Universidade de Aveiro
2012

Departamento de Electrónica, Telecomunicações e Informática

TOMASZ WICHROWSKI

Estudo de redes óticas de acesso de alcance estendido

Study of extended reach passive optical networks

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Badania nad zwiększeniem zasięgu pasywnych sieci optycznych.

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e Telecomunicações, realizada sob a orientação científica do Dr António Teixeira e do Dr Mário Lima, ambos do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro e do Instituto de Telecomunicações – Aveiro.

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Dissertation submitted to the University of Aveiro as part of its Master's in Electronics and Telecommunications Engineering Degree. The work was carried out under the scientific supervision of Dr António Teixeira and Dr Mário Lima, both from the Department of Eletronics, Telecommunications and Informatics from the University of Aveiro and the Instituto de Telecomunicações – Aveiro.

Mr. Tomasz Wichrowski is a registered student of Lodz University of Technology, Lodz, Poland and carried out his work at University of Aveiro under a joint Campus Europae program agreement. The work was followed by Professor Marcin Janicki at Lodz University of Technology as the local Campus Europae Coordinator.

o júri

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agradecimentos

Este trabalho foi para mim uma experiência de vida muito desafiadora e interessante. Á medida que fui realizando o trabalho, encontrei diversas dificuldades, contudo, com a cooperação de certas pessoas fui capaz de atingir o objectivo final. A elas, agradeço todo o apoio prestado, nomeadamente ao Prof. Mário José Neves de Lima e ao Prof. António José Luís Teixeira, assim como á Universidade de Aveiro, pela oportunidade de expandir o meu conhecimento, adquirir novas experiências e pelo acesso ao laboratório e equipamento de testes necessário para o projeto. Gostaria também, de reconhecer o apoio que me foi dado pelo Prof. Carlos Alberto da Costa Bastos e o Dr. Marcin Janicki.

This work was for me a very interesting and challenging life experience. During the realization encountered several difficulties, however, in cooperation with a few people I was able to achieve the ultimate goal. I address my sincere thanks to them. For the guidance and cooperation in this project, as well as an invaluable support for Prof. António Luís Jesus Teixeira and Prof. Mário José Neves de Lima. Additional thanks go to the University of Aveiro educational facility for the opportunity to expand my knowledge, gather new experiences and access to laboratory and test equipment required for the project. I would also like to acknowledge the help and care that they provided to me by Prof. Carlos Alberto da Costa Bastos and Dr Marcin Janicki.

palavras-chave

Extrnder box, Gigabit Pasive Optical Network (GPON),Semiconductor Optical Amplifier (SOA), Long-reach Passive Optical Networks.

resumo

Este documento mostra a pesquisa no desenvolvimento de uma rede óptica GPON, utilizando uma caixa extensora. Começa com uma introdução aos amplificadores ópticos e as suas aplicações prácticas, introduzindo de seguida o leitor, á estrutura da rede GPON/XGPON. A parte práctica consiste em dois estágios: o primeiro que compreende a simulação destas redes, e o segundo, a parte experimental, em que se confirmam os resultados da simulação.

keywords

Extrnder box, Gigabit Pasive Optical Network (GPON),Semiconductor Optical Amplifier (SOA), Long-reach Passive Optical Networks.

abstract

This document presents research on the development of GPON optical network, using an extender box. It consists of an introduction of optical amplifiers on their functions and activities. Then introduces the reader to the network structure, GPON and XGPON. The practical part consists on two stages, the simulation of these networks, and the experimental part following the simulation results.

słowa kluczowe

Półprzewodnikowy wzmacniacz optyczny, gigabitowe pasywne sieci optyczne, sieci optyczne o zwiększonym zasięgu, extender box.

streszczenie

Niniejsza rozprawa przedstawia badania dotyczące rozwoju sieci optycznej wykorzystujących wzmacniacze typu Extender Box. Zawiera on opis działania i zastosowania wzmacniaczy optycznych. Następnie omawia strukturę i organizację sieci optycznych. Część praktyczna prezentuje wyniki symulacji i pomiarów.

Contents

1. Introduction

1.1. Context

Over the past few years the development of electronic services increased. This was due to increased accessibility to public services. There was a change in lifestyle and use of the internet, it is not only a global library of data and programs, but also became the primary communicator, one of the points of everyday existence. Increased availability through public networks, miniaturization and mobility of computers also resulted in the development of networks. All these factors have forced optical networks to increase performance. To ensure adequate signal quality and throughput you need to apply optical transmission medium.
Nowadays it means to have a link 6-10 Mbps. It can be assumed that at the time spread of 3D television, new services and high-speed internet you need to bring about a single user bandwidth of 1 Gbps, and it may already be in the next decade. From the viewpoint of fiber optics to provide such bandwidth is not a problem, as shown by the results of work carried out in major global projects. Also, standards organizations are working on standards and recommendations for next-generation access networks, shown at figure 3, which is reflected both in the development of standard 10G-EPON (IEEE) and the recommendations 10GPON (ITU) (GPON Market Review; Competitive Models in GPON: Initial Phase , 2009). The expected direction of further development of access networks is the gradual implementation of WDM-PON network, to have in the subscriber all the advantages of spectral multiplexing of channels and, consequently, provide unlimited bandwidth subscription.

Development of new generation optical networks is constrained by the demand of subscribers, described by figure 2. It also requires the development of new network elements and systems. Increased channel capacity, high traffic will force the development of new signal amplifiers, splitters and receivers. All these activities are aimed at ensuring adequate signal quality, speed of work for each user.

GPON data distribution network is an introduction to a new kind of systems that allow high performance operation, together with relatively low growth in power consumption. Differences that exist between the new and previous-generation systems is to use the entire length of the fiber, fig.1. This means faster service to your subscription and to improve the quality of transmitted data. The second major difference the structural PON systems is that it does not require an individual port to the consignee, as in the case of PTP systems. PON, however, requires more power for operating the port. It gives the possibility to split the signal between the recipients so that it is divided among a greater number of them 32 or 64. (GPON Market Review; Competitive Models in GPON: Initial Phase , 2009)

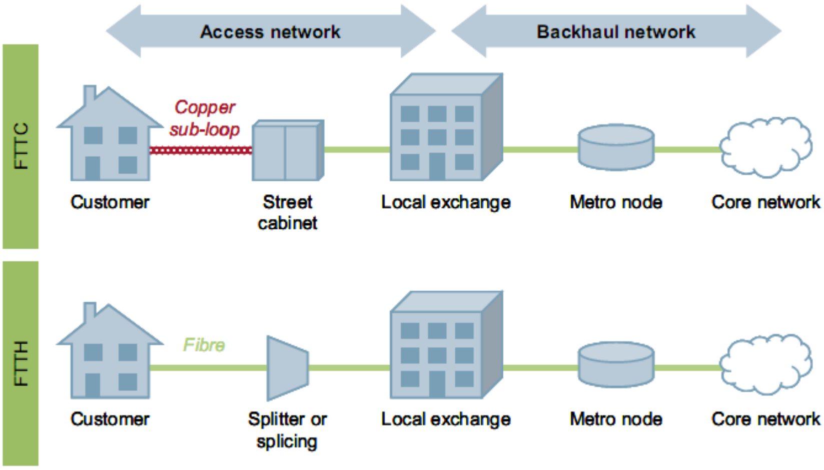

Figure 1. FTTx architectures. (GPON Market Review; Competitive Models in GPON: Initial Phase , 2009)

Current solutions allow you to download up to 10Gbps data and send up to 2,5 Gbps. Limitations to this type of system has a small distribution area 20km and a moderate number of users, 64. Research conducted by many research centers improve the operation of this network. The next generation of fiber optic systems for public use and economic are tested, such as XGPON. It is a natural development of technology in response to customers demand, and development services.

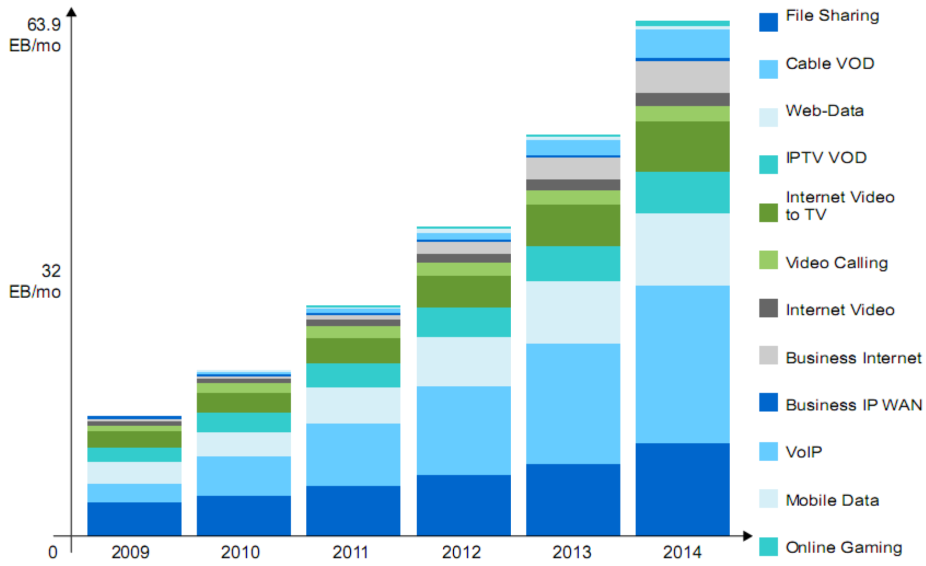

Figure 2. Global Internet Protocol Traffic, 2009–2014. (Altera, 2012)

An example might be 10GPON increased bandwidth and four times the distance to 60km with an increase to 128 users (Altera, 2012). Systems for next-generation PON require the modernization of existing centers, broadcast stations and receivers. This involves a lot of costs to be incurred by the operator and the user indirectly. Therefore, projects are being developed which aim to introduce transitional arrangements so that the process of change was the mildest of all, both users and suppliers.

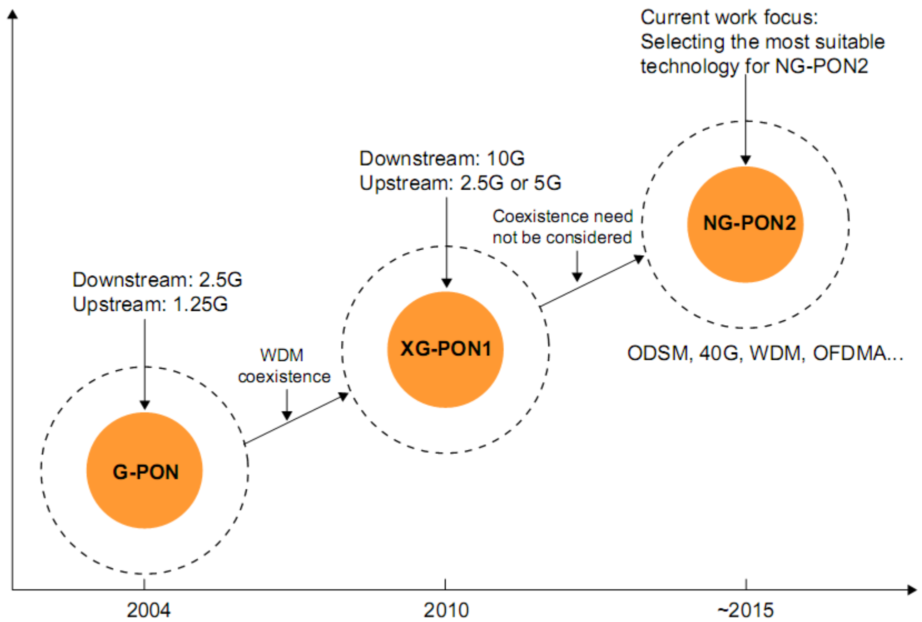

Figure 3. Technology developmente of PON , NG-PON roadmap by FSAN. (HUAWEI TECHNOLOGIES CO., LTD., 2010)

One of these methods is the introduction of a signal amplifier in the signal path fig.4, this element is called the extender box. It will allow temporary satisfy market needs, while not requiring considerable funding.

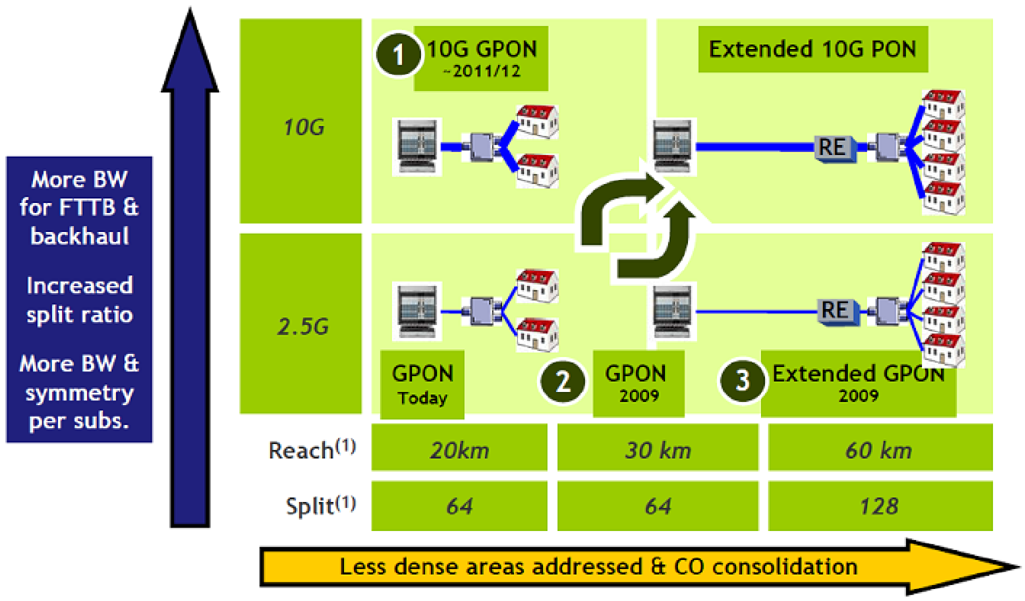

Figure 4. Evolution of GPON systems. (GPON Market Review; Competitive Models in GPON: Initial Phase , 2009)

1.2 Objectives

Modern solutions to ensure high-speed links are widely implemented in developed countries and developing countries, it is certain that these systems over time will replace the current solution.

In this work we refer to the use of extender box for GPON networks to increase its capabilities. This is a temporary solution, it will extend optical network for new users, until the installation of a new network in order not to overload the system. However, research plays a large role in the development of fiber networks. The research work and the characteristics of the Extender Box will surely rise to discussion in the future where the fiber network will designate the next standard speed.

- Study of semiconductor optical amplifiers (SOA)
- Analysis of PON standards (GPON, XGPON)
- Reach extension in GPON
- Develop guidelines for the use of extender box

1.3 Structure

In the document, we can distinguish six main chapters:

- Introduction
- Characteristics of the amplifiers
- Principle of GPON network
- Characteristics of the extender box
- Experimental work
- Conclusions and recommendations for future work

In the second chapter we present optical amplifiers and their principle of operation. This section is primarily based on the theory associated with these issues. The behavior of amplifiers is described due to changes in their parameters, and the main objective is to find the optimal values for the best performance. In addition, simulations were performed to confirm the theory.

In the next section we describe GPON and XGPON systems, in which placed an extender box. Chapter also contains a description of the network and its parameters and the corresponding simulations are carried out to help us understand the key components, and allow us to check all the possibilities of extender box application.

The fourth chapter familiarizes us with the extender box. In this section simulations are carried out to find the best options for the performance of our element. This is directly combined to another chapter, in which laboratory tests are performed, and present the practical operation of the system.

The fifth chapter is devoted to laboratory work that has been carried out. In the introduction, this chapter discusses the parameters of the network on which we worked (GPON). Then, we proceed to the main purpose of this work that is the study of extender box behavior. We experimentally evaluate and confirm the results of earlier simulations.

The final chapter presents the conclusions of this thesis and some future work than can be done.

1.4 Contributions

The main contributions of this work are:

- Familiarize with the operation of semiconductor optical amplifiers and the main parameters;

- Description of operation of Passive Optical Networks, and standards associated (GPON and XGPON);

- Description of operation and use of extender box to increase the network reach of GPON;

- The analysis of simulation results of various Passive Optical Networks network systems, and compare the performance of GPON, XGPON, using extender box;

- Comparison of simulation results with the real GPON scenarios .

2. Semiconductor Optical Amplifier

2.1. Structure

The role of optical amplifiers in fiber optic systems is to amplify the signal power. Amplifiers may be placed in different sites in the network, acting as receiver preamplifiers, power amplifiers for a long stretch of the network, the booster amplifier before splitter, or it can also be arranged linearly along the signal path – in-line amplifier. Figure 5, below shows the location of the amplifier.

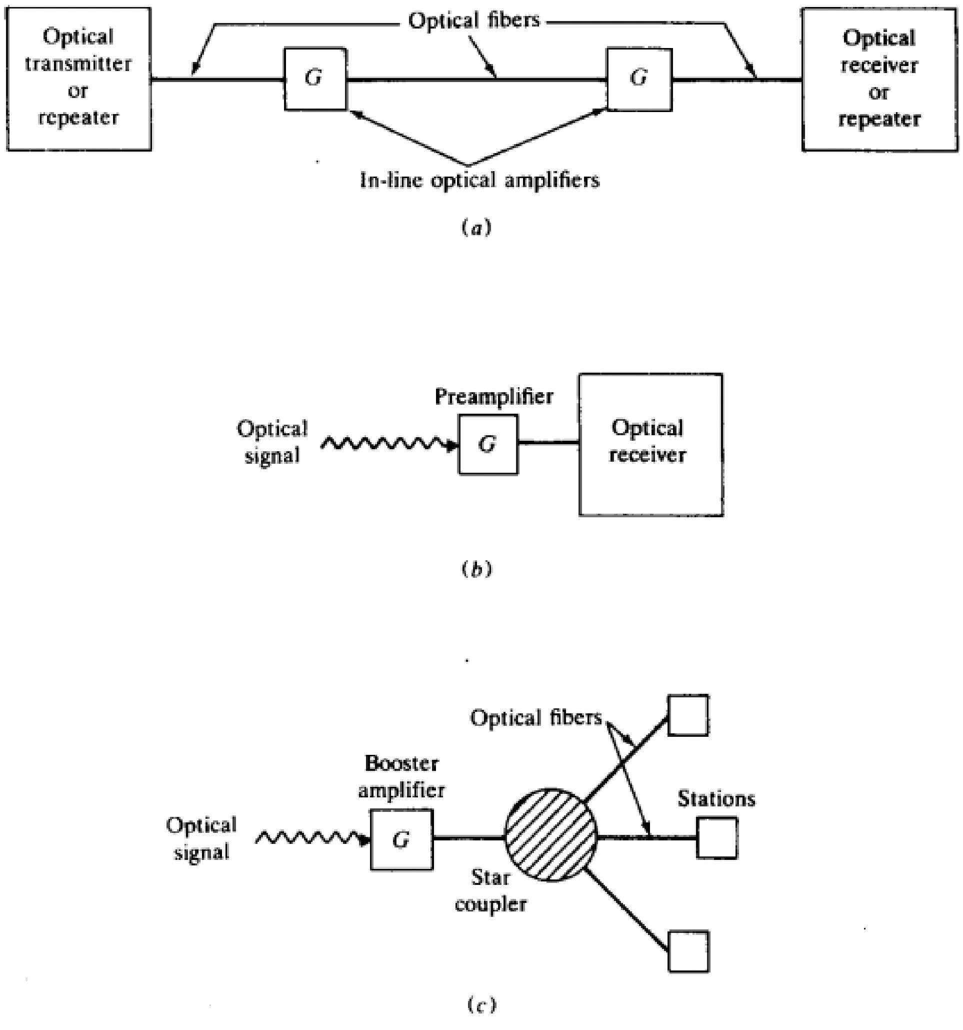

Figure 5. Basic applications of optical amplifiers: (a) amplifier to increase repeater spacing, (b) preamplifier to improve receiver sensitivity, (c) LAN booster amplifier. (Keiser, 1991)

Use as a booster amplifier is connected with placing it just behind the transmitter. This leads to an immediate signal amplification and can increase transmission distance. Depending on the gain and loss in the fiber is the distance can be varied from 10 - 100 km. The use of booster with the preamplifier located at the other end of the fiber allows for an even greater distances of 200-250 km. A booster amplifier can also be used in front of a star coupler. Thus provide compensation signal loss caused by coupler-insertion loss and splitting loss.

Preamplifier is used as a front end amplifier. Its application allows you to strengthen a weak signal before the photodetector. Then, the signal to noise ratio degradation caused by thermal noise in the receiver electronics can be suppressed. Optical preamplifier Provide a large gain factor and a broader bandwidth.

In single mode link effect of the fiber dispersion may be small, but more significant is the attenuation in the fiber. For this purpose are used the in-line amplifier, which enhance the signal and increase the distance signal propagation. They are used on a long line fiber to ensure adequate signal strength and coverage. (Optical fibers,cables and systems, 2009)

Semiconductor optical amplifier, shown at figure 6 and 8, is an active element of a fiber optic network. The principle of operation is similar to the transmitting diode, which is based on a semiconductor gain medium. The optical system, in transmitting diode, typically consists of two mirrors reflecting at least one of which is partially transmissive, these components constitute the resonator frequency for the selected wavelength and a particular direction of motion. System causes the emission of photons for which it is the resonator, which often penetrating active area causing further emissions of photons. The difference that exists is change reflecting mirrors on the anti-reflection coatings (Paschotta, 2012). The input signal is amplified by using an electric current as pump. The injection current creates a certain carrier density in the conduction band, allowing optical transitions from the conduction band to the valence band. The amplifier output signal is amplified and transmitted to the output fiber. Transmission in the fiber takes place in certain wavelength ranges, called optical or transmission windows. The transmission windows refer to the wavelength regions that offer low optical attenuation. Amplifiers of this type operate mainly in the second and third optical window for the 1310nm and 1550nm (Keiser, 1991) (Fiber-Optics.Info, 2012) (Paschotta, 2012).

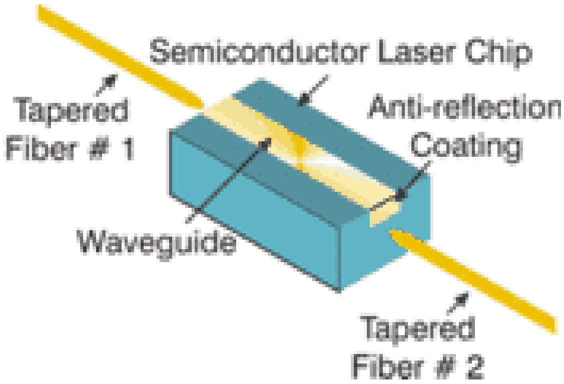

Figure 6. Typical SOA construction. (Fiber-Optics.Info, 2012)

2.2. Types of semiconductor optical amplifiers.

There are two types of SOA amplifiers. The first one is the amplifier operating on the principle of Fabry-Perot, resonant amplifier (FPA), the other a non-resonant, traveling wave amplifier (TWA). FPA and TWA are presented at figure 7,9.

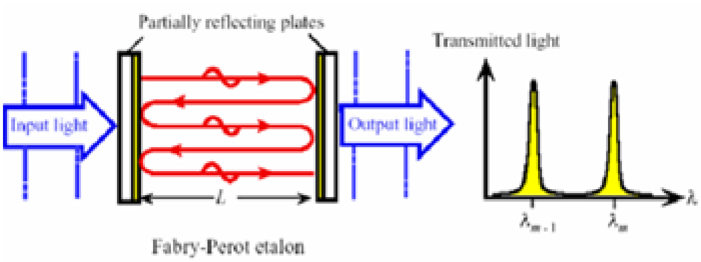

Figure 7. Transmitted light through a Fabry-Perot optical cavity.

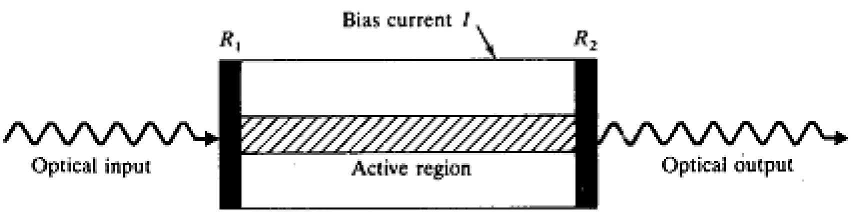

Figure 8. Schematic diagram of a typical semiconductor laser amplifier. (Keiser, 1991)

Amplification factor is obtained by the standard theory of FP interferometers. The principle of operation is to reinforce the input signal, by using the two highly reflective mirror surfaces. Then the light beam bounces between them, going back and forward. Its transmission spectrum as a function of wavelength exhibits peaks of large transmission corresponding to the resonance (Keiser, 1991). Constructive interference occurs if the transmitted beams are in phase, and this corresponds to a high-transmission peak, if the transmitted beams are out-of-phase, destructive interference occurs and this corresponds to a transmission minimum. The carriers should rise to excitation energy levels, so pumping the material must be ensured by providing an electrical voltage to the amplifier.

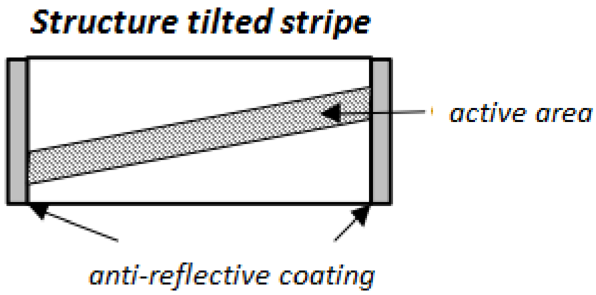

Figure 9. Structure traveling wave amplifier.

Contrarily to the FP amplifier, in traveling wave SOA feedback does not appear. Amplified signal only travels in the forward direction. A traveling wave amplifier can be achieved if the feedback from the end walls is suppressed. For this purpose, is used the anti-reflection coating (Agrawal, 2002).

2.3. Characteristics

2.3.1. Gain

G - gain is defined as the ratio between input and output powers. To get the desired effect, it has to pump carriers and transfer of electrons from the valence band to the conduction band, pumping may be electrical or optical, we get a population inversion. However it is not easy, the gain also depends on the signal frequency, amplifier medium, beam intensity . Gain (1), can be also called amplifier factor. (Agrawal, 2002).

$$G = Pout / Pin \quad (1)$$

Gain coefficient factor allows the determination of the gain medium. This factor is very useful to point parameters of the amplifier, such as optical gain, gain bandwidth, amplification factor and the saturation output power (Agrawal, 2002).

To determine the gain coefficient (2), is shown at fig.10, we must know its components. The peak gain "g0", optical frequency "w", “w0” transition atomic frequency, optical power reinforced signal “P” and saturation power “Ps”. Should also be known the dipole relaxation time “T1” or “T2” relaxation time population (Agrawal, 2002)

$$g(\omega) = \frac{g_0}{1 + (\omega - \omega_0)^2 T_2^2 + P/P_s} \quad (2)$$

Next equation (3) shows relation between gain coefficient and gain of amplifier.

$$G(\omega) = \exp[g(\omega)L] \quad (3)$$

If we change the equation so that both the “G” and “g(w)” will depend on the frequency, we observe that both have a maximum in the same place. The value of “w = w0”, and it decreases with the change “w-w0”. However, the value of gain “G(w)” falls much faster than the gain coefficient “g(w)”. The bandwidth of the amplifier is defined as the FWHM (full width at half maximum) of “G(w)” and is associated with a bandwidth. Picture 10 shows that amplifier bandwidth G(ω) is smaller than the gain bandwidth g(ω) and the difference depends on the amplifier gain itself. (Agrawal, 2002)

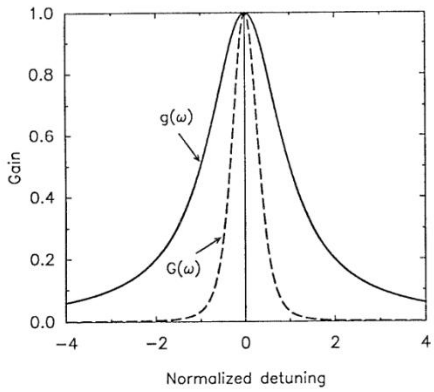

Figure 10. Gain coefficient g(w) corresponding to amplifier gain spectrum G(w) for a two-level gain medium. (Agrawal, 2002)

2.3.2. Noise Figure

When the optical gain in the amplifier SOA is accompanied by spontaneous emission, the part of the photons with different phases and polarization also cause signal amplification. The result is noise, which can be presented as an SNR (Signal to Noise Ratio) at the output of the amplifier. Parameter called the amplifier noise factor (Fn)(4) determines the dependence of the SNR at the output and the input of the amplifier.

$$F_n = \frac{(\mathrm{SNR})_{\mathrm{in}}}{(\mathrm{SNR})_{\mathrm{out}}} \qquad (4)$$

To properly determine the value of the SNR must be added spontaneous emission contribution to the noise receiver. The parameter “n_{SP}” - spontaneous emission factor is dependent on the population of active carriers. The result of this issue is the fluctuation in amplitude of the amplified signal. This means that the amplified signal is attenuated by 3dB (Fn) for ideal amplifiers. In the case of different amplifiers, this figure may be even greater. For the operation of the amplifier to be the best possible, “Fn” should be as low as possible.

Noise ratio in optical amplifier is measured as the amount of added noise to the signal. Specifically, this is a factor that indicates how much of the spectral noise is in the amplifier output, compared with the noise power at its entry. The value of noise depends also on the amplifier gain control (Agrawal, 2002).

This ratio is usually presented in the decibel scale. Additional amplifier noise is not so important if its input is a signal of a very high degree of noise. Then sending a signal to the amplifier does not contribute significantly to the overall value of the noise. Example would be placing the amplifier in a series of two, the excess noise of the second amplifier is not important, since it does not contribute to the total amount of noise (Agrawal, 2002).

2.3.3. Saturation

Optical amplifier is not able to maintain a constant level of gain for arbitrarily high input signals. This requires an additional amount of energy for the signal. Therefore, the increase in gain is reduced for high input power. This phenomenon is called the saturation of the gain. This means that while amplifier working, the gain cannot immediately adjust to the level of the input signal. Figure number 11, shows as the input fluency increases, the output fluency (blue line) starts to saturate. In a multi-pass amplifier, the pulse energy first grows as the number of passes N (red lines) increases, then begins to fall due to cavity losses and gain decrease. The medium stores some portion of energy, which determines the gain. At work, the amplifier can also lead to saturation. When the power input to the amplifier is increased, gain drops due to depletion of active region carriers. The decrease in gain is set when the excited ions population is reduced, whereas the rate of change in the gain is determined by stimulated and spontaneous emission figure12. (Krueger, 2002) (Paschotta, 2012)

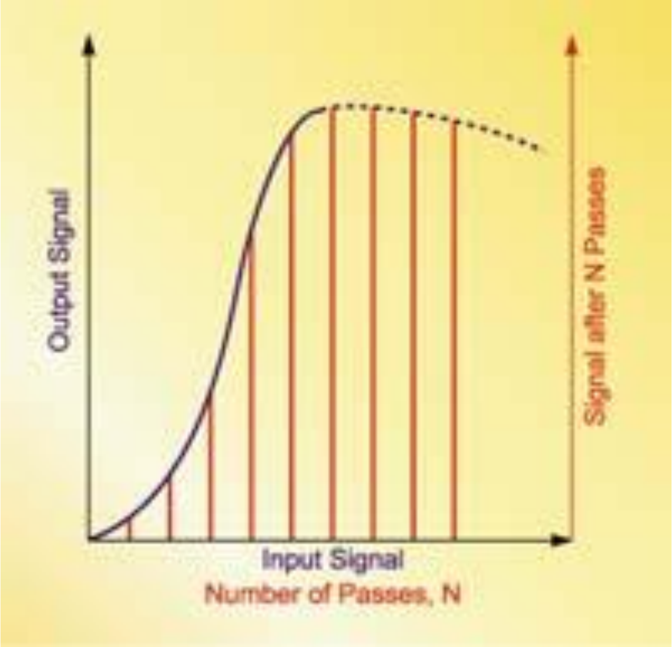

Figure 11:Saturation because of high input signal (Krueger, 2002)

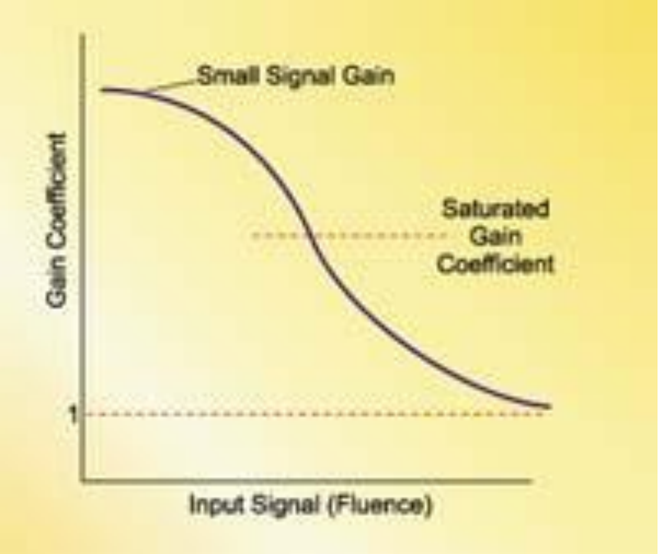

Figure 12: This saturation is usually defined by the saturated gain coefficient—the input signal influence at which the gain has dropped to half the small signal gain. (Krueger, 2002)

2.3.4. Non – linear phenomena

The main reason of non-linear phenomena in the amplifier is carrier density changes induced by the amplifier input signal.

Self - phase modulation (SPM) and Cross - phase modulation (XPM).

Refractive index in the active area of the SOA-type amplifier is not constant. It depends on the carrier density and the material gain. This means that the phase and gain for propagating optical wave are coupled via gain saturation.

$$\alpha_l = -\frac{\pi}{\lambda_0}\frac{dn_e/dn}{dg_m/dn} \quad (5)$$

This phenomenon is closely related to the line-width enhancement factor (5) as a result of the components of free-space wavelength (λ_0), amplifier waveguide effective index (n_e), the material gain coefficient (g_m) and the carrier density (n). Injected signal pulse travels through an SOA amplifier causing change carrier density, directly affects the propagation coefficient. Due to the finite life time of the carriers, front edge of the pulse has a different phase shift relative to edges of the coating. In this way, self- phase modulation (SPM) causes to change the shape of the pulse and its spectrum.

If more than one signal is injected into the SOA, there is a phenomenon called cross - phase modulation (XPM) between signals. This phenomenon causes a phase change, and can be used to create wavelength converters. (Connelly, 2002)

Cross-gain modulation (XGM) and self – gain modulation (SGM).

Another non-linear phenomena arising in SOA is self-gain modulation. The high power pulsed signal saturates the gain of the amplifier. The result is a decrease in gain for the continuous wave signal. After which gain is recovered, because of the redistribution of carriers, and the injection current. This means that dynamic gain is determined by a function of time. Gain recovery mechanism depends on the injection current, carrier heating and spectral hole burning. The amplifier is unidirectional with the current CW which provides carriers. In this way the deficiency of carriers caused by the impulse are continually being replaced by a current carrying carriers. (Niloy K. Dutta, 2006)

In this way the deficiency caused by the impulse carriers are being replaced by a current carrying carriers. The speed of the process is given by the lifetime of carriers it decreases with an increase in injection current density. The injected pulse reduces the gain at the photon energy of this pulse, this causes burns a hole in the gain spectrum. The process is known as spectral hole burning. Following the pulse, the gain spectrum returns to its original shape through redistribution of carriers.

Quick recovery of gain generated by the pulse is better for low frequencies (10 GHz) than for large (40GHz). It also follows the carrier relaxation time for high-energy state, of the active area of semiconductor. Fast relaxation time allows you to create a layer with a supply of carriers. Allow for rapid exchange of carriers after a short pulse. Quick recovery of the gain is important for high-speed SOA. (Niloy K. Dutta, 2006)

In to the amplifier enter two light signals. First is the CW probe signal and a second pump strong signal may lead to the phenomenon of XGM. Phenomenon leads to the transition modulation, between the signals applied to the input of the amplifier. This is where the amplifier will deliver a weak probe light signal and a strong pump signal with a modulation. Then, under the influence of this phenomenon, modulation of the pump goes to the probe. This means that the amplifier is acting as a wavelength converter, causing transposing information at one wavelength to another signal at a different wavelength.

The value specifying the XGM process is conversion efficient η (6), which is defined as the ratio between the modulation index of the probe output to the modulation index of the input pump.

$$\eta = \left| \frac{P_1(0)}{P_0(0)} F(L) \right| \quad (6)$$

With ;

$$F(L) = 1 - e^{-K(L)}$$
$$K(L) = \frac{1}{1 + j\omega\tau\alpha'} \left\{ \alpha' \ln \frac{G_0}{G} - \ln \left[1 - \frac{(G-1) P_T(0)/P_{sat}}{1 + G P_T(0)/P_{sat} + j\omega\tau} \right] \right\} \quad (7)$$

also is needed;

$$\alpha' = \alpha/(\Gamma g_0) \quad (8)$$

To determine this value, is needed to know; waveguide loss coefficient α' is described by the equation (8). Probe $P_0(0)$ and pump $P_1(0)$ average powers, average power of them sum of both $P_T(0)$, modulation frequency ω and spontaneous carrier lifetime τ and unsaturated gain G_0 equation (9) also unsaturated material gain coefficient g_0 (10).

$$G_0 \approx \exp[(\Gamma g_0 - \alpha)L] \quad (9) \qquad g_o = a_1\left(\frac{\tau J}{ed} - n_o\right) \quad (10)$$

This non-linearity in the amplifier SOA are caused by varying the carrier density due to the input signal. Carrier density temporary reaction is dependent on the carrier life time. Carrier lifetime factor is very important from its value depends the gain in the amplifier. (Connelly, 2002)

These phenomena are refer in the rest of the paper. Result of their action has an effect on the behavior of the signal, and is shown in the following simulations.

3. Gigabit-Passive Optical Network

3.1. Introduction

The growing number of network users and greater demands on the network parameters lead to increased competitiveness of optical networks on cable. The rapid development of technology allows for the introduction of new and better systems of information transmission. This led to the development of PON networks, presented by figure number 13, among others. Passive optical networks, allows point-to-multipoint connection via fiber optics. This technology allows multiple users over a single fiber node (16-128). Part of the network line terminal called the OLT, and several end-points (ONUs-optical network units) near end user. This network allows to reduce the amount of optical fibers and a reduction in the office equipment to support it, compared to point-to-point networks.

The most popular systems in the developed technologies are Ethernet PON Passive Optical Network (EPON), and based on ATM technology, broadband passive optical network (BPON). Evolution of broadband passive optical network is GPON - Gigabit Passive Optical Network.

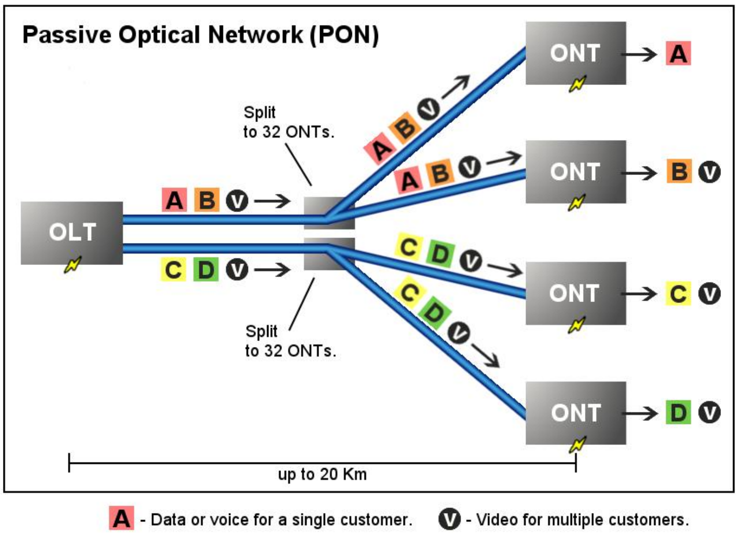

Figure 13. Passive optical network scheme. (wikipedia.org, 2009)

3.2. Gigabit-Passive Optical Network main features.

The standard lengths, between users ONU and OLT are 10 to 20km optical fiber cabling without reinforcement PON can provide many types of services such as providing broadband data, video or audio, known as triple-play services. These networks provide access to individual optical media for home or office. These FTTx solutions, are aimed at increase the possibilities fiber-optic systems.

The use of GPON allows provider to continue the services without having to make hardware changes to the currently existing network. The maximum value of the signal distribution is 1:128, this means the possibility to provide services to 128 customers (ONUs). Equally it is possible to successfully support the links in the distribution ratio 1:32 or 1:64.

Physical diagram, fig.14, of the optical distribution network (ODN) composed of two stages, the first of these is the part corresponding to the transfer of information from the OLT towards the ONU, downlink. Another part is the transmission of information from the user or operator ONU toward the OLT, uplink. (Telecomunication standarization sector of ITU-T, 2010)

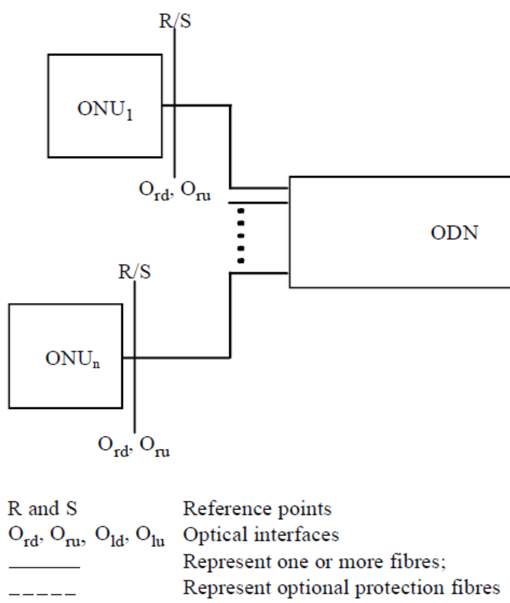

Figure 14. Generic physical configuration of the optical distribution network. (Telecomunication standarization sector of ITU-T, 1998)

The basic work of GPON system is the transmission of information simultaneously in two directions. Where downstream may be 2,5 Gbit/s for the third transmission window 1490 nm, and the upstream speed of 1,25 or 2,5 Gbit/s for the second 1310 nm transmission window (Telecomunication standarization sector of ITU-T, 1998). Considering the downlink, ONUs receives the same frame rate, it recognizes which is its part of the frame and decodes it. When transmitting in uplink OLT receives a frame, which consists of linked parts from among all the ONUs. This frame is created during the connection of all branches, after passing through the coupler. Presented by figure number 15.

The mechanism responsible for proper communication ONU-OLT for upstream is a TDMA (time division multiple access). Certain bandwidth is assigned to each ONU by the OLT. Upstream channels, work in a burst mode, when data cell reach the OLT receiver, they have different amplitude, because branches of the ODN have very likely different attenuation and length. Appropriate time intervals between the data cells are provided by the MAC (Media Access Control) protocol. Length of data cells sent as upstream is not constant, and can be varied depending on the movement of information sent from the ONU, the assigns of sufficient bandwidth provides an algorithm DBA (Dynamic Bandwidth assignment).

The downstream channel works in continuous mode. Cell data sent to all ONUs, they are not separated a time gap between each other. Identical data cells are generated by the OLT and sent to ONU. (Optical fibers,cables and systems, 2009)

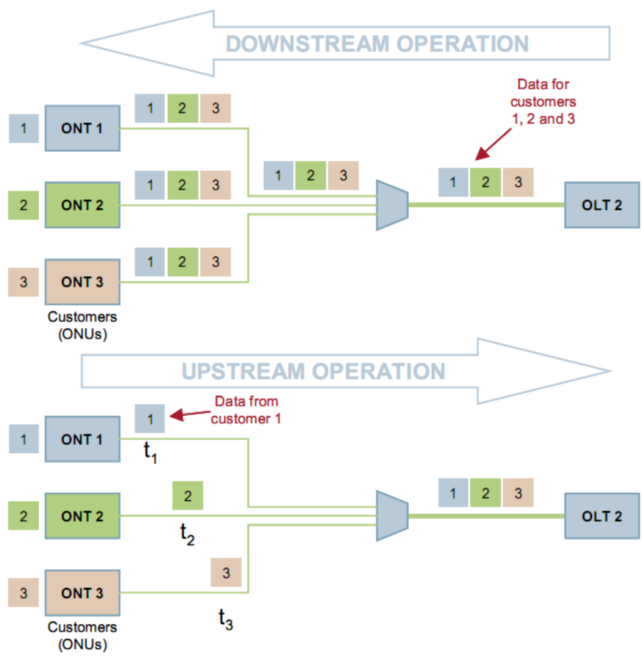

Figure 15. Scheme of the network transmission GPON towards downstream and upstream. (GPON Market Review; Competitive Models in GPON: Initial Phase , 2009)

3.2.1. Power budget

Power budget determines the amount of loss in the optical network, caused by the device used, and the construction of the network. Power budget for GPON has been classified into three groups ,tab 1. Depending on the length of a fiber optic link and end users - used splitters. For class A, the total power budget is 23dB, with a link length of approximately 10km and the splitter to 16 recipients. The second class is denoted as B, the division also introduced due to the precise specifications, and was also a subclass of B +. This concern about the budget systems of the power loss of about 29 dB. The last of the class - the third, also known as C, contains a subinterval C + applies to the output range of 32dB and above. (Serial 10G EPON Downstream using FEC, 2006)

Class	Split Ratio	Distance [Km]	Loss Budget [dB]
I	1:16	10	23
II	1:32	20	29
	1:64	10	
III	1:128	20	35

Tab1. Power budget class. (Serial 10G EPON Downstream using FEC, 2006)

3.3. Simulations of Gigabit Passive Optical Network

3.3.1. Description circuits

The simulation is based on the model 10G-PON system developed in the thesis Andreia Juliana Alves of "Next generation passive optical networks ". (Alves, 2010) . This is a continuation of research on the performance and characteristics of GPON system. For the purpose of the current work, changes to the original model were made. The bitrates are 2,5 Gbps and 1,25 Gbps, respectively for downstream and upstream. The signal transmitted by the OLT is splitted among 64 recipients -ONUs. The purpose of simulation is to examine the quality of the signals coming to one of the recipient and in the opposite direction to the central - OLT. Analyzed mainly are loss due to fiber coupling, splitting ratio, fiber distance also dispersion of fiber, in GPON system.

VPItransmissionMaker is a program for creating and designing various types of optical networks. Allows the simulation of optical network before implementing it. It is a good scientific-research program. It has a large library of models that participate in simulations. Because of its capabilities, and easy operation has been selected to perform the necessary simulations in this work.

3.3.1.1. Models description.

Fiber

The transmission takes place via SMF (single-mode fiber). The behavior of the light pulse in the fiber may be different, this is caused by the different phenomena taking place inside it.

Dispersions general definition refers to the phenomenon in which the velocity of propagation of an electromagnetic wave depends on its frequency. In telecommunications, the term dispersion is used to describe processes in the signal carried by an electromagnetic wave propagating in the medium, which is degraded. This degradation occurs because the various components of the wave (different frequencies or vectors of wave) propagate at different speeds. (Dyspersja światłowodów, 1998)

In fiber-optic communication dispersion term refers to several parameters of the fibers: group-velocity dispersion (GVD) and polarization.

Polarization-mode dispersion (PMD) is caused variations in the shape of the core, the light launched in the fiber changes his state of polarization. This is a factor that limits the optical networks operating at high bit rate.

In SMF there is only one mode, and therefore the inter-modal dispersion disappears. GVD is also called intra-modal dispersion and we can distinguish two sub types: material and waveguide dispersion.

Material dispersion is related to the construction of the fiber - production. Occurs because, the refractive index of the material used in the manufacture of fiber - silica, varies with the optical frequency. On a fundamental level, the origin of material dispersion is related to the characteristic resonance frequencies, at which of the material absorbs the electro-magnetic radiation. (Agrawal, 2002)

Waveguide dispersion is part of GVD caused by group delay,

Light pulse propagation in the fiber leads to dispersion waveguide. This is due to the reflectance factor of the material and is dependent on the wavelength. Pulse moving in the fiber have different values depending on the reflection of the propagation in the fiber cross-section. Ray of light, spread occuring over a distribution wavelengths is obtained from the derivative of the group delay with respective wavelength. Different wavelengths have different group velocity delay. Because of the different signal components move at different speeds, this may lead to distortion of the signal after moving a certain distance in the fiber.

(Agrawal, 2002) (Keiser, 1991)

Errors caused by the prevalence of the phenomenon of dispersion and overlapping modes is called inter-symbol interference (ISI).

GVD-group velocity dispersion, you can specify using the equation. Having regard to the SMF fiber length L and frequency ω.

$$D = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) = -\frac{2\pi c}{\lambda^2}\beta_2 \quad (11)$$

The following factors are; wavelengths λ, group velocity v_g, β propagation constant, C is the speed of light, n is the mode index. The frequency and length of the fibers is taken into account by v_g, which describes the equation (12) and the group index n_g (13), propagation constant is related via equation (14) with the main dispersion equation. Dispersion parameter is expressed in units of ps/(km-nm). (Agrawal, 2002)

$$v_g = c/\bar{n}_g \quad (12) \qquad \bar{n}_g = \bar{n} + \omega(d\bar{n}/d\omega) \quad (13) \qquad \beta_2 = d^2\beta/d\omega^2 \quad (14)$$

Also can be determined an additional time delay for the dispersion describes by equation (15).

$$\Delta T = \frac{dT}{d\omega}\Delta\omega = \frac{d}{d\omega}\left(\frac{L}{v_g}\right)\Delta\omega = L\frac{d^2\beta}{d\omega^2}\Delta\omega = L\beta_2\Delta\omega \quad (15)$$

From GVD it is possible to distinguish two types of the dispersion, which are the material and the wavelength dispersion(16).

$$D = D_M + D_W \quad (16)$$

Formulas (17) describe respectively; material dispersion D_M and dispersion wavelength D_W.

$$D_M = -\frac{2\pi}{\lambda^2}\frac{dn_{2g}}{d\omega} = \frac{1}{c}\frac{dn_{2g}}{d\lambda},$$
$$D_W = -\frac{2\pi\Delta}{\lambda^2}\left[\frac{n_{2g}^2}{n_2\omega}\frac{Vd^2(Vb)}{dV^2} + \frac{dn_{2g}}{d\omega}\frac{d(Vb)}{dV}\right] \quad (17)$$

Additional values that are needed to determine the dispersion values are V-normalized frequency and b-normalized propagation constant. (Agrawal, 2002)

Material dispersion is dominating in lower wavelengths however but for longer wavelengths its value is decreasing and wavelength dispersion is dominating. (Keiser, 1991)

The GVD dispersion in simulation model is described by equation (18), and is dependent on frequency. Frequency parameter represents f_{ref} - frequency reference.

$$D = j\left[\frac{\beta_2(\omega_{ref})}{2}(\omega-\omega_{ref})^2 + \frac{\beta_3(\omega_{ref})}{6}(\omega-\omega_{ref})^3\right] \quad (18)$$

In addition to determine the value of the dispersion is need the propagation coefficients: B2, B3 (19). They are controlled via parameters D_λ and S_λ, respectively fiber dispersion and dispersion slope. Both these values are specified at the reference frequency.

$$\beta_2 = -\frac{c}{2\pi f_{ref}^2} D_\lambda \qquad \beta_3 = -\frac{c}{(2\pi)^2 f_{ref}^3}\left(\frac{c}{f_{ref}} S_\lambda + 2D_\lambda\right) \quad (19)$$

The table present used values.

dispersion	D_λ	16×10^{-6}	s/m^3
dispersion slope	S_λ,	$0{,}08 \times 10^3$	s/m^3
reference frequency	f_{ref}	193.1×10^{12}	Hz

Tab2. Parameters used to set dispersion in simulation.

Attenuation is a reduction in signal strength along with the distance, for light traveling in an optical fiber.

Value of attenuation in the simulation is independent of the frequency, expressed by the parameter "attenuation" and defined as [dB / m]. It is a single value interpreted as attenuation per unit length for every fiber span, or an array of value corresponding to each span in the link.

The table gives factors which are needed to determine the attenuation.

Attenuation	α	$0{,}2 \times 10^{-3}$	[dB/m]
Distance	L	20000 - 60000	m

Tab3. SMF parameters used in the simulation.

For the calculation of weakening of the optical signal in the fiber is used the attenuation coefficient α_p, expressed in the unit of km^{-1}. To determine the attenuation should also know the value of the optical power P(0) launched into the fiber and the optical power at the output after traverse of the fiber P(z), it have to be also knows distance of fiber L.

Equation below shows the relationship defining attenuation (12). (Keiser, 1991)

$$\alpha\left(\frac{dB}{km}\right) = \frac{10}{L}\log_{10}\left[\frac{P(0)}{P(L)}\right] = 4{,}343\ \alpha_p\ \ (km^{-1}) \qquad (20)$$

Transmitter

The transmitter signal from the OLT includes downstream signal generating NRZ module with bit rate 2,5 Gbps, which externally modulates a continuous wave laser at 1490 nm wavelength ,using a Mach-Zehnder modulator.

- **Mach-Zehnder modulator.**

Mach Zehnder modulator (MZM) picture 16, is a device which allows the modulation of a certain length of the light beam. It has two arms, changing the refractive index in them in order of modulate, light is amplified inside. It takes place extinction, due to interference between the lights in the arms. Combiner is designed to combine the streams of light from the two arms of the device, turning in to the output mode. It is designed to cause intentional loss of the light in the wave guide. If there is an intentional asymmetry in transmission of the two arms. (Rune S. Jacobsen, 2006) (U.S. Patent 2011/0007995, 2011)

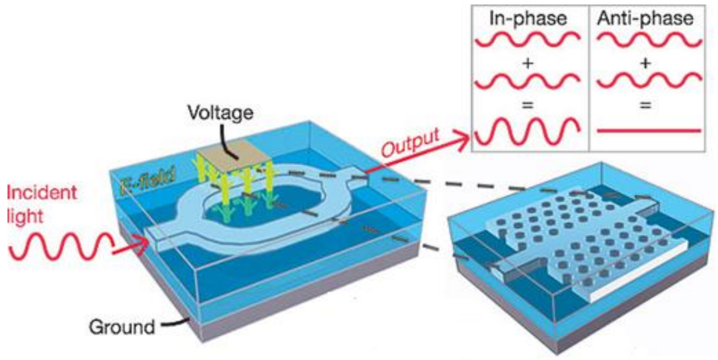

Figure 16. Diagram of a Mach–Zehnder modulator (Rune S. Jacobsen, 2006)

Parameters of simulation block of MZM. Output depends on the phase difference between the two modulator branches. Power transfer function, are the phase changes in each branch caused by the applied modulation signal data. The phase changes take place due to the electro-optical effect.

The output of the modulator depends on the difference between the two branches of the modulator. It is expressed by equation (21).

$$P_{out}(t) = P_{in}(t) \cdot d(t) = P_{in}(t) \cdot \cos^2[\Delta\Phi(t)] \quad (21)$$

Data signal is modulated by the change exchange phase between the branches. Controlling the rate of extinction by parameter $f_{extinct}$,it is possible to make the modulation of signal. The extinction ratio can be specified in dB units according to $\varepsilon = 10\ \log(f_{extinct})$ by setting the parameter Extinction.

$$\Delta\Phi = \frac{\pi}{2}\left(\frac{1}{2} - \mathrm{ext} \cdot \left(data(t) - \frac{1}{2}\right)\right) \quad \text{with } \mathrm{ext} = 1 - \frac{4}{\pi}\arctan(1/(\sqrt{f_{extinct}})) \quad (22)$$

Factors that play an important role in the work of the modulator are; extinction ratio, which respectively gives the signal degradation, and chirp causes a dynamic change in the modulation frequency. Chirp (Compressed High Intensity Radar Pulse), in the optical transmission, for ultra-short pulse, interacts with the dispersion properties of the material. Increasing or decreasing the total dispersion of the pulse in the time of signal propagation.

extinction	ε	20	dB
symmetry factor	k	-0,5	-
chirp sign	σ	negative	-

Tab4. Setup parameters in MZM block used in simulation.

Parameter k, determines the value of chirp, which drives the modulator arms. It has values between -1 (chirp-less) and 1 (single-arm driven). Sense of the frequency chirp is determined by the sign of parameter chirp sign. All parameters are in tab 4.

In the opposite direction- upstream, the ONU to transmit the downstream signal consists of a signal generator with bit rate of 1,25 Gbps, driver non-return to zero and externally modulated continuous wave laser at 1310 nm wavelength. There is also the amplitude modulator, presented at figures 19 and 20.

- **Amplitude modulator.**

Optical amplitude modulators are elements that provide fast electro-optical response, it allows amplitude modulation with frequencies as high as GHz range. Modulator use polarization maintaining single mode fibers to couple the light in and out. The scope of the modulator is set at a certain power range. If the signal is delivered to the modulator smaller then it will be raised to the minimum level of the range. However, if the signal is greater than the assumed upper limits, then it will be reduced to a maximum of the range. The minimum value of the modulation range would mean a logical 0 and logical 1 is maximum of range.

AM modulator, works on the principle of optical signal modulation signal through electrical Supplied representation of the data, and the modulation index m. Power output of the modulator is determined by the formula (23).

$$P_{out}(t) = P_{in}(t) \cdot d(t) = P_{in}(t) \cdot ((1-m) + m \cdot data(t)) \quad (23)$$

Formula defining the function determines the power conversion using this factor, determines the scope of logic signals 0 and 1 Modulation factor is set so that the logical values have, the same value as the MZM. The m index is given in table 5.

modulation index	m	0,9	-

Tab5. Parameter used in amplitude modulator.

Receiver

Optical receiver converts the energy of the optical signal, which is modulated stream of photons to electrical energy, the electron beam as faithfully reproducing the stream of photons that reach it. Signal is detected at ONU, by direct receiver block, using PIN photodiode. It used in this process well-known phenomenon generation electron-hole pairs in a semiconductor material, after the absorption of a photon. These carriers take part in the conduction of electricity. Electrical carrier lifetime should be as short as possible to the interruption of the flow of photons stopped the flow of current. (Agrawal, 2002)

Work of photodiode is determined by the sensitivity. This value is the mean optical power required to obtain a specified bit error ratio out of the receiver, for an input signal with a perfect extinction ratio. Equation described the sensitivity power (24). The sensitivity is related to the following parameters photodiode; responsivity r, thermal noise N_{th}, electrical bandwidth B_e, and desired Q_{eff} which is related to BER (25).

$$\bar{P}_{sensitivity} = r \cdot Q_{eff} \cdot (N_{th}\sqrt{B_e} + qQ_{eff}B_e) \quad (24) \qquad BER = \frac{1}{2}\left(erfc\left(\frac{Q_{eff}}{\sqrt{2}}\right)\right) \quad (25) \qquad erfc = \frac{2}{\sqrt{\pi}}\int_{x}^{\infty} e^{-\alpha^2} d\alpha \quad (26)$$

Qeff parameter has different values for the desired level of BER (eg, for a BER = 10^{-9}, this value is 6). Additional equation describes the complementary error function (erfc) (26).

The sensitivity photodiode is modeled by thermal noise. This is described by (27).

$$N_{th} = \frac{rq}{\sqrt{B_e} Q_{eff}} \bar{P}_{sensitivity} \qquad (27)$$

Thermal noise arises from the thermal fluctuations in the electron density within a conductor. Parameters are presented in tabel 6.

responsivity	r	1	A/W
thermal noise	N_{th}	10×10^{-12}	A/Hz

Tab6. Setup parameters for PIN photodiode.

Amplifiers

- **Erbium Doped Fibre Amplifier**

In the following part of the work are used in the simulation the SOA and EDFA amplifiers. Described in this section is also EDFA, chapter 2 is devoted entirely to the SOA, parameters of SOA used in simulation are below.

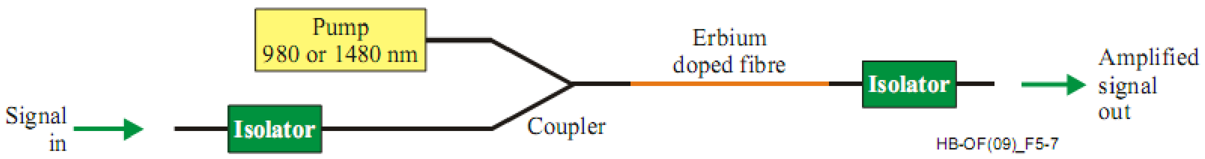

Figure 17. EDFA optical amplifier typical scheme.

Construction of EDFA optical amplifier (figure 17) consists of several elements. One of these is the optical fiber doped with erbium. It connects to the optical pump, which is a semiconductor laser. Erbium ions can be pumped from the different optical frequencies. Often used are 980nm and 1480nm frequencies (fig.18). The basic structure of the amplifier consists of couplers and isolators.

The optical signal through the fiber passes the isolator- that suppresses optical reflections. The laser light and the input signal meet in in the doped fiber via coupler. During operation, the amplifier pump laser induces erbium ions, which give energy by reinforcing the optical signal passing through the fiber. The signal is amplified by stimulated emission phenomenon, inversion resulting from optical pumping. The result of optical pumping that leads to inversion is the amplification of the data signal passing through at a wavelength in the 1550 nm region. A higher degree of inversion leads to lower noise level generated from the spontaneous emission process and is therefore highly desirable for the pre-amplifier stage. (Optical fibers,cables and systems, 2009)

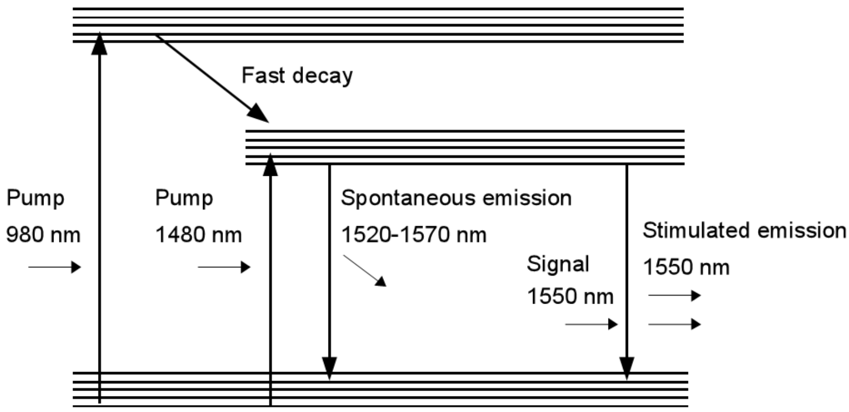

Figure 18. Energy levels of erbium ions in EDFA.

EDFA model we use is with fixed gain shape for system simulations The main parameters that are used are gain and noise figure. Model is working in gain control. Ideal amplifying unit characterized by a frequency-and wavelength-dependent gain. For high frequencies the amplifier's output power, will be limited, as in a real device If the gain is set to an unrealistically high value, the output will always equal the power limit. The maximum output power, relates to the sum of powers of all signals in all channels, and is controlled by enhanced parameters.

Additionally, the amplifier output signal corrupts by the amplified spontaneous emission (ASE) noise. For high gain amplifiers the noise figure is 3 dB above this value in simulation is 4dB. ASE noise is added to the output signal. Spontaneous emission is related to the moving of electrons from the conduction band to the valence band. Spontaneous emission is always present and will, like the signal, experience amplification as it propagates through the fiber. While the ASE level is independent of the signal at low signal powers, high signal powers will deplete the population inversion faster than the pump can maintain, and the increases ASE level. Parameters of EDF amplifier are presented in table below.

gain	G	10	dB
noise figure	NF	4	dB

Tab7. Set up parameters for EDFA.

EDFA for the selected model, the parameters responsible for the gain is G (28), while the noise figure parameter is NF (29), the values shown in the table. Additional parameters are noise and gain tilt, but in case of this amplifier is consider frequency independent gain and noise figure, so this values are set up at zero.

$$G_k^*[dB] = G[dB] + GainTilt \cdot (f_k - f_{tiltref}) \quad (28)$$

$$NF_k^*[dB] = NF[dB] + NoiseTilt \cdot (f_k - f_{NoiseTiltRF}) \quad (29)$$

If we consider the value of the noise and gain independent of frequency, we can use the following formula (30) for noise figure.

$$\mathrm{NF} = 10\log\left[2n_{\mathrm{sp}} \cdot \frac{G-1}{G} + \frac{1}{G}\right] = 10\log\frac{1+2N}{G} \quad (30)$$

- **Semiconductor Optical Aamplifier**

The module used in the simulation is running on a semiconductor optical amplifier traveling-wave (TW). Measure gain is described by a number of factors, carrier density, injection current, scattering, internal losses, optical confinement factor Γ.

Average amplifier gain is described by the gain material g(N) (31), which is dependent on the carrier density and carrier density at transparency point N_{tr}. In addition, the gain is limited by losses α_s, related to the dispersion of the waveguide inside the amp-internal losses, also by the optical confinement factor defined as fraction of the mode power within the active layer.

$$g(N) = \frac{dg}{dN}(N - N_{\mathrm{tr}}) \quad (31)$$

Total profit at the optical wavelength of the SOA can depend on the density of the media, and the rate of profit - gain coefficient, which includes material gain coefficient, plus internal losses and fraction of the mode power within the active layer. The gain is dependent on time due to saturation effects. Value z is expressed in meters, and specifies the location of SOA. Gain (32) is equation described below and includes all the components mentioned above.

$$G(N, z) = \exp[g_{\mathrm{tot}}(N)\, z] = \exp[(\Gamma g(N) - \alpha_s)z] \quad (32)$$

Average power is dependence a function of time, due to the input signal power and the carrier density which are dependent on time as well.

$$P_{\mathrm{out}}^{(n)} = P_{\mathrm{in}}^{(n)} \ \langle \exp[\Gamma g(N(t))L - \alpha_s L] \rangle \quad (33)$$

Output power is described by (33) for a particular n-th signal. Input power in this case is independent of time and the carrier density N(t), it is dependent on the current injection, which controls the amplifier. L in the equation is the length of the amplifier.

Carrier density N(t) is described by equation, this value is dependence of injection current. The recombination rate R(N) includes the spontaneous emission also equation (34) describes a depletion of inversion due to the stimulated emission (tab. 8).

$$\frac{dN}{dt} = \frac{I}{qV} - R(N) - \frac{\Gamma g(N) P_{av}(N,t) L}{Vhf} \quad (34)$$

Current injection I can lead to an increase in the number of carriers to maintain a gain. The parameters described above, specifies the amplifier gain in the simulation we used the default value, changing only the value of the injection current, so as to obtain the desired effect of amplification.

injection current	I	0,038	A
initial carrier density	N	3×10^{24}	m^{-3}
carrier density at transparency point	N_{tr}	$1{,}4\times10^{24}$	m^{-3}
recombination rate	R(N)	$1{,}329\times10^{33}$	m^{-3}/s

Tab8. Setup parameters of SOA.

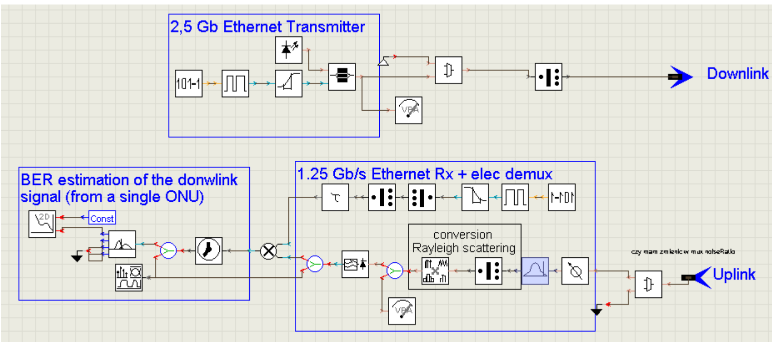

Figure 19. OLT used in simulation.

The Upstream signal after reaching the OLT passes several blocks. One of them is a band pass filter, after which the uplink signal was isolated and recognized by a photodetector. (Alves, 2010)

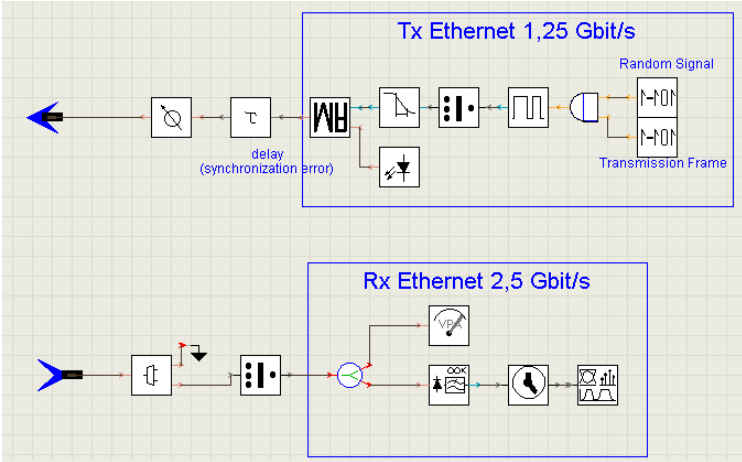

Figure 20. ONU used in simulation.

Studies have been started by assessing the direct connection between the sending and the receiving device (figures number; 21, 22). This allowed to determine the minimum value of received optical power (ROP), for a certain performance, measured in terms of bit error rate (BER), for different conditions, e.g. with increasing attenuation. In the first experiment, we have used only the receiver, without the splitter, referred as back-to-back.

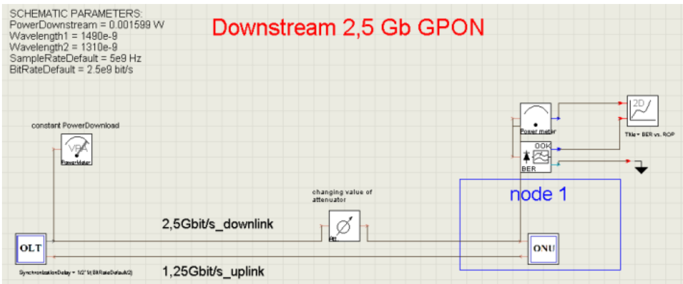

Figure 21. Downstream 2,5Gbps, directly connected.

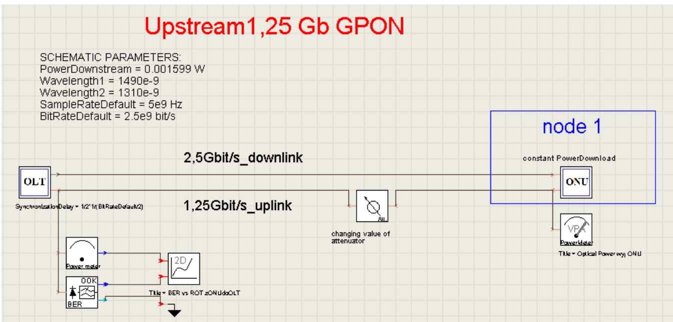

Figure 22. Upstream signal ,in directly connection OLT-ONU.

In the second stage of the simulation, 1:64 splitter and fiber-optic cable with a length of 20km were inserted (fig. 23, 24).

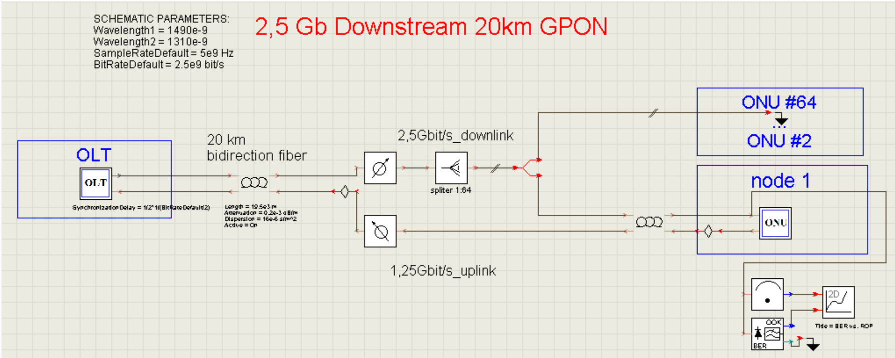

Figure 23. Circuit for downstream 2,5Gbps GPON.

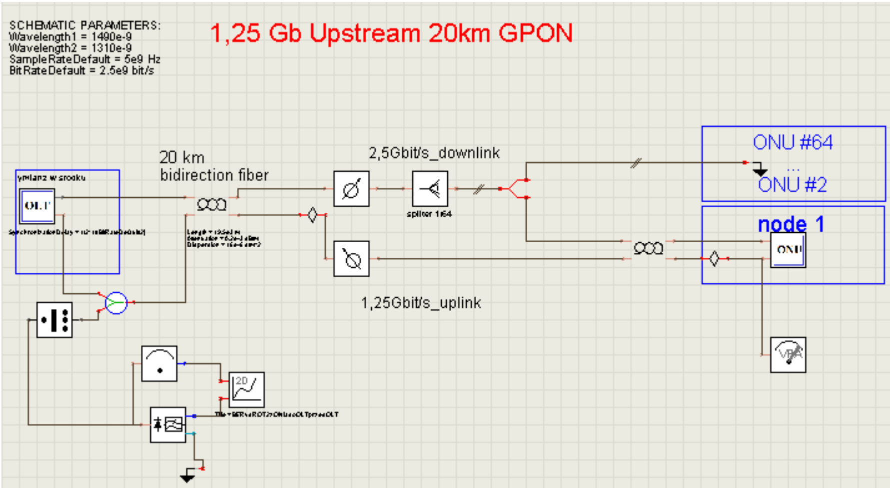

Figure 24. Circuit for upstream 1,25Gbps GPON.

Component	Parameter	Value
Signal Generator	Downstream bit rate Upstream bit rate	2,5 Gbps 1,25 Gbps
Light source	Downstream wavelength Upstream wavelength	1490 nm 1310 nm
Splitter 1:64	Associated loss	18 dB
Fiber	Attenuation Dispersion	0,2 dB/km 16 ps/(nm.km)

Tab9. Parameters of the simulation.

Laser continuous power for the upstream and downstream transmission is in both cases 1,5mW, therefore the associated NRZ mean power at the external modulator output is approximately 0,8 mW (0,9 dBm), figures 25.

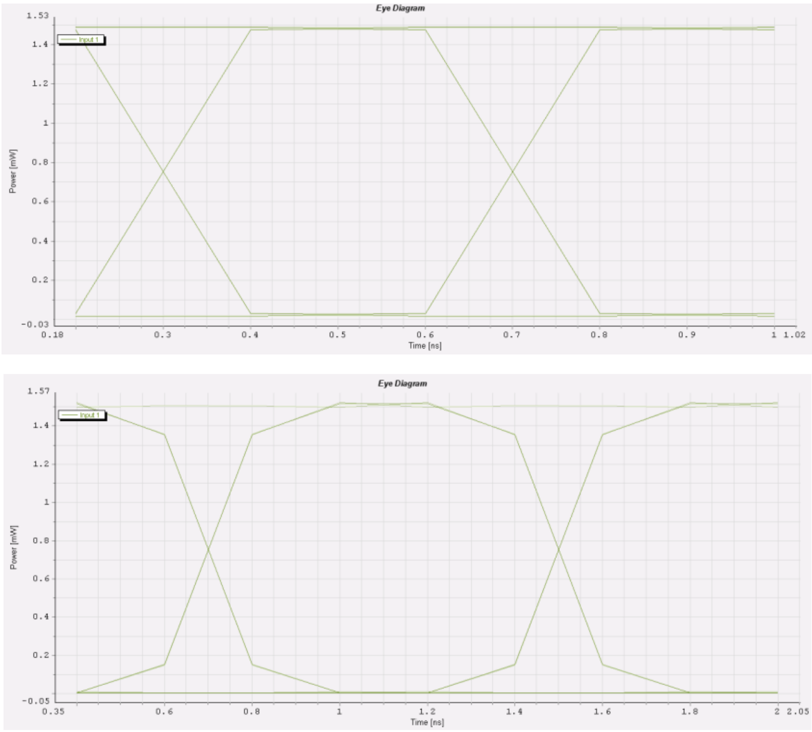

Figure 25. Eye diagrams for output signal from OLT and ONU.

Eye diagrams shown above, are respectively the measurements of outgoing signals from the transmitters. The first concerns the transmitter signal in downlink, while the second - below is the signal at the output of the modulator for the upstream of the ONU. The signals are modulated by different modulators, MZM and amplitude modulator, placed respectively in transmission part of OLT and ONU. Both are powered by the same power (1,5mW), but the output power of transmitters OLT and ONU are slightly different. Approximate value is equal to 0,8 mW, the differences between the signals arising from the method of modulation - the difference between the modulators. This difference can also be seen in eye-diagrams. The eye-opening is more evident in the uplink case (signal from the ONU).

3.3.2. Results.

The simulation is designed to identify what is the system power budget. For this purpose was developed a simulation to reproduce the best, ideal conditions for transmission. The signal does not incur any losses on the input elements of ONU and OLT.

Simulations were carried out with constant power for upstream and downstream transmission. Download and upstream mean power value is -3dBm, for simulations where ONU-OLT are connected directly and also when is used fiber with splitter. The bit error rate (BER) is then obtained for variable attenuation values. Attached pictures (in previous chapter 3.4.1.1) show the schematic of the simulation. The graphs exhibit the value of 1×10^{-3}, the upper limit of BER considering FEC (forward error correction). FEC is a technique used for controlling errors in data transmission over unreliable or noisy communication channels. (Rouse, 2007)

The following charts show the value of the bit error ratio (BER) with respect to received optical power (ROP).

The first scenario assumes experience measuring the received optical power (ROP) versus the bit error rate (BER). Direct connection of transmitter and receiver has ruled out any interference caused by transmission way, (fig. 26).

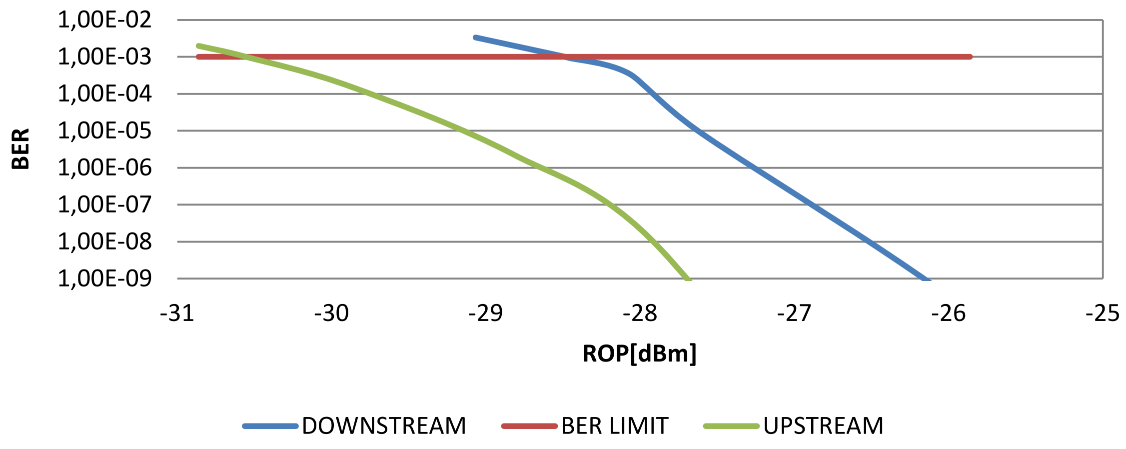

Figure 26. BER vs. ROP obtained in simulation back to back.

Based on the graphs were read the minimum optical power which reaches the corresponding receiver. This power limit is determined by the BER value of 10^{-3} minimum necessary quality. In this case, the minimum value of quality for downstream transmission gives the power budget value of -28,5 dBm. However for upstream transmission result obtained the budget value -30,5 dBm. This difference was caused by the use of different types of modulators in the OLT and ONU.

In the second simulation (figure 27), OLT is separated from the ONU, 20km distance and the splitter was used for 64 users. Splitter limit the total value of ROP causing a weakening of the signal, since splitter 1:64, attenuation is 18 dB. At the same time the signal is attenuated during transmission through the fiber, due to the loss, and there is also dispersion. In order to simulate the fiber causes the attenuation value of $0{,}2 \times 10^{-3}$ dB/m and the dispersion of 16×10^{-6} s/m^2. Total value of losses caused by fiber is 4 dB.

From the results obtained, we can determine the minimum value of ROP like in the back-to-back case and compare them. The minimal values of ROP (for BER of 1e^{-3}) are respectively -29 dBm and -30 dBm for downlink and uplink.

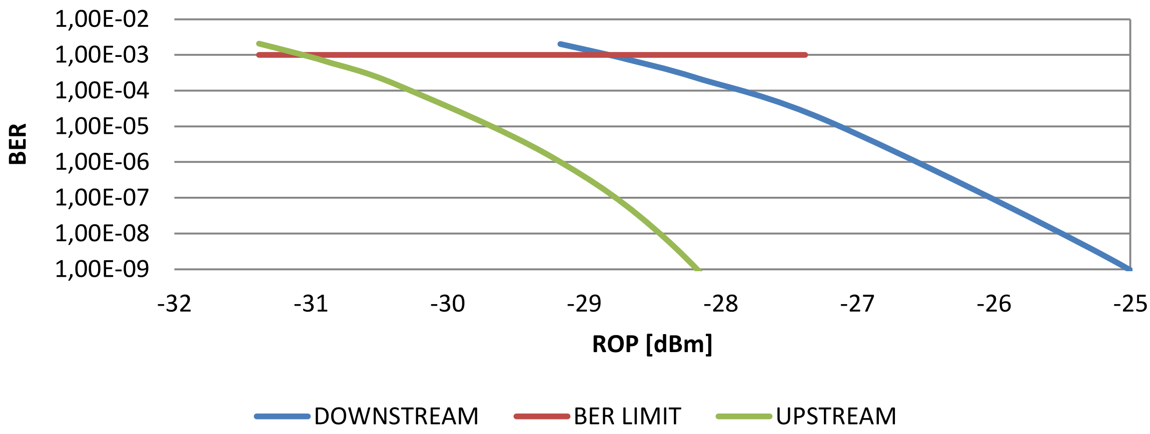

Figure 27. BER vs. ROP simulation with fiber and splitter.

Losses that occur in the second simulation are, 18dB loss resulting from the distribution of the signal through the splitter, 4 dB loss due to the fiber with a length of 20km. The total loss is 22 dB.

By comparing the signals transmitted and received, the differences show, in the graphs that were caused by a different bit rate of the signals. Downstream operates transmission rate of 2,5 Gbps, it is twice the rate of upstream. Signals dispersion in the fiber is different for upstream and downstream. The distance for both directions of transmission of signals is the same. Higher bit rate requires higher ROP, due to the associated dispersion.

Based on simulations, the signal transmitted between the OLT and ONU does not completely attenuated. This means that, at least, a transmission distance of 20 km has been successfully completed, and does not require additional elements in the form of optical amplifiers. This is consistent with the standards for the network that define the practical range of the network to a length of 20km.

For the second simulation, also shown is the BER measurement in relation to the attenuation of the signal (figure 28). Based on simulations, we can observe that for the minimum value of the received signal quality the additional attenuation is 5,7 dB. This means that the system has a power supply that can be used for additional fiber length of 20km, the distance to reach the total length of 40km. A further increasing the length of the fiber will exceed the permissible value of BER, it will signal fading and ISI can occur, preventing correct identification.

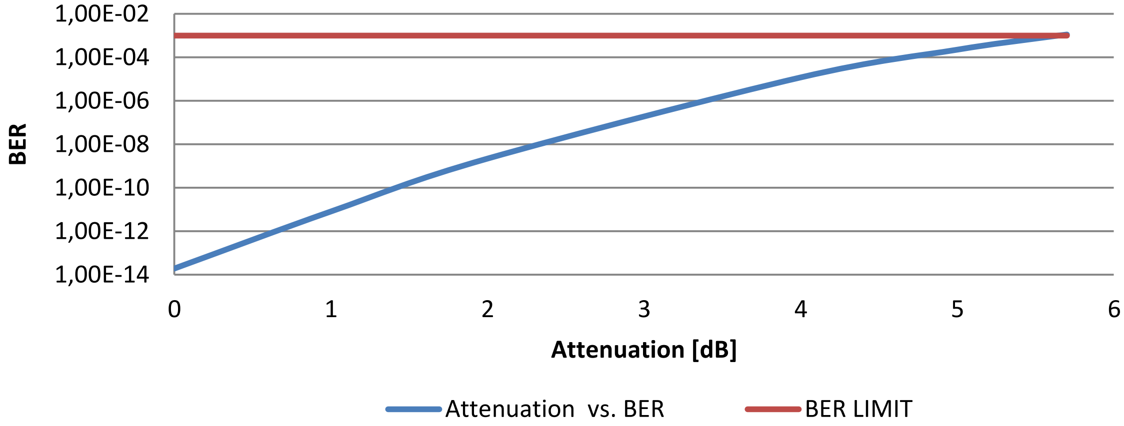

Figure 28.BER vs. Attenuation, circuit with fiber 20km and splitter 1:64 (downstream).

Signal distortion caused by dispersion is not significant, the eye diagram is wide open. They occur signal distortion associated with the SNR, shown at figure 29.

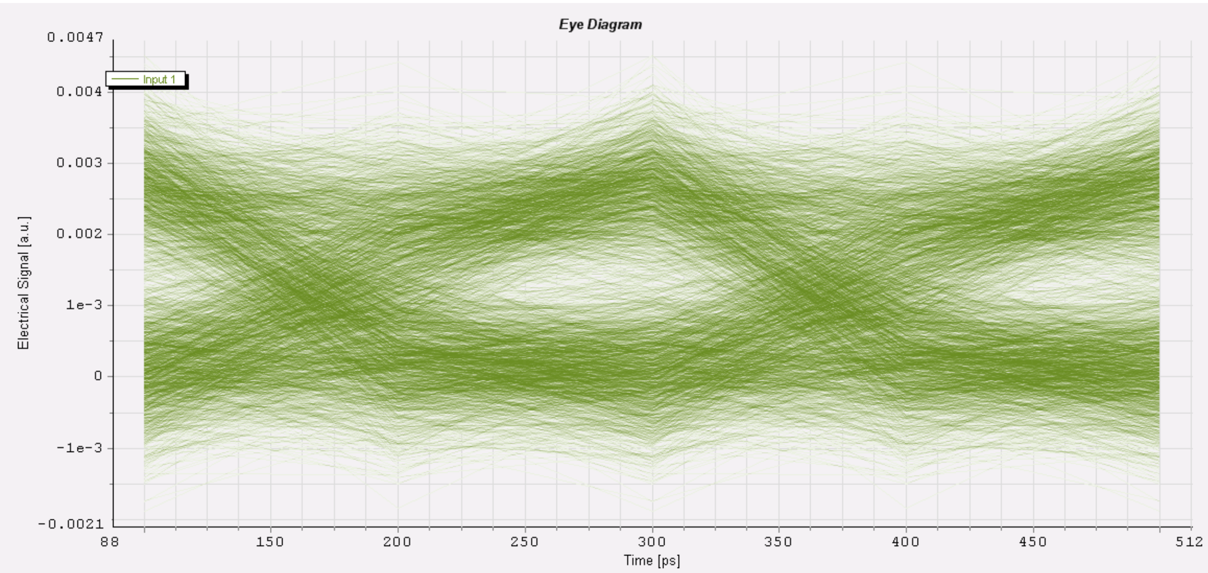

Figure 29. Eye diagram for downstream signal of GPON, used with fiber 20km and splitter.

3.4. X - Gigabit Passive Optical Network

3.4.1. Introduction

In section 3.2 was posted description and operation of GPON networks, they are now developed and introduced widely in the world. However, studies have been initiated over the next generation PON networks, even more efficient than GPON. One of the most developed systems of information transmission, through the passive optical network is the XG-PON. This system is aimed to support nominal transmission rates on the order of 10 Gbps in at least, one direction . There is a sub-class of this system, called XG-PON1, the operating parameters at a nominal line rate of 10 Gbps downstream and 2,5 Gbps upstream (Telecomunication standarization sector of ITU-T, 2010). The XG-PON will allow a smooth migration from GPON systems used in an increasing scale, on the transition towards more efficient systems, next-generation NG-PON.

One of the scenarios (so-called "brown field migration scenario") is the replacing of network, provides progressive placing the XG-PON system, it will initially cover the subscribers who require operators of higher bandwidth and better services. Over time, the number of connections supported, by the new generations surpass the number of connections with GPON. Then this will lead to a migration to XGPON system, which will unify the entire network, increasing overall performance. This method is long term and requires the activity of both types of systems in a certain period of time.

Another scenario, assumed the implementation XGPON network, is the use of the newly established networks. This avoids the costs of reconstruction and modernization of the existing network. The newly built-up areas show the benefits for users, higher bandwidth and / or higher splitting ratio. (Telecomunication standarization sector of ITU-T, 2010)

XGPON system works in networks point-to point and point-to-multipoint. It can be used in a variety of architectures, which can be fiber to the home (FTTH) or fiber to the cell site (FTTCell), fiber to the building /curb (FTTB / C), fiber to the cabinet (FTTCab). The optical distribution network (ODN) is common to all the architectures.

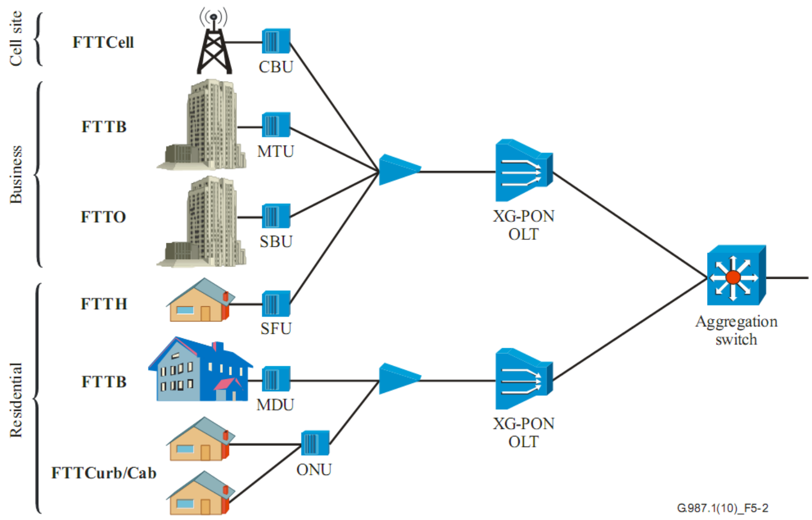

Figure 30. XG-PON architecture scenarios. (Telecomunication standarization sector of ITU-T, 2010)

Modern fiber systems such as XGPON have to meet the growing demands of users, and to support the operation of various types of services for them. XGPON support both single users, and units conducting business activities, also works with mobile backhauling application. The system ensures high quality of service and high bit-rate capability. One of the most demanding services that the system is designed to fill that contribute to the determination of performance standards and quality of the network are: telephone; VoIP, POTS, real-time television; IPTV and digital TV broadcasting and high speed internet access. In addition to business applications, the network should provide access to Ethernet services such as point-to-point, multipoint-to-multipoint and rooted-multipoint Ethernet Virtual Connection. XGPON shall also support accurate frequency / phase / time synchronization for the mobile backhaul application. (Telecomunication standarization sector of ITU-T, 2010)

3.4.2. Main features

Transmission of data XGPON architecture is based on a single fiber. Operating system uses to transmit a wavelength of 1575nm to 1580nm downstream, for upstream transmission wavelength range is from 1260 nm to 1280 nm. International Telecommunication Union standards describe two types of systems XGPON, currently developed and implemented in the future, they are XGPON1 and XGPON2. The first, characterized by the nominal values of 10 Gbps for downstream and 2,5 Gbps for upstream, another of them has an increased value for the upstream transmission, to the value of 10Gbps, downstream is the same as for the first system. (Telecomunication standarization sector ITU-T, 2010)

Network infrastructure allows sharing over 1:32 or 1:64, a new type of network will increase this number. Split ratio growth to the value of 128 or higher 256 (Telecomunication standarization sector of ITU-T, 2010), allows to handle a larger area, is also very attractive to companies providing such services, because of reduce costs. XGPON has a control function TDMA, which support and 256-way logical split. XGPON network type, provides DBA-dynamic bandwidth assignment. It supports the proper functioning of the network, through effective upstream bandwidth sharing between connections. Based on indications of dynamic action of the individual ONU, these indicators of activity can rely on two methods.

The first is a status report (SR), is a direct reporting to the OLT by the ONU buffer occupancy. The second one is traffic monitoring (TM) allows the observation of actual traffic size and compares it with assigned capabilities for upstream transmission. For this purpose, is used OLT. DBA function is to allocate bandwidth among competing outgoing transmissions in terms of actual work. For this purpose, the reference model is used, which is designed to perfect bandwidth sharing. (Telecomunication standarization sector of ITU-T, 2010)

3.5. Simulations of X-Gigabit Passive Optical Network.

3.5.1. Description

The next stage of research is to understand the system XGPON, and make the same simulation in order to compare both systems. In the simulation program had to increase transmission parameters in a manner consistent with the standards of XGPON network. XGPON operates on the bit rate of 10 Gbps. Downstream is set 10 Gbps, and upstream has a value of 2,5 Gbps. Block diagram of the two systems look the same and consist of the same elements. Power for the downstream and upstream rate was set at the same value 1,5mW.

3.5.2. Results

During the simulation, "back to back", obtained the results presented in figures 31. For the downstream transmission gives minimum power budget value of -26 dBm, for transmission in the opposite direction, upstream received power budget -27 dBm. Both values correspond to a BER of 10^{-3}. To reach the limit value of the minimum transmission quality (BER = 10^{-3}) power value for the downstream signal must be greater than the upstream. This is due to the higher bitrate for the downstream, and associated higher spectral occupancy. The limitation imposed by dispersion is therefore higher.

Comparing 10GPON system with the GPON, simulated in the previous section, is possible to observe the differences resulting from an increase in bitrate. Power values to ensure the minimum quality of work are greater than for a network of smaller bit rate.

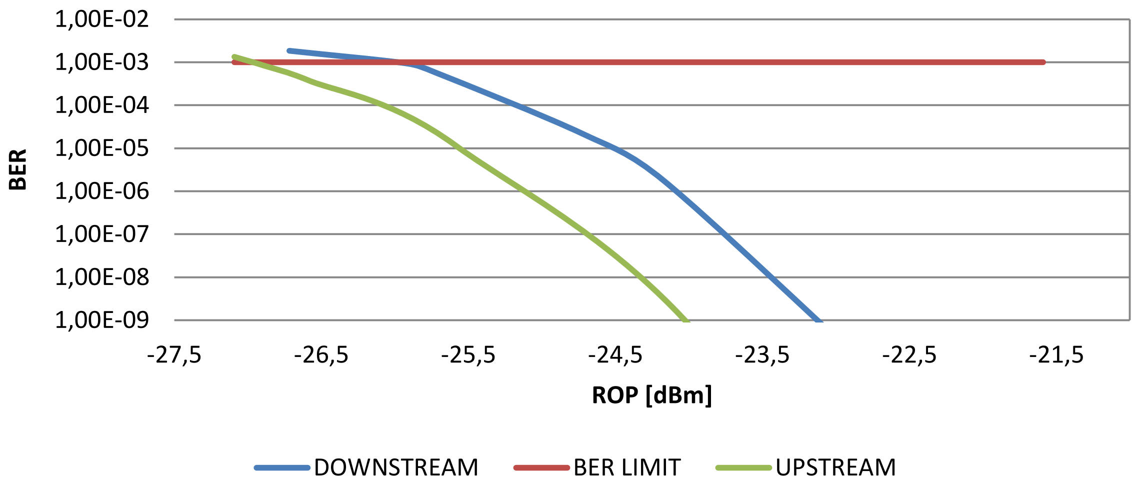

Figure 31. BER vs. ROP, for back to back connection of OLT and ONU for XGPON.

The graph below shows the data transmission, upstream connection and downstream. This kind of system is asymmetric, means it has a different bit rate for the signal downstream and upstream. It also causes different propagation of a signal in the fiber, higher value of bit rate, causing more error because of dispersion.

Added fiber to the system, has weakened both signals. These results do not differ significantly from the simulation “back to back”, but the differences result from the application of optical fiber which comes to loss of signal, and dispersion.

The figure 32 shown that the signal strength at the output of the system for downstream transmission is 0,0034 mW , power budget is obtained -24,6m dB and the received power for the upstream transmission is 0,002 mW, -26,9 dBm.

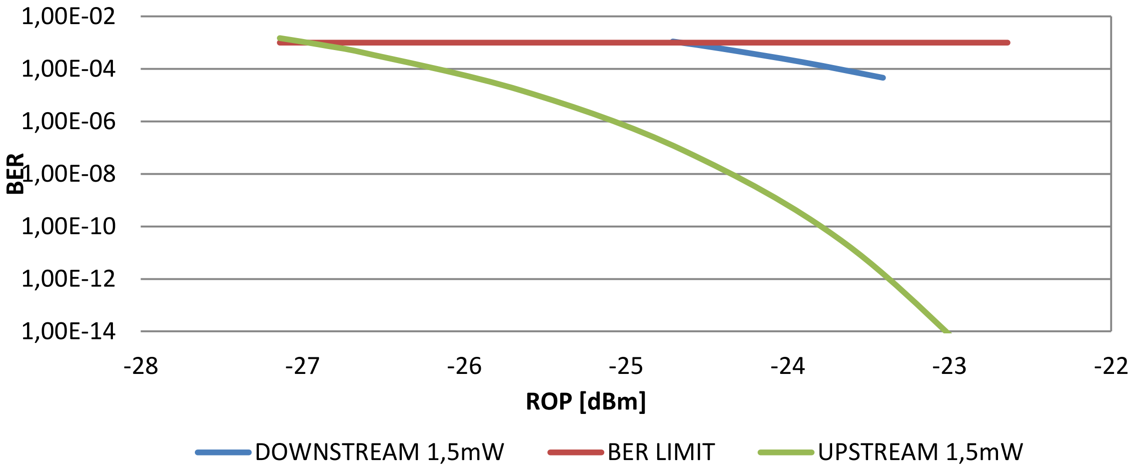

Figure 32. BER vs. ROP, for 10Gbits system, at distance 20km.

Figure above shows graphs of signal transmission for downstream and upstream directions, at different laser power supply. The values of individual channels transmitting are 2,5Gbps upstream and 10Gbps for downstream.

		BER	ROP [dBm]	Laser power
Back to back	GPON D	1,00E-03	-28,5	1,5mW
	GPON U	1,00E-03	-30,5	1,5mW
	XGPON D	1,00E-03	-26	1,5mW
	XGPON U	1,00E-03	-27	1,5mW
Considering fiber and splitter	GPON D	1,00E-03	-28,6	1,5mW
	GPON U	1,00E-03	-31	1,5mW
	XGPON D	1,00E-03	-24,6	1,5mW
	XGPON U	1,00E-03	-26,9	1,5mW

Tab10. Comparison of simulation results between GPON and XGPON

Figure 33 shows the influence of additional attenuation on the bit error rate. The signal in this case is a downstream transmission, exceeds the limit of minimum quality (BER) when additional attenuation reached value of 1,25 dB. This value is smaller than the GPON system, due to an increase in bit rate of the downstream

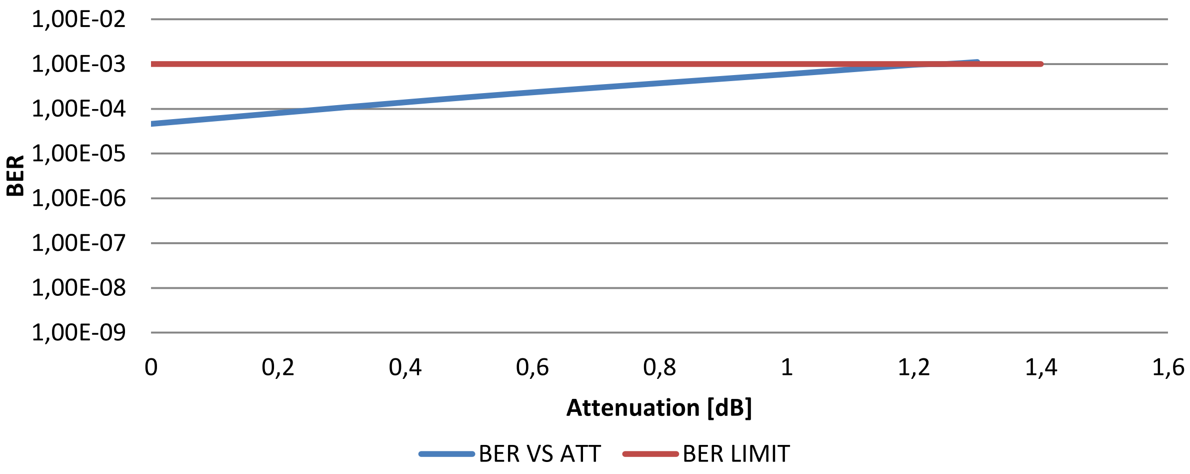

Figure 33. BER vs. Attenuation, for 10Gbits transmission system, distance 20km with splitter (downstream, laser power 1,5mW).

Course of the signal eye diagram (fig.34), shows the behavior of the signal in the optical path from the OLT to the ONU. We observed a significant signal distortion caused by dispersion. The course of signal is more rounded and the eye is more closed.

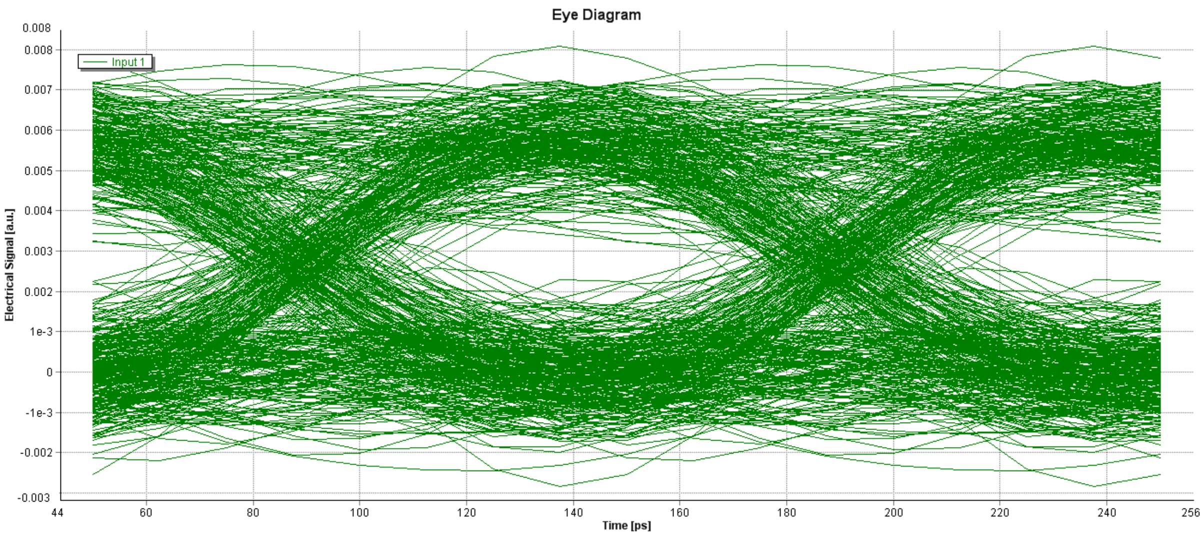

Figure 34. Eye diagram for XGPON , signal downstream optical path with splitter 1:64 and fiber 20km.

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4. Extender box.

4.1. Introduction

The simulations, presented in the previous chapters provides GPON and XGPON network limits. It was shown that it is possible a transmission to distance of 20km and up to 64 recipients. An additional amount of customers or increased distance will cause a significant reduction in the quality of signal received by the user or in the worst cases even the loss of connection. The simulation showed that in the case of GPON, the addition of 4 dB losses will overrun minimum level of signal quality, in the case XGPON is already at 1,25 dB.

In order to increase the PON reach, amplification / regeneration through an "extender box" is needed. The main objective of an extender box is to amplify / regenerate the signal level, to maintain an appropriate signal quality in PON. This component allows you to increase network flexibility, to increase the number of recipients and / or increase the distance of the network. At the same time saves the cost of rebuilding the network in case of expansion. A PON mid-span node extender could allow consolidation by locating OLTs in a reduced number of major central offices. An additional advantage is the extender, require minimal configuration and management. (Russell P. Davey, 2009)

Characteristics of standardization pertaining to extender boxes are recalled in February 2008, the ITU GPON standard for optical reach extension was finalized (ITU-T G987.4) This standard define 60 km reach with an optical budget higher than 27,5 dB achieved in both spans adjacent to the extender box. Both optoelectronic regeneration and optical amplification are considered as solutions for the extender box. The architecture considered is illustrated in figure 35. It can be noticed that a mid-span extender is inserted between the optical distribution network (ODN) and an optical trunk line (OTL). This enables both reach extension and increase in split ratio. A power supply is needed for the mid-span extender. (Fabienne Saliou, 2009)

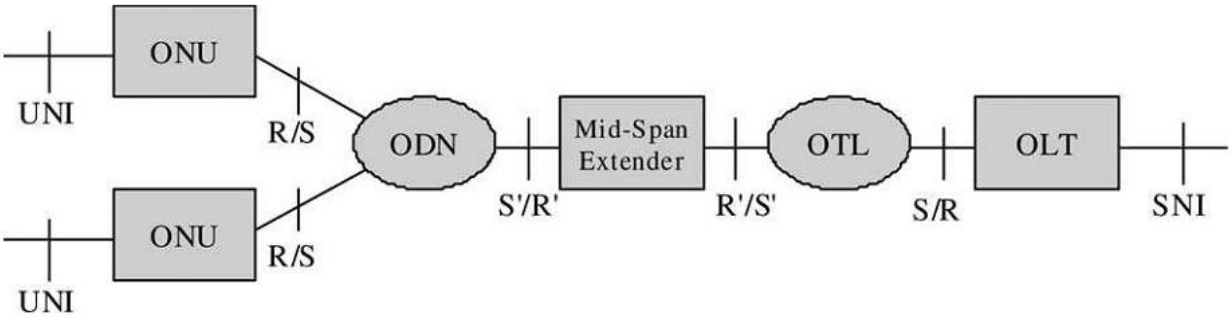

Figure 35. Mid-span reach extension. (Telecomunication standarization sector of ITU-T, 2008)

Semiconductor optical amplifiers (SOAs) are attractive candidates for GPON reach extension. They can provide high gain, low noise figure (NF), low polarization dependent loss, and fast gain dynamics that are suitable for mid-span PON signal amplification. They can be designed to provide gain in the 1310-nm (O-band) and 1490-nm (S-band) windows used by GPON. Other advantages of SOAs relative to fiber amplifiers in this application include their small size, high reliability, and low power consumption. (Russell P. Davey, 2009)

4.2. Simulations

4.2.1. Description

The simulation system is the same as in previous simulations of chapter 3.4. It was supplemented by a SOA and EDFA preamplifier as extender box(figure 36), for research purposes. The measurements focus on downstream transmission bitrates of 2,5 Gbps over a distance of 60 km, increased relative to previous simulations. In the setup the number of users will also be changed, in the first simulation 64, then 128. The observed results will help us determine the impact of the amplifier on the system performance.

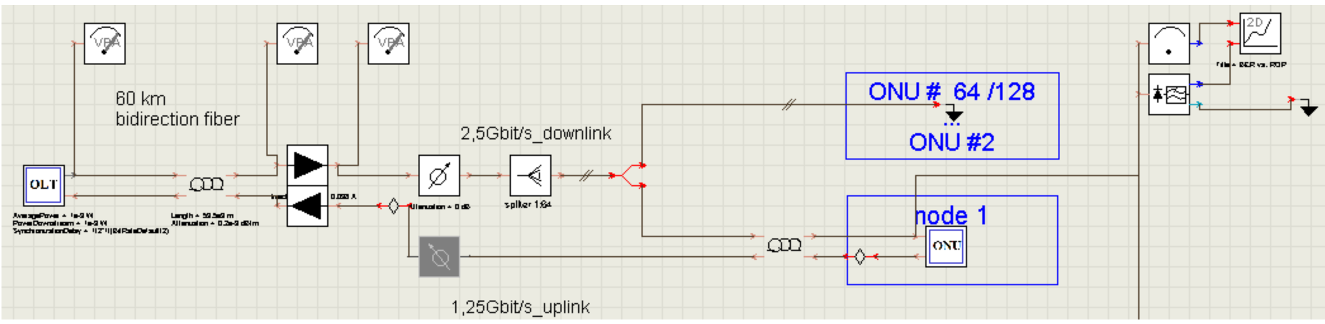

Figure 36. Circuit for measuring power budget, and the gain of the extender box.

In this case, the loss is as follows; 0,2 dB/km, resulting from the fiber, at a distance of 60 km, gives us a loss of 12 dB, and splitter losses, 1: 64, thus 18 dB, and for 1:128 is 21 dB.

4.2.2. Results

The goal is to identify the minimum gain value, that is needed to make the data transmission does not exceed the limit of bit error ratio of 10^{-3}. During simulation, the SOA pre-amplifier, acts as an extender box. For 2,5 Gbps downstream transmission was carried out two simulations, the first of which shows the use of extender box at a distance of 60km with 64 network users, in the second simulation the number of users was increased to 128.

The obtained results are presented respectively in figures 37, showing that in the first case, for 64 users, the gain needed is 4,75 dB. The first shows the minimum gain value that is needed to provide a signal to the receiver. Value of the power amplifier which introduces into the system is 4,75 dB. This reinforcement is possible to transmit over a distance of 60 km to 64 users.

This value is higher, because of the distortion introduced by SOA and account for extra dispersion. ODN power budget in this case is -28,5 dB.

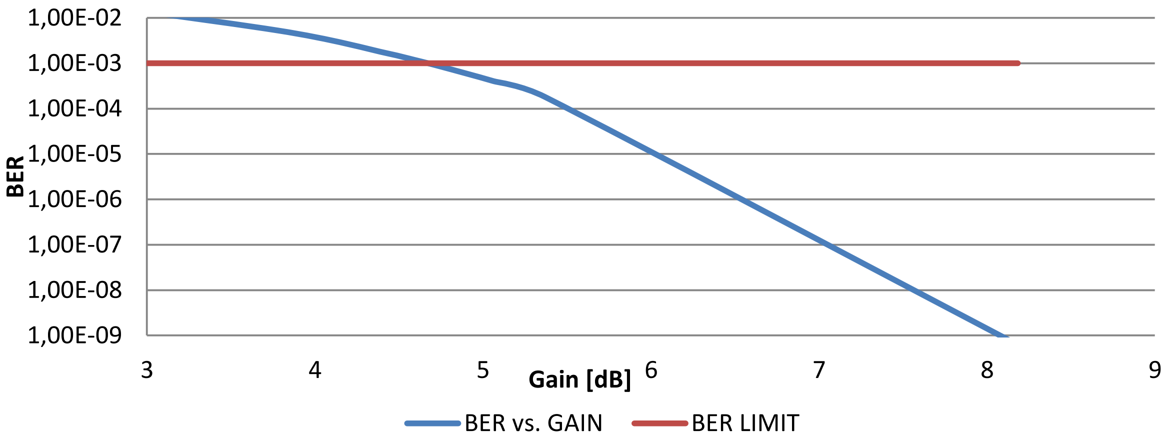

Figure 37. BER vs. Gain [dB] , extender box application to transfer 2,5 Gbps downstream at a distance 60 km and a 1:64 splitter.

Another simulation was carried out under the same conditions with an increased number of subscribers - to 128. Increasing the number of ports on the splitter, rises the signal loss caused by the division to more people. These losses are now 21dB.

Amplifier for signal regeneration in optical fiber link has to provide more gain than the previous one. The graph 38, shows the minimum value of this gain, which in this case is 7,7 dB. For the second case when used splitter 1:128 , ROP at the end of signal path was -28,6 dB.

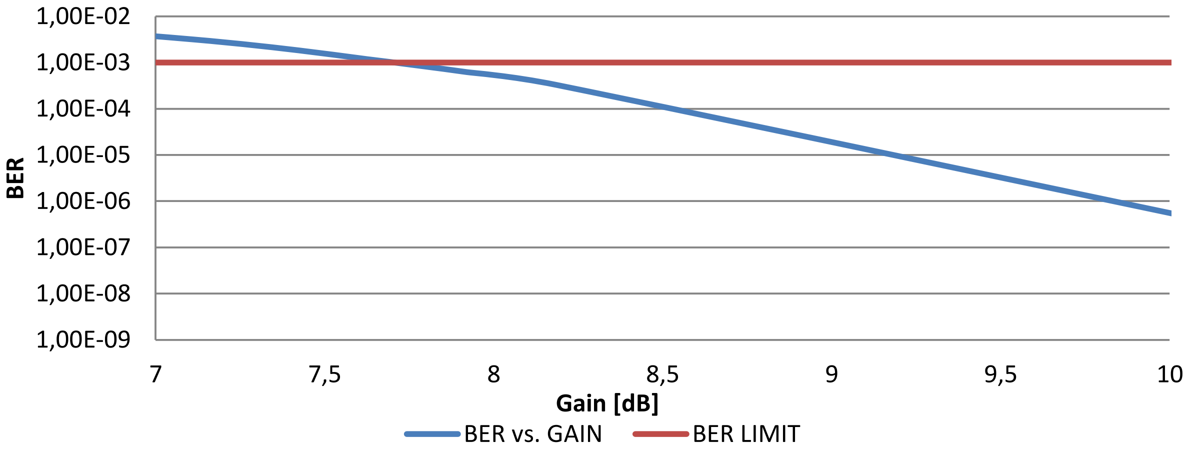

Figure 38. BER vs. Gain, extender box application to transfer 2,5 Gbps downstream at a distance 60 km and a 1:128 splitter , with SOA used.

Comparison of the amplifiers, the examination is based on the same characteristics of the system. Total distance of network is 60km, and conducted research for 64 and 128 customers. The following results show the effect of EDFA amplifier.

In the first simulation, the minimum value of the signal quality, we get the output if the signal is amplified by about 4,8 dB, presented by figure 39. Below this value, the signal will be saddled with too many errors, it means that the ISI will cause the received signal will be different than the signal given. Received optical signal at ONU of such gain is -28,5 dB. The gain is a result of many factors, components of the EDFA amplifier. The amplification must be greater than the absorption within the amplifier to obtain the gain.

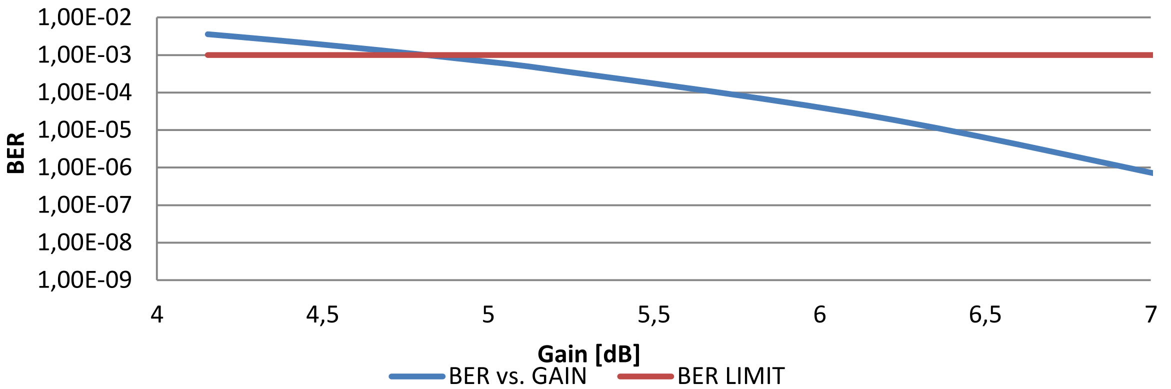

Figure 39. BER vs. Gain, extender box application to transfer 2,5 Gbps downstream at a distance 60 km and a 1:64 splitter.

Doubling the splitter to 128, increasing the signal loss caused by the division of an optical signal. This requires an increase in gain from the amplifier, is needed 7,86 dB as it shown at figure 40. Value of the power budget for the ODN is -28,4dBm.

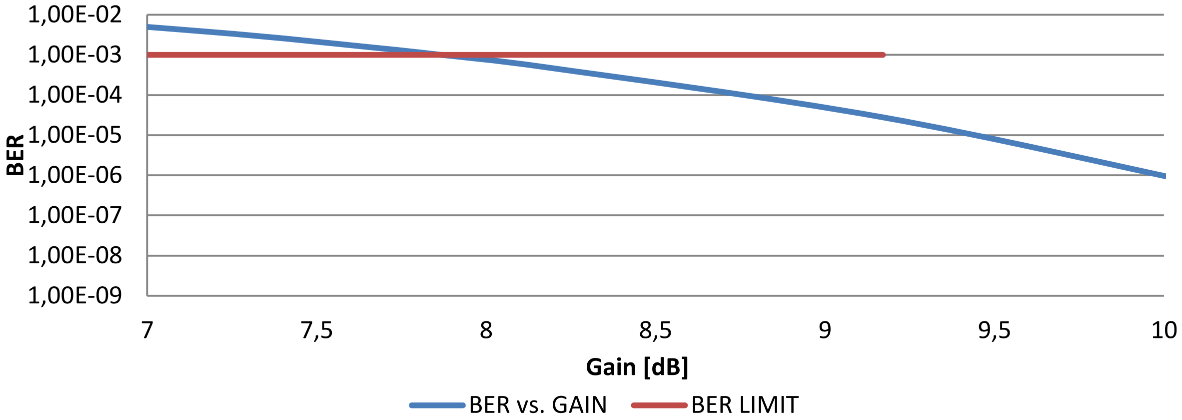

Figure 40. BER vs. Gain , extender box application to transfer 2,5 Gbps downstream at a distance 60 km and a 1:128 splitter, used EDFA.

Below is a eye diagram (figure 41) of the GPON simulation, taking into account the length of the fiber 20 km, amplifier and 1:64 splitter. The first diagram shows the signal of SOA amplifier, another type of EDFA amplifier. A significant improvement can be observed after the application of signal amplifiers. The signals have been reshape and strengthen, to reach the receiver.

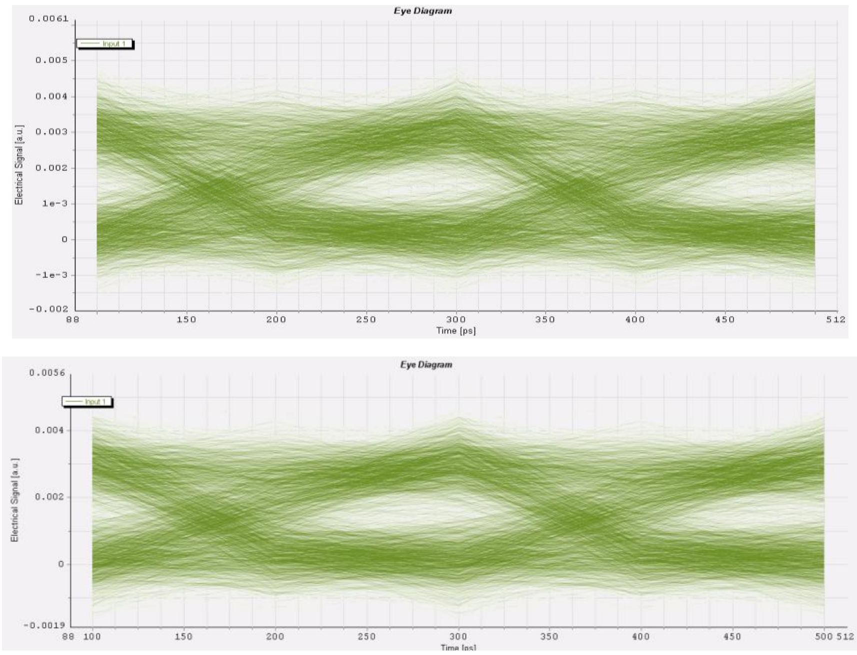

Figure 41. The first eye diagram shows the signal for downstream transmission with used of SOA, one for EDAF.

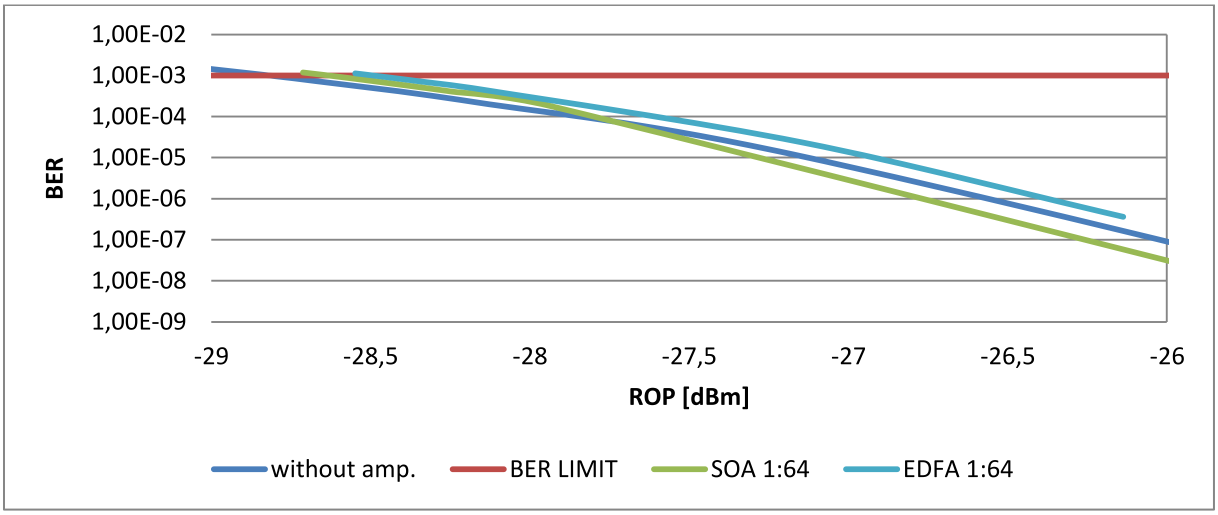

Figure 42. Results for optical network without amplifier and with SOA and EDFA amplifiers.

5. Laboratory

5.1. Introduction

This introduction is devoted to issues related to the work in the laboratory. In the next part will be a description of the laboratory, where tests were conducted. There will be presented diagrams of the optical network connection, and a description of the experience that has been done.

5.1.1. Laboratory equipment

For research purposes was used IXIA traffic generator (fig.43), connected to the corresponding elements of the optical network. The next most important elements are the signal transmitter OLT model OLT7-8CHOLT7-8CH, and the ONU receiver codenamed PTINONT7RF1GE. Furthermore, additional components were used in order to perform tests.

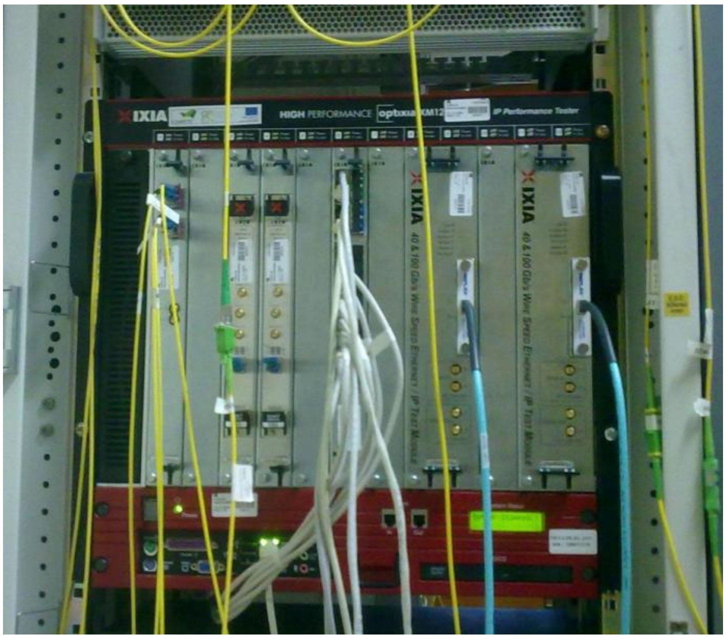

Figure 43. IXIA Optixia XM12 equipment.

Traffic Generator uses the appropriate software "IxNetwork," which allows remote control of hardware. This element is a very good way to simulate the behavior of real traffic data in the optical network. This card has several copper Ethernet ports That support up to 1Gbps in Full Duplex mode. Each port operates bi-directionally, allowing you to send and receive data traffic. GPON OLT hardware is cooperating with the traffic generator. It has eight Ethernet interfaces. The first is used to connect the OLT (fig.44) to the traffic generator IXIA. It has 8 connectors of PON, each of which can handle up to 64 recipients.

Figure 44. OLT.

Manufacturer	PT Inovação
Model	OLT7-8CH
Transmitter wavelenght	1490 nm
Receiver wavelength	1310 nm
Trasmit power (MGPON datasheet)	+5<Pout<+6 dBm
Trasmit power (measured)	3.6 dBm
Maximum receive power (MGPON datasheet)	-10 dBm
Receive sensitivity (MGPON datasheet)	-31 dBm
Transmit rate	2.5 Gbps
Receive rate	1.25Gbps
Connector type	SC-PC
Power supply	DC -48V
Working temperature	-5ºC to 50º C

Tab11. OLT parameters.

At the other end of the fiber network is ONU, picture of it is presented by figure 45. It recognizes OLT through appropriate configuration ID. The table describes the parameters OLT and ONU.

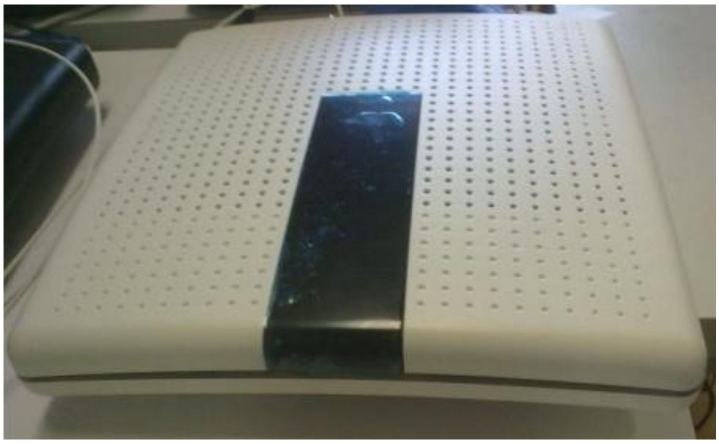

Figure 45. ONU.

Manufacturer	PT Inovação
Model	PTINONT7RF1GE
Transmitter wavelenght	1310 nm
Receiver wavelength	1490 nm
Trasmit power (MGPON datasheet)	+1 to +6 dBm
Maximum receive power (MGPON datasheet)	-8 dBm
Receive sensitivity(MGPON datasheet)	-27 dBm
Transmit rate	1.25 Gbps
Receive rate	2.5 Gbps
Connector type	SC-APC
Power supply	DC +12V
Working temperature	

Tab12. ONU parameters.

Another device that is a key element of research is the extender box. For the purpose of the laboratory was selected amplifier SOA. It has great potential transfer band in the bands S and O. Diagram of the amplifier is shown in figure 46. The various transmission channels within the amplifier are separated by the add / drop filter, who is also the noise filter. The device is equipped with a photo - detector, which measures the value of input and output of the system.

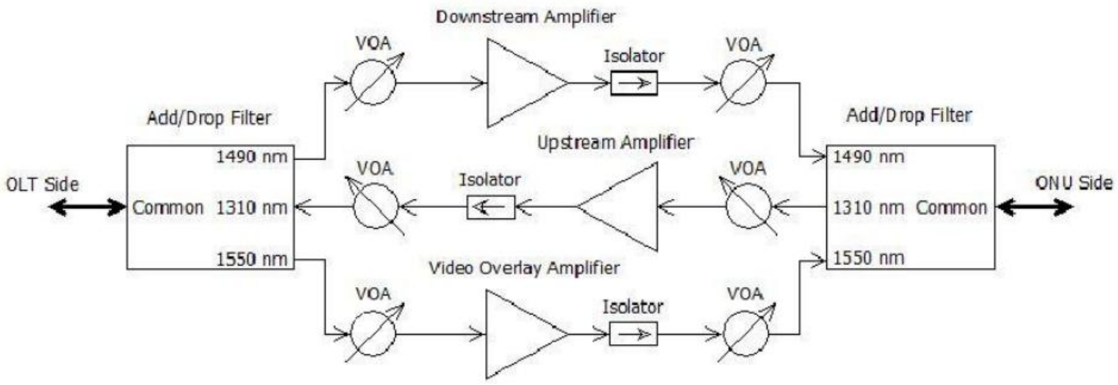

Figure 46. Extender box function scheme.

5.1.2. Description of the experience

The main goals of this study are to compare the GPON network performance without and with the extender box. Observe the changes that have introduced the system to include a signal amplifier. Make the appropriate power budget measurements for both systems. Based on the survey will receive appropriate proposals which will help in understanding the use and operation of the extender box. They will be included in the final section summarizes the entire research process.

For this purpose, it was built in the laboratory a GPON network system with appropriate parameters (fig. 47 and 48), 20km distance fiber and splitter 1:8. This will allow to check the layout of computer simulations were carried out earlier, and to determine the initial parameters, which are a reference point for further experiments. Next to the existing system will attach extender box. In such a system will conduct similar research networks.

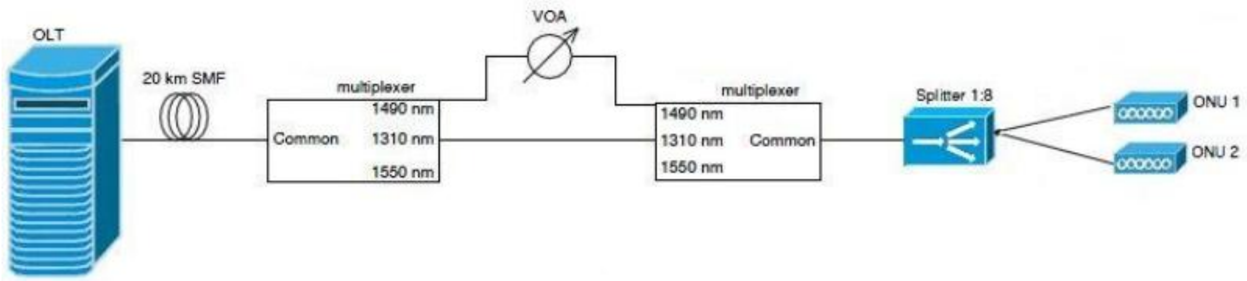

Figure 47. GPON system scheme for downstream transmission.

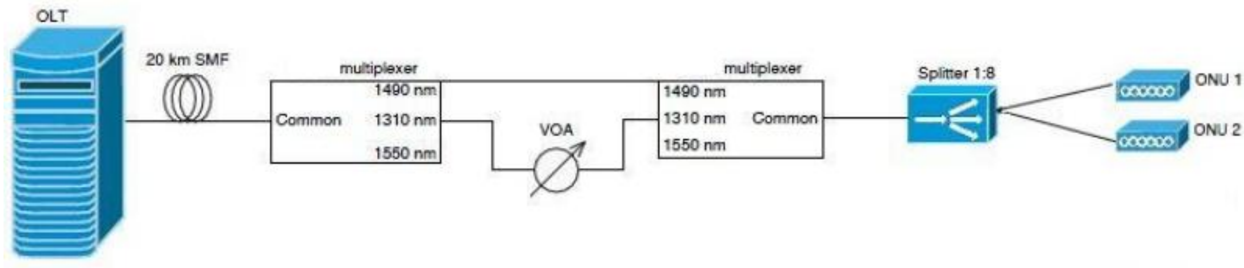

Figure 48. GPON system scheme for upstream transmission.

5.2.Results

The first test is performed on the system of figure 47 and 48. The aim is to characterize the GPON network power budget. The system was investigated in both transmission directions, downstream and upstream. The network is working properly when it is free from any losses. The experience that we have conducted is not fully identical with the simulation carried out using the VPItransmision Maker. Limitations that occur due to the limits of the device simulation of network traffic, IXIA traffic generator could provide a maximum speed of up to 1Gbps. During the test traffic generated in the system amounted to 400Mbps.

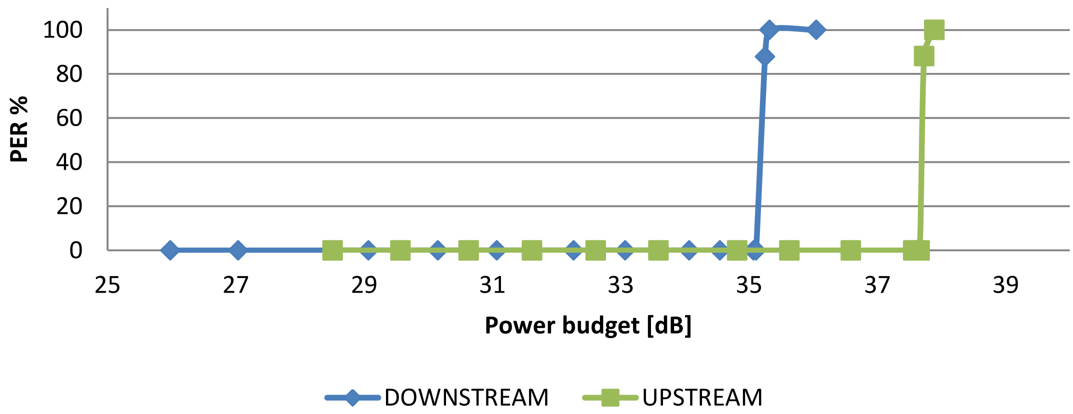

Figure 49. Power budget for GPON.

For transmission downstream, maximum power budget is 34 dB. This is the value above which packet error ratio starts to rise above the zero, described by figure 49. This means that the limit is exceeded, packets sent by the growing amount of errors - misread packets. The complete loss of signal power is obtained at 35dB.

For the analysis in the opposite direction - upstream, the maximum power budget is equal 36 dB. The total loss of transmitted packets correctly yields the power budget of 38 dB (fig 49).

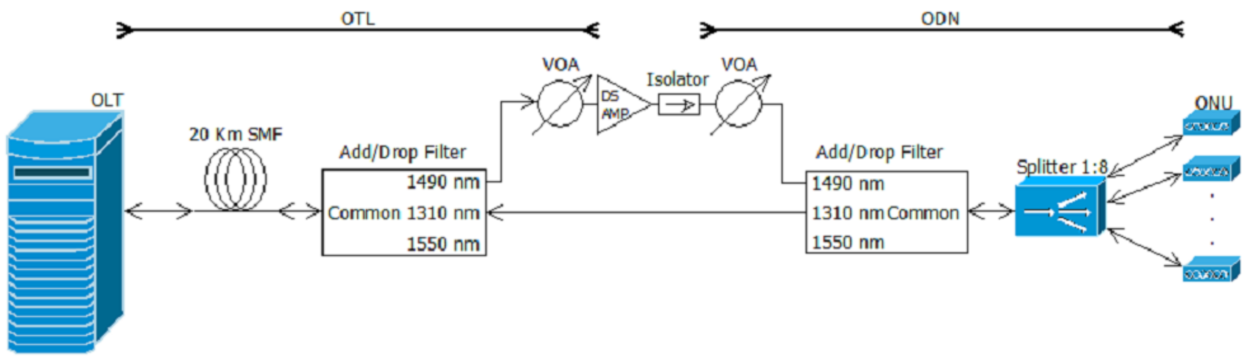

Figure 50. Extender box added to GPON network, scheme.

Next experience is carried out with the use of extender box for the downstream signal. Measurement was made under the budget of the signal at different values of OTL. Figure 50 above, shows the diagram of the network connection. The simulations (fig. 51) are for fixed values of OTL, and the corresponding values of ODN:

- 10dB at OTL and 28 dB at ODN;
- 15dB at OTL and 27 dB at ODN;
- 20dB at OTL and 26 dB at ODN.

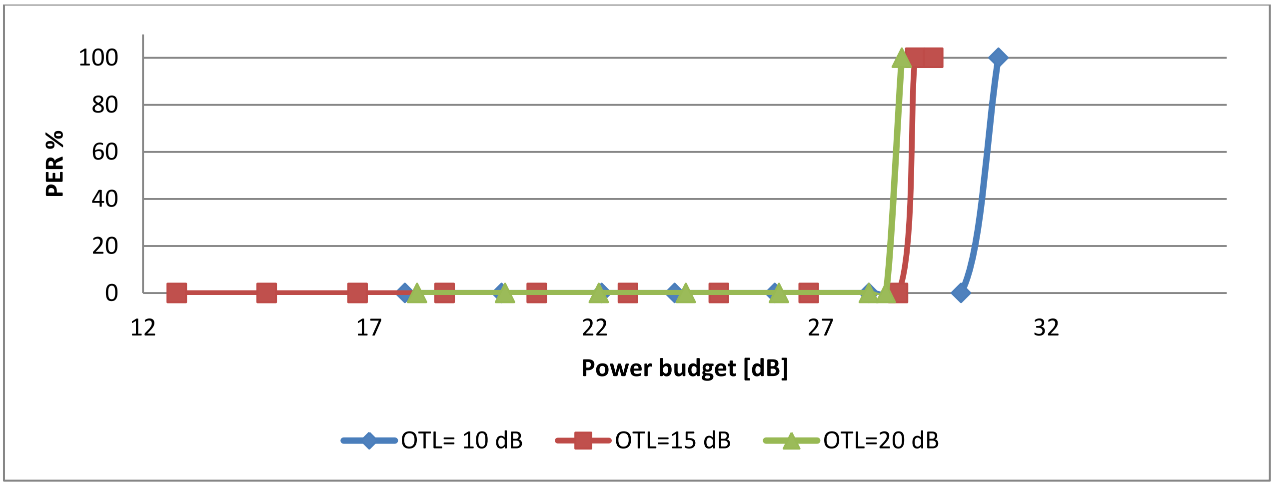

Figure 51. PER as a function of ODN power budget for different OTL power budget.

Work of amplifier is to strengthen in an appropriate manner the transmitted signal. For this purpose extender box contains the possibility to adapt itself to operate at the optimum environment - allowed by the standard. The device is in the area equipped, VOAs - Variable Optical Attenuators, which put the SOAs in their best operating point, adapting the gain. At the ODN, the signal range is between 26 and 28 dB. This range is recommended by international standards (13 and 28 dB) and for OTL scope of the survey is 10, 15, 20 dB. In this case, the value of norm should be approximately 23dB. In the case of a downstream.

Comparing the results gained from the experience of simulation, we can determine that for the same value of OTL, the result of power in the ODN, is the same. Simulation has been confirmed experimentally, and the behavior of the amplifier enabled to receive a signal within the range specified standards. In the case involving the simulation of extender box (Chapter 4.2) OTL value was approximately 15 dB and the ODN for the amplifier SOA approximately 28dB.

6. Conclusions and further work

Work on the main level is dedicated to a GPON optical network. This system is a answer to a increased demand operators, for more increasingly users demanding. It describes in detail the operation of the network. The use of FTTH technology, which allows the use of fiber and increases the speed of data transfered directly to the recipient. GPON study, included in the work identified the limits of the area that is in the form of distance and the number of potential customers. This became the basis of the transition to the next upgrade and add to the network an extender box.

Successive conducted simulations and laboratory experiments have identified a new network coverage and its parameters. Measurements were made under the budget for the system and compared with the guidelines of international standards. At the same time work allows to understand the validity of the use of optical amplifiers and their performance.

One of the chapters describes the use of XGPON network, is another stage of GPON networks. XGPON increased data transfer to 10 Gbps downstream and 2,5 Gbps upstream. In addition, it has a wider range of activities, more customers, far range.

The use of extender box is a smooth transition of GPON technology to XGPON, and later to the NG-PON systems. Allows the reduce of costs. or their spread, over a longer period during the network upgrade. Amplifiers used in systems such FTTC / B can also be used in the XGPON.

The current PON systems have their limitations, one of which is the capacity, arising from the applied technology, data base using time division based on TDM (Time Division Multiplexing). Another solution 10G-EPON and XG-PON1 are also systems using TDM, TDMA, operating at a higher data rate. It also allows the use of optical amplifiers to expand the network to more areas of activity.

As a work in the future, a new quality of service and a facility of a better transmission type is WDM-PON network. Operation of the system is not based on TDM or TDMA as in the case of GPON. However, it also excludes the possibility of using this feature. Multi wave WDM-PON structure via pairs installed in each channel optical wave, allows for flexible dosing and transport scaling to smaller bit rates, as well as more cost-effective use of resources specific optical broadband.

The main principle of WDM-PON system consists in assigning to each subscriber (ONU, ONT) is steam (up / down) dedicated optical channels at different wavelengths lambda (λ). The system can without collision handle a single fiber several wavelengths in one direction or both directions by one or two fiber WDM. This approach ensures that each node dedicated to this application central office - OLT, in addition to ease of use (transmission optical point-to-point), facilitates the connection of subscribers following their desired speed and protocol, together with guaranteed QoS expected by the audience.

List of images

List of tables

List of acronyms

1G	First Generation
2G	Second Generation
10GPON	10 Gigabit Passive Optical Network
AM	Amplitude Modulation
ASK	Amplitude Shift Keying
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
CDMA	Code Division Multiple Access
CNR	Carrier-to-Noise Ratio
CO	Central Office
C.S	Carrier Suppressed
CW	Continuous Wave
dB	decibels
dBm	decibels milliwatt
DWDM	Dense Wavelength Division Multiplexing
FM	Frequency modulation
EDFA	Erbium Doped Fiber Amplifier
Gbps	Gigabit per second
GHz	GigaHertz
GVD	Group Velocity Dispersion
GPON	Gigabit Passive Optical Network

IEEE	Institute of Electrical and Electronics Engineers
ISI	Intersymbol Interference
LAN	Local Area Network
LO	Local Oscillator
LPF	Low-Pass Filter
Mbps	Megabit per second
MHz	Megahertz
MMF	Multi Mode Fiber
MZI	Mach-Zehnder Interferometer
MZM	Mach-Zehnder Modulator
NF	Noise Figure
OCS	Optical Carrier Suppression
OEO	Optic-Electric-Optic
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OFM	Optical Frequency Multiplication
OLT	Optical Line Terminal
ONT	Optical Network Termination
ONU	Optical Network Unit
OSNR	Optical Signal to Noise Ratio
OOK	ON-OFF Keying
PD	Photodetector
PMD	Polarization Mode Dispersion

PM	Phase Modulation
PON	Passive Optical Network
PRBS	Pseudo-Random Bit Sequence
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SGM	Self Gain Modulation
SMF	Single Mode Fiber
SOA	Semiconductor Optical Amplifier
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
TDM	Time Division Multiplexing
VCSEL	Vertical Cavity Surface Emitting Laser diode
VPI	Virtual Photonics Inc. (simulation software manufacturer)
WDM	Wavelength Division Multiplexer
XGM	Cross Gain Modulation
XPM	Cross Phase Modulation
XGPON	10 Gigabit Passive Optical Network

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