



TECHNICAL UNIVERSITY - GABROVO

Faculty of Electrical Engineering and Electronics

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**METHODS AND ALGORITHMS FOR RESEARCH ON MULTIPLEXED
SIGNALS IN PASSIVE OPTICAL COMMUNICATION NETWORKS**

A U T H O R ' s S U M M A R Y

of a dissertation

for acquiring the educational and scientific degree "Ph. Doctor"

Field of higher education: 5. Technical Sciences

Professional field: 5.3 Communication and Computer Engineering

Doctoral program: "Communication Networks and Systems"

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Scientific supervisor: Prof. Stanimir Mihaylov Sadinov, PhD

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Gabrovo, 2025

The dissertation work was discussed and directed for official defense at a session of the Extended Department Council of the Department of Communication Engineering and Technologies at the Faculty of Electrical Engineering and Electronics of the Technical University – Gabrovo, held on 17.12.2025.

The dissertation work contains 126 pages. The scientific content is presented in an introduction, four chapters and a conclusion, and includes 128 figures and 12 tables. 79 literary sources are cited. The numbering of the figures, tables and equations in the Author's abstract is consistent with that in the dissertation work.

The development of the dissertation work was carried out in the Department of Communication Engineering and Technologies at the Faculty of Electrical Engineering and Electronics of the Technical University – Gabrovo.

The official defense of the dissertation will take place on March 26, 2026 at 1:00 p.m. in Room 2215, University campus No. 2 “Bazhdar” of the Technical University – Gabrovo.

The materials related to the defense are available to those who are interested in Room 3209, University campus No. 3 “Rectorate” of the Technical University – Gabrovo.

The reviews and opinions of the members of the scientific jury and the Author's abstract are published on the university's website: www.tugab.bg.

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I. GENERAL CHARACTERISTICS OF THE DISSERTATION

Relevance of the problem

Methods and algorithms for research on multiplexed signals in passive optical communication networks (PON) are important for several key reasons, which cover both the physical layer and network efficiency and reliability. Multiplexed signal analysis algorithms allow solving a number of optimization problems such as optimal allocation of available resources, minimizing spectral overlap and losses, and increasing the total capacity without physically expanding the network.

Since in passive optical networks the signals are combined and separated passively, this leads to interchannel interference, chromatic and polarization dispersion, and nonlinear effects at high speeds. Signal analysis and processing methods would help to accurately separate the signals, reduce the bit error rate (BER), and increase the quality of service (QoS).

All of the above indicators are critical for the scalability of PON networks. Methods and algorithms for research on multiplexed signals are the basis for reliable, high-speed and scalable passive optical networks. They allow to increase capacity, reduce errors, support new services and optimize costs - without changing the passive optical infrastructure.

This dissertation work analyzes the main methods and offers a synthesis of algorithms and practically oriented models for studying and solving optimization problems in optical communication systems using wavelength division multiplexing.

Purpose and objectives of the dissertation work

The purpose of the dissertation work is to develop correct models and setups for research on the processes of multiplexing of signals by wavelength and to present methods and algorithms for improving the reliability and efficiency of communication and the quality of services in multi-channel passive optical networks.

To achieve the formulated goal, it is necessary to solve the following *generalized objectives*:

1. Creation and description of a methodology for a comprehensive study of the processes of multiplexing and signal transmission in multi-channel passive optical networks.
2. Synthesis and development of simulation models in the OptiSystem and Matlab/Simulink environments for research on the processes of coding and optical modulation and for studying their influence on the efficiency of the multi-channel passive optical network model.
3. Conducting a research on the parameters of a multi-channel passive optical network and the possibilities for improving the quality of transmitted information, the efficiency and range of the network under different configuration parameters and statistical processing of the results.

4. Development of a practical laboratory model for studying the influence of the setting parameters and configuration parameters on the Quality of services and the efficiency of the multi-channel optical network and to propose methods and measures for its improvement.

The research methods are mainly identified into separate chapters, such as analytical, simulation and practical methods, and cover the dependencies of the parameters characterizing the implementation of the individual models.

Scientific novelty

The scientific novelty of the dissertation can be reduced to the following more significant contributions:

1. Synthesis of a methodology and algorithm for optimal planning, sizing, modeling and research of passive optical networks with spectral multiplexing of signals.
2. Development and research of complex imitation models of multi-channel high-speed optical communication networks for solving optimization problems according to the criteria of achieving a minimum BER value or maximum Q factor and ensuring maximum network performance and efficiency for different input signal parameters.
3. Development and research of a specialized experimental setup of a passive optical network (PON) with spectral multiplexing of signals for the delivery of interactive services, designed to perform three main tasks: to allow a wide variety of practical research (traffic processing, introduction of new services and modules for management and communication, etc.); to be a platform for conducting general research in the field of passive optical networks; to provide convenient and easy training of personnel.

Applicability

The applicability of the dissertation work is related to the creation of methodologies of procedures related to correct approaches in modeling, selection and implementation of architecture, the necessary equipment and correct configuration, through monitoring and evaluation of signal parameters in passive optical networks with spectral multiplexing of signals, related to improving the reliability and efficiency of communication and the Quality of services in them.

Approbation of the dissertation work

The main stages of the development of the dissertation work are presented in six publications at international conferences and scientific journals, fully covering the minimum requirements for the criterion under consideration. One of the papers was presented at the international scientific conference UNITECH

2025, three of the papers were presented at the national conference "TechCo 23-24" and two of the papers – at the "Student Scientific Session 2024" of the Technical University - Gabrovo. Two of the publications are self authored. The publications were published in preceedings with scientific review in the 2023-2025 study period, and actually represent nearly 2/3 of the content of the dissertation work. The publications present a large part of the research carried out and the main conclusions of the dissertation work are discussed.

Structure and volume of the dissertation work

The dissertation work includes an introduction, four chapters, a conclusion, a list of abbreviations used, a list of publications on the dissertation work and a list of references. The total volume is 126 pages and includes 128 figures and 12 tables. 79 literary sources are cited.

II. CONTENTS OF THE DISSERTATION

CHAPTER 1. CURRENT STATUS AND PROBLEMS IN PASSIVE OPTICAL COMMUNICATION NETWORKS WITH SPECTRAL MULTIPLEXING

1.1. Multi-channel optical communication lines and their importance

The growth of information flows in recent years, as well as their globalization, place extremely serious demands on the communication aspects of our material culture and, to a particularly high degree, on fiber optic communication systems (FOCS).

1.1.1. Multiplexing of the fiber optical line in the time domain

As the first stage of creating multi-channel FOCS, time-dithering of fiber optical line (FOL) is used.

Time-Division Multiplexing (TDM) technology is implemented in that part of the FOCS transmission subsystem, which is before the modulator (and before the optical source), i.e. at the electronic level. The complete communications signal is initially electronic, and after modulating the optical source, it becomes optical.

1.1.2. Multiplexing of the fiber optical line in the wave domain

In cases where it is necessary to transmit extremely large amounts of information over long distances, it may turn out that a given specific compression of the FOL in the time domain, i.e. implemented with the TDM technology, is not enough. Then we proceed to the second stage of the construction (more precisely, the completion) of the multi-channel FOCS, namely - to additional compression of the FOL, but already in the wave (in the chromatic) domain. This compression is carried out by jointly using K subFOCS of the TDM type (with N_c channels in each of them), divided by wavelength, i.e. with wave ranges distributed along the λ axis.

1.2. Architecture of modern multi-channel optical communication systems

1.2.1. Structural diagram of an optical system with TDM technology

An exemplary structural diagram (in a significantly simplified form) of the transmission part of a TDM FOCS is presented in Fig. 1.1. It is denoted by $T(i)$, because this FOCS can be considered as the i -th TDM subFOCS in the WDM infraFOCS (as is done below).

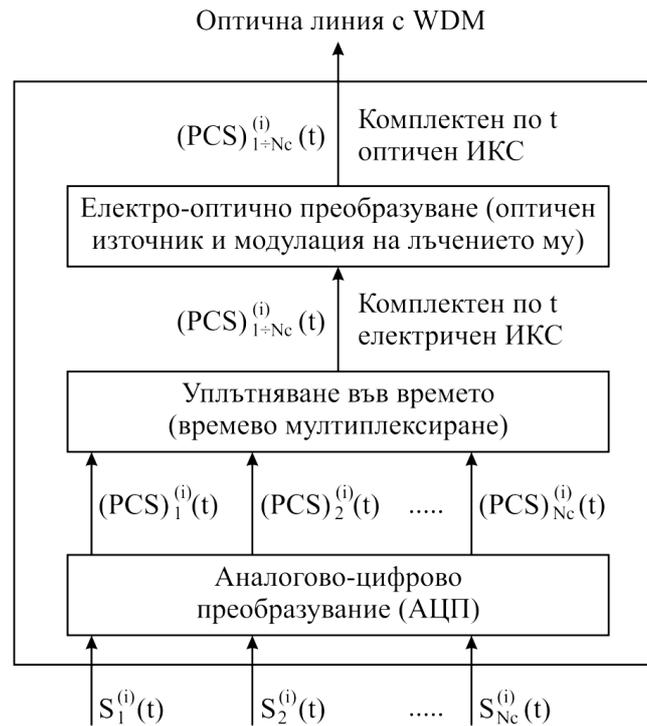


Fig. 1.1. Transmission part of the i -th FOCS with TDM (denoted by $T(i)$)

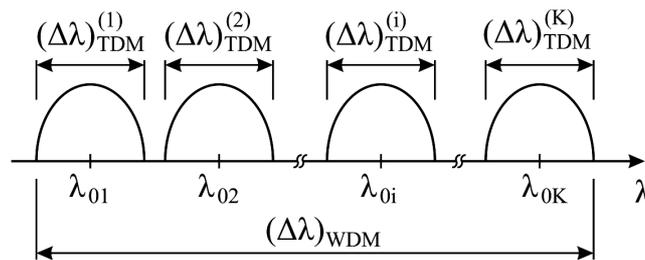


Fig. 1.2. Diagram along the λ axis of FOCS with WDM technology

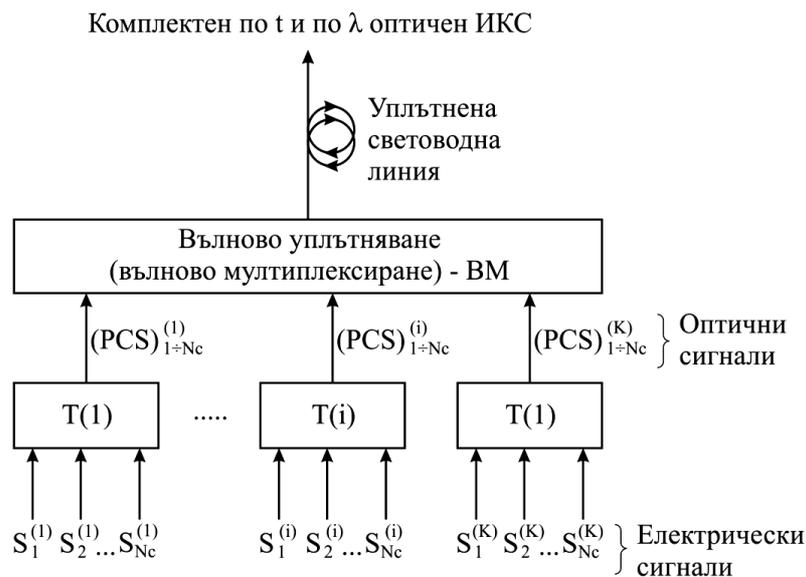


Fig. 1.3. Transmission part of FOCS with WDM

1.2.2. Structural diagram of an optical system with WDM technology

Fig. 1.2 shows in a simplified form the arrangement along the wave axis λ of the wave intervals occupied by the individual (K in number) sub-FOCSs with TDM in the composition of one infraFOCS with WDM.

Fig. 1.3 presents (also in a simplified form) the structural diagram of the transmission part of the infraFOCS with WDM.

1.3. Basic parameters of optical lines with spectral multiplexing

The technical characteristics of WDM systems are mainly determined by the following characteristics of the individual components:

- Power and stability of the laser transmitter.
- Number of channels.
- Frequency spacing between channels.
- Modulation rate of the laser transmitter.
- Gain coefficient of EDFA amplifiers.
- Gain coefficient of the optical receiver.
- Characteristics of the optical fibers.

These parameters describe the main characteristics of the WDM system.

1.4. Main problems in optical lines with spectral multiplexing

1.4.1. Wavelength drift and signal power

Absolutely stable light radiation sources do not exist. The signal power and the central wavelength always change over time.

The reason for the constant variation in frequency and power is temperature changes, back reflection and the chirping of the laser radiation frequency.

1.4.2. Crosstalk noise

Crosstalk – this is the unwanted interference of a signal from one channel with signals from other channels. The level of crosstalk is difficult to determine accurately before the system is fully installed and started. Crosstalk must be measured in a real situation in the presence (or in extreme cases, simulation) of actual signals.

1.4.3. Nonlinear effects

Nonlinear effects, which are not normally apparent during fiber testing, may only become significant after the network is put into service. The switching on and start-up of equipment can lead to nonlinear effects. All nonlinear disturbances should be controlled during the start-up of the equipment and periodically during the operation of the entire network.

1.4.4. Four-wave mixing

Among the many nonlinear effects, four-wave mixing (FWM) is a special case that requires special attention due to the severity of its impact on network performance. The nonlinear interaction of optical signals can lead to the appearance of spurious signals whose wavelengths can coincide with the wavelengths of adjacent channels and disrupt the functioning of the network.

1.4.5. Polarization-mode dispersion

In long fiber spans, which are typical in real networks, polarization-mode dispersion (PMD) occurs for a number of reasons: due to internal inhomogeneities in the fibers, mechanical disturbances at the places of bending and stresses in the fiber, various temperature effects, etc.

1.4.12. Chromatic dispersion

By carefully selecting and thus controlling the value of chromatic dispersion, nonlinear effects can be reduced several times. In some cases, with an acceptable level of total dispersion, it is possible to minimize various nonlinear effects in the fiber.

1.4.13. Other parameters of WDM systems

The technical characteristics of the components in optical communication lines are also influenced by a number of other parameters and factors, which include:

- Parameters related to crosstalk (interception):
 - in-band interception level (dB);
 - out-of-band interception level (dB);
- Parameters related to the signal frequency:
 - ripple (dB);
 - insertion loss (dB);
 - channel width (GHz);
- Parameters related to polarization:
 - differential group delay time GDT (ps);
 - polarization-dependent total loss PDL (dB);
- Reduction of the signal-to-noise ratio (dB) associated with the degradation of the laser, optical amplifiers and other components of a WDM system.

1.5. Analysis and conclusions to Chapter 1

Since passive optical communication networks with spectral multiplexing are mainly used in urban environments and have a large range, it is necessary to look for effective models for their planning and optimization, which is

associated with better management efficiency and continuous monitoring and improvement of the Quality of the services offered.

Creating practically oriented and user-friendly models of signal processing in the network and of the network itself is of great importance for ensuring the reliability, efficiency and Quality of service in the network. When modeling the optical communication channel, the main task is to find a compromise between the range and capacity of the network, the efficiency of the equipment used, the parameters and configuration parameters of the network. The bandwidth, the Quality factor (Q-factor) and the Energy budget of the communication channel are considered as global parameters, because they simultaneously affect the efficiency and reliability of the optical communication network.

The energy parameters of the transmitting equipment, the sensitivity of the receiving equipment and the optical parameters and channel configuration of the optical transmission lines in multi-channel passive optical communication networks affect their range and capacity, as well as the parameters related to the Quality of service to end users.

1.6. Purpose and objectives of the dissertation

The essence of a multi-channel passive optical communication network is to provide the necessary wide range of broadband services to its subscribers by reliable transmission of optical signals over a large range, which can be achieved through effective signal processing (coding and optical modulation of signals), optimal balancing of the energy budget and effective evaluation of the transmission channel. Therefore, the present dissertation aims to show to what extent this is possible by developing appropriate methods and algorithms for studying the processing and reliable and efficient transmission and reception of multiplexed signals in passive optical communication networks.

Given the state of the art and problems in broadband passive optical networks with spectral multiplexing analyzed in Chapter 1, the goal of the dissertation is to develop correct models for research on the processes of multiplexing signals by wavelength and to present methods and algorithms for improving the reliability and efficiency of communication and the Quality of services in multi-channel passive optical networks.

To achieve the formulated goal, it is necessary to solve the following generalized objectives:

1. Creation and description of a methodology for a comprehensive study of the processes of multiplexing and signal transmission in multi-channel passive optical networks.
2. Synthesis and development of simulation models in the OptiSystem and Matlab/Simulink environments for research on the processes of coding and optical modulation and for studying their influence on the efficiency of the multi-channel passive optical network model.

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4. Development of a practical laboratory model for studying the influence of the setting parameters and configuration parameters on the Quality of services and the efficiency of the multi-channel optical network and to propose methods and measures for its improvement.

CHAPTER 2. MODELING OF A MULTI-CHANNEL OPTICAL COMMUNICATION NETWORK

2.1. Synthesis of a simulation model of a 4-channel WDM system

Here, the implementation of a simulation model of a multi-channel WDM system for studying the parameters and characteristics of transmitted optical signals will be discussed. The selection and setting of the individual blocks in the model is consistent with the following exemplary initial conditions:

- Number of operating channels: 4;
- Operating wavelength range: $\lambda = 1550$ nm;
- Number of sections: up to 6; Length of the communication line: up to 600 km
- Type of optical fiber: SMF;
- Optical signal modulation formats: NRZ, RZ;
- Channel bandwidth: 2.5 Gbps.

The modeling software used is Optiwave OptiSystem, which is a comprehensive software package for planning, designing, testing and simulation of optical lines for connections at the physical layer of modern optical networks.

2.1.1. Global parameters of the simulation model

The following global parameters are set for this simulation model (Fig. 2.1):

- Bit rate: 2500000000 Bits/s (2.5 Gbps)
- Simulation duration (Time window): 5.12.10⁻⁸ s;
- Sample rate: 160 GHz;
- Sequence length: 128 bits;
- Samples per bit: 64;
- Number of samples: 8192.

2.1.2. Creating transmitters for the 4-channel WDM system

To implement a 4-channel WDM system, it is necessary to multiplex/demultiplex the optical signals from 4 separate optical signal sources. For this purpose, 4 externally modulated optical transmitters were created, each of them containing a laser optical signal source, a digital electrical signal source, an electrical signal encoder in NRZ or RZ code and a Mach-Zehnder modulator

of the optical signal.

2.1.3. Multiplexing of signals

The received 4 modulated optical signals at different wavelengths in the 1550 nm range must be wavelength multiplexed, which is done using a WDM multiplexer.

2.1.4. Creating the optical sections

The length of each optical section is set by the length of the optical fiber in the Optical Fiber block (available in Component Library/Default/ Optical Fibers Library). The length of the optical fiber for the purposes of the simulation model is 100 km. The settings of the optical fiber block are as follows (Fig. 2.9):

- attenuation: 0.2 dB/km;
- dispersion: 17 ps/nm/km;
- effective fiber area: 80 μm^2 ;
- fiber refractive index: $n_2 = 2.6 \cdot 10^{-20} \text{m}^2/\text{W}$;
- fiber length 100 km.

2.1.6. Creating optical receivers

The settings of the PIN photodetector are as follows:

- receiver sensitivity: -25 dBm;
- responsivity: 1 A/W;
- dark current: 10 nA.

2.1.7. Connecting the measuring instruments

The arrangement of the measuring instruments in the model can be seen in the complete diagram presented in Fig. 2.16.

The following instruments will be used for the study:

- Optical Time Domain Visualizer;
- Optical Spectrum Analyzer;
- BER Analyzer;
- WDM Analyzer;
- Optical Power Meter.

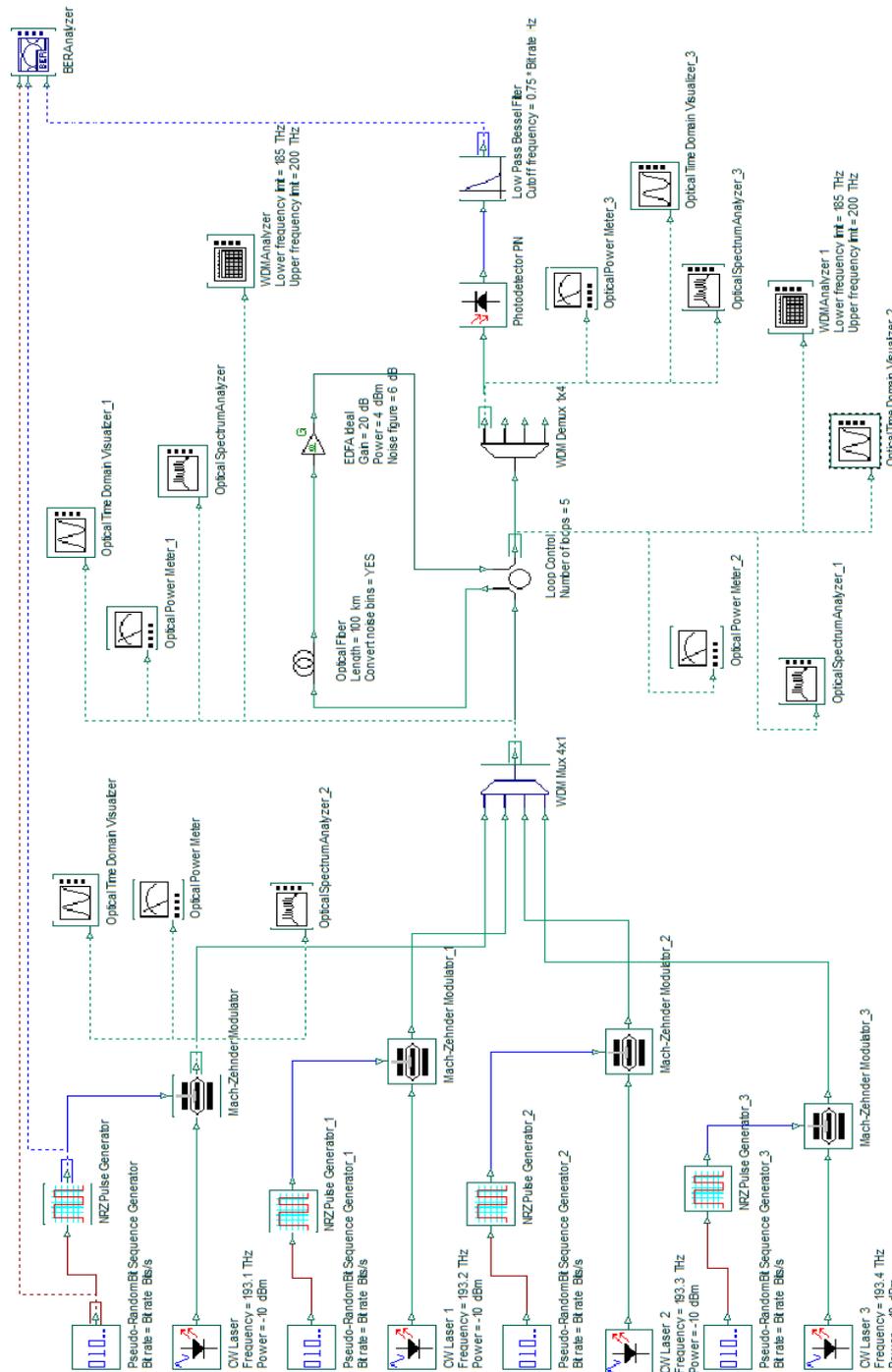


Fig. 2.16. Full view of the simulation model of a 4-channel optical communication line with wavelength multiplexing

2.1.8. Simulation model of a 4-channel WDM system – full view

Fig. 2.16. shows the already implemented complete circuit, with the help of which the simulation studies of the research of a 4-channel WDM system in the case of NRZ encoding of the optical signal will be implemented.

In RZ encoding, as already mentioned, an RZ pulse generator block is used (RZ pulse generator instead of NRZ pulse generator).

2.2. Methodological guidelines for conducting measurements and testing a WDM system

Network operators are required to constantly monitor the quality of transmission over the fiber. The purpose of system testing is to demonstrate the system's operability and the integrity of data transmission. Fig. 2.17 shows an example of an optimal sequence of tests in a WDM system.

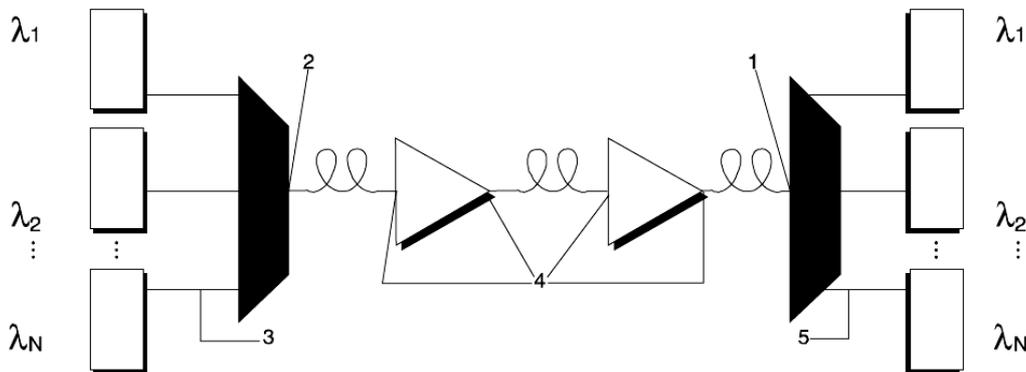


Fig. 2.17. WDM System Troubleshooting Testing Sequence

1. The first step is to test the demultiplexer at the end of the link. This allows you to determine whether further additional tests are necessary. Using a multiwavelength meter (MWM), the OSNR value is measured at the wavelength accuracy of each channel. For acceptable BER values (e.g. 10^{-12}), the OSNR value at the end of the communication line should be no less than 18 dB (typical OSNR values are 22 dB). Depending on the system and type of photodetector, the signal power in the channel should be about -8 dBm. The channel wavelength should correspond to the nominal value within a few tens of pm (to conduct a measurement with such accuracy, a multiwavelength meter MWM is required).
2. If issues in the link are detected at the first stage of measurements, the signal power level at the output of the multiplexer output should be measured. Its nominal value can vary from -5 to 2 dBm depending on the requirements of the service provider. If the measured value differs from the nominal value, it is necessary to measure the losses in the multiplexer.
3. After the faulty channel(s) has been determined based on the results of the previous measurements, the signal power and the central wavelength for the corresponding laser transmitter should be checked.
4. In the next step, the EDFA modules are checked. Their gain should be linear and the same for all channels. A difference in gain of more than 3 dB is unacceptable.
5. When testing digital systems (SDH, SONET, IP, etc.), the transmission quality should be checked. For an acceptable BER level, the power of the received signal should be at least -20 dBm. This measurement does not apply to optical measurements: it requires electronic equipment.

2.3. Conclusions to Chapter 2

1. When designing a multi-channel optical communication network, it is necessary to set requirements that must be followed in order to ensure quality communication in the optical communication channel, regardless of the limitations of the number of channels, the transmitted optical power in each channel, the influence of the optical transmission medium on the propagation of the multiplexed optical signal in the communication channel. Considering the variety of speeds, coding and processing of signals, the number of channels and the range of the system, careful planning of the initial configuration parameters of the network is necessary.
2. Of essential importance in determining the efficiency of the network is the calculation of the theoretical range of the network. For this purpose, the efficiency of the various methods for modulating optical signals, losses from the propagation medium, the mutual influence of the multiplexed signals during their propagation in the optical fiber, as well as the energy budget of the network must be taken into account.
3. The increase in the number of channels and the bandwidth used leads to an increase in various nonlinear effects in the transmission channel, respectively, to problems with the Quality of services. It can be seen that the transmission of information at high speed is limited by the number of wave channels simultaneously transmitting information, as well as by the transmission speed and the parameters of the optical medium.
4. The different modulation formats of optical signals directly affect the range of the network and the resistance of multiplexed optical signals to the influence of nonlinear effects and interference in the transmission channel. The radiated optical power has maximum permissible values, exceeding which worsens the performance indicators of the network.
5. When planning a multi-channel network, the power balance is made end-to-end for each of the individual channels. It reflects the losses during signal propagation and, accordingly, the reserves for their compensation. In analytical planning, some parameters are used that are related to the specific standard of the optical fiber used. The power balance largely depends on the selected modulation format, the transmitted optical power and the sensitivity of the receiver, the multiplexing/demultiplexing parameters and the optical transmission medium.
6. The main stages of planning and modeling a multi-channel optical network begin with sizing, which takes into account the number of channels, the connection speed and the network range, as well as the threshold values for ensuring the Quality of service. The second stage includes a balanced determination of the complexly related configuration parameters with defined indicators for assessing the effectiveness of the network model. The last part is the assessment and optimization of the analytically determined energy

budget of the network and adjustment of the configuration parameters of the network model.

CHAPTER 3. RESEARCH AND COMPARATIVE ANALYSIS OF MULTICHANNEL OPTICAL COMMUNICATION NETWORKS

3.1. Parameters of the study of the simulation model of a 4-channel WDM system

Through the developed simulation model of a 4-channel optical communication line with spectral multiplexing (Fig. 2.16), 2 different cases of research have been implemented, the purpose of which is to solve different optimization problems in search of the best parameters for a certain channel configuration in the communication line:

- Research and analysis of the simulation model of a 4-channel WDM system with NRZ modulation;
- Research and analysis of the simulation model of a 4-channel WDM system with RZ modulation.

For each of these 2 main studies, an optimal value of one specific parameter is sought at fixed values of given parameters and changes in precisely defined parameters. The optimal value of the parameter is determined based on a criterion set for each study.

The main criteria with respect to optical communication lines with spectral multiplexing are:

- a set permissible value of BER: $BER = 1 \cdot 10^{-12}$ is assumed;
- Q-factor value at a permissible BER value: $Q > 6$;
- optical signal-to-noise ratio OSNR: $OSNR > 12$;
- optical power level.

As additional criteria in the evaluation of system parameters, the main characteristics of the optical signal are used:

- eye diagram opening – directly related to the BER and Q-factor of the system;
- spectral diagram of the optical signal – to evaluate the influence of various effects such as signal dispersion, four-wave mixing in multi-channel mode and the level of noise in the channel;
- time-domain diagram of the optical signal – to evaluate intersymbol interference, group delay time, etc.

The studies for 2 main cases (with NRZ and RZ modulation of optical signals) are carried out in the following sequence:

- 1) Study to determine the optimal radiated power of the channel optical transmitters P_{TX} ;
- 2) Comparative analysis to determine the limits of the operating parameters of the 4-channel WDM system for the two different modulation options of the optical signals: NRZ and RZ.

- 3) Comparative analysis to determine the efficiency and optimal operating conditions of the 4-channel WDM system for different numbers of optical sections NAS (i.e. different lengths of the optical line) and different levels of transmitted power of the channel optical transmitters P_{TX} .

3.2. Study and analysis of the simulation model of a 4-channel WDM system with NRZ modulation.

3.2.1. Parametric analysis when changing P_{TX} and using NRZ modulation

The results of the study are presented graphically in Fig. 3.1, 3.2 and 3.3.

Fig. 3.1, 3.2 and 3.3 show the graphical dependencies showing the influence of the optical power P_{TX} of the transmitter on the resulting values of the Q-factor (Max. Q Factor), the BER value (Min. BER) and the value of the received optical power P_{RX} for the given channel.

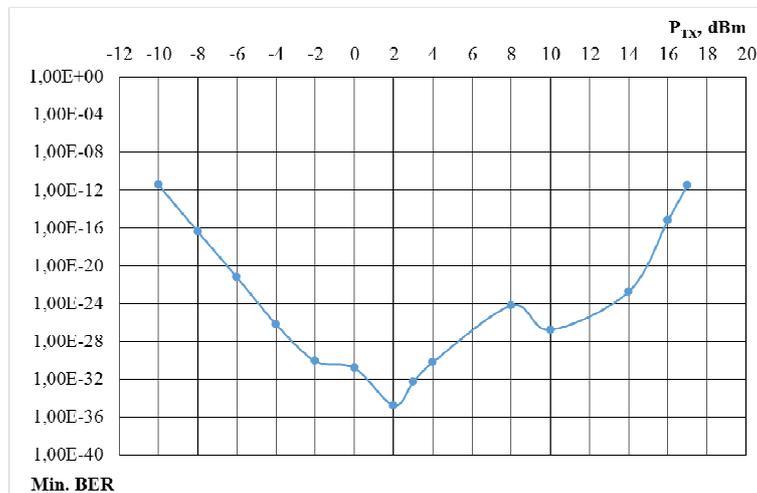


Fig. 3.1. Graphical dependence of BER on the change of P_{TX} for NRZ modulation

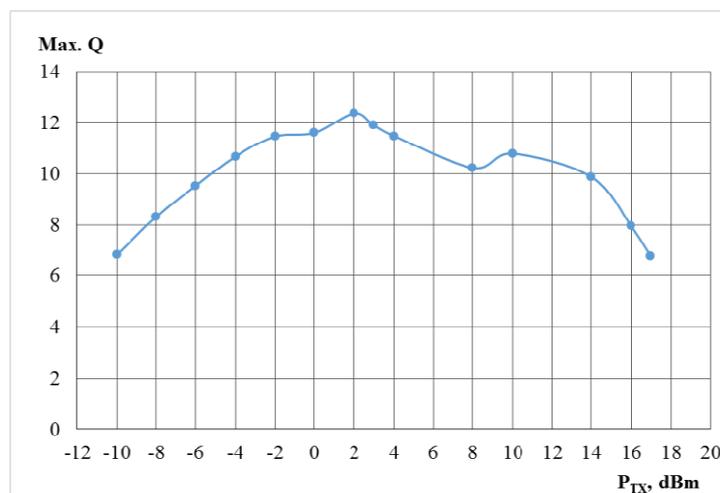


Fig. 3.2. Graphical dependence of Q-factor on the change of P_{TX} for NRZ modulation

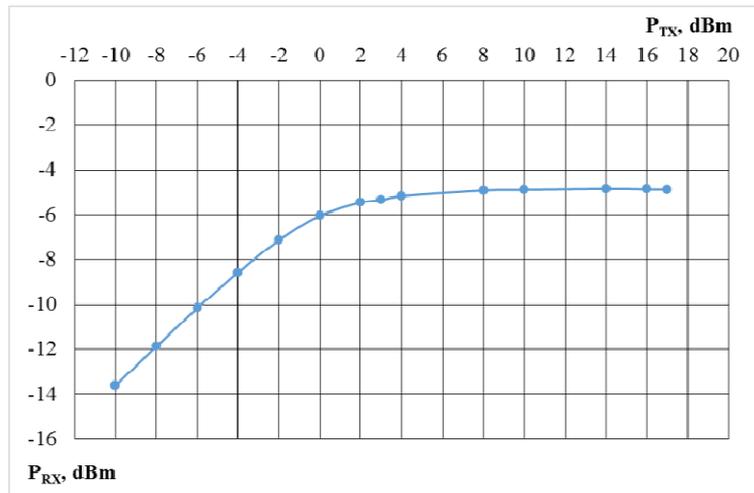


Fig. 3.3. Graphical dependence of P_{RX} on the change of P_{TX} for NRZ modulation

3.2.2. Visualization of the characteristics of optical signals when changing P_{TX} and using NRZ modulation

The results of this study are presented for three specific cases. Fig. 3.4 illustrates the resulting eye diagrams of the received signal, which graphically illustrate its digital parameters for the 3 main cases of P_{TX} .

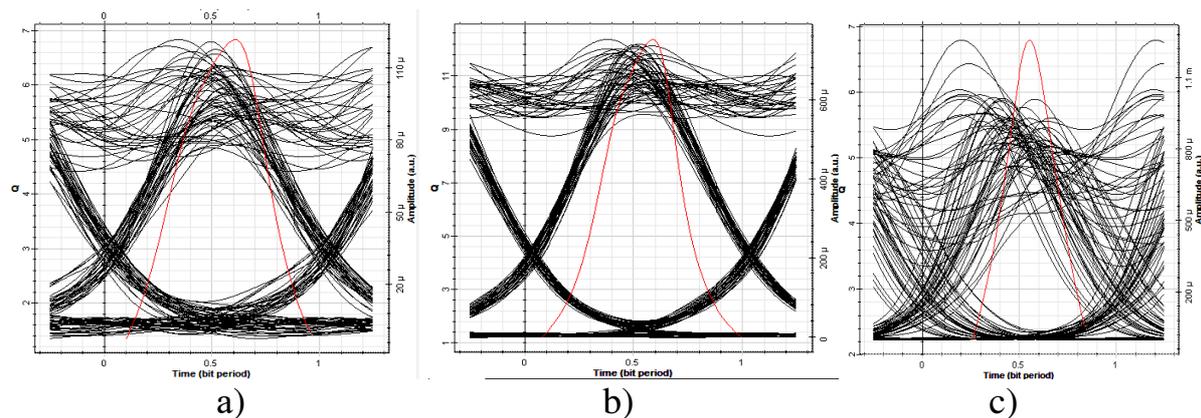
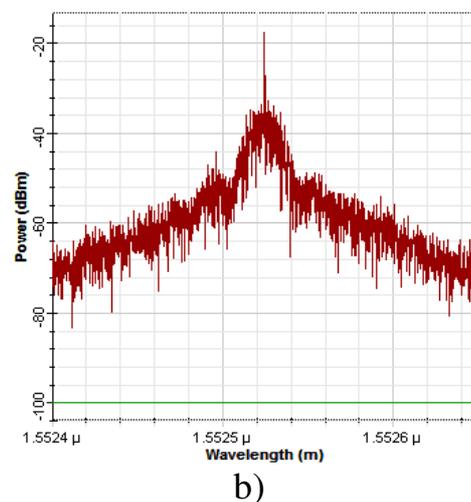
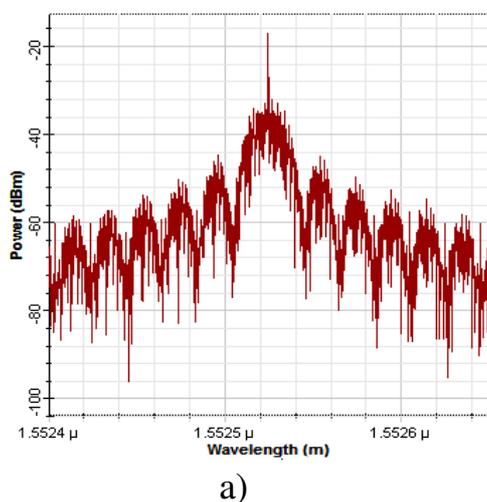


Fig. 3.4. Eye diagrams of the optical signal for NRZ modulation:
 a) $P_{TX\ min} = -10\text{dBm}$, b) $P_{TX\ opt} = 2\text{dBm}$, c) $P_{TX\ max} = 17\text{dBm}$



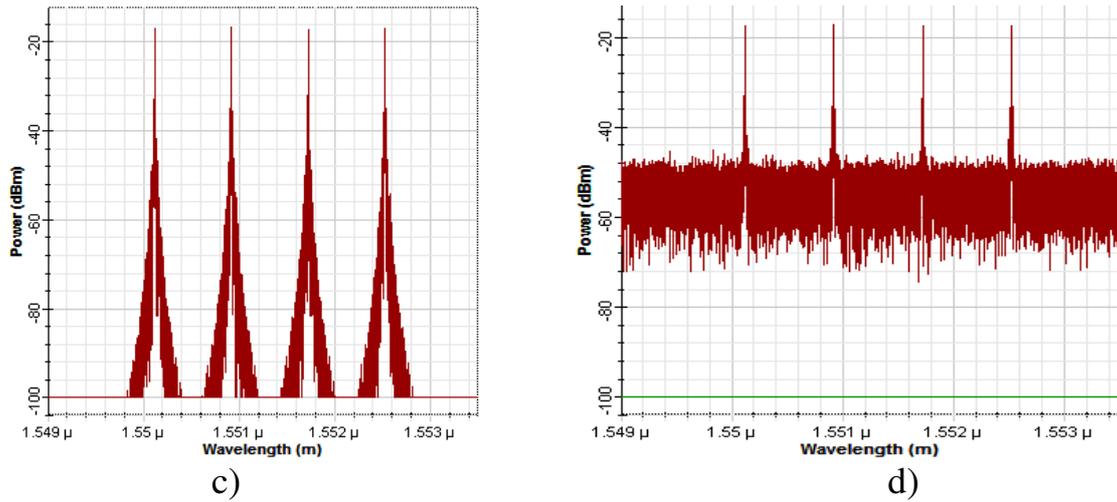


Fig. 3.5. Spectral characteristics of the optical signal at $P_{TX\ min} = -10\ dBm$ at: a) the output of an optical transmitter, b) the input of an optical receiver, c) the output of the optical multiplexer and d) the input of the optical demultiplexer

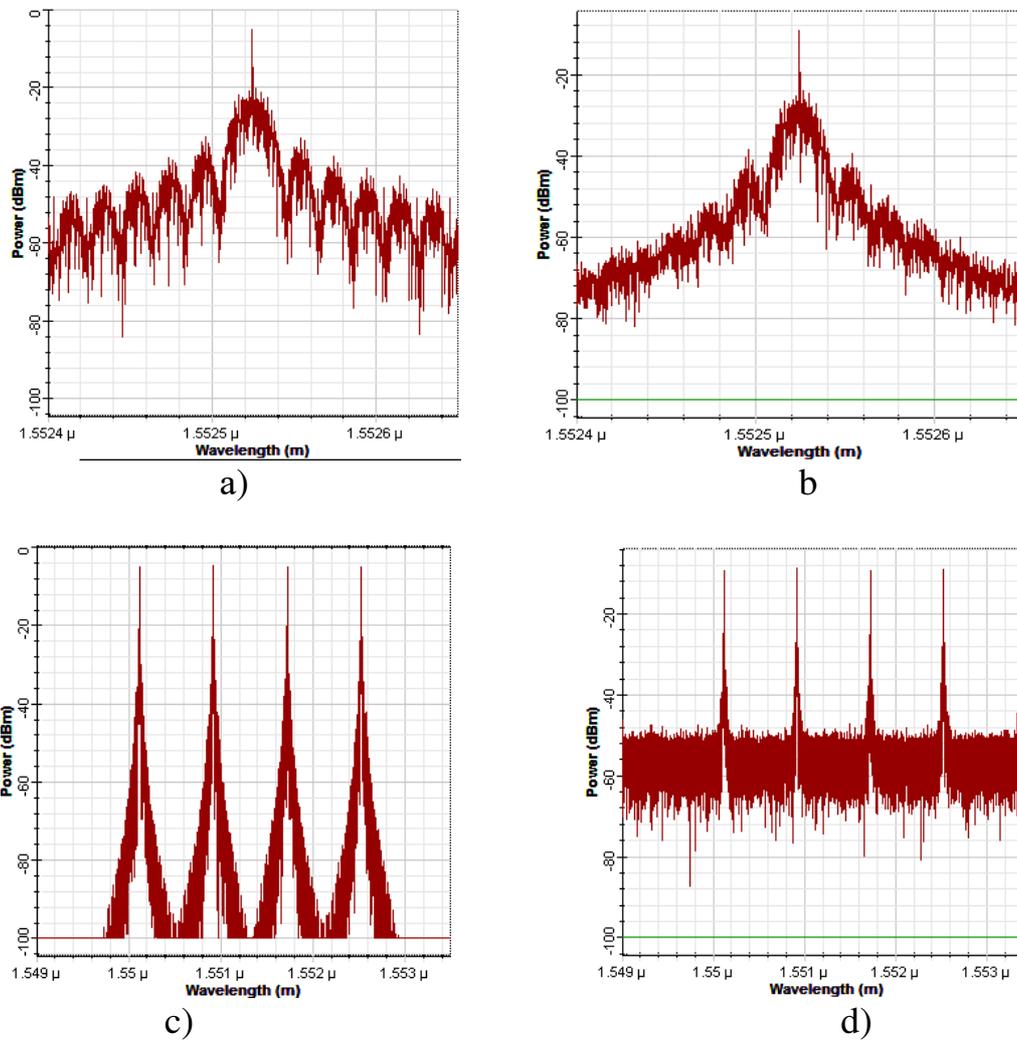


Fig. 3.6. Spectral characteristics of the optical signal at $P_{TX\ opt} = 2\ dBm$ at: a) the output of an optical transmitter, b) the input of an optical receiver, c) the output of the optical multiplexer and d) the input of the optical demultiplexer

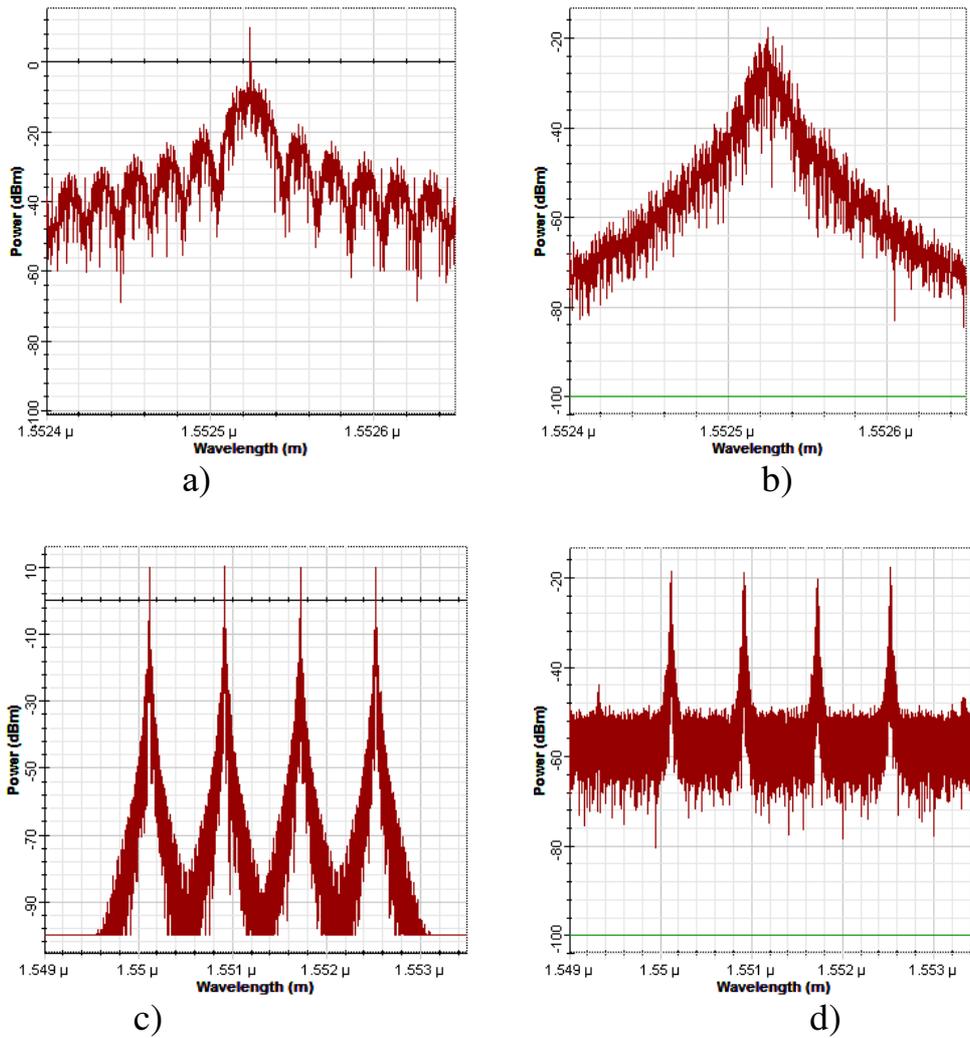


Fig. 3.7. Spectral characteristics of the optical signal at $P_{TX\ max} = 17\ dBm$ at: a) the output of an optical transmitter, b) the input of an optical receiver, c) the output of the optical multiplexer and d) the input of the optical demultiplexer

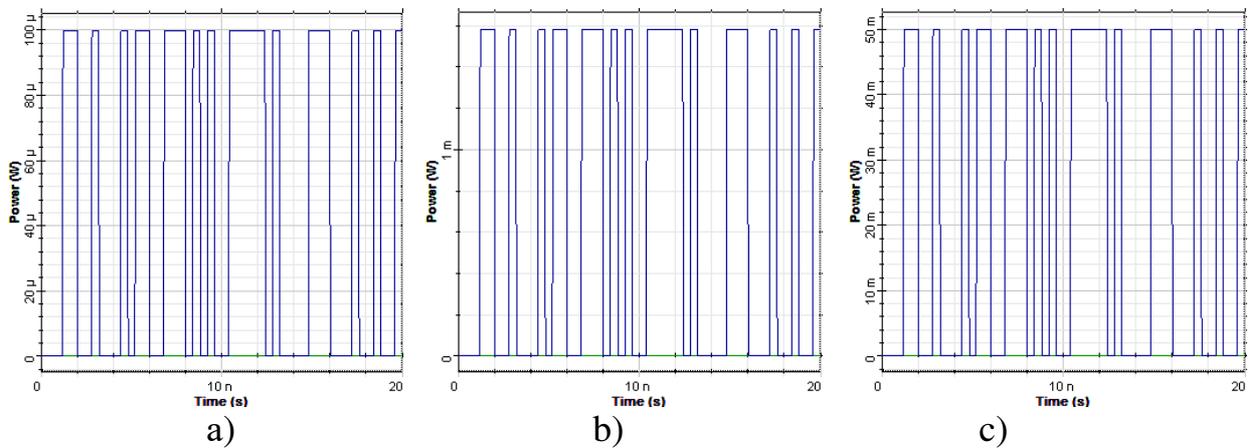


Fig. 3.8. Time diagrams of the optical signal at the output of an optical transmitter under NRZ modulation and a) $P_{TX\ min} = -10\ dBm$, b) $P_{TX\ opt} = 2\ dBm$, c) $P_{TX\ max} = 17\ dBm$

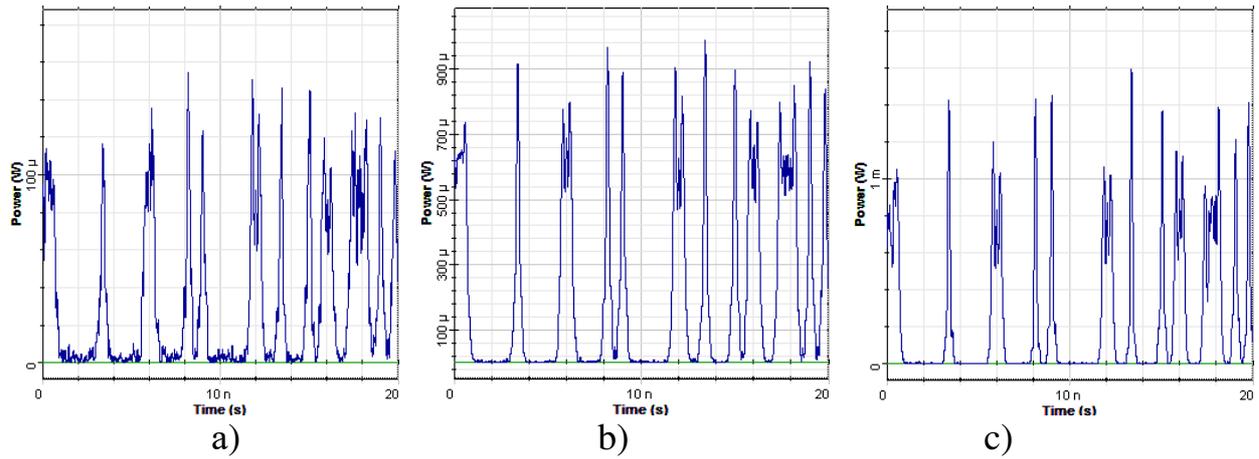


Fig. 3.9. Time diagrams of the optical signal at the input of an optical receiver with NRZ modulation and a) $P_{TX \min} = -10\text{dBm}$, b) $P_{TX \text{opt}} = 2\text{dBm}$, c) $P_{TX \max} = 17\text{dBm}$

Fig. 3.5, 3.6 and 3.7 show the spectral characteristics of the optical signal for the key points of the model for the three different cases.

Fig. 3.8 and 3.9 show the time diagrams of the optical signal for the key points of the model in the three different cases.

3.2.3. Comparative analysis of results in NRZ modulation

Fig. 3.10 presents a summary of the spectral characteristics of the optical signal at the input of an optical receiver under NRZ modulation for the minimum, optimal and maximum limit values of the optical power of the transmitter.

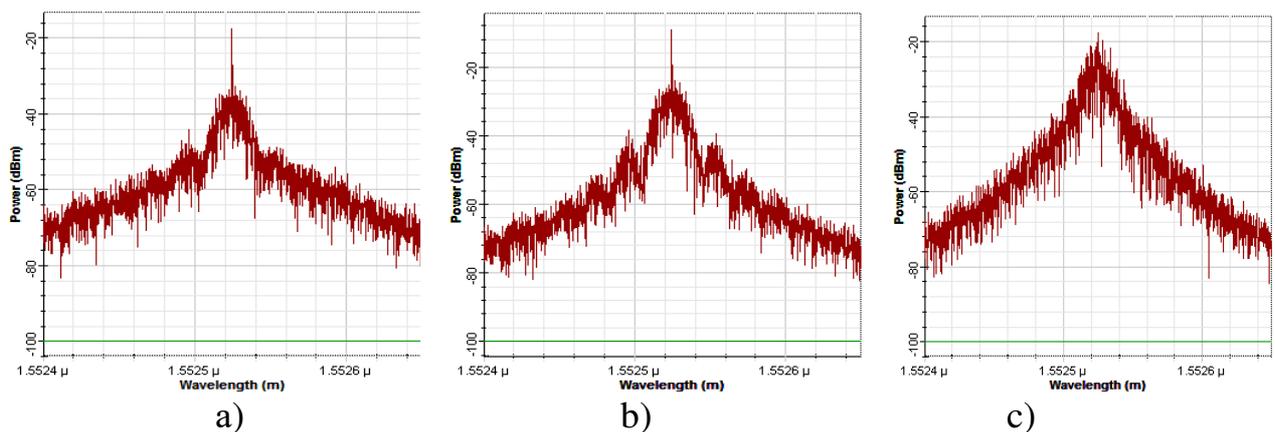


Fig. 3.10. Spectral characteristics of the optical signal at the input of an optical receiver with NRZ modulation for a) $P_{TX \min} = -10\text{dBm}$, b) $P_{TX \text{opt}} = 2\text{dBm}$, c) $P_{TX \max} = 17\text{dBm}$

Fig. 3.11 presents the spectral characteristics of the multiplexed optical signal at the input of the optical demultiplexer.

Table 3.2 presents a summary of the values of the measured basic parameters obtained for the two limit values ($P_{TX \min}$ and $P_{TX \max}$) and for the optimal value

($P_{TX\ opt}$) of the optical power of the transmitter in NRZ modulation.

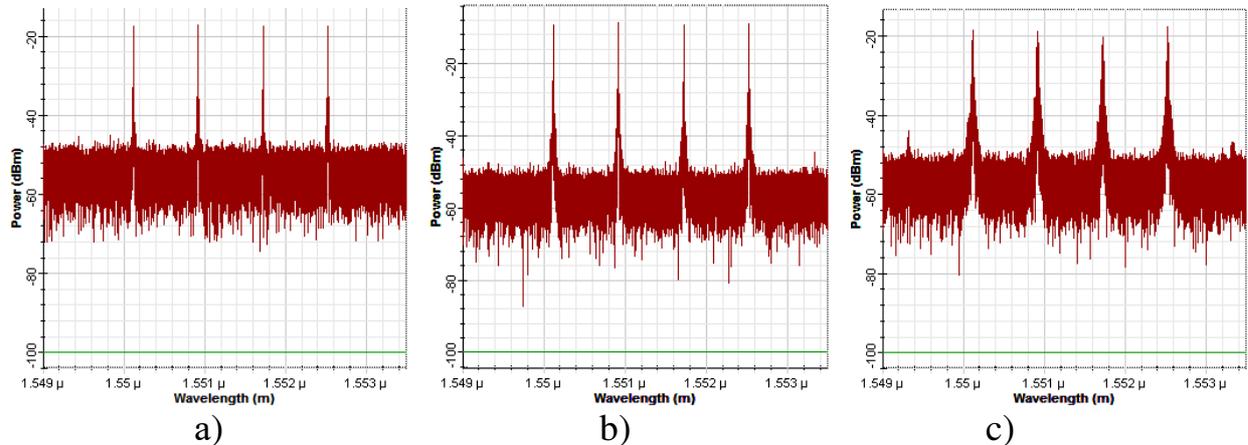


Fig. 3.11. Spectral characteristics of the multiplexed optical signal at the input of the optical demultiplexer in NRZ modulation for a) $P_{TX\ min} = -10\text{dBm}$,
b) $P_{TX\ opt} = 2\text{dBm}$, b) $P_{TX\ max} = 17\text{dBm}$

Table 3.2. Experimental results when changing P_{TX} for NRZ modulation

Parameters	$P_{TX\ min} = -10\text{ dBm}$	$P_{TX\ opt} = 2\text{dBm}$	$P_{TX\ max} = 17\text{dBm}$
Power P_{RX} , dBm	-13,603	-5,454	-4,876
Average noise level in single channel, dBm	-80	-83	-84
Average noise level in the multiplex, dBm	-53,5	-54,5	-56,2
Optical pulse rise time, ns	0,283	0,409	0,430
OSNR in single channel (In./ Out.), dBm	73,06 / 12,03	73,06 / 22,03	73,06 / 23,18
Signal spectrum width per channel	80 pm	130 pm	240 pm
Level and number of parasitic wavelengths	-	-44,7 dBm x 1	-44 dBm x 2

One of the main goals of the presented simulation models and the research carried out with them is to find a solution to an optimization problem – determining the optimal optical power of the transmitter as a function of the value of several parameters. Fig. 3.12 presents the summarized results of the multiparameter analysis.

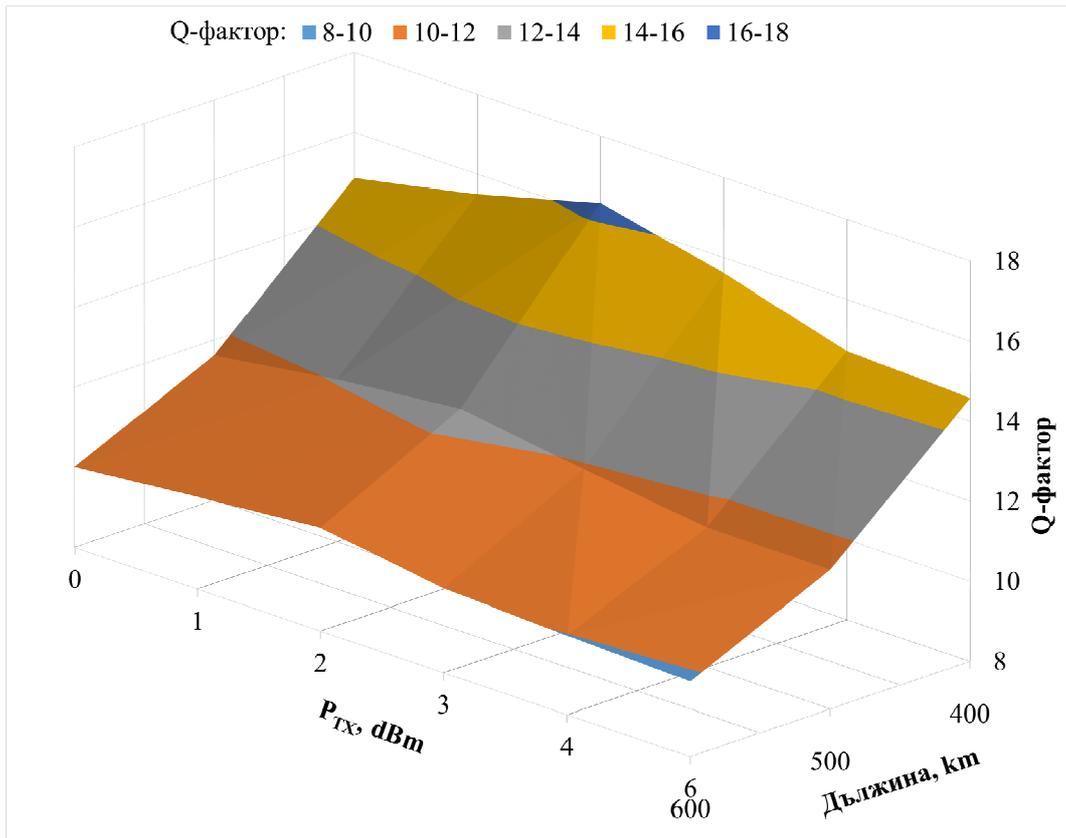


Fig. 3.12. Graphical dependence of the Q-factor on P_{TX} and the length of the optical line l for NRZ modulation

3.3. Study and analysis of the simulation model of a 4-channel WDM system with RZ modulation

3.3.1 Parametric analysis when changing P_{TX} and using RZ modulation

The results of the study are presented graphically in Fig. 3.13, 3.14 and 3.15.

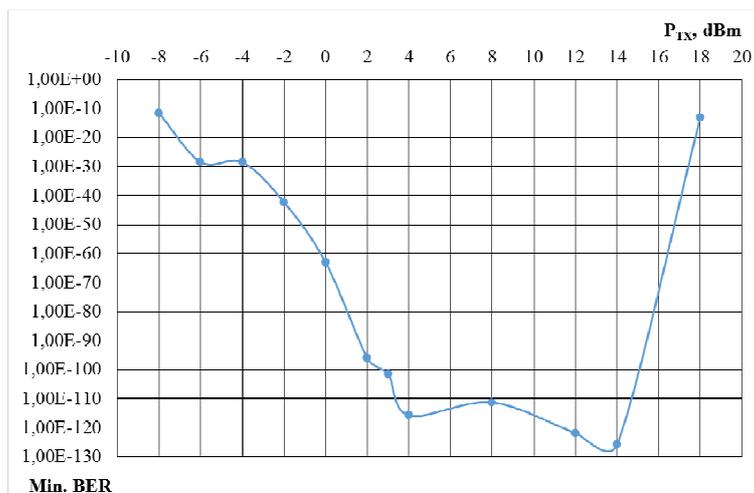


Fig. 3.13. Graphical dependence of BER on the change of P_{TX} for RZ modulation

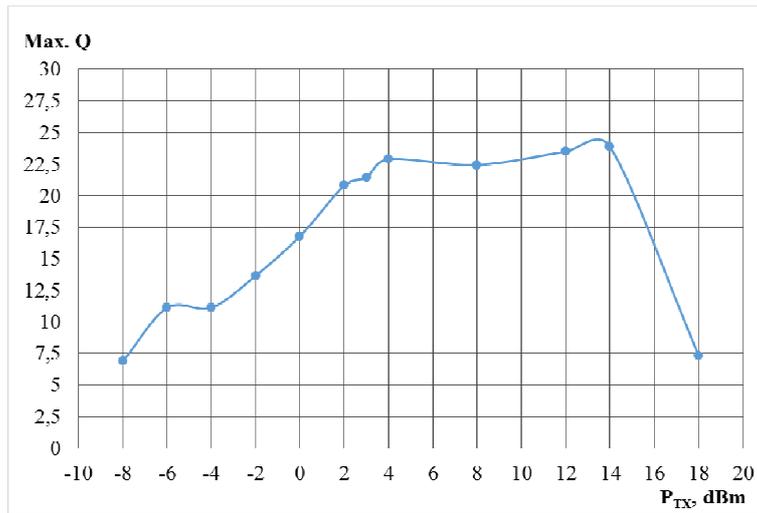


Fig. 3.14. Graphical dependence of Q-factor on the change of P_{TX} for RZ modulation

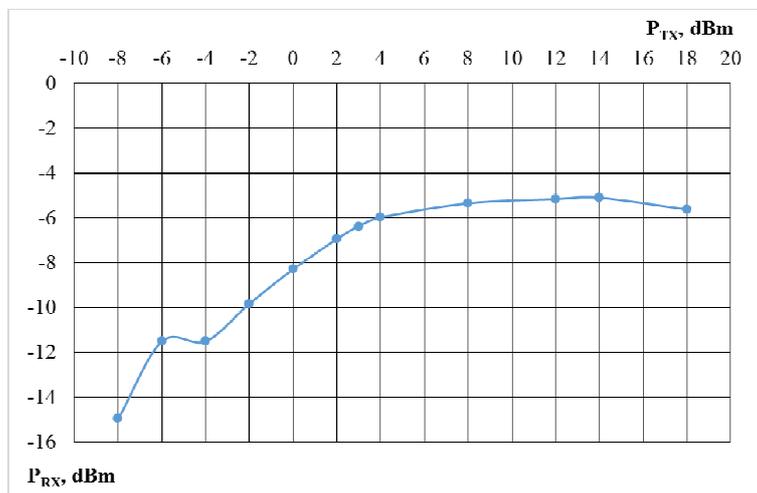
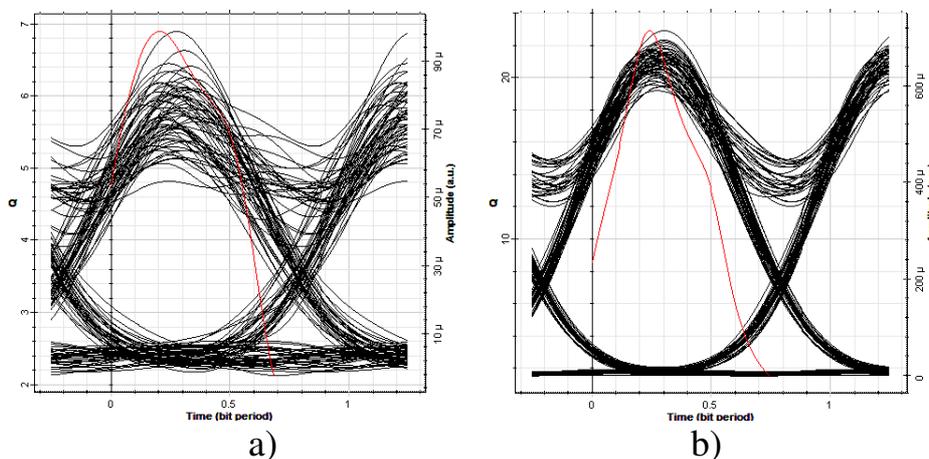


Fig. 3.15. Graphical dependence of P_{RX} on the change of P_{TX} for RZ modulation

3.3.2. Visualization of the characteristics of optical signals when changing P_{TX} and using RZ modulation

The results of this study are presented for three specific cases.



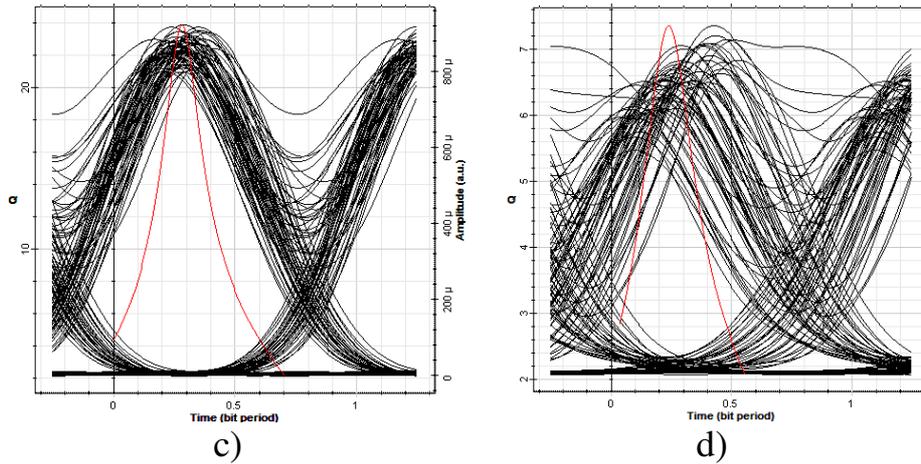


Fig. 3.16. Eye diagrams of the optical signal for RZ modulation:
 a) $P_{TX\ min} = -8\text{dBm}$, b) $P_{TX\ opt1} = 4\text{dBm}$, c) $P_{TX\ opt2} = 14\text{dBm}$, d) $P_{TX\ max} = 18\text{dBm}$

Fig. 3.16 illustrates the resulting eye diagrams of the received signal, which graphically illustrate its digital parameters for the 4 main cases of P_{TX} .

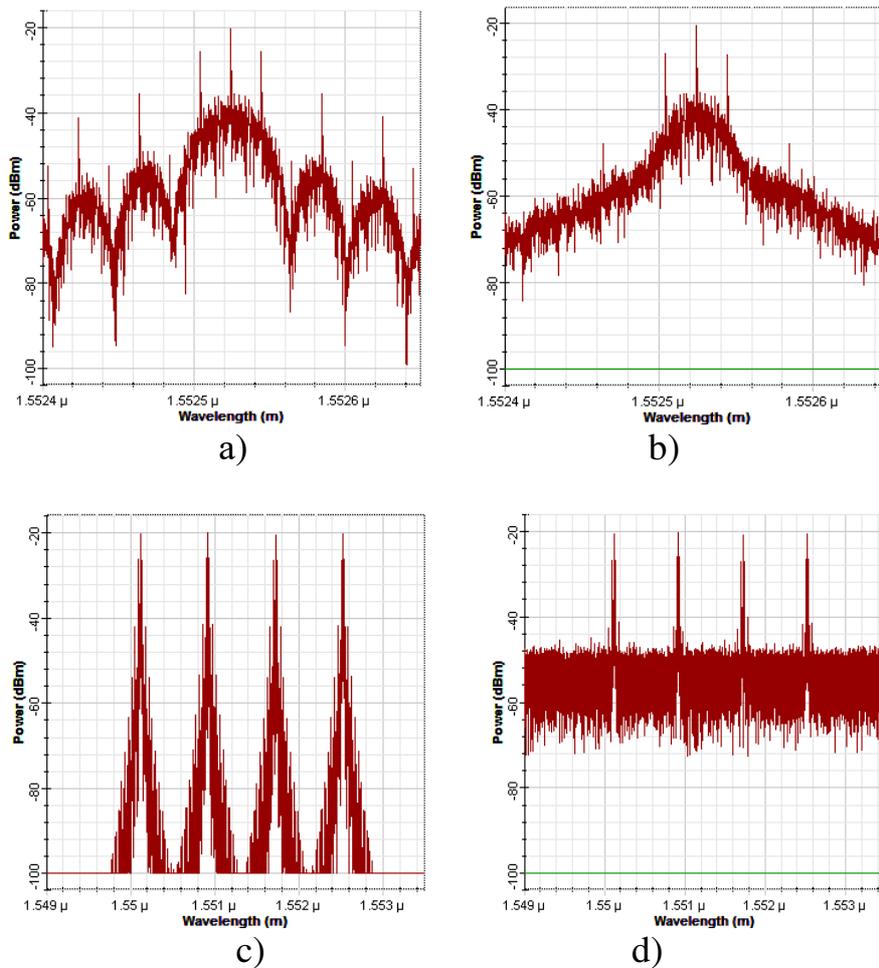


Fig. 3.17. Spectral characteristics of the optical signal at $P_{TX\ min} = -8\ \text{dBm}$ at:
 a) the output of an optical transmitter, b) the input of an optical receiver, c) the output of the optical multiplexer and d) the input of the optical demultiplexer

Fig. 3.17, 3.18, 3.19 and 3.20 show spectral characteristics of the optical signal for the key points of the model in the three different cases.

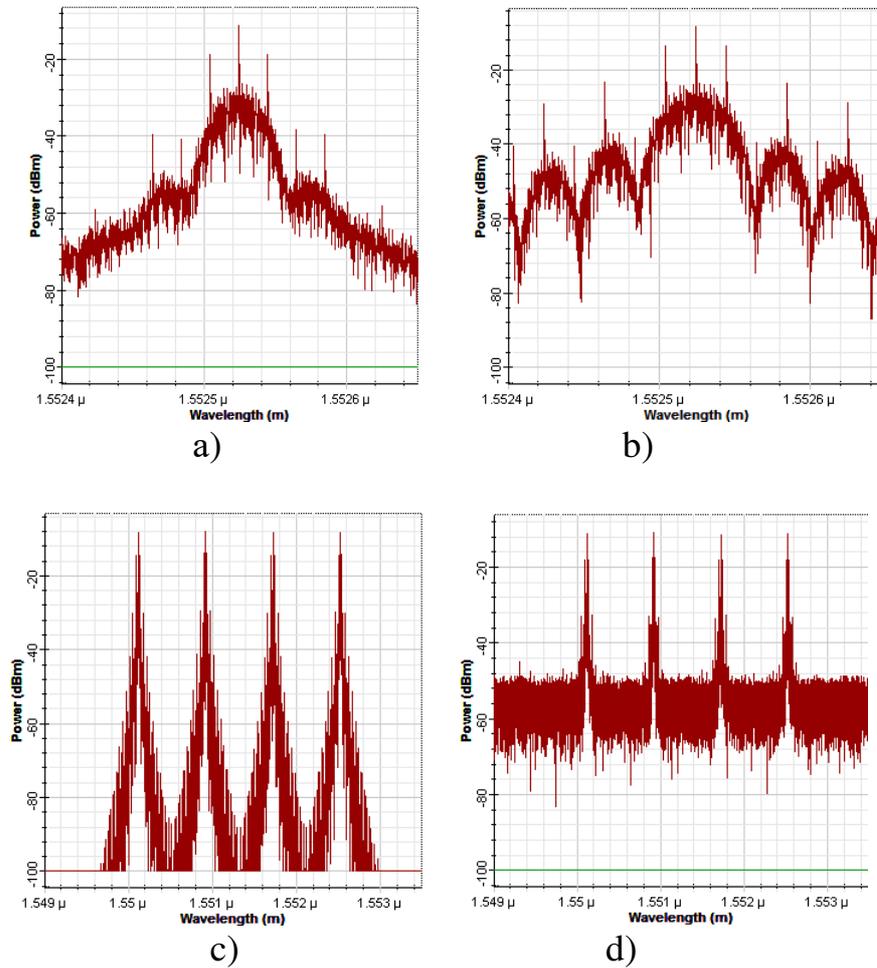
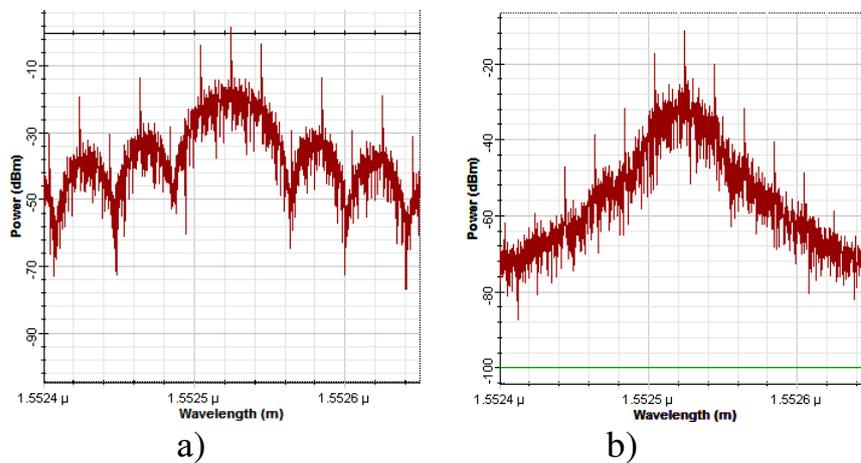


Fig. 3.18. Spectral characteristics of the optical signal at $P_{TX\ opt1} = 4$ dBm at: a) the output of an optical transmitter, b) the input of an optical receiver, c) the output of the optical multiplexer and d) the input of the optical demultiplexer



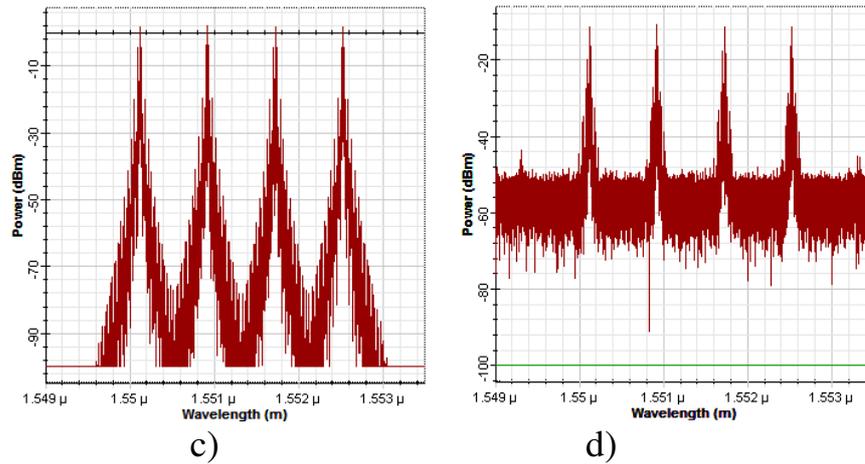


Fig. 3.19. Spectral characteristics of the optical signal at $P_{TX\ opt2} = 14$ dBm at: a) the output of an optical transmitter, b) the input of an optical receiver, c) the output of the optical multiplexer and d) the input of the optical demultiplexer

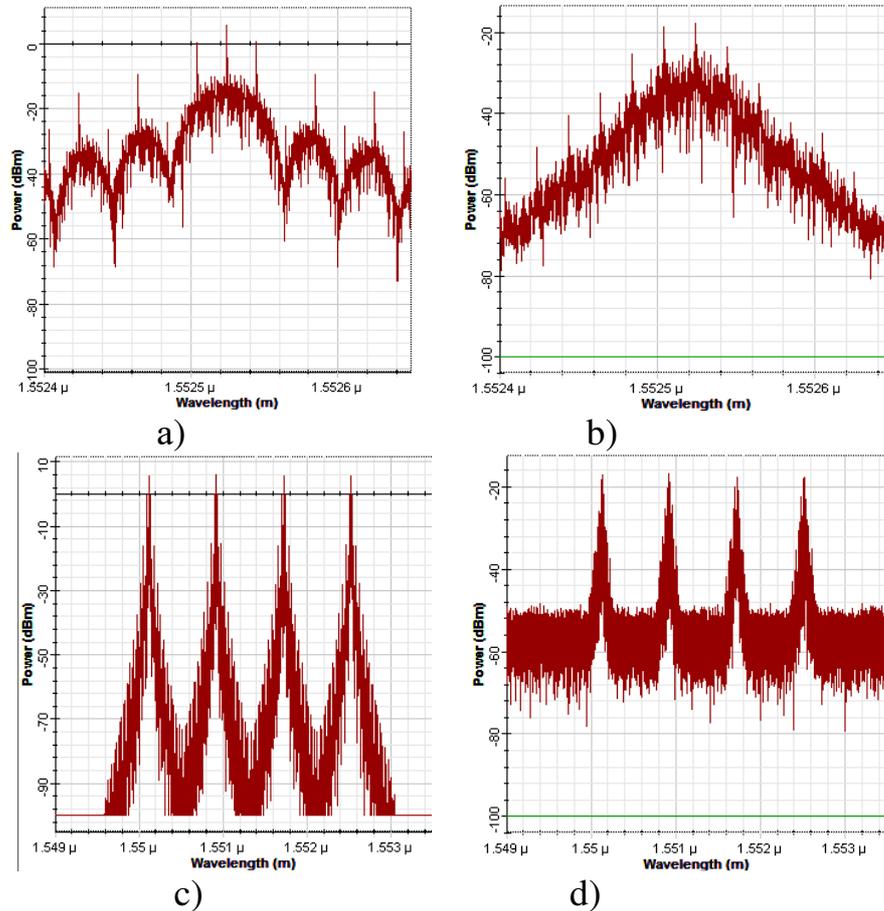


Fig. 3.20. Spectral characteristics of the optical signal at $P_{TX\ max} = 18$ dBm at: a) the output of an optical transmitter, b) the input of an optical receiver, c) the output of the optical multiplexer and d) the input of the optical demultiplexer

Fig. 3.21 and 3.22 show the time diagrams of the optical signal for the key points of the model in the three different cases.

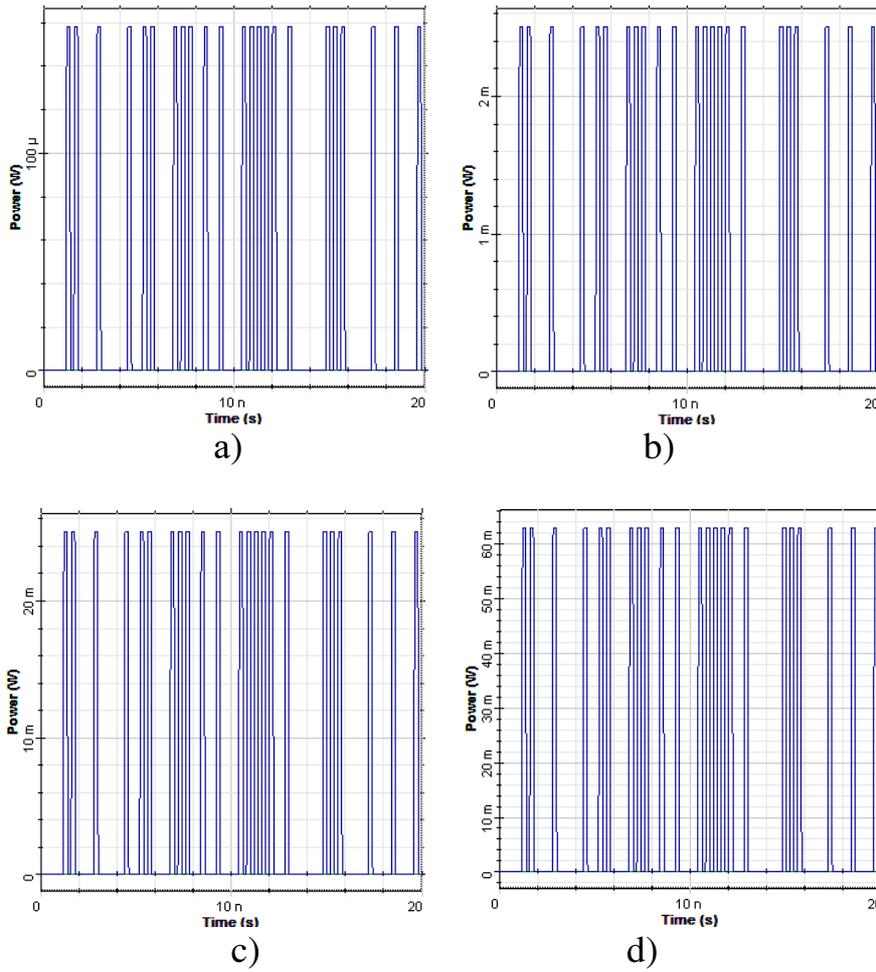
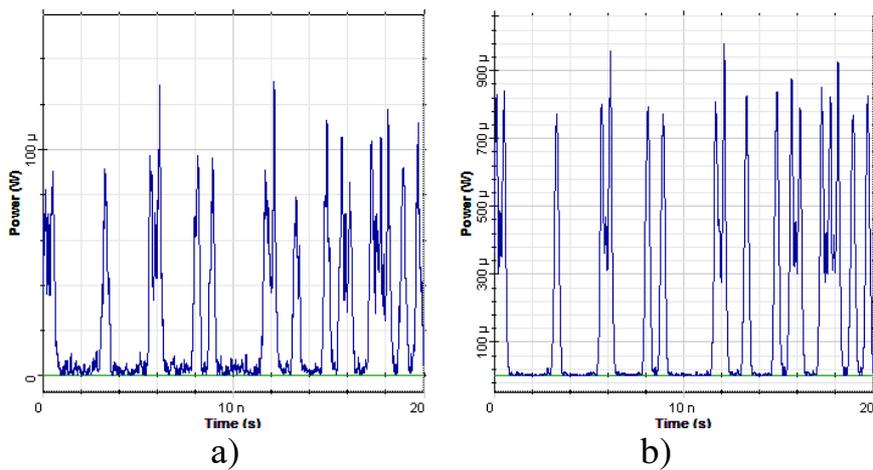


Fig. 3.21. Time diagrams of the optical signal at the output of an optical transmitter with RZ modulation and a) $P_{TX\ min} = -8\ dBm$, b) $P_{TX\ opt1} = 4\ dBm$, c) $P_{TX\ opt2} = 14\ dBm$, d) $P_{TX\ max} = 18\ dBm$



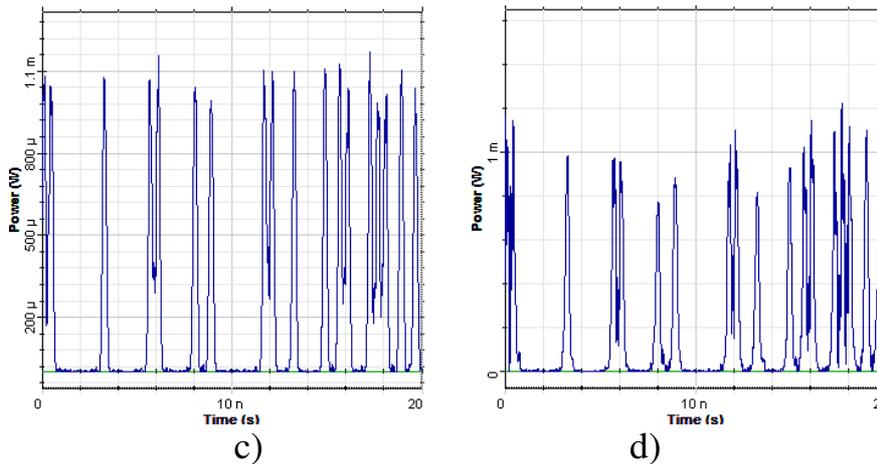


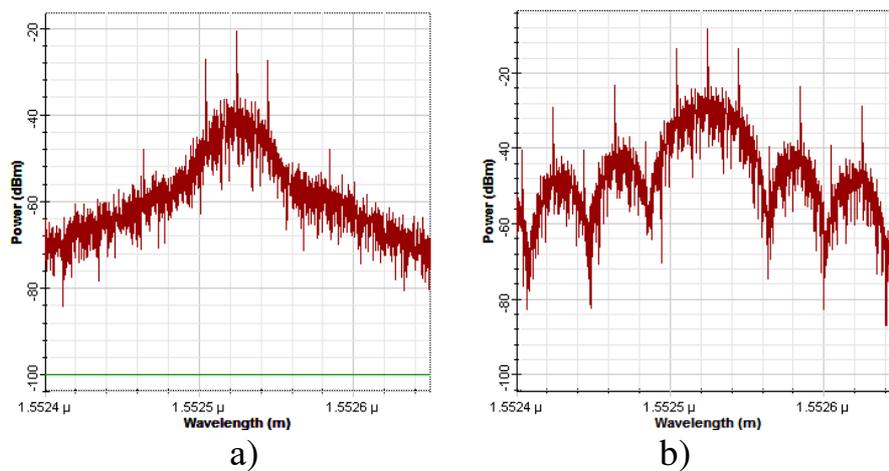
Fig. 3.22. Time diagrams of the optical signal at the input of an optical receiver with RZ modulation and a) $P_{TX\ min} = -8\ dBm$, b) $P_{TX\ opt1} = 4\ dBm$, c) $P_{TX\ opt2} = 14\ dBm$, d) $P_{TX\ max} = 18\ dBm$

3.3.3. Comparative analysis of results in RZ modulation

In addition to the comparison presented in Fig. 3.21 and Fig. 3.22 in the parameters and shape of the time diagrams of the optical signal under RZ modulation and different levels of the optical power of the transmitter, a similar generalized comparison can be made with respect to the spectral characteristics of the optical signal for both one of the channels and the total multiplexed signal.

Fig. 3.23 presents in a generalized form the spectral characteristics of the optical signal at the input of an optical receiver under NRZ modulation for the minimum limit, optimal and maximum limit value of the optical power of the transmitter.

Fig. 3.24 presents, respectively, the spectral characteristics of the multiplexed optical signal at the input of the optical demultiplexer.



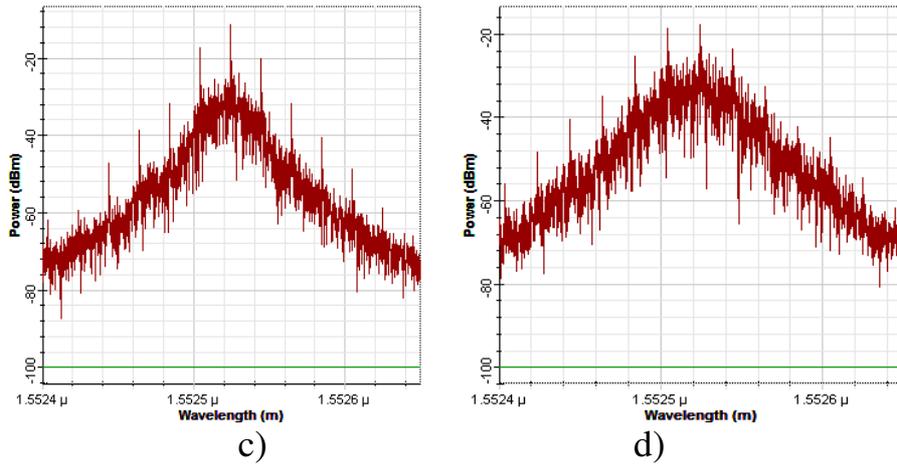


Fig. 3.23. Spectral characteristics of the optical signal at the input of an optical receiver with RZ modulation for: a) $P_{TX\ min} = -8\ dBm$, b) $P_{TX\ opt1} = 4\ dBm$, c) $P_{TX\ opt2} = 14\ dBm$, d) $P_{TX\ max} = 18\ dBm$

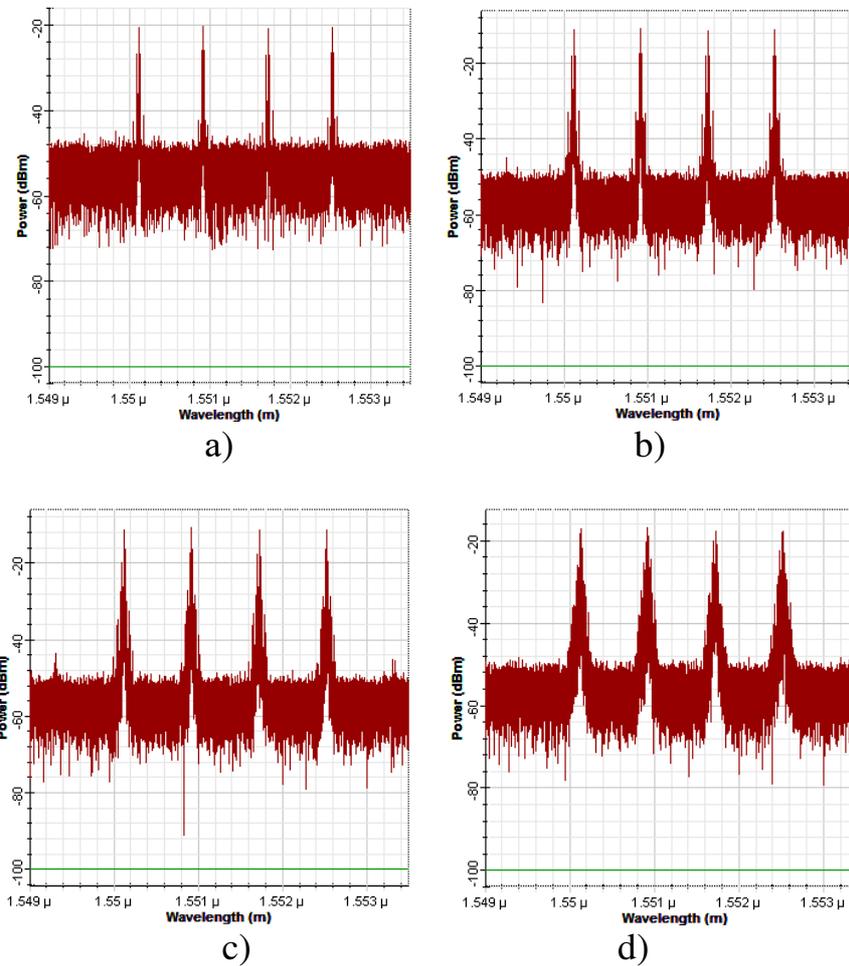


Fig. 3.24. Spectral characteristics of the multiplexed optical signal at the input of the optical demultiplexer with RZ modulation for: a) $P_{TX\ min} = -8\ dBm$, b) $P_{TX\ opt1} = 4\ dBm$, c) $P_{TX\ opt2} = 14\ dBm$, d) $P_{TX\ max} = 18\ dBm$

Based on the analysis of the time and spectral characteristics presented in Fig. 3.21 to Fig. 3.24, Table 3.5 presents in a summarized form the values of the

measured basic parameters obtained for the two limit ($P_{TX\ min}$ and $P_{TX\ max}$) and for the two optimal values ($P_{TX\ opt1}$ and $P_{TX\ opt2}$) of the optical power of the transmitter with RZ modulation.

Table 3.5. Experimental results when changing P_{TX} for RZ modulation

Parameters	$P_{TX\ min} = -8$ dBm	$P_{TX\ opt1} = 4$ dBm	$P_{TX\ opt2} = 14$ dBm	$P_{TX\ max} = 18$ dBm
Power P_{RX} , dBm	-4,953	-5,977	-5,094	-5,62
Average noise level in single channel, dBm	-80,23	-82,35	-83,26	-82,96
Average noise level in the multiplex, dBm	-53,50	-55,81	-56,01	-56,13
Optical pulse rise time, ns	0,297	0,308	0,335	0,377
OSNR in single channel (In./ Out.), dBm	66,84 / 10,77	66,84 / 21,46	66,84 / 23,02	66,84 / 22,87
Signal spectrum width per channel	80 pm	150 pm	200 pm	290 pm
Level and number of parasitic wavelengths	-	-45,39 x 1	-44,09 x 2	-

In a similar way, here, in Table 3.5 and in Fig. 3.25, the summarized results of the multiparameter analysis are presented with the main goal of determining the optimal optical power of the transmitter as a function of the value of several parameters.

The main criterion for evaluating the parameters of the optical signal is assumed to be the Q-factor, seeking its maximum. From the results presented in Table 3.6 and in Fig. 3.25 it is seen that $Q_{max} = 30.347$ and this is achieved with an optical line length of 400 km and $P_{TX} = 12$ dBm.

Table 3.6. Experimental results from multiparameter analysis

$$Q = f(P_{TX}, l) \text{ for RZ modulation}$$

Q-factor		Line length (l), km		
		400	500	600
P_{TX} , dBm	0	14,858	11,612	10,005
	2	16,324	12,369	10,582
	4	14,709	11,492	9,978
	8	28,954	22,443	16,173
	12	30,347	23,494	17,087
	13	29,84	24,615	17,184
	14	29,438	23,876	17,383
	16	20,228	17,344	13,354

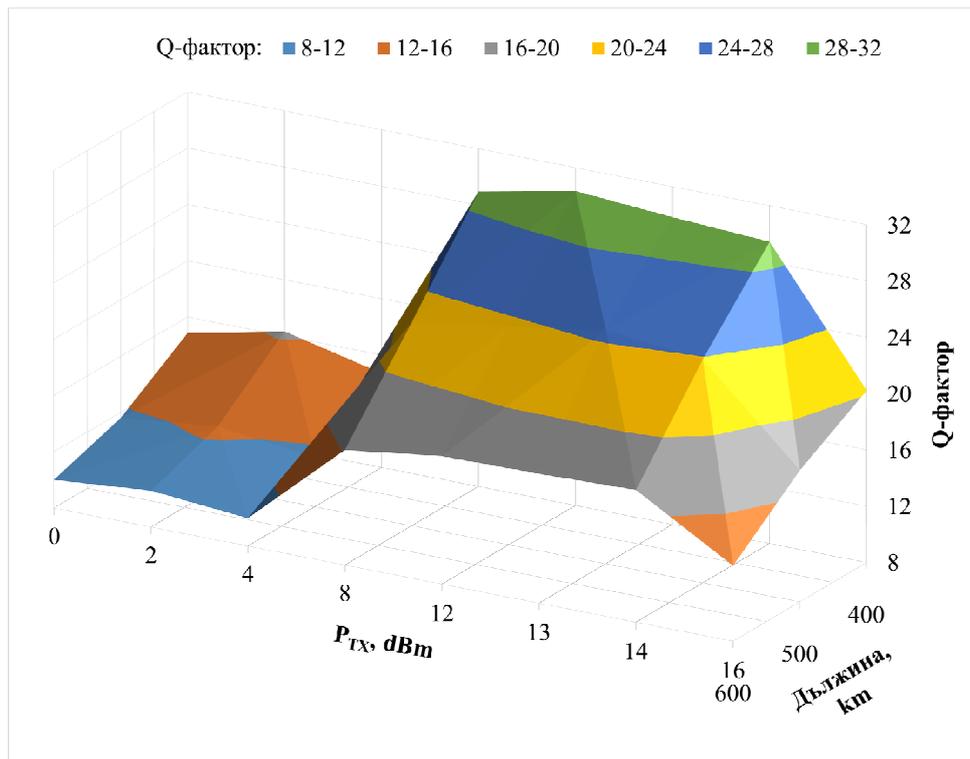


Fig. 3.25. Graphical dependence of the Q-factor on P_{TX} and the length of the optical line l for RZ modulation

3.4. Comparative analysis between the results obtained when studying the two types of modulation NRZ and RZ

Fig. 3.26 to Fig. 3.28 present comparative graphical dependences of the main quality indicators for the purpose of comparison when using RZ and NRZ modulation.

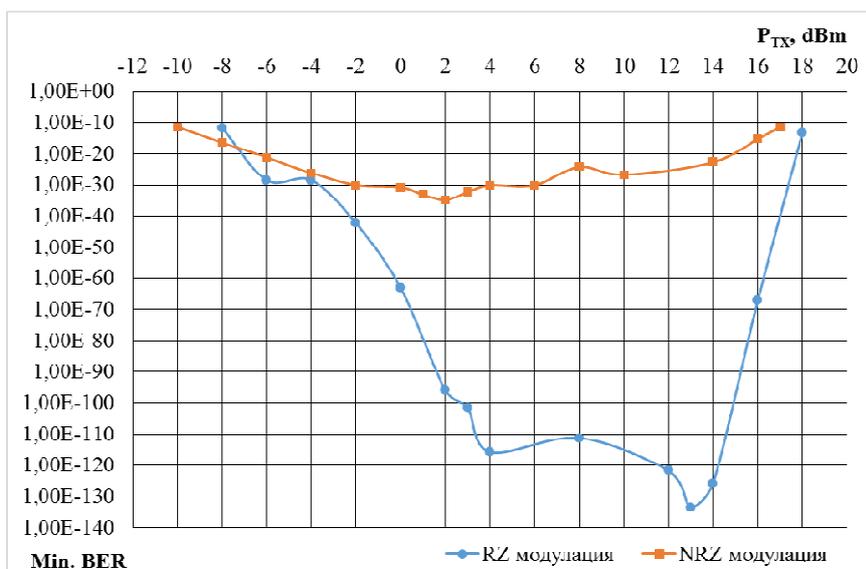
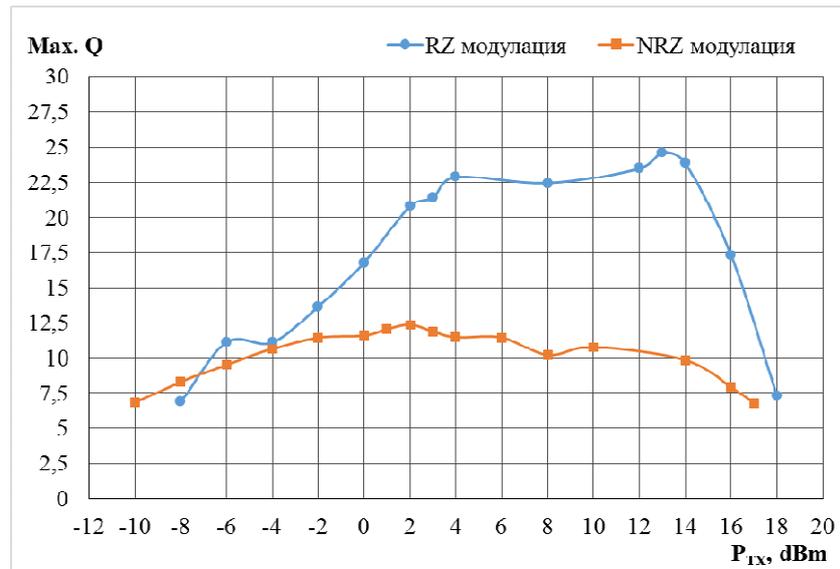


Fig. 3.26 Comparative graphical dependence between P_{TX} , dBm and Min. BER



Фиг. 3.27. Сравнителна графична зависимост между P_{TX} , dBm и Max. Q Factor

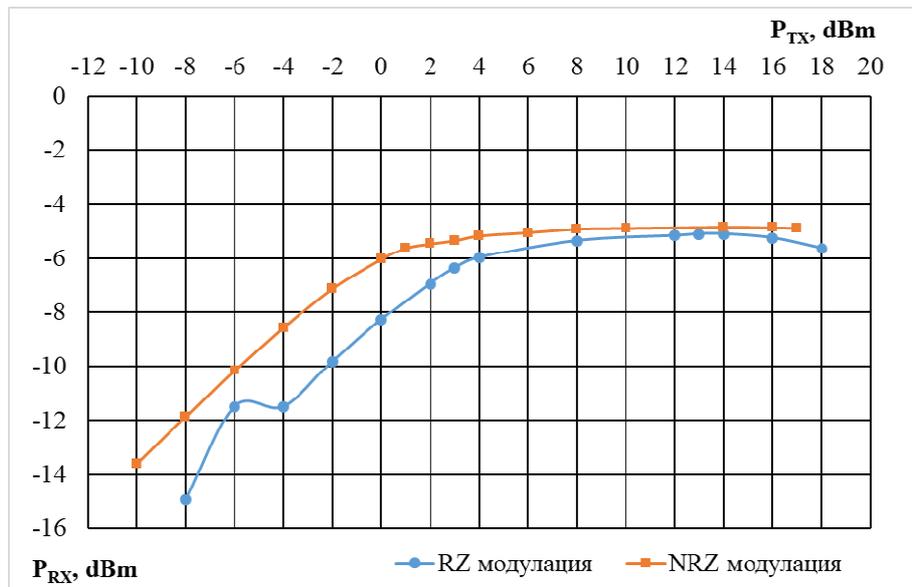


Fig. 3.28. Comparative graphical dependence between P_{TX} and P_{RX} , dBm

As can be seen from Fig. 3.26 and Fig. 3.27, when using RZ modulation, much better values of BER (largest minimum), respectively of Q-factor (largest maximum) are achieved, and this in a wide range of variation of the input optical power P_{TX} .

3.5. Synthesis of an algorithm for optimal planning and optimization of the parameters of a multi-channel optical communication line

Based on the considered characteristics and the conducted research and analysis, Fig. 3.29 presents a developed algorithm for optimal planning and optimization of the parameters of a multi-channel optical communication line with spectral multiplexing of signals.

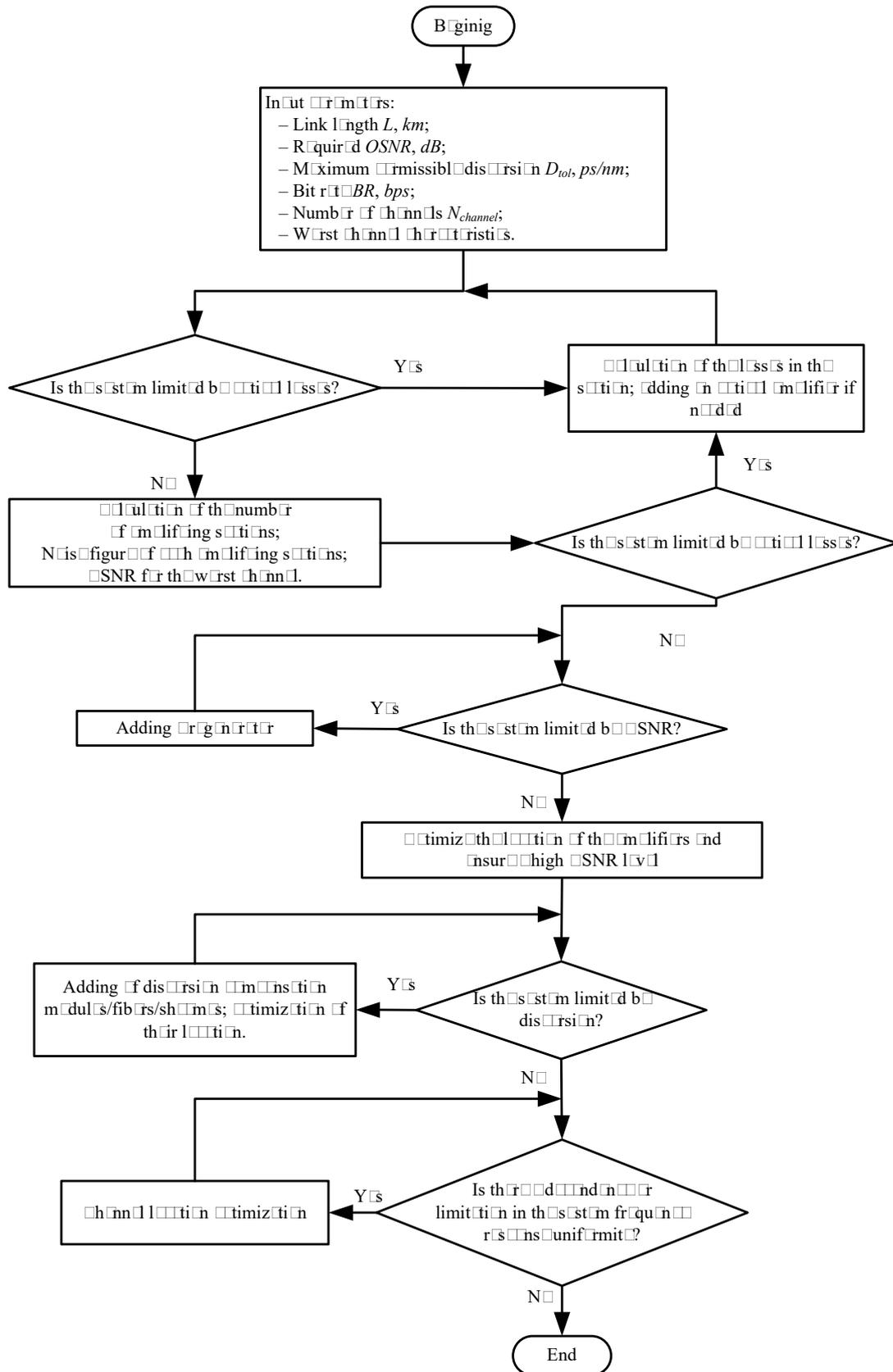


Fig. 3.29. Algorithm for optimization of optical transmission lines in WDM optical communication networks

3.6. Conclusions to Chapter 3

1. The developed simulation models offer convenient and easy analysis and solution of optimization problems in the design and analysis of the behavior of optical networks with spectral multiplexing.
2. The use of RZ modulation provides better signal parameters – minimum BER value and maximum Q-factor for a wide range of optical power of the optical transmitter, compared to the use of NRZ modulation.
3. Regardless of the better parameters, when using RZ modulation, worse time and spectral characteristics are obtained – a higher level of intersymbol interference and wider spectra with higher sideband levels compared to NRZ modulation.
4. The deterioration of optical signals is causally related to the amplitude attenuation and the dispersion broadening of the code pulses. The negative effects of both processes, as well as other nonlinear effects and interference, have quantitative expressions that increase with the length of the line and the number of optical channels.
5. Nonlinear distortions in optical fibers are due to several phenomena that occur at unacceptably high levels of transmitted signals. They can be divided into two groups - nonlinearities associated with optical power dissipation and nonlinearities associated with the Kerr effect.
6. Nonlinear effects associated with self-phase modulation and four-wave mixing are extremely characteristic and have a great impact on optical systems with spectral multiplexing of signals.
7. Effects associated with light scattering are characterized by a threshold level that is highly sensitive to the length of the optical line.
8. If the average optical power inserted into the fiber is kept constant, an optical RZ pulse with a 50% duty cycle will have twice the peak power value of an NRZ pulse. Since the RZ pulse has a wider optical bandwidth than the NRZ pulse, it is more affected by the influence of dispersion in the fiber;
9. The high optical density in the fiber core leads to the appearance of nonlinear effects. RZ pulses have a higher peak power and as such are more susceptible to FWM, SPM and XPM. In the presence of SPM, however, these pulses can undergo compression (solitons) and be more efficient than NRZ pulses;
10. The best modulation format in the presence of nonlinear effects depends on the effect of the dispersion control scheme, since dispersion causes the energy of a single pulse to be dissipated over time;
11. RZ modulated signals are more resistant to PMD than NRZ encoded signals because the energy is confined to the center of the bit period;
12. The results prove that in RZ-based modulations, optical signals provide better basic receiver sensitivity when the average power in the fiber is kept constant;
13. A major drawback when using RZ modulation is the generation of significant sidebands in the optical spectral characteristics of the signals.

CHAPTER 4. IMPLEMENTATION OF AN EXPERIMENTAL STAND FOR THE STUDY OF MULTIPLEXED OPTICAL SIGNALS IN A PASSIVE OPTICAL NETWORK

4.1. Development of a block diagram of an experimental stand for studying multiplexed optical signals in a passive optical network

Fig. 4.1 shows the block diagram of a concept (conceptual design) for the implementation of a practical model of an experimental stand for the study of multiplexed optical signals in a passive optical network (PON), which would allow for conducting scientific research, solving optimization problems and training students and technical personnel.

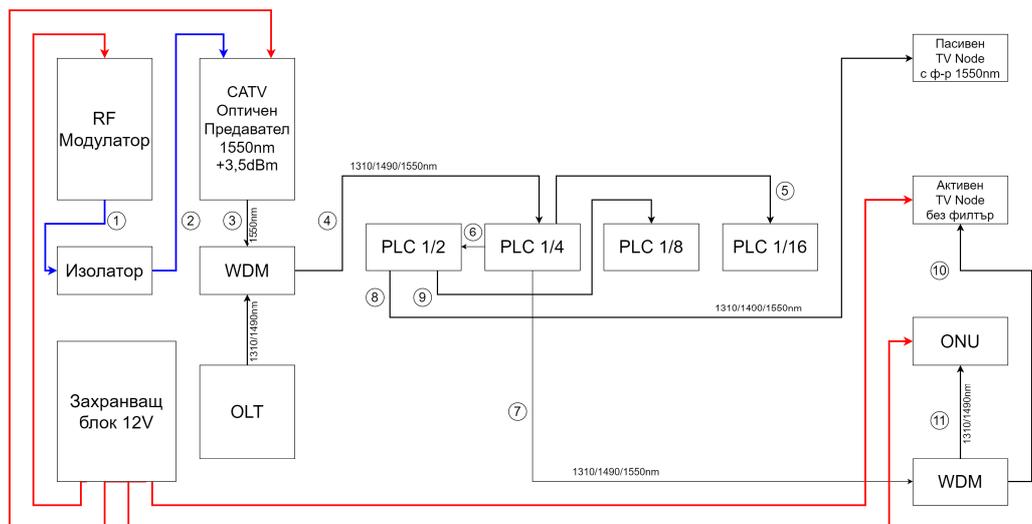


Fig. 4.1. Block diagram of an experimental stand for studying multiplexed optical signals in a passive optical network (PON)

As can be seen from Fig. 4.1, the model consists of three channels:

- downstream channel at 1550 nm (DS@1550nm) for transmission of broadcasting services, in particular television;
- downstream channel at 1310 nm (DS@1310nm) for forward transmission (download) of data, in particular IP packets (Internet delivery);
- upstream channel at 1490 nm (US@1490nm) for reverse transmission (upload) of data, in particular IP packets (Internet delivery);

The three channels are spectrally multiplexed and the multiplexing is performed in two stages. In the first stage, through the built-in SFP transceiver module in the OLT, which emits at 1490 nm and receives the signal from the ONU at 1310 nm, the multiplexing and simultaneous bidirectional transmission of wavelengths at 1490nm and 1310nm is performed over single SMF optical fiber. In the second stage, the optical signal 1490/1310 nm is multiplexed with a wavelength of 1550 nm, which is performed on the headend side by a WDM filter, and on the subscriber side by a DWM filter or the same one that is built

into the end client devices.

4.3. Development and research of a simulation model of multiplexed optical signals in a PON network

The purpose of this simulation model is to explore different optical network configuration options:

- At different powers of the power inserted by the optical transmitter into the optical fiber;
- At different lengths of the optical line;
- At a combination of input parameters in search of optimal network settings.

4.3.1. Simulation modeling of multiplexed optical signals in a PON network

Based on the block diagram of a passive optical network shown in Fig. 4.1, a developed simulation model of multiplexed optical signals in a PON network is shown in Fig. 4.17.

The simulation model consists of three channels:

- Two downstream channels (DS) – one for transmitting broadcast services (such as TV content) and one for transmitting IP data in the forward direction (download);
- one upstream channel (US) – for transmitting IP data in the reverse direction (upload)

The downstream channels have wavelengths of 1550 nm and 1310 nm, the upstream channel has wavelengths of 1490 nm.

The downstream channel at wavelength 1550 nm is formed by the following blocks:

- CATV Optical Transmitter block;
- Patch cord optical fiber connectors;
- Active TV Node optical receiver block.

The upstream channel at a wavelength of 1310 nm is formed by the following blocks:

- ONU optical transmitter block;
- Patch cord optical fibers;
- PLC splitters;
- WDM.

The upstream channel at a wavelength of 1490 nm is formed by the following blocks:

- OLT optical transmitter block;
- Patch cord optical fibers;
- PLC splitters;
- WDM.

The three channels are spectrally multiplexed using optical power adders – WDM. The three channels are demultiplexed using optical splitters – WDM.

Through this simulation model, the behavior of the circuit can be studied under the following assumptions:

- Input optical power 0dBm for DS and US channels;
- NRZ encoding of the optical signal in the transmitters;
- Simulation at different lengths of the optical line: from 8 m (limited by the total length of the patch cords used in the practical model) to 10 km (typical length of PON networks for urban conditions, for example for television and internet delivery);
- Use of single-mode optical fiber (SMF) with kilometer attenuation $\alpha = 0.3$ dB/km.

4.4.2. Research on the simulation model of a passive optical network

Fig. 4.18 shows the eye diagrams for the three optical channels for the case of the practical implementation of the model – with an optical line length of 8 m, and Fig. 4.19 – the eye diagrams for the two optical channels for the limiting case – with a maximum optical line length of 10 km.

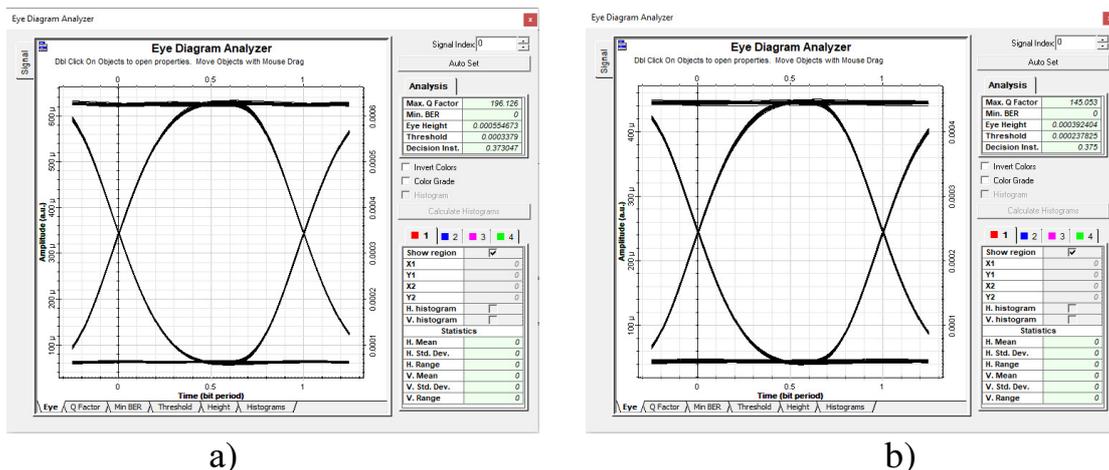


Fig. 4.18. Eye diagram and Q-factor of the optical line for a length of 8 m of the optical line: a) DS 1490 nm, b) DS 1550 nm

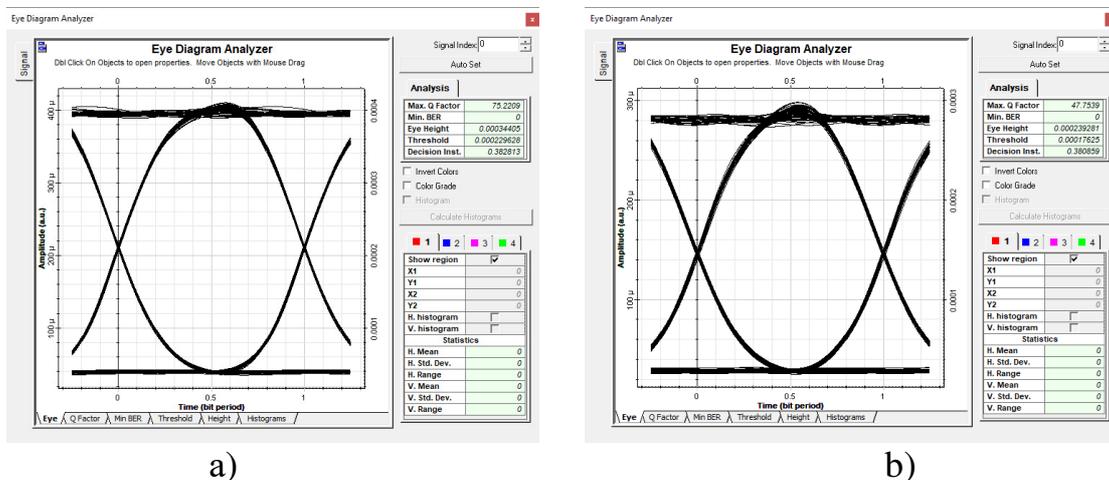


Fig. 4.19. Eye diagram and Q-factor of the optical line for a length of 10 km of the optical line: a) DS 1490 nm, b) DS 1550 nm

Fig. 4.20 shows the time diagrams of the optical signal before demultiplexing of the two channels at optical line lengths respectively for the case of the practical model (8m) and for the maximum permissible case (10km).

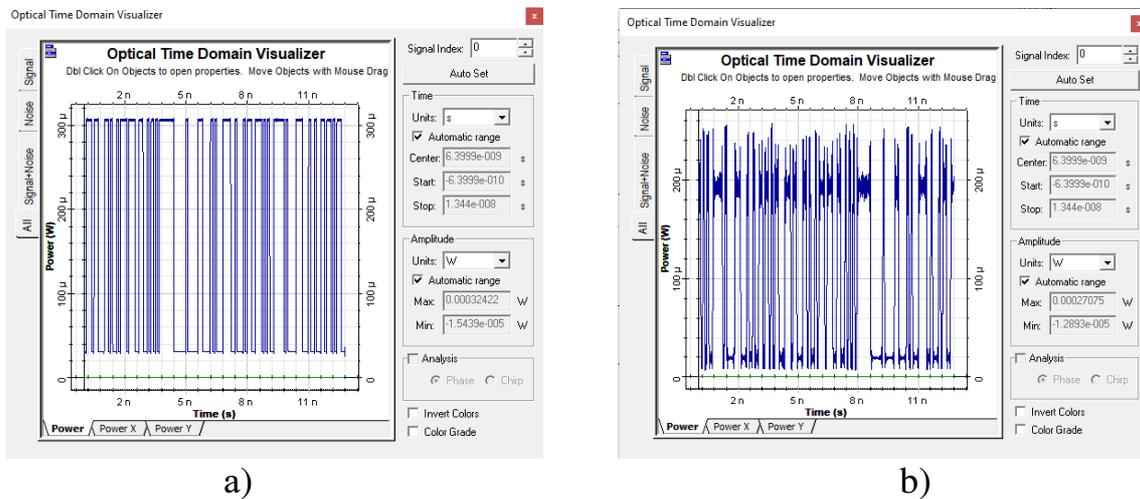


Fig. 4.20. Time diagrams of the received optical signal before demultiplexing for optical line length: a) 8 m and b) 10 km

Fig. 4.21 shows the spectral characteristics of the optical signal before demultiplexing of the three channels at optical line lengths for the case of the practical model (8m) and for the maximum permissible case (10km), respectively.

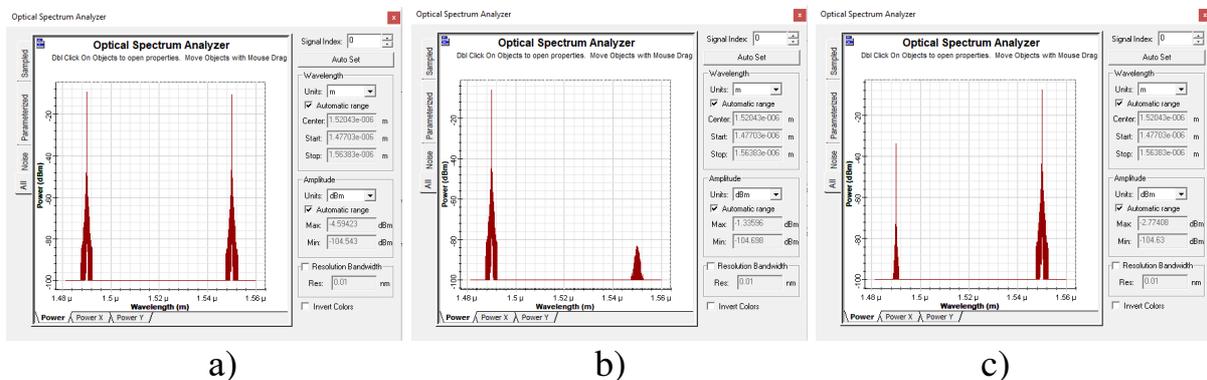


Fig. 4.21. Spectral diagrams of the received optical signal before demultiplexing for the length of the optical line: a) for both wavelengths, b) for 1490 nm and c) for 1550 nm from WDM

4.5. Development and experimental study of a practically implemented model of a stand for studying multiplexed optical signals in a passive optical network

4.5.1. Development of a practically implemented model of a stand for studying multiplexed optical signals in a passive optical network (PON)



Fig. 4.23. General view of the implemented stand for studying multiplexed optical signals in a passive optical network

Based on the block diagram presented in the conceptual design in Fig. 4.1 and the selected equipment in pt.4.2, a test bench for studying multiplexed optical signals in a passive optical network (PON) has been developed. The general appearance of the practical model is shown in Fig. 4.23.

4.5.2. Experimental study of a practically implemented model of a stand for studying multiplexed optical signals in a passive optical network (PON)

The experimental study of the model was implemented by measuring the power level of the optical signals at selected control points in both directions (DS and US). The results of the experimental study are shown in Tables 4.2 to 4.6.

Table 4.2. Measured optical signal power level in 1/2 PLC splitter

PLC 1/2	1490 nm/dBm	1550 nm
Port 1	-6.10	-6.17
Port 2	-10.32	-10.37

Table 4.3. Measured optical signal power level in 1/4 PLC splitter

PLC 1/4	1490 nm/dBm	1550 nm/dBm
Port 1	-1.40	-5.56
Port 2	-1.67	-5.67
Port 3	-1.44	-5.48
Port 4	-1.39	-5.05

Table 4.4. Measured optical signal power level in a 1/8 PLC splitter

PLC 1/8	1490 nm/dBm	1550 nm/dBm
Port 1	-16.31	-20.62
Port 2	-16.35	-20.66

Port 3	-16.28	-20.60
Port 4	-16.32	-20.64
Port 5	-16.30	-20.59
Port 6	-16.29	-20.54
Port 7	-16.50	-20.66
Port 8	-16.47	-20.70

Table 4.5. Measured optical signal power level in a 1/16 PLC splitter

PLC 1/16	1490 nm/dBm	1550 nm/dBm
Port	-17.17	-21.34
Port	-17.16	-21.24
Port	-17.05	-21.25
Port	-17.26	-21.45
Port	-17.18	-21.36
Port	-17.25	-21.52
Port	-17.36	-21.45
Port	-17.16	-21.34
Port	-17.12	-21.41
Port	-18.18	-22.50
Port	-17.34	-21.69
Port	-18.60	-22.76
Port	-17.36	-21.42
Port	-17.19	-21.25
Port	-17.32	-21.16
Port	-17.36	-21.50

Таблица 4.6. Измерено ниво по мощност на оптичния сигнал на входа на ONU

ONU	1490 nm	1550 nm	1310 nm
dBm	-4.02	-6.5	+4.03

4.6. Conclusions to Chapter 4

1. A simulation and practical model of a stand for studying multiplexed optical signals in a passive optical network (PON) has been developed.
2. The developed model offers flexible options for theoretical and practical training of students, technical personnel, as a platform for conducting various simulation and practical research in the field of passive optical networks and broadband service delivery.
3. The developed practical model has many advantages such as its small size, wide range of capabilities, flexible modular structure and can easily be used as part of a larger network structure. The model also has a disadvantage – the fixed wavelengths used by the optical transmitter (1550nm), ONU (1310nm), and the optical SFP module of the OLT (1490nm).
4. There is a wide range of possibilities for conducting theoretical and practical research on the simulation and practical models: use of different

types and lengths of optical fibers; optimization of equipment parameters; research of optical nonlinear effects in the transmission network; emulation of signals for various types of services and analysis of traffic load; emulation of a large number of users, etc.

CONCLUSION

Optical WDM-PON networks provide significant opportunities for the evolution of next-generation broadband infrastructures, offering a powerful foundation for high-capacity, secure, and future-proof communication services. By allocating a dedicated wavelength to each user or service, WDM-PON eliminates the bandwidth sharing limitations found in traditional TDM-based systems, enabling symmetric multi-gigabit performance and exceptional quality of service. This architectural advantage opens the door to a wide range of modern applications, from ultra-reliable enterprise connectivity to cloud services, high-definition streaming, and real-time industrial automation.

The inherent scalability of WDM-PON provides operators with a long-term growth path: new users or services can be accommodated simply by adding new wavelengths without changing the existing optical infrastructure. This makes WDM-PON extremely attractive for supporting densely populated urban installations, as well as for expansion into rural areas. Wavelength isolation also improves network security, making it ideal for government, defense, financial institutions, and mission-critical sectors where data protection is essential.

WDM-PON is uniquely positioned to play a central role in emerging technologies such as 5G/6G mobile fronthaul, smart city platforms, and distributed edge computing. The combination of long range, low latency, and high capacity is perfectly aligned with the stringent requirements of modern wireless networks and intelligent systems. As global data traffic continues to grow, WDM-PON stands out as a reliable and flexible solution that can meet increasing performance demands while reducing operational costs through its passive, energy-efficient design.

Overall, WDM-PON represents a transformative opportunity for network operators and service providers, offering the technological capabilities needed to build resilient, high-performance optical access networks capable of supporting the digital future.

The main point in achieving quality of service in optical passive networks with spectral multiplexing is related to linear coding and modulation in optical transmission channels from the point of view of ensuring maximum transmission distance, high Q-factor, respectively BER, good spectral characteristics and energy budget of the system, taking into account the main limiting factors, transient characteristics and limitations from dispersion and attenuation along the fiber, nonlinear effects and the number of optical sections.

By using the advantages of good characteristics and reliability of optical transmitters and receivers, low losses and wide bandwidth of optical fibers, a wide variety of multi-channel optical systems with different types of linear coding and modulation in optical transmission lines can be implemented. Mach-Zehnder structures of modulators are widely used.

Simulation modeling and ongoing research on WDM-PON optical networks are essential to improving the efficiency, reliability, and scalability of modern broadband infrastructures. WDM-PON is a complex technology that integrates wavelength management, optical propagation, passive components, and user-specific channel isolation. Because these systems involve multiple variables – such as wavelength allocation, power control, dispersion effects, and network topology – simulation models provide a safe, cost-effective, and highly flexible environment for analyzing system behavior prior to real-world deployment. Through simulation, researchers can predict performance, identify potential bottlenecks, and optimize system parameters without the financial and logistical constraints of physical testing.

Simulation tools enable experimentation with new architectures, algorithms, and technologies, such as dynamic wavelength allocation, advanced modulation formats, and AWG-based routing strategies. This accelerates innovation and supports the development of next-generation WDM-PON designs capable of meeting rapidly increasing bandwidth demands. The research also helps assess the impact of emerging applications – such as 5G/6G fronthaul, IoT ecosystems, cloud services, and edge computing – ensuring that WDM-PON networks can evolve to support future communication demands.

Simulation-based research plays a key role in enhancing network security and resilience. By modeling various failure scenarios, sources of interference, and cyberthreats, engineers can develop strategies to strengthen the resilience of WDM-PON infrastructures. This is especially important for applications that require high reliability, such as industrial automation, healthcare systems, and government networks. Overall, the creation of accurate simulation models and continuous research into WDM-PON systems are critical to understanding system behavior, reducing deployment risks, fostering innovation, and ensuring that WDM-PON technology remains the leading solution for high-performance optical access networks. These efforts not only improve current network designs but also pave the way for smarter, more adaptable, and future-ready optical communication systems.

CONTRIBUTIONS TO THE DISSERTATION WORK

Scientifi-applied contributions:

1. A methodology and algorithm for optimal planning, sizing, modeling and research of passive optical networks with spectral multiplexing of signals are proposed.
2. Simulation models are synthesized for research, analysis, performance assessment and solving optimization problems in high-speed (10Gbps) multi-channel optical networks using different optical modulation formats (NRZ and RZ) of signals and various complex configuration parameters.
3. The degree of influence of high optical density in the fiber core on the occurrence of nonlinear effects (FWM, SPM and XPM) in different optical modulation formats of signals (RZ and NRZ) is studied. It is established that RZ pulses have a higher peak power and as such are more susceptible to FWM, SPM and XPM. However, in the presence of SPM, these pulses can undergo compression (solitons) and be more efficient than NRZ pulses.
4. Dependencies related to determining the boundary conditions and the maximum value of the Q-factor for different input parameters and network range, determining the losses during radio propagation, the eye diagrams of the channel optical signals and the optimal value of the input optical power have been derived.

Applied contributions:

5. Simulation models of multi-channel high-speed optical communication networks have been developed and studied to solve optimization problems according to the criteria of achieving a minimum BER value (Min. BER) or maximum Q factor and ensuring maximum network performance and efficiency at different input signal parameters.
6. A practical model / experimental setup of a passive optical network (PON) with spectral multiplexing of signals for the delivery of interactive services has been developed and studied, designed to perform three main tasks: to allow a wide variety of practical studies (traffic processing, introduction of new services and modules for management and communication, etc.); to be a platform for conducting general research in the field of passive optical networks; to provide convenient and easy training for personnel.
7. Experimental research steps have been defined and experimental results are presented for the complex determination and evaluation of the energy balance and parameters of the model for the study of multiplexed optical signals in a passive optical network, using specialized measuring equipment.

LIST OF PUBLICATIONS ON THE DISSERTATION WORK

- [A.1] Angelakis, M., **Kipreos, E.**, Angelov, K., Educational demonstration platform for IP-video streaming and monitoring of television content, Proceedings: VIII National Scientific Conference with International Participation TC Lovech "TechCo 2024", June 28, 2024, Lovech, ISSN - 3033-1323, pp. 112-116.
- [A.2] Popov, V., **Kipreos, E.**, Angelakis, M., Implementation of 3D objects in video processing, using Blender, Student Scientific Session `2024, 18.10.2024, Gabrovo, ISSN: 1313-3055, Volume 1, pp. 84-89.
- [A.3] Todorov, N., **Kipreos, E.**, Angelakis, M., Monitoring the liquid level during bottling, through image processing and analysis, Student Scientific Session `2024, 18.10.2024, Gabrovo, ISSN: 1313-3055, Volume 1, pp. 90-95.
- [A.4] **Kipreos, E.**, Sadinov, S., Angelakis, M., Angelov, K., Study of the effectiveness of applying WDM-DCF compensation in fiber-optic communication systems. Proceedings: IX National Scientific Conference with International Participation TC Lovech "TechCo 2025", June 27, 2025, Lovech, ISSN: 3033-1323, pp.151-156.
- [A.5] **Kipreos, E.**, Investigation and analysis of the impact of electromagnetic fields and radio frequency radiation in urban environments. Proceedings: IX National Scientific Conference with International Participation TC Lovech "TechCo 2025", June 27, 2025, Lovech, ISSN: 3033-1323, pp. 246-251.
- [A.6] **Kipreos, E.**, Modeling, research and analysis of approaches for minimizing distortions in optical WDM systems. Proceedings: International Scientific Conference "Unitech 2025", 20-22 November 2025, Gabrovo, ISSN: 1313-230X.

TITLE: “METHODS AND ALGORITHMS FOR RESEARCH ON MULTIPLEXED SIGNALS IN PASSIVE OPTICAL COMMUNICATION NETWORKS”

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ABSTRACT

In Chapter 1, an analysis of the current state and areas of research and development in passive optical communication networks with spectral multiplexing is made. The main problems in this type of networks are analyzed and summarized. As a result, the main goal and tasks of the dissertation are formulated and motivated.

In Chapter 2, a generalized approach to modeling a multi-channel optical communication network is presented, a basic model is developed and a methodology for conducting measurements and testing of WDM PON systems is compiled.

In Chapter 3, simulation studies are performed and analyses of the results for a simulation model of a multi-channel WDM system with different formats of optical external modulation of signals and configuration of optical sections are presented. An algorithm for optimal planning and optimization of the parameters of a multi-channel optical communication line is synthesized.

In Chapter 4, a conceptual design, modeling, practical implementation and research of an experimental stand for studying multiplexed optical signals in a passive optical network are presented. The architecture of the stand is presented, the key control points for conducting research are presented, discussed and analyzed, and experimental results from conducting measurements are presented.

Keywords: passive optical network, wavelength division multiplexing, optical signal, optical modulation, optical spectrum, eye diagram, power budget