

Modeling and Simulation of Fiber Optic Transmission Links

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Abstract

The main aim of the paper is modeling and simulation of fiber optic transmission. It also deals with ways to increase the capacity of fiber optic transmission links by using WDM (Wavelength Division Multiplexing) system. The parameters of the fiber optic transmission link were measured on a real optical transmission links and a model for simulation was set up. A simulation of increasing the capacity of a fiber optic transmission link was made in two ways. The first one is to increase the transmission speeds of the individual channels of the WDM system, and the second one is to increase the number of WDM system channels with lower individual speeds. The simulation results showed that the second method provides better quality of WDM service. The additional experiment was done on an existing ITU T G.655 optical fiber intended for WDM systems whose parameters were measured. Bit error rate and Q parameter for WDM system of 4 and 16 channel was used to check quality of proposed solution.

Keywords: fiber optic, transmission link, WDM, link capacity, simulation

1 Introduction

Analyzing the capacity of optical networks, whether it concerns existing systems or new ones that are just being designed, is always major challenge. Mathematically, it is practically impossible to calculate the possibility of establishing all the routes of the optical network and their capacities. The solution is found in modeling optical networks and designing computer simulators, which, based on mathematically described components and environments, simulate the functioning of the network and optical fiber transmission systems.

This paper presents the basic features of Optisystem simulators for telecommunications network, and the methods of increasing the capacity of transmission fiber optic links have been analyzed in a practical example. The capacity of fiber transmission links can be increased by increasing the channel speeds of the WDM (Wave Division Multiplexing) system and/or by increasing the number of channels in the WDM system. This paper systematized the scientific research achievements of speed increase under laboratory conditions. These achievements have been standardized and commercially applied. Parameters of real fiber optic transmission links were measured for the purposes of this paper. Based on

these parameters, a simulator was created using the Optiwave-OptiSystem program. Subsequently, the analysis of increasing the capacity of fiber transmission links was realized using two methods first, by increasing the channel speed, and then by increasing the number of channels of the WDM system. The results of the simulation of the increase in the transmission speeds for the actual fiber optic transmission system are given. The paper is structured so that in the first part of the paper is a general overview of the simulation with reference to the Optiwave-OptiSystem software simulator. A model setup was made for simulating the actual system. Also, two different methods of increasing the capacity of a fiber optic transmission link were simulated. In the end, results of the simulation are analyzed in the conclusion.

2 Modeling of Fiber Transmission System

A real system is an organized interdependent set of elements that form a complex whole and work together to achieve a given aim or function, regardless of whether the system already exists or its existence is planned in the future. The model is used to obtain informations about the real system based on the results of simulations that represent an abstract experimental system of the model.

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Models have a hierarchical structure, each component of the model can represent a smaller system or submodel [1].

The objective of experimental modeling is to obtain as much useful information about the behavior of the system in real conditions by setting the conditions of the experiment based on the set input/output signals. Modeling requires an ideal relationship between approximations/simplifications (which introduce an error into the simulation) and the complexity of the mathematical description of the real system. The use of unsuitable models or the inappropriate use of modeling itself is responsible for countless disasters whether it was on personal, technological or/and historical level. Modeling is the most important conceptual tool of the mankind. The aim of the TCS simulation is the development of hardware with the associated software - protocols that will provide appropriate response on the appropriate stimulation. The key of the development of any model is in the fact that the impact on the virtual model of any piece of equipment is determined by only a few main parameters. The telecommunications network model represents an appropriate formal description of the telecommunication system. The model simply presents or formally describes the elements of the communications system. The TCN simulation model includes: nodes, interfaces, links between nodes, queues, protocols, a discrete communication system, applications and auxiliary models.

Optiwave-OptiSystem is designed to meet the needs of researchers, fiber optic telecommunications engineers, system integrators, students and a wide range of other users. The biggest advantage of this simulator is the graphical simplicity with a large library of components that can be intuitively connected into the system. Optiwave meets the request of the new optical telecommunications market for a powerful but simple tool for the design of optical system and components on optical fibers and Optical Free Space. Optisystem is part of the Optiwave toolkit that allows users to plan, test and simulate (in the temporal and frequency domains). Since Optisystem simulator version 17 was used in this paper, it is important to note that double-clicking on any component provides an overview of the literature used for modeling and simulation of that component. The

overview is given in the form of a standard book help menu. The chapters offered with the components provide complete excerpts from the literature, which is listed at the end of the instructions for the simulator components in the form of references list. The paper does not cite this literature directly so it wasn't needed to be listed in the references of the paper itself. Optisystem provides the possibility of hierarchical organization of the simulation, where certain parts of the simulation model can be presented as blocks, or as one component. Optisystem contains an option for automatic cycles and optimization of the simulation. The simulation results are displayed in 2D and 3D graphics as well as tabularly. Thus, Optisystem provides the ability to design and plan optical networks of various types from LAN (Local Access Network) computer networks, through access networks to large transport backbone networks [2].

3 Increasing the Capacity of Fiber Optic Transmission Link

The transmission of information via telecommunications networks has grown rapidly over the last few decades. Most of the transmission of this data was performed via optical networks with wave multiplexing WDM systems. But the question of limiting the capacity of the optical channel arises.

3.1 Review of research in the field of increasing the capacity of fiber optic transmission links

The first Tbps (terabit per second) speeds were achieved in 2009 in Alcatel's research centers. It was a Dense WDM system with 155 channels and channel speeds of 100 Gbps (gigabit per second). The maximum range of this system was 7000 km. This was followed by solutions with an increase in the number of channels of different research centers. However, it is considered that the turning point towards reaching the theoretical maximum information capacity of the channel happened with the development of the channel speed system 400 Gbps in 2017 in the laboratories of BT&Huawei.

Table 1. Overview of increasing the transmission speed of fiber optic transmission links

Year/Organization	Effective speed (Tbps)	Number WDM channels	Per channel speed	Distance (km)
2009 / Alcatel-Lucent [3]	15.5	155	100	7000
2010 / NTT [4]	69.1	432	171	240
2011 / NEC [5]	101.7	370	273	165
2016 / BT & Huawei [6]	5.6	28	200	about 140
2017 / BT & Huawei [7]	11.2	28	400 G	250
2020 / RMIT [8]	39.0	160	244	76.6

The solutions found by researchers in laboratories are standardized and commercially applied in order to increase the transmission capacities of optical fibers. It is important to point out that improvements have been made in the field of development of optical and electronic components. In fact, improvements have been made in the domain of improving the performance of optical components and in the domain of improving spectral efficiency. It can also be seen from the Table 1 that the increase of the total capacity of the optical transmission link - optical fiber was done by increasing the number of WDM system channels, but also by increasing the WDM channels speed.

3.2 Parameters of practical optical transmission link

The simulator was made for the existing optical telecommunication system with optical fiber cables type ITU T G.655 [9]. The numerical values of the parameters used by the simulator are in accordance with the IEEE 802.3av standard and the corresponding interpretations of the recommendations and standards of the ITU organization [10].

The central wavelength is 1552 nm or 1931 THz with a channel width of 0.1 THz. A pseudo-random array generator with NRZ binary source (Not Return to Zero) was used for the transmitter. The signal carrier was realized using CW laser (Continuous Wave Light Amplification by Stimulated Emission of Radiation). CW laser as a source of continuous light signal has a laser beam with controlled heat output and constant duration - beam intensity.

Modulation was performed using a Mach-Zehnder modulator. A PIN photodiode with Bessel filters was used for the receiver. The parameters of the optical fiber are determined by the measurement results on the real system and they are as follows:

- longitudinal fiber attenuation 0.18 dB / km
- chromatic dispersion 4.8 ps / nm * km
- The zero wavelength of the optical fiber chromatic dispersion is 1467 nm
- chromatic dispersion slope coefficient 0.057 ps / nm² _ km
- polarizing dispersion 0.1 ps
- polarization dispersion coefficient 0.01 ps / pkm
- the total length of the route is 89.7 km

The case of realization of bit rate per one fiber of the row 40 Gbps was analyzed. The system can be made using a WDM system with 16 channels of individual speeds of 2.5 Gbps or with 4 channels of individual bit rates of 10 Gbps. Figure 1 shows a block view of the basic model for

measuring the optical fiber parameters of a real system. The optical fiber has a total length of 89 km, extensions achieved by fusion splices and two connectors. Optical fiber attenuation, then longitudinal attenuation, chromatic dispersion, and fiber polarization dispersion were measured.

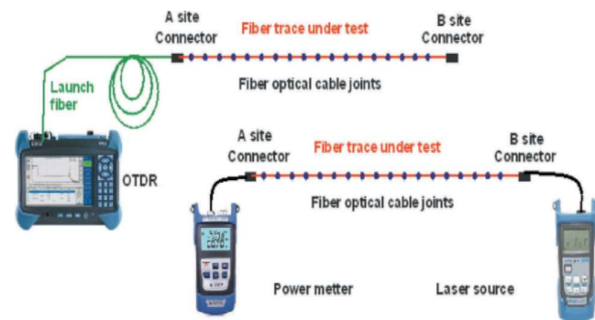


Figure 1. Presentation of the measurement model of a practical transmission system, i.e. measurement on an installed optical cable

3.3 WDM system with 16 channels

Figure 2 shows the model of the communication system simulator for the first case with 16 channels. The system on the left has 16 transmitters that transmit signals to the multiplexer. One transmitter is composed of a pseudorandom source, NRZ generator, Laser source and Mach-Zehnder modulator. The optical multiplexer performs wave multiplexing and transmission with optical fiber to the right receiving side. The demultiplexer separates the multiplexed channels and directs them to a specific receiver. There are 16 receivers and they consist of a Bessel filter, a photodiode and a narrow-band Bessel filter.

The following tools were used to measure the parameters of this system:

- optical power meters,
- WDM analyzers,
- spectrum analyzers,
- BER (Bit Error Rate) analyzer with the option of displaying eye diagrams

All tools except the BER analyzer were used on the transmitting and receiving side.

Figure 3 shows the spectrum measurements at the output of the multiplexer and one branch of the demultiplexer on the receiving side. It is clear that one transmission channel is filtered on the receiving side.

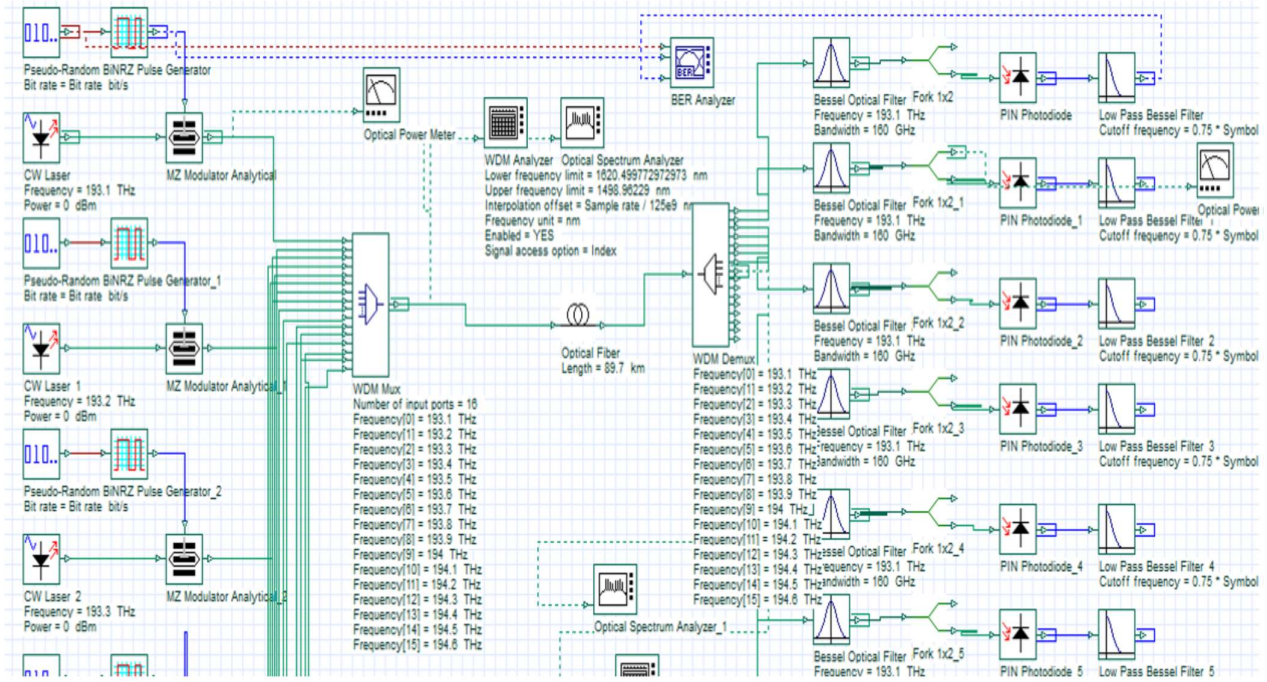


Figure 2. Model view of a 16 channel WDM system (due to complexity only part of the system is shown)

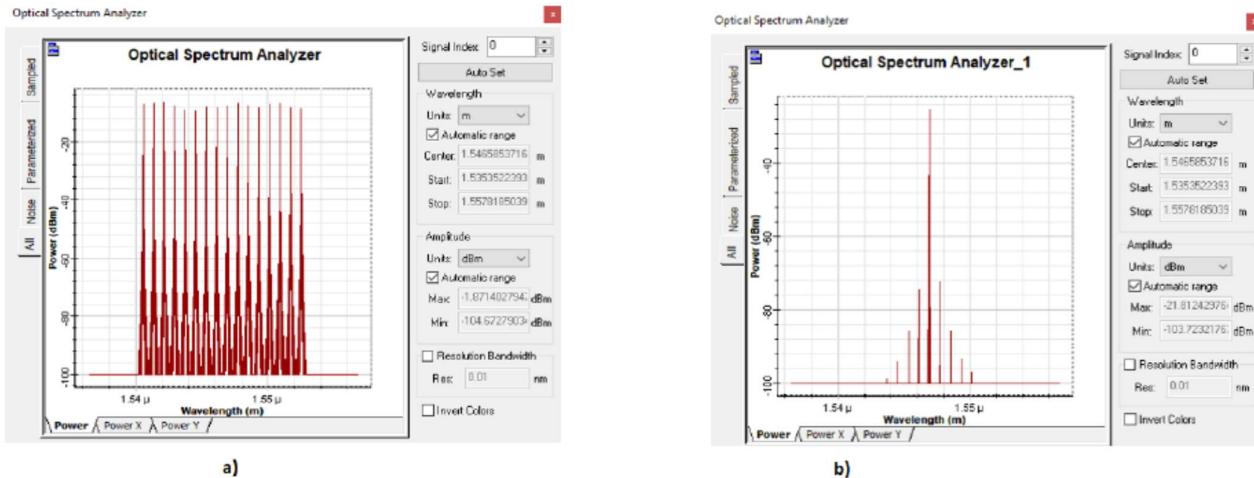


Figure 3. Results of 16-channel WDM spectral analysis simulation: a) transmitting side, b) receiving side filtered one channel

Optical power loss meters are set to measure the power at the output of the transmitter and at the output of the receiving filter. After completing the iterations of the simulation, the obtained attenuation of the light signal during its transmission through the WDM system amounts 22,068 dBm. The total attenuation for an optical fiber can be calculated as follows:

$$T = LxF + NxS + mxC \tag{1}$$

where:

- L [km] is total cable length;

- F [dB / km]. The specific attenuation of the fiber depends on the wavelength, and also depends on the temperature. The practical measured value of 0.18 dB / km was used in the paper;
- N. Number of connections (extensions) and pigtails of the optical cable;
- S [dB]. Attenuation at joints (extensions) and pigtails should be as small as possible, and at most 0.1 dB per joint;
- M. Number of connectors;
- C [dB]. A typical connector attenuation is 0.5 dB.

Thus, the calculation gives a total attenuation of the optical fiber of 21.52dB: for the measured values from Figure 3, it is necessary to add the attenuation of the optical multiplexer, then the attenuation introduced by the demultiplexer and the Bessel filter [11], [12] which gives approx. 28.5 dB total attenuation of the optical link. The obtained attenuation of the optical link when converted to dBm agrees well with the attenuations obtained by measurement on the simulator. Figure 4 shows the BER simulation results for the 16 channel WDM system. The BER parameters of the simulation results will be elaborated below. It is clear that it is possible to achieve transmission by a modeled system without 16-channel multiplexing amplifier. The transmission speed per channel is 2.5 Gbps.

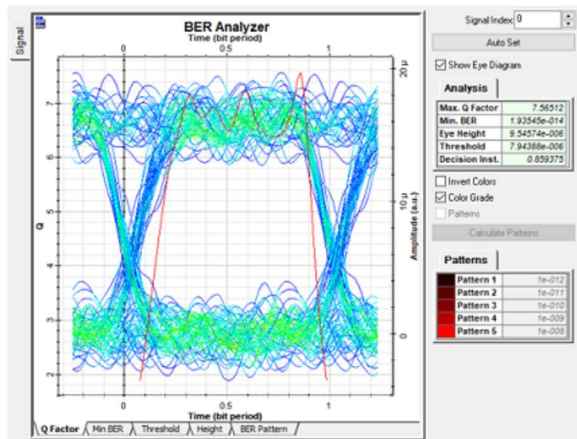


Figure 4. Simulation results 16 channel WDM system BER tester with eye diagram

3.4 WDM system with 4 channels

The 4-channel WDM system means speed of 10 Gbps per channel. In this way, with only 4 transmitters, the projected speed per optical fiber of 40 Gbps is achieved. Figure 5 shows a 4-channel WDM system. The lesser complexity of this system compared to the 16 channel system is clearly visible. The same components were used for the receiver as with the 16 channel system only with increased bit rates. The multiplexer is four-channel with the same channel width of 0.1 THz. The receiver also uses the same components as the 16 channel WDM system. Basically, the difference between a 16 channel 2.5 Gbps and a 4-channel system with 10 Gbps is in laser sources. Power loss measurements were also performed for this system.

Analysis of simulation results for measurements of light signal power losses during transmission by WDM system with 4 channels in three points:

- signal power at the output of Mach - Zender modulator,
- power before photodetector without amplifier and
- signal power before photodetector with built-in EDF amplifier in the middle of the fiber optic route, a conclusion was that is needed to install an EDF amplifier.

So, after the effect of signal attenuation on the transmission was noticed, an EDF amplifier was installed. Figure 6 shows the simulation results for the eye diagram, Q factor, and BER. It is very clear in the eye diagram how much EDF amplifier improved signal.

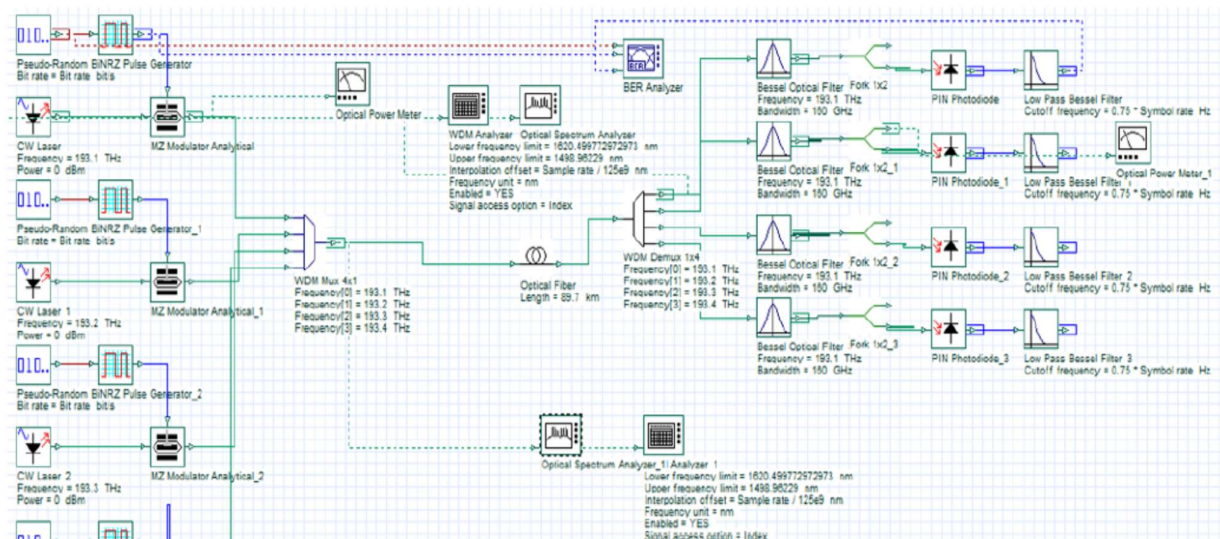


Figure 5. Model of 4 channel WDM system with review of measuring tools

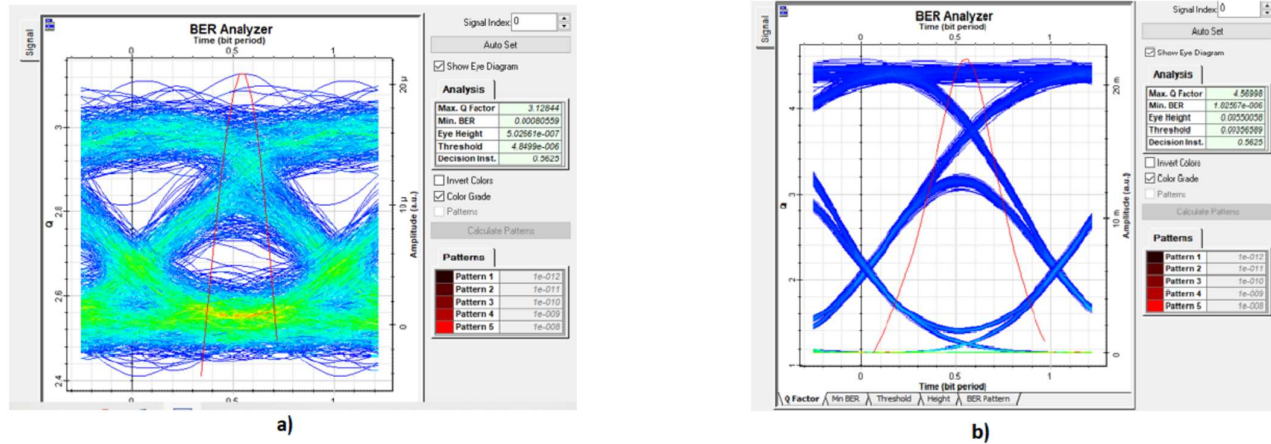


Figure 6. Result of WDM analysis with 4 channels BER simulation results: a) Eye diagram without EDFA and b) Eye diagram with EDFA (Erbium Doped Fiber Amplifier)

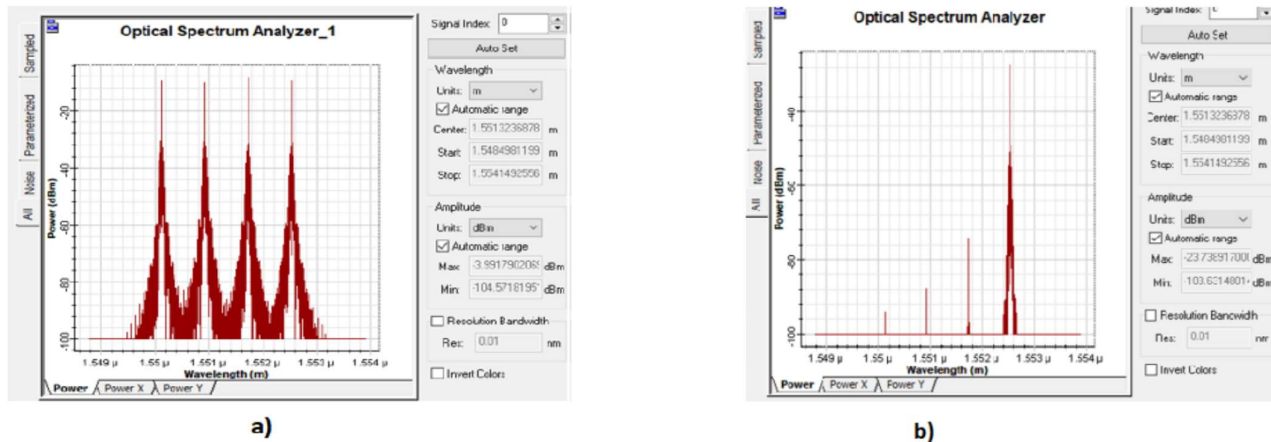


Figure 7. Result of WDM analysis with 4 channels spectrum appearance a) on transmitting and b) receiving side filtered only one channel

Figure 7 shows the measurement results of the simulation for spectral analysis of a four-channel WDM system. By comparing the power measurement results in WDM systems with and without EDF amplifiers, the effect of the amplifier on the optical signal power is visible. The EDF amplifier was used to compensate for the effect of signal attenuation, and the graphic of the eye diagram clearly shows the efficiency of this amplifier. The simulation results obtained by measuring the BER and the graphic of the eye diagram show the influence of dispersion and signal attenuation on the transmission. Therefore, in the second iteration, the simulation was done with an EDF amplifier connected in front of the demultiplexer.

3.5 BER and Q parameters in WDM systems

The two factors that limit the capacities and distances of transmission by optical TCN are the Q factor (Quality factor) and the BER factor. The Q factor is a

dimensionless positive quantity that describes the quality of the output signal. BER represents the number of reception errors in regard to the total number of transmitted bits. In order to correctly transmit the signal to the greatest possible distances, the smallest possible BER and larger Q factor are needed [13], [14]. BER can also be defined as the percentage of incorrectly transmitted bits in total number of transmitted bits. If BER is 10^{-6} for a total of 1,000,000 bits transmitted, it means that one bit is incorrectly transmitted. Increasing the transmission speed reduces the pulse duration. Increasing the transmission distance increases: the influence of dispersion, nonlinear effects of optical fiber, the influence of spontaneous emission, increases BER and decreases the Q factor [15]. For practical WDM TCN the allowed BER is of the order of 10^{-9} and less. The allowable Q factor values for WDM networks can be calculated mathematically and they are of the order of 6 and more [16].

The relation of Q factor and BER for WDM TCN has been analyzed in detail in the literature [16]. Analysis of the impact of increasing transmission rates, the number of channels in the WDM system, transmission distance, is given in the literature [17], [18]. Figure 8 presents the ratio of values for BER and Q parameters is given [16]. It is clear that the increase in input signal strength increases nonlinear factors so that there is greater degradation in the optical fiber. Therefore, on a real system with channel speeds of 10 Gbps, a classic regenerator was installed instead of an EDF amplifier, which solved dispersion, attenuation and nonlinear effects.

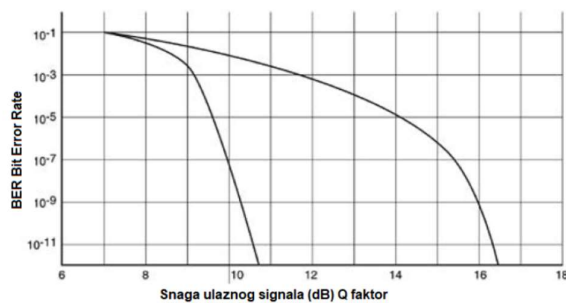


Figure 8. Relation of input signal and Q factor

4 Conclusion

Optical telecommunication networks due to their complexity have developed models and simulators for different aspects of analysis. The analysis can be conducted in order to improve the work of existing TCN, but also to develop new TCN. Various simulators have been developed for these purposes; non-commercial, which require more prior knowledge and commercial, which are easier and more accurate to use. The paper used a commercial widely accepted version of the Optisym simulator version 17. Using this simulator has shown that a WDM 4 channel system with channel speeds of 10 Gbps cannot be used on real existing 89.7 km long optical cable. Although it seems simpler, the simulation showed the parameters $Q = 3.12$ and $BER = 8 \cdot 10^{-4}$ without EDF amplifier, and $Q = 4.57$ and $BER = 1.8 \cdot 10^{-6}$ with EDF amplifier. The values obtained are below the allowed limits for a WDM system with a total baud-rate of the order of 40 Gbps. Simpler solution won't work in real condition. Simulation of different types of WDM systems on a real existing optical cable showed that it is financially much more cost-effective to use a system with a larger number of channels with a lower transmission speed. Systems with lower channel speeds use cheaper components and do not require additional dispersion control.

It is important to point out that the simulation was done on an existing ITU T G.655 optical fiber intended for

WDM systems whose parameters were practically measured. However, without additional amplification and dispersion control, it is not possible to transmit per wavelength at a transmission speed of the order of 10 Gbps at a distance of 89.7 km. In addition to dispersion control, it is necessary to use more expensive lasers, with special temperature conditions, which significantly increases the complexity of the system and its financial costs. A WDM system with 16 channels and channel speeds of the order of 2.5 Gbps looks more complex, but it actually meets the transmission criteria $Q = 7.56$ and $BER = 1.9 \cdot 10^{-14}$. In addition, this system uses more financially acceptable lasers that do not require additional temperature conditions, as well as additional dispersion management.

Competing Interest Declaration

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

No data or additional materials were utilized for the research described in the article.

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