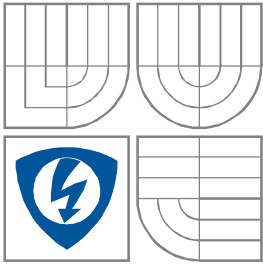


BRNO UNIVERSITY OF TECHNOLOGY



FACULTY OF ELECTRICAL ENGINEERING
AND COMMUNICATION

DEPARTMENT OF TELECOMMUNICATIONS

DESIGN OF PASSIVE OPTICAL NETWORK

MASTER'S THESIS

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Specialization of study: Communications

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ABSTRACT

The steady increase in the demand for broadband services and the consequent increase in the volume of generated traffic in our communication networks have motivated the need to implement next generation networks in our territories. This master's thesis aims to explain the design and planning of a passive optical network (PON). The main idea of this project is to build a fictitious environment that will allow us to study in depth on FTTx networks and decide which the most optimal option for this environment. To make this possible, first, we will look into the main element of these networks, optical fiber, in order to get to know its operating principles and most important features in detail. The theoretical part will be followed by the definition of FTTx networks and point-to-point and point-to-multipoint configurations, moving to elaborating at length on PON and conclude which of its technologies will be the most optimal ones nowadays. Finally, in the practical part, simulation software that meets the design requirements will be chosen, the design of passive optical network will be made and in the simulation results which justify that the network is viable and can be implemented in a real case will be obtained.

KEYWORD: Optical fiber, Passive Optical Network, FTTx, Point to Point, Point to Multipoint, WDM, Simulation

Design of Passive Optical Network

Proyecto Final de Carrera

Especialización: Comunicaciones

Autor: Juan Salvador Asensi Pla

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RESUMEN

El constante incremento en la demanda de servicios de banda ancha y el consecuente aumento del volumen de tráfico que se genera en nuestras redes de comunicaciones, han motivado la necesidad de implementar redes de nueva generación en nuestros territorios.

El presente proyecto final de carrera tiene como objetivo explicar el diseño y la planificación de una red pasiva de fibra óptica (PON). La idea principal de este proyecto es construir un entorno ficticio que nos permitirá profundizar en detalle en las redes FTTx y decidir cuál es la opción más óptima para este entorno. Para hacer esto posible, en primer lugar se va a hablar sobre el elemento principal de estas redes, la fibra óptica, para conocer con detalle sus principios de funcionamiento y sus características más importantes. La parte teórica seguirá con la definición de las redes FTTx y las configuraciones punto a punto y punto a multipunto, para pasar a hablar detenidamente sobre las redes PON y concluir cual de sus tecnologías será la más óptima hoy en día. Por último, entraremos en la parte práctica en la que se elegirá un software de simulación que se ajuste a los requisitos de diseño, se realizará el diseño de la red óptica pasiva y se obtendrán los resultados de simulación que justifiquen que la red es viable y puede ser implementada en un caso real.

PALABRAS CLAVE: Fibra óptica, Red Óptica Pasiva, FTTx, Punto a Punto, Punto a Multipunto, WDM, Simulación

PROHLÁŠENÍ

Prohlašuji, že svoji semestrální práci na téma "Návrh sítě FTTx" jsem vypracoval samostatně pod vedením vedoucí semestrální práce a s použitím odborné literatury a dalších informačních zdrojů, které jsou všechny citovány v práci a uvedeny v seznamu literatury na konci práce.

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V Brně dne 17/05/2011

.....

podpis autora

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Chapter 1

Introduction

The optical fiber is the most advanced transmission medium and the only one capable of supporting next generation services. The main advantages of having a last mile of optical fiber are many: higher bandwidth, longer distances from the central to the subscriber, the more resistance to electromagnetic interference, increased security, reduced signal degradation... Moreover, the fact of using PON technology assumes the elimination of repeaters and optical amplifiers and therefore reducing the initial investment, lower power consumption, less space, fewer points of failure...

The proliferation of broadband applications such as high definition television (HDTV) broadcast, broadband Internet access or teleworking, has created a growing interest among service providers by improving networks to supply broadband services to residential and small business. To make this possible there must be a high efficiency between the total cost of infrastructure and services that can be offered to end users. The Wavelength Division Multiplexing (WDM) is the technology that can deliver the best solution by considering the Dense Wavelength Division Multiplexing (DWDM) for long distance applications and Coarse Wavelength Division Multiplexing (CWDM) as the ideal solution for access networks and metropolitan areas, taking into account the tradeoff between the cost of components and the ability of services offered. For example, CWDM using a channel spacing of 20 nm can relax the tolerances of the components used, such as filters, multiplexers and demultiplexers, routers or switches and the operating characteristics of the active components such as lasers.

The objective of this thesis aims to demonstrate that the last mile can also be constructed from fiber, giving to the same the benefits of the information transmission through this medium. These networks, which have already taken their first steps in some areas of eastern EU and Japan, are called FTTx (Fiber To The x). Therefore, it will detail how an optical fiber deployment could be made in a fictitious environment formed by five different areas that could easily fit to the expansion of a big city.

Throughout this document is going to provide a description of the theoretical basis, major characteristics and parameters of the optical fiber, to help the reader to understand how this transmission technology works and all the advantages that offers over other types of networks such as copper or coaxial cable. Once seated the knowledge of the optical fiber is passed to briefly define the types of FTTx networks that exist and their configurations point-to-point and point-to-multipoint. With this, it will have the information needed to describe in more detail the principles of Passive

Optical Networks (PON). In another chapter it will discuss the generic operation of a PON, taking into account all elements of this type of network and which are its advantages compared to Active Optical Networks (AON). Subsequently it will analyze in detail the various types of PON networks, the new next-generation PON (NG-PON) to conclude which will be the optimum technology for this design. Finally, taking into account all design considerations, it will make a detailed planning of what will be the network with all the necessary elements for deployment. The last step will be to choose a simulation program that meets all design requirements, execute the design and get the results that demonstrate that the design of passive optical network works and therefore is viable for practical implementation.

To be able to establish high-speed services to end users, it is necessary that the engineering design of the network passes through two clearly differentiated phases:

1. The design of the passive optical network. It is the first phase of design and comprises all physical and structural elements that make up the fabric of the network, since its beginning in a central office to each household or businesses which the service is provided.
2. The design of the active network. It is the second phase of design and is comprised of all communication equipments and other active elements that allow the data transfer from the central office to the homes, and which provide services to end users.

Since the second phase of the design consists on the installation of very specific characteristic equipments of each manufacturer and will be supplied by the operator which will provide the end services, it is not important to achieving the objectives of this project.

Communications equipments that constitute the active part of an FTTx network are not relevant for the transfer of information because they only filter user services by one or more geographical areas. It will only be subject to development of this project the passive network design. The fact that the study is very general allows the physical network design can be extrapolated to any situation and any network of the same type.

Chapter 2

Fundamentals of Optical Fibers and Communication

Given the importance of the transmission channel for a good communication, throughout this chapter it will detail all general aspects with which must have take into account in a network of fiber optic transmission. The main element of study in this chapter is the optical fiber, around which it shall specify the other key elements in an optical communication network.

2.1. Introduction

Optical fiber is a transmission medium commonly used in data networks, like passive optical networks and others. It can be defined by a thin, transparent and flexible glass or plastic, by which light pulses are sent in order to represent data to be transmitted. The beam is completely contained and it spreads inside the fiber at an angle of reflection above the critical angle of total reflection, according to Snell's law.

Optical fibers are widely used in telecommunications, since they allow sending large amounts of data at a great distance and having higher bandwidths (data rates) than other forms of communication. They are the transmission medium par excellence to be immune to electromagnetic interference and because signals travel along them with less losses.

This transmission mode allows the transport of a multitude of information, used for applications such as broadband Internet, telephone and cable television, through more effective signals than copper wires.

Throughout the chapter, it will detail the generic characteristics of the optical fiber particularizing the most influential aspects of it on the passive optical fiber networks.

2.2. Basics of optical fibers

As mentioned above, optical fiber is a dielectric waveguide that operates at optical frequencies and transmits information in the light form along its axis.

In this section it will explain the principles and physical laws that obey any type of optical fiber and make possible their operation as optical waveguides.

2.2.1. Electromagnetic waves

An electromagnetic wave is the propagation of electromagnetic radiation through space and theoretical aspects are related to the waveform solution that supports Maxwell's equations. Unlike mechanical waves, electromagnetic waves do not require a material medium to propagate; i.e., they can move through the vacuum.

Light waves are electromagnetic waves whose frequency is within the range of visible light. Each pulse of light is a single electromagnetic field in propagation or "mode". Particularized solutions for Maxwell's equations for the various pulses of light are those that determine the propagation of electromagnetic fields in waves through optical fiber.

In light waves, like all electromagnetic waves, there are electric and magnetic fields at each point of space, which fluctuate rapidly. As these fields also have a magnitude and a given direction, they are vector quantities.

Other important concept in relation to the waves is the number of oscillations per second at a point of the light wave, which it is known as frequency. Also important is the concept of wavelength, which is defined as the distance along the direction of propagation between two points in phase, i.e., points occupying equivalent positions in the wave.

Below is an example of wavelength in a sine wave:

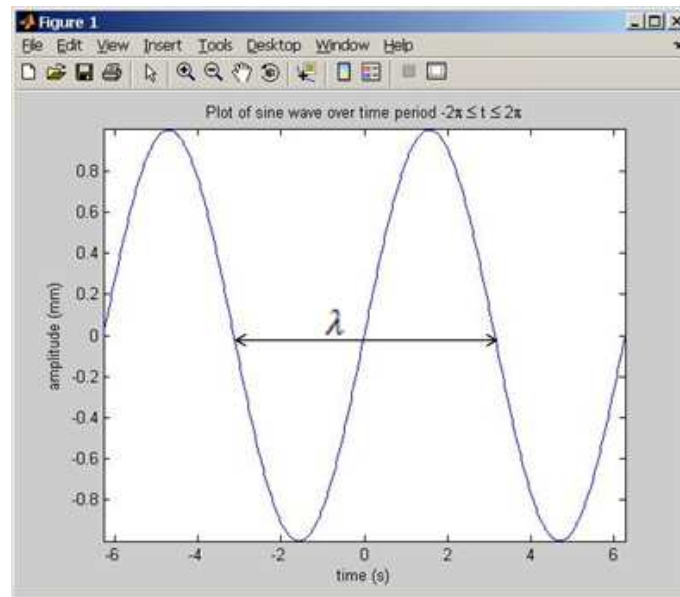


Figure 1: Representation of a sine wave of 2π period

There is another important parameter that defines another property of waves, which is the speed propagation of it on a particular environment. Thus, there is a direct relation between speed of propagation, frequency and wavelength. The speed of an electromagnetic wave is defined as the product of frequency and wavelength:

$$v_p = \lambda \cdot f \quad (1)$$

In cases in which the wave propagates through a vacuum, the above equation is particularized assigning the value of the propagation speed of light speed in vacuum c , being $c = 3 \cdot 10^8 m/s$, and λ_0 the value of wavelength in a vacuum:

$$c = \lambda_0 \cdot f \quad (2)$$

There are thus, infinite values of λ and f that satisfy the equation (1), and in fact, there is a wide range of electromagnetic waves whose characteristics obey this equation. The set of these waves is called spectrum given the enormous range of variation of the wavelength.

The following figure shows the electromagnetic spectrum of light, depending on the wavelength and frequency:

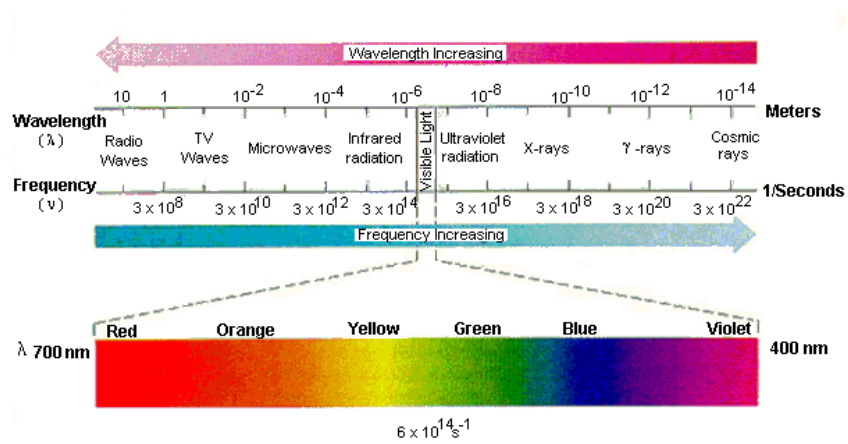


Figure 2: Electromagnetic spectrum of light
 [http://chemed.chem.purdue.edu/genchem/topicreview/bp/ch6/index.php]

In the visible spectrum, different wavelengths are differentiated by colors. This way, the visible range is from 350 nm (violet) to 750 nm (red). White light is obtained from the mixture of all visible wavelengths.

The speed of a wave in a vacuum is always the same regardless of wavelength, and therefore, it is equal for all wavelengths. However, the speed of light in material substances is lower than in a vacuum and it varies for different wavelengths.

This will allow defining the index of refraction in the next section.

2.2.2. Refraction and reflection

When a ray of light propagates through a homogeneous medium and strikes the surface of a second homogeneous medium with different composition, part of the light is reflected and the other part penetrates as a refracted ray in the second medium, which may or may not be absorbed. Then, refraction produces a change in the direction of a ray or beam of light rays entering in the medium with different propagation speed.

The plane of incidence is defined as the physical plane formed by the incident ray and the normal (i.e., the vector perpendicular to the surface of the medium) in the point of incidence.

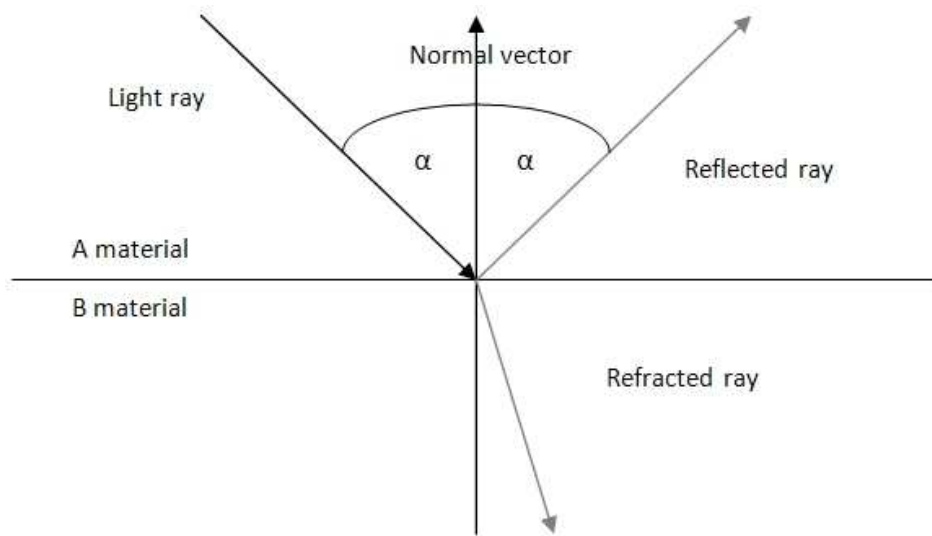


Figure 3: Law of Reflection and Refraction

This way, we can say that the light beam incident on another medium with different composition or transmission speed of light is divided into two beams: one reflected in the first medium, and the other refracted crossing the edge.

From the above theory, in which a beam is subdivided into two beams of light traveling on different mediums, it can extract two fundamental laws of optical physics to quantify the two events: the Law of Reflection and the Law of Refraction, also known as Snell's Law.

The Law of Reflection says that when a light ray strikes on the boundary between two homogeneous and isotropic transparent mediums, part of the incident beam is reflected at the same angle and the other part is transmitted to other medium.

Other important law to understand the operation of the light guided within the fiber is the Law of Refraction (Snell's law). To understand this law, first it must define the index of refraction as the relationship between the speed of light in vacuum (c) and the speed of light in that medium (v_p).

$$n = \frac{c}{v_p} \tag{3}$$

Once this is understood, the law of refraction says that the relationship between the sine of the angle of incidence and the sine of the angle of refraction is equal to the ratio of the speed of the wave in the first medium and the speed of the wave the second medium, or better known by the following formula:

$$n_1 \cdot \sin \theta_1 = n_2 \cdot \sin \theta_2 \quad (4)$$

Where: n_1 = refractive index of the first medium, θ_1 = Angle of Incidence, n_2 = index of refraction of the second medium and θ_2 = angle of refraction.

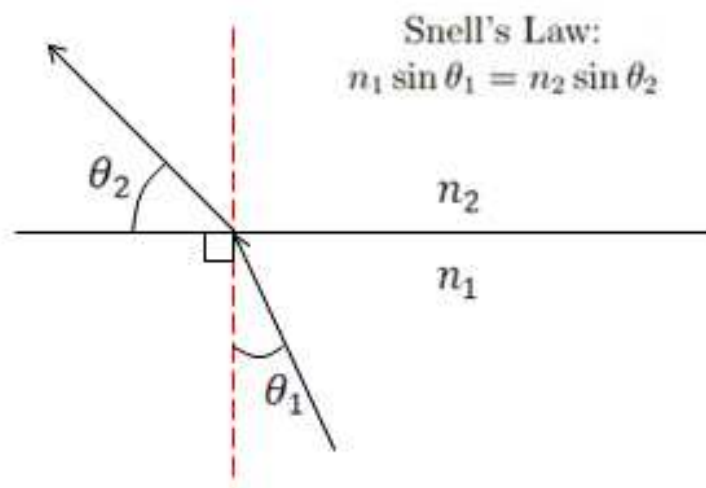


Figure 4: *Snell's Law*

Another important concept that it must take into account for the guiding of light within the fiber is the Total Internal Reflection, which is based on the Law of Reflection.

The Total Internal Reflection phenomenon occurs when, in the refraction, the angle of incidence is greater than the critical angle, and therefore all light is reflected.

In the area of interest to this project, it is noteworthy that the optical fiber is a new practical application of total internal reflection. Thus, when light enters through an end of a solid tube of glass or plastic, it can be totally reflected on the outer surface of the tube, and after a series of successive total reflections, out the other end.

All these concepts are needed to explain how information can be transported over our optical fiber networks. In order to do this, in the next section it will explain the operating principle of light within an optical fiber.

2.2.3. Operating principles of optical fibers

It is important to note that, to make possible transmission of information through optical fiber, it is necessary to inject light beams from a light source (usually LED or LASER) in the same fiber.

Incoming light pulses enter into the fiber core, and get passed through it bouncing off the walls lining that surrounds the core. This is possible because the refractive index difference between core and cladding, and because the refractive index of the coating is less than the core. Finally, the light rays reach the opposite end of the fiber, which arrive at the receiver and they are transformed into electrical signals.

In short, the principle of operation of the optical fiber is based on the principle total internal reflection, which has been explained in the previous section. The transmitter emits rays of light at an angle of incidence greater than critical angle allowing the transmitted beam is reflected first in the coating.

This same process is repeated again and again through the entire cable. Since angles of incidence and reflection are equal, some beams continue to be reflected and transmitted in a zigzag pattern through the entire length of the fiber. Thus, the light energy from the transmitting source is contained in the nucleus.

However, not all the beams of light from the power source Light enter to the core, or they enter but cannot be transmitted through internal reflections in the fiber. This is because the light hitting the interfaces core-cladding, it makes this with a less angle than the critical angle, losing that energy into the coating by refraction.

Below is the principle of propagation through optical fiber based on Snell's law:

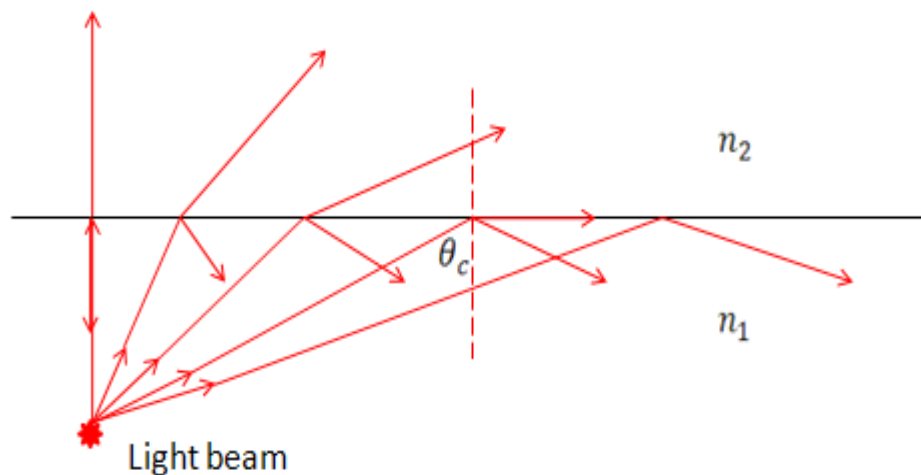


Figure 5: Principle of operation of optical fiber

In Figure 5, a reference rays are taken with different incident angles on the fiber core, which holds that $n_1 > n_2$.

Looking from left to right, the first three rays have a lower incidence angle than the critical angle, so that the beam is refracted on the cladding, losing energy in the core of the fiber.

The fourth beam, has an incidence angle exactly equal to the critical angle, therefore the phenomenon of total internal reflection occurs for the first time but dissipates energy at the boundaries.

The fifth ray, which has an incidence angle greater than the critical angle, it obeys the Law of Total Reflection for the remainder confined to the core.

If we consider that all light rays impinge at an angle above the critical angle are trapped inside the nucleus, a virtual cone is generated and is called the cone of acceptance. Therefore, all rays impinging on the fiber outside the cone of acceptance do not propagate through it lengthwise. It can be represented graphically as follows:

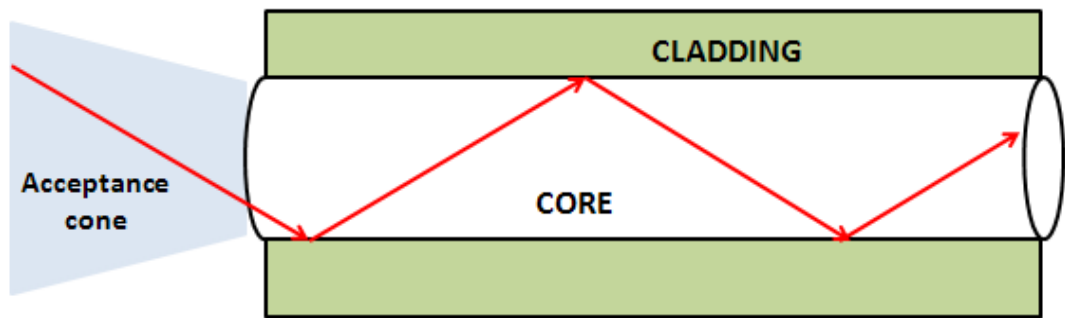


Figure 6: *Optical fiber cable acceptance cone*

The larger the cone of acceptance of an optical fiber, the greater the amount of rays can be transmitted by such mediums, and therefore does not need to be so precisely at the time of emitting light from the transmitter. Moreover, a greater number of beams of light inside the fiber, it involves a variation in the directions of propagation of the rays, and their quality decreases.

2.2.4. Composition and geometry

The fiber optic cables are manufactured with various materials to achieve the effect described above and adapt to the environment of the installation. Thus, external cables must be strong, weatherproof and resistant to ultraviolet radiation (UV) and maximum temperature variations that can occur during installation and throughout its life. On the other hand, the internal cables must be strong and flexible, with the required degree of fire resistance or smoke emission. The most common components are: polyethylene, polyvinyl chloride (PVC), polyurethane, and polyfluorinated hydrocarbons, ethylene vinyl acetate, aramid ropes... and other materials for the steel shell, torn wire, the central member and interstitial filling [6].

An optical cable consists of a set of generic elements present in any cable, regardless of the structure and composition. It can be present the optical cable as a structure consisting of six concentric layers, being these:

- Optical fiber: This layer is composed of optical fibers responsible of transmission of information. (1)
- Secondary Protection: mechanical protection that usually is loose or dense, with interstitial filler. (2)
- Traction element: typically Aramid, Kevlar or fiberglass. (3)

- Protective inner cover: made of PE, PVC or polyurethane. (4)
- Protective shell, usually steel. (5)
- Protective outer jacket: PE, PVC, polyurethane or fluoropolymer. (6)

In Figure 7 is shown the most important elements of an optical fiber that are described above and encoded with numerology 1 to 6:

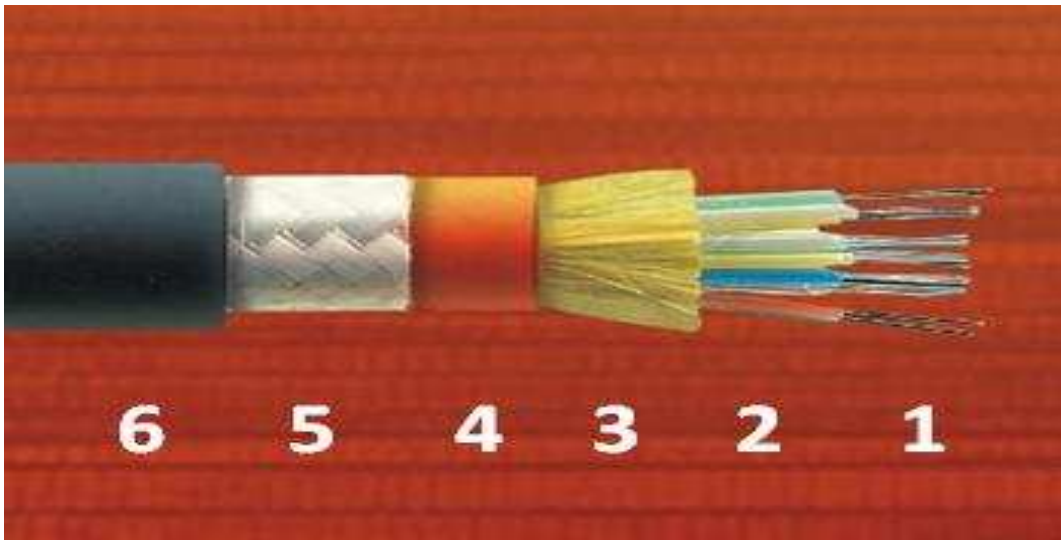


Figure 7: Structure of optical fiber cable

Based on the above generic settings and their respective concentric layers, there are several basic structures of optical fiber cables. The most common are cables with loose structure and cables with dense or adjusted structure, but there are other less significant structures such as armored cables, self supporting aerial, submarines, OPGW, hybrid and composite, etc...

Turning now to the important part of the cable, which is the same optical fiber, it can say that any optical fiber consists essentially of three concentric layers or structures which are detailed below:

Core: The core, also known as transmitter tunnel, is the innermost part of the fiber and is responsible for driving the optical signals from the light source to the receiving device. It is one continuous glass fiber made from high temperature ultra-pure quartz, plastic or silicon dioxide.

Often, the silica glass (SiO_2) is usually doped with materials such as phosphorus oxide (P_2O_5), germanium oxide (GeO_2) or boron oxide (B_2O_3) to adjust its refractive index.

It has a very small diameter, ranging between 10 to 300 μm . The higher is the core diameter the greater the amount of light the cable can carry. Indeed, the fiber optic cables across the board are classified according to their diameter.

Cladding: It is the middle part of the fiber, which surrounds and protects the core. This medium has a refractive index lower than the core, so that acts as a reflective layer which keep the waves trying to escape the nucleus.

It is manufactured with high temperature and made of silicon crystalline nature, and is generally quartz or transparent plastic. This layer usually adds several layers of plastic to absorb the potential impact or shock that the fiber can get and provide extra protection against excessive cable bending.

Coating or buffer: The coating is the outer part of the fiber and acts as a shock absorber, protecting the core and the cladding from damage and external agents. In short, the cable provides some mechanical protection to manipulation. It is made of plastic material, capable of protecting the fiber from moisture, crushing, rodents and other environmental hazards.

In many cases the coating is clearly divided into two sublayers: the primary coating (buffer) and the secondary coating (coating).

This cover can be easily removed by physical or mechanical means to splicing and gives the fiber a predetermined outer diameter, that can be 125, 250 (in case of having only one primary coating) or 500 or 900 μm (if also have an additional secondary cover).

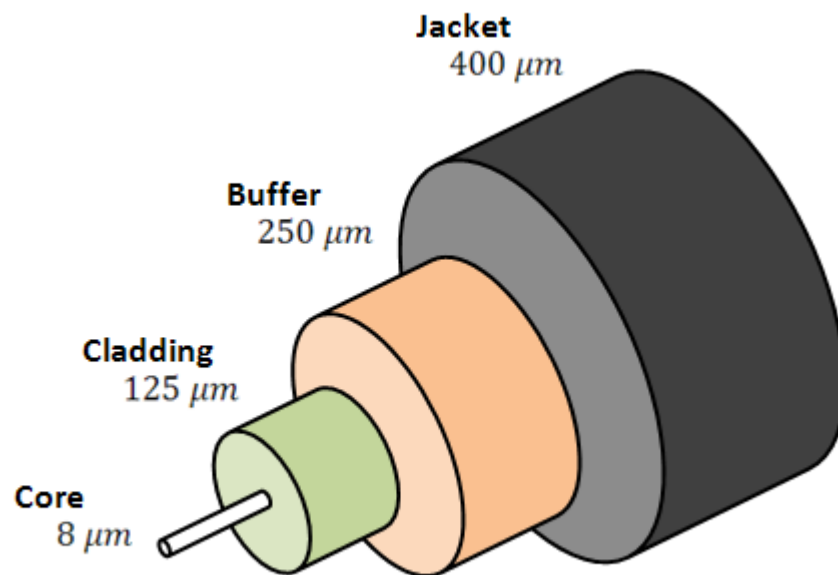


Figure 8: Geometry of optical fiber

2.2.5. Classification and types of optical fibers

An optical fiber is a dielectric waveguide operating at optical frequencies. The propagation of light along a waveguide can be described in terms of a set of guided electromagnetic waves called the *modes* of the waveguide. These guided modes are referred to as the bound or trapped modes of the waveguide, and each guided mode is a pattern of electric and magnetic field lines that is repeated along the fiber at intervals equal to the wavelength [7].

Once the ray has entered into the fiber core, there are a limited number of optical paths that a light beam can take through a fiber. If the diameter of the fiber core is large enough to allow multiple different pathways for light to travel along the fiber, the fiber is called “multimode”. Single-mode fiber has a much smaller core that allows light rays traveling exclusively by a single mode. In the following sections it will detail these types of fiber:

2.2.5.1. Multimode optical fiber

As its name suggests, this type of fiber can propagate several transmission modes simultaneously. This is possible because the core diameter of such fibers is wide (50 microns or 62.5 microns), so that the coupling of light into its different modes is simpler. The following figure shows a section of a multimode optical fiber:

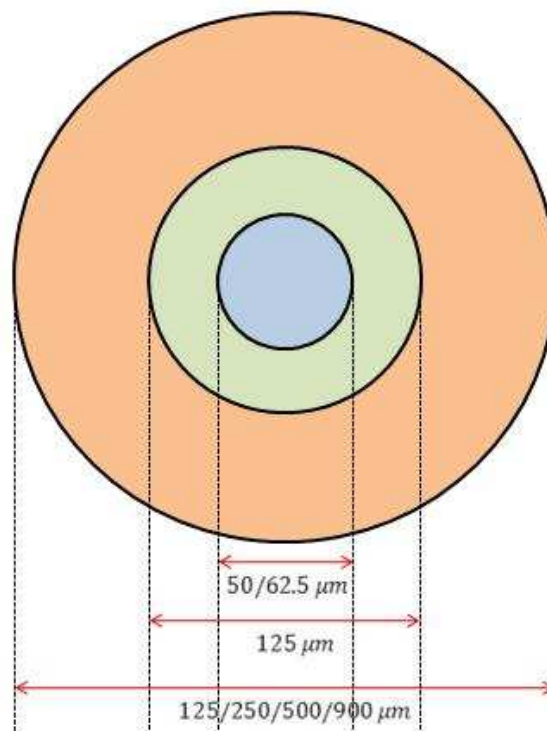


Figure 9: Section of multimode optical fiber

In turn, multimode optical fibers are classified according to the index of refraction of the core. They can be multimode step-index and multimode graded-index, as detailed below:

- **Multimode step-index optical fiber:** This group includes all those fibers in which the value of the index of refraction in the core and the coating is always constant, and also the value of the refractive index of the core is significantly higher than the coating, so that, the refractive index when moving from one area to another change abruptly.

- **Multimode graded-index optical fiber:** In this type of optical fiber, the core has not a constant refractive index, but is made from concentric layers of optical material with refractive index value that decreases from the center to the outside. Anyway, this value is always greater than the refractive index of the coating.

2.2.5.2. Single-mode optical fiber

As its name suggests, this type of fiber allows propagation of only one single mode of transmission. This is possible because the core diameter of such fibers is very small (between 8 μm and 10 μm), so that only allow the propagation of a fundamental beam.

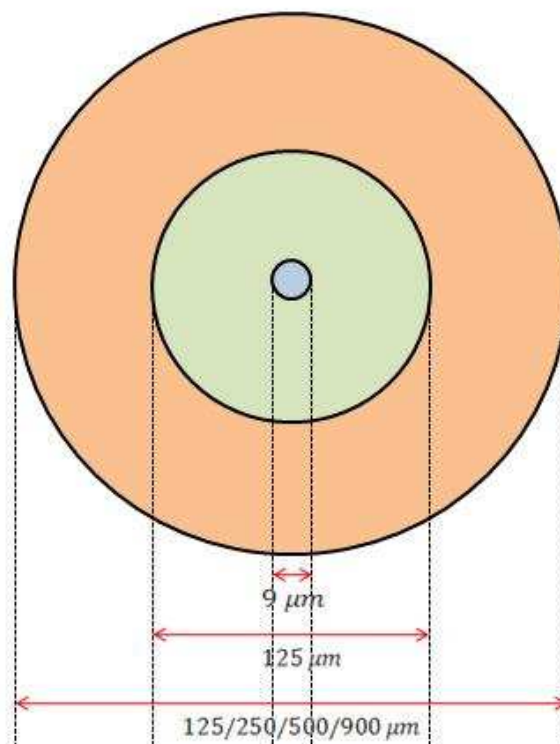


Figure 10: Section of single-mode optical fiber

Although they delete the modal dispersion, these fibers are affected by other type of dispersion called chromatic dispersion. Chromatic dispersion is produced by the light source as a result of spectral coherence. There are no ideal light sources with null bandwidth and infinite coherence, but always emit different residual wavelengths around a fundamental wavelength.

The manufacture of the core is performed through a material whose index of refraction is significantly higher than the coating, which leads to define it as a step-index fiber.

High rates can be achieved with this type of fiber (on the order of hundreds of Gbps), making it an attractive fiber for demanding high bit rate. This coupled with its lack of modal dispersion makes it ideal for long distance links.

In addition, as a result of having a very small core diameter, the cone of acceptance is also small and light-emitting have been to transmit a very precise and narrow beam for a perfect fit. So, LEDs (which are very cheap) cannot be used but it is necessary to use lasers that are more expensive.

In turn, single-mode optical fibers are classified according to the manufacture of fiber materials in SMF, DSF and NZDSF fibers, whose main features are listed below:

- **Standard single-mode fiber (SMF):** Standard single-mode optical fibers have very basic features. Therefore, they have an attenuation of 0.2 dB/Km and chromatic dispersion on the order of 16 ps/km·nm in wavelength of 1550 nm. For a wavelength of 1330 nm has a zero chromatic dispersion, but the attenuation of the signal is doubled.
- **Dispersion shifted fiber (DSF):** Single-mode optical fibers have dispersion-shifted features that improve the chromatic dispersion over the previous. They have attenuation of the order of 0.25 dB/km (greater than SMF fiber) but have a zero chromatic dispersion in a wavelength of 1550 nm. Its main drawback is due to nonlinear effects, such as the phenomenon of fourth wave mixing (FWM) that precludes the use of these optical fiber systems by wavelength division multiplexing (WDM). This fiber was introduced into the market in the mid 80's and remains in use, yet it has never become as common as standard single-mode fiber.

- **Non-zero dispersion shifted fiber (NZDSF):** Single-mode non-zero dispersion shifted optical fibers arise to try to solve the drawbacks of the previous fiber. They have a chromatic dispersion value close to zero but not zero (hence the name) at a wavelength of 1550 nm. By contrast, they achieve largely offset the effects of nonlinear phenomena by chromatic dispersion.

In the figure 11 is graphically shown the different types of optical fiber explained above:

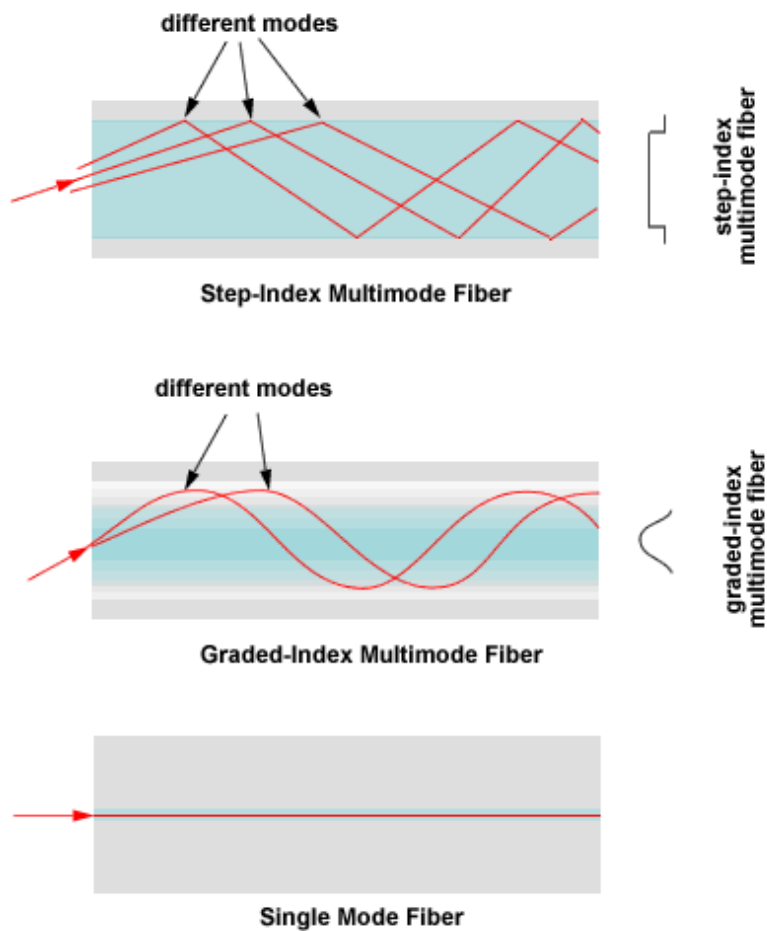


Figure 11: Multimode and single-mode optical fibers

2.3. Optical fiber parameters

Once it is known the structure and composition of an optical fiber, it is necessary to know the parameters that characterize the fibers. These parameters will help to know which the most important characteristics of these cables and their strengths and limitations are.

There are two groups of parameters which encompass each and every one of them, and they are the structural parameters and transmission parameters. All of them establish the conditions under which you can perform data transmission.

2.3.1. Structural parameters

The structural parameters are those related to the geometry and characteristic structure of each fiber. These parameters determine and characterize the types of optical fibers on the market, so that the classification of fibers directly depends on them. There are many and varied types of parameters that characterize the fibers but the most important are [9]:

- Refractive index profile, which allows fibers with different dispersions.
- Size of core and cladding, which determine the type of propagation: single-mode or multimode.
- Mode field diameter, which indicates how the geometrical distribution of light occurs in the spread mode.
- Numerical aperture, which indicates the number of rays that can enter the core of an optical fiber transmission.
- Cutoff wavelength, which determines that the optical fiber transmits on an only single mode of propagation.

2.3.2. Transmission parameters

Signal attenuation is one of the most important properties of an optical fiber, because it largely determines the maximum separation between a transmitter and a receiver. Since repeaters are expensive to fabricate, install, and maintain, the degree of attenuation in a fiber has a large influence on system cost. Of equal importance is signal distortion. The distortion mechanisms in a fiber cause optical signal pulses to broaden as they travel along the fiber. If these pulses travel sufficiently far, they will eventually overlap with neighboring pulses, thereby creating errors in the receiver output. The signal distortion mechanisms thus limit the information-carrying capacity of a fiber [7].

2.3.2.1. Attenuation

The light that travels through an optical fiber loses power as it moves along it, and therefore, with distance. Attenuation losses limit transmission distance and depend on the wavelength of light and material through which it spreads.

Signal attenuation is defined as the ratio of the optical output power P_{out} from a fiber of length L to the optical input power P_{in} . The symbol α is commonly used to express attenuation in decibels per kilometer [7]:

$$\alpha = \frac{10}{L} \log \left(\frac{P_{in}}{P_{out}} \right) \quad (5)$$

As we can see in Figure 12, the lowest losses are at a wavelength of 1550 nm, a value that is heavily used for long distance transmission, while the highest values are in shorter wavelengths.

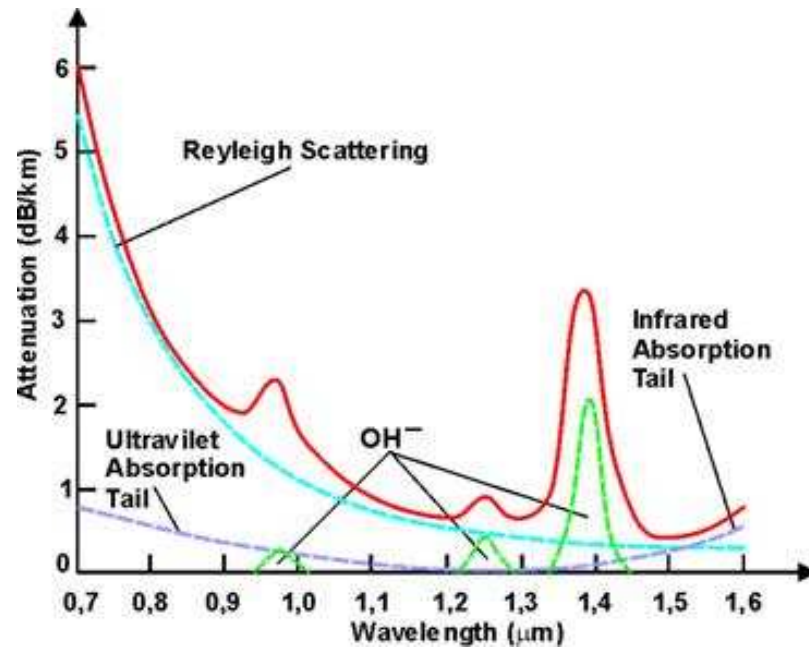


Figure 12: Total attenuation in a fiber optic as a function of wavelength
[\[http://www.invocom.et.put.poznan.pl/~invocom/C/P1-9/swiatlowody_en/p1-1_2_2.htm\]](http://www.invocom.et.put.poznan.pl/~invocom/C/P1-9/swiatlowody_en/p1-1_2_2.htm)

Below 800 nm is not convenient to use the fiber due to high attenuation by Rayleigh scattering. Above 1600 nm, attenuation problems are presented by the effect of infrared radiation. In addition, the emitters and photodetectors technology for this wavelength is very recent. Therefore, optical fiber communications typically operate in a wavelength region corresponding to one of the following “telecom windows” [11]:

- The first window at 800–900 nm was originally used. Therefore, the first telecom window is suitable only for short-distance transmission.
- The second telecom window utilizes wavelengths around 1.3 μm, where the loss of silica fibers is much lower and the fibers’ chromatic dispersion is very weak, so that dispersive broadening is minimized. This window was originally used for long-haul transmission. However, fiber amplifiers for 1.3 μm (based on, e.g. on praseodymium-doped glass) are not as good as their 1.5 μm counterparts based on erbium. Also, low dispersion is not necessarily ideal for long-haul transmission, as it can increase the effect of optical nonlinearities.

- The third telecom window, which is now very widely used, utilizes wavelengths around 1.5 μm . The losses of silica fibers are lowest in this region, and erbium-doped fiber amplifiers are available which offer very high performance. Fiber dispersion is usually anomalous but can be tailored with great flexibility.

The signal attenuation into the fiber does not depend on bandwidth and modulation because the carrier frequency is greater by several orders of magnitude to frequency modulation which does not happen in other conventional waveguides. The attenuation of light in an optical fiber is produced as a result of various effects and losses can be classified into extrinsic and intrinsic losses:

Extrinsic losses: Such losses are due to extrinsic factors to the nature of the fibers as are the parameters of curvature and the joints between optical fibers, or external parameters due to the installation or temperature at which the fiber is subjected. As a result of these, attenuations are produced in the light transmitted along the fiber, which mainly lead to a loss of signal strength along the transmission by reducing the value of the amplitude of the signal.

Intrinsic losses: Such losses are due to intrinsic factors to the nature of the fibers, and therefore characteristic of the manufacturing and operational working of the same. As also occurs with extrinsic losses, these losses originate decreases in the transmitted signal power, reducing the amplitude of the signal. For example, the most important intrinsic losses are:

- Inherent losses in the fiber during the manufacturing process thereof.
- UV and IR absorption, which cause the called transmission windows of the optical fiber or optimal wavelength bands for the light transmission.
- Fresnel reflection, caused by a jump or change of refraction index in the union of the fiber.
- Rayleigh scattering, occurs when light collides on its path with foreign particles to the continuous medium by which it spreads.

- Absorption due to impurities is a major cause of signal loss in an optical fiber. The most common impurity is the OH⁻ molecule, which remains in the fiber as a residue despite stringent manufacturing techniques. It has a fundamental absorption at 2700 nm and its harmonics produce three absorption peaks at 1383 nm, 1250 nm, and 950 nm. These absorption peaks define the three typical windows of operation.

2.3.2.2. Dispersion

Dispersion is an inherited property of the fiber that can be attributed to the spreading of an optical pulse in time domain due to the difference in the velocities of the various spectral components that are associated with that optical pulse. We have to note that each optical pulse has different spectral components or multiple frequencies. Each spectral component has its own velocity and can travel through a different path. Because of this, each component reaches the exit end of a communication channel (fiber) at different intervals of time. This difference in time experienced by the various spectral components leads to a longitudinal spreading of the pulse of a cylindrical waveguide [12].

Dispersion results in losses in the bandwidth of the signal, as well as loss per distance traveled (as in the case of attenuation). The bandwidth of an optical fiber is a measure of transmission capacity, limited by the total dispersion of the fiber or widening of the transmitted pulse. This limits the ability to transmit information as pulses are distorted and widened along the transmission, overlapping each other and become indistinguishable to the receiver.

Likewise, dispersion restricts transmission distance so as the bandwidth of the same and it is a function of the optical fiber length, since the higher the fiber length the more pronounced the effect. This type of dispersion in the bandwidth can be subdivided into three categories:

- **Modal dispersion**, caused by the different ways or modes that follows a beam of light in fiber, with the result that the different rays light travels different distances and reach the other end of the fiber in different time instants.

- **Polarization mode dispersion (PMD)**, produced because the fiber is not exactly a cylindrical waveguide, which results in a phenomenon called birefringence whereby causes a propagating pulse that loose the balance between the polarization components.

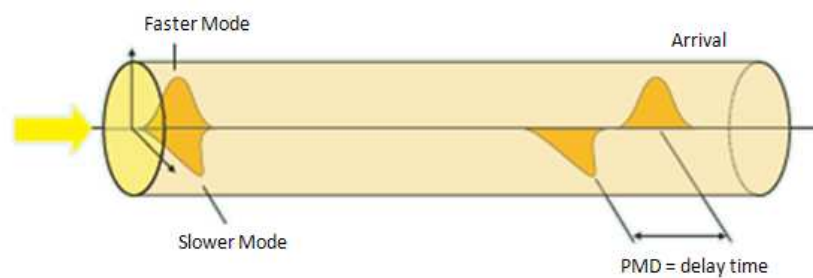


Figure 13: Pulse broadening through polarization mode dispersion

- **Chromatic dispersion**, which arise as a result of the dispersion material and waveguide dispersion (own material and geometry of the fiber) and it is due to the variation of refractive index of an optical medium with the wavelength.

2.3.2.3. Nonlinearities

The fact of assuming that optical communication systems behave linear is an appropriate approximation when operating at moderate power levels (magnitudes of the order of mW) and transmission rates do not exceed 2.5 Gbps. But at higher speeds (around 10 Gbps) or higher powers, effects of certain nonlinearities begin to be important, and in the case of WDM systems these effects are very important even with powers and moderate transmission rates, determining the number of channels in the system and the separation between them.

The nonlinearities of the fibers can be classified into two categories:

- Those that occur as a consequence of the dependence of the refraction index with the applied field intensity, known as Kerr effect, which in turn is proportional to the square of the amplitude: self-phase modulation (SPM), cross-phase modulation (CPM) and the four wave mixing (FWM).
- Those produced by diffraction effects in the fiber, due to interaction of light waves with photons (molecular vibrations) in silicon of the core: stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS).

2.4. Advantages and disadvantages of optical fibers

Classical communications systems use electrical signals supported by coaxial cable, copper, radio channel, etc. depending on the type of application to provide service. These systems have some drawbacks and limitations that made it necessary to find other ways to transfer data, based on other signals, such as fiber optics.

The main fact that a fiber use light energy as a transmission medium, it presents an important set of advantages over other media used in the transmission of analog and digital signals.

2.4.1. Advantages of optical fibers

The main advantages of optical fiber as transmission medium compared to other systems based on electromagnetic signals over metals are [1]:

- They allow higher throughput. The signals travel throughout optical fiber cables approaching the speed of light ($c = 3 \cdot 10^8 \text{ m / s}$) while the electrical signals travel through the cables at a speed between 50 - 70% of it, depending on the type of cable.
- Greater transmission capacity. They can be achieved speeds exceeding 2 Gbps, since the transmission rate increases with frequency. The fact to have inherently greater bandwidth enables the simultaneous transmission of large amounts of information. This property is directly related to the previous.
- They have total immunity to electromagnetic interference. Optical fiber does not produce any electromagnetic interference and it is not affected by radiation or nuclear electromagnetic pulses (NEMP) accompanying nuclear explosions.
- It do not exist problems to return to ground, and cross-interference reflection as in electrical transmission lines.
- Attenuation in transmission increases more slowly with distance than in the case of electrical cables, allowing greater distances between signal repeaters.

- It can get bit error rates typical of the order of 10^9 compared to rates of the order of 10^6 to reach those coaxial cables. This increases the effective speed of data transmission, reducing the number of retransmissions or the amount of redundant information necessary for detect and correct transmission errors.
- They do not have a risk of short circuit or other damage of electrical origin.
- Fiber optic cables, weigh one-tenth of copper shielded cables, for example. This is a very important consideration in military applications, typical of ships and aircraft.
- They usually have a much smaller diameter cable. In addition, they are much more flexible and easier to install than electrical cables.
- The fiber optic cables are suitable for use in a wide range of temperatures, since they support extreme temperatures better than cables with metallic origin.
- Unlike the copper cables, the transmitted signal cannot be drawn from a fiber without tampering it. This way, the optical fiber communication provides 100% signal security.
- It is possible to increase transmission capacity by adding new data channels using different wavelengths to those already employed, by WDM techniques.
- Optical fiber has a higher resistance to environments and corrosive liquids than electric cables.
- Raw materials, which are used in the manufacture of optical fibers, are very abundant, and it is hoped that eventually the manufacturing cost is reduced to a level similar to metallic cables.
- The operational half-life and average time between failures of a fiber optic cable are much higher than an electrical origin cable.

2.4.2. Disadvantages of optical fibers

Optical fiber not only has advantages. It also has some drawbacks, which it is not convenient to forget, because in some circumstances they limit studies and deployment projects in some networks based on this transmission medium [1]:

- The cost, either installation or transmitters and receivers, is usually high compared with other types of communications. In addition, companies do not charge for time used, but the amount of information transferred to the computer that is measured in megabytes.
- Electro-optical conversion. Before connecting an electrical signal to optical fiber, the signal must be converted to light spectrum (850, 1310 or 1550 nm). This conversion is carried out by an electronic device on the end of the transmitter, which provides an own format to the communication signal and the signal becomes optics using a LED or a solid state laser.
- Particular installation. Because the fiber is predominantly silica glass, special techniques are needed for engineering and installation of the links. No longer apply conventional methods wire cable installation as, for example, welding or crimping. It also requires the right equipment to test and put into service cables. Technicians must be trained and previously prepared for the installation and commissioning of optical fibers.
- Repairs. An optical fiber cable that has been damaged is not easy to repair. Thus, repair procedures require a team technician with enough skill and ability in handling equipment. In some situations it may be necessary to repair the entire cable. This problem could be even more complex, given the large number of people using this service. Therefore, it is important to design an own system with physically different routes that will address such contingencies.

With all this, you can perform an initial assessment, which highlights the multitude of benefits that fiber has over electric transmission mediums. Despite the drawbacks, most of them are decreasing over time. Being a fairly recent mode of transmission, allows this research are very active. On the other hand, there is an optical fiber support mature enough to serve very high performance.

Chapter 3

Introduction to FTTx System

The application of PON technology for providing broadband connectivity in the access network to homes, multiple-occupancy units, and small businesses commonly is called *Fiber-to-the-x*. This application is given the designation FTTx [14].

The next chapter consists of an extensive collection of FTTx optical transmission systems, and specifically the FTTH system by which the design and deployment of the proposed network in this project is based. Therefore, it describes general operation of such networks, standards of architecture and operating structure, as well as the current situation in the world and the services that they offer, and in the near future will be able to offer. This will provide an overview of FTTH technology and in-depth the knowledge of the particular circumstances of such networks.

3.1. FTTx networks

FTTH networks belong to the family of FTTx transmission systems within the world of telecommunications. These networks, which are considered broadband, have the ability to transport large amounts of data and information at very high bit rates up to a point close to the end user.

The FTTx family comprises a set of technologies based on transport of digital signals through optical fiber as transmission medium. Different levels of scope, depending on the degree of optical fiber closer to the end user, which arise as a result of a greater or lesser price reduction of these systems.

All FTTx networks support a logical network configuration of tree, star, bus and ring, and all with the ever present possibility of using active components depending on the location of users or end customers.

Depending on the degree of penetration of FTTx, these networks can be classified into the following [14]:

- FTTB, *fiber-to-the-business*, refers to the deployment of optical fiber from a central office switch directly into an enterprise.
- FTTC, *fiber-to-the-curb*, describes running optical fiber cables from central office equipment to a communication switch located within 1000 ft (about 300 m) of a home or enterprise. Coaxial cable, twisted-pair copper wires (e.g., for DSL), or some other transmission medium is used to connect the curbside equipment to customers in a building.
- FTTH, *fiber-to-the-home*, refers to the deployment of optical fiber from a central office switch directly into a home. The difference between FTTB and FTTH is that typically, businesses demand larger bandwidths over a greater part of the day than do home users. As a result, a network service provider can collect more revenues from FTTB networks and thus recover the installation costs sooner than for FTTH networks.
- FTTN, *fiber-to-the-neighborhood*, refers to a PON architecture in which optical fiber cables run to within 3000 ft (about 1 km) of homes and businesses being served by the network.
- FTTO, *fiber-to-the-office*, is analogous to FTTB in that an optical path is provided all the way to the premises of a business customer.
- FTTP, *fiber-to-the-premises*, has become the prevailing term that encompasses the various FTTx concepts. Thus FTTP architectures include FTTB and FTTH implementations. An FTTP network can use BPON, EPON, or GPON technology.
- FTTU, *fiber-to-the-user*, is the term used by Alcatel to describe their products for FTTB and FTTH applications.

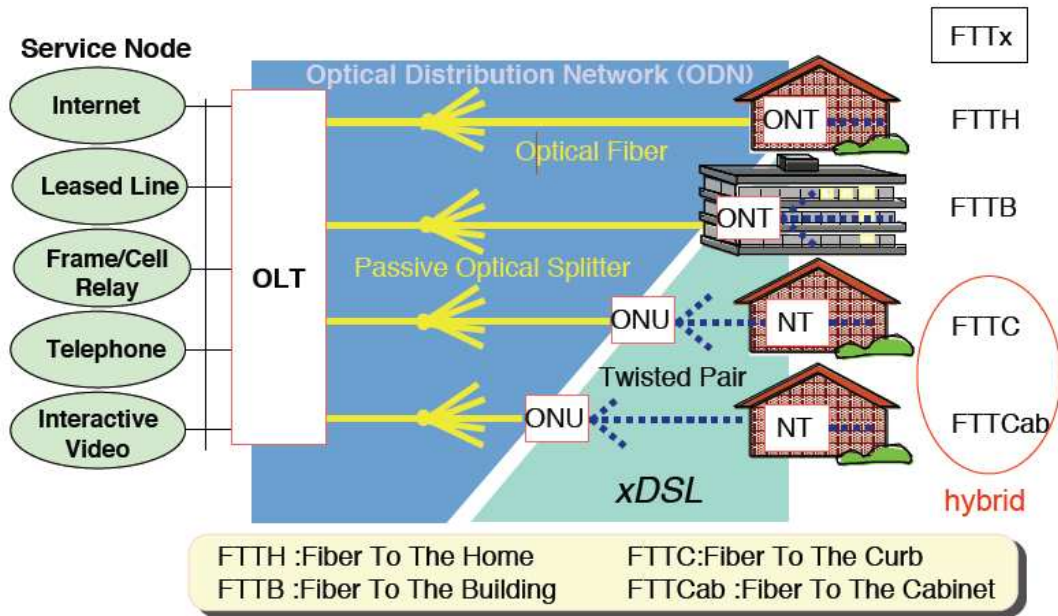


Figure 14: Some FTTx scenarios
[\[http://policom.dei.polimi.it/education/comunicazioni/lezione-PON.pdf\]](http://policom.dei.polimi.it/education/comunicazioni/lezione-PON.pdf)

The use of fiber optics as medium of transmission to homes, and so, to end users, ensures network completely adapted to the needs of both current and future. The reuse of this physical infrastructure saves money over time despite strong outlay in initial phase, amortizing it in a short time.

3.2. General architecture of an FTTH network

FTTH technology involves the introduction of fiber optic in global network, both the backbone network operator as the last mile. In relation to the last mile, it includes the fiber from the central office to each household that requires services.

The interconnection between the end subscriber and the distribution node which is going to provide the services can be done through various physical configurations, which are detailed below.

3.2.1. Point-to-point configuration

Point to point configuration, in terms of optical fiber is concerned, it is specifically a link between the central node and the end user.

Transmission point to point links are operated by companies that have access to fiber optic in outside plant and need to connect remote locations with some communications capability, which can vary from a voice or telephone link, up to high-speed data link.

As for the active part of the network is concerned, it is noteworthy that the equipment used for transmission of information in point to point links are PDH or SDH, besides WDM. These links have high capacity and are very useful in the business world.

However, not all are benefits. In case of use of this configuration for home users, it would be a high cost of deployment, to which any operator, whether telecommunications or neutral, is willing to address.

In addition, it would break the pattern of global network configuration, because tree or star configuration, it would be dismantled, increasing the cost of network expansion as well as operation and maintenance.

3.2.2. Point-to-multipoint configuration

Point to multipoint configuration, in terms of fiber optics is concerned it is in which FTTH networks are based. Typically, this configuration is called PON (Passive Optical Network).

Architecture based on PON or passive optical networks is defined as a global system devoid of active electronic elements in the last mile. As it is one of the most important points in this project, it will devote an entire chapter to explain what they are and how such networks work.

Chapter 4

Introduction to Passive Optical Networks

A passive optical network is a network which by its nature provides a variety of broadband services to users through optical fiber access. PON allows removing all active components between the server and client introducing in place optical passive components to guide the traffic throughout the network. Its principal element is the optical splitter.

The usage of passive architecture can reduce costs and are mainly used in FTTH networks. By contrast, the bandwidth is not dedicated, but rather multiplexed in a single fiber in the network access points. In short, this is a point-to-multipoint configuration network.

Moving from the network to the user, it can say that PON architecture consists of the following equipment: an Optical Line Terminal (OLT) at the service provider's central office and a number of Optical Network Units (ONUs) or Optical Network Terminals (ONTs) close to end users.

4.1. Generic operation of a PON

As has been described in the previous section in general terms, a passive optical network always works under transmission between the OLT and the different ONT's through optical splitters, which multiplex or demultiplex signals based on their origin and destination.

Therefore, they appear three distinct devices in the network: the OLT, the ONT and the splitter, each of which has a necessary and priority function on the passive optical network. Below are detailed the function and general characteristics each of them.

4.1.1. Optical Line Terminal

The OLT is located in a central office and controls the bidirectional flow of information across the ODN (Optical Distribution Network). An OLT must be able to support transmission distances across the ODN of up to 20 km (currently could be more with EDFA). In the downstream direction the function of an OLT is to take in voice, data, and video traffic from a long-haul network and broadcast it to all the ONT modules on the ODN. In the reverse direction (upstream), OLT accepts and distributes all the traffic from the network users [14].

Simultaneous transmission of separate service types on the same fiber in the ODN is enabled by using different wavelengths for each direction. For downstream transmissions, a PON uses a 1490 nm wavelength for combined voice and data traffic and a 1550 nm wavelength for video distribution. Upstream voice and data traffic use a 1310 nm wavelength [14].

Each OLT is tasked to avoid interference between the contents of downlink and uplink channel, using two different wavelengths superimposed. For this, techniques for WDM (wavelength division multiplexing) are used, and are based on the use of optical filters.

An optical power measurement at the OLT is also required to ensure that sufficient power is delivered to the ONTs. This should be done during the initial activation because it cannot be repeated without interrupting service for the entire network once the network has been connected.

Finally, note that the OLT does not emit the same light output at all ONT fairly, but depends on the distance they are from the plant. Therefore, a user close to the central need less power, while a remote user will need a higher power.



Figure 15: OLT

[http://www.motorola.com/Video-Solutions/XP-EN/Products-and-Services/Broadband-Access/Optical-Line-Terminals/AXS2200_XP-EN]

4.1.2. Optical Network Terminal

An ONT is located directly at the customer's premises. There its purpose is to provide an optical connection to the PON on the upstream side and to interface electrically to the customer equipment on the other side. Depending on the communication requirements of the customer or block of users, the ONT typically supports a mix of telecommunication services, including various Ethernet rates, T1 or E1 (1.544 or 2.048 Mbps) and DS3 or E3 (44.736 or 34.368 Mbps) telephone connections, ATM interfaces (155 Mbps), and digital and analog video formats [14].

A wide variety of ONT functional designs and chassis configurations are available to accommodate the needs of various levels of demand. The size of an ONT can range from a simple box that may be attached to the outside of a house to a fairly sophisticated unit mounted in a standard indoor electronics rack for use in large MDU or MTU applications, such as apartment complexes or office buildings. At the high-performance end, an ONT can aggregate, groom, and transport various types of information traffic coming from the user site and send it upstream over a single-fiber PON infrastructure. The term grooming means that the switching equipment looks inside a time-division-multiplexed data stream, identifies the destinations of the individual multiplexed channels, and then reorganizes the channels so that they can be delivered efficiently to their destinations [14].

In summary, we can say that the ONT are elements capable of filtering the information associated with a particular user from the OLT. They also have the function of encapsulating a user's information and send it toward the OLT header to redirect it to the appropriate network.

Each ONT receives all the signals sent by its corresponding header ONT, like the rest of ONTs of the same stage. Information of the OLT is transmitted by broadcast TDM, and reaches all ONT by alike. However, the ONT has the task of filtering the information that only goes directed himself (at a given time interval).

The figure below shows graphically Operation of a time-division multiplexing process:

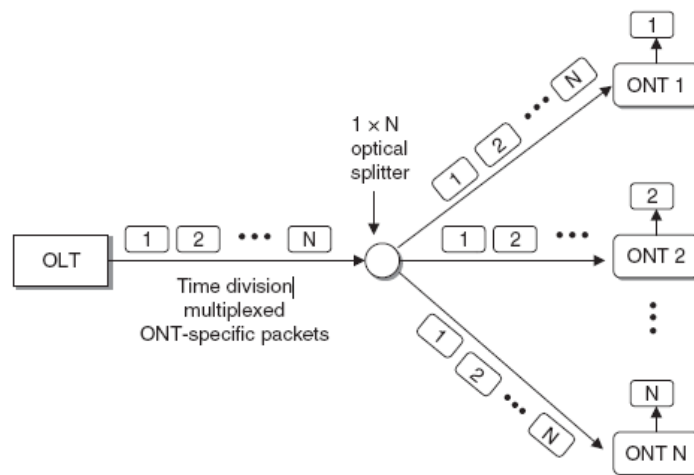


Figure 16: Operation of a time-division multiplexing process [14]

4.1.3. Splitter

Splitters are passive power dividers that allow communication between the OLT and their respective ONT who serve. However, not only are dedicated to multiplex or demultiplex signals, but also combine power: they are bidirectional optical distribution devices with one input and multiple outputs:

- The signal which enters from input port (downlink), it proceeds from the OLT and it is divided among multiple output ports.
- The signals which enter from the exits (uplink), they come from ONT and they are combined at the entrance.

The fact of being completely passive elements, it allows them to operate without extern power, lowering their cost of deployment, operation and maintenance. They just introduce optical power loss on communication signals, which are inherent in nature.

There is an inverse mathematical relationship between the losses introduced by the divisor and the number of outputs of the same, being this:

$$Attenuation_{SPLITTER} = 10 \log \frac{1}{N} \quad (6)$$

Therefore, a splitter with two outputs, in the worst case, it loses 3 dB (half power) at each exit.

Graphically, it can be expressed the operation of a splitter with the following Figure:

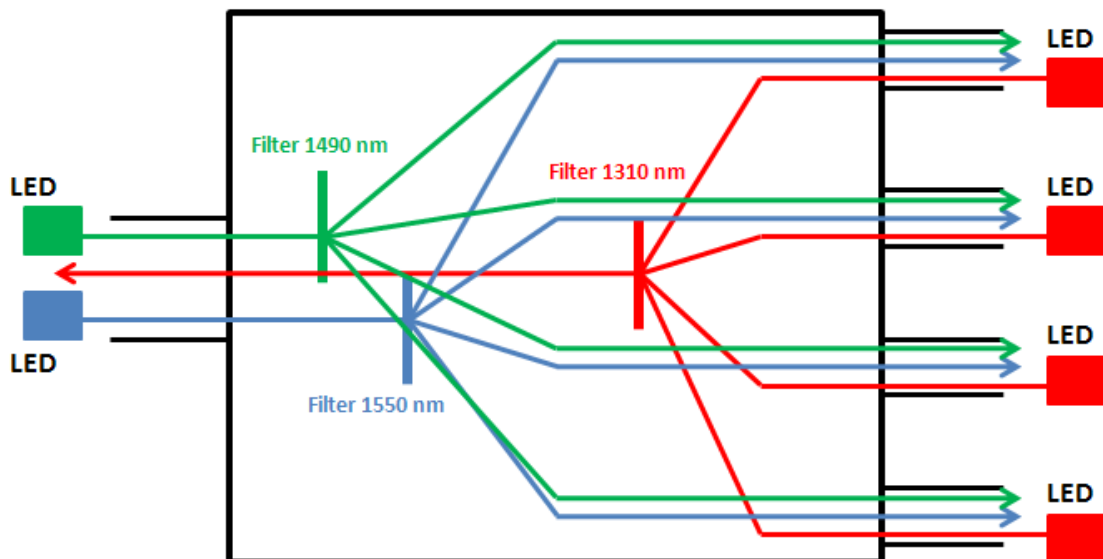


Figure 17: Generic operation of optical splitter

There are various types of splitters, as not all are built from same technology. However, the common divisors are two types:

- For devices with large number of outputs (> 32 outputs) splitters based on planar technology are used.
- For devices with fewer outputs (<32 outputs) splitters based on fused bi-conical couplers are used.

4.1.4. Description of operation of Passive Optical Network

Once detailed all the elements that build a PON, it is necessary to know how the global system works and the behavior of the network with all the interconnected elements, from the head OLT towards ONT users, and vice versa.

The most important thing to note in the generic operation of the network is the existence of two channels, one ascending and one descending. However, both generally work through the same physical cable, so different wavelengths are assigned to each transmission channel and, depending on traffic, coexisting in the same fiber at least 3 different wavelengths: one for video flow in the upstream channel, and two for data flow of uplink and downlink respectively.

Below is going to be analyzed in more detail both transmission channels:

4.1.4.1. Downstream channel

The downstream channel is the direction of information from the OLT operator to the ONT located on the end user. In this network, the PON behaves like a point-multipoint network.

The OLT includes plenty of added voice and data frames that go towards PON, through the P-OLT (voice and data) and the V-OLT (video). Frames collected by these teams are transformed to signals which inject in the different branches of the users. These branches are formed by one or two fibers that carry signals bi or unidirectional, and are passively coupled by optical splitters that allow the union of all the ONT in the network, without intermediate regeneration of signals (avoiding active elements).

These dividers are responsible for receiving information from the OLT and send all the information to all their outputs. Once the information arrives to ONTs, each will only be able to process the traffic it belongs, or for which have the access by the operator, thanks to the AES (Advanced Encryption Standard) security techniques. In this procedure, TDM (time-division multiplexing) broadcast protocol is used, sending information to each user in different times.

The OLT has different pre-set time intervals, each one corresponded to a particular user. So, in function of each temporal segment, the ONT of each user filters the information addressed to him.

An important aspect to consider is the wavelength (λ) which the OLT transmit information to ONT. These lengths vary according to if a tree branch or ONT connection has a single fiber or two fibers.

4.1.4.2. Upstream channel

The upstream channel is the direction of information from the ONT end user to the OLT operator. In this network, the PON behaves like a point to point.

Each ONT includes the added frames of voice and data (from each user) that are directed toward the OLT. At this point, the ONT performs the same operation as the OLT in the downstream channel, i.e., turn the frames into injecting signals through optical fiber that have been dedicated to the user.

The splitters of each stage are in charge of collecting information from all corresponding ONTs and multiplex it in a single output fiber towards the operator OLT.

In order to transmit information from different ONT on the same channel, is necessary (as in the downstream channel) the use of TDMA, so that each ONT sends the information in different time intervals controlled by the OLT unit.

As for the working wavelengths, it is noteworthy that regardless of whether the connection of the ONT to the splitter is two or single fiber, the wavelength of the upstream channel work is always the same. The information sent by the user (voice and/or data), always travel at $\lambda_D = 1310 \text{ nm}$.

4.2. Advantages and disadvantages of PON

To understand why FTTx architecture is based on PON network, it is necessary make a direct comparison between the point-to-point (P2P), passive point-to-multipoint (PON) and active point-to-multipoint networks (AON).

Below is a comparative table showing advantages and disadvantages of each of the three types of network configuration cited above, that clearly justify the use of FTTx PON compared to other configurations.

Network Type	Positive Aspects	Negative Aspects
Point-to-Point	<ul style="list-style-type: none"> • High capacity 	<ul style="list-style-type: none"> • High cost of deployment
Active Point-to-Multipoint (AON)	<ul style="list-style-type: none"> • High capacity 	<ul style="list-style-type: none"> • High cost of deployment • High cost of operation and maintenance
Passive Point-to-Multipoint (PON)	<ul style="list-style-type: none"> • High capacity • Use of passive elements (lower investment) • Low cost of operation and maintenance • Flexibility and scale • All services in a fiber • ITU G.983.3 standardization 	<ul style="list-style-type: none"> • Protection methods required against sabotages • High impact on breakdown at central OLT

Table 1: Comparative table of different types of networks

As shown in the table above, PON are the most appropriate to the design of physical network architecture for FTTx deployments. The fact of having lines specifically dedicated for user towards to central office (where the OLT is), considerably reduces the cost of initial network deployment. This is not covered by point-to-point networks, which despite providing a high bandwidth per user, it's not worth their high cost of deployment.

As for active networks, the inclusion of active elements increases not only the cost of deployment of the network itself, but also the operation and maintenance of

the same, forcing to manage and centralize it by software and hardware level. PON reduces these unnecessary costs.

In conclusion, the use of PON architectures means very important advantages when designing, installation and subsequent maintenance of the network.

4.2.1. Advantages of PON

Many of the PON properties are given by the use of fiber, and of course, of the passive elements that compose the network, which added to the specific configuration of a star or tree give it certain advantages over other topologies. This gives to PON two undoubtedly important advantages: cost savings in implementation and the capacity and bandwidth of passive optical networks.

However, these advantages are not the only ones, and among other, the most relevant are listed below:

- A PON allows for longer distances between central offices and customer premises. While with the Digital Subscriber Line (DSL) the maximum distance between the central office and the customer is only 18000 feet (approximately 5.5 km), a PON local loop can operate at distances of over 20 km [16].
- There is the possibility of providing every information source in a different wavelength, avoiding the mix of signals to each other, and facilitating diffusion from the OLT to the different ONTs. Therefore, signals voice and data are managed by so-called P-OLT, which operates in second window wavelengths, and video signals in diffusion managed by the so-called V-OLT, operating in third window wavelengths. This fact gives scalability to PON transmission system, given the variety of wavelengths to use for the same by CWDM / DWDM.
- To this, it adds the reduced cost of network deployment in the outside plant. The use of passive elements in the network supposes a lower cost of implementation. On the one hand it reduces the cost of installation of

active elements, and on the other hand the cost of passive element itself, which is much lower.

- The installation of PON from these elements is much more economic, and prevents operation and maintenance costs, such as absence of falls or maintenance of the network feeds.
- Finally, it is noteworthy that the high bandwidth allowed by systems based on PON architectures which can reach the 10 Gbps rate down to the user. The need to increase the bandwidth and the speed is nowadays just another justification for the use of PON. This is an essential support for services such as HD Video, services called "on demand"...

4.2.2. Disadvantages of PON

Despite the many advantages that have the PON to own intrinsic configuration, there are some disadvantages associated with it. However, there are not significant enough to avoid choosing PON as the best possible configuration.

One of the first disadvantages to be considered is that caused by distribution of information from the OLT to the different ONTs. The fact that a divisor distributes information from the OLT to all ONTs that are connected to the same stage or distribution tree, it causes a reduction in network efficiency.

The total capacity is divided into many ONT connected to the splitter, so that the efficiency of the channel is lower than in a point-to-multipoint link. In addition, because PON has a preset speed, it is forced to work at that speed but providing different speeds to the customer service. For example, an ONT that provides 100 Mbps to the customer is required to work at higher speed rates: 1.25 Gbps or 2.5 Gbps.

Moreover, the fact that all information flow through the same physical channel increases the likelihood of sniffing on the network, losing security, and forcing to establish a high level of encryption.

Regarding security, PON architecture is sensitive to external sabotage. This problem is given by the nature of the transmission medium itself. Injection of constant light to a particular wavelength masks all communication and service tends to fall.

Another important aspect is the fact that a stage or distribution tree, depend exclusively on a single OLT. A fault in the OLT header supposes a high impact on the network, since all the ONT and splitters connected to it are affected. However, the installation of few OLT supposes a cost reduction of network deployment enough considerable.

The ONTs of PON are quite sensitive to the level drops, and in many cases, the power budget of the network is quite limited. This budget is directly related to:

- The capacity of splitters. A greater number of users, less power reach everyone from the OLT.
- Maximum distance to achieve. The greater the distance between the OLT and end users, less power will reach the corresponding ONTs.

However, despite the disadvantages mentioned above, the most advantageous configuration for the deployment of FTTx is PON. Two of the most important conditions that justify the use of this architecture are:

- The economic savings resulting from deploying PON networks regarding other two configurations (point to point and active optical network).
- The flexibility of the network, which allows the usage of a channel by a large number of users.

4.3. PON technologies

Passive Optical Networks are a family of networks (xPON), whose origin is found in a first network that was defined by FSAN, a group of 7 telecommunication operators with the aim of unifying the specifications for broadband access to households. Below is an evolution of PON standards since its inception.

4.3.1. APON

It was the first network that was defined by FSAN (Full Service Access Network). APON bases its transmission downlink in bursts of cells ATM (Asynchronous Transfer Mode) with a maximum rate of 155 Mbps shared between the ONT numbers that are connected. His initial problem was the limitation of 155 Mbps which later was increased to 622 Mbps.

In each ATM cell is introducing two more cells (PLOAM), responsible of indicate the addressee of each cell and for maintenance. These networks are referred to as APON (ATM Passive Optical Network), and are standardized under ITU-T standard G.983.1.

4.3.2. BPON

Under the same standard, ITU-T G.983.x (ed. 2005), also came up the so-called BPON (Broadband Passive Optical Network). It emerges as evolution of APON, given the speed limitation of the same.

BPON networks are also based on ATM cell transmission, but they have the difference respecting to APON because they can support other broadband standards. In its first version, BPON networks were defined under a fixed rate of 155 Mbps transmission for both uplink and downlink. However, later was amended to admit asymmetric channels:

- Downlink: 622 Mbps
- Uplink: 155 Mbps

However, despite improvements over APON, they had a high cost of implementation, as well as various technical limitations. Thus, it has been moving slowly to solve the problems posed by this technology, which today allows asymmetric speeds of up to 1.2 Gbps in the following way [17]:

Downstream	Upstream
155 Mbps	155 Mbps
622 Mbps	155 Mbps
622 Mbps	622 Mbps
1,244 Gbps	155 Mbps
1,244 Gbps	622 Mbps

Table 2: *BPON downstream/upstream bit-rate combinations*

On the other hand, apart from support different transmission speeds allowing transmit all the information (upstream and downstream) on 1 or 2 single-mode fibers (as ITU-T G.652 standard), with a maximum range of 20 km between optical splitter and ONT, and between ONTs of the same stage.

Wavelengths of work that sets the standard BPON, they vary depending on whether you use 1 or 2 fibers for each ONT, although for both sets a dedicated wavelength to video broadcast from the OLT to the ONT, being this different from those used in the transmission of voice and data. The wavelengths are:

- For 1 fiber per ONT, sharing upstream and downstream:
 - ◆ Downstream channel: $\lambda=1480-1500$ nm
 - ◆ Upstream channel: $\lambda=1260-1360$ nm
 - ◆ Video: $\lambda=1550-1560$ nm

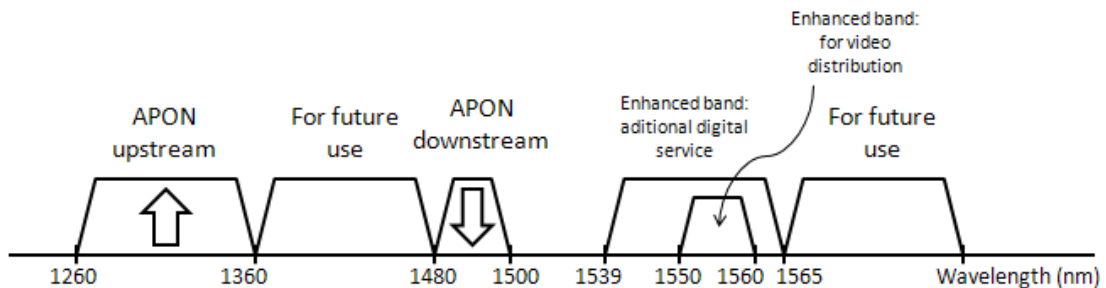


Figure 18: *Wavelength allocation plan in ITU-T G.983.3*

- For 2 fibers for each ONT, one for upstream and one for downstream:
 - ◆ Downstream channel: $\lambda=1260-1360$ nm
 - ◆ Upstream channel: $\lambda=1260-1360$ nm
 - ◆ Video: $\lambda=1550-1560$ nm

BPON networks support a maximum ratio of 32 splitters per OLT, and each splitter supports up to 64 outputs to ONT users. This brings a total of:

$$Users_{MAX} = 32 \frac{splitters}{OLT} \cdot 64 \frac{users}{splitter} = 2.048 \frac{users}{OLT}$$

4.3.3. EPON

Parallel to the evolution of PON, standardized by the ITU and that have their origin in the FSAN, there is a new specification made by the working group EFM (Ethernet in the First Mile), established by IEEE. The intention of the FSM in this sense was to take advantage of the characteristics of optical fiber technology in PON and apply them to Ethernet. In this way, they created the standard EPON (Ethernet PON) under the rule IEEE 802.3ah (ed. 2004) that nowadays is still in development.

The EPON architecture is based on the transport of Ethernet traffic, but maintaining the characteristics of the IEEE 802.3 specification, and therefore, leave aside the transfer of ATM cells, in which APON and BPON standards are based and encapsulates information on Ethernet frames. This allows providing EPON the following advantages over APON and BPON standards:

- It allows working directly to Gbps speeds because of being supported on Ethernet. This flow is not single-user since it has to be shared among many users (ONT) as the system has.
- Interconnection between EPON stages is simpler.

- Certain costs are reduced arising from the non-use of ATM and SDH elements, typical of the above networks.

As transmission speeds are concerned, EPON establishes a symmetric speed line of 1 Gbps, both for downstream and upstream channels. This technology is also called GEPON (Gigabit Ethernet Passive Optical Network) due to work at speed of Gigabit.

It is noteworthy that standardization only allows transmission in downstream and upstream under only 1 single-mode fiber (according to ITU-T G.652 standard), with a maximum range of 10 km between splitter and ONT, and between ONTs of the same stage (there is provision for extending the distance to 20 km in both cases).

The EPON standard establishes a dedicated wavelength for the broadcast of video from the OLT to the ONTs as the BPON standard, being this different that those used in voice and data transmission. The wavelengths are:

- Downstream channel: $\lambda=1480-1500$ nm
- Upstream channel: $\lambda=1260-1360$ nm
- Video: $\lambda=1550-1560$ nm

EPON supports a maximum ratio of 16 splitters per OLT, and each divider supports a maximum of 64 outputs to ONT users. This brings a total of:

$$Users_{MAX} = 16 \frac{splitters}{OLT} \cdot 64 \frac{users}{splitter} = 1.024 \frac{users}{OLT}$$

In this case, the standard supports less number of ONT users connected and in service to the same OLT, regarding to BPON standard. Exactly, the difference between both would be:

$$\frac{Users_{BPONmax}}{Users_{EPONmax}} = \frac{2.048 Users/OLT}{1.024 Users/OLT} = 2 \text{ times more BPON users than EPON}$$

However, despite the EPON standard involves reduce the number of ONTs connected to the same OLT, the speed ratio is increased in the same proportion considering BPON in its basic configuration, as follows:

$$\frac{Ratio_{EPON}}{Ratio_{BPON}} = \frac{1244 Mbps}{622 Mbps} = 2 \text{ times more EPON speed than BPON}$$

Finally, it is noteworthy that despite being EPON a standard that allows greater speed than BPON, it does not reach more since the maximum distance between the OLT and ONTs keeps the following proportion:

$$\frac{Reach_{BPON}}{Reach_{EPON}} = \frac{20 km}{10 km} = 2 \text{ times more BPON reach than EPON}$$

4.3.4. GPON

Today, the more advanced standard on which is still working, it is who is born from the evolution of the BPON. To work better with changes in communication technologies and to meet rapidly growing demand, ITU-T created the series of standards ITU-T G.984.x for Gigabit capacity PON, which were the basis of the standard GPON (Gigabit PON).

GPON allows transmission of information encapsulated in two technologies:

- ATM, just likes in the case of the BPON standard, but improved.
- Ethernet or TDM, using for that the GEM (GPON Encapsulation Method) based on GFP (Generic Framing Procedure).

Improvements that GPON offers respecting all of its previous standards is, in general, increasing the bandwidth in transmission and providing security to the own network by protocol level.

Thus, GPON allows varied transmission rates in the range of between 622 Mbps (as his predecessor BPON) to 2,488 Gbps in the downstream channel. Like BPON, this standard allows data transmission both symmetric and asymmetric where rates of transmission for each one are:

- Symmetric transmission, flow rates between 622 Mbps and 2,488 Gbps for downstream and upstream channel.
- Asymmetric transmission: Different flow rates for downstream and upstream channel:
 - ◆ Downstream channel: up to 2,488 Gbps.
 - ◆ Upstream channel: up to 1,244 Gbps.

The fact of allow a very high bandwidth, enables the transmission of practically any multimedia information and supports any operator service. Moreover, given their full service support (either via ATM or over Ethernet and TDM), makes him global support multiservice:

- Voice transmission.
- Ethernet 10/100 Base-T.
- ATM Service.
- Leased lines.
- Wireless extension
- Etc.

The wavelengths of work that sets the GPON standard vary depending on whether you use 1 or 2 fibers for each ONT, although for both sets a dedicated wavelength for video broadcast from the OLT to the ONTs, being this different from those used in the voice and data transmission. The wavelengths are the following:

- For 1 fiber per ONT, shared for transmission and reception:
 - ◆ Downstream channel: $\lambda=1480-1500$ nm
 - ◆ Upstream channel: $\lambda=1260-1360$ nm
 - ◆ Video: $\lambda=1550$ nm

- For 2 fibers for each ONT, one for transmission and another one for reception:
 - ◆ Downstream channel: $\lambda=1260-1360$ nm
 - ◆ Upstream channel: $\lambda=1260-1360$ nm
 - ◆ Video: $\lambda=1550$ nm

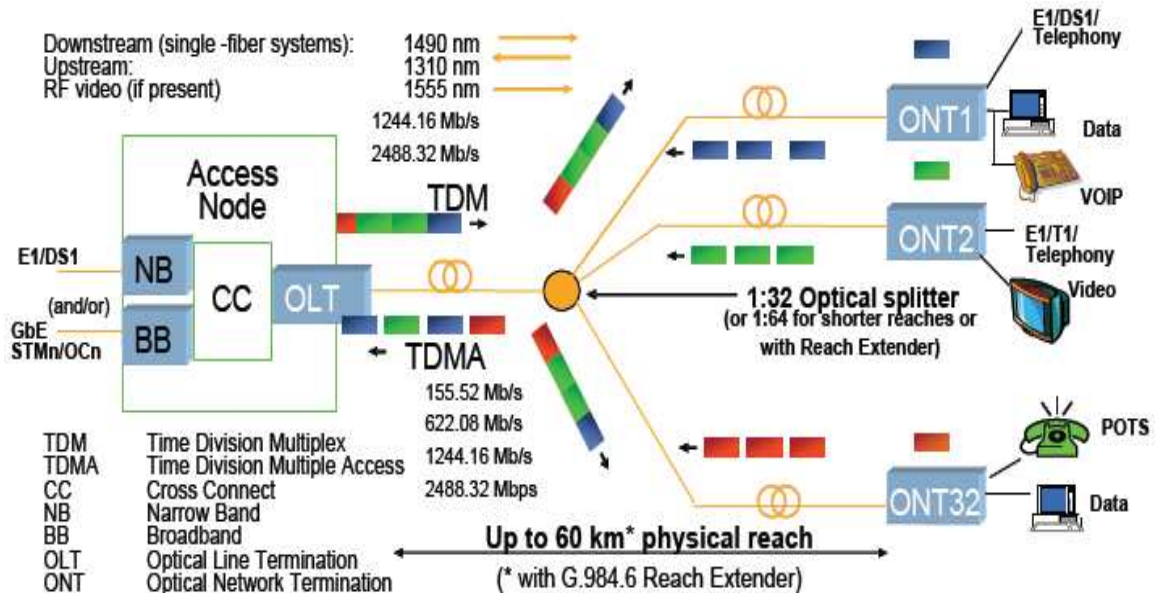


Figure 19: G-PON Access System

[<http://policom.dei.polimi.it/education/comunicazioni/lezione-PON.pdf>]

GPON supports 128 splitting ratio per OLT, and each splitter supports a maximum of 64 outputs to ONT users. This brings a total of:

$$Users_{MAX} = 128 \frac{splitters}{OLT} \cdot 64 \frac{users}{splitter} = 8.192 \frac{users}{OLT}$$

Comparatively, the GPON standard allows increasing significantly the number of ONTs connected to the same header OLT. The proportion respecting to BPON and EPON standards is:

$$\frac{Users_{GPONmax}}{Users_{EPONmax}} = \frac{8.192 \frac{Users}{OLT}}{1.024 \frac{Users}{OLT}} = 8 \text{ times more GPON users than EPON}$$

$$\frac{Users_{GPONmax}}{Users_{BPONmax}} = \frac{8.192 Users/OLT}{2.048 Users/OLT} = 4 \text{ times more GPON users than BPON}$$

The difference, as you can see, is notorious among them, which suggests that GPON technology allows minimizing the cost of deployment, as it will need less number of installed OLTs to cover a given area.

Regarding to transmission rate, GPON also increases the data transfer speed, being the ratio between the three standards the following:

$$\frac{Ratio_{GPON}}{Ratio_{BPON}} = \frac{2,488 Gbps}{622 Mbps} = 4 \text{ times more GPON speed than BPON}$$

$$\frac{Ratio_{GPON}}{Ratio_{EPON}} = \frac{2,488 Gbps}{1,422 Gbps} = 2 \text{ times more GPON speed than EPON}$$

Not only can transfer data faster, but also provides increased reliability since it has a secure transmission protocol level, introducing fields in ATM/Ethernet for this mission.

Finally, it is remarkable the increase in the distance between the OLT header and different ONTs, which is greatly increased at the rate of the following ratio:

$$\frac{Reach_{GPON}}{Reach_{BPON}} = \frac{60 km}{20 km} = 3 \text{ times more GPON reach than BPON}$$

$$\frac{Reach_{GPON}}{Reach_{EPON}} = \frac{60 km}{10 km} = 6 \text{ times more GPON reach than EPON}$$

Concluding the analytical data comparison between some standards and others, it can define the GPON standard as a standard up to 4 times faster, allowing up

to 6 times the distance between OLT and ONTs, and supporting up to 8 times more users than the other standards.

4.3.5. Other PON technologies: NG-PON

4.3.5.1. WDM-PON [27]

Thought by many to be the next thing in FTTx, WDM-PON (Wave Division Multiplexing Passive Optical Network) provides the dedicated bandwidth of a point-to-point network with the fiber sharing inherent in PON networks. Not a standard today, WDM PON is not still fully defined but carriers and vendors expect up to 32 subscribers to be served by a single WDM-PON access fiber.

The WDM-PON architecture is identical to that of EPON and GPON (and their 10G versions) FTTx architectures. However, instead of a splitter, WDM-PON usually has an Arrayed Waveguide (AWG) filter that separates the wavelengths for individual delivery to subscriber ONTs.

Advantages of the WDM approach are inherent in the completely separate downstream wavelengths for each subscriber. This provides more bandwidth to each subscriber, more security, and better operational control since there is no interference in the downstream direction among the various wavelengths.

The biggest disadvantage of WDM-PON is its cost (and its maturity as a FTTx technology). Each subscriber requires its own dedicated transceiver at the OLT, and this is one of the cost advantages of the other PON technologies lost with WDM PON. Additionally, the AWG filter is expected to be more expensive than the splitters used with GPON, EPON, and BPON.

The diagram below shows a typical WDM-PON network:

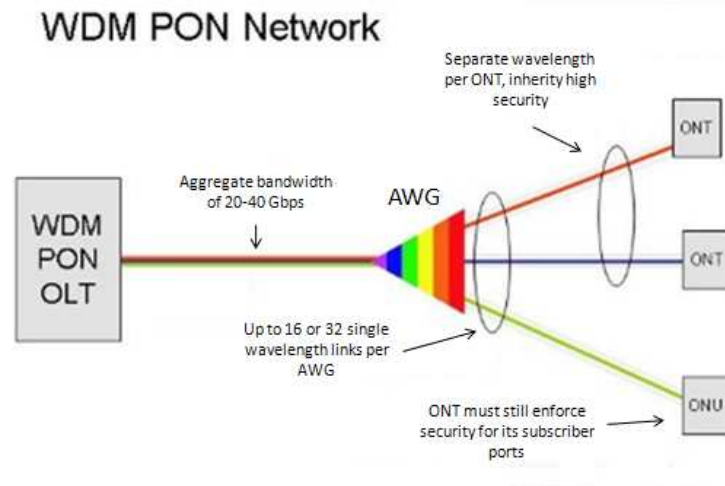


Figure 20: WDM-PON Network

4.3.5.2. 10G-GPON and 10G-EPON

Applications and services such as HD IPTV, video-on-demand (VoD), voice over IP (VoIP), video conferencing, online gaming and peer-to-peer (P2P) networking make that in the future will be necessary to implement new technologies from existing standards. The most recent standards in development are currently under way at the IEEE P802.3av (10G-EPON) and ITU-T/FSAN (10G-GPON). This NG-PON (Next Generation Passive Optical Networks) will be briefly explained, since they are very recent standards, even still in study and very expensive, so it will be applicable for future projects.

10G-PON (XG-PON) is a broadband transmission standard defined by ITU (ITU-T Recommendation G.987), that can deliver shared internet speeds of 10 Gbps over passive optical networks and it was approved on 2010-10-07. Nowadays it is still completing parts of this standard.

This is the next generation 10 gigabit standard that follows from GPON (Gigabit-capable PON) and enables its coexistence with installed equipment of the same network. In addition, 10GPON can be an extension of current GPON and deployment could be reused.

The diagram below shows a typical 10G GPON Fiber to the Home (FTTH) network. In 10G GPON, the downstream rate on the fiber is 10 Gbps. Upstream could be 1.25 (current GPON upstream rate, not shown), 2.5, or 10 Gbps, and the higher the upstream rate, the higher the cost of the optics in the Optical Network Terminals. Current GPON networks use ONT optics transmitting at 1.25 Gbps upstream, and this

will be by far the cheapest alternative for a 10G GPON ONT transceiver, which is usually the most expensive component in the ONT. Dynamic Bandwidth Assignment (DBA), as specified in G.984.3, allows over subscription in the upstream direction, and this eliminates much of the requirement for higher upstream rates. [30]

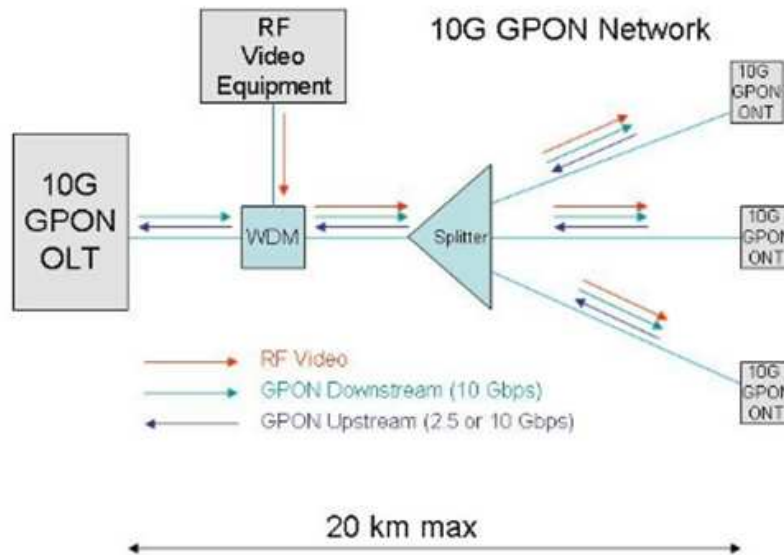


Figure 21: 10G-GPON Network Diagram

The number one electronic cost in a PON network is the unshared ONTs, though the cost of installing the fiber optics generally drives the complete cost equation. There could easily be thousands of ONTs per single moderate-sized OLT. A critical element to keeping the cost of the ONT down is an inexpensive optical transceiver, and 10G GPON transceivers capable of transmitting 10G upstream are considerably more expensive than 2.5G and 1.25G upstream capable transceivers. Although upstream has been getting a lot of attention lately, the cost of the ONT gets a lot of attention by the carriers, so expect 10G GPON upstream rates on the lower end initially and for quite a while in FTTH networks.

Finally, this standard can be summarized in its two most common ways:

- XG-PON1 (Asymmetric 10G-PON): 10 Gbps downstream and 2.5 Gbps upstream.
- XG-PON2 (Symmetric 10G-PON): 10 Gbps downstream and upstream, but would require more expensive lasers to deliver the upstream transmission speed.

Respecting to 10G-EPON, it refers to 10 Gigabit Ethernet Passive Optical Network standard about broadband transmission that was defined by IEEE (IEEE P802.3av). Unlike 10G-PON, this standard was approved in September 2009.

The 802.3av standard places significant emphasis on the coexistence of 1 Gbps and 10 Gbps EPON systems on the same network. The diagram below shows a 10G-EPON access network.

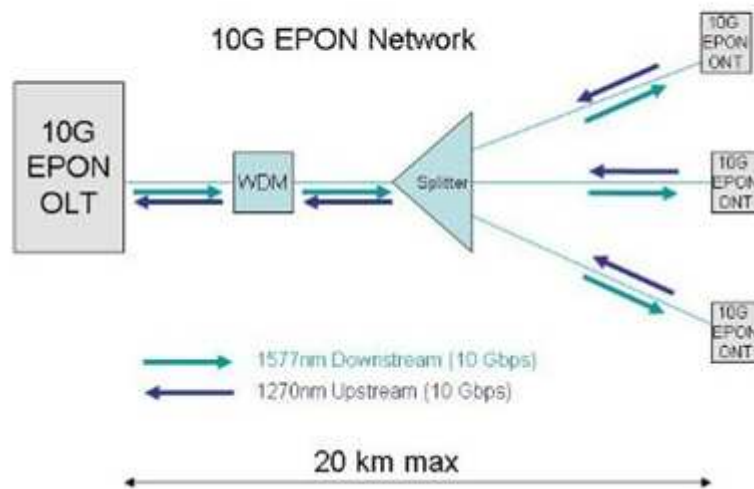


Figure 22: 10G-EPON Network Diagram

Downstream on 10G EPON is broadcast Ethernet frames and Idle characters. Upstream uses Time Division Multiple Access (TDMA) with each ONT transmitting in its own timeslot, which can vary in size over time to optimize upstream. As burst transmissions from different ONTs can have different line rates (due to different bit rate between 1Gbps to 10Gbps), this method is termed dual-rate TDMA.

In the downstream direction, the 1 Gbps and 10 Gbps channels have different wavelengths, with 1 Gbps transmission into 1480-1500 nm band and 10 Gbps transmission limited to 1575-1580 nm band. In the upstream direction, the 1 Gbps and 10 Gbps bands overlap. 1 Gbps band spreads from 1260 to 1360 nm and 10 Gbps band uses from 1260 to 1280 nm band. This allows both upstream channels to share the same spectrum region characterized by low chromatic dispersion, but it requires the 1 Gbps and 10 Gbps channels to be separated in time domain.

As the 10G-PON standard, this standard supports two configurations:

- Asymmetric: operating at 10 Gbps in the downstream direction and 1 Gbps in the upstream direction.
- Symmetric: operating at 10 Gbps data rate in both upstream and downstream directions.

Asymmetric 10/1G-EPON appear less challenging than the symmetric option, as this specification relies on fairly mature technology. The upstream transmission is identical to that of the existing 1G-EPON (as specified in IEEE Std. 802.3ah), and will rely on field-proven and mass deployed burst-mode optical transceivers. The downstream transmission, which uses continuous mode optics, will rely on the maturity of 10 Gbps point-to-point Ethernet devices. [31]

The main driver for 10/10G-EPON is the necessity to provide adequate downstream and upstream bandwidth to support the MDU's. When deployment strategy is MDU configuration, one EPON OLT may be connected up to thousand subscribers. [31]

4.3.6. Comparative synthesis among xPON standards

In the previous sections it has made an analytical data comparative obtained by different standards xPON. These data can be condensed and completed in the following table:

Features	BPON	EPON	GPON
Standard	ITU-T G.983.x	IEEE 802.3ah	ITU-T G.984.x
Transmission rate (Mbps)	Down: 155, 622, 1244 Up: 155, 622	Down: 1250 Up: 1250	Down: 1244, 2488 Up: 155, 622, 1244, 2488
Fiber type	Single-mode (ITU-T G.652)	Single-mode (ITU-T G.652)	Single-mode (ITU-T G.652)
Number of fibers per ONT	1 or 2	1	1 or 2
Operating wavelengths	For 1 fiber: Down: 1480-1500 nm Up: 1260-1360 nm Video: 1550 nm For 2 fibers: Down: 1260-1360 nm Up: 1260-1360 nm Video: 1550-1560 nm	Down: 1480-1500 nm Up: 1260-1460 nm Video: 1550-560 nm	For 1 fiber: Down: 1480-1500 nm Up: 1260-1360 nm Video: 1550-1560 nm For 2 fibers: Down: 1260-1360 nm Up: 1260-1360 nm Video: 1550-1560 nm
Max. Number of splitters per ONT	32	16	128
Max. reach (OLT-ONT)	20 km	10 km (prev. 20 km)	60 km
Max. Distance among ONTs	20 km	10 km (prev. 20 km)	20 km
Max. insertion losses	0 dB	15/20 dB	15/20/25 dB
Traffic mode between OLT and ONT	ATM	Ethernet	ATM, Ethernet, TDM
Transmission architecture	Symmetric, asymmetric	Ethernet (symmetric)	Symmetric, asymmetric
Comments	Improvement of APON. Support for other services than just ATM-based	Very popular in Asia. GE-PON is a special case of EPON	Upgrade of BPON. Improved OAM&P. Dominating in the US

Table 3: Comparative table xPON standards

Chapter 5

Design of a WDM GPON

5.1. Considerations of designing and planning of a FTTx Network

Throughout this block, the most interesting and important parameters to take in account in planning FTTx networks will be described. However it will not carry out a comprehensive study of the network at all levels, but which only will make the physical level of the network as a passive configuration and services that this PON will provide to end users. Therefore, it will execute the design of a pure PON, not including active network elements.

5.1.1. Layers of an FTTx network [32]

There is no defined standardization of the level structures and functions of FTTx networks, except physically. Some entities have developed certain characterization of FTTx networks including structural levels similar to OSI levels. But in the case of this thesis and because the design includes the development of network infrastructure, it will opt for the layered structure given by the FTTH Council Europe.

An FTTx network can be considered to have different layers: the passive infrastructure comprising the ducts, fiber, enclosures and other outside plant; the active network comprising the electrical equipment; retail services, which provides internet connectivity and managed services like IPTV; and of course the end users. Some people also visualize an additional layer, the content layer, lying above the retail services layer and the end users, which can be exploited commercially by so-called “over the top” content providers.

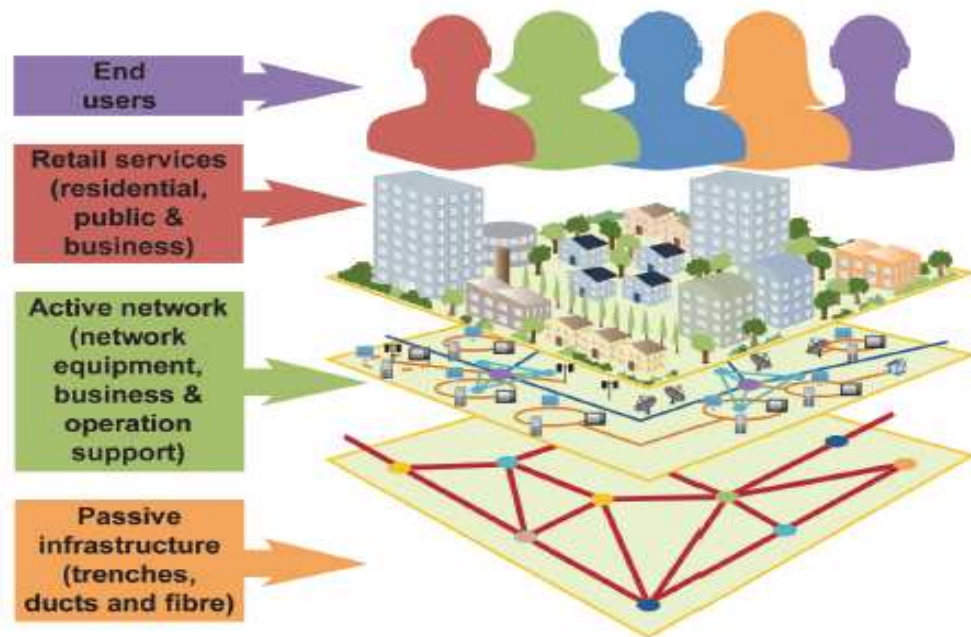


Figure 23: FTTx Network layers [32]

This technological structure has implications for the way that an FTTx network is organized and operated. Let's look at these in more detail:

- **Passive infrastructure** comprises all the physical elements needed to build the fiber network. This includes physical objects such as the optical fiber, trenches, ducts and poles on which it is deployed, fiber enclosures, optical distribution frames, patch panels, splicing shelves and so on. The organization in charge of this layer will normally be responsible for network route planning, right-of-way negotiations, and the civil works to install the fiber.
- **Active network** refers to the electronic network equipment needed to bring the passive infrastructure alive, as well as the operational support systems required to commercialize the fiber connectivity. The party in charge of this layer will design, build and operate the active equipment part of the network.

- **Retail services** come into play once the passive and active layers are in place. This is the layer where basic internet connectivity and other managed services such as IPTV are packaged and presented to consumers and businesses. Besides enabling those services technically, the company responsible for this layer is also in charge of customer acquisition, go-to-market strategies, and customer service.

Each network layer has a corresponding function. The network owner is in charge of the first layer, although they may outsource its construction to a third party. The network operator owns the active equipment, while the retail services are provided by the internet service provider (ISP).

The traditional telecom model is based on “vertical integration”, in which one entity controls all three layers of the network. This is often the case for incumbent operators, for example, Orange in France, Telefónica in Spain and Verizon in the United States.

On the other end of the spectrum is the fully separated ownership of the different layers, as is the case in some parts of Netherlands where Reggefiber controls the passive infrastructure, BBNed runs and operates the active network and provides wholesale access, and various retail service providers package the broadband access with their services and sell directly to the end-users.

5.1.2. Network elements

For the design of an FTTx network or link, it needs to establish and accomplishing the following parameters:

- Maximum transmission distance
- Optical attenuation balance for the system
- Fiber type
- Attenuation for connectors
- Attenuation by union or splice
- Maximum reflection (backward)
- Connector types
- Range of aging or mechanical lifetime

Throughout the following sections, it will describe the most important characteristics to decide the appropriate elements to meet the requirements of link distance, optical attenuation and capacity required.

5.1.2.1. Optical fiber types

The choice of optical fiber is determined by various parameters, being the most important and restrictive dispersion and optical attenuation. The advantages of single-mode fiber (high transmission capacity and low optical attenuation) make this medium as the most attractive for FTTx networks. So, always single-mode fibers are used on FTTx networks.

The fact of using single-mode optical fibers in FTTH network allows homogenizing access to the rest of the network which already uses this type of fiber, giving it transparency and uniformity. It also simplifies the operation, maintenance and development. Therefore, it recommends the usage of this type of fiber for FTTH access network, as recommended by IEEE 1000Base-LX and 10GBASE-LX. It can identify as the best options the usage of fibers G.652D or G.657A and G.657B for FTTH.

Newer fibers which conform to the G.652.D standards eliminate the water peak attenuation and allow for full operation of all 20 ITU CWDM channels in metropolitan networks. ITU-T G.652D defines a full spectrum, low water peak fiber with low PMD and represents the most comprehensive standard for standard single-mode fibers. [35]

But the private service providers are demanding that the cable manufacturers adhere to ITU-T G.657 standards. This standard describes two categories of single-mode optical fiber suitable for use in the access networks.

Category A fibers are suitable for transmission in the O, E, S, C and L-band (throughout the 1260 to 1625 nm range). Fibers in this category have the same transmission and interconnection properties as G.652.D fibers with improved bending loss and tighter dimensional specifications.

Category B fibers are suitable for transmission at 1310, 1550, and 1625 nm for restricted distances that are associated with in-building transport of signals. These fibers have different splicing and connection properties than G.652 fibers, but are capable at very low values of bend radius. [35]

5.1.2.2. Number of fibers per user

When designing a network, you have to take into account the current needs and projections regarding future service requirements referred, such as expansion of basic services, inclusion of alarms, etc.

The total number of fibers per end user or subscriber is determined by the degree of utilization of active opto-electrical components that exist on the network. Most point to point systems are based on the use of two fibers per link, one dedicated to upstream and the other for downstream. But in this project, and given that it will use the WDM technology, the uplink and downlink channels will travel through the same fiber but at different wavelengths. This implies that the number of fibers and the connectors are cut in half, saving cost and space.

5.1.2.3. Connector types

Connectors that are commonly used for national, regional and municipal networks to connect each other require higher performance and quality than those used to connect end users in an FTTx network.

In our FTTx network, it can use different types of connectors: SC, LC, MU ... depending on the price, performance, life expectancy and usage, although there are some recommendations for choosing one based on the final network, and are listed below:

- Use SC, LC or MU connectors for WDM single-mode systems that have one fiber per subscriber.
- Use any type of duplex connectors for systems with two single-mode fibers per subscriber.
- Use duplex SC, LC or MT connectors for multi-mode systems with two fibers per subscriber.

5.1.2.3. Type of unions between fibers

Fiber connections which have better performance in terms of losses concerns are the fusion splices, and are the most commonly used today. No but also tend to be frequent mechanical splices.

A good fusion should typically have a loss of about 0.1 to 0.15 dB of attenuation for single-mode optical fiber according to ITU recommendation G.652. The attenuation produced by the union of fibers is not critical in many systems, but in order to ensure a lifetime of more durable splice, it is recommended to fusion if attenuation is greater than 0.3 dB.

Moreover, the maximum recommended attenuation for any kind of fusion or mechanical splice should not exceed 0.3 dB loss. And it is the fusion joints which offer better performance and fulfilling, as a rule, such a requirement.

Special care is needed when estimating the attenuation by fusion or splices. The estimate of this parameter is not always accurate, and although is not required the metric verification of each union, it is necessary to verify the complete attenuation of the link to study the contribution of each union to the system.

5.1.3. Retail services

Once an overview of the network elements such as passive infrastructure, this section will deal with a little more detail the type of services that FTTx network can offer to its customers, which will help later to have a forecast of bandwidth that meets all their needs.

Retail services can be divided up according to market segments of this project:

- Residential
- Business
- Public sector

5.1.3.1. Residential [32]

Typical residential services include:

- Basic telephony (using VOIP)
- Internet access
- IPTV

A retail package that includes all three elements is termed “triple play”.

Retail ISPs may also choose to offer other services for customers, such as web space, online backup, technical advice and so on. These services may be bundled together with the basic package.

An increasing number of consumers are demanding reliable, high-speed broadband connectivity in order to access an expanding range of internet activities, including online shopping, online banking, school homework, access to public services online, catch-up TV, online gaming, and many more.

Catch-up TV is an example of over-the-top (OTT) internet application, because it is available to anyone with internet access. This is distinct from broadcast IPTV services, which are provided by the retail service provider exclusively to its customers.

Many internet applications also require good upstream data rates. Examples are back-up to an online data vault or online video calling. The network owner may also wish to offer specialized services, for example:

- A housing association-owned network might offer a central system for booking landlord visits and building maintenance.
- A municipal network might offer local TV broadcasts or views from CCTV cameras.
- A power utility might team with the network owner to offer an integrated system to implement smart grid and/or home automation technologies.

The high capacity available from FTTH provides a good platform for delivering new services, but don't get carried away. Getting the basics right (fast, reliable broadband) is a good way to secure customer loyalty.

Broadband on its own is a profitable product (in fact it is the most profitable product for many service providers) according to a study on next-generation access service portfolios by Yankee Group (2009).

5.1.3.2. Business [32]

Many large enterprises are already hooked into optical fiber networks because they have high bandwidth, high reliability and high security requirements that far exceed those of the residential sector. As a result of their special requirements, these large businesses are not usually linked directly to the same infrastructure as residential customers.

However, research has found that there is a considerable market opportunity to address the underserved lower end of the business market. Small and medium-size businesses (SMEs) can easily be served from a typical FTTH network. Even if the network is consumer focused, it is worth speaking to any businesses that happen to be within the coverage area.

The technical network requirements for businesses may not be substantially different for those for consumers, but business users may be interested in tailored service packages with extra features such as uptime guarantees, lower contention, higher security, and business-grade customer service. Speak to local businesses to assess their needs.

Cloud services, and application outsourcing, are becoming popular with businesses. It's understood that these services will work with high speed symmetric fiber connections only.

Further opportunities may exist to provide services that require features only fiber can deliver, for example:

- Video conferencing and telepresence are further examples of business services.
- High-frequency trading where participants need lowest latency connections to stock exchanges.
- A virtual orchestra where musicians need low latency connections to their remotely located colleagues (this could be an interesting model for the professional music recording business).

5.1.3.3. Public sector [32]

Don't neglect the public sector when drawing up your FTTH network plan. Schools, libraries, hospitals, doctors surgeries and local government buildings all require connectivity and have expanding requirements as more ICT is brought into the school curriculum, libraries become digital access points, doctors share patient records electronically, and governments put more public services online. These organizations can become anchor tenants on the network.

5.2. Planning of the WDM-GPON

This chapter is aimed to implement that all methods of design and planning of an FTTx system that have been detailed in previous chapters may apply to a fictitious environment but could be perfectly real. It will require all elements of an optical fiber system for implementing the recommendations and procedures of planning and design of an FTTx network and that allows building our passive optical network.

To this end, it proposes a model of a valid neutral operator to rent to any cable operator without requiring them to invest in physical infrastructure. Given the volume of work involves the design specification of the entire network, and since the design of the active part of the network depends heavily on transmission equipment, is intended as an exclusive design of PON, and therefore a passive design of the FTTx network.

5.2.1. Project description

It proposes a model of passive optical infrastructure for a neutral operator that puts its fiber optic network available to different cable operators in the market. This model consists of deploying a WDM GPON from a central telecommunications to different areas where end users will enjoy the services that only optical fiber network can provide.

The project will see the following information:

- Design and planning of the chosen network architecture for deployment of FTTx network based on WDM PON networks and the feasibility study system.
- Supply all materials and components necessary to deploy a passive optical infrastructure of an FTTx network, which includes from OLT to the optical jack (ONT) in the house.

The supply and installation of active equipment will be provided by companies which provide cable service, as well as the operation, service and active maintenance of the network.

5.2.2. Access network design

To perform an optical infrastructure deployment in the best possible way, is essential to know the scenario of deployment, its particularities, highlighting the most important features, and so on.

The area under deployment is a fictitious environment as an expansion of a city but it could easily belong to a real environment. Here we can clearly see 5 distinct areas that will need a new generation network for meet their needs:

- Hospital area: in that it can find a huge hospital that covers the whole region and have all the latest technological advances.
- Business offices area: it will find 2 buildings with a total of 30 offices that will give service to several companies.
- Residential area: it is a distribution of 20 single-family homes that they will require a full suite of triple play service.
- Mall and school area: next to the residential area it will be located a school and a shopping center that at least will enjoy access to broadband internet and HDTV.
- Buildings area: Finally it will find another residential area similar to above but in the form of apartment buildings. In that it will be located 2 buildings employing a total of 22 apartments and they will also need triple play service.

Below it displays a virtual picture of the 5 areas that it will give service through passive FTTx networks.

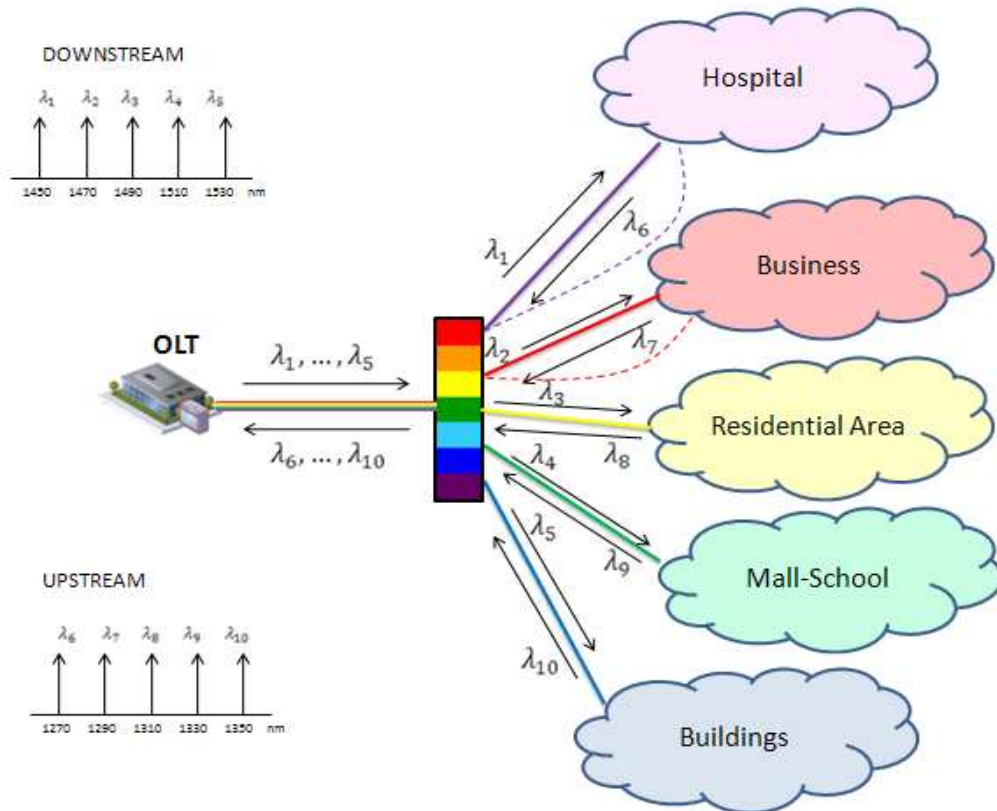


Figure 24: Deployment scenario

Having seen the overall design of that it will be our passive optical network, it will divide the design into 5 sections that correspond to the 5 areas to be designed.

5.2.2.1. Hospital area

The area where it will place the hospital is located 3 km from the SPLITTER and therefore a total of 8 km from the central office. It will arrive to this area a link that would support GPON up to 1,244 Gbps symmetric and will provide LAN and Wi-Fi access in all major points of the hospital. This will cover the required services such as broadband Internet, HDTV, VoIP, telemedicine and diverse applications for real-time control.

Below is shown a drawing of the area:

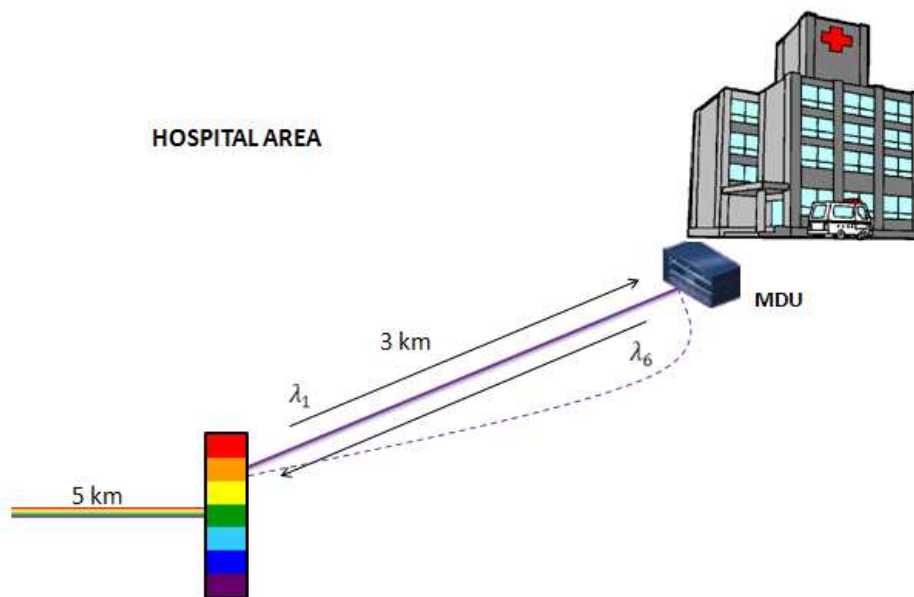


Figure 25: Hospital area

5.2.2.2. Business offices area

This is an extension of the business area, where it will build two office buildings, in which each one will have 15 offices, making a total of 30 offices.

Each of these offices will require services such as broadband internet, HD Videoconference, FTP, VoIP, cloud computing ... with that today and for future forecasts, 75 Mbps would be enough.

Therefore, the bandwidth required for these 30 offices would be $75 \text{ Mbps/office} \cdot 30 \text{ offices} = 2250 \text{ Mbps}$, so a FTTB design with a 2.488 Mbps symmetrical GPON link would be sufficient to cover all needs.

Note below the drawing of the extended business area:

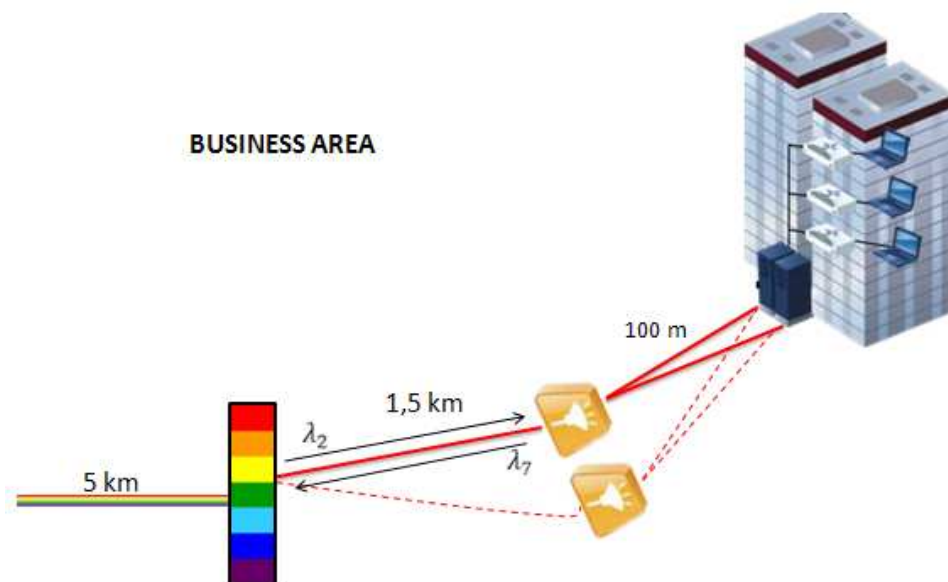


Figure 26: Business area

5.2.2.3. Residential area

The residential area will have 20 single-family houses, located 1 km from the optical SPLITTER and 6 km from the OLT, which will demand last generation triple play service. These services may include:

- Broadcast:
 - 2 HDTV channels: $2 * 15 \text{ Mbps} = 30 \text{ Mbps}$
 - 1 3D channel: 50 Mbps

- Real-time applications:
 - HD videoconference: 7 Mbps
 - Online games: 1 Mbps
 - Home automation, VoIP, audio... 2 Mbps

- Broadband internet:
 - Web, mail, P2P... 10 Mbps

This will make a total of 100 Mbps per household and therefore it will need a bandwidth of $100 \text{ Mbps}/_{user} \cdot 20users = 2 \text{ Gbps}$ to provide this service to all users.

With this in mind, it just needs a GPON link with 2,488 Gbps downstream and 1,244 Gbps upstream.

Next picture shows a schematic of residential area with the 20 households:

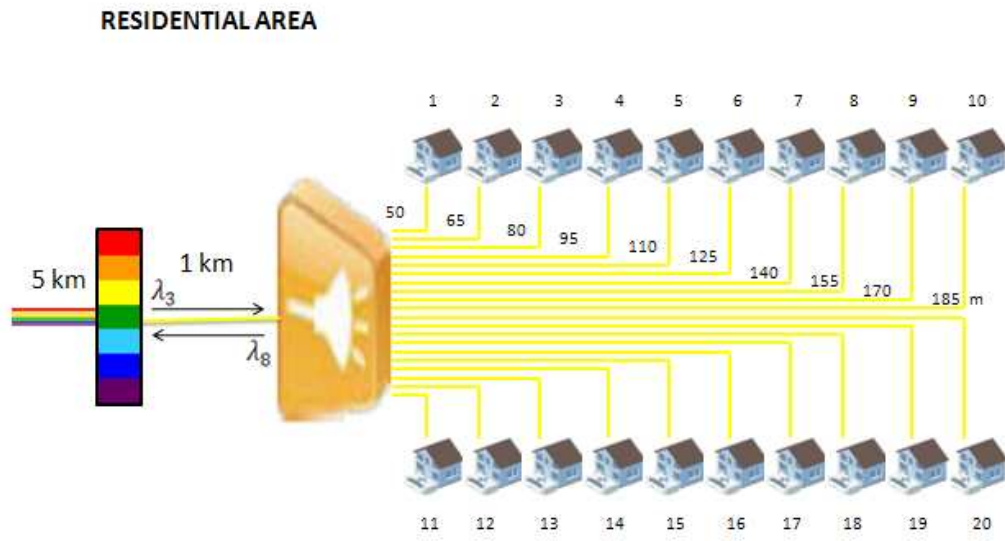


Figure 27: Residential area

5.2.2.4. Mall and school area

It will now describe the zone next to the residential area, where it will locate a school and a shopping mall. This area is also 1 km from the optical SPLITTER and therefore 6 km from the central office. Speaking about services, it will be required broadband internet access from a local area network (LAN) in different classrooms of the school, apart from VoIP, and broadband Internet with Wi-Fi service that will be given to the various shops and restaurants in the mall, apart VoIP and HDTV.

The bandwidth of all this depends on the number of stores that want to have the service, but with a symmetric 1.244 Gbps GPON connection will be enough to supply the entire area.

The infrastructure development shall be shared from the optical fiber to the splitter that will be located in the area and it will distribute the traffic to the two buildings which will be equipped with LAN access at school and other LAN and Wi-Fi in the mall. This can be seen in the following scheme:

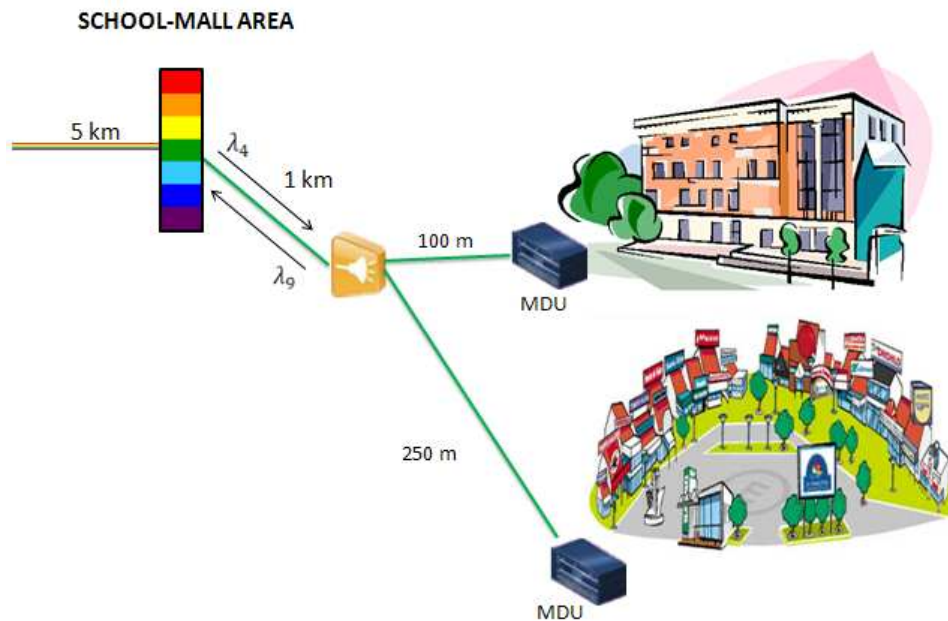


Figure 28: School-Mall area

5.2.2.5. Buildings area

Finally is the last area that will serve our passive optical network. This is the extension of buildings area in which it will be built two buildings: the first with 5 floors that will house 10 homes, and the second with 6 floors and 12 apartments.

Talking about the services they require, it will be the same as residential users, i.e. next generation triple play service that it will consist of:

- Broadcast:
 - 2 HDTV channels: $2 * 15 \text{ Mbps} = 30 \text{ Mbps}$
 - 1 3D channel: 50 Mbps

- Real-time applications:
 - HD videoconference: 7 Mbps
 - Online games: 1 Mbps
 - Home automation, VoIP, audio... 2 Mbps

- Broadband internet:
 - Web, mail, P2P... 10 Mbps

Each of the apartments will need 100 Mbps and therefore a total bandwidth of $100 \text{ Mbps}/\text{User} \cdot 22 \text{ Users} = 2,2 \text{ Gbps}$ to provide all users.

This can be solved through access to FTTH consist of one GPON link with 2,488 Gbps downstream and 1,244 Gbps upstream. With one splitter the signal will be divided and it will reach the corresponding MDU, which will distribute the connection throughout the building via a LAN. The following scheme will see the building area:

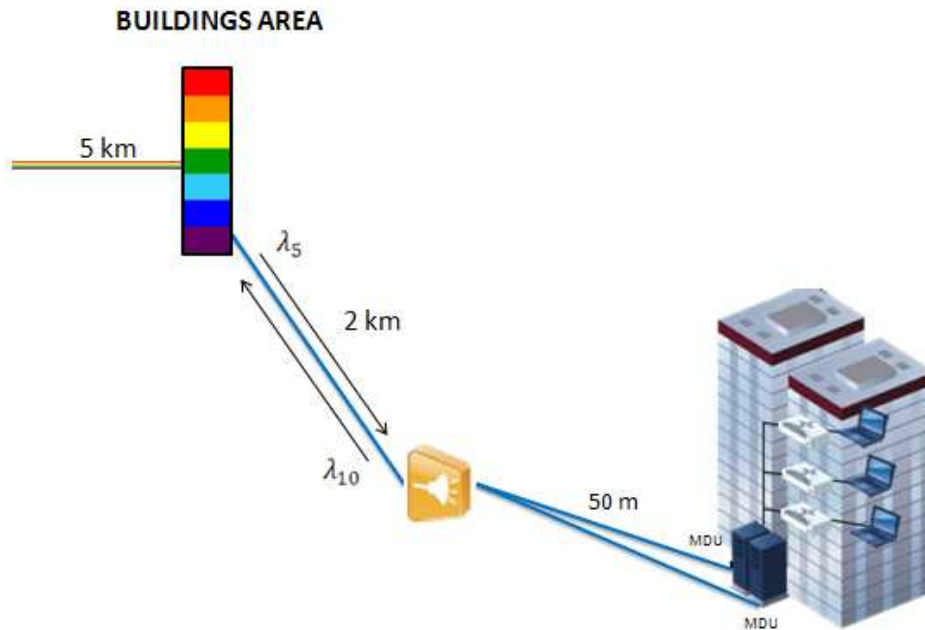


Figure 29: Buildings area

5.2.3. Choice of network elements

Once it has seen in detail all the scenarios that make up the network and the services that end users will need, it's time to talk about the elements that will be used to develop the design. In Figure 26 it can remember the deployment of our GPON design, viewing in the following figures these areas in detail.

5.2.3.1. OLT

This is one of the most important elements of the network, which is in charge of distributing the traffic to clients and it performs router functions to provide all the services demanded by users.

Unlike other equipment on the network, the OLT and the different ONTs are the only active components, so it will be the operator who chooses these elements.

However, as network designer, it can choose from several options to locate the OLT, each of which has advantages and disadvantages:

- Core Central Office:
 - ☺ Long distance coverage.
 - ☺ Easy operation and maintenance.
 - ☹ Low density of users.

- Central Office:
 - ☺ Better radio coverage.
 - ☺ Easy operation and maintenance.
 - ☺ Balance of resources (connections, fiber optic cables, ducts, feed, etc.).

- Outdoor Cabinet:
 - ☺ Saving fiber optic cables.
 - ☹ More complex maintenance.
 - ☹ Reduced coverage radio.
 - ☹ Electric power needs.
 - ☹ On-site administration.

With this in mind, the only OLT it needs will be located in the central office allowing a better radio coverage and much cheaper operation and maintenance costs than in outdoor cabinet. Furthermore, the central office is more appropriate because in it are distributed most of the communications of the city.

5.2.3.2. Optical fiber cables

As discussed in paragraph 5.1.2.1., optical fibers that meet the ITU G.652D and ITU G.657 recommendation are the most appropriate for our design, since they eliminate the water peak and therefore they can be used throughout the whole band from 1260 to 1625 nm range, fundamental requirement for this CWDM design.

Therefore, ITU G.652D fibers will be used in all our design, except for residential area and the last school-mall access, where it will use ITU G657A fibers. This is because they are compatible with ITU G.652D fibers and in the last part of the network, space requirements and manipulation of the fiber are much more stringent and therefore

these last fibers (ITU G657A) are optimized for the curvatures and this way they offer fewer losses.

After selecting the optical fiber, the next step is to choose the type of cable that will support these fibers.

To make a design more economic, it will proceed to the installation in micro-trenches because it allows reducing the impact of civil works in the installation of new cables and it can cost 1/3 of a normal channeling. It consists of making a very small ditch which can varies between 1 and 10 cm wide and 10 to 20 cm in depth depending on the diameter of the cable to install.



Figure 30: Installation in micro-trenches

[<http://www.telnet-ri.es/soluciones/cable-fibra-optica-y-componentes-pasivos/microzanjas-para-la-instalacion-de-fibra-optica/>]

Therefore, ESP-coated optical cables will be used because they are designed for underground installation of outside plant and are particularly suitable for direct installation and buried in trenches or micro-trenches. These cables are armed with steel tape, giving them special characteristics of mechanical strength.



Figure 31: ESP fiber optic cable

[<http://www.telnet-ri.es/productos/cable-fibra-optica-y-componentes-pasivos/cable-de-tendido/esp/>]

Construction details for ESP cable are the following:

1. - Dielectric Fiber-Glass Reinforced Plastic Central Reinforcement Element (CRE).
2. - PBT Loose Tube Assets, containing optical fibers and passive tubes wired in S-Z around the E.C.R. and coated with water-blocking material.
3. - Copolymer corrugated steel as a reinforcement element for traction and rodent protection.
4. - Polyethylene coating.

Being clear about what type of optical fiber is optimum for our design, and the appropriate cable for the installation mode of the network, it just needs to know the number of fibers to use for the deployment and the length of these. It should be noted that when it talks about optical fiber it will correspond to G652D optical fiber with ESP-coated cable or G657A optical fiber with ESP-coated for the latest section in the

residential area and school-mall access. Therefore, they are going to be described starting with the OLT and ending in the ONTs of each zone.

The first section of the network will correspond to the optical fiber from the OLT and connects it to the optical splitter. This fiber will have a longitude of about 5 km.

From the optical splitter will leave 8 optical fibers, 6 of them will distribute all the information to the respective areas, and the remaining two fibers that are redundant will go to hospital and the business area, and will only be used in case of fault.

Two of the fibers will reach the hospital and will have an approximate length of 3 km. The two fibers will be connected to a MDU (Multi-Dwelling Unit) through a multiplexer, which will let pass the signal through the first fiber, and will only connect with the second in case of failure of the first. Thus, the hospital will not lose access to all services. Finally, from the MDU will leave a local area network that will connect with all the necessary points of the hospital.

Two other fibers of about 1.5 km long will reach the business area and each one will be connected to an optical splitter to split the signal into other two to reach the MDUs that will be located in each of the two buildings. This last section will be about 100 meters. In each of the MDUs also it will connect a multiplexer in the same way as in the case of the hospital. It is recalled that is being designed in this way to ensure the connection in the event of a problem with the optical fiber. As in the case of the hospital, from MDU it will serve to the offices throughout local area network.

Now located at the residential area, it will use a fiber optic cable of 1 km (which will also come from the optical splitter) to reach the area. At this point, it will place a splitter to split the signal in another 20 to reach all customers in the area. Therefore, it will need 20 optical fibers of different lengths. The first two cables will have a length of 50 meters and the following will increase its length by 15 meters (since this is the distance between two consecutive houses). In summary it needs: two cables of 50, 65, 80, 95, 110, 125, 140, 155, 170 and 185 meters, which make the 20 cables needed to supply all customers. Each of them will arrive to a different home, and will be connected to their respective ONT.

The school-mall area will be easier. In that will only reach a 1 km optical fiber which will be connected to a splitter, and so divided into two other signals that will reach each one a different building. Therefore, it will need two cables, one of 100 meters to reach the school and another of 250 meters to get the mall. On these two points will be placed two MDUs to supply via LAN and Wi-Fi both the shopping mall and school.

Finally, the last will be the buildings area, as it has seen in previous sections it will need three optical fibers to supply all customers. The first one will be about 2 km and the other two that will reach the MDU of its corresponding building will have 50 m. As in previous cases, the MDU will distribute the information to each of the apartments by copper and coaxial cable.

It is important to consider the reserve of cables. This means that for each of the optical fibers to be implemented, it always will leave a reserve of about 5 or 10 meters of cable in case of it needs to move any network element (rack, splitter, ONU ...) it has a sufficient provision of cable to make the move possible. Obviously, this extension cable will mean negligible losses.

To facilitate understanding, it has drawn a diagram with all optical fiber cables and their lengths:

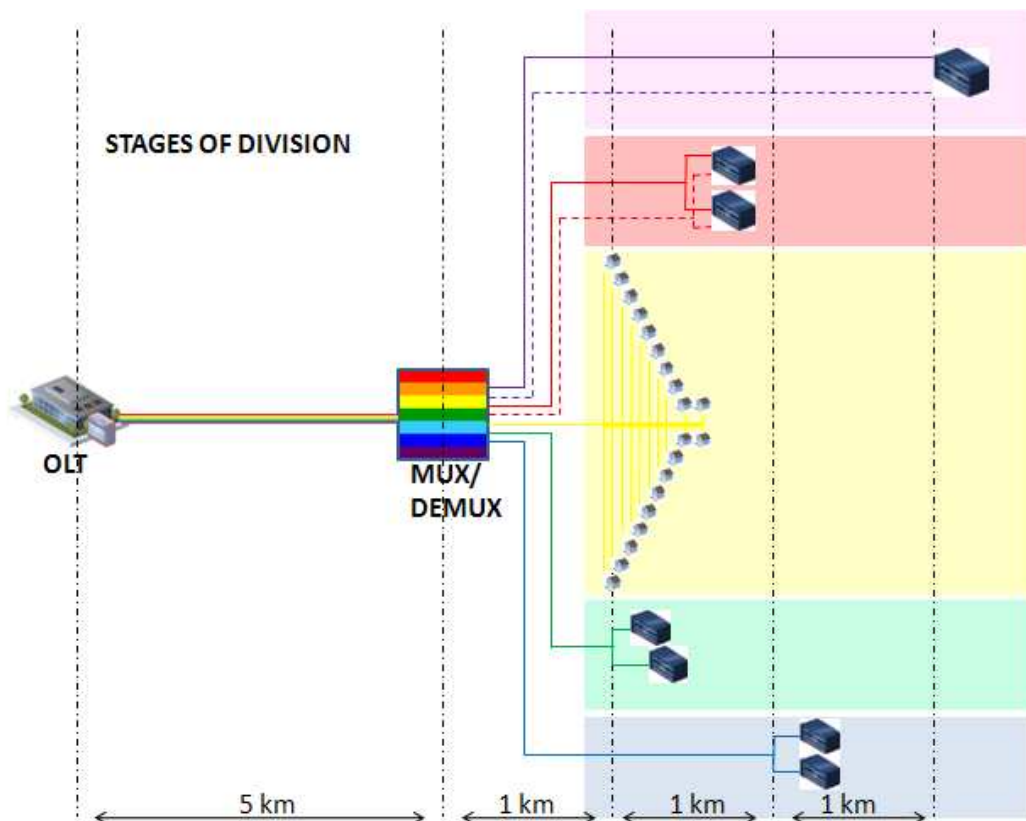


Figure 32: Stages of division

5.2.3.3. Connectors

Fiber optic connectors are an important element within the range of passive devices, allowing the alignment and joining of two optical fibers and in the best possible conditions. A poor union can be transformed into high losses, and therefore may cause that the actual network application does not conform to previously design.

In the previous paragraph has been described the type of fiber and cables to be used for the deployment of passive optical network. It is time now to talk about the connectors that allow joining the fibers with the other equipment on the network.

It will choose SC (Standard Connector) type connectors because its square profile allows more easily attach the fibers by a push-pull mechanism that protects the ceramic ferule. The SC connector is the most popular in both LAN and transport networks.

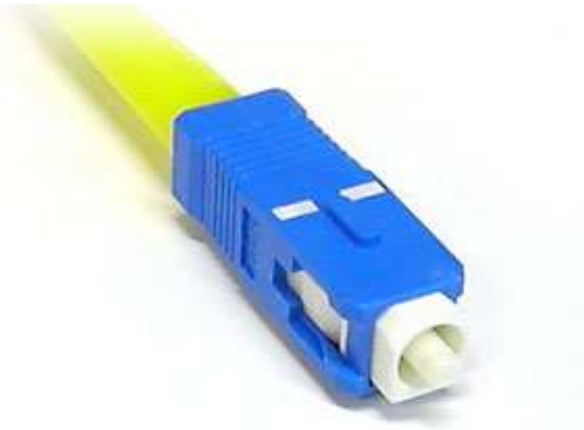


Figure 33: SC connector

[<http://www.timbercon.com/SC-Connector.html>]

It is also important to discuss about the finish of the ferules in the optical connector. The original fiber connector is based on physical contact (PC connector), through which the two fibers are connected on a flat surface to avoid air between two flat surfaces. But nowadays the polishing APC (Angled Physical Contact) is used, in which the end of the ferule is polished with an angle of 8° in the result that much of the reflections that do not match the main mode will divert to the coating. In this way it can get a return loss of -65 dB.

In some parts of the design as might be the splitters, it may choose to use connectors or splices. The splices tend to have better performance in terms of losses, but hinder the mobility when connecting and disconnecting the fiber. Therefore, in the design SC connectors with APC polish will be used because that will allow greater ease of usage in case of changes or testing of the network.

Being clear about the type of connector and the polish which it will use, it can only find out how many connectors it needs to deploy the network. Viewing the above scheme (Figure 34) it can deduce that 36 optical fibers will be installed, so it will need two fiber connectors to connect the ends. This will make a total of 72 SC connectors.

5.2.3.4. Optical Splitters

In order to expand the access network, it will be used optical splitters or dividers.

A splitter allows the derivation of the optical signal by two or more different fibers. They are designed to introduce insertion losses approximately equal in all its output branches and there are several techniques for the manufacture of splitters:

- Fused bi-conical taper (FBT).
- Planar Lightwave Circuit (PLC).

FBT is an old technology that is based on the fusion of two fibers coupling with a specific region of the wavelength range that has more losses compared with PLC technology, although both can be used in PON.

The PLC Splitters (Planar Lightwave Circuits) are based on optical waves developed on a silicon substrate. The silicon substrate is an element that has very good optical properties. This technology allows construction of high performance optical splitter with high density of channels and low size, so that will be considered for the network access design.

Since the splitters involve a significant loss of power in relation to other network components, the design of a network must be carefully balanced between: high branching fibers, distances to customers and powers managed by equipments, so that meet the main specifications.

For the location of the splitters, there are two basic options:

- **Outdoor Cabinet:** in which the splitters are placed in lockers located in strategic places, which has the advantage of lower costs of deployment and on-site maintenance required.
- **Basement:** the splitters are placed in rooms or closets Telecommunications existing near of the user, for example, in a building. It has the advantage of saving fiber optic cables compared to the inefficient use of PON ports and requiring on-site maintenance.

For this design the splitters will be located in Outdoor Cabinets mainly for the reason that the expansion of the network is provided placing splitters at strategic points, and not indoors where the usage of ports would be limited to a small number of customers.

Finally, it just needs to decide how many splitters will be placed on the network and what will be the ratio of division:

- For the hospital area, no splitter is needed since the same optical fibers arrive directly to the MDUs.
- For the business area, it needs a couple of splitters with division ratio of 1:2 for each of the two fibers can connect the two buildings.
- In the case of the residential area, it will need a 1:32 optical splitter to encompass a division of 1 to 20. Therefore, this splitter will be the minimum necessary (it can find 1:2, 1:4, 1:8, 1:16, 1:32, 1:64 even 1:128 division ratios, but it's strongly recommended the minimum ratio possible to get the minimum losses).
- In the mall-school area is needed another 1:2 splitter to distribute the traffic to the two buildings.
- As in the case of the offices, in the buildings area the optical fiber will need a splitter with division ratio of 1:2 for each of the two fibers that will reach MDUs.

5.2.3.5. ONT and MDU

The ONT (Optical Network Terminal) is the last element of our network. This charge of optical-electrical conversion oriented to the subscriber obtains the required services. Must be located in user's home ending the optical fiber and provides the user interfaces.

As it has talked about the OLT, the ONT is an active device to be selected by the operator to operate the network. In general, it must be the same manufacturer as the OLT, although it is working to achieve interoperability between manufacturers, which would open the market and lower prices.

There are a big variety of ONTs, depending on the services they want to provide and the interfaces that provides to user. In our case we need ONTs adapted to triple play service and can provide POTS, Ethernet, HDTV and 3D video.

In the case of buildings such as apartments, offices, schools, malls, hospitals ... and in general anything that does not mean a single user, it will be used MDUs (Multi Dwelling Units) to provide more than one user, since the ONT can only serve a customer.

To complete the equipment of our network, it will just have to see the number of MDUs and ONTs required:

- In the hospital area just needs a MDU to provide service via LAN.
- In the offices area, it takes two MDUs, one for each building.
- In the residential area, with 20 ONTs (one for each client) will be enough.
- In the school-mall area, it will require two MDUs, one for the school and one for the mall.
- And for the last area, with two MDUs will give service to two apartment buildings.

This makes a total of 20 ONTs and 7 MDUs to supply all costumers.

5.3. Choice of simulation program

Once thought by which technology is going to design the network, the next step is to choose a simulation program that meets the needs of design and which it allow covering all aspects.

The simulation using software in the field of telecommunications networks is now a very useful tool for companies and universities of the sector at the time to recreate the behavior of a system in which different services and applications are running in defined conditions the user.

The fact of simulate allows to detect network problems before they are implemented, test new networking solutions, testing new communications technologies even including theoretical models that in reality could be difficult to construct. All this makes it a very useful and powerful tool for the design of communications networks.

Taking this in mind, it will choose the simulation program Optisystem 9.0 for the design of our WDM PON network.

5.3.1. Optisystem 9.0 simulation program[®]

Optical communication systems are increasing in complexity very quickly. The design and analysis of these systems, which typically include nonlinear devices, are extremely complex and time-intensive, and therefore, these tasks can only be done efficiently with the help of new advanced software instruments.

OptiSystem 9.0 is an innovative optical communication simulation system that design, test and optimize virtually any type of optical link at physical layer level, from video broadcasting analog systems until dorsal intercontinental links.

It is a system-level simulator based on realistic modeling of optical fiber communication systems. It has a powerful simulation environment and a hierarchical definition of components and systems. Their capacities can be easily extended by adding user-defined components, and can be interfaced with a wide range of complementary tools.

A friendly graphical user interface controls the layout of optical components and network topology, systems, components and graphical presentation. An extensive library of active and passive components includes realistic parameters dependent on wavelength. These sweeps parameters are used to investigate the effect of device-specific data on system performance.

Key Features

The main interface features OptiSystem include:

-Library Components

To be fully effective, the component modules must be able to reproduce the actual behavior of the device and the purposes specified under selected accuracy and efficiency. The Component Library includes OptiSystem hundreds of components, all of which have been validated to deliver care results that are comparable to real applications.

-Components measured

OptiSystem Component Library lets to manage the parameters that can be measured in real devices. It also integrates with test measurement equipment from different suppliers.

-Mixed signal representation

OptiSystem can handle mixed signal formats for electrical and optical signals in the Component Library. It calculates signals using the appropriate algorithms related to the simulation efficiency and accuracy cogeneration required.

-Quality and operating algorithms

To predict the system operating, OptiSystem calculates parameters such as BER and Q Factor using numerical analysis or semi analytical techniques for systems limited by interference from symbols and noise.

-Advanced visualization tools

These visualization tools produce spectrums OSA, signs with "chirp", eye diagrams, polarization state, constellation diagrams... It also includes WDM analysis tools, showing signal strength, gain, noise factor, and optical signal to noise ratio OSNR per channel.

-Data monitors

It can select ports in components for data backup and attach monitors after the end of the simulation. This allows processing the data after the simulation without having to recalculate. You can also attach an arbitrary number of displays in the same port.

- Hierarchical simulation with subsystems

To make a simulation tool flexible and efficient is essential to provide models in different levels of abstraction, including system, subsystem and component levels. OptiSystem has a truly hierarchical definition of components and systems, software tools are used specifically for fiber optic components and integrated at the component level, and allowing the simulation can be as detailed as desired.

-User defined components

It can add new components and subsystems based on libraries and subsystems defined by user, or use co-simulation with other tools.

-Multiple layouts

It can create many designs using the same project file allows it to create and modify designs quickly and efficiently. Each project file can contain multiple versions of design. Versions of design are calculated and modified separately, but the calculation results can be combined across different versions, taking into account the comparison of different designs.

-Reports

A report fully "customized" allows displaying any set of parameters and results available in the design. The reports produced are organized in reconfigurable spreadsheets, text, 2D and 3D graphics. This also includes the export of HTML templates with "layouts" preformatted report.

-Parameter sweeps and optimizations

The simulations can be repeated with an iterated variation of the parameters. OptiSystem can also optimize any parameters to minimize or maximize any results or search for objective results. You can combine multiple scans of multiple parameters and optimizations.

- Lists of materials

OptiSystem table provides a cost analysis of the system designed, specified by the system, "layout" or component. The cost data can be exported to other applications or spreadsheets.

Applications

OptiSystem design allows automation of virtually any type of optical link in physical layer, and the analysis of a broad spectrum of optical networks, from long-range systems to MANs and LANs.

The range of OptiSystem applications includes:

- The design of an optical communication system from the component level to system level in physical layer.
- CATV or TDM / WDM network design.
- Passive Optical Networks (PON), FTTx.
- Optical systems in free space optics (FSO).
- Systems of Radio on Fiber (ROF).
- Design of SONET / SDH networks.
- Transmitter, optical channel, amplifier, and receiver designs.
- Estimation of BER and system penalties of different receptor models.
- BER for an amplified system and power budget calculation links.

5.4. Design of the WDM-GPON and Results

We are now possibly in the most important section of the project, which will describe the design of the WDM PON.

At this section, the parameters and scenarios of simulation will be shown and described. The purpose is to show the behavior of links of optical fiber when the signal goes through all the elements such as optical fiber, splitters, multiplexers and the goal is to find a good quality of signal in all receivers.

The final goal pursued with this thesis is to evaluate the performance of the whole system. The parameters used to evaluate this behavior will be the BER and the Eye Diagram.

The first condition used to assess the performance of the link is generally BER (Bit Error Rate) at the receiver. Simulations are done trying to approach at the receiver a minimum BER. Any simulation with a $BER < 10^{-4}$ at some point of the network will show that the link is not consistent and reliable.

It has been assumed the use of FEC techniques that will be used for correcting errors and bringing them from 10^{-4} to 10^{-12} . These techniques can be for example Reed-Solomon (255,239) defined at the standard ITU G.709.

The second condition corresponds to the eye diagram. Viewing this diagram it can describe the quality of the received signal. In the presence of ISI, when the pulse does not satisfy the Nyquist criterion, the diagram will tend to close vertically. For error-free transmission in the absence of noise, the eye must be kept some vertical opening, or otherwise it will exist interference between symbols that will cause errors. When the eye is not fully closed, the interference between symbols reduces the value of allowable additive noise. Therefore, the higher vertical opening the greater immunity to noise.

The following sections will describe the design, displaying the various network scenarios and analyzing the most important parameters. For that, it will begin with a comprehensive description of the entire network, and as in previous sections, it will continue with the detailed analysis of each of the different areas that compose the design. Finally it will obtain the results of each ONU, which will mean that the network is viable and therefore its practical implementation would work.

5.4.1. WDM PON: Complete design

This is the complete design of our WDM-PON. As reflected in previous sections it will describe each of the elements with their most significant parameters and which its function in the design is. To facilitate understanding, it will describe the design from the OLT to the different ONT's for downstream, and from the ONTs of the different areas to the OLT for upstream.

It can see the complete design in Figure 34 that is located on the next page.

On the left side of the design you can see the OLT which will transmit information to different users and it will receive information from the ONT's. All this information will be transmitted multiplexed at different wavelengths through a single optical fiber, and then demultiplexed to spread to different areas in downstream, and multiplexed from different areas in upstream. As explained in previous sections, the simulation also has been divided in 5 areas.

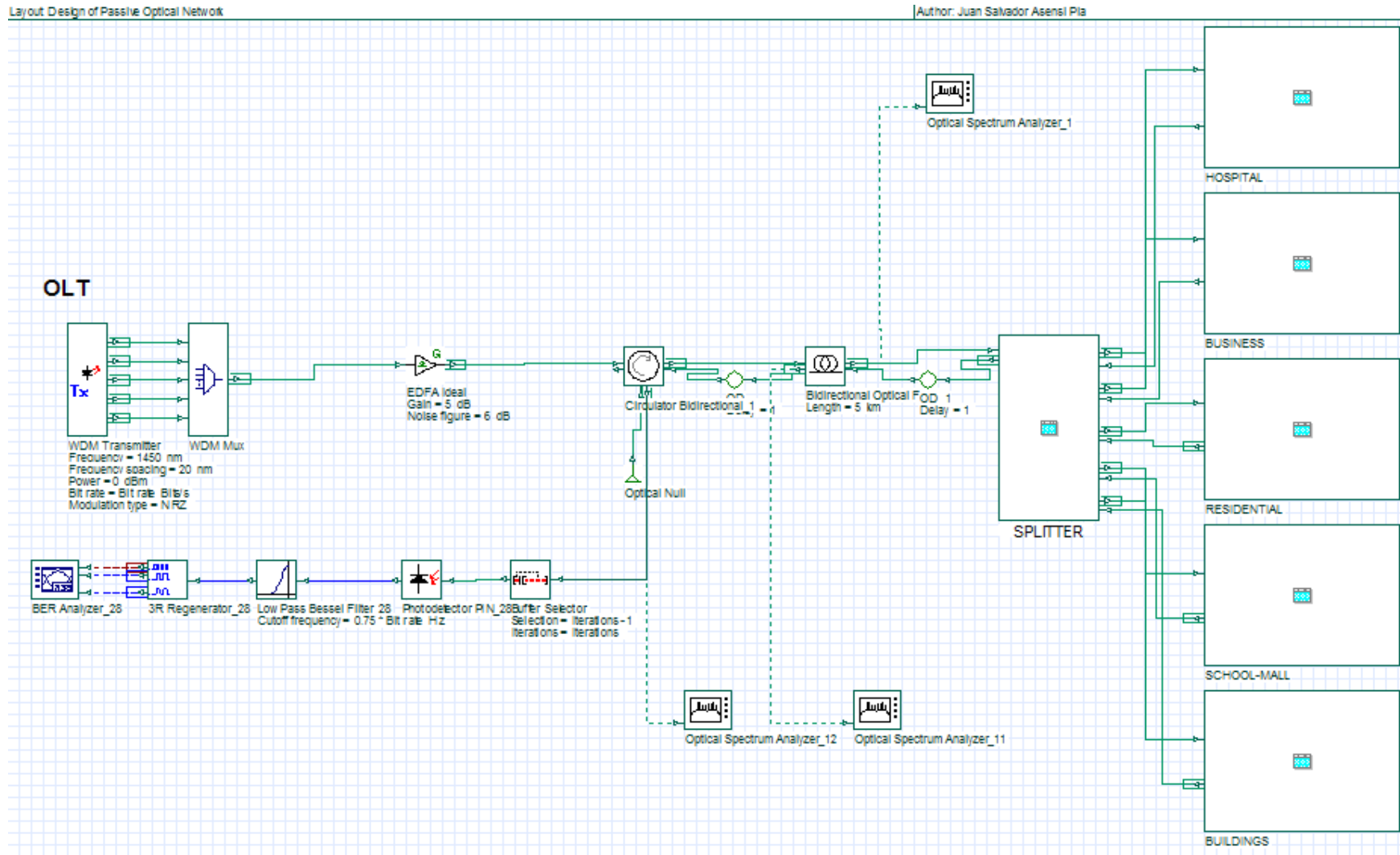


Figure 34: WDM PON – Complete design

The most important global parameters of the network can be seen in the following figure:

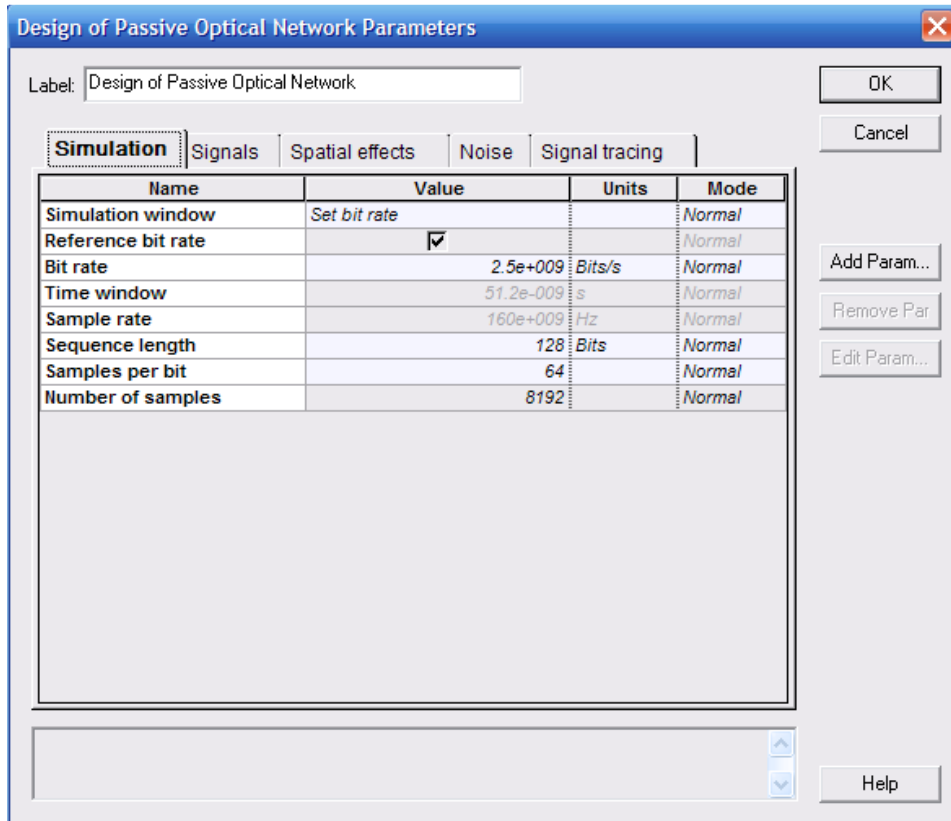


Figure 35: WDM PON – Global parameters

The global bit rate used for the design will be 2.5 Gbps. This bit rate will be used throughout the design because if the network is working for this bit rate it will work for all other bit rates as outlined in previous sections because they will be lower than this.

Other important parameters are the sequence length (128 bits) and the samples per bit (64). These will make a total of 8192 samples and are important because it needs a large enough sequences for simulate the network at these high bit rates.

It's also important the iterations of the simulation. In this case, we need 7 iterations for make the design work, because it needs to insert optical delays. These optical delays are required in some devices when they do not have all signals in the input ports.

Once described the most important global parameters, it is going to describe the network operation in downstream and upstream.

5.4.1.1. WDM PON in downstream

In downstream, the optical signal will direct from the OLT to the end users (ONT's).

Returning to Figure 34, the first network element is the optical transmitter located at the OLT. This laser will broadcast five different wavelengths from 1450 nm to 1530 nm with a frequency spacing of 20 nm. The transmission power will be 0 dBm and it will use NRZ modulation.

The next element that is needed is an optical multiplexer, which will multiplex these five wavelengths to transmit on a single fiber. It will have a bandwidth of 80 nm, just to cover the five necessary wavelengths. This multiplexer 1:5 (which actually correspond to a multiplexer 1:8) will have insertion losses of 2 dB.

Given the large losses that the residential area will have due to the great division that the signal will suffer, it should be placed to place in the OLT an EDFA amplifier of about 5 dB of gain to ensure good quality signal in the case of major losses.

In addition, because the OLT will have to handle both the downstream and upstream traffic, it will insert an optical circulator with insertion losses of 3 dB and return losses of 65 dB.

Being described the elements of the OLT, the optical signal will be inserted in the optical fiber which will reach the multiplexer located at 5 km from the central office. The most important parameters of this fiber, which will carry information in both directions, are 0.2 dB/km of attenuation, 16.75 ps/nm/km of dispersion and 0.075 ps/nm²/km of dispersion slope.

Next is attached the spectrum of the signal that has been inserted into the optical fiber:

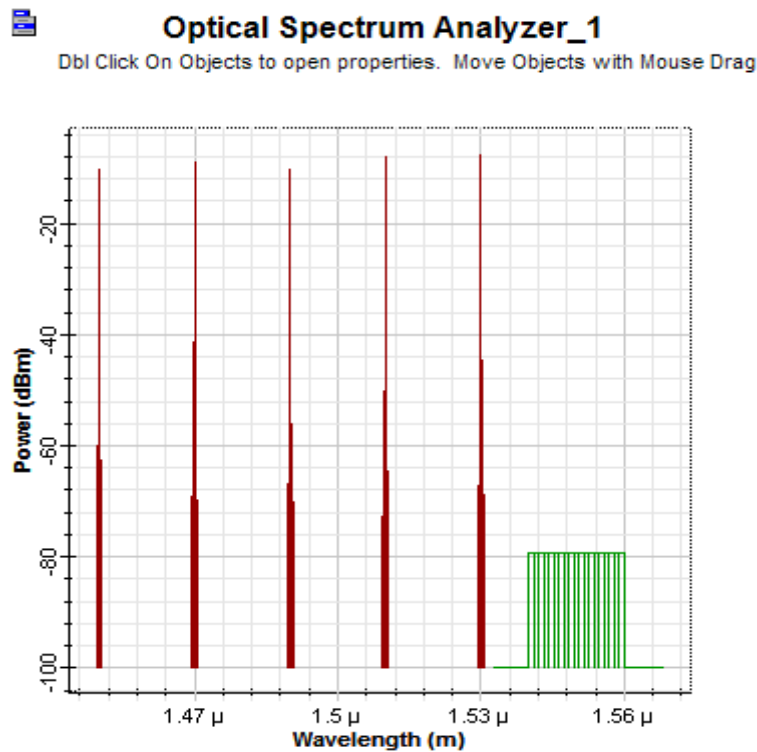


Figure 36: WDM PON – Downstream spectrum into the first optical fiber

Following the fiber, we can see the SPLITTER block which will contain a multiplexer and demultiplexer (splitters). Each will be useful in one direction of traffic. For downstream traffic, the signal from optical fiber will be demultiplexed into 5 different branches, each of them with a different wavelength. This 1:5 splitter will have starting frequency of 1450 nm, with a frequency spacing of 20 nm. As explained in the previous multiplexer, the splitter also will be implemented in reality as 1:8 splitter, therefore it will also have insertion losses of 2 dB.

Below is attached the schematic of SPLITTER block:

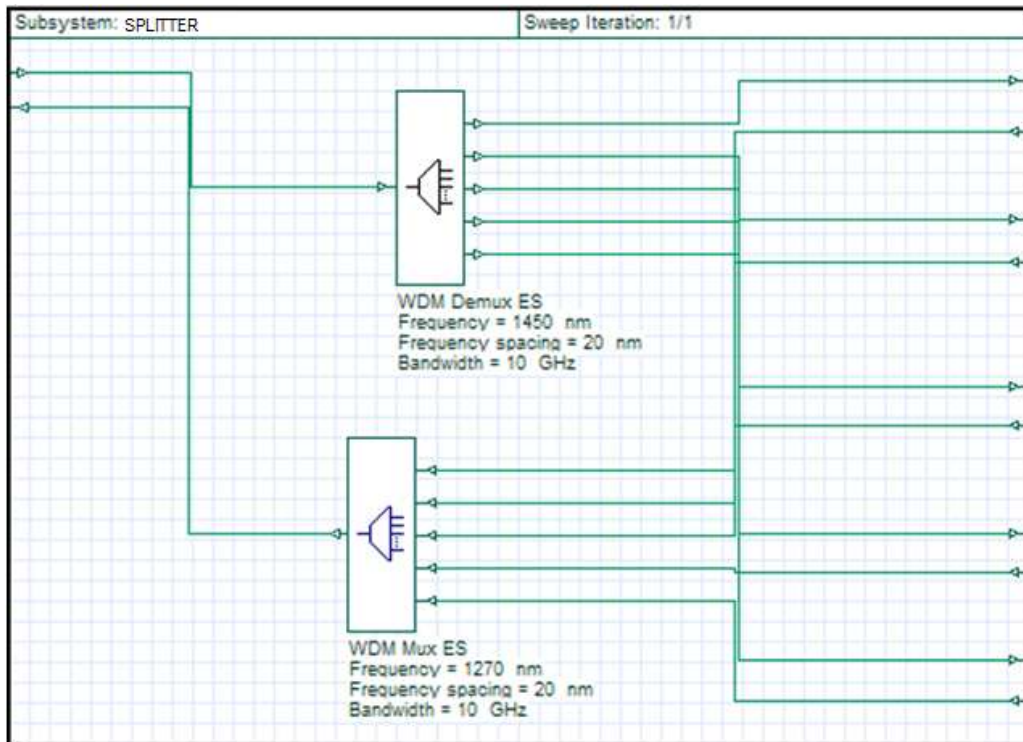


Figure 37: WDM PON – SPLITTER Block

The first branch of the splitter will be directed to the block corresponding to the HOSPITAL area, the second to the BUSINESS area and so on until the fifth that will be directed to the BUILDINGS area.

Turning now to the **HOSPITAL Block** (Figure 38), we find first an optical fiber of 3 km of length, which also will carry information in both directions. Its parameters are the same as those described above for the other fiber. Note that optical delays that occur around the optical fiber are required to perform the simulation, since all network elements need to sign all inputs for make the simulation run. At the initial time, the value of the input connected to the optical delay will be zero, and it will have a delay of 1 time interval for the next moments.

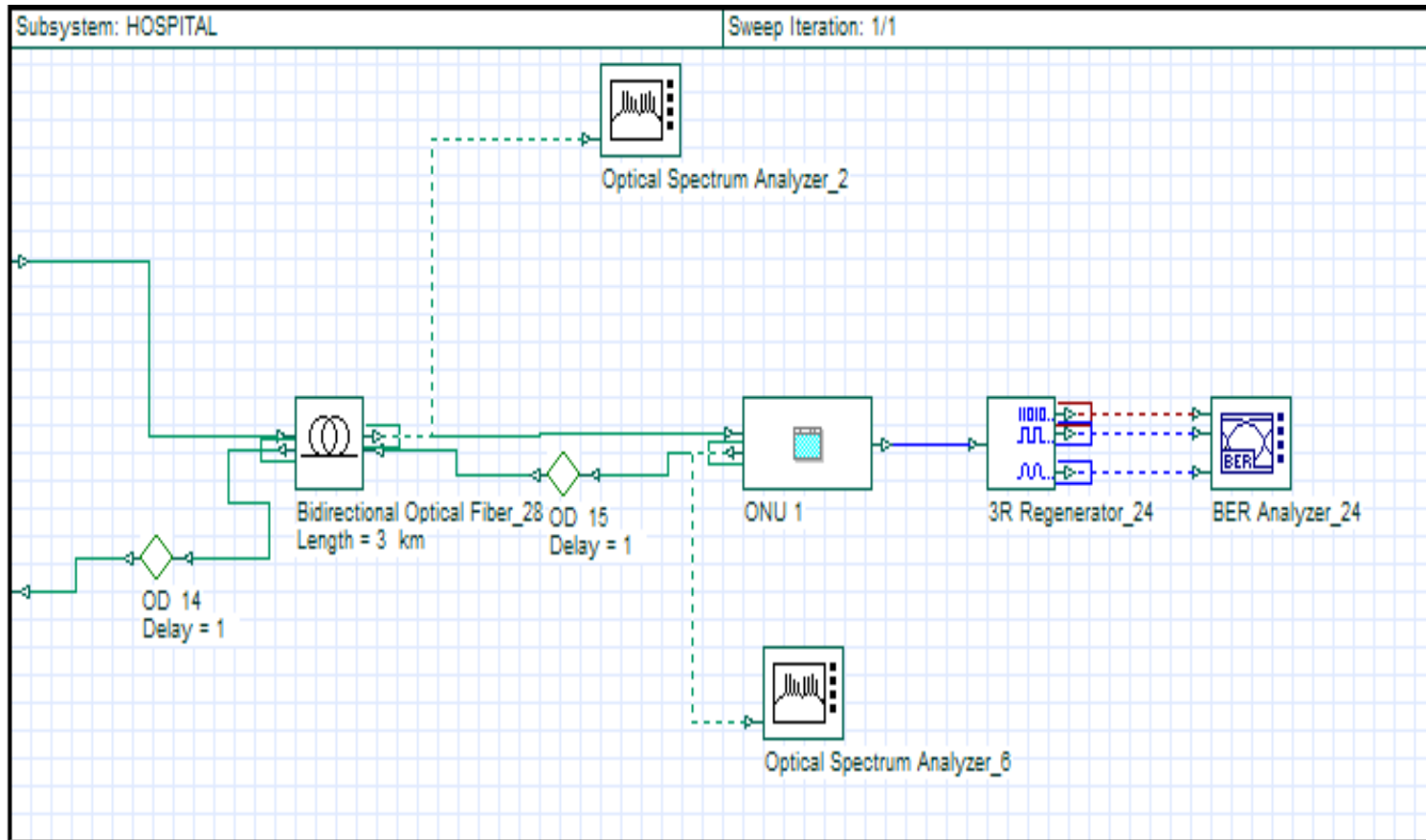


Figure 38: WDM PON – HOSPITAL Block

With the Optical Spectrum Analyzer connected to the bidirectional optical fiber, it can see the spectrum of the signal that will reach the ONU. As we expected, the peak will be centered in 1450 nm.

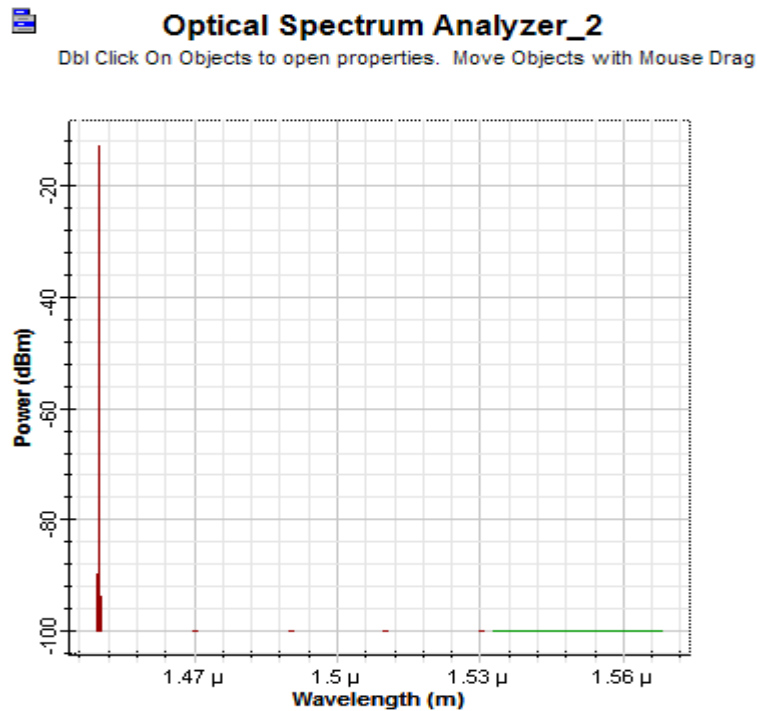


Figure 39: WDM PON – Downstream spectrum into HOSPITAL Block

The last element of this block will be the Optical Network Unit (ONU) where the signal will be received and transformed into electrical form to visualize it in the BER Analyzer. This block is shown in Figure 40 and it will consist in a photodetector PIN which will transform the optical signal to electrical signal, that will be filtered by a low pass Bessel filter with a cutoff frequency of $0.75 \cdot \text{Bit rate}$ (in this design 2.5Gbps). The optical transmitter in upstream direction will be explained in the next section.

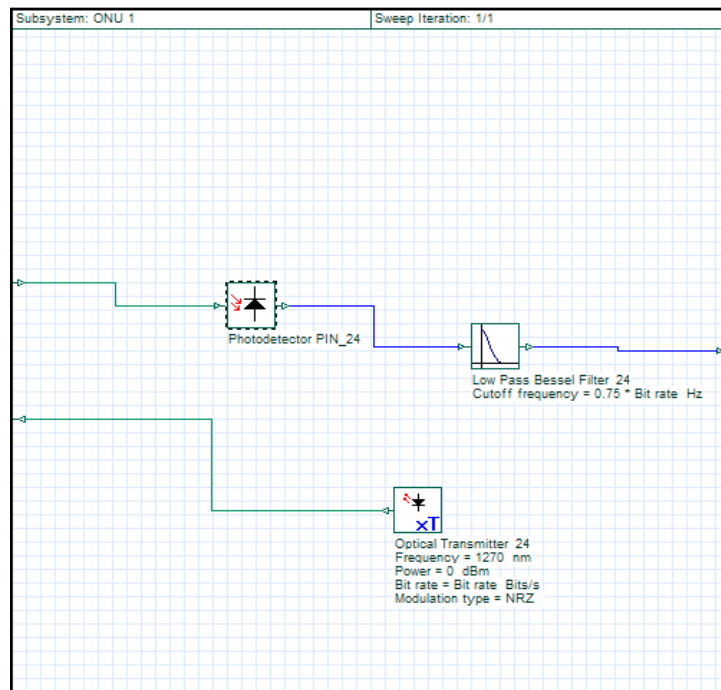


Figure 40: WDM PON – ONU Block

Once described the hospital area, we are going to focus on the **BUSINESS Block**.

In this block it is going to receive the bit rate at 1470 nm. The first element that it is going to find is a bidirectional optical fiber of 1.5 km in which the parameters will be the same as the last fiber. Immediately we will find a 1:2 splitter which will divide the signal into two needed branches to reach the two buildings. The most important parameter of this splitter is insertion loss. For a splitter with division ratio of 1:2, typical losses are about 3.5 dB. Since the same division is going to cause a loss of $10 \cdot \log(2) = 3$ dB, we will add an insertion loss of 0.5 dB to get 3.5 dB of attenuation in each branch.

The bidirectional splitter will split the signal into two branches, each connected to a bidirectional optical fiber of 0.1 km with the same parameters mentioned above. Finally, each fiber will reach its respective ONU, that in the downstream direction will be identical to the previous one but it will have some changes in upstream that they will see in the next section.

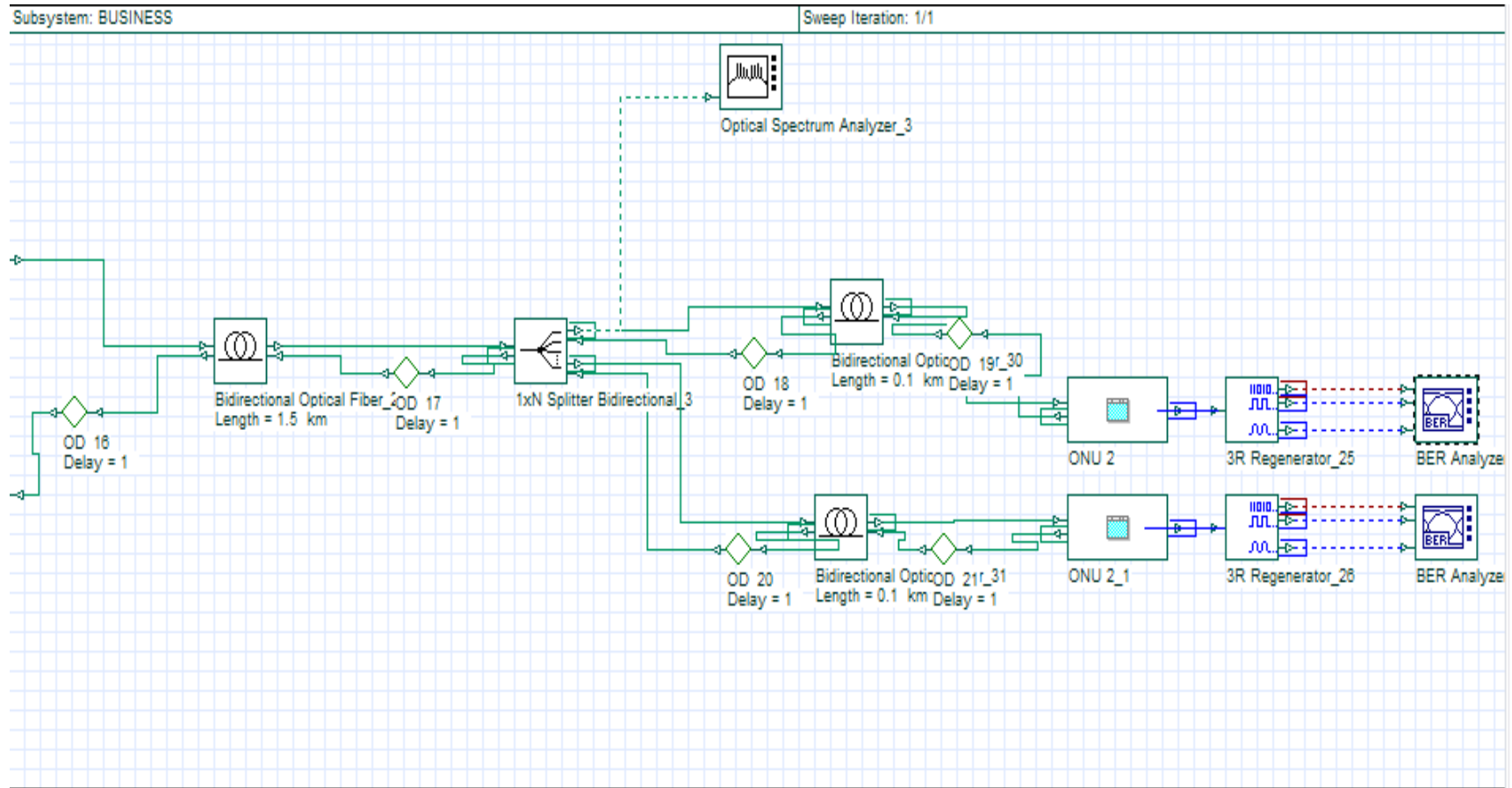


Figure 41: WDM PON – BUSINESS Block

Visualizing the Optical Spectrum Analyzer it can see the carrier centered in 1470 nm:

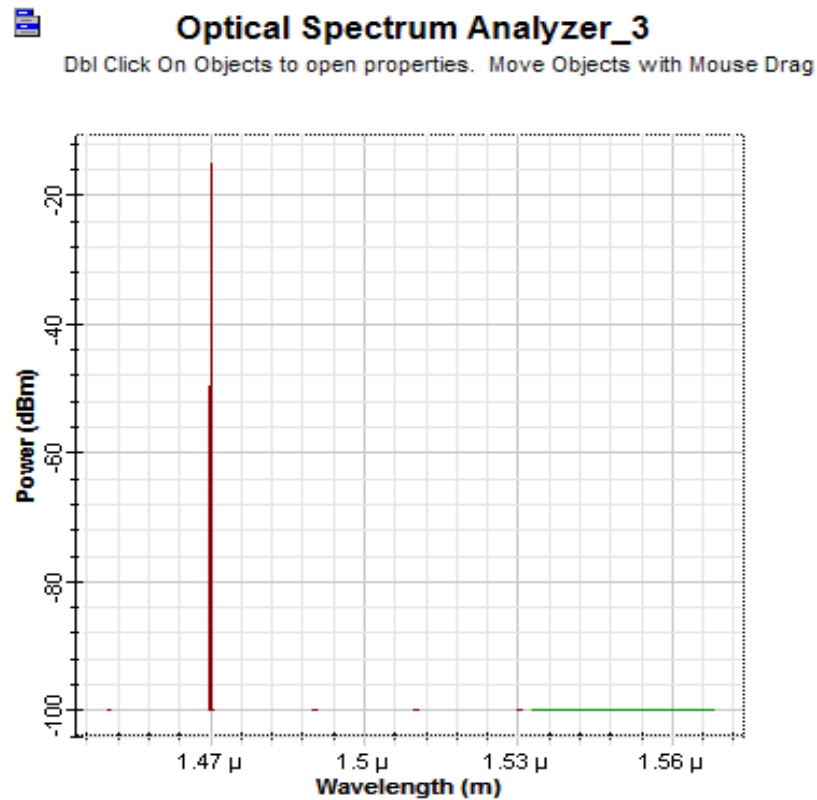


Figure 42: WDM PON – Downstream spectrum into BUSINESS Block

The next block to be found is the **RESIDENTIAL block**, which it will reach a carrier at 1490 nm to broadcast information throughout the area. The first element we see in this block is the bidirectional optical fiber of 1 km length, which it will come connected from the optical SPLITTER seen before and will reach the splitter 1:20 which will broadcast information to all households. This splitter would correspond in reality to a splitter with split ratio of 1:32 with a mean insertion loss of 16.5 dB. Since in this case each branch will have a loss of $10 \cdot \log(20) = 13$ dB, it will add an insertion loss of 3.5 dB with a total of 16.5 dB at each branch.

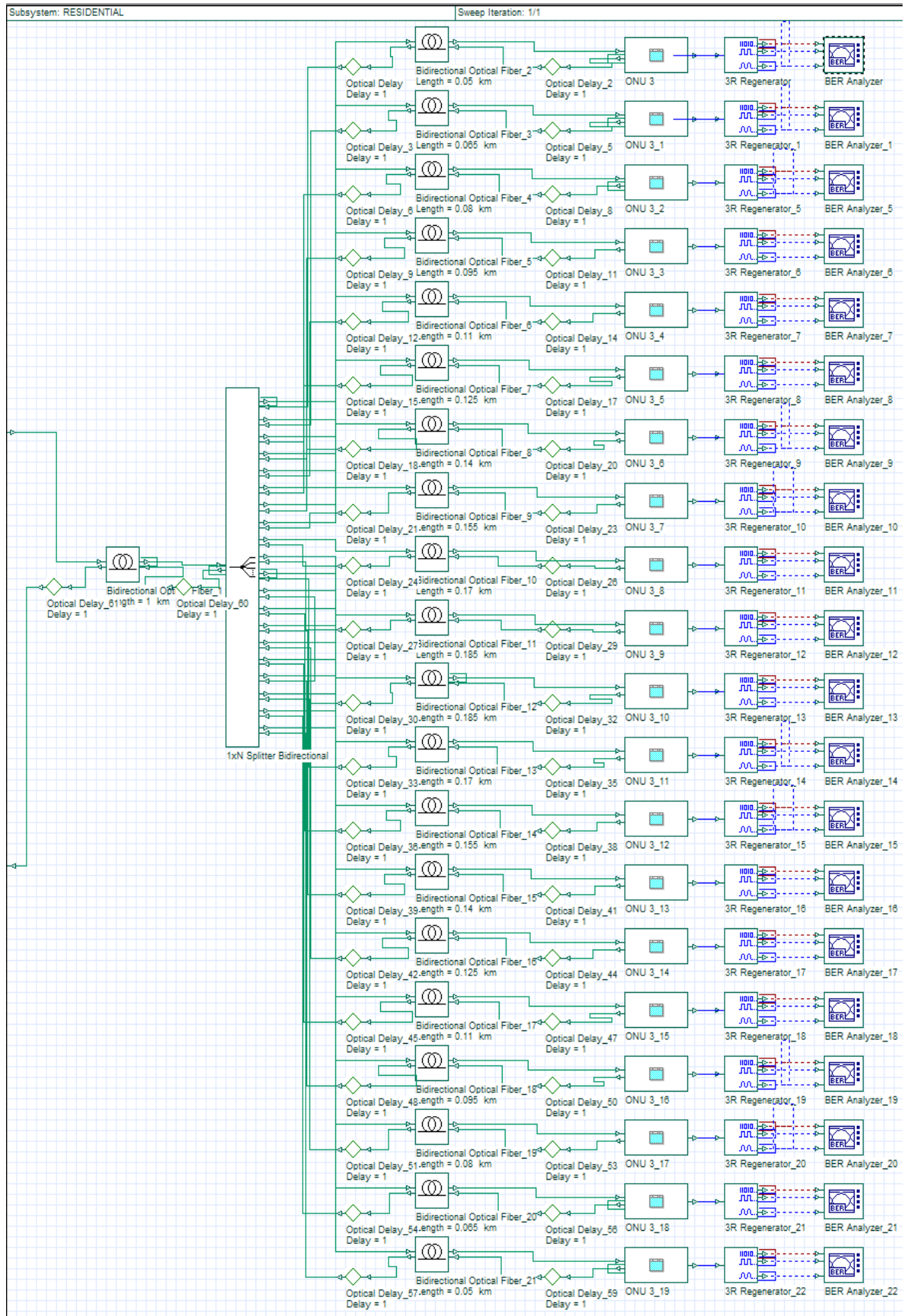


Figure 43: WDM PON – RESIDENTIAL Block

Each of the 20 branches that leave the splitter will be connected to a different length optical fiber. As explained in previous sections, the two shortest will have a length of 50 meters and the other will be increased by 15 meters to the longest that will have a length of 185 meters. The ONU's connected to optical fibers, in the case of downstream, are identical to those seen previously.

In this case, an optical carrier centered at 1490 nm will reach the RESIDENTIAL block:

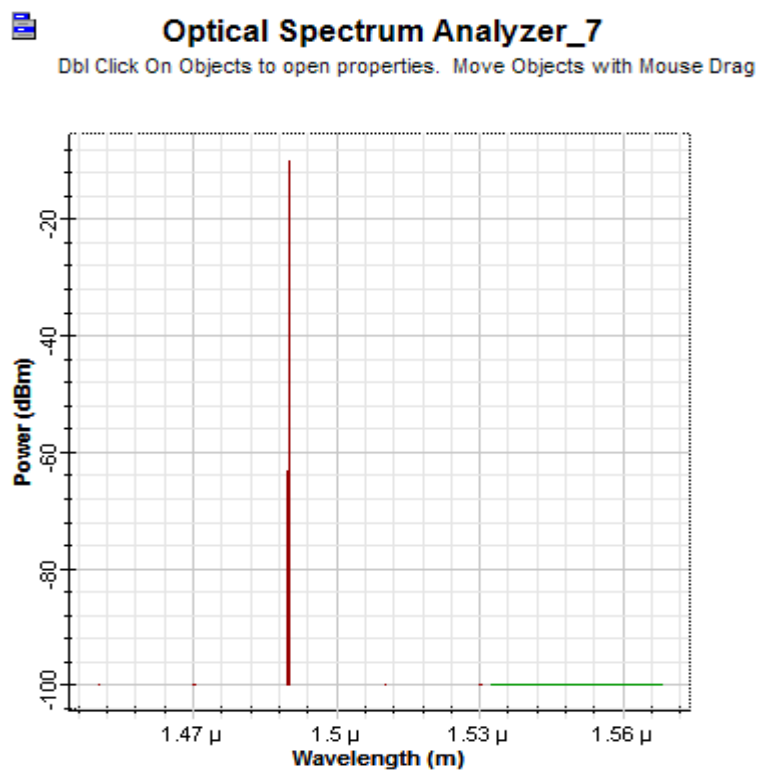


Figure 44: WDM PON – Downstream spectrum into RESIDENTIAL Block

We turn now to the block where is going to place the network access that will serve the mall and the school (**SCHOOL-MALL Block**). To this part of the network an optical carrier centered on 1510 nm will reach. As before, the first element is bidirectional optical fiber connecting the optical SPLITTER with the splitter in the area. In this case, the fiber will have a distance of 1 km. The optical splitter will have a division ratio of 1:2 and will be exactly equal to the proposed in the building area ($10 \cdot \log(2) = 3$ dB will add 0.5 dB for a total of 3.5 dB insertion loss).

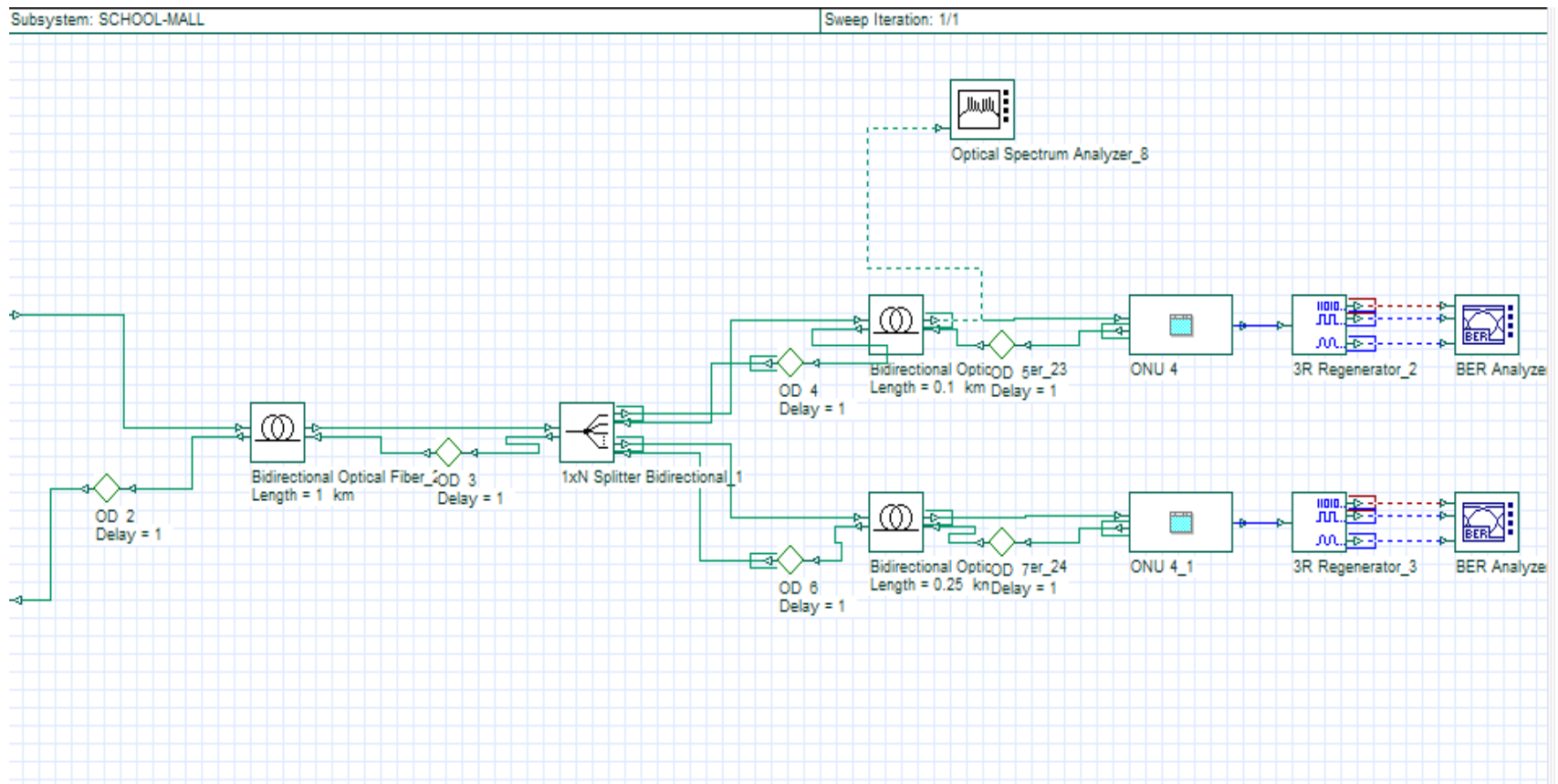


Figure 45: WDM PON – SCHOOL-MALL Block

Finally we need a bidirectional optical fiber of 100 meters to reach the first ONU which will provide service to school and another of 250 meters to arrive at the second ONU which will offer service to the shopping centre. Below is attached the carrier centered at 1510 nm which will reach the area:

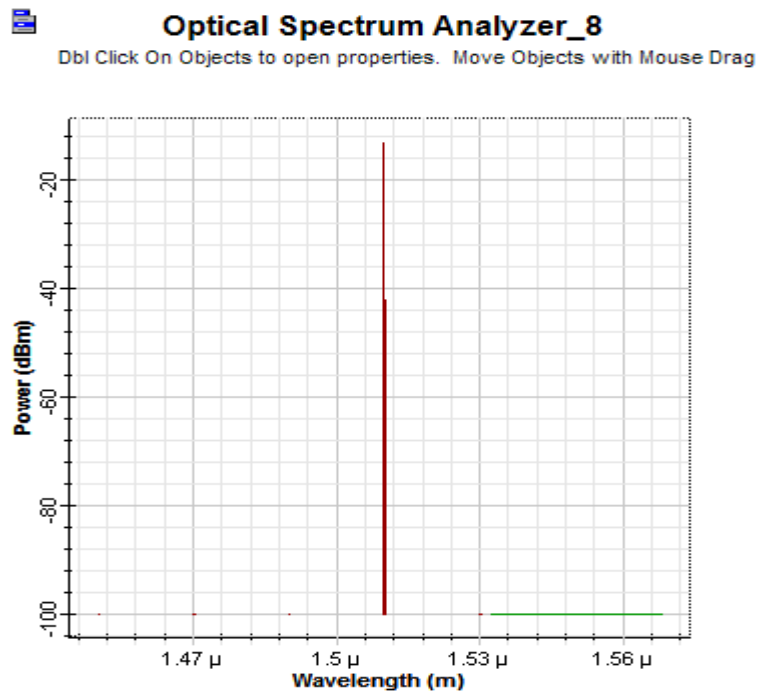


Figure 46: WDM PON – Downstream spectrum into SCHOOL-MALL Block

The last block corresponds to the access network located in the area of buildings (**BUILDINGS Block**). The optical carrier that will reach this block is the latest from the optical SPLITTER and that is centered on 1530 nm. This SPLITTER will be connected to a splitter with 1:2 splitting ratio using a bidirectional optical fiber of 2 km of length and the same parameters as the previous. The 1:2 splitter will also be identical to those above, with a total insertion loss of 3.5 dB. To this splitter will be connected two fibers of 50 meters long that will connect with the corresponding ONU. Each will serve a different building.

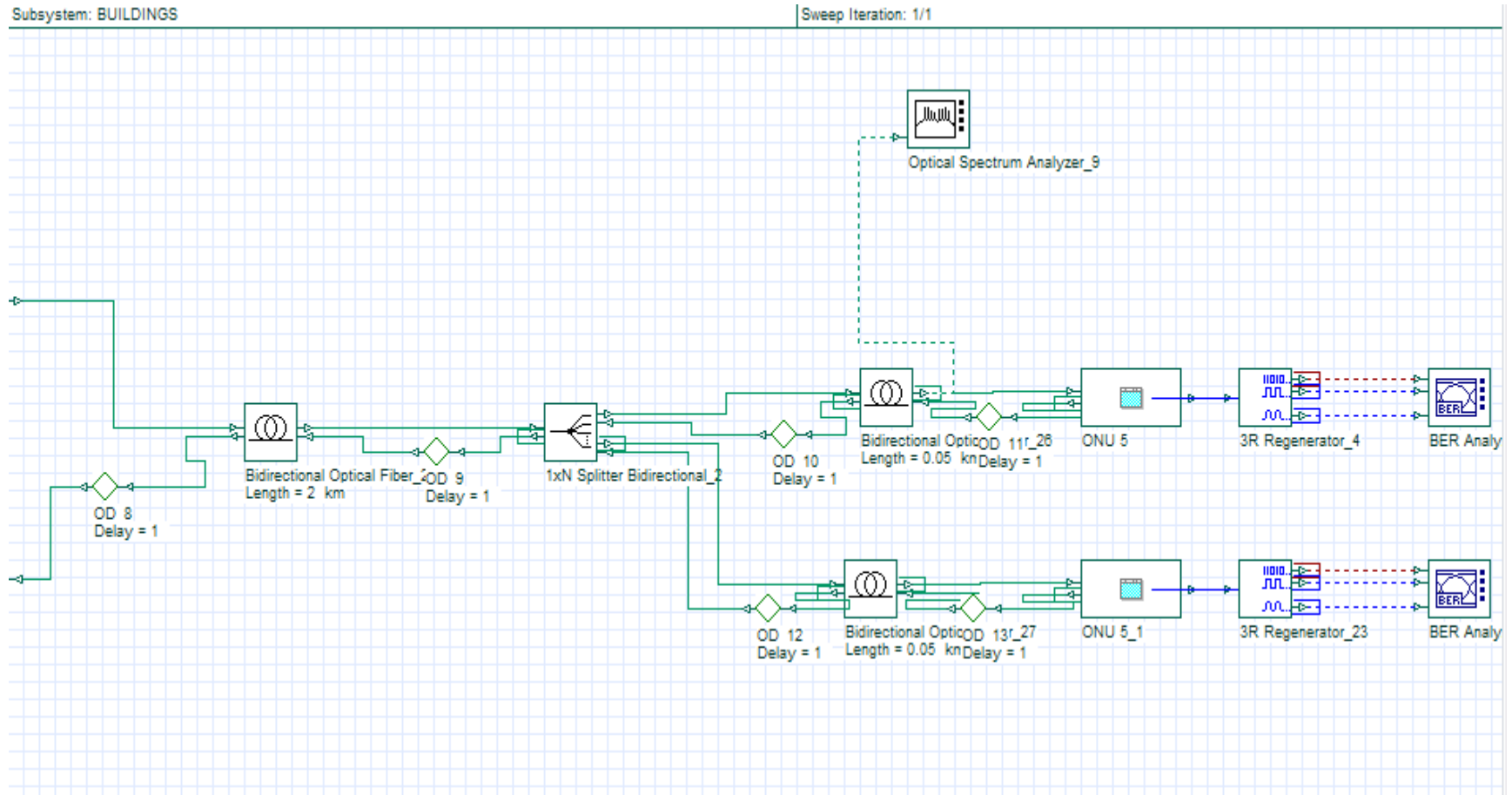


Figure 47: WDM PON – BUILDINGS Block

The optical spectrum analyzer shows the optical carrier that it was expected and it is centered on 1530 nm:

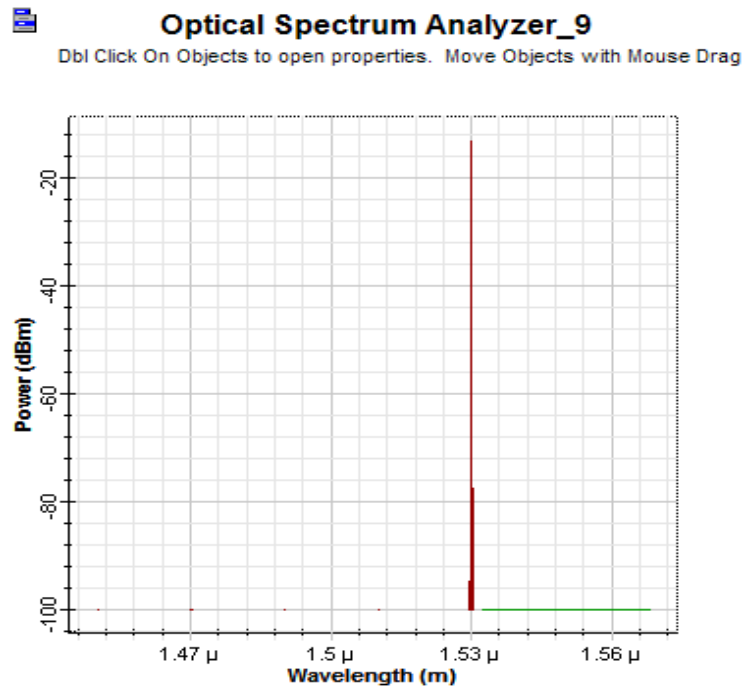


Figure 48: WDM PON – Downstream spectrum into BUILDINGS Block

5.4.1.2. WDM PON in upstream

In upstream direction, the optical signal will travel from each of the end user (ONT's) to the OLT. Therefore, we will review the various blocks that define the five areas and end up explaining the OLT as the receiver. Note that the signal in upstream will pass through the same elements and therefore they will have the same characteristics and parameters.

It is also important to note that in each area is going to be transmitted in a different wavelength. Therefore, TDMA will be implemented in each of the areas for each user transmits in a determined instant of time. This will avoid that two users might collide when they wish to transmit information at the same time.

Returning to Figure 34, the first block to be analyzed will be the **HOSPITAL Block**. In it we will find the ONU that in this case will transmit at 1270 nm with a power

of 0 dBm, NRZ modulation and 2.5 Gbps bit rate. It can see the transmitter of the hospital ONU in Figure 40. The optical signal will cross the same elements of the block, but this time in upstream.

The next section consists on the **BUSINESS Block** (Figure 41). In it we can see two ONU's which will transmit at 1290 nm wavelength. The parameters of these ONU's will be the same: 0 dBm of optical power, NRZ modulation and bit rate per default.

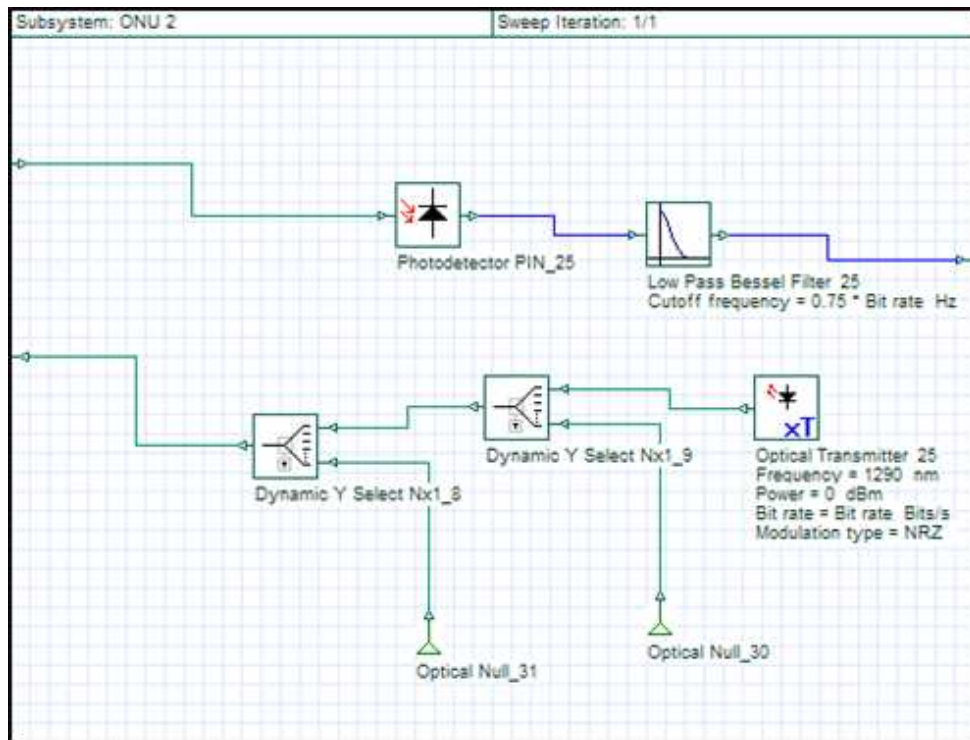


Figure 49: WDM PON – Business, Residential, School-Mall and Buildings ONU Block

In this case, as it has more than one transmitter operating on the same wavelength, it must take into account the time division multiple access (TDMA). Therefore it will use a Dynamic Select Y which it will allow to pass the signal only at a determined time instant and the rest will be zero. Since we have only two ONU's, we will use the following formula to define the time interval of each one:

$$\text{Timeslot} * (1/\text{Bit rate}) * \text{Sequence length} / 2 + \text{Time window} / 2$$

where Timeslot will be 0 in the first ONU and 1 in the second.

The Figure 50 shows the signal transmitted by the two ONU's in the time domain and therefore proves that the signals transmitted by the various ONU's do not overlap in time:

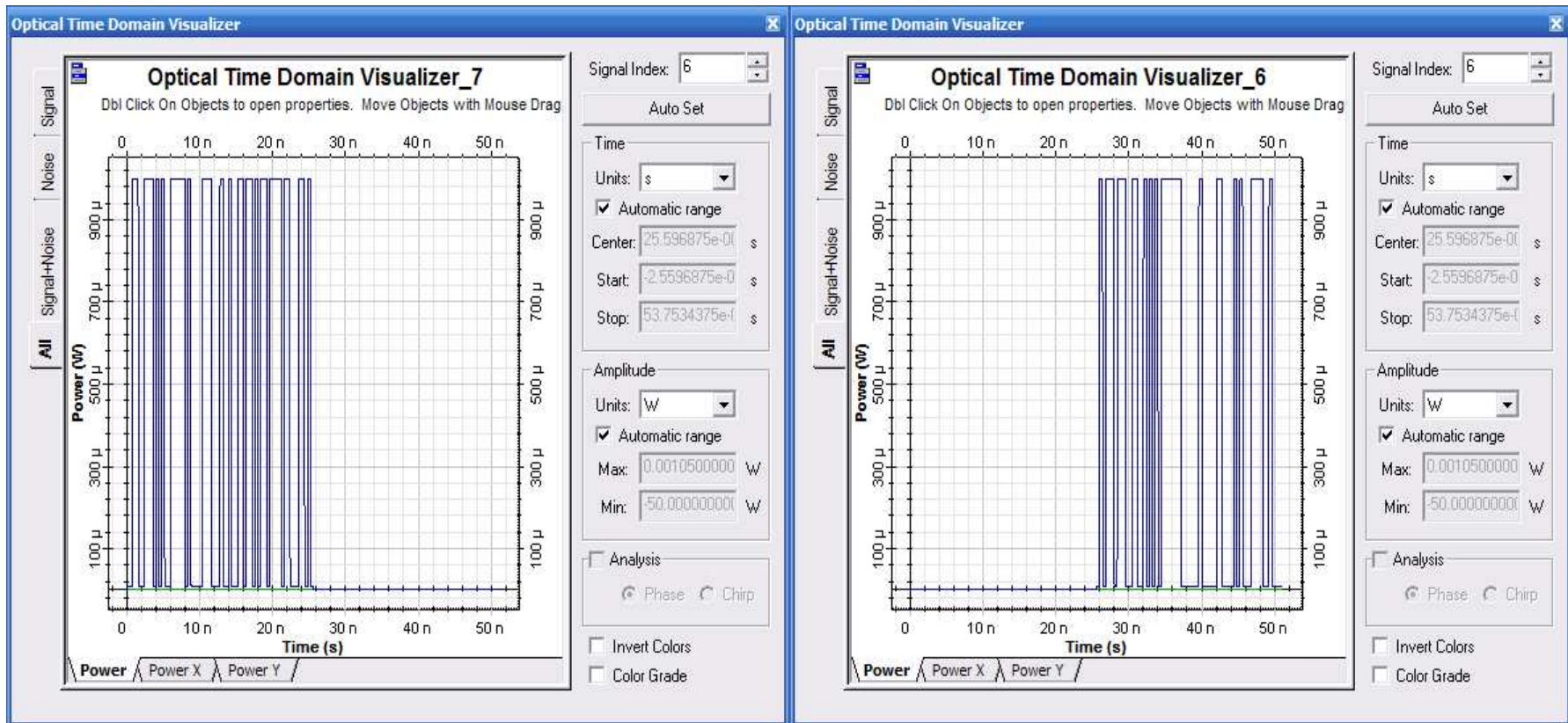


Figure 50: WDM PON – Optical Time Domain Visualizer in BUSINESS Block

We turn now to analyze the **RESIDENTIAL block** (43). In that we will find 20 ONU's corresponding to the 20 homes and which will transmit data with a default bit rate and a wavelength of 1310 nm. These ONU's will have the same look as before and will also transmit with a power of 0 dBm and NRZ modulation.

However, to adjust the interval of time that has to transmit each ONU, we must change the formula in the Dynamic Select Y by the following:

$$\text{TimeSlot} * (1/\text{Bit rate}) * \text{Sequence length}/20 + \text{Time window}/20$$

where TimeSlot will value 0 for the first ONU, 1 for the second, and so on until the twentieth ONU which will value 19.

The following figure shows the first three time intervals for the first three ONU's. Obviously, the others will fulfill the formula above and therefore will transmit at time intervals unique to each:

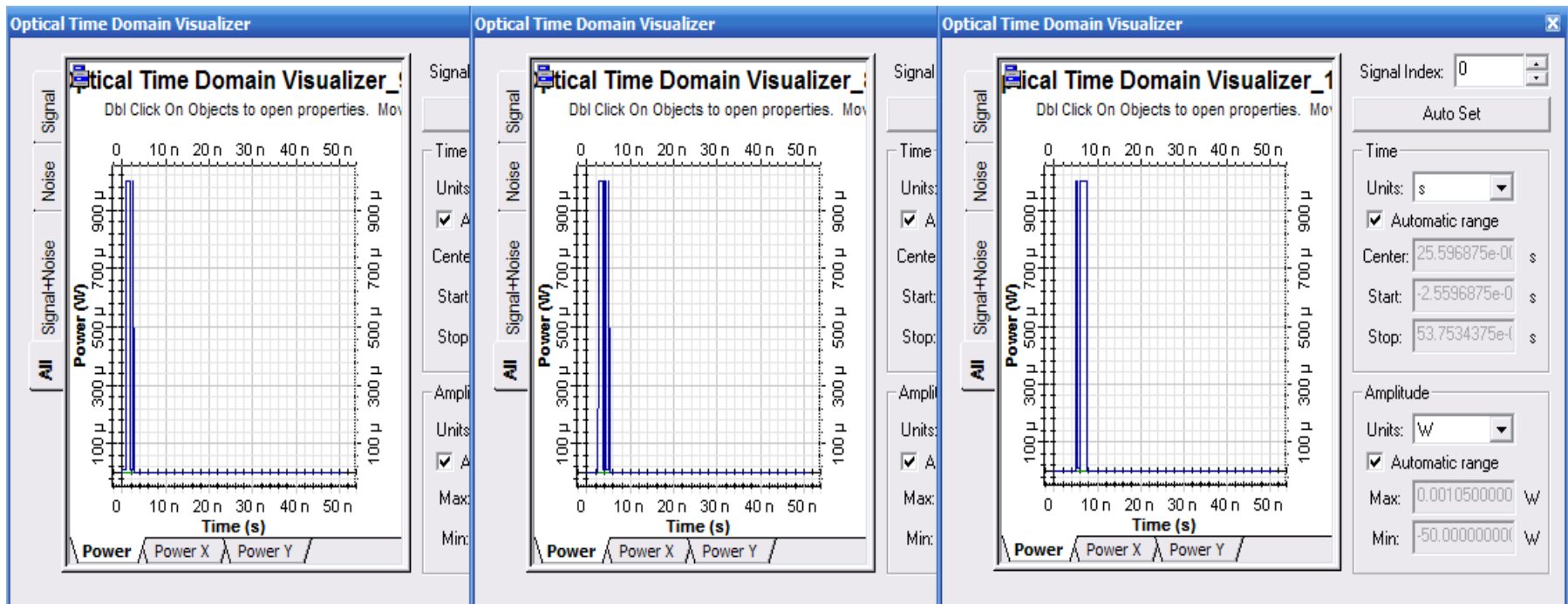


Figure 51: WDM PON – Optical Time Domain Visualizer in RESIDENTIAL Block

The block for the school and the mall (**SCHOOL-MALL Block** shown in Figure 45) will have features similar to business block described above. The ONU's will broadcast at a wavelength of 1330 nm and the transmitter will have the same parameters as above.

Respect to TDMA, we will use other time the described formula in the business block: $\text{TimeSlot} * (1/\text{Bit rate}) * \text{Sequence length} / 2 + \text{Time window} / 2$, where again TimeSlot will be 0 for the first ONU and 1 for the second.

In Figure 52 is shown a representation of the signal in time domain for the two ONU's:

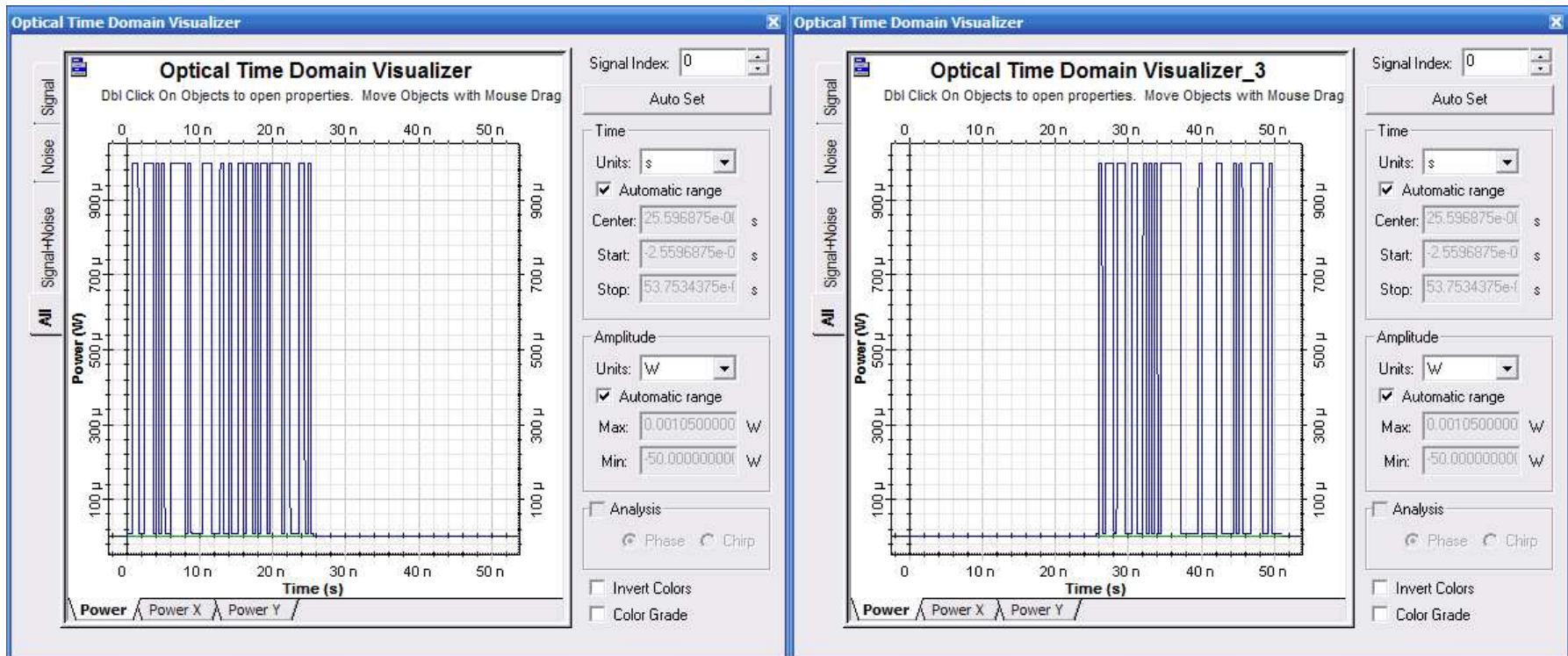


Figure 52: WDM PON – Optical Time Domain Visualizer in SCHOOL-MALL Block

We are now in the last block design: the **BUILDINGS Block** shown in Figure 47. The two transmitters of this block will have the same characteristics as the transmitters of the previous block, except that they will send information in a wavelength of 1350 nm. In addition, the same formula is used to get that the information transmitted by users do not overlap, i.e., they also will use TDMA.

The following figure shows again the temporal representation of the optical signal of the transmitters of each block:

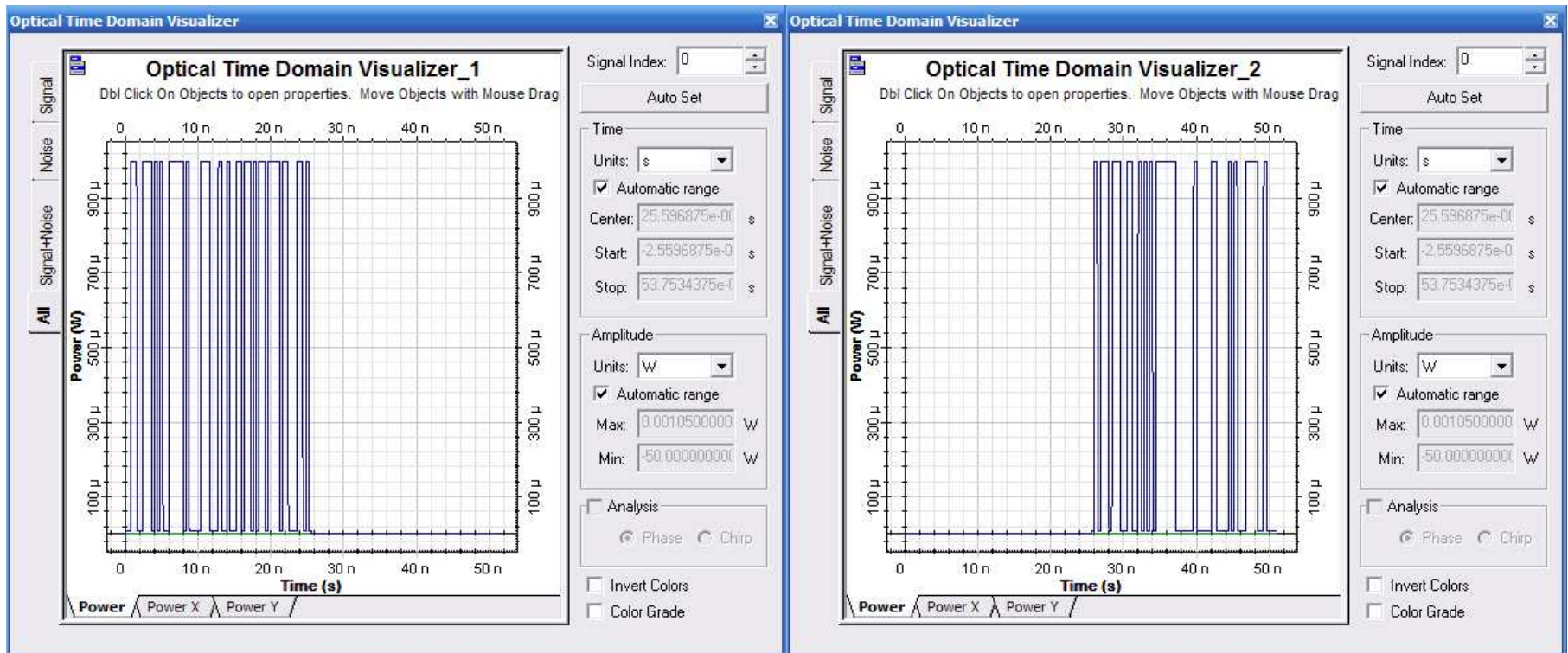


Figure 53: WDM PON – Optical Time Domain Visualizer in BUILDINGS Block

With all the signals from the different blocks will be multiplexed the five wavelengths using an optical multiplexer 5:1 (8 to 1 in reality) which is within the SPLITTER block seen in Figure 37. This multiplexer will have insertion losses of 2 dB and a starting frequency of 1270 nm with a frequency spacing of 20 nm. With these parameters will get multiplexing the five upstream wavelengths that can be seen in the following figure:

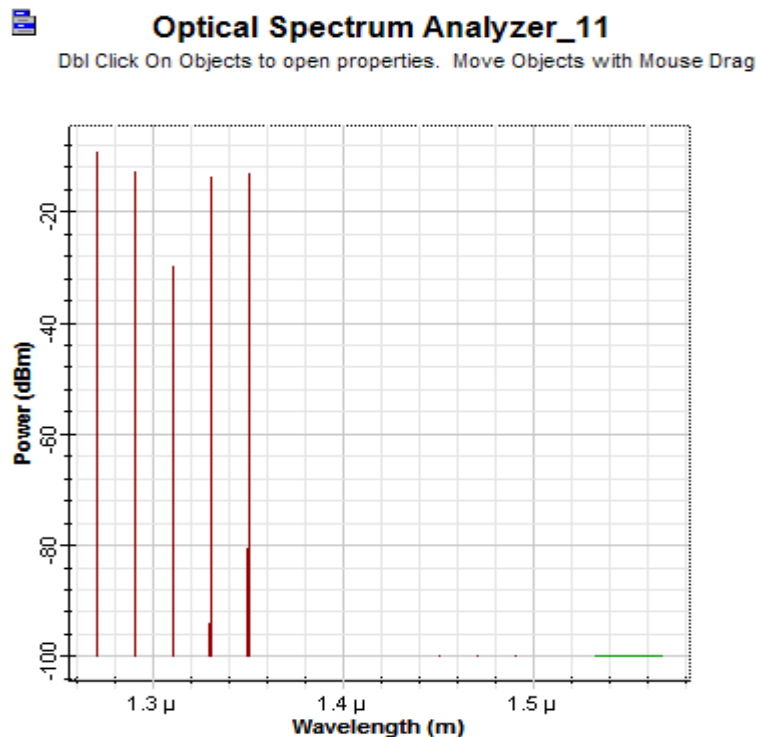


Figure 54: WDM PON – Upstream spectrum into the optical fiber

This signal consists of the 5 upstream optical carriers that will be sent through bidirectional optical fiber of 5 km connecting the SPLITTER Block with the OLT. This fiber is the same as that described above for downstream, so it will get the same parameters.

Finally the signal will arrive at the OLT, where it will cross by a bidirectional optical circulator and will be sent to the optical receiver.

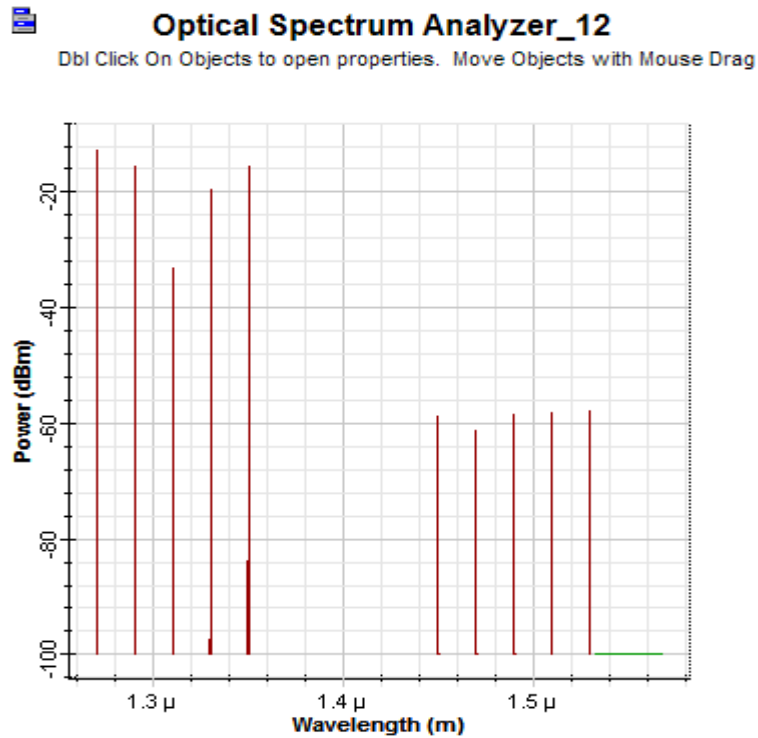


Figure 55: WDM PON – Upstream spectrum into the OLT receiver

The first element of the receiver will be the Buffer Selector, which will be used to select only the latest iteration of the simulation, which will be the one with the correct results. After this element, the signal will pass through the PIN Photodetector where it will be converted to electrical domain and as in other cases will be filtered through a Low Pass Bessel Filter with a cutoff frequency of $0.75 * \text{Bit Rate}$. To end, this signal will be regenerated in order to be displayed on the BER Analyzer.

5.4.2. WDM PON: Results

Having explained the whole design, it just needs to get the results that will decide if the design works or not, and therefore whether it will be feasible to implement in a practical case.

The results that are going to expose are the eye diagram, the quality factor, the probability of error (BER) and the decision threshold as a function of the width of the bit.

In the case of the ONU located in the **HOSPITAL Block**, it has been obtained the following results:

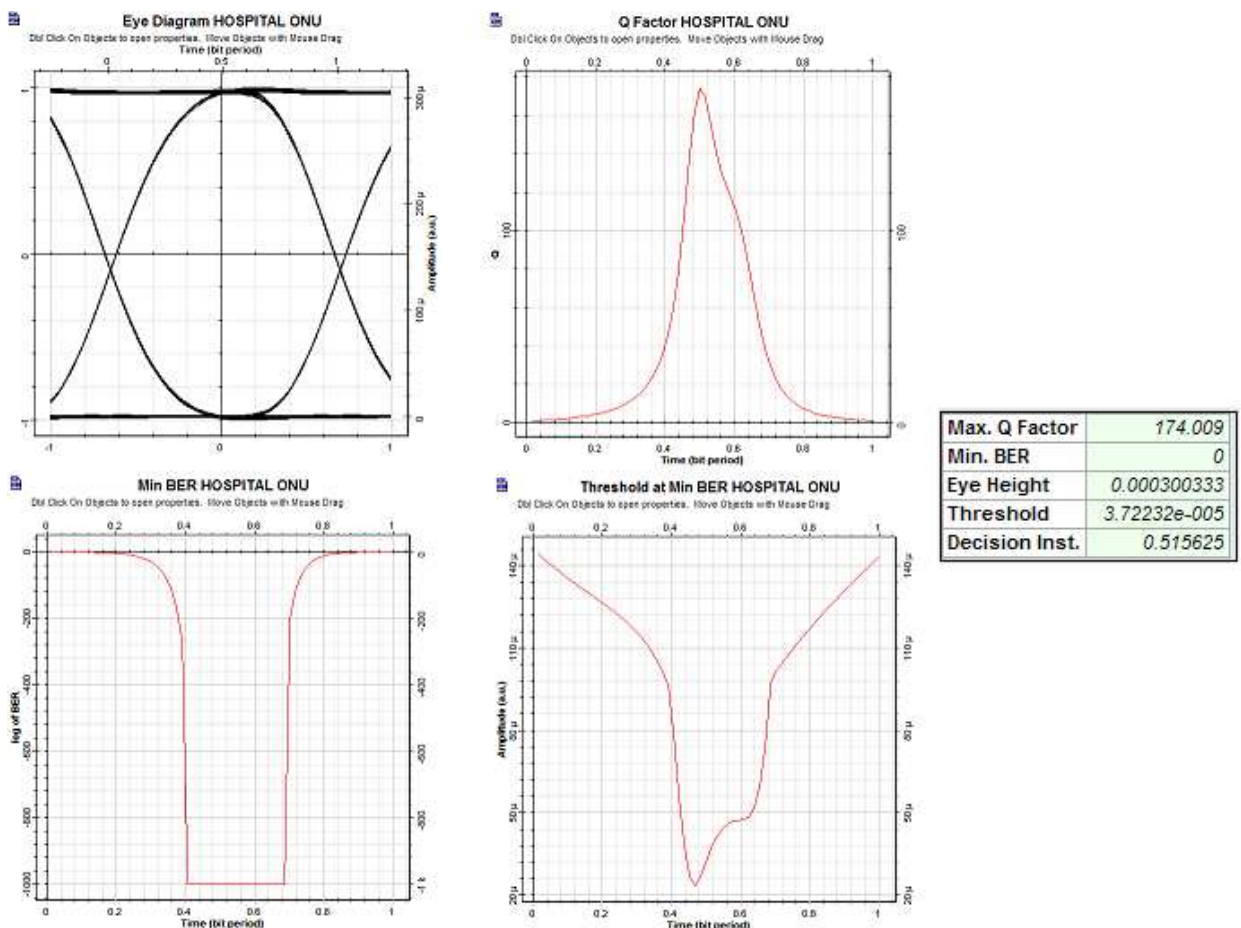


Figure 56: WDM PON – HOSPITAL ONU Results

In the **BUSINESS block**, the path that the signal covers to two ONU's is exactly the same since the last fiber has the same dimensions. So the results are identical:

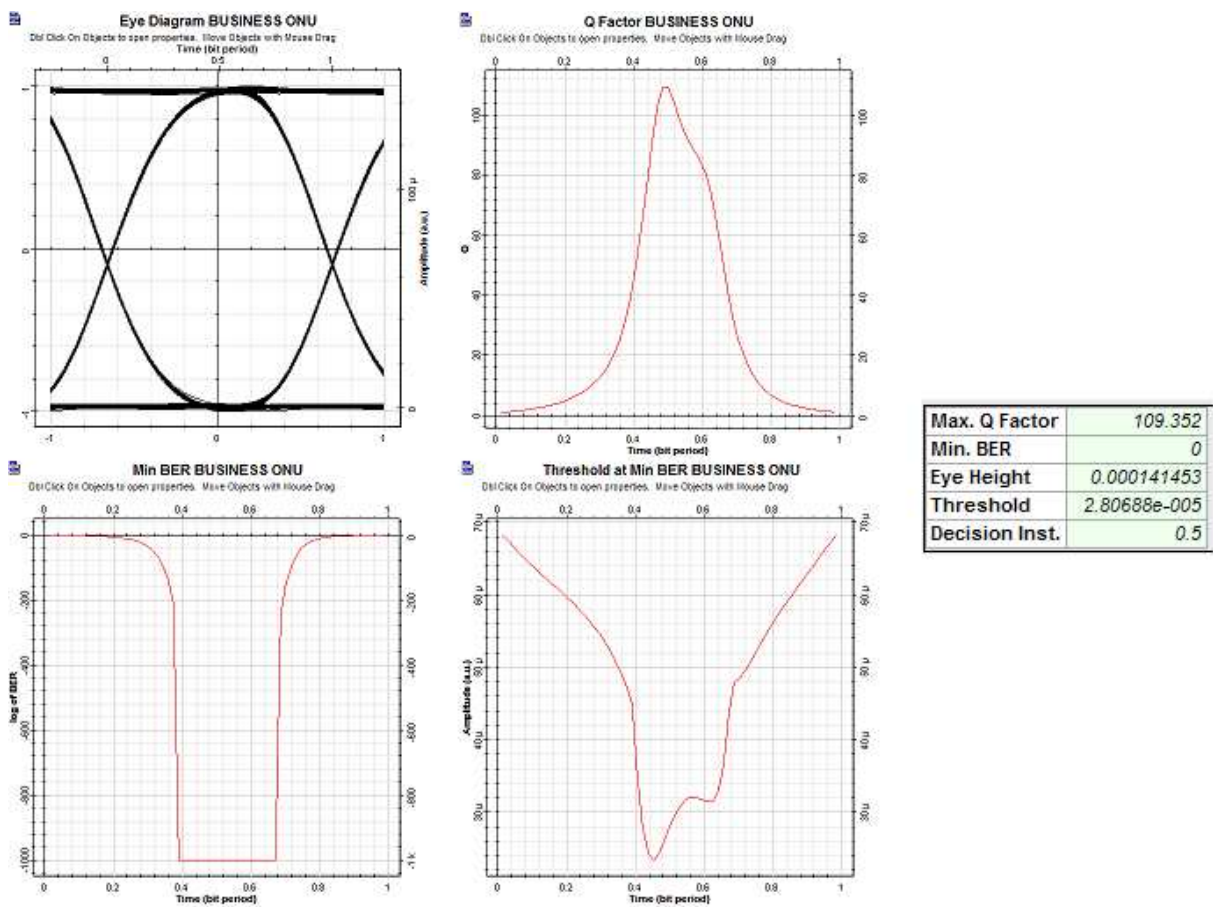


Figure 57: WDM PON – BUSINESS ONU Results

The **RESIDENTIAL Block** will have 20 ONU's. As expose the results of the 20 ONU's will require a lot of space, we are going to put the results of the closest ONU (located at 50 meters from the splitter) and the farthest ONU (situated at 185 meters from the splitter).

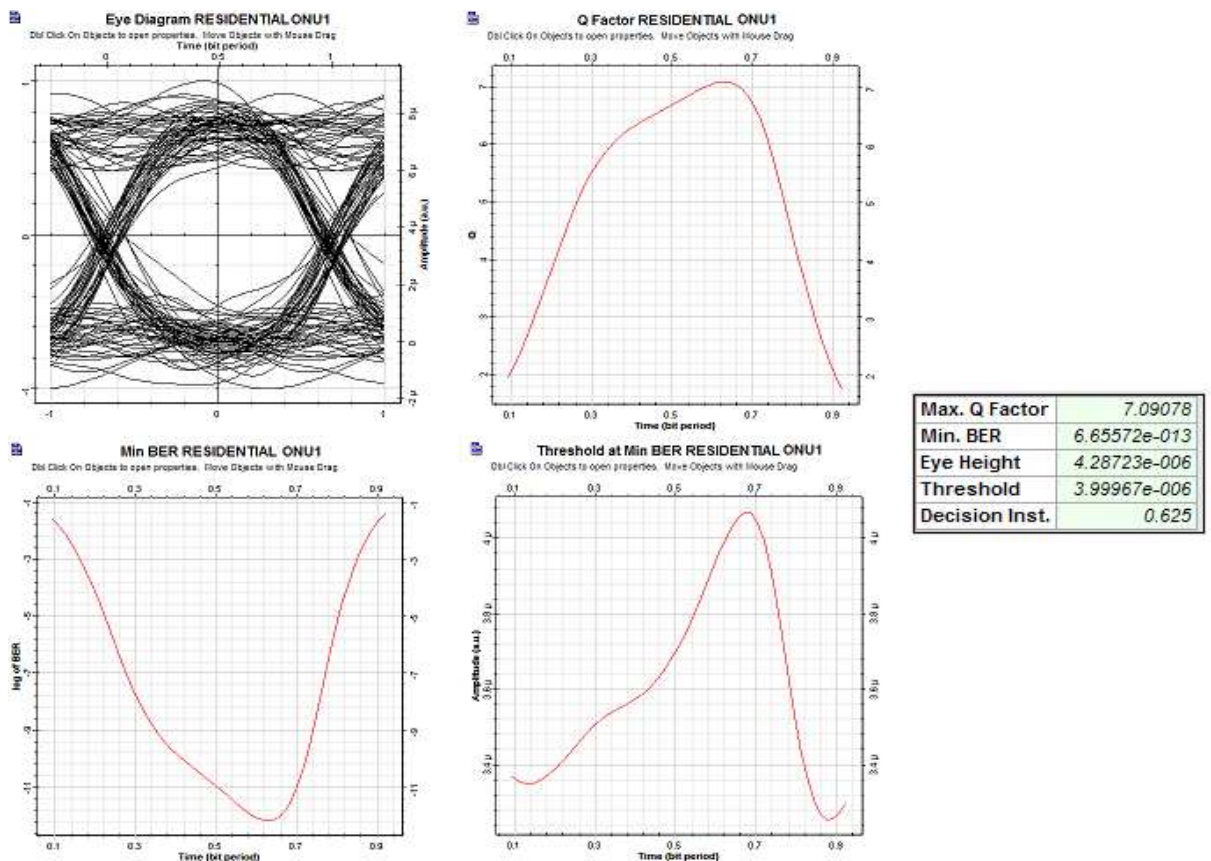


Figure 58: WDM PON – RESIDENTIAL ONU1 Results

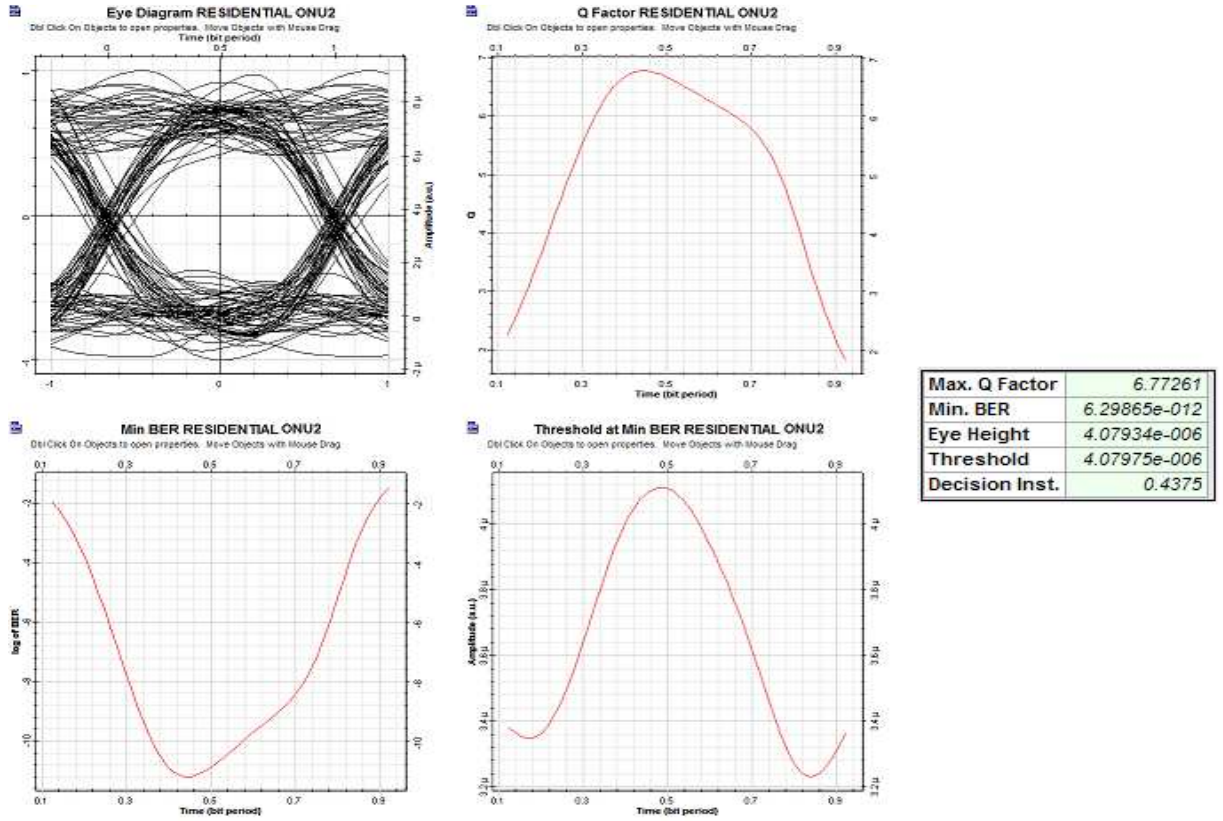


Figure 59: WDM PON – RESIDENTIAL ONU2 Results

The results are very similar, although as it expected, the results of the ONU placed on the shortest fiber will be a bit better than the results of the ONU at the end of the longest fiber.

Turning now to the **SCHOOL-MALL Block**, the results for the two ONU's are:

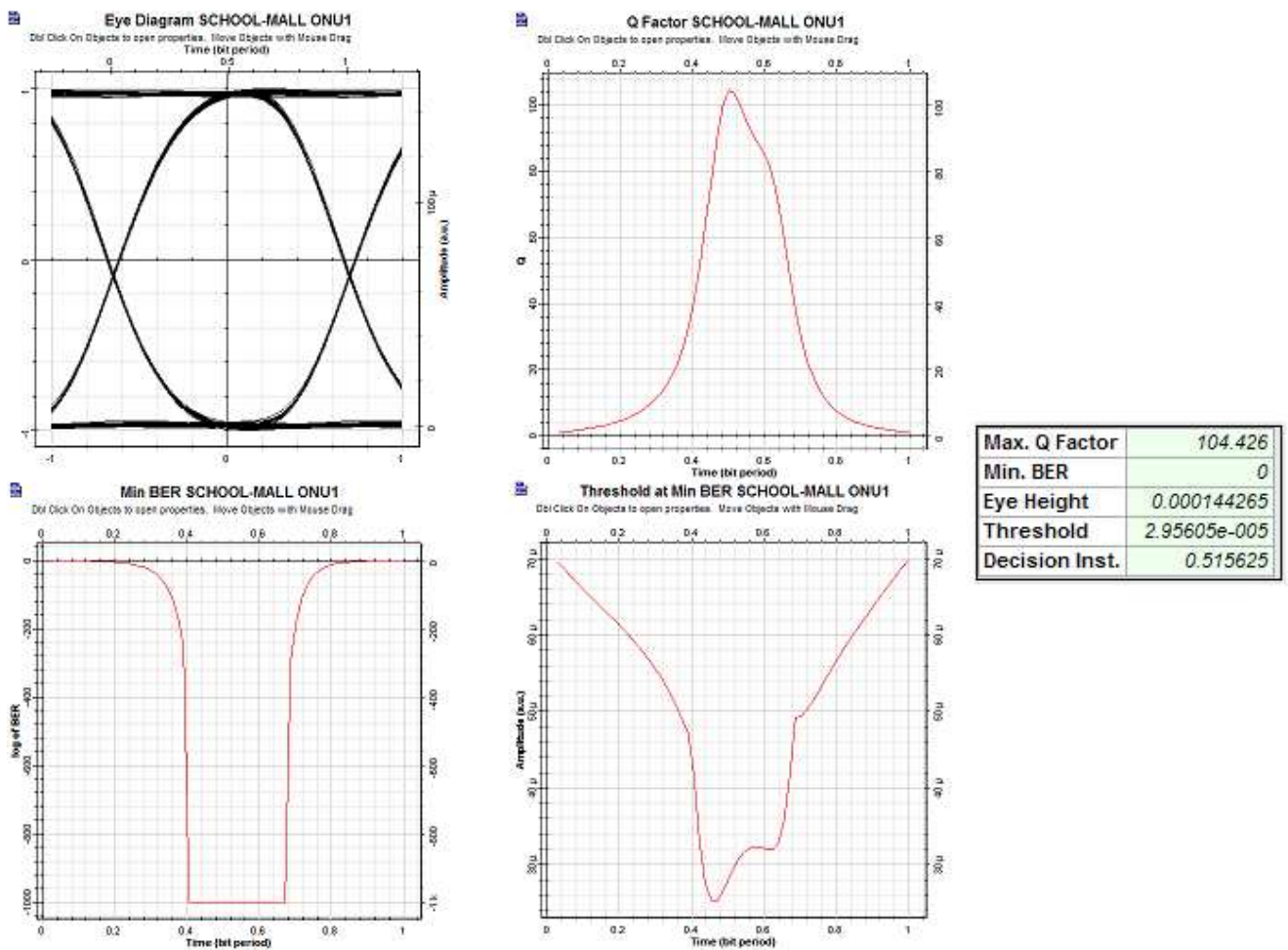


Figure 60: WDM PON – SCHOOL-MALL ONU1 Results

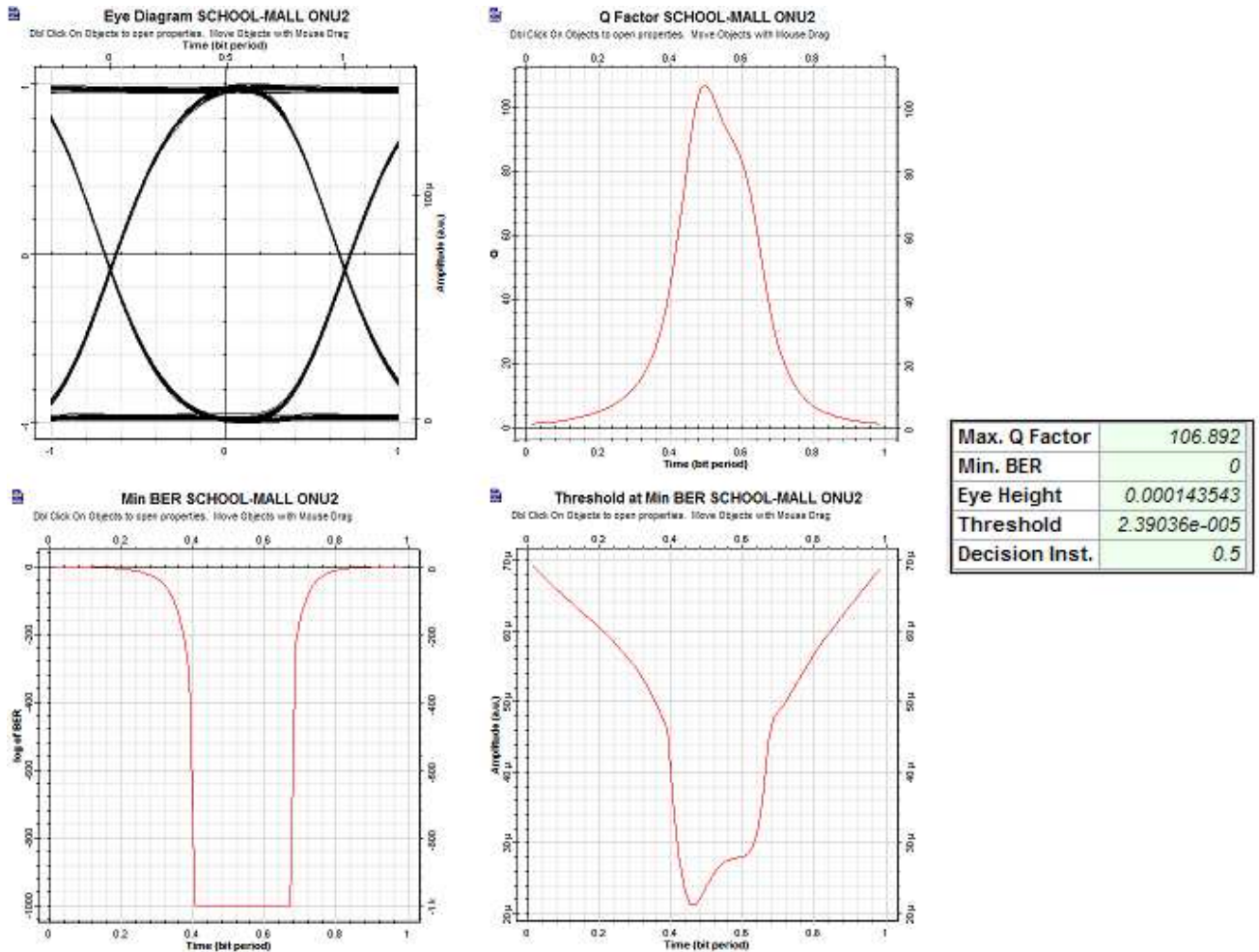


Figure 61: WDM PON – SCHOOL-MALL ONU2 Results

As in the previous case, the only difference between the two paths is the last section of optical fiber, which in one case will be 100 meters and in the other 250 meters. Therefore, the results are very similar.

The last block in downstream is **BUILDINGS Block**. As in the case of the business block, the paths that the signal covers are identical, so both ONU's will offer the same results:

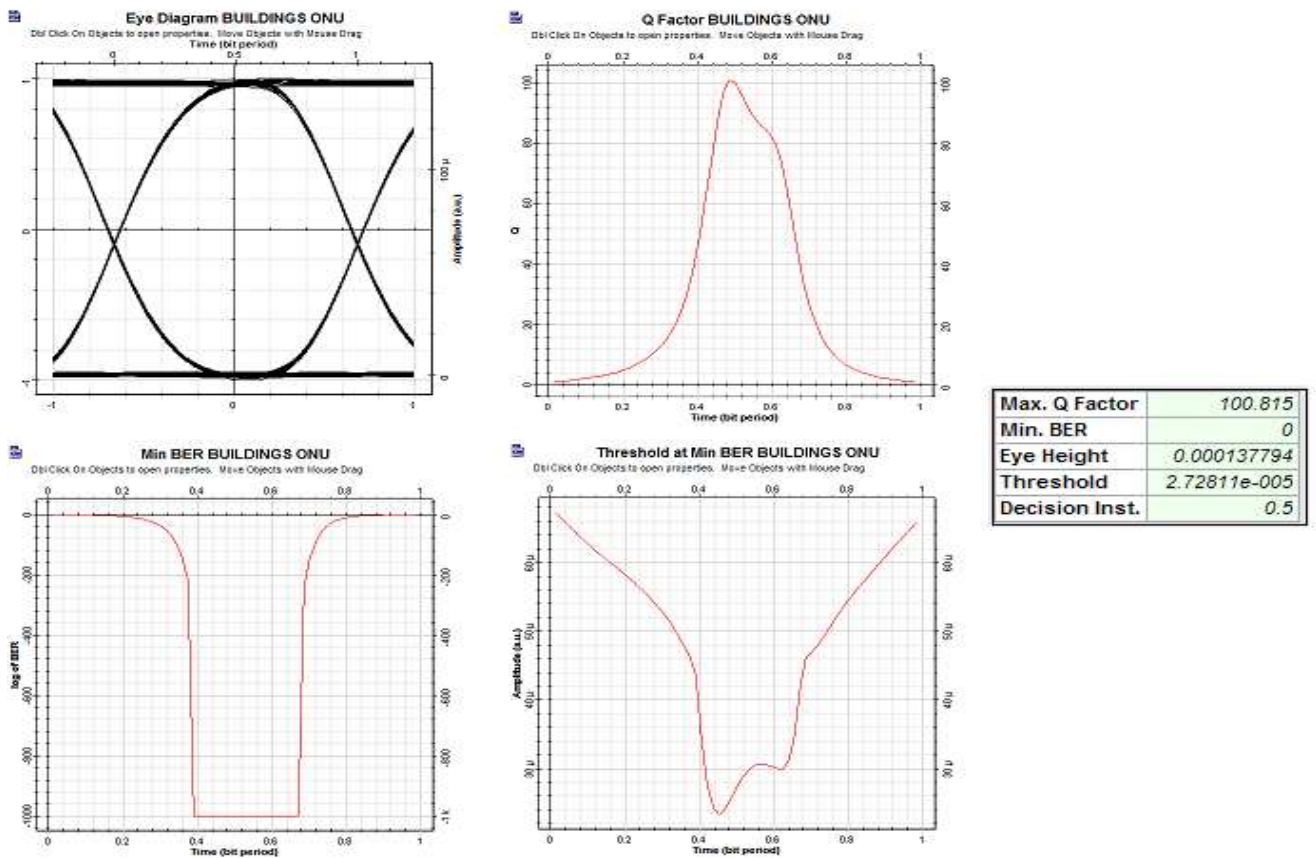


Figure 62: WDM PON – BUILDINGS ONU Results

As for the uplink, the results obtained in the OLT are:

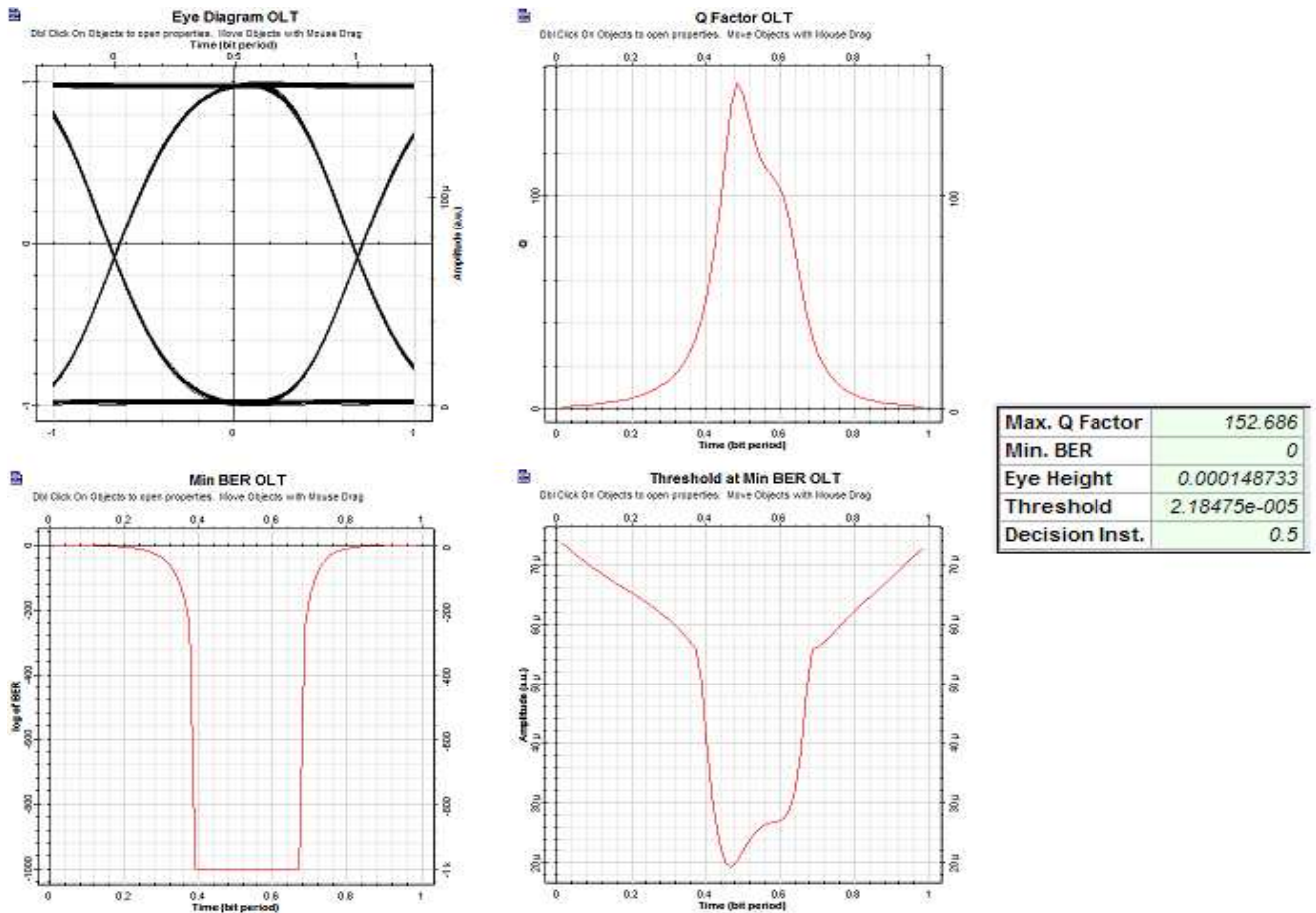


Figure 63: WDM PON – OLT ONU Results

With all this demonstrates the quality of design in both upstream and downstream.

Chapter 6

Summary and Conclusions

In this concluding section is pretended, on the one hand to summarize the sections on which it has worked on the thesis, and on the other hand to show the conclusions of the designed network and which could be the lines that could be followed for future network improvement.

Throughout the project it has undertaken a number of general guidelines whose development has resulted in a thorough understanding of a passive optical network. These basically are:

- Theoretical detail and physical basis of the operation of optical networks.
- Planning and design of a PON.
- Simulation and obtained results by the designed network.

The detailed theory of optical networks is considered essential for correct understanding of FTTx networks, as well as necessary to perform a particular design of passive optical network on which such networks are built. When making any design, it is essential to know the technology with which it is based as the final solution will depend on the needs that arise and the features and topology of each network type.

Thus, in Chapter 2 has been detailed the physical basis of optical technology such as operating principles, composition and geometry, fiber types and the most important structural and transmission parameters as attenuation, dispersion and nonlinearities, and it has concluded with the explanation of the advantages and disadvantages that may have the usage of this technology. Previous understanding of the methodology of transmission through optical fiber has allowed knowing the advantages of these systems at the physical level and the limitations that have optical fiber networks, to take into account in the physical network design phase.

Chapter 3 deals with the types of FTTx networks that exist, which are defined taking into account as far as the optical fiber reaches in the access network. Once defined these types, it has talked about the point-to-point and point-to-multipoint configurations. It is important to consider these concepts to define what type of network it wants to design. In this case FTTB and FTTH networks have been used for access to our different areas, with a global point-to-multipoint configuration allowing us to save in optic wiring.

In Chapter 4 has discussed the PON. The first step has been to describe the operating principles of a network of its kind for both the uplink and downlink, taking into account all the elements of the passive network. It has made a comparison with point-to-point networks and active optical networks (AON), concluding PON design optimal for its exploit of bandwidth and its lower implementation costs. Having defined the PON as the best option, advantages and disadvantages of these types of networks have mentioned and it have defined all the standards that exist today (from APON to next generation networks such as 10G-PON or WDM-PON). Finally it have done a comparison between these technologies, choosing WDM-PON as the best option because of its greater speed, reach and number of users supported.

Once we know the structure and characteristics of these networks, the last and most important chapter has been dedicated to the design, simulation and obtaining the results of the proposed WDM-PON network.

In the first section has discussed the design considerations of this kind of network. First, it has defined a 4 levels network standard where we have focused on the first level (passive Infrastructure) as it is one that covers the design in which the project is based.

After explaining the services that the different areas will require, it has passed to the network planning. In this section a description of the project has made, physically describing each of the areas and analyzing the bandwidth required to meet the needs of all customers in each area. Having described each area in detail, it has taken into account all the elements that are necessary for the implementation of the network, such as the OLT and the ONU's (to be chosen by the operator to manage the network), optical fiber standards and cable types to use, the optimal connectors for this passive network and the size and location of optical splitters, arguing in each case why the election and how many will be needed. Also it has taken into account the reserves of the cables, that will allow to make movements of the elements of the network in case of any change or expansion, and provide redundant links to critical areas such as business area and the hospital area, to ensure as far as possible that the proper functioning of the service in case of failure or any power outage is guaranteed.

Once clear the distribution network and all the elements needed for its construction, it is important to use a simulation program that meets the needs of design, covering all aspects. In this case, it has opted for the OptiSystem 9.0 simulation software, since it meets all our requirements.

The last section focuses on the final design of the network and the results that show that the network works. The images show what has the design been and an explanation of all the important elements and parameters that have taken into account to make it work. To make more understandable the design, the explanation has been separated into two parts, downstream and upstream, and as in other sections, the scheme has been divided in 5 areas that define the entire design. Finally, it has attached the obtained results in each of the ONT's, being these the eye diagram, the quality factor, the BER and the decision threshold for the minimum BER.

These results have showed a BER of about 10^{-12} for the worst case that will be of the farthest house in the residential area. This shows the high reliability that will have in each of its points the implement of this network.

The choice of optical fiber as transmission medium allows guaranteeing longevity of the network during the coming years. The logical and physical design of the same establishes optimal conditions for the current implementation of the system but also offer the possibility of future expansion.

The fact of using the Gigabit PON technology on CWDM enables nowadays the possibility to connect a large number of users. In addition, the specified equipment will be valid for migration to future standards as 10GPON, DWDM and other technologies that improve the performance of optical fiber and provide the best possible performance.

Other features that have the design is the high degree of availability and network capacity, the ability to integrate multiple systems and services and the possibility of interconnecting these networks with other wide area networks and adding local networks by creating LAN.

At present, there would have no sense to design a municipal network that is not expandable in the future to offer FTTH connections to each user. This thesis has taken this into account and have raised a fiber network that bring the fiber to the maximum number of users so in medium to long term the current infrastructure is reusable for future use.

The deployment of next generation networks over FTTH networks is becoming more common and the emergence of companies such as neutral carrier model are an important solution for the evolution of them. Companies that are launched in this field are increasingly common, with important views of the future at technological and economic level.

GLOSSARY

AES Advanced Encryption Standard
APC Angled Physical Contact
APON ATM Passive Optical Network
AON Active Optical Network
ATM Asynchronous Transfer Mode
AWG Arrayed Waveguide Grating
BER Bit Error Rate
BPON Broadband Passive Optical Network
CATV Cable TV
CCTV Closed-Circuit TV
CPM Cross-Phase Modulation
CWDM Coarse Wavelength Division Multiplexing
DSL Digital Subscriber Line
DSF Dispersion-Shifted Fiber
DWDM Dense Wavelength Division Multiplexing
EDFA Erbium-Doped Fiber Amplifier
EPON Ethernet Passive Optical Network
FBT Fused Bi-conic Tapered
FEC Forward Error Correction
FSAN Full Service Access Network
FTP File Transfer Protocol
FTTB Fiber To The Building
FTTC Fiber To The Curb
FTTH Fiber To The Home
FTTN Fiber To The Neighborhood
FTTO Fiber To The Office
FTTP Fiber To The Premises
FTTU Fiber To The User
FTTx Fiber To The x
FWM Four Wave Mixing
GEM GPON Encapsulation Mode
GFP Generic Framing Procedure
GEAPON Gigabit Ethernet Passive Optical Network
GPON Gigabit Passive Optical Network
HDTV High-Definition TV
IEEE Institute of Electrical and Electronics Engineers
IPTV Internet Protocol TV
ISP Internet Service Provider

ITU-T International Telecommunications Union - Telecommunication Standardization Sector

LAN Local Area Network

LASER Light Amplification by Stimulated Emission of Radiation

LC Little Connector

LED Light-Emitting Diode

MAN Metropolitan Area Network

MDU Multi-Dwelling Unit

MTU Multi-Tenant Unit

MU Miniature Unit

NG-PON Next Generation Passive Optical Network

NRZ Non-Return to Zero

NZDSF Non-Zero Dispersion-Shifted Fiber

OAM Operations, Administration and Maintenance

ODN Optical Distribution Network

OLT Optical Line Termination

OPGW Optical Ground Wire

ONU Optical Network Unit

ONT Optical Network Termination

PE PolyEthylene

PLC Planar Light Circuit

PLOAM Physical Layer OAM

PMD Polarization Mode Dispersion

PON Passive Optical Network

POTS Plain Old Telephone Service

PVC PolyVinyl Chloride

P2P Peer-to-Peer

SBS Simulated Brillouin Scattering

SC Standard Connector

SMF Single-Mode Fiber

SPM Self-Phase Modulation

SRS Simulated Raman Scattering

TDM Time Division Multiplex

TDMA Time Division Multiple Access

VOIP Voice-Over-Internet Protocol

V-OLT Video Optical Line Termination

WDM Wavelength Division Multiplexing

WDM-PON Wavelength Division Multiplexing Passive Optical Network

xPON x Passive Optical Network

XG-PON 10 Gigabit Passive Optical Network

10G-EPON 10 Gigabit Ethernet Passive Optical Network

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