac{dN(t)}{dt} = \frac{I_{in}(t)}{q} - \frac{N(t)}{\tau_n} - g \frac{N(t) - N_0}{1 + \epsilon S(t)} S(t) + F_N(t), \quad (1)$$

$$\frac{dS(t)}{dt} = g \frac{N(t) - N_0}{1 + \epsilon S(t)} S(t) - \frac{S(t)}{\tau_p} + \frac{\beta N(t)}{\tau_n} + F_S(t), \quad (2)$$

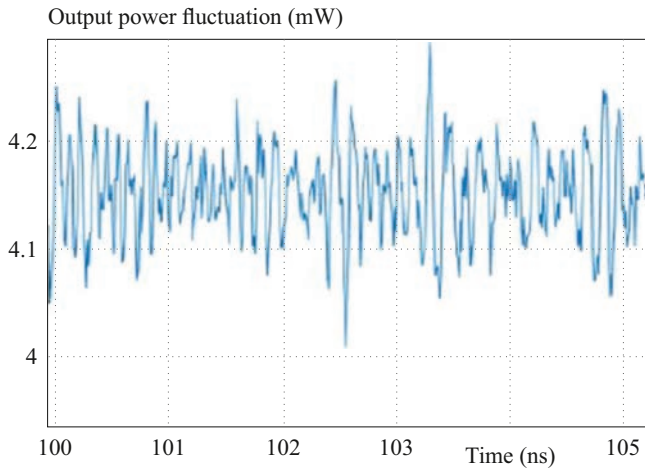


Fig. 2. Output power fluctuation characteristics of the DFB laser block

Table 1. Input parameters for the DFB laser characteristics

| Parameter | Unit | Extracted value |
|------------|----------|-----------------------|
| τ_n | ns | 0.33 |
| τ_p | ps | 7.15 |
| g | s^{-1} | 1.13×10^4 |
| ϵ | - | 4.58×10^{-8} |
| β | - | 3.54×10^{-5} |
| N_0 | - | 8.2×10^6 |
| η_d | - | 0.21 |
| α_f | - | 1.55 |

Table 2. Parameters for the output EDFA characteristics

| Parameter | Unit | Extracted value |
|----------------------|---------------|-----------------------|
| r | μm | 1.4 |
| $\Gamma_p(980)$ | ps | 0.64 |
| $\Gamma_p(1480)$ | s^{-1} | 0.43 |
| Γ_s | - | 0.4 |
| ρ | - | 6.3×10^{24} |
| τ_e | ms | 10 |
| σ_{1-2} | - | 2.4×10^{-25} |
| σ_{2-1} | - | 3.8×10^{-25} |
| $\sigma_{1-3}(980)$ | - | 2.7×10^{-25} |
| $\sigma_{1-3}(1480)$ | - | 1.5×10^{-25} |
| λ_s | nm | 1550 |
| λ_{p1} | nm | 980 |
| λ_{p2} | nm | 1480 |

$$\frac{d\theta(t)}{dt} = \frac{\alpha_f}{2}g(N(t) - N_{\text{avg}}) + F_\theta(t), \quad (3)$$

where g stands for the gain slope constant coefficient, N_0 is the carrier density at transparency, N_{avg} is the time averaged carrier number, ϵ is the gain compression factor, τ_p is the photon lifetime, $I(t)$ yields the injection

current, β is the spontaneous emission coupled into a lasing mode, q represents the electron charge, τ_n is the electron lifetime, α_f is the linewidth enhancement factor, η_d is the total differential quantum efficiency factor. For accurate output laser characteristics, it is essential to consider noises that occur in the active region of the DFB laser. The spontaneous emission, the electron hole recombination and many other actions cause noise signals that can be assumed to be Langevin noise sources $F_i(t)$ with the Gaussian distribution and zero mean values, where i can be substituted with N , S or θ . A complete list of input parameters for the DFB laser characteristics and their extracted values is displayed in Tab. 1. More about a noise source modelling for the DFB laser can be found in [16],[17].

Equations (1)-(3) are solved using the Runge-Kutta method of the fourth order. This method uses a short time for a sufficient approximation of output laser characteristics $\Delta t = 10$ ms. The time step can be reduced if more accurate approximation of output curves is needed, but the simulation time is rapidly increased. The light wave is represented as a high-frequency electric wave. The central wavelength λ_C for the DFB laser is set to 1550 nm corresponding to the 193,1 THz frequency, the bias current I_B is set to the 35 mA level. The optical wave is represented as a complex envelope because meeting the sampling theorem with such a high central frequency would rapidly increase the simulation time. The average output power P_{output} is 4,15 mW and the noise power P_{noise} with the 0,1 mW level represents a significant noise contribution due to the average power value. In Fig. 2, it can be seen output power fluctuations of the DFB laser with noise parameters.

2.2 Possibilities for the EDFA numerical simulations

For extended long-haul optical transmission systems and/or for utilization of multilevel modulation techniques, optical signals can be preamplified before the opto-electronic conversion. So, an influence of the EDFA amplification must be analyzed before including into the Optical Receiver block. A preamplifier calculates the signal amplification and the noise contribution added to this amplification, based on the operating wavelength, the amplitude of received signals, the pumping power and the doped fibers length. A final output signal power level with the added noise can be calculated according to (4).

$$P_{S_{\text{out}}} = P_{S_{\text{in}}}(\sigma_{1-2} + \sigma_{2-1})ekhc \times \frac{N(W_{1-2}k\lambda\sigma_{1-2}P_{\text{ASE}} + W_{1-3})}{W_{1-2} + W_{2-1} + k\lambda(\sigma_{1-2} + \sigma_{2-1})P_{\text{ASE}} + W_{1-3} + \frac{1}{\tau}} - \Gamma_s\rho L\sigma_{1-2}, \quad \text{with } k = \frac{\Gamma_s}{hcA}, \quad (4)$$

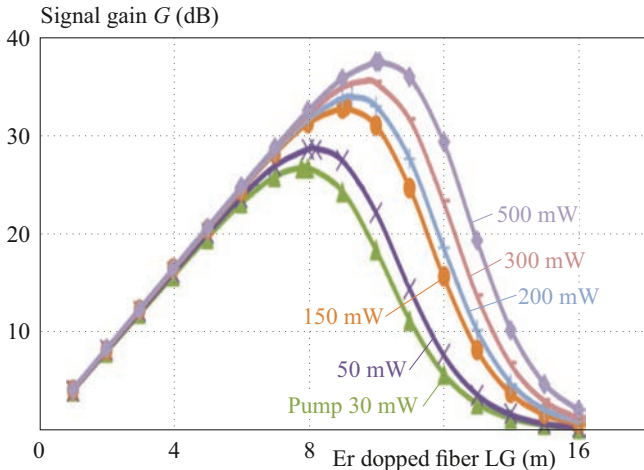


Fig. 3. Dependency of the signal gain on Er doped fiber lengths

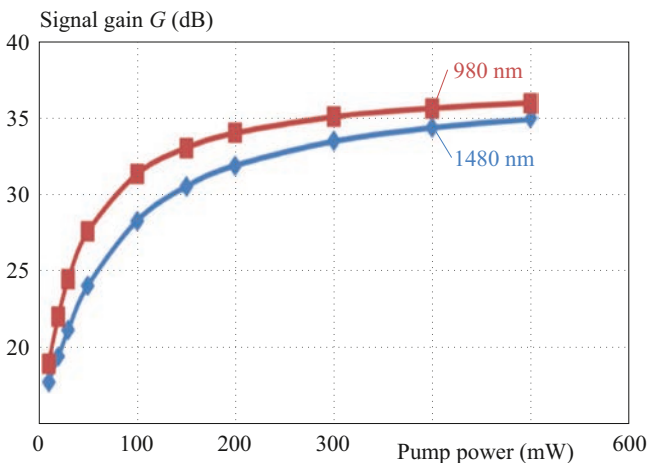


Fig. 4. Dependency of the signal gain on pump power

where Γ_s is the overlap factor, h is the Planck constant, P_{ASE} is the noise power, λ_S represents the signal wavelength, σ_{1-2} is the absorption factor, σ_{2-1} is the emission factor both due to this signal, and σ_{1-3} is the absorption factor due to pump signal, W_i represents transition rates between energy states, τ is the electron lifetime, L is the erbium doped fiber length, c is the light speed, A is the core area of the erbium doped fiber and P_{Sin} is the input signal power. A complete list of parameters for the output EDFA characteristics and their extracted values is displayed in Tab. 2. Extracted values of parameters are presented in [18].

A change in the EDFA signal gain can be achieved by changing the erbium doped fibers length, the pumping power and/or the pumping wavelength. The first, the signal gain increases with increasing the erbium doped fibers length only to a certain value, as shown in Fig. 3. Then, the signal strength begins to drop with noise mechanisms until the 16 dB value, when reaches the 0 dB gain. We can see that the maximum EDFA gain is achieved at the 980 nm pumping wavelength at 7.2-10.1 m doped fiber lengths.

The second, the signal gain increases with increasing the pump power and is approaching asymptotically to its highest value, as can be seen in Fig. 4. To be specific, a difference 2,58 dB in the signal gain is between pump powers 150 mW and 500 mW. Furthermore, we can achieve the average gain at the 980 nm pumping wavelength is better around 3.185 dB for the 9 m erbium doped fiber length than at the 1480 nm pumping wavelength. Based on our simulation results, the erbium doped fiber length is set to 9 m, the working wavelength of the pumping source is used 980 nm, and the pumping power value can be used in the 100-200 mW range. Then, an amplification of the one signal channel is within the 31.28-33.95 dB range that represents a common gain for single-channel EDFA amplifiers in real-time operations.

3 Exploitation of the PM 16-QAM modulation technique

3.1 Implementations of the PM 16-QAM modulator

The PM 16-QAM modulation format is a combination of the 16-QAM modulation format and the polarization multiplex technique. Two 16-QAM modulated signals are transmitted in two independent polarization planes. The light produced by the DFB laser block is divided by coupler into two light beams with equal power and then each light beam is polarized into $+45^\circ$ or -45° angles, so there is 90° phase difference between them. This operation is provided by the Polarization beam splitter block.

The 16-QAM modulation format can transmit four information bits in one transmission symbol. The rectangular constellation format can be achieved by combining two QPSK constellations where one of them is attenuated by 3 dB as can be seen in Fig. 5.

In Fig. 6, a complete block scheme of the PM 16-QAM modulator with both vertical and horizontal polarization modes is presented. The Bernoulli generator block produces eight Gaussian-shaped bit streams from which four are used to control arms of MZM modulators. Two QPSK constellation signals are produced and the output 16-QAM constellation signal can be achieved by combining them. Information bit streams modulate polarized DFB laser beams.

3.2 Implementations of the PM 16-QAM demodulator

The transmitted PM 16-QAM signal must be divided into two polarization planes before detecting. A signal in each polarization plane is preamplified by the EDFA amplifier and then mixed in 90° optical hybrids in appropriate polarization modes. Subsequently, a signal from the optical hybrid is sent to balanced receivers. Balanced receivers consist of two APD diodes. APD diodes are simulated as opto-electronic converters with given quantum efficiency and added noise parameters. Noise parameters include also inherent noises arising because of basic physical effects in opto-electronic components used in the optical receiver. The main components of this noise category

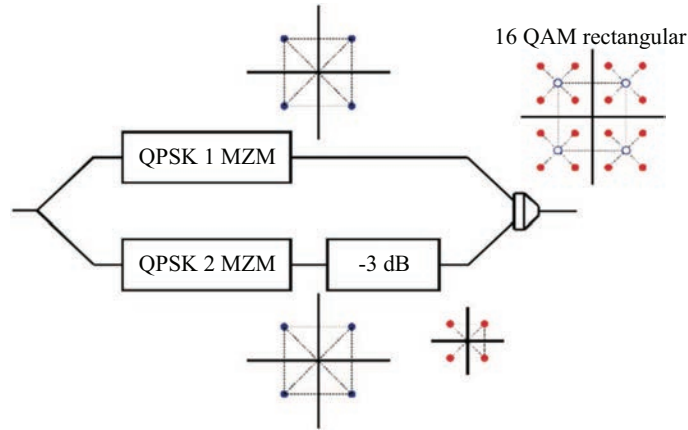


Fig. 5. The 16-QAM modulation constellation principle

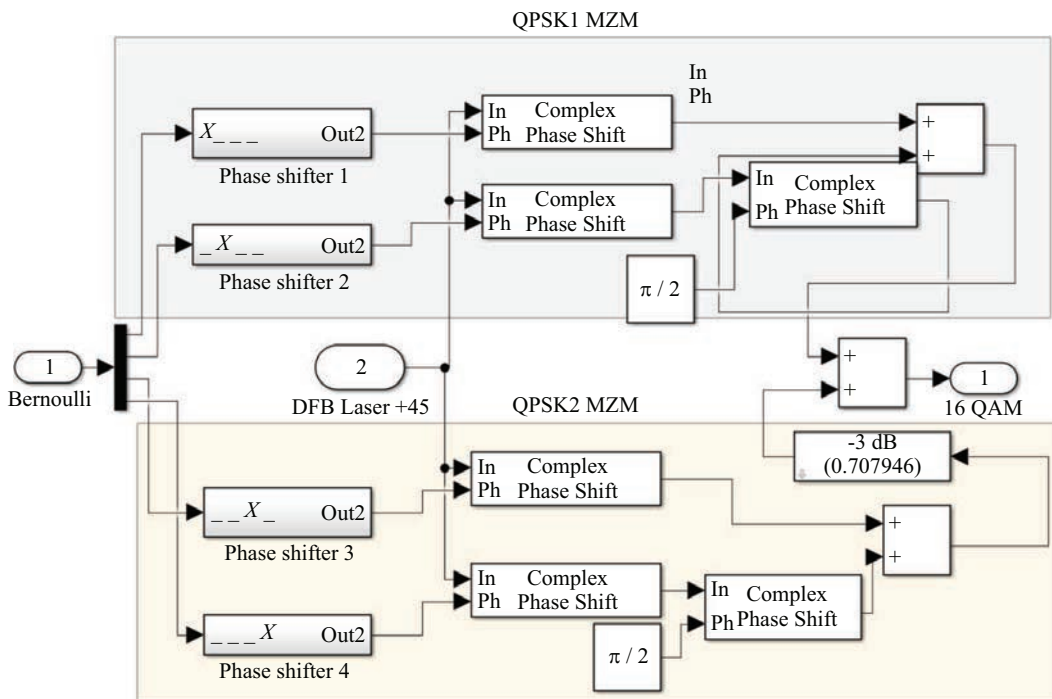


Fig. 6. The complete block scheme of the PM 16-QAM modulator

are the thermal noise i_T generated by the resistors, the quantum shot noise i_S generated by the opto-electronic conversion and the dark current noise i_Q produced in the absence of optical power. The mathematical representation for different sources of the receiver noise can be written as follows [10],[19]

$$\langle i_T \rangle = \frac{2}{\eta_{PD}} \sqrt{k_B T R B}, \tag{5}$$

$$\langle i_S \rangle = \frac{1}{\eta_{PD}} \sqrt{2qIB}, \tag{6}$$

$$\langle i_Q \rangle = \frac{1}{\eta_{PD}} \sqrt{2qI_{dc}B}, \tag{7}$$

where k_B is the Boltzmann constant, T is the absolute temperature in Kelvin, R is resistance, B is the detection bandwidth, η_{PD} is the photodiode responsivity, I is the current produced by the photodiode, q is the electron charge and I_{dc} is the photodiode dark current. A complete list of parameters for APD diode characteristics and their values used in (5)-(7) are in Tab. 3, [20].

A complete block scheme of the PM 16-QAM demodulator is in Fig. 7. Signals from balanced receivers go to the Matlab embedded block that provides an appropriate presentation of the constellation diagram.

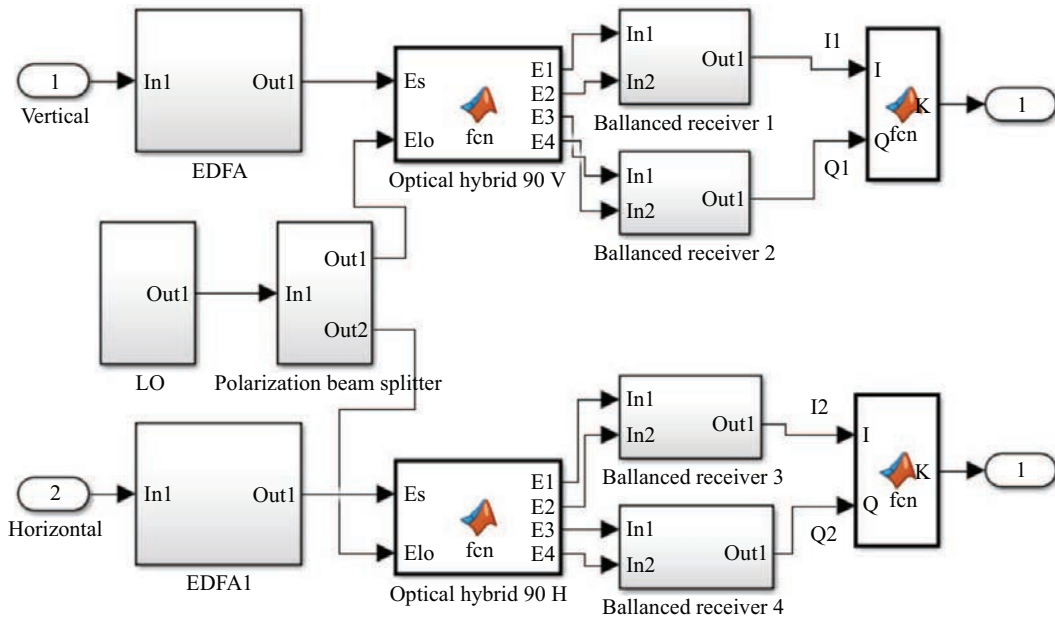


Fig. 7. The complete block scheme of the PM 16-QAM demodulator

Table 3. Parameters for the APD diode characteristics

| Parameter | Unit | Value |
|-------------|--------------------|-------|
| T | $^{\circ}\text{C}$ | 25 |
| B | GHz | 2.5 |
| η_{PD} | A/W | 0.9 |
| R | Ω | 50 |
| I_{dc} | nA | 10 |

4 Simulation results and discussion

Commercial simulation software tools are often expensive and not easily adaptive. Many of them are not based on measurements parameters and the data extraction for further processing is difficult if even possible. Therefore, we have decided to create our own simulation platform based on the Matlab Simulink environment, which has become the universal modelling tool in most universities and research laboratories around the world. Furthermore, it is important to search for a simulation platform that will be able to accurately describe behavior of different optical components from the optical transmission system under varying working conditions and their limitations. So, our simulation platform is based on measured parameters acquired from real optical transmission systems to predict performance and limitations of optical components more precisely.

The simulation of enhanced optical metropolitan networks is performed in Matlab R2017b Simulink. [8],[10],[11]. For evaluating of the PM 16-QAM modulation technique, following parameters of the optical transmission system

are predetermined. The SMF block for related simulation experiments represents a transmission medium of the single-mode optical fiber with negative environmental influences where following parameters are used: the polarization mode dispersion $PMD = 0.1 \text{ ps}/\sqrt{\text{km}}$, the chromatic dispersion $CD = 10 \text{ ps}/(\text{nm}\cdot\text{km})$, the transmission length $L = 80 \text{ km}$, the total attenuation $a_{total} = 16.8 \text{ dB}$, the central lasing wavelength $\lambda = 1550 \text{ nm}$. It is considered the application of the 9 m erbium doped fiber length and the 150 mW pumping power value that represents the EDFA amplification 31.28 dB at the 980 nm pumping wavelength reached before the optoelectronic conversion. Environmental influences of the optical fiber medium on transmitted signals in the optical transmission system are more specified in [9],[12],[13]. In Fig. 8(a), we can see a constellation diagram of the PM 16-QAM vertical plane for the optical signal before transmitting in the optical fiber and entering the SMF block. In Fig. 8(b), there is displayed a constellation diagram of the PM 16-QAM vertical plane for the same optical signal after outputting the SMF block and optical receiving.

Concurrently, the eye diagram of the PM 16 QAM vertical plane for the optical signal after outputting the SMF block and optical receiving is presented in Fig. 9. We can see that this type of modulation format has four transitions in the quadrature and phases components as shown on the PM 16-QAM constellation diagram.

Presented results obtained by the simulation platform for the optical transmission system verify that the PM 16-QAM modulation technique can be integrated as a perspective solution for enhanced optical metropolitan networks utilizing the optical amplification. There are indeed demands that must be fulfilled for its successful and effective exploitation. The PM 16-QAM modulation format can reach four times higher spectral efficiency, it means

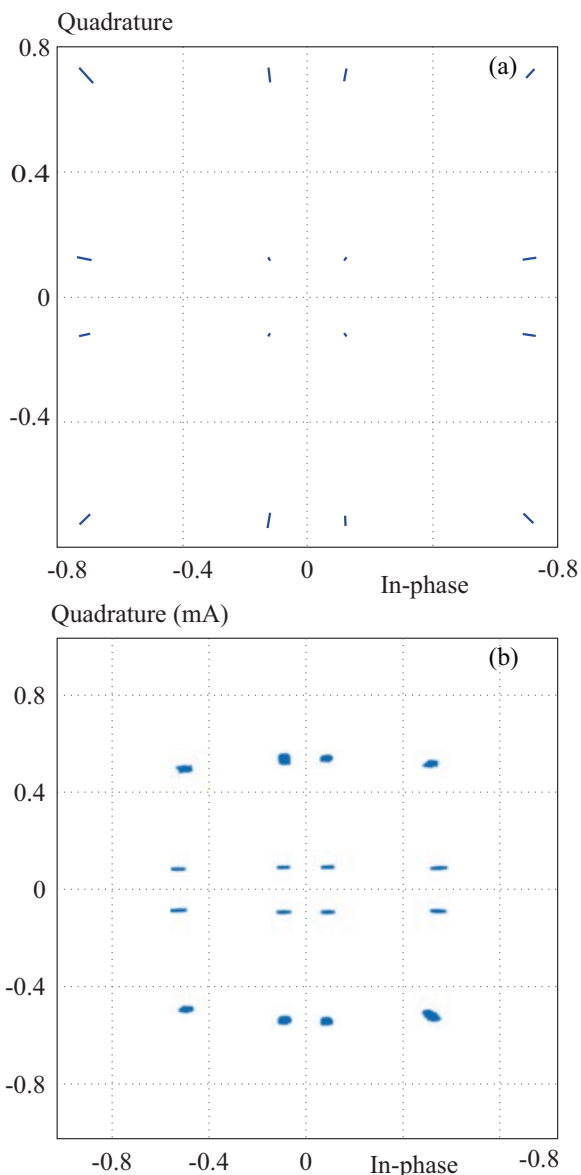


Fig. 8. The constellation diagram of the PM 16-QAM vertical plane: (a) – before transmitting in the optical fiber and entering the SMF block, (b) – after outputting the SMF block and optical receiving

besides that it needs four times higher OSNR values than the PM QPSK. This modulation format is also four times less resistant to phase noises arose through a transmission (a phase noise of the local oscillator, a nonlinear phase noise due to the optical fiber). For reaching the highest spectral efficiency, it is necessary a Nyquist filtering of signals in the electric domain [21] and a CFP2 ACO pre-equalization in digital-to-analog convertors [22]. For increasing the transmission reach, it will be necessary utilizing a combination of EDFA and Raman amplifiers. Another demand for the PM 16-QAM deployment is creating a flexible wavelength grid [23]. For actual PM 16-QAM spectral bandwidth after shaping by Nyquist pulses, a reconfigurable optical add-drop (ROADM) must be adjusted. At compliance these demands, this considered

modulation format can be implemented in metropolitan networks with expected reach of 400-1000 km.

Except demands in the optical domain, extensive digital signal processing in the electric domain is expected to be solved and performed. In [6], it was demonstrated that PM 16 QAM signals can be transmitted over long-haul distances in deployed networks with aged fibers by using an all-distributed Raman amplification system combined with high coding gain FEC. In [7], it was investigated the tolerance of 16-QAM signals to filtering effects and nonlinear effects arising from adjacent channels with different modulation formats. Also, FEC was presented as a critical enabling technology for further advancements in modulation formats.

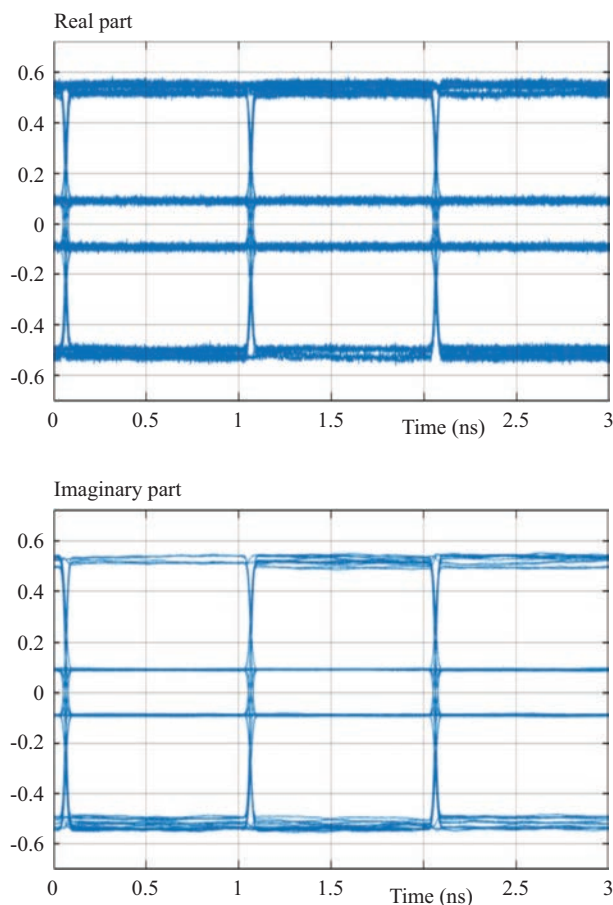


Fig. 9. The eye diagram for the PM 16-QAM vertical plane after outputting

The most important requirement for the PM 16-QAM implementation into the 400 G single-wavelength system is a required coherent receiver involving a sequence of several specific techniques. The first step is sampling, and quantization of analog signals received from the photodiode by fast analog-to-digital convertors. Further, a sampling signal must be time justified for components in phase. Consequently, a chromatic dispersion is compensated using finite impulse response filters [24] followed by a compensation of nonlinear effects [25-26]. One of last steps is a frequency and phase equalization and recovery.

A difference of frequencies at the heterodyne detection must be zero adjustment using an algorithm of the digital phase locked loop. By means of Viterbi-Viterbi algorithm, a phase estimation of the received symbol is determined. The last step is a digital demodulation. Considering various amplitude and phase noise influences on each received symbol, a hard decoding related to the Euclidean distance between a received symbol and a reference constellation is not possible to use. An algorithm of the expectation maximization optimizes a received constellation using a recovery of centroids. This method allows to overcome a destruction of the constellation form on the base of actual received data.

5 Conclusions

The PM 16-QAM modulation seems to be interesting for implementation in optical metropolitan networks enhanced with the signal amplification after compliance some demands. In [25], a research on the application of PM 16-QAM for metropolitan networks has been well described and an experimental setup to emulate and demonstrate the WDM transmission experiment were used. However, much work remains to experimentally craft guidelines for PM 16-QAM transmission especially signal processing and subcarrier spacing trade-offs influence nonlinear transmission performance. Before the expensive experimental setup, we prefer creating of appropriate simulation platform for the optical transmission system. A novelty can be found in adjusting, optimizing, and building of the proposed optical system and functional parts for any modulation format used.

For experimental efforts, we consequently realized a simulation platform for the optical transmission system that is based on measured parameters acquired from real optical transmission systems in order to predict performance and limitations of optical components more precisely at the signal transmission under varying working conditions. By this way, essential noise tolerances for comparison with the data under real conditions are included.

This simulation platform is presented together with its relevant optical components and possibilities for numerical simulations of the DFB laser and the EDFA amplifier blocks are closely characterized. The simulation of these optical devices is based on parameters extracted from real devices by measurements and real noise contributions are also taken into account for simulated devices. Except complete block schemes of the PM 16-QAM modulator and demodulator, a way for exploitation and implementations of considered modulation format in the simulation platform is introduced with more details.

Based on results obtained by the simulation platform for the optical transmission system, we can verify that the PM 16-QAM modulation technique can be integrated as a perspective solution for enhanced optical metropolitan networks utilizing the optical amplification. Moreover, a discussion on demands in both optical and electric domains that must be fulfilled for its successful and effective

exploitation is opened. In this context, our contribution can be used as a learning material and/or for further research in the subject.

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