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Simulation of bidirectional traffic in WDM-PON networks

Abstract. The paper is focused on the design and simulation of bidirectional WDM-PON networks using the OptSim v5.2 simulation software. First, this type of passive optical network is described. Then the possibilities of its simulation, especially simulation of bidirectional traffic, which is not commercially supported by this software, are also shown. Finally, an analysis of the transmission parameters is given.

*Streszczenie. W artykule opisano projekt i symulację dwukierunkowej sieci typu WDM-PON przy wykorzystaniu oprogramowania OptSim. Na wastępie opisano sieć pasywną a następnie przedstawiono symulację ruchu dwukierunkowego. Przedstawiono parametry transmisji. (**Symulacja ruchu dwukierunkowego w sieci typu WDM-PON**)*

Introduction

Conventional passive optical networks have been used for many years, since 1998, when the passive optical network APON (ATM Passive Optical Network) according to ITU-T (International Telecommunication Union) was standardized. The development of passive optical network standards continued with BPON (Broadband PON) [2], GPON (Gigabit PON) and XG-PON [4]. The rival standardization union IEEE (Institute of Electrical and Electronics Engineers) also developed a passive optical network in 2004, when the EPON (Ethernet PON) passive optical network, which were to be a direct competitor of GPON networks, was standardized [3]. These two types of optical access networks are now the most widely used. The newest standard of IEEE is 10GEPON, that of ITU-T is XGPON, which compared to previous generations allow 10 Gbit transmission and greater splitting ratios (up to 1:128, previously only 1:32) [1]. However, a disadvantage of conventional passive optical networks based on time multiplexing TDM (Time Division Multiplexing) is that end users share the bandwidth.

In recent years, the next generation of passive optical networks based on wavelength multiplexing WDM (Wavelength Division Multiplexing) began to be developed. This passive optical network is called WDM-PON (Wavelength Division Multiplexing PON). An advantage of this principle is that although users also share a single fiber, each user has their own channel. In the case of the conventional PON, the total transmission rate is divided among end users, while with the WDM-PON networks each wavelength channel has its own transmission rate. Nowadays, there are commercially available WDM-PON systems which allow 128 channels, where each channel data rate can be up to 10 Gbps [7]. However, due to the very high price of the newest 10 Gbps systems their introduction into practice is really slow. More often, 1 Gbps systems with 32 channels are used.

Any practical implementation of the optical network should be preceded by a design and subsequent simulation in the simulation software. With these sophisticated tools, it is possible to debug the behavior of the proposed system and thus save a lot of funds. The world's leading software used for the design and simulation of optical networks includes the optSim product of the American company RSoft Design and the optiSystem product of the Canadian company Optiwave.

This paper presents an example design of WDM-PON networks, the simulation and analysis of transmission parameters in the optSim v5.2 environment for bidirectional traffic, which is not supported by the RSoft Company.

WDM-PONs

WDM is based on the idea of associating several optical channels, which were previously required to be transmitted separately, each in a single fiber. On each of the carrier frequencies in the transmitters there is superimposed transmitted information. The multiplexer combines the contribution of all *n* channels into a single optical fiber. If we want to realize *n*-channel connection, we need to have in addition to one multiplexer and demultiplexer also *n* modulators, demodulators and light sources.

In WDM-PON networks, the dense wavelength division multiplexing is most commonly used. This technology is one of the most advanced systems that are used in optoelectronics. The distance between channels is only 0.8 nm or 0.4 nm, theoretically as little as 0.2 nm (ultra-DWDM) [5]. Consequently, it allows transferring tens of channels over one optical fiber. Optical fiber channels are transmitted in parallel and independent of one another. This increases the transmission capacity of optical links several times. The ITU-T G.694.1 standard specifies individual transmission channels in a wavelength range from 1490 nm (200.95 THz) to 1620 nm (186.00 THz), the S, C and L bands.
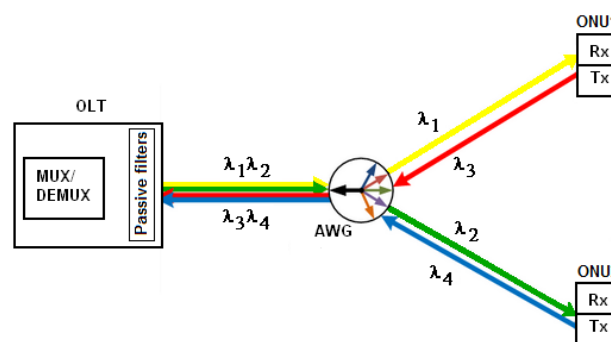

Fig. 1. Principle of WDM-PON network

Passive optical networks based on the classical time division are gradually approaching their maximum limit of bandwidth. That is why the next generation of optical access networks will certainly be based on the principle of wavelength multiplexing. In terms of physical network topology, the WDM-PON network is a passive topology (point-to-multipoint), because of using passive AWG (Arrayed Waveguide Grating) couplers. The logical topology, however, is point-to-point, because each end user has a dedicated transmission channel and does not have to share the bandwidth with others, as is the case in classical PON networks.

Types of WDM-PON

The first variant considers only a fixed wavelength assigned to all end ONUs (Optical Network Units), i.e. classic splitters will be used in the network and the downstream signal will propagate to all end users. ONU has a fixed filter that transmits only the given carrier wavelength. In the upstream, each ONU unit has its individual transmitter wavelength, which will transmit outgoing data streams. ONU units are also tuned to one common wavelength, which is used for the broadcast. The disadvantages of this implementation are similar to conventional PON networks; in the downstream it is necessary to prevent eavesdropping by various cryptographic methods. A fixed assignment of wavelengths makes the network inflexible in relation to changes, and transmission capacities are used uneconomically. Another disadvantage is that in the network there cannot be two ONUs communicating on the same wavelength. In this variant, DFB (Distributed Feedback) lasers are used [12].

The second variant uses instead of the common splitters directional splitters AWG. The difference with the previous option is obvious: in the downlink the coming signal is divided through AWG into individual wavelengths, whose carriers propagate to individual ONU units in separate channels. In the upstream, there is the same principle as in the first variant. Each ONU transmits data on its dedicated wavelength. The advantage of this variant is mainly the smaller insertion loss of AWG than that of conventional splitters [16]. This value is about 4 - 5 dB, regardless of the number of wavelengths. Another advantage stems from the removal of filters in ONU units, which means a reduction in the total attenuation. In this variant, too, DFB lasers are used [12].

A third possibility of WDM-PON implementation is based on the combination of AWG and conventional splitters or cascade sorting. This combination uses wavelength and time division multiplexing. Both multiplexes have their advantages and disadvantages. The time division multiplexing is not able to use the maximum bandwidth of the optical fiber. However, wavelength multiplexing is expensive. To achieve the best topology properties for the signal transmission, a combination of these multiplexing methods was developed [11]. This combination uses the separation of optical signals based on wavelength multiplexing (in AWGs) combined with time multiplexing. This topology is also called WDM/TDM PON or HPON (Hybrid PON) [1]. Using universal ONU units and optional wavelengths also allows channel allocation to units based on the current needs and requirements. This mechanism is known as DWA (Dynamic Wavelength Assignment) [1].
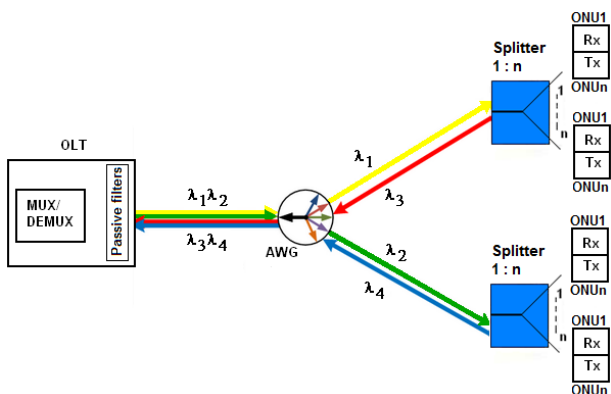

Fig. 2. WDM/TDM PON.

The fourth option is the implementation of WDM-PON, based again on the principle of AWG splitters: the difference is in the ONU units used. It uses the Fabry Perrot (FP) laser optically locked on the stimulation wavelength coming from AWG [5]. The incoming light beam passes through a filter, which separates the incoming direction of the signal, and continues to the receiving part of the ONU. Another part of the light beam passes through the filter farther to the FP laser. By locking the FP laser on the stimulation wavelength the spectrum of the FP laser, which was originally formed by periodic waves, is changed to a spectrum with a narrow spectral line, which makes it possible to use it as a laser transmitter for the WDM-PON system [12]. This principle is used, for example, in the WDM-PON system of the LG-Nortel Company.
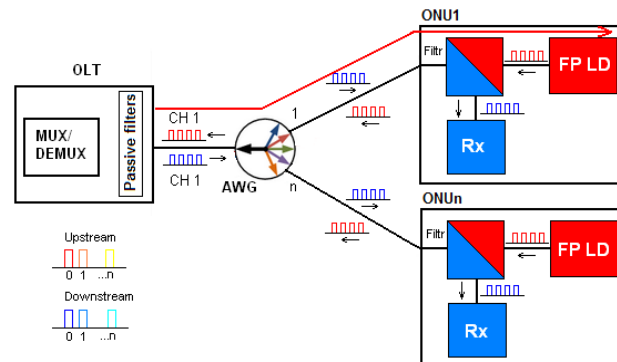

Fig. 3. WDM-PON system with Fabry-Perrot lasers [12].

In addition to these four types of WDM-PON systems many other kinds have been proposed and demonstrated. Recently, several schemes based on SOAs (Semiconductor Optical Amplifiers) have been proposed because they can reuse the downstream signal received at the ONU for the transmission of upstream signal [14]. In [6] the bidirectional FTTH (Fiber To The Home) WDM-PON system was proposed. In this system a WDM transmitter is used as a seeding source at a wavelength of 1550 nm. The system is based on the traveling semiconductor optical amplifier (TSOA). Thanks to TSOA, a distance of 50 km was achieved for both downstream and upstream channels with a bitrate of 10 Gbps and 64 ONUs.

In [9] the WDM-PON architecture using a cyclic AWG and a reflective filter was proposed. This system uses a single optical laser to generate both the downstream and the upstream wavelength channels. It was demonstrated for 32 DWDM channels and error-free symmetric 10 Gbps data transmission over 20 km of single-mode fiber.

One of the goals of WDM-PON research is also focused on extending a long-reach PON (more than 20 km). In [8] a long-reach WDM-PON was proposed. This scheme provides conventional point-to-point (P2P) connection and simultaneously a broadcasting service by superimposing for each WDM channel. The differential phase shift keying (DPSK) modulation was used for broadcasting while the subcarrier multiplexing (SCM) modulation was used for the P2P downstream signal. Both modulations were provided by the OLT unit. The ONUs were realized as colorless for upstream data transmission by re-modulating a part of the downstream signal with a Reflective Semiconductor Optical Amplifier (RSOA). This proposed long-reach system allows bidirectional transmission through a 60 km long optical distribution network with a bitrate of 5 Gbps [8].

Nowadays the most widely used WDM-PON real systems have a 1 Gbps bitrate with a maximum of 32 ONUs. That is why we very often need to simulate these types of WDM-PONs. There are only two specialized simulation environments - optSim and optiSystem. OptiSystem is more sophisticated than optSim for the simulation of Optical Access Networks (OAN), because it

allows the simulation of bidirectional traffic. On the other hand, optSim is better-suited for simulations of nonlinearities. Both simulation environments are very expensive. This paper could help the users of optSim, who want to simulate bidirectional WDM-PON.

OptSim

OptSim is an advanced software optical simulation package designed for professional engineering and advanced research into optical networks at the physical layer. It can be used to design optical communication systems and simulate their performance. OptSim is designed for modeling, with easy-to-use Windows and Linux platforms. This package includes advanced components and algorithms. The simulation results are close to real conditions. OptSim is a software simulation package composed of a set of interconnected blocks. Each block represents a part of the system. Physical signals are passed between the components as in a real communication system. Each block is simulated separately, using the parameters specified by the user for this block, and the signal information is transferred from it to the other blocks. The blocks are graphically represented as icons. Internally, they are represented as data structures and numerical algorithms. OptSim contains an extensive library. The models of components are under continuous development due to ongoing research and cooperation with specialists.

System description and simulation

The simulations were performed in the optSim version 5.2 environment according to a proposed topology (see Fig. 4). The topology was divided into three parts: OLT (Optical Line Terminal), distribution parts before the AWG, distribution parts after AWG (they were divided into blocks with the same distance from AWG). Since the optSim simulation environment is unable to set bidirectional traffic, a loopback "Loop" was created whose transmitting power is set according to the respective ONU units. The simulated topology consists of three independent branches. Due to such extensive simulations, we focused only on one branch. In the simulations we considered athermal cyclic (colorless) AAWGs (Athermal Arrayed Waveguide Grating). All optical components are temperature-dependent (wavelength depends on temperature) [10], but we do not consider it in this simulation.
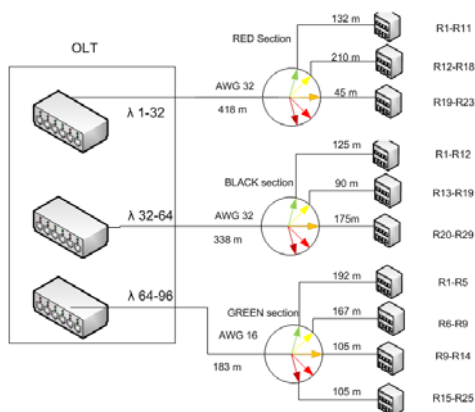

Fig. 4. Block scheme of proposed WDM-PON

Transmitter / receiver - OLT

The transmitting part of the unit consists of lasers for 32 wavelengths with a power level of 5.5 dBm. An optical spectrum analyzer and power meter are also connected to the unit. The receiving part of the unit consists of a loopback which is used to receive the reverse direction.

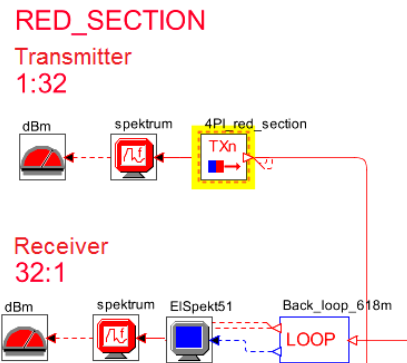An electrical spectrum analyzer is also connected to the unit.

Fig. 5. Transmitting / receiving part OLT

Distribution part after AWG

This part is divided into the two parts – before of the AWG, where the fiber is inserted (set according to ITU G.652.D) from the OLT and AWG coupler. The power meter and optical spectral analyzer are inserted after the AWG. There is also a "virtual splitter", which is transparent for the simulation and is used for loopback.
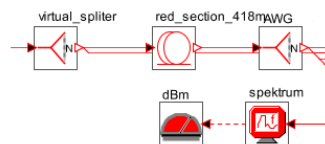

Fig. 6. Distribution part before the AWG

Distribution part after AWG

The distribution part after AWG consists of blocks of terminal stations connected to the fibers with similar distances from the AWG. On the terminal units, optical intensity, spectral analysis, and electrical parameters (eye diagram, bit error rate - BER) are measured.
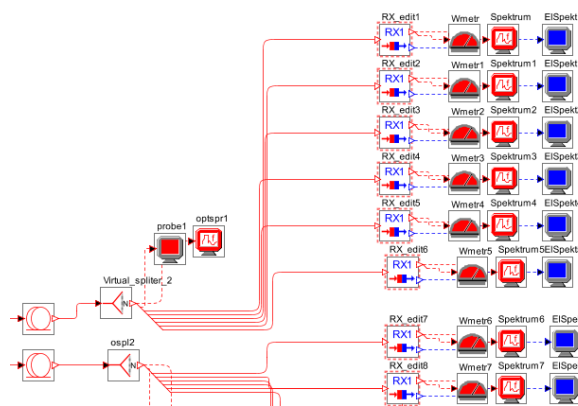

Fig. 7. Distribution part after AWG + ONUs

The parameters of the link were set as follows:
- Transmitting power of the OLT   5.5 dBm
- Transmitting power of the ONU   - 8 dBm
- Attenuation of AWG   4 dB
- Type of AWG   Cyclic
- Fiber   G.652.D
- Receiver sensitivity   -21 dBm
- Length   288 – 65000 m
- Downstream pilot frequency   190.5 THz
- Upstream pilot frequency   195.5 THz
- Frequency grid   100 GHz
- Bitrate   10 Gbps
- Modulation NRZ (Non Return to Zero)

Loopback for upstream transmission

A major disadvantage of the optSim simulation environment compared to the rival tool optiSystem is the absence of bidirectional transmission. For this reason, a feedback loop was created which is used for the simulation of upstream direction.

The internal structure is shown in Fig. 8. On the input, there is an optical signal of downstream direction to enable measuring both directions of transmission with a spectrum analyzer (Fig. 14). The block TXn is the transmitter for 32 wavelengths in the C band. This signal also passes through an optical fiber of the same length as the downstream direction. Both signals are then combined and routed to the receiver.
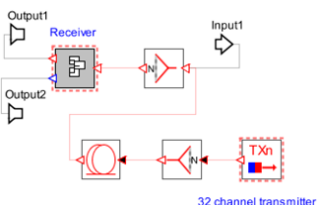

Fig. 8. Internal structure of loopback

Simulation results and discussion

We can divide the simulations into two parts – simulation of downstream (OLT→ONU) and upstream (ONU→OLT) direction. In the simulations it is possible to measure power levels at each point, optical and electrical spectrum, eye diagram, etc.

Simulation of downstream traffic

Fig. 9 shows a simplified topology between the OLT and the ONU and the points of measuring and comparing the parameters. The simulation does not consider the attenuation of splices and connectors.
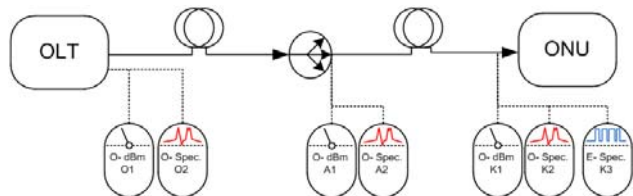

Fig. 9. Localization of measuring points

Table 1. Measured values dependent on length

Length	λ	Power (O1)	Power A1	Power (K1)	BER (K3)	Q (K3)
[m]	[nm]	[dBm]	[dBm]	[dBm]	[-]	[-]
Measured values for proposed topology						
288	1582.0	4.89	-1.00	0.38	1×10^{-40}	24.20
349	1594.0	4.91	0.90	-1.66	1×10^{-40}	21.10
356	1575.0	3.60	-0.58	-1.12	1×10^{-40}	22.40
503	1578.0	4.91	1.00	-0.83	1×10^{-40}	21.60
560	1582.5	5.29	1.21	0.45	1×10^{-40}	25.79
628	1584.5	4.62	0.97	-1.08	1×10^{-40}	21.70
1227	1593.0	5.90	1.02	-1.20	1×10^{-40}	19.04
2775	1560.0	5.281	1.63	-1.52	1×10^{-40}	19.64
Measured values for more lengths						
3000	1572.0	5.08	-2.00	-1.15	1.00×10^{-40}	47.60
9000	1570.0	5.20	-2.03	-2.84	1.00×10^{-40}	14.60
18000	1560.0	4.62	-2.13	-5.26	1.00×10^{-40}	14.03
25000	1574.0	5.08	-1.93	-5.79	1.37×10^{-19}	9.08
50000	1584.5	4.82	-1.99	-7.18	4.80×10^{-6}	5.07
65000	1574.5	5.00	-2.01	-12.12	2.20×10^{-2}	2.00

Table 1 shows the values measured in simulations and relates them to the measuring points from Fig. 9. The table is divided into two parts. The first part is designed for the simulation of the proposed topology. In the second part, there are the route lengths used to determine the maximum theoretical distance of the WDM-PON technology.

The values of the first part show that the power level is very changeable. This is caused by the set fiber parameters such as non-linear effects and wavelength. The simulation also includes the effects of electrical and optical noise. The bit error rate (BER) calculated for such a short distance is 10^{-40}, the simulation program cannot calculate the BER at such a short distance and the error rate is idealized. The value of BER should not fall below 10^{-9} for passive optical networks [13].

Fig. 10 shows the spectrum of 32 channels transmitted by the OLT unit in the L band.
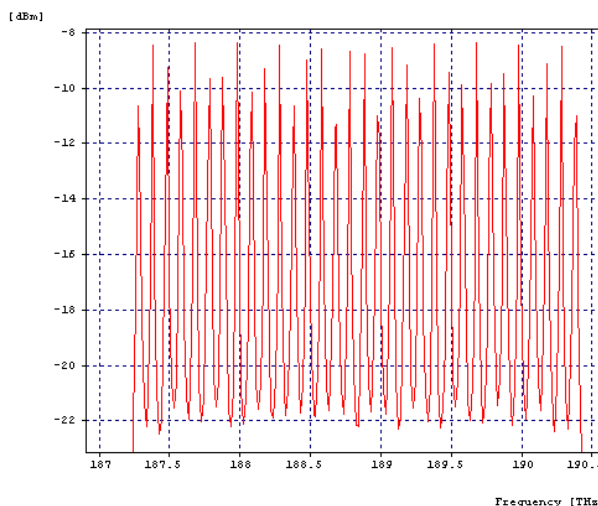

Fig. 10. Spectral analysis of downstream by the OLT unit.

Fig. 11 shows the output of a spectrum analyzer at the ONU unit, i.e. a separate channel.
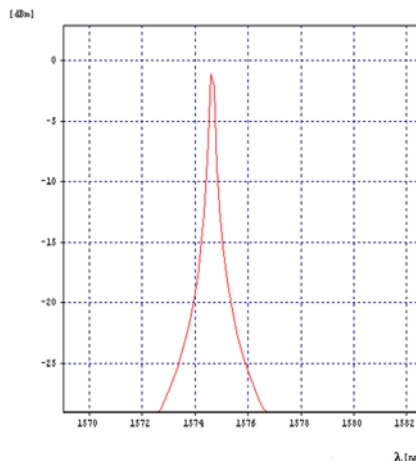

Fig. 11. Optical spectrum in a singel channel

Eye diagram and Q-factor for individual distances

From theoretical assumptions it is clear that with increasing line distance the quality will decline. From the perspective of the ONU unit, the power level must not fall below the usual level, i.e. -21 dBm (maximum sensitivity of the ONUs). This value is dependent on various factors such as fiber length, radius of fiber bend, damaged fiber, dispersion, purity of connectors, etc. To find this quality easily, we used the eye diagram and the Q-factor. The simulation software runs this measurement and

visualization after the conversion of the optical signal to an electrical signal.

The Q-factor gives us an analog quality of the digital signal with respect to the signal-to-noise ratio. The value of the Q-factor is higher, if the BER is lower. It is given by equation (1) [15]:

$$(1) \qquad Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} [-],$$

where: I_1 - logic level "1", I_0 - logic level "0", σ_1 - standard deviation of the logic level "1", σ_2 - standard deviation of the logic level "0" [15].

Bit error rate is defined as the ratio of incorrectly received bits to the total number of bits received over time. The bit error rate is the main indicator of the overall quality of the optical system. The calculation of the bit error rate from the knowledge of the Q-factor is expressed by equation (2) [15]:

$$(2) \qquad BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp\left(\frac{-Q^2}{2}\right)}{Q\sqrt{2\pi}} [-],$$

For distances of less than 3 km, the eye diagram was smooth with no signs of degradation, so we focused on the simulation of longer distances. The eye diagram for a distance of 3 km is shown in Fig. 12. The BER is still undetectable (less than 1×10^{-40}) and the value of the Q-factor is 47.6.
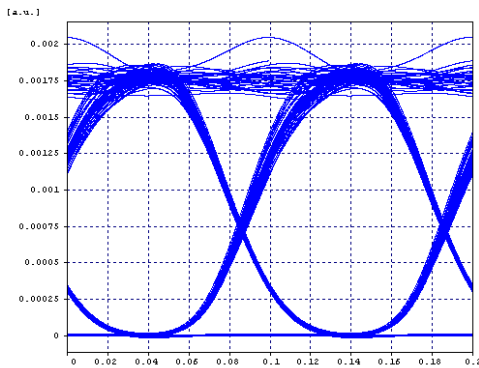

Fig. 12. Eye diagram for 3 km distance

For a distance of 18 km, the BER is still undetectable; the value of the Q-factor is the same as in the previous case. The difference for distances of 3 and 18 km is minimal; the eye diagram is only slightly worse. In the case of increasing distance up to 25 km, there is a perceptible change (see Table 1). The BER has reached values of 1.37×10^{-19} and the Q-factor is 9.08.
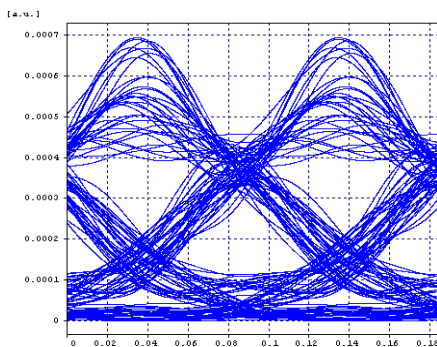

Fig. 13. Eye diagram for 50 km distance

In practice, these values can be considered to be real. If the distance is 50 km, the eye closure is noticeable, the BER reaches a value of 4.8×10^{-6} and the Q-factor is 5.07. The value of BER is very high, but the network should still be able to work (the network will be able to work, but with a higher packet loss, jitter and latency) [13].

At distances greater than 60 km, there is a total closure of the eye and such a network is not able to work. The main problem of this long distance is the chromatic dispersion (CD). The maximum value of the total chromatic dispersion with a bitrate of 10 Gbps is 1000 ps/nm [2]. If the length is 60 km and the CD coefficient is 17 ps/(nm·km), the total chromatic dispersion will be 17x60 = 1020 ps/nm [2]. For such a long distance it is necessary to compensate the chromatic dispersion. We do not consider the compensation of CD in this simulation. We wanted to find the maximum transmission parameters without any compensation. A commercially available WDM-PON network allows a maximum distance of 20 km and 128 channels with a bitrate of 10 Gbps [7]. Theoretically, it is possible to use optical amplifiers and extend the reach up to 80 km [7].

Bit error rate and Q-factor are parameters that also affect attenuation, noise and nonlinear effects. WDM systems are generally known to have a significantly lower BER and a higher Q-factor compared with TDM-PON.

Simulation of upstream traffic

Simulation in this direction is quite difficult, as was already mentioned. The upstream direction was created as a new transmitter with a power of -8 dBm and 32 channels. The optical signal from this WDM transmitter was summed through the "virtual splitter" with the signal from the OLT.

Fig. 14 shows the spectral analysis of bidirectional traffic. It is possible to see here 32 channels transmitted by the ONUs in the C band and 32 channels transmitted by the OLT unit in the L band. We can clearly compare the difference in power levels between OLT and ONU unit.
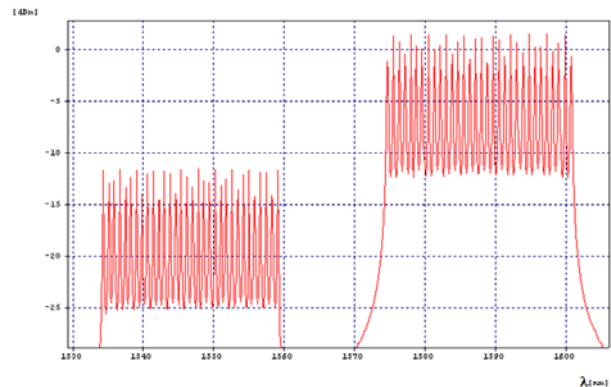

Fig. 14. Spectral analysis of bidirectional traffic.
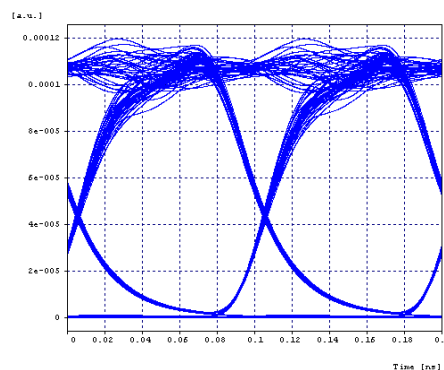
Eye diagram and Q-factor

Fig. 15. Eye diagram for 1227 m distance in the upstream

The situation is very similar to downstream with fiber lengths ≤ 18 km. The value of BER is 1×10^{-40} and the Q-factor is 30. These values are for a fiber length of 1227 m.

Conclusion

The aim of this paper is to describe the technology of a passive optical network based on wavelength division multiplexing WDM-PON and the simulation of bidirectional traffic in optSim version 5.2. In practice today we can mostly come across conventional passive optical networks that use time-division multiplexing. However, it is only a matter of time before the networks start to be insufficient in terms of bandwidth. That will be the moment when we will need to reach for the next-generation technology, known as the next-generation PON. As a promising and commercially available option there is WDM-PON.

Before any building of optical networks, it is necessary to pay attention to their design. Ideally, the design is based on outputs of the simulation software. This allows us to analyze the transmission parameters before actually building the network and reveal any deficiencies.

In this paper we focused on the simulation of WDM-PON network in the optSim environment. A topology for 96 terminal stations was proposed. The disadvantage of this simulation software is the absence of the tools for bi-directional transmission, which is very important for networks based on wavelength division multiplexing. A loopback was therefore created which makes up for this lack. Thus, it was possible to analyze the transmission parameters in bidirectional traffic.

In the analysis, we focused on the spectrum of sub-channels, their power levels and bit error rate. Thanks to simulation, we could assess, for example, the effect of increasing distance between the OLT and ONU unit on individual parameters and the connection between them.

Results of the analysis give us information about the maximal transmission parameters in WDM-PON networks based on the classical principle with fixed wavelengths. The maximum safety distance usually specified by the manufacturer of WDM-PON systems is about 20 km. Simulation confirmed that the BER for a distance of 25 km is 1.37×10^{-19}. The maximum BER value for passive optical networks is 10^{-9} [13]. Theoretically, the maximum length of a distribution network could by greater than 25 km, but we have to consider the attenuation of optical connectors, splices, etc.

Acknowledgments

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