RESEARCH SPECTRAL EFFICIENCY OF NEW MODULATION FORMATS IN FIBER-OPTIC NETWORKS

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Abstract

The rapid growth of the use optical technologies requires the development of methods and means to improve the spectral efficiency and noise immunity of fiber-optic networks when using wavelength multiplexing. On the basis of the research a new approach to the construction of the method of calculation spectral efficiency indices of new modulation formats in fiber-optic networks has been developed. The proposed method calculation of indicators takes into account the efficiency indicators fiber-optic transmission systems, the algorithm demodulator synthesis and effective methods modulation formats such as M-ary Quadrature Amplitude Modulation, Differential Phase Shift Keying and M-ary pulse position modulation. On the basis of the calculation method, important analytical expressions evaluating the characteristics of line capacity and noise immunity of optical signal reception are obtained.

Keywords: Spectral efficiency, signal to-noise ratio, fiber optic network, bit rate, line capacity, noise immunity.

I. Introduction

Nowadays, in conditions constant growth of the range infocommunication services and applications provided by optical telecommunication systems based on wavelength multiplexing technology, increasing volume transmitted packet streams, rapid growth requirements to noise immunity of multiservice traffic message reception and the issues effective frequency resource allocation are most acute [1, 2].

The advanced technologies future generation wave multiplexing and 2030 network include both WDM (Wavelength Division Multiplexing), CWDM (Coarse WDM), DWDM (Dense WDM), IoT (Internet of Think), and HDWDM (High DWDM), AI (Artificial Intelligence), 5G-NR-U (New Radio-Unlicen), and 6G (Generation) [2, 3, 4, 5].

In optical telecommunication systems considering the above mentioned modern spectral technologies, one of the important indicators is the line capacity, network performance, frequency efficiency and noise immunity reception optical signals in the provision of infocommunication services and applications.

On the basis of research it was established [6, 7, 8] that one of the important methods of increasing spectral efficiency and noise immunity in fiber-optic networks when using new modulation formats are methods of mathematical modeling. Among them, the spectral efficiency of modulation formats and optimal methods optical signal reception and efficient methods of signal-code design [9, 10] using modern WDM and DWDM systems with free-length , .

Taking into account the above mentioned, the task of research and the problem of providing the required spectral efficiency and noise immunity of the paths of fiber-optic transmission systems, as one of their most important characteristics, is quite relevant.

In [7, 9, 11] some problems line capacity, bandwidth, and spectral efficiency of telecommunication systems related to the optimization of the demodulator of a noise-tolerant receiver are analyzed. In [5, 12], noise immunity, modulation methods, spectrum expansion, and issues noise-tolerant coding in optical communication systems, which are only defined signal-to-signal-noise ratios.

An optimization problem arises to investigate the spectral efficiency and noise immunity performance fiber-optic networks built according to the latest wavelength multiplexing technology.

The purpose of this work is to develop a new approach to create methods for calculating the characteristics of spectral efficiency and noise immunity of signal reception in fiber-optic networks using efficient modulation formats.

II. General statement of the research problem

Conducted a study of the characteristics fiber-optic networks based on WDM and DWDM technology show [7, 9, 12] that the spectral efficiency and noise immunity of reception characterizes its ability to provide a given quantity and quality of transmitted messages with the least amount time, bandwidth , signal power and guaranteed quality of service.

Considering the constituent components of the vector communication quality, both spectral efficiency, line capacity, and bit error probability reception in terms of the performance of fiber-optic networks based on DWDM technology, which functional dependence is described as follows:

$$S_{EF}(E_b, \lambda_i) = W[SNR(E_b, N_0), V_b(b_i, \lambda_i), E(\lambda_i), \eta_{SE}(\Delta F_k, \lambda_i)] \tag{1}$$

where $SNR(E_b, N_0)-$ function, taking into account the signal-to-noise ratio (Signal to-Noise to Rate) at the demodulator input with consideration of bit signal energy E_b and interference power spectral density N_0, which characterize the complex indices fiber-optic networks based on DWDM system; $\mathrm{V_b}(b_i, \lambda_i)-$ bit rate message with wavelength λ_i and with binary code element b_i and these are binary symbols from the Galois field $F_2(b_i) = GF(2) = \{0,1\} \to b_i = \{0,1\}$; $\eta_{SE}(\Delta F_k, \lambda_i)-$ spectral efficiency fiber-optic transmission systems, which characterizes the channel utilization efficiency over the frequency band ΔF_k with wavelength λ_i, (bps/Hz) and is equal to [2]:

$$S_{SE}(\Delta F_k, \lambda_i) = [V_b(\lambda_i)] / \Delta F_k] \geq 1 \tag{2}$$

where $E(\lambda_i)-$ line capacity fiber-optic transmission systems and can be increased by increasing both the bit rate transmission and the number spectral channels N_k, is expressed as follows:

$$E_{\mathrm{DWDM}}(\lambda_i) = V_b(b_i, \lambda_i) \cdot N_k \tag{3}$$

where N_k – is the number of spectral channels and is equal to the ratio of the light amplification bandwidth $\Delta\lambda_y$ to the inter-channel spacing width $\Delta\lambda_k$ and is expressed as $N_k = (\Delta\lambda_y / \Delta\lambda_k) > 40,...,96$ channels.

Expression (1), (2) and (3) define the essences of the proposed new approach and characterize the spectral efficiency and fidelity performance of transmission systems.

It is worth noting that the task managing heterogeneous spectral efficiency resources when using modulation formats, researching and evaluating the fidelity of message transmission using the performance criterion fiber optic transmission systems in providing a wide range of multimedia services has not yet been fully explored [5, 9, 11, 12].

Modulation formats for $V_b(b_i, \lambda_i) \geq 40\,Gbps$ are divided into amplitude-based M-QAM and phase-based DPSK (Differential Phase Shift Keying), which reduces the width of the optical spectrum occupied by the signal, $\Delta\nu_S$ (for binary formats, $\Delta\nu_S = 2V_b(b_i, \lambda_i)$), increases the spectral efficiency of the modulation $\eta_{SE}(\Delta F_S, \lambda_i) \to \max$, and thus enables high bandwidth fiber optic transmission systems.

Therefore, there is a need to study the DWDM system and create a new approach to build a method for calculating the spectral efficiency and noise immunity using new modulation formats, allowing to optimize the characteristics of fiber-optic networks based on DWDM technology.

III. Structural diagram of the investigated DWDM system link

The surface roughness formed during the cutting of HARDOX-500 steel workpieces varies based on numerous technological, kinematic, structural, and processing environment factors. Consequently, one of the most important technological factors affecting the roughness formed on the surface during abrasive waterjet cutting is the pressure of the water-abrasive mixture applied to the cutting zone. An increase in the pressure of the water-abrasive mixture enhances the cutting capabilities of the water-abrasive, which plays the role of the cutting tool in the steel cutting process, thereby intensifying the cutting of the workpiece. Our research has determined that the study of the surface roughness dimensions in hydroabrasive machining varies widely depending on the processing conditions and regime parameters of the process. Therefore, examining the regularities of roughness changes during the machining of the selected material is one of the important tasks for identifying the advantages of the process. In this case, the roughness formed on the processed surface, depending on the optimal cutting process, has been determined through experimental research to remain within the required limits. In the experiments, a workpiece thickness of 15 mm was taken, with a longitudinal feed rate of S_{long}=26,7 mm/min, an abrasive particle size of 80 μm, and an abrasive consumption of Q=125g/l, while the surface roughness obtained during abrasive waterjet cutting [3] is shown in Figure 1, and the dependence of the obtained experimental and theoretical values on the influence of the water-abrasive jet is presented in Tables 2 and 3.

As mentioned above - constantly emerging types infocommunication services and their new user applications create an increasing load on the backbone optical transport network with increased efficiency. Transportation high-speed traffic flow requires the latest data transmission technology, which, on the one hand, has sufficient spectral efficiency and performance, on the other hand, provides the operator with the ability to scale the network without changing the infrastructure and quality of communication. These requirements are met by the technology of spectral multiplexing WDM and DWDM, which is the main technology for building backbone fiber-optic transmission systems [5, 9].

WDM wave multiplexing is a physical layer technology that is the transmission of multiple optical signals in a single optical fiber at different wavelengths. The first WDM systems were dual channel with transmission at wavelengths $\lambda_i = (1.31,...,1.55)\,\mu m$.

Somewhat later multi-channel solutions appeared: CWDM and DWDM , where the names refer to the density of information optical channels in the optical band. DWDM is a technology of dense spectral multiplexing. Optical channels are located in the range from 1.53 to 1.565 μm with a step of 0.4 nm, 50 GHz or 0.8 nm, 100 GHz [7, 9].

Pic.1 shows the principle of operation of the structural scheme of wavelength multiplexing with optical amplifiers - Erbium Doped Fiber Amplifier (EDFA).

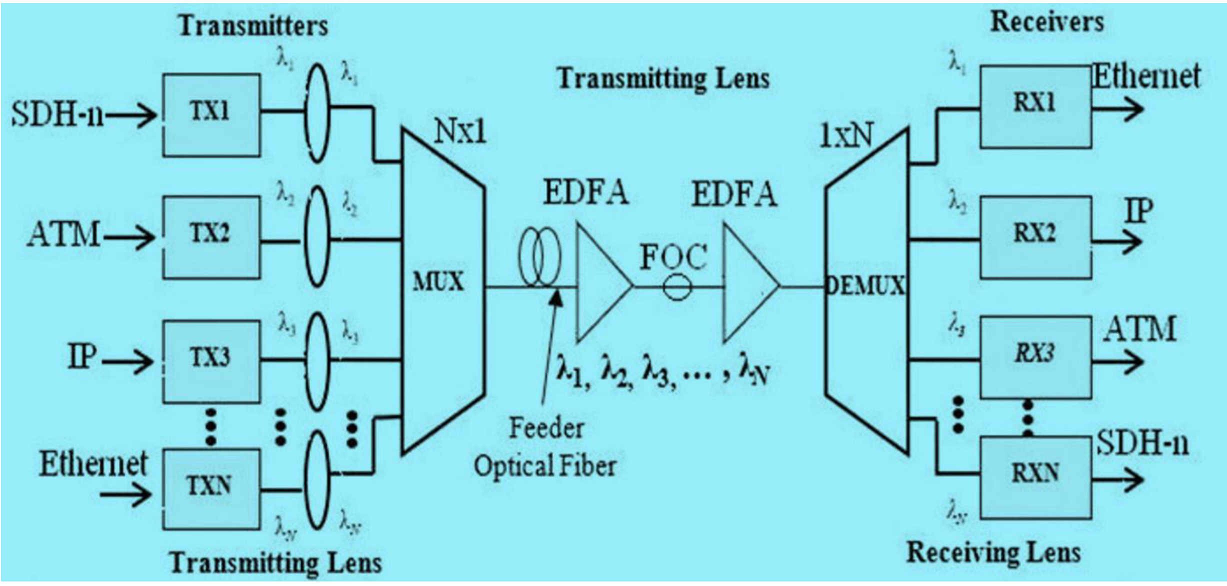

Figure 1: *DWDM system - FOC transmission optical signals on many wavelengths with EDFA optical amplifiers*

From the schematic, it can be seen that figure1 consists of the following important blocks: optical transmitter (TXN), Erbium Doped Fiber Amplifier (EDFA), Fiber Optical Cable (FOC, ITU-T, G.652, SSMF (Standard Single Mode Fiber)) and receiver (RXN). In addition, the main components of a DWDM system are:

- Transponders that generate signals at different wavelengths;
- Multiplexers (MUX), which combine signals from different fibers at different wavelengths on a single fiber, and demultiplexers (DEMUX), which separate multiple signals at different wavelengths from a single fiber over different fibers;
- Amplifiers that amplify a multichannel signal during its transmission over optical fiber, EDFA.

In this scheme, the used erbium-doped fiber amplifier (EDFA) allows uniform amplification of information channels at different wavelengths just in that spectral range of optical fiber where the signal attenuation is minimal, i.e. $\alpha_z(\lambda_i) = A_d \cdot (1/L_y) \rightarrow \min$ at the range $C(\lambda_i) = (1.530,...,1.565)\mu m$, (where the $A_d -$ allowable losses in the FOC).

In DWDM system for transmission optical signals primarily use the spectral bands $C(\lambda_i) = (1.530,...,1.565)\mu m$, $S(\lambda_i) = (1.460,...,1.530)\mu m$ and $L(\lambda_i) = (1.565,...,1.625)\mu m$. For the technology of spectral compaction wavelengths in the working bands are used and can be described by a one-dimensional matrix of the form

$$E[L_y(m,k)] = |\lambda_1, \lambda_2, ..., \lambda_{i.\max}| \ \ , \ m \neq k, \ \ i = \overline{1,n} \tag{4}$$

where $L_{ó}(ò\,,k)-$ is the length of the section between network elements in the transmission system; m and $k-$ respectively, indices for the numbers of the initial and final network elements-for the operating bands $C(\lambda_i)$, $S(\lambda_i)$ and $L(\lambda_i)$ when using a frequency grid 50 GHz.

The carrier spacing in DWDM systems for optical networks can be $\Delta F_{DWDM} = (25,...,200)\,GHz$. However, in modern fiber-optic networks the most commonly used channel grid with a 50 GHz step.

It should be noted that the technology WDM and DWDM transmission with a wide possibility creates a basis for the organization of flexible high-speed intelligent fiber-optic networks, providing transparent transmission ever-growing traffic, including delay- sensitive. Directly related to the performance DWDM systems is the efficiency and noise immunity of fiber optic networks.

IV. Analysis and evaluation of spectral efficiency of multilevel modulation formats

It is known [7, 12], that the spectral efficiency of fiber-optic transmission systems based on DWDM technology is the ratio of the bit rate information transmission ($bps = Bod$) to the bandwidth $\Delta\nu_k$ and is measured in the index (bps/Hz). For M-QAM ($M-$number of signals), modulation formats, spectral efficiency is expressed as:

$$S_{SE}(\Delta F_k,\lambda_i) = [V_b(\lambda_i)]/\Delta\nu_k] \geq 1 \ \ , V_b(\lambda_i) \geq \Delta\nu_k \tag{5}$$

Formula (5) defines the spectral efficiency of multilevel modulation formats, which characterizes how efficiently bandwidth is used in an arbitrary DWDM system.

For M-QAM modulation formats, the spectral efficiency is expressed as:

$$S_{SE}(\Delta F_k,\lambda_i) = \frac{R_k / T_b(\lambda_i)}{\Delta F_k} \cdot \ell og_2 m \geq 1, \quad m = 2^M \tag{6}$$

where R_k - is the rate of the interference-free code, $R_k = (3/4) < 1$, $T_b(\lambda_i)-$ is the bit cycle in the system and is equal to $T_b(\lambda_i) = 1/V_b(b_i,\lambda_i) = \frac{T_S}{M}\cdot 2^M$, M - is the coding level.

Using M-QAM modulation formats ($M \geq 4$) and formulas (5) and (6) at $V_b(\lambda_i) = 40\,Gbps$ and $\Delta F_k = 100GHz$, then $S_{SE}(\lambda_i) = 0.40\,bps/\mathrm{Hz} \geq \mathrm{S_{SE.all.}}(\lambda_i)$ and $\lambda_i = 1.55\,\mu m$, where $\mathrm{S_{SE..all.}}(\lambda_i)-$ is the acceptable value of spectral efficiency [2, 9].

Now, based on (5) and (6), we can express the DWDM system capacity through the spectral efficiency of modulation formats:

$$E_{DWDM}(\lambda_i) = \mathrm{S_{SE}}\,(\Delta F_k,\lambda_i)\cdot\Delta\nu_{ó} \tag{7}$$

In this representation, the capacity optical links when using a DWDM system does not depend explicitly on the bit rate transmission, but is directly proportional to $\Delta\lambda_y$.

The analysis shows [5, 7, 9, 11] that to increase the channel transmission rate and, consequently, the spectral efficiency by a factor of two can be achieved by polarization multiplexing. In this case, two independent message streams are transmitted at the same wavelength in orthogonal polarization states.

To increase the spectral efficiency and line capacity, we consider the most widely used M-ary pulse position modulation (M-PPM), which reduces the optical signal bandwidth. Taking into account the M-PPM parameters, the spectral efficiency of new modulation formats is expressed as follows [12]

$$S_{SE}(M,\lambda_i) = (1/\text{Ì}\ )\cdot \ell\text{og}_2\binom{M}{m} \tag{8}$$

Based on (8), when using M-PPM modulation formats, the required bandwidth optical communication networks is determined as follows:

$$C(M,\lambda_i) = M \cdot V_b(b_i,\lambda_i)/\ell og_2\binom{M}{m} \tag{9}$$

Considering (8) and (9), the line capacities of the WDM and DWDM system can be determined as follows:

$$E_{\text{DWDM}}(\lambda_i) = (\Delta\nu_y / M)\cdot \ell og_2\binom{M}{m} \tag{10}$$

On the basis expression (8), (9) and (10), the package Communications Toolbox in Matlab environment (R 2019b) [10] was used and numerical values were obtained by means of which the graphical dependence was plotted, $S_{SE}(M,\lambda_i) = \text{W[OSNR (h), M, } \text{V}_\text{b}(\text{b}_\text{i},\lambda_\text{i})]$.

Figure.2. Shows the graphical dependence of spectral efficiency on the optical signal-to-noise ratio.

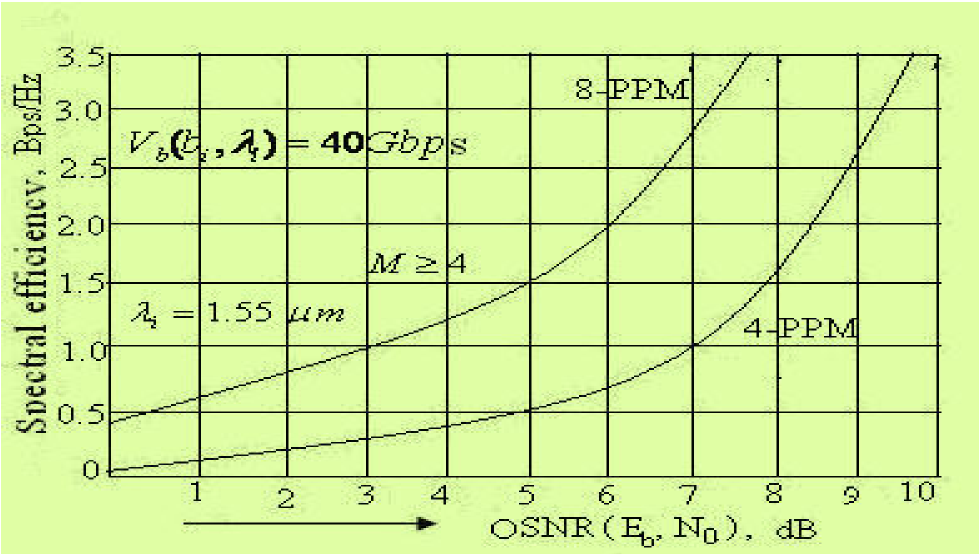

Figure 2: *Graphical dependence spectral efficiency on optical signal to-noise ratio when using the new 4-PPM and 8-PPM modulation formats*

Analysis graphical dependencies $S_{SE}(M,\lambda_i) = \text{W[SNR (h), M, } \text{V}_\text{b}(\text{b}_\text{i},\lambda_\text{i})].$, depicted in figure 2, clearly show the improvement spectral efficiency with increasing signal to-noise ratio when using PPM signals 4-PPM and 8-PPM types for a given bit rate $\text{V}_\text{b}(b_i,\lambda_i) = 40\,Gbps$, $\lambda_i = 1.55\,\mu m$ and $M \geq 4$.

V. Investigations of noise immunity optical signals reception in DWDM system

Nowadays, optical telecommunication systems have stringent requirements on bit rates transmission, signal processing methods and noise immunity optical signal reception [3, 11]. To solve this problem, efficient modulation formats M-ary Quadrature Amplitude Modulation (QAM) type were chosen.

For modulation formats such as M-QAM - one of the main criteria for assessing the quality of communication, is the working characteristics noise immunity reception optical signals in DWDM system, showing the dependence of the probability erroneous reception per symbol and the probability of bit errors from the required optical signal to noise ratio (OSNR, Optical Signal to - Noise Ratio):

$$P_{BER}(h) = W[SNR(E_b, \lambda_i, N_0)],\ P_{SER}(h) = W[SNR(E_b, \lambda_i, N_0)] \tag{11}$$

Suppose that in a DWDM system QAM signal is orthogonal in nature. For an orthogonal system $OSNR(E_b, \lambda_i, N_0)$ is expressed as follows:

$$SNR(E_b, \lambda_i, N_0) = \mathrm{SNR}\ (\mathrm{h}, \lambda_\mathrm{i}) = \sqrt{P_S T_S / N_0} \tag{12}$$

where $N_0 -$ is the power spectral density of the optical signal under the influence of additive white Gaussian noise (AWGN, Additive White Gaussian Noise).

Taking into account expressions (12) we determine the probability bit errors optical reception signals in DWDM system. Given the noise components of the output signal and the noise variance AWGN or error variance σ_A^2, it is possible to estimate the value of $OSNR(E_b, N_0)$ when receiving M-QAM signals ($M -$ number of QAM modulation levels), which with σ_A^2 is expressed as follows [7, 8]:

$$OSNR(E_b,\ \sigma_A^2) = O\mathrm{SNR}\ (\sigma_\mathrm{A}^2) = (E_b^2 / 2\sigma_A^2) \cdot \ell og_2 M \tag{13}$$

It follows from (13) that $OSNR(E_b, \lambda_i, N_0)$ is determined only by the signal energy E_b and error variance σ_A^2, which does not depend on the shape of the optical signal under study.

Given the formats QAM modulation in DWDM system and expressions (11),...,(13) the probability of bit error of reception is calculated as follows [5, 12]:

$$P_{BER}(h) = 1 - \{\frac{1}{2^{m-1}\sqrt{2\pi}} \int_{-\infty}^{\infty} [2 - \mathrm{erfc}(\mathrm{u}/\sqrt{2})]^{\mathrm{m-1}} \cdot \exp[-0.5[(u - OSNR(E_b, \lambda_i, \sigma_A^2)]^2]^m\, du\}^{\mathrm{m}} \tag{14}$$

Formula (14) defines the dependence of the probability error reception of one *m* subcarriers on $OSNR(E_b, \lambda_i, N_0)$, which characterizes the probability bit errors of optical signal reception.

Note that on the basis calculation methods similarly, it is possible to obtain analytical expressions for bit error probability and $OSNR(E_b, \lambda_i, N_0)$ when using M-QAM type QAM-64 and QAM-256.

On the basis formula (14), the Communications Toolbox package in Matlab(R 2019b, 9.7; 64 bit) environment was used [10]. One of the modules this extension is the graphical environment BERTool with the help which the dependence bit error probability on $OSNR(E_b, \lambda_i, \sigma_A^2)$ was plotted. The following numerical value swore used to plot the graphical dependence:

$OSNR(E_b, \sigma_A^2) = [1,...,24]\,dB$, $\lambda_i = 1.55\,\mu m$ and $V_b(b_i, \lambda_i) = (5,...,10)Gbps$, modulation scheme QAM-8 and QAM-16.

Figure 3 the dependence of the bit error probability on the signal-to-noise ratio per bit, $P_{BER}(h) = \mathrm{W}[\mathrm{OSNR}(\mathrm{E_b}, \sigma_A^2), \mathrm{M}, \mathrm{V_b}(\mathrm{b_i}, \lambda_i)]$ was presented based on numerical values.

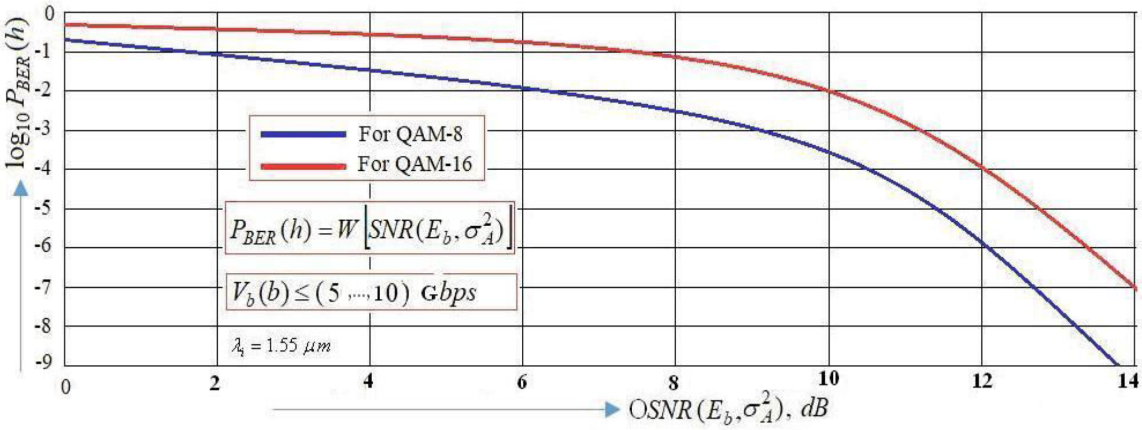

Figure 3: *Graphical dependence bit error probability on OSNR when using QAM-8 and QAM-16*

Graphical dependence, depicted in figure 3, clearly demonstrates the improvement bit error probability level in DWDM system with increasing modulation $M \geq 8$ and $\lambda_i = 1.55\,\mu m$ when using new QAM-8 and QAM-16 modulation formats.

The conducted studies have shown that in the DWDM system, when using new modulation formats such as M-PPM, the requirement for optical $SNR(h)$ increases with the growth of positional modulation to achieve the same value of the probability error in receiving P_{BER} an optical signal.

The conducted studies have shown that in a DWDM system, when using new modulation formats such as M-PPM, the requirements for optical SNR increase with the growth positional modulation to achieve the same value of the probability error in receiving an optical signal P_{BER}. Figure 4 shows a family of graphical dependencies $P_{BER} = \mathrm{F}[\mathrm{V_b}(\mathrm{b_i}, \lambda_i), \mathrm{OSNR}(\mathrm{h})]$.

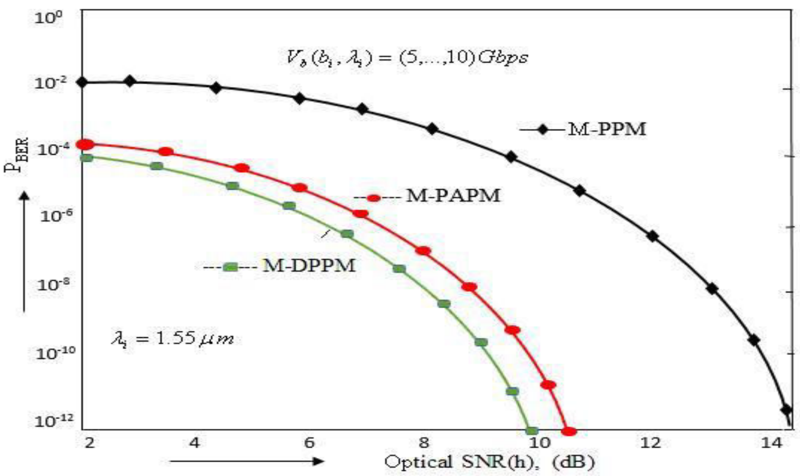

Figure 4: *Graphical dependence of the probability of bit errors P_{BER} on the optical SNR(h)*

From the family graphic dependencies it follows that with increasing optical $SNR(h)$ the probability bit errors is minimized due to the use new formats such as M-ary PPM, M-ary PAPM

(M-ary Pulse Amplitude and Position Modulation) so and M-Digital PPM at a given speed $V_b(b_i, \lambda_i) = (5,...,10) Gbps$.

The above-mentioned efficient and new modulation formats with high noise immunity types can be used in various infocommunication applications, including free-space optical (FSO) lines, hybrid optical fibers, optical wireless communications, next generation FSO, satellite communication systems and atmospheric optical communications.

VI. Conclusions

1. As a result of the study of fiber-optic networks, a new approach to the creation of methods for calculating the spectral efficiency and noise immunity optical signal reception using wavelength multiplexing was proposed.

2. The principle constructing fiber-optic networks using WDM and DWDM technology was analyzed, a structural diagram fiber-optic systems for transmitting optical signals via FOC at many wavelengths with EDFA optical amplifiers based on wavelength multiplexing was proposed.

3. Based on the calculation methods, analytical expressions were obtained that allow estimating the line capacity indicators, spectral efficiency of new modulation formats, optical signal-to-noise ratio and bit error probabilities in a DWDM system.

4. Numerical calculations of spectral efficiency and noise immunity indicators of reception were carried out in the MATLAB environment and graphical dependencies were constructed for comparative analysis using new modulation formats M-QAM and M-DPPM.

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