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GPON e vídeo sobre meio livre

GPON and video over Free Space Optics

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

Dedico este trabalho aos meus pais e irmão, por me guiarem sempre no sentido do sucesso, e ao meu namorado, pelo apoio e compreensão.

o júri / the jury

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Palavras-chave

Redes Ópticas Passivas, GPON, FSO, Vídeo, Reach Extension

Resumo

A procura por maiores larguras de banda nas redes de telecomunicações em curtos períodos de tempo tem crescido bastante. Mas tem-se verificado um desequilíbrio em termos de flexibilidade, eficácia e custo, uma vez que há zonas de difícil acesso, onde se torna caro levar uma fibra, e há ligações que podem ser apenas temporárias, outras de longo termo. É o chamado problema de “last mile bottleneck”.

Uma das possibiblidades para ultrapassar estes obstáculos, é a utilização de uma tecnologia chamada óptica de meio livre (mais conhecida pela tradução inglesa “Free Space Optics”, ou FSO). Esta tecnologia, mesmo sendo já antiga, apresenta ainda alguns desafios em termos de perdas na atmosfera ou de possíveis desalinhamentos do emissor e receptor, por exemplo.

Neste trabalho é feito um estudo de uma ligação de FSO, aplicando-lhe um sinal GPON, que é uma rede óptica passiva, bastante usada pelos operadores de telecomunicações hoje em dia.

Em primeiro lugar é feita a caracterização do sinal GPON apenas em fibra, assim como do “Extender Box” existente no laboratório, e só depois se fez o teste desse sinal sobre uma secção de FSO. Aplicou-se também um sinal de vídeo para perceber se o facto de passar na secção de FSO afectava a qualidade do mesmo.

São feitas também algumas simulações de modo a perceber de que forma é que as perdas na ligação e o BER são afectados pela turbulência e pelo comprimento da própria ligação.

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Keywords

Passive Optical Networks, GPON, FSO, Video, Reach Extension

Abstract

The seek for higher bandwidth in telecommunications networks on short timelines has grown quite. But it has been found an imbalance in terms of flexibility, efficiency and cost, because there are areas of difficult access, where is expensive the deployment of fiber, and there are connections that could be only temporary, and others are long term. It's called the last mile bottleneck problem.

One of the possibilities to overcome these obstacles is the usage of a technology called Free Space Optics (FSO). That, even if already old, still faces some challenges in terms of atmospheric losses or possibility of misalignment between the emitter and the receptor, for example.

In this work a FSO connection is studied, applying a GPON signal, which is a passive network, quite used by the telecommunications operators nowadays.

First a GPON signal characterization is done, only with fiber cables, as well as the Extender Box existent in the laboratory, and then the test of that signal over a FSO section is carried out. A video signal was also applied in order to assess the impact of the FSO section in its quality.

Some simulations are also done in order to understand how link losses and BER are affected by turbulence and by the link length itself.

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List Of Acronyms

ACM	Adaptive Coding and Modulation
ADSL	Asymmetric Digital Subscriber Line
APON	ATM Passive Optical Network
APSK	Asymmetric Phase-Shift Keying
ASE	Amplified Spontaneous Emission
ATM	Asynchronous Transfer Mode
BCH	Bose-Chauhuri-Hcquengham
BER	Bit Error Rate
BPON	Broadband PON
CATV	Community Antenna Television
CNR	Carrier Noise Ratio
CO	Central Office
COFDM	Coded Orthogonal Frequency-Division Multiplexing
CW	Continuous Wave
DSNG	Digital Satellite News Gathering
DTVC	Digital TV Contribution
DVB-C	Digital Video BroadcastCable
DVB-S	Digital Video Broadcast Satellite
DVB-T	Digital Video Broadcast Terrestrial
EDFA	Erbium Doped Fiber Amplifier
EPON	Ethernet Passive Optical Network
FSO	Free Space Optics
ER	Extinction Ratio
EVM	Error Vector Magnitude
EVOA	Electrically Controlled Variable Optical Attenuator
FEC	Forward Error Correction
FP-LD	Fabry-Perot Laser Diode
FTTB	Fiber To The Building
FTTC	Fiber To The Curb
FTTH	Fiber To The Home
FTTN	Fiber To The Node
FTTP	Fiber To The Premise
FTTx	Fiber To The x
GEM	GPON Encapsulation Method
GPON	Gigabit Passive Optical Network
HDTV	High Definition Tv
IEEE	Institute of Electrical and Electronics Engineers

IP	Internet Protocol
IPTv	Internet Protocol Tv
ITU	International Telecommunication Unit
ITU-T	ITU-Telecommunication Standardization Sector
JPEG	Joint Photographic Experts Group
LDPC	Low Density Parity Check
LNB	Low-Noise Block
MPEG	Moving Picture Experts Group
MZI	Mach–Zehnder Interferometer
NF	Noise Figure
NRZ	Non Return To Zero
NTSC	National Television System Committee
OA	Optical Amplifier
OBF	Optical Bandpass Filter
ODN	Optical Distribution Network
OEO	Optical-Electrical-Optical
OLT	Optical Line Termination
ONT	Optical Network Termination
ONU	Optical Network Unit
OOK	On-Off Keying
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal Noise Ratio
OTL	Optical Trunk Line
PAL	Phase Alternating Line
PER	Packet Error Rate
PON	Passive Optical Network
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RS	Reed Salomon
SBS	Stimulated Brillouin Scattering
SBST	Stimulated Brillouin Scattering Threshold
SCM	Sub-Carrier Multiplexing
SDTV	Standard-Definition Television
SECAM	Séquentiel Couleur à Mémoire
SGM	Self-Gain Modulation
SHSDSL	Symmetric High-Speed Digital Subscriber Line

SMF	Single Mode Fiber
SOA	Semiconductor Optical Amplifier
SPM	Self-phase Modulation
SRS	Stimulated Raman Scattering
STB	Set Top Box
TDMA	Time Division Multiple Access
TV	Television
TWA	Traveling Wave Tube Amplifier
UNI	User-Network Interface
VDSL	Very-High Bit Rate DSL
VOA	Variable Optical Attenuator
VOD	Video OnDemand
WAN	Wide Area Network
WDM	Wavelength Division Multiplex
WDM-PON	Wavelength Division Multiplex PON
WiMax	Worldwide Interoperability for Microwave Access
WLAN	Wide Local Area Network
XGM	Cross Gain Modulation
XPM	Cross Phase Modulation

1 Introduction

1.1 Context and motivation

Telecommunications' influence in society's life is huge. It affects almost all types of human activity, since banking, administration, government, commerce, education, health, transportation, culture, entertainment, and so on. It is already an essential part of social morphology, and there is a growing need to be "networked". This led to a new market demand, and consequently to an exploration of new network solutions.

The best choice for access networks is fiber, because it has an enormous transmission capacity, low maintenance and flexibility to support several services. It is really efficient, and operators are replacing the old copper structure with fiber. But there are several specific situations where it is not possible to use fiber. For example, in historical parts of cities, when it is not authorized to dig holes to pass the cable, neither use aerial cables; to surpass a mountain, or a big rock in the way; to quickly connect two buildings without digging the road, which causes many trouble in traffic for example, and so on. In these cases, there is a technology that easily solves the problem, which is Free Space Optics (FSO).

Free Space Optics is a wire free optical system, which transmits visible or infrared beams through the atmosphere. It can work for distances of several kilometers. The only physical requirement is a clear line of sight between the transmitter and the receiver, and enough power in the transmitter.

It is also an efficient way to quickly restore a break cable connection. It is of easy installation, and removable, and there are many factors that can cause breaks. Excavation is the main one, being responsible for 80% of the direct buried cable failures, and 65% for cables installed in ducts [**1**], but workmen, rodents, floods, and others, can also make damages in cables. In these situations, the repair time is 13.8 hours [**1**], including the time for the repair personnel to arrive on site, locate the cable fault, make the repairs and reinstall the cable. If it is urgent, the restoration of the service by installing an emergency cable and temporary splices takes normally 4 to 6 hours [**1**].

Free Space Optics is also a possible solution to the called "last mile bottleneck problem", which is the loss of speed in the termination network (core and metro networks are extremely fast because use fiber connections, and access networks sometimes use copper, coaxial cable, radio and, less often, fiber).

There are still many challenges to surpass, mainly due to environmental factors. Atmospheric conditions, such as fog, rain, wind, can cause attenuation and even loss of signal. Is necessary to do a previous study of the type of weather in the specific place where to implement the system.

1.2 Objectives

Telecommunications operators are choosing to replace the existing cable structure with fiber, investing in Passive Optical Networks, mainly in GPON technology. But, as seen before, it is a real challenge to reach every place in the world. FSO is a great solution to overcome many problems faced by the operators.

So, the main purpose of this work is to understand how a FSO section may affect the performance of the GPON signal. In order to do that, first it was characterized the GPON system existent in the laboratory and the alignment of the FSO transmitter and receiver was assessed. Then it was realized that, with all the losses in the FSO link, it would be necessary an amplifier, so an Extender Box was also tested. When all the components involved were characterized, it was tested the GPON signal over a FSO link, with different setups, and also a video signal.

To complete the study, and because it was important to understand how the FSO link is affected by the weather conditions, some simulations were performed, using a commercial photonic simulator, VPI, from Virtual Photonics TM.

1.3 Structure

This document is organized in four chapters, which are the following:

1 Introduction

2 Optical Networks

3 Free Space Optics

4 Simulation and Laboratory Results

The first chapter presents the context and motivation for this work, its objectives and goals, the structure and the contributions.

In the second chapter the optical networks, mainly the passive ones, which are the most used, are presented. The architectures of each technology are presented, their characteristics and the standards for communication. It is an expositive chapter, where it is possible to understand how the access networks are structured.

Also in the second chapter, a study of the video emission techniques is done. It includes cable, satellite and terrestrial distribution. The main features of each one, its advantages and disadvantages are presented.

The third chapter is an exposition about free space optics. It explains how different atmospheric effects affect an optical beam, such as rain, fog, scintillation, turbulence, etc. It also includes a study about the subsystem free space optics, and its components: lenses and mirrors.

In Chapter four the laboratory and simulation results are presented. First, a characterization of the GPON system available was done, with and without Extender Box, and the amplifiers from the Extender Box were characterized. Then, the GPON signal over free space optics was tested, using several configurations, considering fiber, FSO, splitters and Extender. Also in this chapter the simulation results are presented. There is a description of the modules that simulate FSO systems and some simulation results, where some situations that was not possible to test in the laboratory were covered, such as the variation of the losses and BER with the link length or with the C_n^2, which is an atmospheric parameter that measures the strength of scintillation.

The fifth chapter makes an appreciation of the work done, including some conclusions about the usage of free space optics in the access networks, and some topics for future work that can be done in this field.

1.4 Contributions

The main contributions that this work provides are:

- Description of Free Space Optical technology, as well as Passive Optical Networks and RF Video Overlay;
- Laboratory test of several setups containing sections of fiber cables and sections of Free Space Optics, with and without Reach Extender;
- Observe the influence of Free Space Optics in the performance of a GPON signal and also in video signal, by laboratory measurements, done indoor;
- Simulation of Free Space Optical setups;
- Observe the influence of an increase of distance and turbulence in a FSO length, by simulation.

2 Optical Networks

2.1 Introduction

The progress of multimedia technologies has brought with it a need for higher bandwidth in the information transport services. One of the most efficient ways to transport information is using a fiber optic access infrastructure. Fiber To The X (FTTx) is a generic term that comprises the many variants of that infrastructure. Depending on the place where the distribution made with fiber ends, there are several distinct configurations:

- Fiber to the Node (FTTN) – it's an architecture where the optical fiber reaches the street cabinet, which can be far from the subscriber. The connection between the node and the subscriber is made using the existing copper lines or coaxial cable. This type of architecture is adequate for small areas with few subscribers;
- Fiber to the Curb/Cabinet (FTTC) – Is very similar to FTTN, but usually the street cabinet is closer to the subscribers;
- Fiber to the Premises (FTTP) – is a generic term to FTTB or FTTH;
- Fiber to the Building (FTTB) – There's a dedicated fiber that reaches each building, but stops there. The connection to the subscriber household can be made by copper or coaxial cable;
- Fiber to the Home (FTTH) – each subscriber is connected by a dedicated fiber.

These configurations are represented in Figure 2.1.

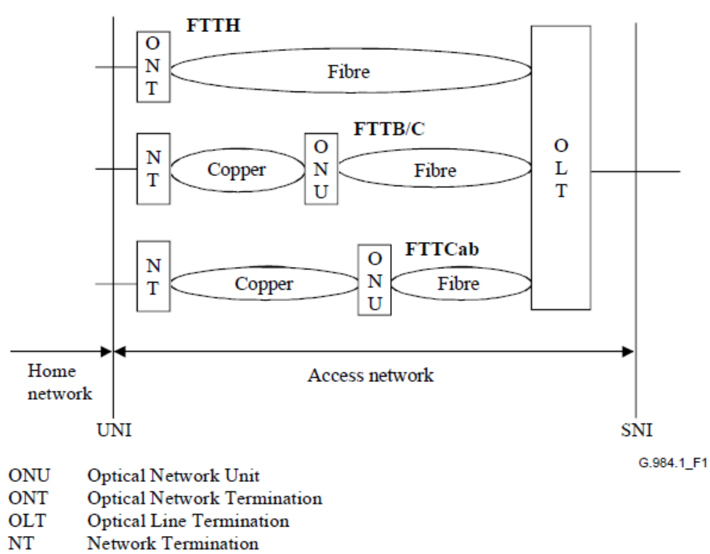

Figure 2.1 - PON network [2]

There are basically two types of architectures that can be used: Point-to-Point and Passive Optical Network. In the first, also known as star network, there is a dedicated fiber to each and every end-user. It is an active network that uses Ethernet, generally. Instead of the high speeds that this technology reaches, the most used topology is PON (Passive Optical Network), because point-to-point architectures require central switches with a dedicated port per user (which increases the price) and demands more fiber extension.

Passive Optical Networks (PONs), that are point-to-multipoint architectures, in opposite to point-to-point, do not use a fiber for every user, but use one to connect multiple end-nodes. This is the main characteristic of this network: the fiber is shared by the multiple users (Figure 2.2). There are several topologies to achieve this: ring, bus or tree, and each topology have its own technical and financial benefits, but they all are similar.

Despite being the most used, PON has some disadvantages, like shared bandwidth, which means that the usage from one user can influence other users (split-ratio), also it is not easy to upgrade bandwidth of an individual user, users need to be upgraded all at once and central switches require more complexity to integrate and separate customer streams.

Another relevant characteristic of PON architecture is the fact that all equipment used in the distribution is passive; the only active components are the OLT (Optical Line Termination, that is in the Central Office), and the ONU/ONT (Optical Network Unit/Optical Network Termination, in the costumer household/office). Beyond these, a Reach Extender in the distribution line may also be used, including active components, to increase the transmission distance.

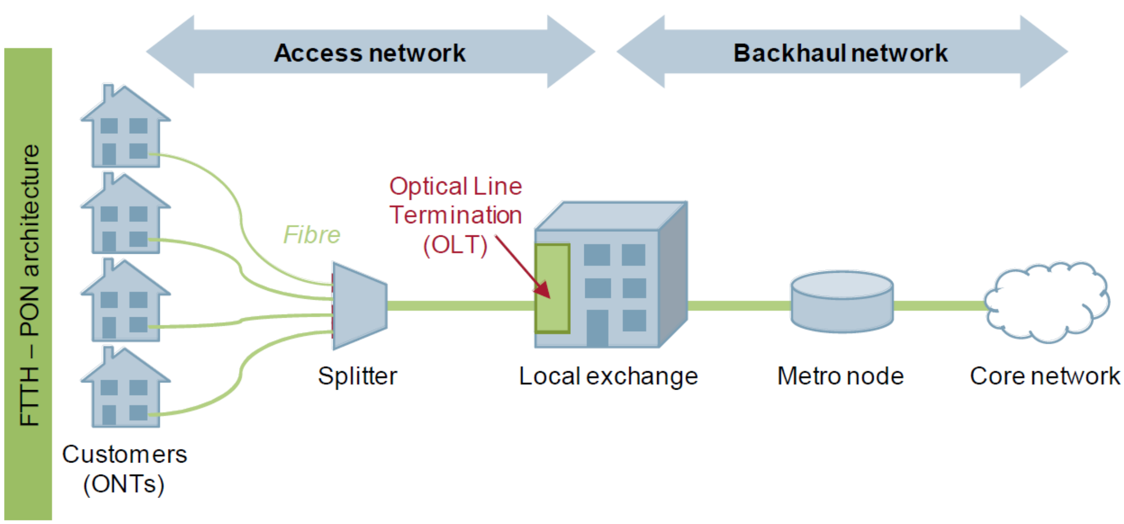

Figure 2.2 - Passive Optical Network Architecture [3]

There are three basic ways to do the splitting in a PON-network (as can be seen in Figure 2.3): [**4**]

- Fiber split close to the home of the user. One fiber is used to pass a group of homes. At each home a separate splitter is installed to divert the signal to and from the home. This is the most used fiber distribution solution, but makes it hard for other operators to share the infrastructure through local loop unbundling. If the network is shared this needs to be done through wholesale broadband access. (Figure 2.3 - A)
- Fiber split half way. A small bundle of fibers is brought to a street cabinet. In the street cabinet the optical signal is split and from the street cabinet the connection branches out using a point to point connection where every household has its own fiber. Switching providers is as easy as switching fibers from one provider's splitter to another's, although this does require a truck roll to the splitter, introducing costs for switching. (Figure 2.3 - B)
- Point-to-point with PON: The network is built as a point to point network, but can be used as both a PON and P2P-network with the splitter at the local exchange. (Figure 2.3 - C)

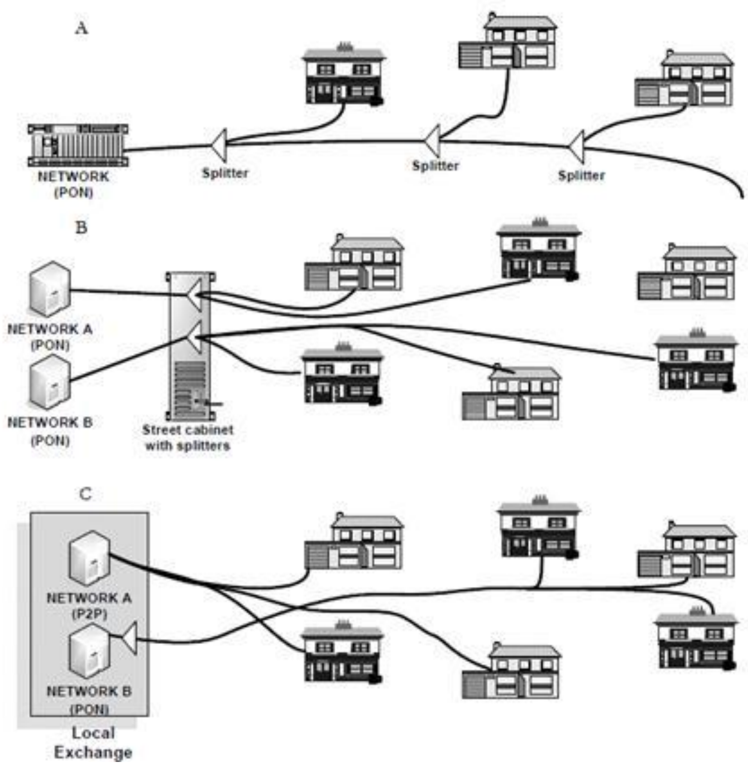

Figure 2.3 – PON splitting [4]

There are many PON architectures standards, among them: APON (Asynchronous Transfer Mode PON), BPON (Broadband PON), EPON (Ethernet PON), GPON (Gigabit-

Capable PON), WDM-PON (Wavelength Division Multiplexing PON). Below is shown some of them.

2.2 APON/BPON

It was the first standard of the PON architectures. Firstly published in 1995 and updated in 2001, was used and continuous developed until recently. Is defined in the regulations set G.983. Since that both APON and BPON are architectures based in the same protocol, ATM, and so very similar, they are included in the same section.

The G.983.1 recommendation describes downstream speeds of 155.52 Mbps, 622.08 Mbps and 1244.16 Mbps and for upstream 155.52 Mbps and 622.08 Mbps. It defines both symmetric and asymmetric systems; the possible combinations for downstream/upstream speeds are all summarized in Table 2.1. [**5**]

Downstream	Upstream
155.52	155.52
622.08	155.52
622.08	622.08
1244.16	155.52
1244.16	622.08

Table 2.1 - Bit rate combinations on APON/BPON (Mbps)

Originally, wavelengths of 1310 nm and 1530 nm, for upstream and downstream, respectively, were specified. But, to satisfy the increasing needs of new services, a wavelength distribution was defined, which includes video distribution, among others. Figure 2.4 shows the spectrum allocation.

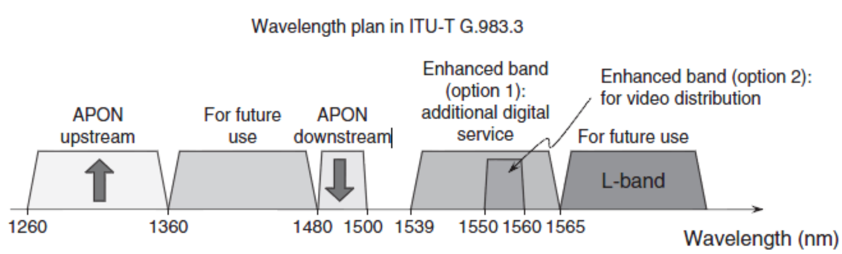

Figure 2.4 - Wavelength allocation in G.983.3 standard

As noticed in Figure 2.4, there are specific frequency bands for video overlay (1550 to 1560 nm), and for transmission of digital services, as SONET/SDH (1539 to 1565 nm). There are also two bands, 1360 to 1480 nm and above 1565 nm, reserved for future use.

To take advantage of these additional bands, it is necessary to use a multiplexer for the wavelengths in the OLT and in the ONU, which introduces losses and non-linearities (cross-talk) in the system. This standard (G.983.3) also defines the loss requirements and the isolation of these multiplexers.

2.3 GPON

This architecture was the successor of APON/BPON. It was finished in 2005, but is still in development. It is defined in G.984 standard from ITU, and refers to PONs with capacity of Gigabits (GPON – Gigabit-capable PON). The reason why it was created, and APON/BPON was replaced, was the fact that ATM technology was unable to increase as was expected, having been replaced by Ethernet and IP, and the interface between these and ATM is very complex.

In this architecture, the transmission rates can be 1.2 Gbps for upstream traffic and 2.4 Gbps downstream, or 2.4 Gbps in both ways (upstream and downstream), despite the first combination being the most used. [**2**]

Relatively to the range, this technology reaches a maximum of 60 Km of logical range, but the physical range is restrictive, because it is only 10 Km if Fabry-Perot lasers are used (required for high transmission rates, above 1.25 Gbps, inclusive), or 20 Km, using any another type of laser. [**2**]

The maximum delay of the services supported by this technology is 1.5 ms. Specifically, GPON system must have a mean transfer delay time of less than 1.5 ms, at maximum. [**2**]

Usually, this architecture has a split ratio of 1:64, but it can be extended to 1:128 with amplification. This characteristic is very important to the operators, whose purpose is to have the best possible split ratio, to be able to cover more clients and thus take more advantage of the network, but it implies an increase on the power budget. [**2**]

This technology operates at the following wavelengths: for upstream direction it uses the range of 1260 to 1360 nm, and for downstream 1480 to 1500 nm, when using only one single fiber, or 1260 to 1360 nm, for two fibers systems. [**6**] It also supports the wavelength allocation defined in APON/BPON, having available a specific wavelength for video overlay. For video the band from 1550 to 1560 nm is used, such as APON. This feature requires multiplexers in the OLT and in the ONU, as mentioned before for the case of APON, and which introduces losses and non-linearities (cross-talk).

The line code used in GPON is NRZ (Non Return to Zero), both for upstream and downstream. [**6**]

For error correction (FEC – Forward Error Correction), the standard G.984.3 recommends the usage of the cyclic code Reed-Solomon. Its use allows coding gain, which is defined as the difference of optical power in the receiver. This code (Reed-Solomon) adds redundancy to the information to transmit, which allows the decoder to detect and correct the transmission errors. [**7**]

The error correction algorithm is optional, and rarely used in GPON, because it is possible to reach a 2.4/1.2 Gbps bit rate, using class B+ fibers.

The GPON standard defines two types of protocols: Ethernet and GEM (GPON Encapsulation Method). The second one, GEM, allows the existence of variable size frames.

GPON transmission

The data transport scheme used is GPON Encapsulation Method (GEM), which is a connection-oriented and variable-length framing mechanism, and is independent of the type of the service node interface at the OLT and the UNI (User-Network Interfaces) interfaces at the ONUs. Each GEM frame has a GEM header with 5 bytes and a GEM payload with variable length. [**7**]

GPON transmission is different for downstream and upstream. In downstream, the OLT sends frames to the transmission medium; each GEM frame has an identifier, in the GEM Port-ID. All ONUs receive the entire data, but each ONU filter the GEM frames that do not belong to it, and processes only the ones with the respectively GEM Port-ID. [**7**]

The upstream transmission uses Time Division Multiple Access (TDMA), which is a multiple access protocol where the OLT attributes time slots to each ONU, in order to avoid packet collisions. The OLT also assigns a number, the Allocation-ID (Alloc-ID) to an ONU to identify a traffic-bearing entity that is a recipient of upstream bandwidth allocations within that ONU. Those bandwidth allocations of different Alloc-IDs are then multiplexed in time, accordingly to the bandwidth maps transmitted by the OLT. The GEM frames are identified by the ONU with the GEM Port-ID. [**7**]

This type of multiplexing needs synchronization because the GEM frames have variable lengths and ONUs are at different distances from the OLT. In order to do it, first the OLT uses a procedure named ranging, in which the logical distance between each ONU to the OLT is obtained, with the objective of determine the time of each ONU upstream transmission. This is done during the ONU activation and may be done also while the ONU is in service. Then, the OLT confirms if the time slots of each ONU do not generate collisions. [**7**]

Reach Extension

It is possible to have networks with more than 20 Km of physical reach, using a reach extension. The recommendation that defines the architecture and interface parameters for GPON systems with extended reach is G.984.6, from ITU-T. The usage of a reach extension increases the reach of the network, and may also increase its split ratio. The maximum reach possible is 60 Km, with loss budgets of 27.5 dB, in both spans. [**8**] The architecture of a network with Mid-Span Extension is show in Figure 2.5.

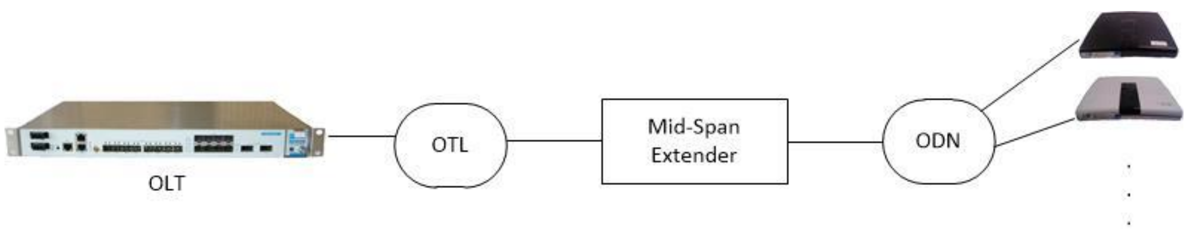

Figure 2.5 - Mid-Span Reach Extension

There are two technological possibilities to do this, using an optical-electrical-optical (OEO) regenerator or an optical amplifier (OA), between the OLT and the ONU. Also hybrid schemes can be used, for example to use regeneration in the downstream and optical amplification in upstream, or the reverse. [**8**]

In case of using the optical amplifier, two amplifiers are needed, one for downstream and other for upstream, to provide an optical power gain. This type of architecture may also include optical bandpass filters (OBFs), in order to reduce the bandwidth of the ASE (Amplified Spontaneous Emission) introduced by the optical amplifier, and also reduce ASE-ASE beat noise and ASE-based power-offset in the optical receiver, and in this way achieve an higher performance. [**8**]

If using regenerators, those receive the optical signal, reshapes and retimes it in the electrical domain and then retransmits in the optical domain. In this case, one can choose to use a 2R or 3R regenerator; 2R re-modulates and re-amplifies, and 3R re-modulates, re-amplifies and re-times. G.984.6 standard doesn't specify 2R details of the regenerators. [**8**]

Hybrid architectures with an optical amplifier for downstream, need a clock reference for upstream. [**8**]

Obviously, the reach extender must be compatible with all the GPON equipment, and with the transmission rates used in downstream and upstream. In terms of OLT management, the extender must be treated as a proxy, in order to be only in the physical layer and be transparent in the network layer. [**8**]

The mid-span extender requires electrical power, which can be an issue because the extender can be located anywhere in the field. It also needs batteries for backup, in case of failures of the power source, and the power consumption must be restrained. [**8**]

The extender must also support the transmission of video and have mechanisms to reduce crosstalk. [**8**]

2.4 EPON

This standard was finished in 2004, by IEEE, in the 802.3ah standard. It differs from the previous ones because it uses only the Ethernet protocol. This technology gained relevance because of being capable to support full optical access with less stringent timing requirements, and due to its capacity to encapsulate variable size packets. Since it was introduced in the market, it caught the company's interest, because the interface with Ethernet WANs already available is very simple. [**9**]

There are two specifications defined to the physical layer: 1000BASE-PX10 and 1000BASE-PX20, whose maximum reaches are 10 and 20 Km, respectively. [**9**]

It allows symmetrical speeds of 1.25 Gbps. [**9**]

The line code used in this technology is 8b/10b. This code permits an easy clock recovery, because it yields an enough number of bit transitions and generates an output with a DC balanced value. The use of the error correction algorithm is optional, and the recommended algorithm for EPON standard is the same as for GPON, RS (255,239). [**9**]

The wavelength range for downstream is 1480 to 1500 nm; in upstream the range of 1260 to 1360 nm. It is also possible to allocate additionally the range of 1550 to 1560 nm for video transmission. [**9**]

The split ratio supported by this technology is 1:16, but it can be extended to 1:32 if used with an error correction algorithm. [**9**]

Data transmission in EPON is done differently depending on whether it is considered the upstream or downstream direction. In the downstream case, that is the OLT – ONU direction, the packets are broadcasted, each packet having a variable size, between 46 and 1500 bytes. Each packet has also a header with information about the receiver, even though there can be packets destined to all ONUs (called transmission packets), and others destined to a certain group of ONUs (multicast packets). Every ONUs receive all the packets, even those not destined for them; it is the ONU that discards them, and receives only the ones that are destined to it. [**9**]

In the upstream direction, ONU – OLT, transmission is done through a multiple access protocol, Time Division Multiple Access (TDMA), in which a time slot is assigned to each ONU for sending data, and then all the data is time multiplexed and sent to OLT. [**9**]

2.5 RF Video Overlay

The first analog TV showed up during the 50's, still in black and white. In the late 60's there were already color TVs, and, from then on, technology has been improved. [**10**]

Analog TV emissions have a very reasonable quality, which was always a difficult for the success of digital TV. Its booster was the settling of JPEG standard (Joint Photographic Experts Group), and later the MPEG (Motion Picture Experts Group). In the beginning of the 90's the DVB standard was created (Digital Video Broadcasting).

In Europe, digital TV is already a reality: there are millions of digital TV receivers, over the DVB system. Worldwide there are now hundreds of millions of digital TV subscribers, and an increasing is expected in the near future. [**10**]

One of the digital TV advantages is the fact that noise is less perceptible in the image received by the user: while in analog TV the disturbance caused by the noise was more noticeable, it is not perceptible in digital transmission, since the FEC system fixes most of the errors, up to a certain level of noise; when it is higher than the supported by the FEC algorithm, the video stops.

Other advantages of digital formats are: the possibility of doing multiple copies, without degradation of the quality; creation of special effects, unachievable in analog format; and the simplification of international transmissions, independently from the transmission standard used in the diffusion (NTSC, PAL, SECAM, D2-MAC, MPEG). [**11**]

However, there is a disadvantage: it requires high bit rates, being impossible the transmission to the final user without a previous signal compression. [**11**]

In the last years, new digital TV distribution formats appeared: by cable, terrestrial and, more recently, by the telephone line (IPTV over ADSL). The greater availability of compression more effective formats, added with the decrease of the prices of high resolution TVs, compatible with HDTV, has allowed a real and visible progress of HDTV.

Last, but not least, the growing sophistication of mobile phones, already with relatively big screens and high resolutions, associate to the development of transmission standards adapted to mobility, as DVB-H (DVB – Handheld) or DVB-SH (DVB – Satellite services to Handhelds), announces the development of a personal TV, transportable to everywhere. [**11**]

Digital Television

The actual standard for digital TV distribution is DVB (Digital Video Broadcasting), which is based in MPEG-2 or MPEG-4 compression standards. MPEG-2 is used in SDTV (Standard Definition Television), whereas MPEG-4 was essentially designed for HDTV (High Definition Television). [**11**]

TV signal can reach the users by many ways: cable – DVB-C (DVB – Cable), satellite – DVB-S (DVB – Satellite), or terrestrial – DVB-T (DVB – Terrestrial). [**11**]

In the transmission process, first, the analog video and audio signals are converted to digital, by analog-digital conversion. After the compression process, a SDTV signal has a bit rate from 2 to 7 Mbps, or 15 Mbps in HDTV case, and audio signal has 100 to 400 Kbps. Services' packing and multiplexing (video, audio and date) is done according to MPEG-2 TS (MPEG-2 Transport Stream) Standard. Every MPEG-2 stream are composed by MPEG-2 TS packets with a 188 bytes fixed size.

After coding, MPEG-2 TS passes through a DVB-C, DVB-T or DVB-S (or another) modulator. It adds FEC and converts the base band signal into the intended RF frequency.

An analog to digital conversion of video and audio signals is represented in Figure 2.6.

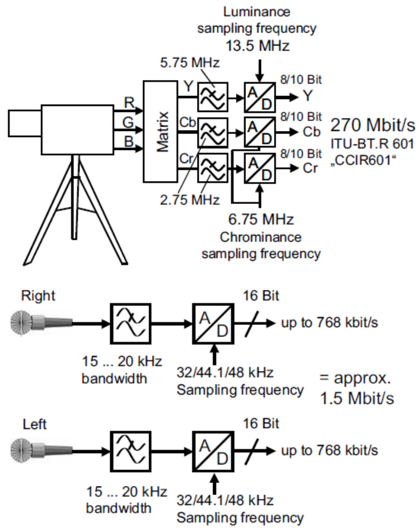

Figure 2.6 - Analog-Digital conversion of video and audio signals [10]

DVB-S and DVB-S2

TV reception by satellite is nowadays a very common technology, because its installation is really simple and inexpensive (in Europe, a complete reception system, with dish, LNB (Low Noise Block) and receptor, is available for less than 100 Euro, and there are no further costs) [**10**], and there are lots of free channels, both analog and digital.

In a broadcast satellite transmission, one channel has usually a bandwidth of 26 to 36 MHz, where the uplink is in the 14 to 19 GHz range and downlink from 11 to 13 GHz. Typically is used a symbol rate of 27.5 MS/s (since the spectrum must be thinner than the transponder bandwidth). As the modulation format used by DVB-S standard is QPSK (Quadrature Phase Shift Keying), which allows for 2 bits per symbol, the data rate is 55 Mbps. [**10**]

It uses QPSK as modulation format because that is resistant to intense noise levels and is capable of handling pronounced non-linearities, typical in satellite transmissions. Noise is due to the enormous distance between the satellite transmitter and the receiving antenna (near 36000 Km), which causes interferences due to the free space attenuation, that is about 205 dB. Non-linearities are caused by the modulation characteristic of TWA (Traveling Wave Tube Amplifier), which is an active element of the satellite transponder. These non-linearities cannot be compensated, for the reason that it would cause a decrease of energy efficiency. [**10**]

A FEC code should be used, due to the large quantity of errors that occur in this type of transmission. The code used is Reed-Solomon (204,188), together with a convolutional code. RS (204,188) adds 16 bytes of redundancy at each packet (whose size becomes 204). Thus, the receptor is able to correct up to 8 errors in a 204 bytes packet. Since this is not enough, a convolutional code is added, which increases the data flow. Even so, this increase is controllable by a parameter in the code, the coding rate. In DVB-S, a coding rate of ¾ is used, resulting in a transmission rate of 38.01 Mbps. [**10**]

Then, symbols are mapped in the QPSK constellation, with Gray coding [**12**], and then a raised cosine filter is applied, with a roll-off factor of 0.35, which limits the signal bandwidth and at the same time optimizes the eye diagram. [**10**] [**11**] [**12**]

The minimum CNR allowed in the receiver is 16.4 dB. [**13**]

DVB-S2 standard emerged from DVB-S and DSNG (Digital Satellite News Gathering), which is a satellite communications standard for mobile units. It is also compatible with DVB-S, being possible to transmit a DVB-S stream and an additional DVB-S2 stream.

DVB-S2 allows many modulation formats: QPSK, 8PSK, 16APSK (Amplitude Phase Shift Keying) and 36APSK. It is also compatible with data streams different from MPEG-2; allows Adaptive Coding and Modulation (ACM), which permits that the code and the modulation adapts to the receiver conditions, increasing the error correction and using robust modulations schemes when the signal strength is low. [**10**] [**12**]

The FEC system used is a combination of BCH (Bose-Chauhuri-Hcquengham) with intern codification LDPC (Low Density Parity Check).

The error protection used in DVB-S2 allows that the efficiency increases extremely (about 30%), approaching of the Shannon limit.

The roll-off factor can be 0.20, 0.25 or 0.35. [**11**]

The data rate is nearly 49 Mbps, but it can fluctuate with the coding rate used (symbol rate of 27.5 MS7s). [**10**]

This standard was created to support a great sort of applications, such as: broadcast services (digital TV, HDTV), interactive services (data services, including internet access, to provide interactive services), DTVC/DSNG (Digital TV Contribution and Satellite News Gathering) (occasional and temporary transmissions of TV news or sound, for purposes of diffusion), professional services (data distribution and other professional applications for point-to-point or point-to-multipoint, including interactive services to professionals). [**12**]

DVB-C

In many countries, and especially in areas of high population density, radio and television distribution is done by cable, because it can offer an high number of channels and high speed internet.

The standard used for this type of communication is DVB-C. The great advantage over the satellite communication is the smaller quantity of noise in the transmission, because the cable (coaxial or optical) has transmission characteristics quite better than the free space, used in satellite communication. That way the use of higher order modulation formats is possible.

Cables can have a bandwidth between 50 and 450 MHz, or between 50 and 860 MHz. There is also a return channel in the frequency band beneath 65 MHz. [**10**]

This standard can support several modulation formats: 16QAM, 32QAM, 64QAM, 128QAM and 256QAM. Usually, 64QAM and 156QAM are used when MPEG-2 packet distribution is done by coaxial cable and optical fiber, respectively. The roll-off factor of the filter is 0.15. Each channel have a bandwidth of 8MHz. Regarding the error correction, only the RS (188,204) code is used. [**10**] Using a 256QAM, the minimum BER allowed in the receiver is 34 dB. [**13**]

As modulation formats with higher quality and a FEC algorithm are used, higher transmission rates are possible to obtain.

DVB-T

The standard used in terrestrial transmission of television, DVB-T, supposes the use of COFDM (Coded Orthogonal Frequency Division Multiplex) as modulation format of MPEG-2 streams. Thus, one obtains an hierarchical modulation, allowing, in a single channel, the transmission of the same program with different FEC, transmission rate and image quality. Higher priority data is modulated in QPSK, with better error correction but lower transmission rate; lower priority data uses higher order modulation formats as 16QAM or 64QAM, with higher transmission rates and video quality.

The bandwidth of each DVB-T channel may be 6, 7 or 8 MHz, operating in 2K mode (2046 subcarriers) or 8K (8192 subcarriers). The first one has a bigger spacing between subcarriers (4 KHz), but a shorter symbol period, making it more susceptible to delays, but less susceptible to frequency scattering (Doppler effect), when compared to 8K (which presents a spacing between subcarriers of 1 KHz). [**10**]

Error correction is done identically to DVB-S, that is, using RS (188,204) code, followed by a convolutional code.

In order to compare the several formats mentioned before, summary characteristics are presented in Table 2.2.

Parameter	DVB-C	DVB-S	DVB-S2	DVB-T
Video encoding	MPEG-2 OU MPEG-4 AVC (H264)			H264, H263, …
Audio encoding	MPEG-1 (layer II), Dolby Digital ou AAC			G7xx, AAC
Transportation packet	188 bytes	188 bytes	188 bytes	188 bytes
External code	Reed-Solomon (204,188)	Reed-Solomon (204,188)	BCH	Reed-Solomon (204,188)
Internal code	Convolutional	LDPC	¼ a 9/19	Convolutional
Roll-off factor	15%	35%	20, 25 ou 35%	N.A.
Modulation	16 a 256 QAM	QPSK	QPSK a 32 APSK	OFDM 2K/8K
Channels size	6, 7 ou 8 MHz	27 ~36 MHz	27 ~36 MHz	6, 7 ou 8 MHz

Table 2.2 - Standards comparison [11]

3 Free Space Optics

Free Space Optics (FSO) is a technology already used in the past, mainly in military applications, and it has been reappearing in recent times, now for both military and civil purposes. This establishes wireless data transmissions through modulated light beams. Other designations usually appear, such as Optical Wireless or Lasercom (Laser Communications).

The main interest in this technology concentrates on the fact that this allows very high data rates, in the order of tens of Gbps, because of the high frequency of the carrier (300 THz), and consequent large bandwidth. Has also the advantage of using a non-licensed frequency. It is of easy installation and is insensitive to electromagnetic interferences, jamming and wiretapping. The connection between the FSO equipment and the fiber is direct, without the need of intermediate conversion. [**14**] All these features make it very viable in the market, namely in the last mile access, airbone communications, satellite and even submarine, temporary mobile connections and permanent connections between buildings.

It provides a flexible and cost effective service, which allows overcoming the problem known as "last mile bottleneck", because it allows high data rates. In fact, the "bottleneck" problem exists not only in the last mile, but also in the core and in the edge of the network, but FSO can be used in any place of the network, as will be confirmed below.

The only difference between the transmission through air and in a fiber cable is the medium. An interesting fact is the speed difference, light travels faster through air than through glass, approximately 300.000 km/s and 200.000 km/s, respectively. [**15**]

In a situation where the physical connection is unfeasible and is necessary a high bandwidth, the using of FSO is primordial. In reality, this is the only technology, inside wireless technologies, that is capable to guarantee several Gbps of bandwidth, being also the less expensive (compared with any other wireless technology with equivalent characteristics).

All these advantages, combined with low cost associated to implementation, high level of protection and data security inherent of this technology, high flexibility and high scalability, make it suitable for a wide range of situations: first/last mile in urban areas with high population density, access networks for isolated buildings, high velocity LAN-to-LAN, chip-to-chip connections, transitional and temporary network connections, submarine and spatial communications (instead of the growing interest in these two applications, terrestrial FSO is still predominant). [**14**]

The systems commercially available are the opaque ones, in which the optical signal is terminated to an electrical receptor, and subsequently sent through the atmosphere through a dedicated laser. There are already many FSO equipments available in the market, to interconnect with optical fiber or Ethernet components. Currently is under study a new type of system, fully transparent, which is able to reach higher bandwidths (comparable to the optical fiber). In these systems there are no losses proper of the electrical optical conversions (OEO). [**14**]

The greatest disadvantage inherent to this technology is its susceptibility to factors that cause attenuation, and, in some situations, total loss of the connection. It is also necessary an unobstructed line of sight, it has to assure a low BER (BER < 10^{-9}) and has to guarantee high reliability. It is an unpredictable medium.

The main difficulties that influence this technology's full operation are the atmospheric conditions, that affect the distance and viability of the connections. Before the implementation of this technology in a specific geographic location, it is essential to evaluate the type of weather of that place, specifically. Despite that, generally speaking, short range connections remain operational even in adverse weather conditions.

To study the availability of a FSO system in a specific place, it is needed to know the statistics of the total attenuation expected in that place and the amount of attenuation which can be tolerated by the FSO system at a given range. Evidently there is a great amount of values that are assumptions.

The main issues that can affect and compromise the availability of the link are the following:

- Fog: it is one of the main factors that cause serious attenuation and possible link loss. Basically it is water vapor in the form of water droplets, with diameters of only a few hundred microns, which can modify light characteristic or obstruct the passage of light, because of absorption, scattering and reflection. Moderate continental fog can result in an attenuation of 130 dB/Km, and dense maritime fog can reach up to 480 dB/Km. [**14**]
- Rain: although less significant than fog, rain also affects the FSO links. It depends on the rain rate R. For rain rates typical in continental climate of middle Europe, which are about R = 5 mm/h, attenuation is approximately 3 dB/Km [**14**] only. If there is rain falls of R=100 mm/h, it could generate attenuations of approximately 30 dB/km [**14**]; luckily, it occurs rarely and only in short peaks both in Europe and in the United States. Analogous considerations can be made for heavy snowfall, of over than 5 cm in 3 hours, where attenuations over 45 dB/km were measured. [**14**]

- Absorption: it occurs when the water molecules destroy photons, causing attenuation (decrease of the beam power). It depends on the wavelength.
- Scattering: it redistributes the energy direction, causing multipath effects, and a significant reduction in beam intensity, mainly for longer distances. It doesn't cause energy loss. There are three types of scattering: Rayleigh, Mie and nonselective scattering. The first one, Mie scattering, is relevant when the particle and the wavelength have similar sizes, and is the main attenuation process to influence FSO performance. Rayleigh scattering occurs when the wavelength of light is higher than the particle size. [**14**]
- Physical obstructions: sometimes birds can temporarily obstruct the line of sight, and block the beam, but usually this is a short interruption and easily resumed. It can be surpassed with a multibeam system.
- Building sway: the alignment between the transmitter and the receiver can be ruined by the movement of buildings.
- Scintillation: results from temperature variations, and can cause fluctuations in signal amplitude. One familiar example of scintillation in the atmosphere is the twinkling of stars and the shimmering of the horizon on a hot day.

3.1 Atmospheric propagation characteristics

As mentioned above, weather conditions are the major weakness of FSO links. These conditions can cause random optical power fluctuations in the received beam, which result in beam deformation, scintillation effects and beam wander, and the atmospheric attenuation cause reduction on the detected optical power level.

Atmospheric attenuation

Atmospheric attenuation refers to the attenuation of light traveling through the atmosphere, and is caused by the interaction of the laser beam with air molecules and aerosols, along the propagation. The optical beam power decays exponentially with the propagation distance, as can be seen in the optical transmittance mathematical description: [**14**]

$$\tau = \tau_a + \tau_s = \frac{P(l)}{P(0)} = \exp(-\alpha\, l) \qquad \textbf{Equation 1}$$

where α is the overall attenuation coefficient, which is given by four different processes: molecular absorption, molecular scattering, aerosol absorption and aerosol scattering, $\tau_a$is the absorptive transmittance and τ_s the scattering transmittance.

So, the transmission in the atmosphere can be described as a function of the link distance: [**16**]

$$l_{atm} = 10 \log \tau \quad \left[\frac{dB}{Km}\right]$$ **Equation 2**

The absorptive transmittance can be calculated using the following empirical expression, for any transmission window (and assuming that variations in the transmission are caused by changes in the water content of the air): [**14**]

$$\tau_a = \exp\left(-A_i\, w^{\frac{1}{2}}\right), \qquad w < w_i$$
$$\tau_a = k_i \left(\frac{w_i}{w}\right)^{\beta_i}, \qquad w > w_i$$ **Equation 3**

Where w is the precipitable water, in millimeters, encountered by the light beam, and is given by: [**14**]

$$w = 10^{-3}\, \rho\, l$$ **Equation 4**

and ρ is the absolute humidity, in g/m^3: [**14**]

$$\rho = RH\, (-0.74 + 90.96 \exp\left(\frac{T}{13.67}\right) - 85.4 \exp\left(\frac{T}{13.52}\right))$$ **Equation 5**

where RH is the relative humidity percentage and T is the temperature in degree Celsius.

A_i, k_i, β_i and w_i are constants dependent on the atmospheric window, that can be seen in Table 3.1.

Window boundaries (nm)	A_i	k_i	β_i	w_i
720 – 940	0.0305	0.800	0.112	54
940 – 1130	0.0363	0.765	0.134	54
1130 – 1380	0.1303	0.830	0.093	2
1380 – 1900	0.211	0.802	0.111	1.1
1900 – 2700	0.350	0.814	0.1035	0.35
2700 – 4300	0.373	0.827	0.095	0.26
4300 – 6000	0.598	0.784	0.122	0.165

Table 3.1 – Constants [14]

Another factor that causes attenuation is the scattering. Here, there is no power loss, only a directional distribution. There are two scattering mechanisms, mainly: Rayleigh scattering, when the wavelength of the light is higher than the particle size, and the Mie scattering, when the particle size is comparable with the wavelength of the radiation.

The scattering transmittance can be calculated by: [**14**]

$$\tau_s = \exp(-l\left(C_1\,\lambda^{-\delta} + C_2\,\lambda^{-4}\right)) \qquad \textbf{Equation 6}$$

where C_1 and δ are constants given by the size distribution and aerosol concentration, and $C_2 = 0.00258\,m3$ accounts the Rayleigh scattering. $C_1$and δ can be related with the visual range, V, in Kilometers at 550 nm, by: [**14**]

$$C_1 = \frac{3.91}{V}\,0.55^{\delta} \qquad \textbf{Equation 7}$$

δ can take values of 1.6 for very good visibility, and approximately 1.3 for average visibility. If the visual range is less than 6 Km, δ is given by: [**14**]

$$\delta = 0.585\,V^{1/3} \qquad \textbf{Equation 8}$$

If it is in the presence of precipitation, which can be rain or fog, the scattering coefficient will increase: [**14**]

$$\tau_{rain} = \exp(-(0.05556 + 0.00848\,R - 3.66\,10^{-5}R^2)l) \qquad \textbf{Equation 9}$$

where R is the rainfall rate, in mm/hr.

So, the total attenuation will be the sum of Equation 3, Equation 6 and Equation 9.

Turbulence

Atmospheric turbulence is a phenomenon that occurs when there are multiple scattering in the atmosphere caused by index of refraction fluctuations. In other words, there are air cells with different temperatures, which are arbitrarily distributed along the line of view of the link; these differences in the cells' temperatures causes different values of index of refraction, which causes slight bending of the rays of light. This effect is represented in Figure 3.1. This affects amplitude and phase of the optical signal.

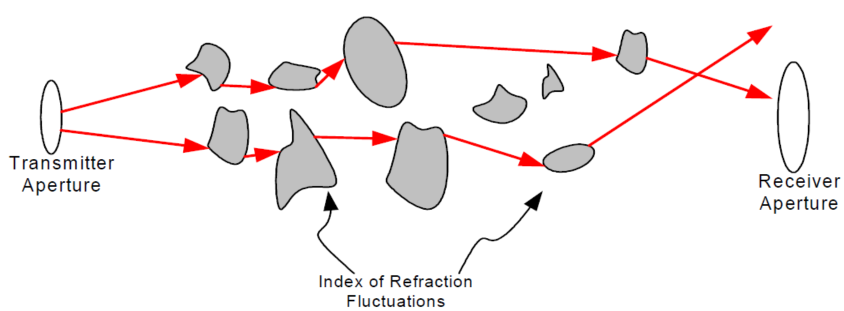

Figure 3.1 - Fluctuations on the index of refraction [17]

To measure the strength of the turbulence a parameter named atmospheric structure coefficient is used, C_n^2, which is directly related to wind speed. This is given by: [**14**]

$$C_n^2 = \left(\frac{h^{-4/3}}{3000^{-4/3}}\right) \cdot \frac{\left(\frac{79 \times 10^{-6} \cdot P}{(T+273.15)^2}\right)}{5.49 \times 10^{-13}} \cdot \left(\left(2.2 \times 10^{-53} \cdot 3000^{10} \cdot \left(\frac{v \cdot \sin(\theta)}{27}\right)^2\right) \cdot e^{-3} + 10^{-16} \cdot e^{-2}\right) \quad \textbf{Equation 10}$$

where h is the height in meters, P the air pressure in milibars, T is the temperature in degree Celsius, v is the wind speed in m/s and θ the angle between the beam and the wind.

Usually, C_n varies between 5×10^{-7}, in case of strong turbulence, and 8×10^{-9}, for weaker turbulence.

One interesting fact is that C_n^2 can change throughout the day. Figure 3.2 shows some measurements of that, taken in San Diego, California, USA, at the AirFiber facility.

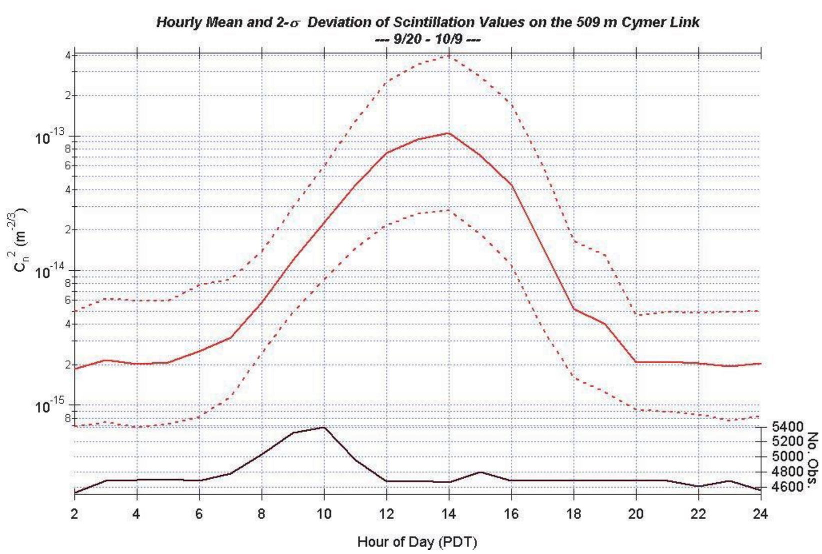

Figure 3.2 - Measurements of C_n^2 in San Diego, California, USA [18]

As can be seen in Figure 3.2, the worst values for C_n^2 were taken by midday, when the temperature is greatest. This means that there are more scintillation events happening then.

Turbulence can lead to two different effects, depending on the scale size of the air cells: if the scale of the turbulence cells is larger than the beam diameter, then the dominant effect will be the beam wander, which is the rapid displacement of the beam spot; instead, if the scale of turbulence cells is smaller than the beam diameter, then the dominant effect will be scintillation, which is the beam intensity fluctuation.

Radial variance of beam wander can be described by:

$$\sigma_r^2 = 1.90\, C_n^2\, (2\, w)^{-1/3} l^3$$ **Equation 11**

where w is the spot size at the transmitter.

With the values of C_n^2, it is possible to do a study of the variance in intensity fluctuations at the receiver, using the following formula:

$$\sigma_R^2 = 1.23\, C_n^2\, k^{\frac{7}{6}}\, L^{\frac{11}{6}}$$ **Equation 12**

where $k = 2\pi/\lambda$ and L is the link length.

Kolmogorov described the turbulence as eddies, where the larger ones are split into smaller eddies without loss of energy. The size of the eddies can be of a few meters, denoted as outer scale L_0, until a few millimeters, designated as inner scale l_0. This is represented in Figure 3.3.

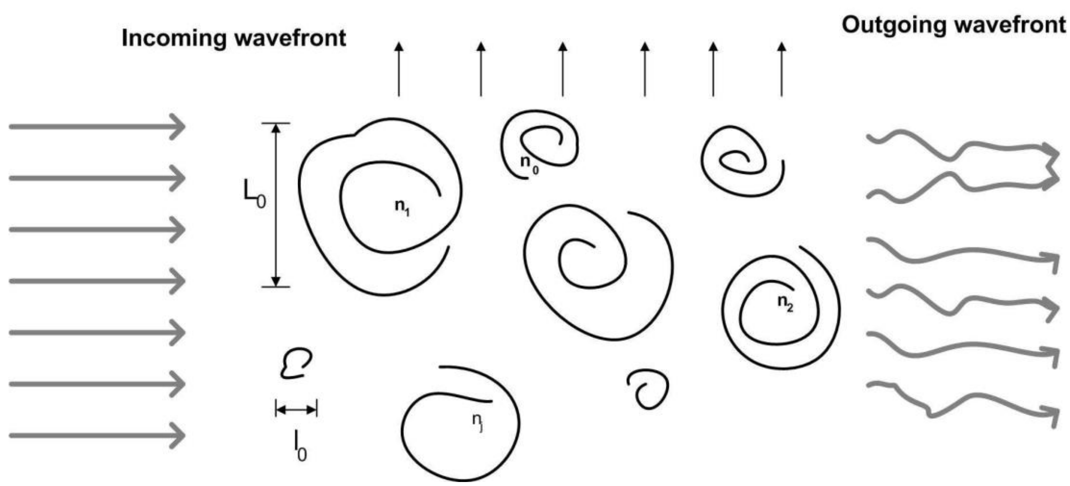

Figure 3.3 - Turbulence model according to the Kolmogorov theory [16]

Thermal Blooming

In the atmosphere molecular absorption of the beam energy can occur, which leads to variations of the air temperature and can lead to changes in the index of refraction. If it is in the presence of wind, it can cause density waveform destruction and beam bender.

The displacement of the beam relative to the receiver can be calculated by:

$$u = \frac{5\,(\gamma-1)(n-1)\,l\,\left(\frac{\langle I_0\rangle}{w}\right)^2}{6\,\gamma\,P\,100\,|v\sin(\theta)|}$$ **Equation 13**

where γ is the ratio of specific heats (its value in the air is 1.4), n is the refractive index of the air and I_0 is the optical power at the transmitter.

Scintillation

The scintillation index can be calculated by the following expression: [**17**]

$$\sigma_I^2 \cong \exp\left(\sigma_{In\,x}^2 + \sigma_{In\,y}^2\right) - 1$$ **Equation 14**

where:

$$\sigma_{In\,x}^2 = \frac{0.49\left(\frac{\Omega_G-\Lambda_1}{\Omega_G+\Lambda_1}\right)^2\sigma_B^2}{\left\{1+\frac{0.4(1+\Theta_1)(\sigma_B/\sigma_R)^{12/7}}{(\Omega_G+\Lambda_1)\left(\frac{1}{3}-\frac{1}{2}(1-\Theta_1)+\frac{1}{5}(1-\Theta_1)^2\right)^{6/7}}+0.56(1+\Theta_1)\sigma_B^{12/5}\right\}^{7/6}}$$ **Equation 15**

and

$$\sigma_{In\,y}^2 = \frac{0.51\,\sigma_B^2\,(\Omega_G+\Lambda_1)\,(1+0.69\,\sigma_B^{12/5})^{-5/6}}{\Omega_G+\Lambda_1+1.2\,(\sigma_B/\sigma_R)^{12/5}+0.83\,\sigma_R^{12/5}}$$ **Equation 16**

with:

$$\Theta_0 = 1$$

$$\Lambda_0 = 2\,\frac{2\,L}{k\,W_0}$$

$$\Theta_1 = \frac{\Theta_0}{\Theta_0^2+\Lambda_0^2}$$

$$\Lambda_1 = \frac{\Lambda_0}{\Theta_0^2+\Lambda_0^2}$$

$$\Omega_G = \frac{16\,L}{k\,D_G^2}$$

$$\sigma_B^2 \cong 3.86\, \sigma_R^2 \left\{0.40\, [(1+2\Theta_1)^2 + 2\Lambda_1^2]^{5/12} \cos\left[\frac{5}{6}\, tan^{-1}\left(\frac{1+2\Theta_1}{2\Lambda_1}\right)\right] - \frac{11}{16}\Lambda_1^{5/6}\right\}$$ **Equation 17**

$$\sigma_R^2 = 1.23\, C_n^2\, k^{7/6}\, L^{11/6}$$ **Equation 18**

L is the link length, $k = 2\pi/\lambda$, $W_0$is the launch waist and D_G the receiver aperture.

To obtain the attenuation due to scintillation, in dB: [**17**]

$$\alpha \cong 10\log(1 + 1.63\, \sigma_R^{\frac{12}{5}}\, \Lambda_1)$$ **Equation 19**

3.2 Optical subsystems

FSO systems currently use designs based on lenses and/or mirrors. These components can be used on the transmission or on the receive side of the link, and they have a great importance on the performance. [**15**]

Lenses are based on the physics of light refraction and their properties depend on the shape of the lens and the material they are made. On the other hand, mirrors are based on reflective properties of materials.

Geometrical Optics

Classical optics is divided in two basic fields: geometrical (or ray) optics and physical (or wave) optics. In geometric optics, light is considered to consist in narrow beams, which help us understand the reflection and refraction phenomena, and therefore the use of lenses and mirrors. Physical optics considers light as an electromagnetic wave, allowing us to understand phenomena such as light wave interference, diffraction and polarization. As the objective is to characterize lenses and mirrors, it will be done accordingly to geometric optics, which is only valid when the wavelength is very small compared with the size of the structures with which the light interacts, which is the case. Physical optics will not be discussed here. [**15**,**19**]

When light travels in a media different from the vacuum, its speed will change, accordingly to the equation: [**15**]

$$v = \frac{c}{n}$$ **Equation 20**

where c is the speed of light in a vacuum ($c = 3 \times 10^8\ m/s$) and n is the refractive index of the medium.

When light rays are travelling, they follow a straight direction along the propagation path, unless there is a change in the media. In this case, if there is a media with different refractive index, the light rays will be reflected, as illustrated in Figure 3.4.

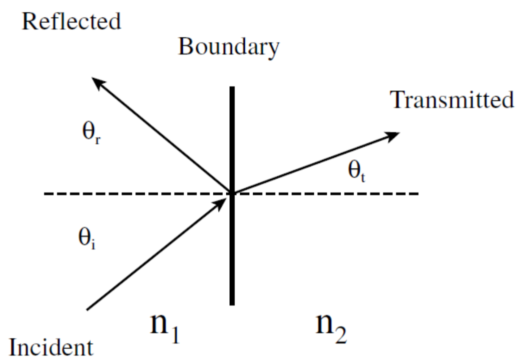

Figure 3.4 - Incident, reflected and transmitted light rays at the interface of two media with different refractive indices

The relation between the transmitted and incident angles is described by Snell's Law:

$$\frac{\sin\theta_t}{\sin\theta_i} = \frac{n_1}{n_2}$$ **Equation 21**

There are two important implications of Snell's Law:

- The transmitted beam is bent toward the normal direction when the incident light enters from a material with a lower refractive index into a material with a higher refractive index.
- The transmitted beam is bent away from the normal direction when the incident light enters from a material with a higher refractive index into a material with a lower refractive index.

Basic Design of Optical Lenses

A lens is made of some transparent material, usually glass, which refracts light rays in order to form an image. They can be seen as a series of tiny refractive prisms, where each one produces its own image, and all together create an image that can be focused at a single point.

Lenses can be characterized by their shape and the materials they are made. While the shape determines if the lens is converging or diverging, the constituting material has a refractive index that defines its refractive properties.

A converging lens, or convex, guides incoming light inward to the center axis of the beam path. That type of lenses are thicker in the middle and thinner at their upper and lower edges. They focus the incoming light rays to a point, called the focal point, which is separated from the lens at a distance called focal length. (Figure 3.5 and Figure 3.6)

A diverging lens, or concave, guides incoming light outward away from the axis of the beam path. These lenses are thinner in the middle and thicker at their upper and lower edges. (Figure 3.5 and Figure 3.6)

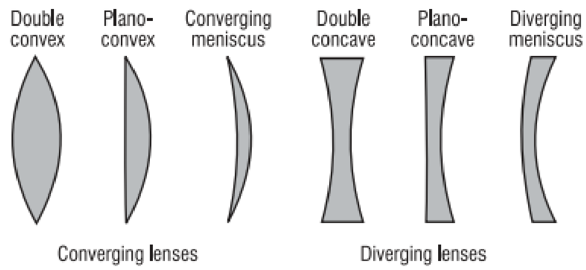

Figure 3.5 - Lenses shapes [19**]**

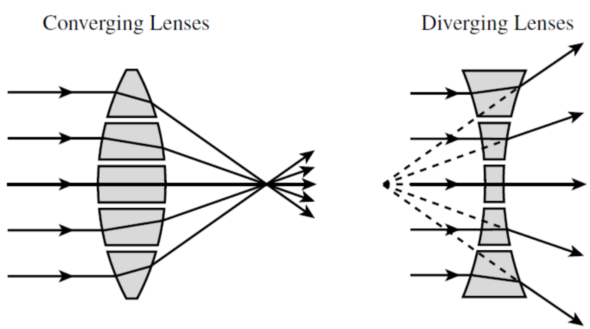

Figure 3.6 – Lenses focal points [**15**]

4 Simulation and Laboratory Results

4.1 Laboratory Results

4.1.1 GPON characterization

Before using GPON in the desired environment, a characterization of the system was made, to compare them with the standards.

The equipment used was an OLT and an ONU, a traffic generator (IXIA) and some optical components (as fiber cables, connectors,…). The IXIA traffic generator, in Figure 4.1, produces traffic with the desired characteristics and, with the IxNetwork software, which is remotely connected to the IXIA equipment, it is possible to configure traffic, ports, control the equipment and analyze results.

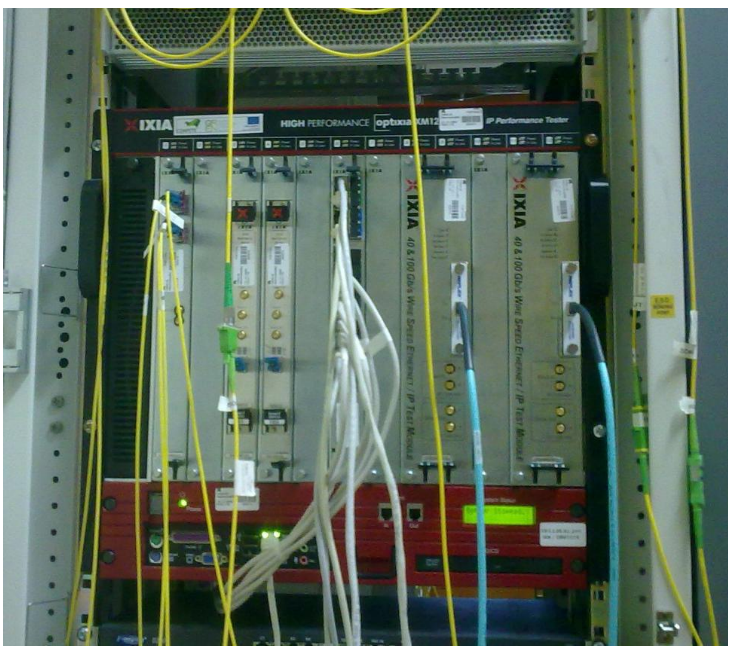

Figure 4.1 - IXIA Optixia XM12 equipment

When the traffic is applied, IXIA generates it and it goes through an Ethernet cable to the OLT. Then, it goes through the fiber cable until the respective ONU, which in turn transmits it back to IXIA.

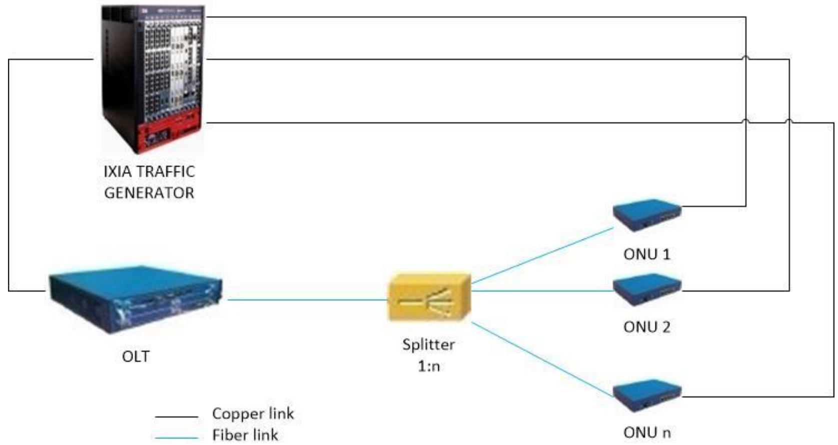

Figure 4.2 - GPON connection diagram (based on [20])

In order to analyze transmission results, the IxNetwork software presents, among other, the number of frames sent and received and the packet error rate, which is the percentage of packets received incorrectly relatively to the ones sent.

The GPON system consists on an OLT (OLT7-8CH), which can be seen in Figure 4.3 and whose characteristics are summarized in Table 4.1, and two ONUs (PTINONT7RF1GE), shown in Figure 4.4 and their characteristics in Table 4.2.

The GPON OLT has 8 PON slots, each one supporting 64 clients, and 8 Ethernet interfaces. The connection between the OLT and IXIA traffic generator is done in the first Ethernet port. The OLT also has 2 additional Ethernet interfaces and a RS232 port for equipment configuration.

Figure 4.3 – OLT GPON (OLT7-8CH)

As can be seen in Table 4.1, OLT transmit power is 3.6 dBm, its maximum receive power is -10 dBm and receive sensitivity is -31 dBm. It transmits at 2.5 Gbps and receives at 1.25 Gbps.

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

Table 4.1 - OLT characteristics

Figure 4.4 - ONU G-PON (ONT7RF1GE)

The two ONUs that exist in the laboratory are similar, but they exhibit different sensitivities: ONU 2 (which is the black one, in Figure 4.4) has -25 dBm, while ONU 1 (the white one in Figure 4.4) has -27 dBm. The maximum receive power for both ONUs is -8 dBm. The transmitter wavelength is 1310 nm, which corresponds to upstream traffic direction, and the receiver wavelength is 1490 nm, that is the downstream direction. They transmit at 1.25 Gbps and receive at 2.5 Gbps.

Manufacturer	PT Inovação
Model	PTINONT7RF1GE
Transmitter wavelength	1310 nm
Receiver wavelength	1490 nm
Transmit power (MGPON datasheet)	+1 to +6 dBm
Maximum receive power (MGPON datasheet)	-8 dBm
Receive sensitivity (MGPON datasheet)	-27 dBm
Transmit rate	1.25 Gbps
Receive rate	2.5 Gbps
Connector type	SC-APC
Power supply	DC +12 V
Working temperature	-5 to +85 ºC

Table 4.2 - ONU characteristics

In order to characterize the system, some tests were done, using the setup in Figure 4.5. The error correction is turned off.

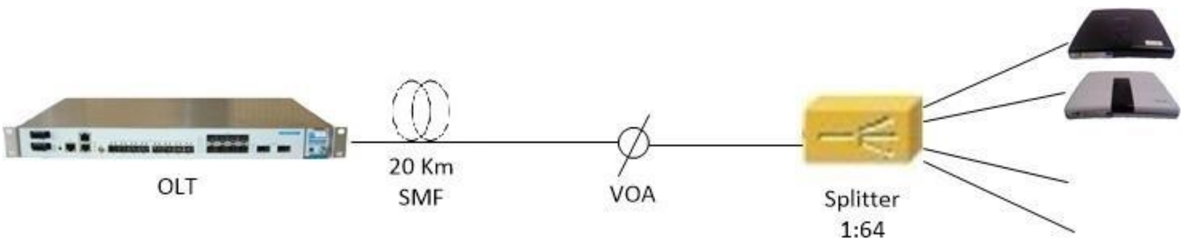

Figure 4.5 - GPON characterization setup

ONU maximum rate

The aim of the first test was to understand the maximum transmission rate of the system. Knowing this, it is possible to choose the transmission rate, depending on the requirements of the network (low error rate or maximum speed). Theoretically, OLT can transmit a maximum rate of 2.5 Gbps and receive 1.25 Gbps, as can be seen in Table 4.1, and each ONU can receive 2.5 Gbps and transmit 1.25 Gbps, accordingly to Table 4.2. However, since the IXIA card used only allows 1 Gbps, it was impossible to reach those values. So, the maximum rate will be 1 Gbps, both for downstream and upstream.

To obtain the practical value for the maximum rate of the system, packet loss percentages were obtained for different values of frame rates, using the setup of Figure 4.5, but first only with one ONU (ONU 1, and then ONU 2), and only then with the two ONUs simultaneously, as in the figure. The power at the output of the splitter was -25 dBm.

The traffic generated by IXIA, and configured by IxNetwork, had 1000000 packets, and the maximum rate that the software allowed was 976 Mbps.

Figure 4.6 shows the results when using only ONU 1, Figure 4.7 only ONU 2 and in Figure 4.8 are the results when using both at same time.

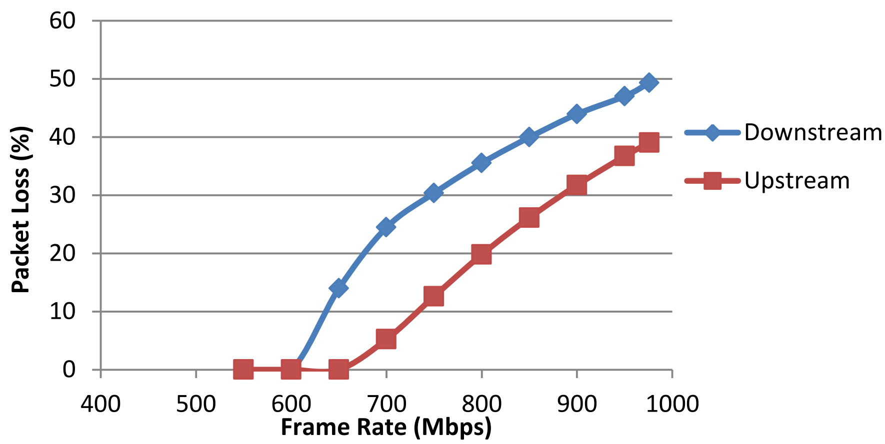

Figure 4.6 - ONU 1 maximum rate

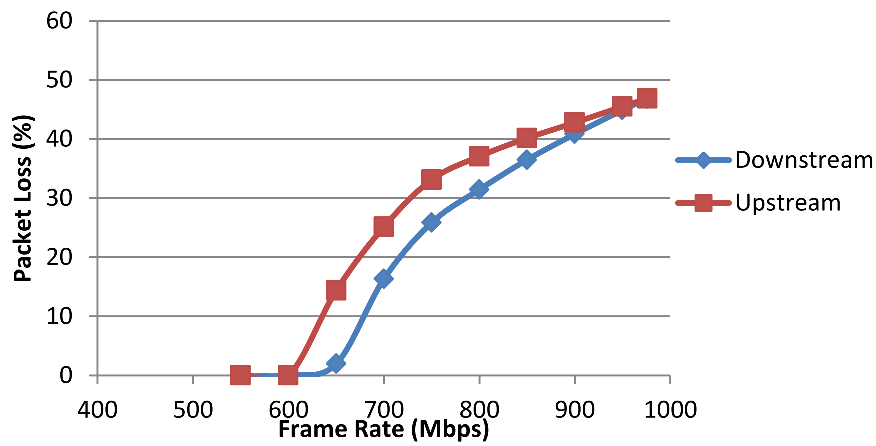

Figure 4.7 – ONU 2 maximum rate

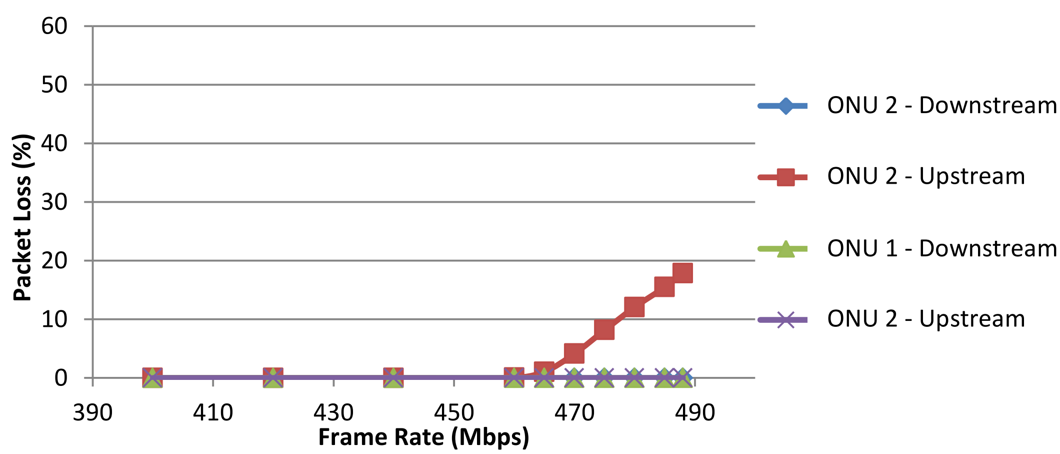

Figure 4.8 - Two ONUs maximum rate

The results obtained show that, when there is only one ONU connected, there are no losses until 600 Mbps, for both ONUs. But even for the maximum transmission rate, the packet loss is always less than 50%.

When the two ONUs are connected, the maximum rate for each one is half than in the previous situation. That means that the maximum transmission rate for each ONU is 488 Mbps. As can be seen in Figure 4.8, the packet loss is always 0%, except for the upstream direction in ONU 2, which starts to increase from 470 Mbps, and reaches the maximum (488 Mbps) with a packet loss of 17,8%.

Maximum Power budget

In order to find out how much power budget the system tolerates, the packet loss for several values of attenuation was obtained. To do that, the VOA (Variable Optical Attenuator) was used to vary the attenuation in the network. The setup in Figure 4.5 was tested, with a fixed frame rate of 400 Mbps and 1000000 packets. The results for each ONU are presented in Figure 4.9 and Figure 4.10.

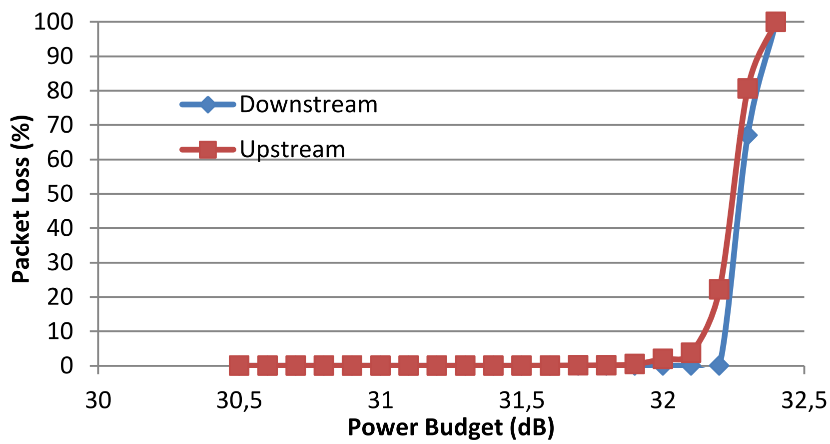

Figure 4.9 - ONU 1 maximum power budget

For ONU 1, the maximum power budget is 32.2 dB for downstream and 32 dB for upstream. So, a maximum budget of 32 dB is considered to allow the transmission in both directions.

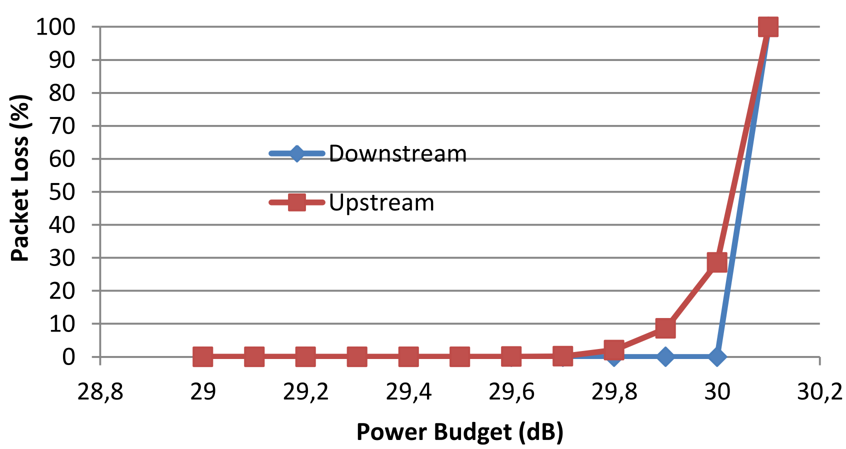

Figure 4.10 - ONU 2 maximum power budget

For the ONU 2, the limit of the power budget is 30 dB for downstream, and 29,8 dB for upstream. Thus, we shall use less than 29,8 dB.

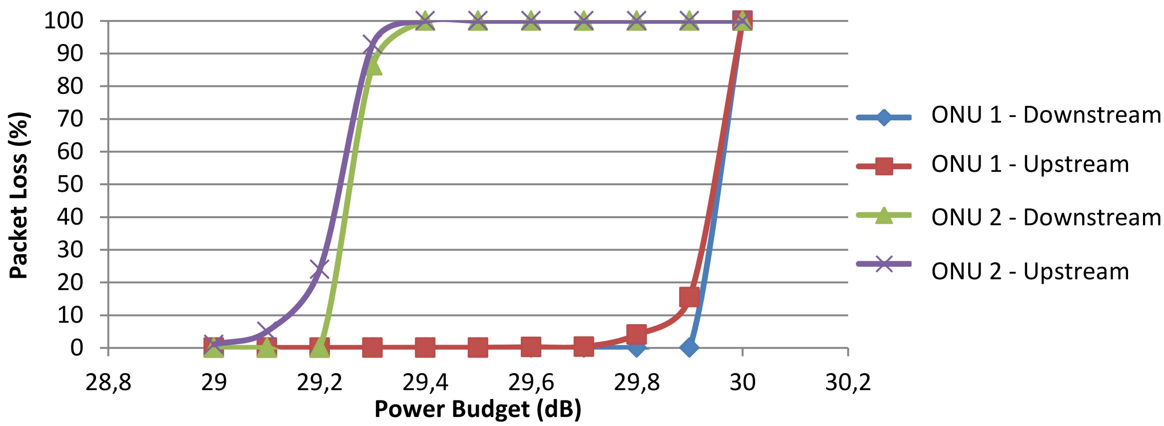

Figure 4.11 - Two ONUs maximum power budget

When the two ONUs are connected, the maximum power budget that ONU 1 supports is 29,2 dB, while ONU 2 allows 30 dB, both for upstream and downstream, as can be seen in Figure 4.11. The maximum value that allows error free transmission in any ONU is 29 dB.

4.1.2 Extender Box characterization

The Extender Box that exists in the laboratory is shown in Figure 4.12.

Figure 4.12 - Extender Box

This Extender Box includes three amplifiers, one for downstream, one for upstream and another for video. The downstream amplifier is SOA CIP SOA-S-OEC-1550 and the upstream is Alphion SOA29p. The bias current of the downstream amplifier is 145 mA, and the upstream is 445 mA. These are the current values that produce the maximum gain and minimum noise figure. [**21**] [**22**]

With the purpose of characterizing the Extender Box, some tests were performed. The first one shows measured the gain saturation of the amplifier with input power. Then, we tested several values for the bias current, and again analyzed how the amplifier gain responds.

To perform these tests, the setup in Figure 4.13 was used for downstream. In the case of upstream, it was impossible to use that setup, because the transmission is done in burst mode, and not in continuous mode as in downstream, so an external laser was used with the same wavelength used for GPON upstream (1310 nm), as seen in Figure 4.14. The bias current of the laser was 73 mA and the output power 3 dBm.

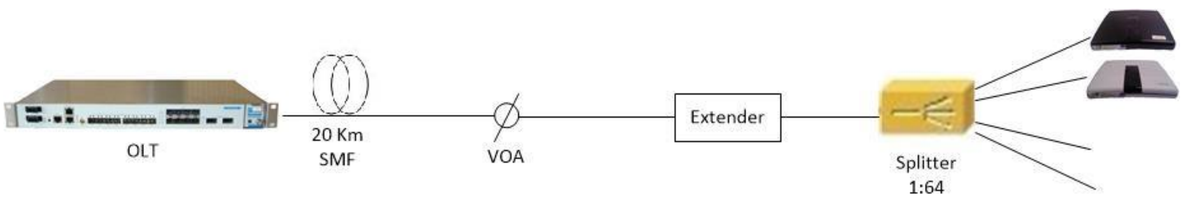

Figure 4.13 - GPON with Extender Box setup

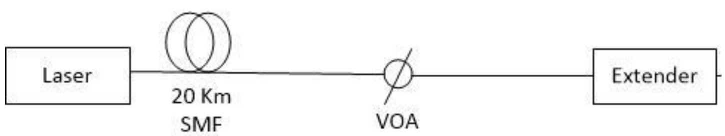

Figure 4.14 - Setup for test Extender Box upstream

Amplifier gain as function of the input power

To implement this test, the setups described before were used: Figure 4.13 for downstream and Figure 4.14 for upstream. In the case of downstream, the bias current set in the amplifier was 145 mA, and the results are displayed in Figure 4.15.

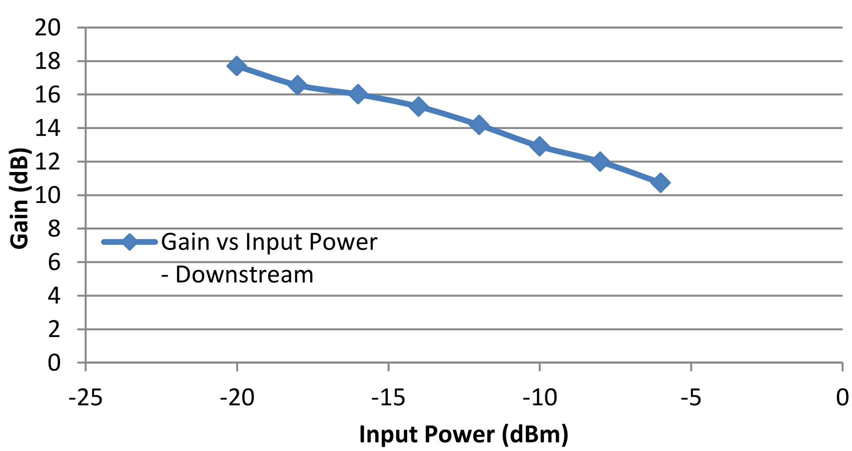

Figure 4.15 - Gain vs Input Power in downstream

As can be seen in Figure 4.15, the gain of the downstream amplifier can vary between 10.7 dB and 17.7 dB, depending on the input power (-6 dBm to -20 dBm, respectively). We observe that the amplifier is saturated and the gain decreases when the input power increases.

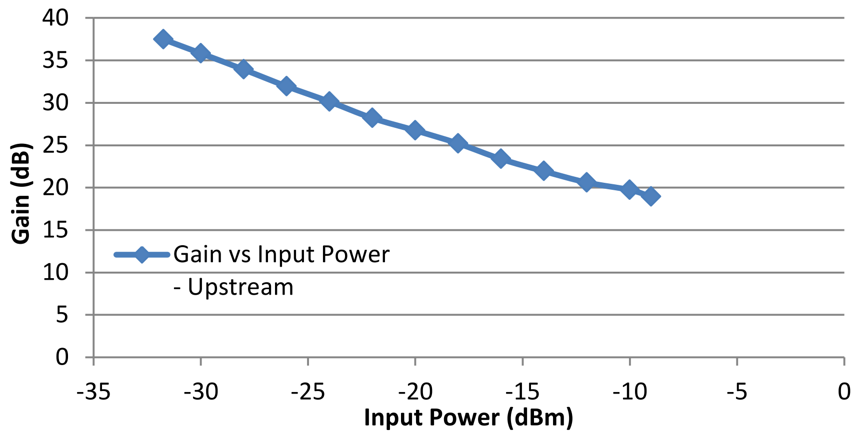

Figure 4.16 - Gain vs Input Power in Upstream

In upstream, it is possible to confirm in Figure 4.16 that the gain varies from 18.9 dB to 37.5 dB, for input powers from -9 dBm to -31.8 dBm. We observed the same behavior as in the previous case.

With this study it is possible to conclude that the highest gain is verified when the input power is lower, but the highest output power of the Extender happens for the highest input power values, even if the gain is smaller. This is valid both for downstream and upstream.

Amplifier gain as function of the bias current

In this experiment, the input power was fixed to one value that allowed a higher gain, and tested several values of bias current.

For downstream, the input power was -18 dBm. The results are shown in Figure 4.17.

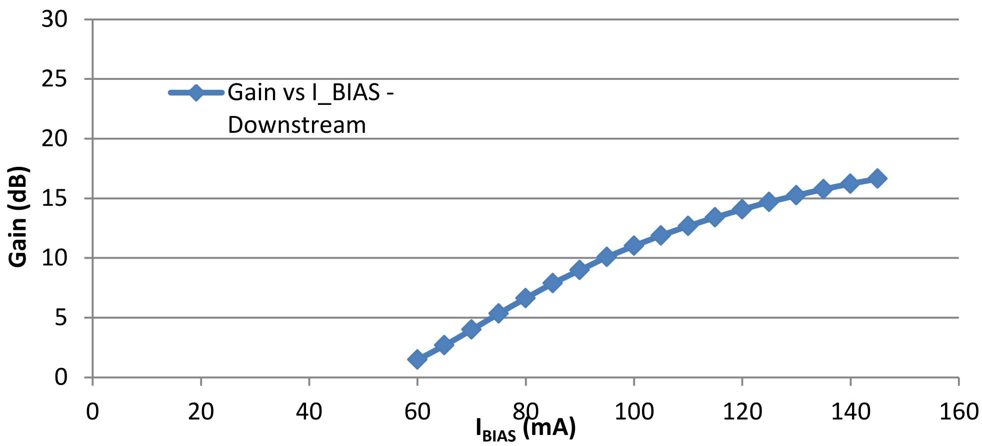

Figure 4.17 – Gain vs Bias Current in Downstream

As can be verified in Figure 4.17, for the referred input power the gain increases from 1.5 dB to 16.6 dB, as the bias current varies from 60 mA to 145 mA, respectively.

In the upstream situation, the input power was -20 dBm. Results are presented in Figure 4.18.

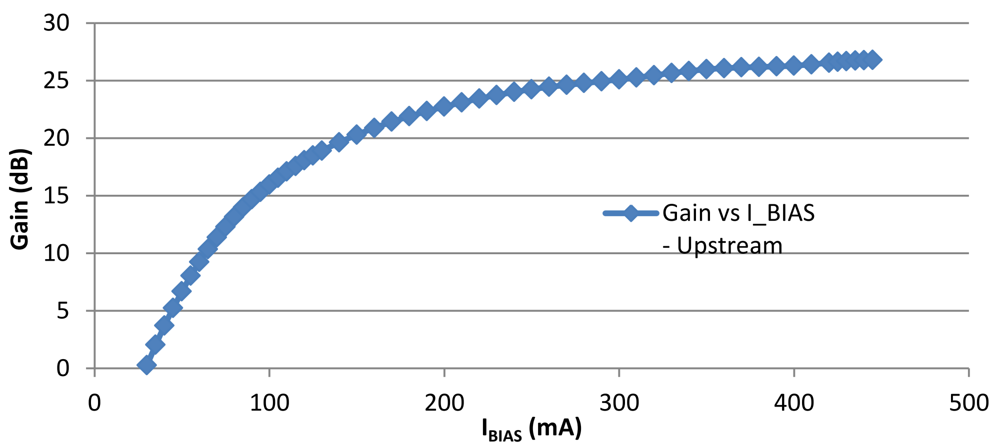

Figure 4.18 - Gain vs Bias Current in Upstream

In this case, the gain increases rapidly for currents higher than 30 mA, and then we observe the gain saturation. At 445 mA, we get a gain of approximately 27 dB.

Both for upstream and downstream, the maximum gain occurs for the highest bias current.

4.1.3 GPON and Video over FSO

Now is achieved the main purpose of this work: test all of these technologies through a FSO link. To be able to do this, it is essential to align the system previously. All of this work is done by hand; first the transmitter (which is a collimator) and the receiver are placed more or less in the same direction, and also the lenses in the middle. In this case, two converging lenses were used in order to focus the beam. Then is connected a red laser, with a visible wavelength, in order to align the system. But, as the equipment is wavelength sensitive, the alignment done with the red laser will not work in the infra-red. So, after connecting the infra-red laser, it is essential to perform a final alignment. But this time this is a little harder, because the human eye cannot see infra-red wavelengths, so an infrared sensor has to be used that, when placed in the line of sight, allows us to see the spot corresponding to the beam.

The last step of the alignment is to try to minimize the losses, using the micrometer screws in the receiver. With these screws is possible to change the height, width or angle of reception. The optical power is being monitored after the receiver, in order to know when it reaches the maximum value.

After this procedure, the best that was achieved was a link of 2.29 m with two lenses, and with a power budget of 12.7 dB. The link is presented in Figure 4.19.

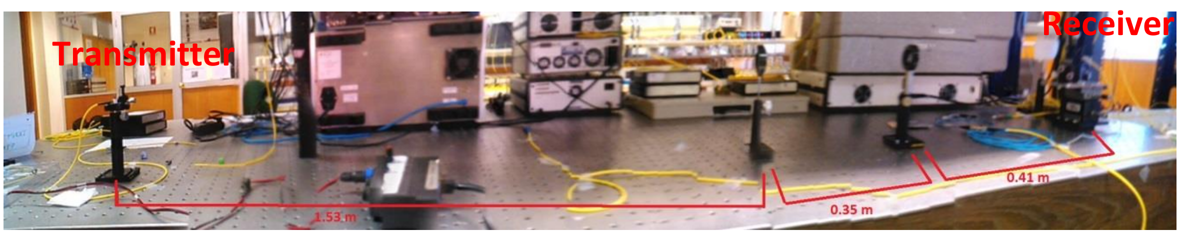

Figure 4.19 - FSO link

The interface between GPON system and FSO is direct: the light in the fiber is send through the transmitter, which is only a collimator. There are no electrical to optical conversions.

It is important to mention that these tests were performed in a laboratory environment, so the weather conditions were very favorable to the transmission.

In order to perform the tests, 5 different setups were considered: 3 of them with the objective of test the GPON signal, and other 2 to test also a video signal.

Setup 1 (GPON)

To test the GPON technology over a FSO section, 3 setups were tested. The first one, in Figure 4.20, was simply the OLT transmitting to one ONU in back-to-back, over FSO.

Figure 4.20 - GPON over FSO - setup 1

With this setup mounted, the packet loss percentages were measured for several frame rates. The results are in Figure 4.21 and Figure 4.22, for ONU 1 and ONU 2, respectively.

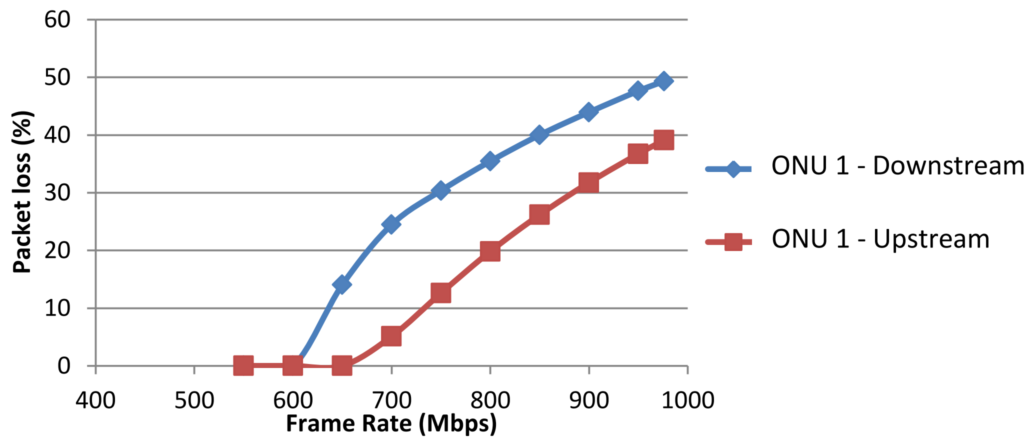

Figure 4.21 – Results for the setup 1 with ONU 1

As can be seen in Figure 4.21, ONU 1 starts to have some losses at 650 Mbps for downstream and 700 Mbps for upstream, but even for the maximum rate, the losses are always less than 50%. These results coincide with the ones without FSO, done in GPON characterization (see Figure 4.6).

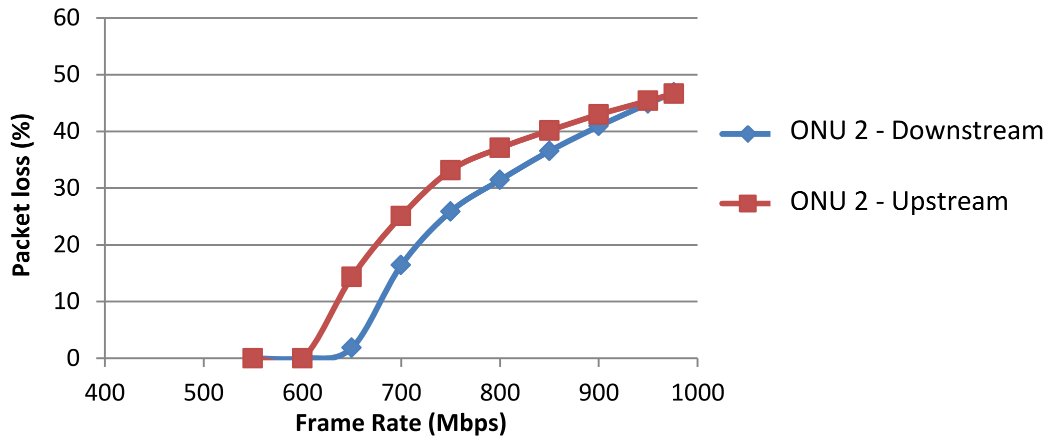

Figure 4.22 - Results for the setup 1 with the ONU 2

In Figure 4.22 is perceptible that ONU 2 presents losses from 700 Mbps for downstream and 650 Mbps for upstream, and, equally to ONU 1, the losses are always less than 50%. Again, the results are similar with the ones without FSO (see Figure 4.7).

Both the ONU 1 and ONU 2 presented results in accordance with the ones when there was no FSO link. It lead us to conclude that the FSO link didn't degrade the quality of the signal.

Setup 2 (GPON)

Then, it was tested a setup with only a FSO section and a 1:32 splitter, with the ONUs connected to it.

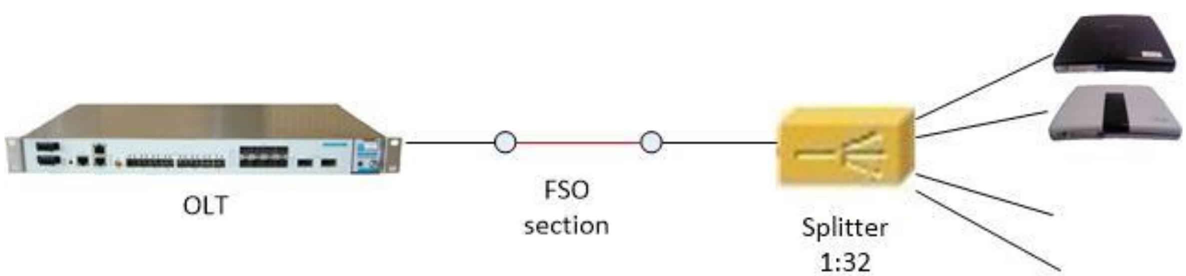

Figure 4.23 - GPON over FSO - setup 2

After the setup was mounted, it was tested only one ONU at a time, ONU 1 and then ONU 2, and then those two simultaneously. The results for each situation are shown next.

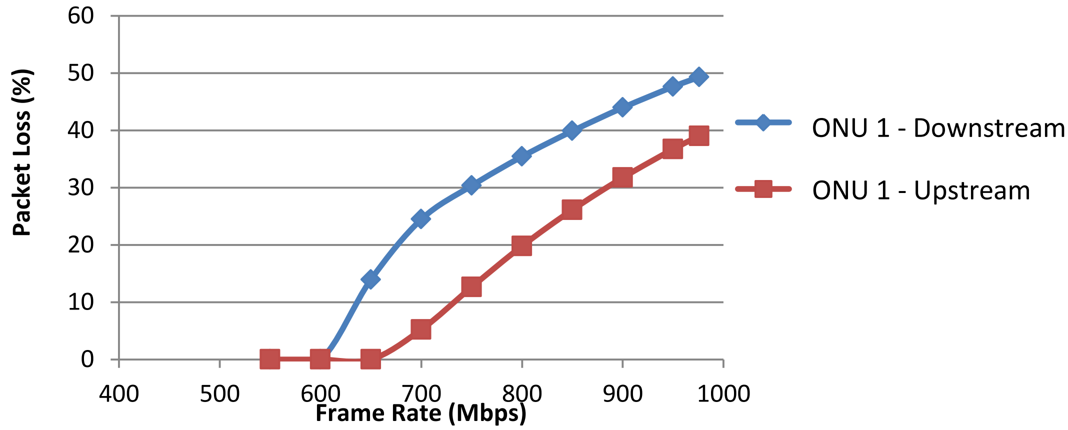

Figure 4.24 - Results for the setup 2 with ONU 1

ONU 1 presented losses from 650 Mbps in downstream and 750 Mbps in upstream, as noticeable in Figure 4.24.

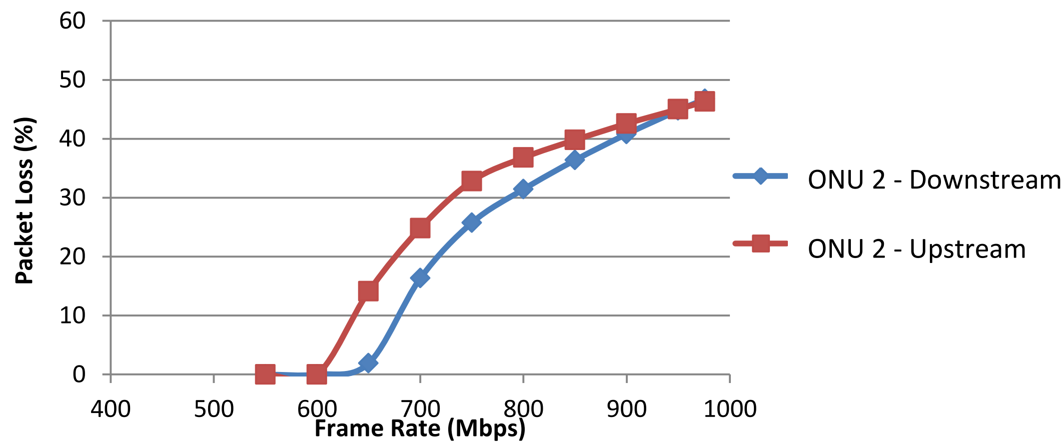

Figure 4.25 - Results for the setup 2 with ONU 2

ONU 2, as can be seen on Figure 4.25, started to have losses in downstream since 700 Mbps and in upstream since 650 Mbps.

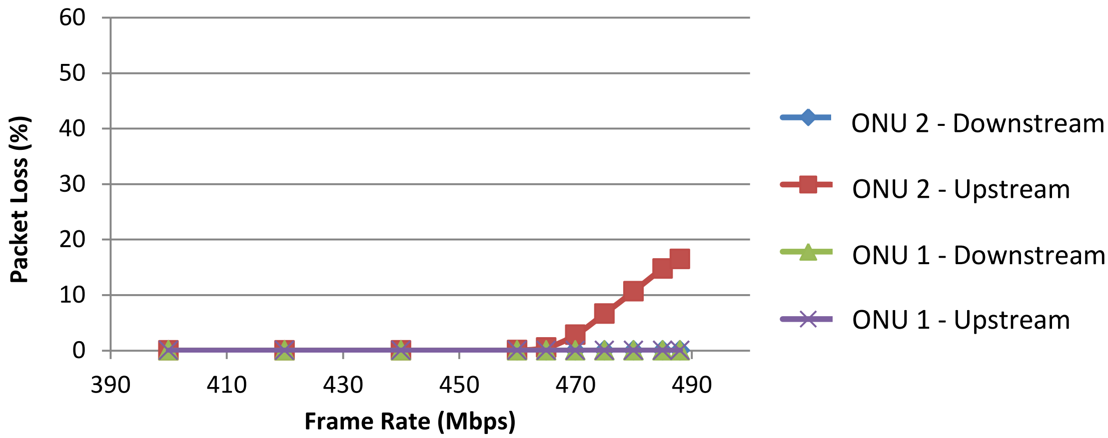

Figure 4.26 - Results for the setup 2 with two ONUs

The results for the two ONUs connected simultaneously are displayed in Figure 4.26, where is possible to see that the only losses happened in ONU 2 and just in upstream, since 480 Mbps.

In the same way as before, the results are equal whether we use the FSO section or not, both for one ONU at a time as for the two ONUs simultaneously.

Setup 3 (GPON)

Finally, the last setup was composed by 20 Km of fiber, a FSO section, the Extender Box, a 1:64 splitter and two ONUs, as depicted in Figure 4.27.

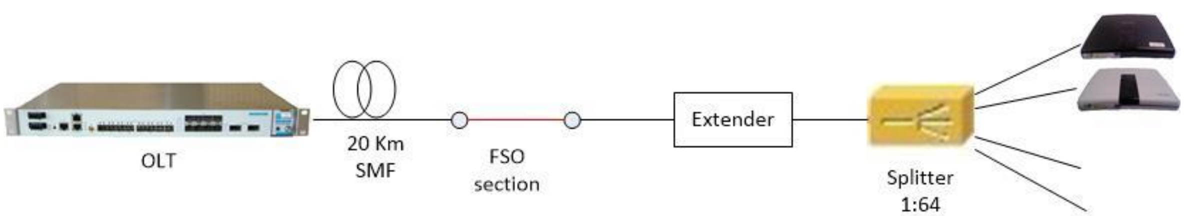

Figure 4.27 - GPON over FSO - setup 3

Once more, the tests performed were the same: first with only one ONU at a time, and then with the two ONUs at the same time.

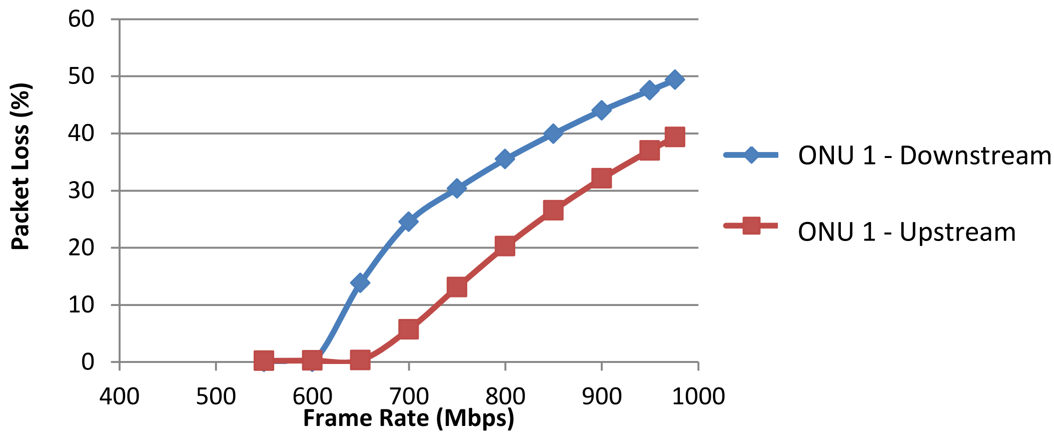

Figure 4.28 - Results for the setup 3 with ONU 1

ONU 1 didn’t present losses in downstream until 650 Mbps and in upstream until 750 Mbps. After those values it started to present losses, once again less than 50%.

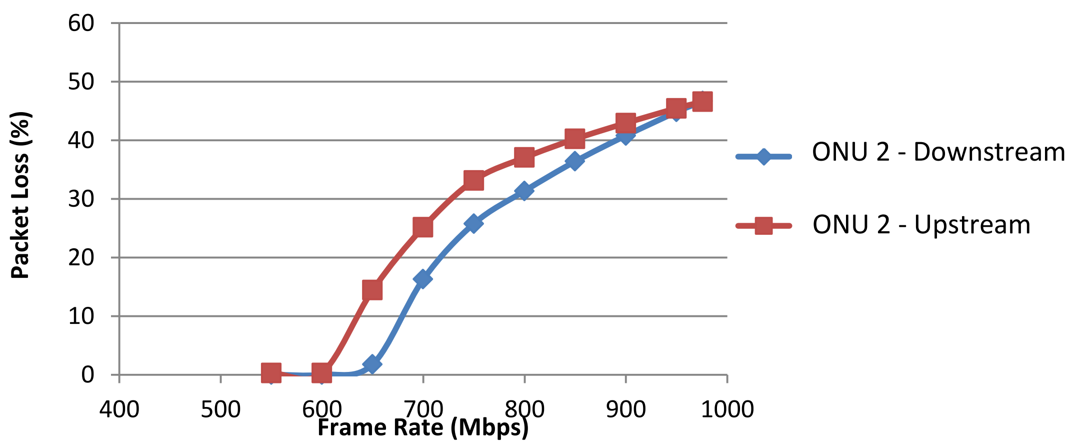

Figure 4.29 - Results for the setup 2 with ONU 2

For ONU 2, began to occur losses from 700 Mbps in downstream and 650 Mbps in upstream.

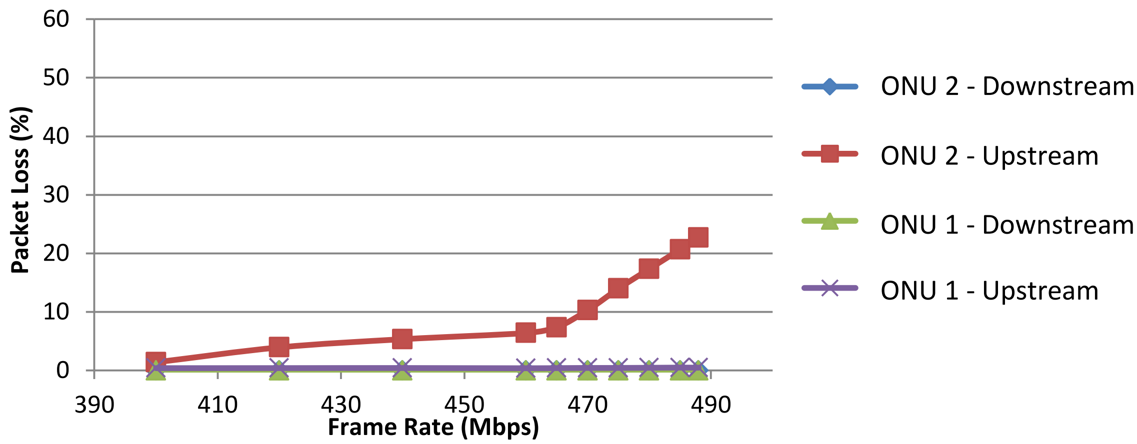

Figure 4.30 - Results for the setup 3 with two ONUs

When the two ONUs were connected at the same time, there were no losses, except for the ONU 2 in upstream, that started to lose some packets since 470 Mbps.

Also in this setup, the results shown that there are no difference, in terms of signal quality, between the setups with or without FSO link. The transmission of GPON in a network with a FSO section is possible, in cases of clean weather.

So, for the three setups, the results were almost the same as the ones did before to characterize the system, without FSO. The results observed allow us to conclude that for the FSO link considered, there were not any additional effects introduced, affecting the quality of the GPON signals, except for the additional losses, that could be compensated using amplification, what would be expected because the conditions are ideal and the distance is short.

Setups 4 and 5 (Video)

In this section, a video signal over a FSO link was tested. The video signal was DVB-C, the frequency band is between 50 MHz and 900 MHz and the modulation format is 256 QAM.

To include the video signal, it was necessary to use two triplexers. The first one divides the GPON downstream and upstream wavelengths, 1490 and 1310 nm, respectively, and the second one combines these two signals with the video, which is transmitted at 1550 nm. Three setups were tested. First, only the video signal with GPON, but without FSO, was tested, as can be seen in Figure 4.31. Then, setup 4, presented in Figure 4.32, has only a FSO section and a VOA to control the received power. Setup 5, characterized in Figure 4.33, is similar to setup 4 but also has a 20 Km fiber section.

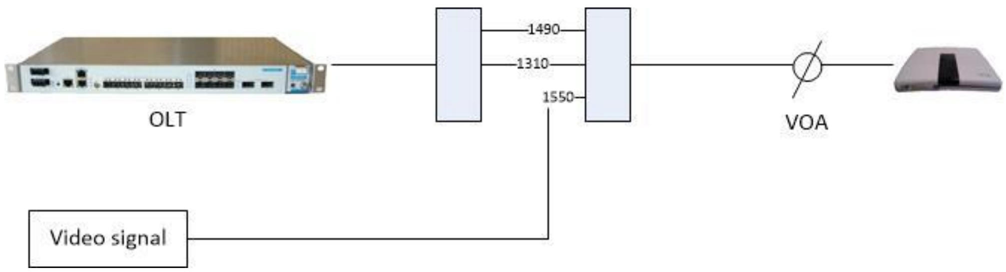

Figure 4.31 - Video setup

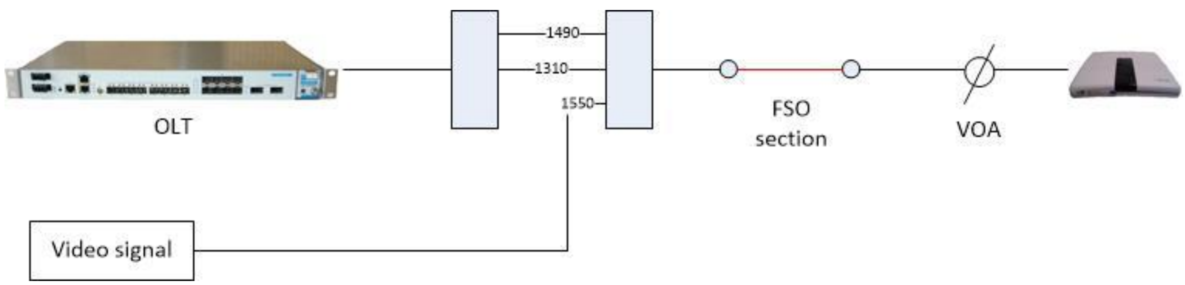

Figure 4.32 - Video over FSO - setup 4

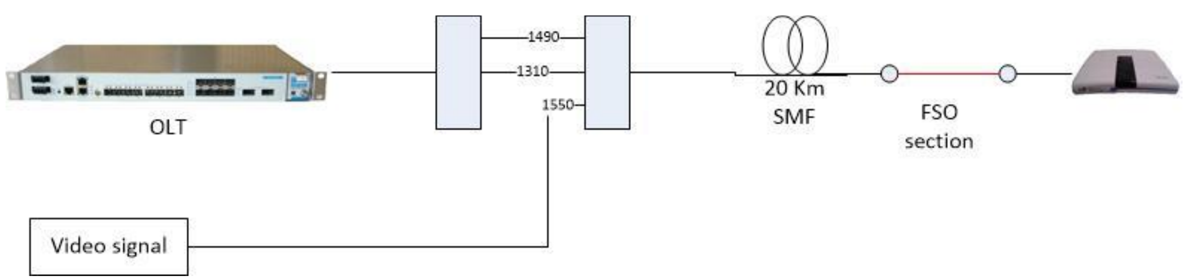

Figure 4.33 - Video over FSO - setup 5

Only ONU 1 was used, and the spectrum of the signal was obtained, in order to measure the CNR of the video signal. The results obtained for each setup were the following:

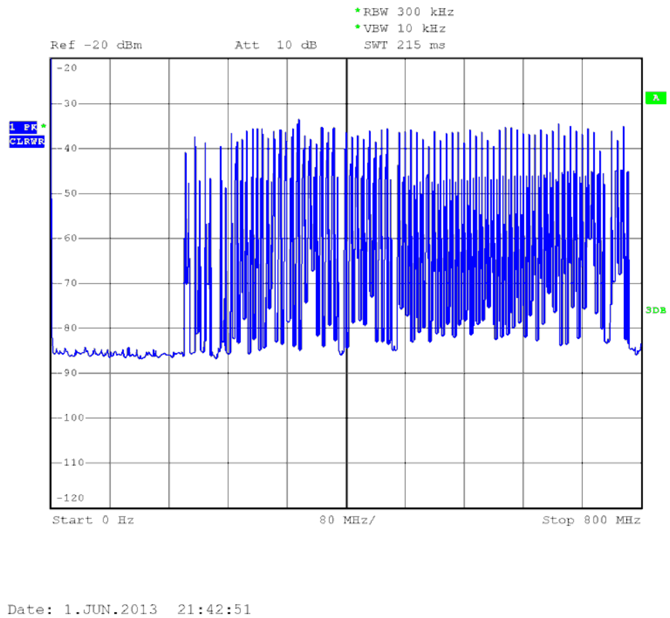

Figure 4.34 - Spectrum of video signal, without FSO

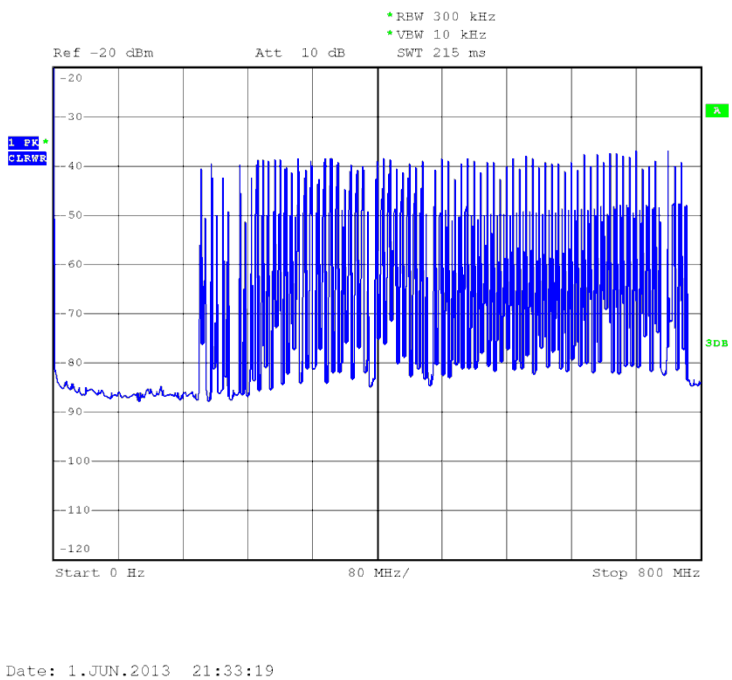

Figure 4.35 - Spectrum of video signal, for the setup 4

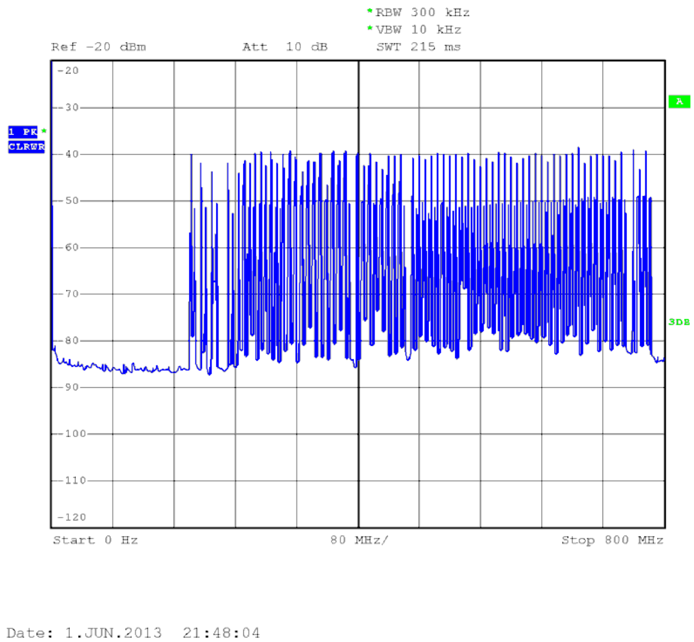

Figure 4.36 - Spectrum of video signal, for the setup 5

In Figure 4.34 is possible to see that the CNR of the video signal is about 50 dB. In Figure 4.35 and in Figure 4.36 is visible that the CNR is about 45 dB. So, it is possible to conclude that the video lost some quality when was tested in setups with a FSO segment, but it is still substantially above the limit of 34 dB of the standard. It was an expected result because it has already been verified that the GPON signal performance were unaltered, and it was expected that it would happen also for video.

4.2 Simulation Results

The laboratory results shown several setups with a 2,29 meter FSO link. In practice, a link of this length is not very profitable, usually longer links are used in the field. Another key difference is the climatic conditions: an outside link is exposed to all types of weather, which, as has been seen previously, deeply affects the signal. Due to lack of time and appropriate equipment, it was not possible to test an outside link; to do that, it would be necessary a more stable transmitter and maybe a better receiver, because the link had many losses and it is possible that it is due to the receiver aperture. Still, it is important to observe the influence of weather in the performance of the link, which has been done by simulation and is presented below.

4.2.1 FSO Modules

To simulate the FSO setup it was used a commercial photonic simulator named VPI, from Virtual Photonics TM. The modules used were FS_Scintillation and FS_ScintillationS. Those modules assume that the Gaussian beam from the transmitter is colimated and considers a Kolmogorov spectral model.

FS_Scintillation is a module that calculates the scintillation index, scintillation fluctuation and attenuation due to scintillation. To do this, it describes the mathematic expressions of those variables, using Python TM Programming Language, and generates noise with those characteristics. This module uses the parameter wind speed to drive the frequency of scintillation events. The strength of scintillation is ruled by the atmospheric structure constant, C_n^2.

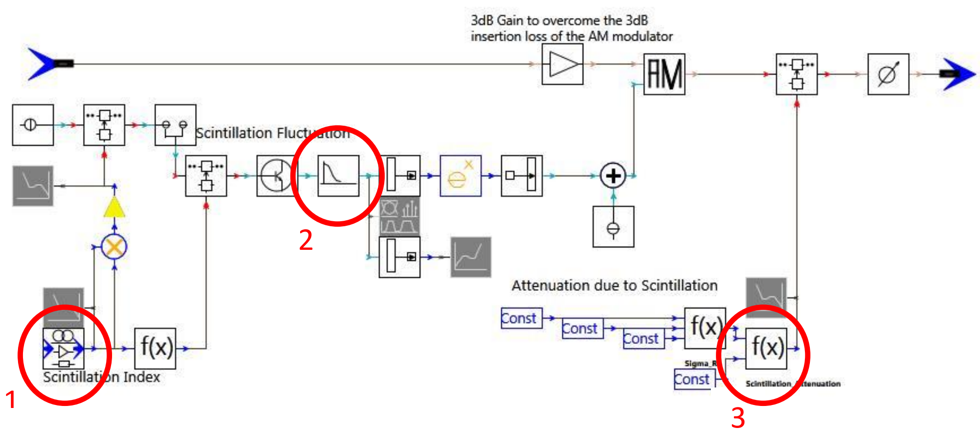

Figure 4.37 - VPI Module - FS_Scintillation

The input parameters that must be entered and the respective pre-defined values are the following:

Length	2000 m
CNsquared	7e-12
Wavelength	1.55e-6 m
LaunchWaist	2e-2 m
ReceiverApertureDia	10e-2 m
WindSpeed	10 m/s
ScintillationSpectralWidth	50 Hz

Table 4.3 - Input parameters of FS_Scintillation

The scintillation index is calculated in the module identified with the number 1 in Figure 4.37, which describes the Equation 14.

The number 2 in Figure 4.37 is a band pass filter, with a bandwidth equal to the parameter ScintillationSpectralWidth, and the center frequency is the following:

$$! \text{"}expr\ \{WindSpeed\}/sqrt(\{Length\} * \{Wavelength\}/(2 * \{PI\}))$$

To obtain the attenuation due to scintillation, in dB, which is described in Equation 19, the module indicated with the number 3 in Figure 4.37 is used.

FS_ScintillationS is similar to FS_Scintillation because calculates the scintillation index, scintillation fluctuation and attenuation due to scintillation, but it does not take into account the wind speed.

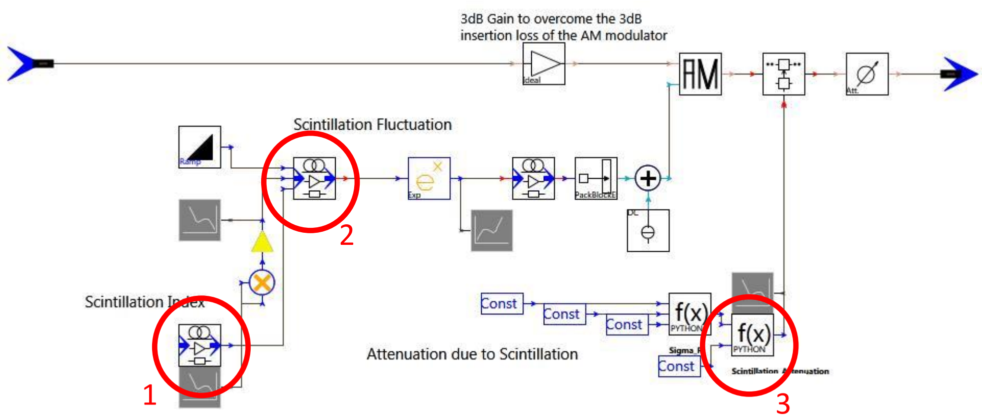

Figure 4.38 - VPI Module - FS_ScintillationS

The input parameters necessary for this module and its respective pre-defined values are the following:

Length	2000 m
CNsquared	7e-12
Wavelength	1.55e-6 m
LaunchWaist	2e-2 m
ReceiverApertureDia	10e-2 m

Table 4.4 - Input parameters of FS_ScintillationS

The numbers 1 and 3 in Figure 4.38 are the same as the ones in Figure 4.37, they also calculate the scintillation index (1) and the attenuation due to scintillation (3). Number 2, in Figure 4.38, represent a Gaussian noise generator.

4.2.2 Results

In order to understand how the performance of the FSO link changes with the scintillation, a link using the module FS_Scintillation was simulated, with a NRZ signal of 10 Gbps. The setup can be seen in Figure 4.39.

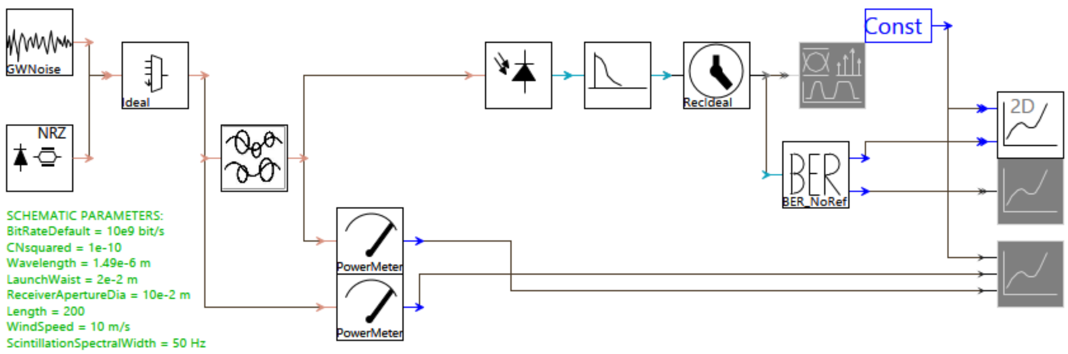

Figure 4.39 - Simulation setup

The NRZ signal used had a bit rate of 10 Gbps and the wavelength used was 1490 nm. The receiver aperture diameter, which was a parameter of the scintillation module, was 10 cm, the wind speed 10 m/s and the scintillation spectral width 50 Hz. Length and C_n^2 were swept in order to see how the losses in FSO link and BER values change. Several measures were taken, which are shown below.

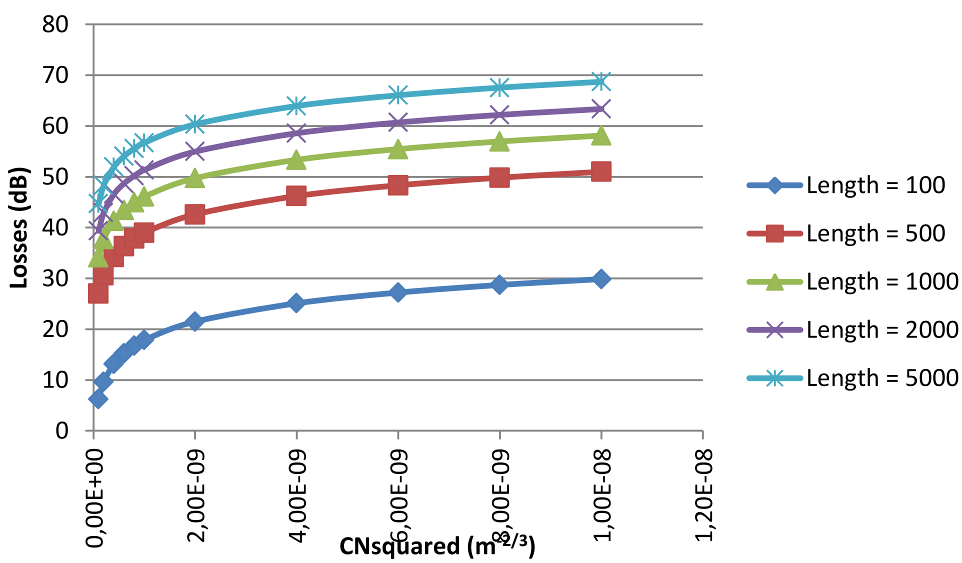

Figure 4.40 - Variation of the losses with the CNsquared

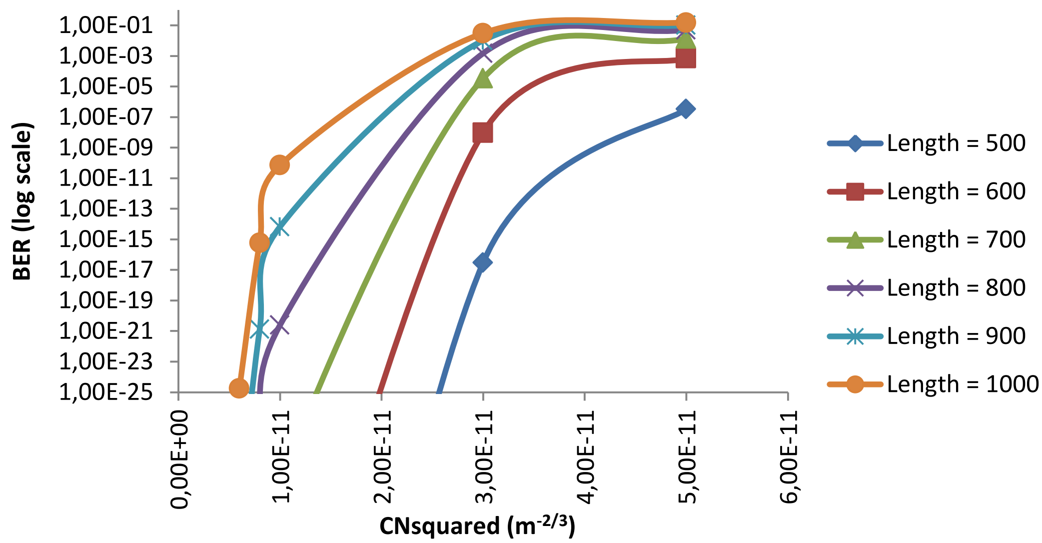

Figure 4.41 - BER variation with the CNsquared

In Figure 4.40 and Figure 4.41 it is visible that the losses and BER increase with the C_n^2. In the case of BER, it is low for lower values of C_n^2, but when it increases, there is a large increase in the BER value.

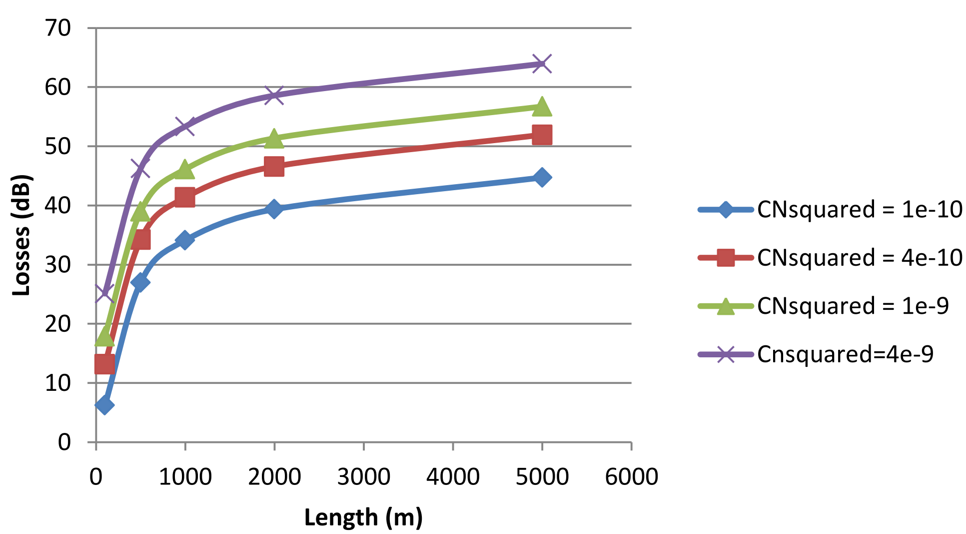

Figure 4.42 - Variation of the losses with the length

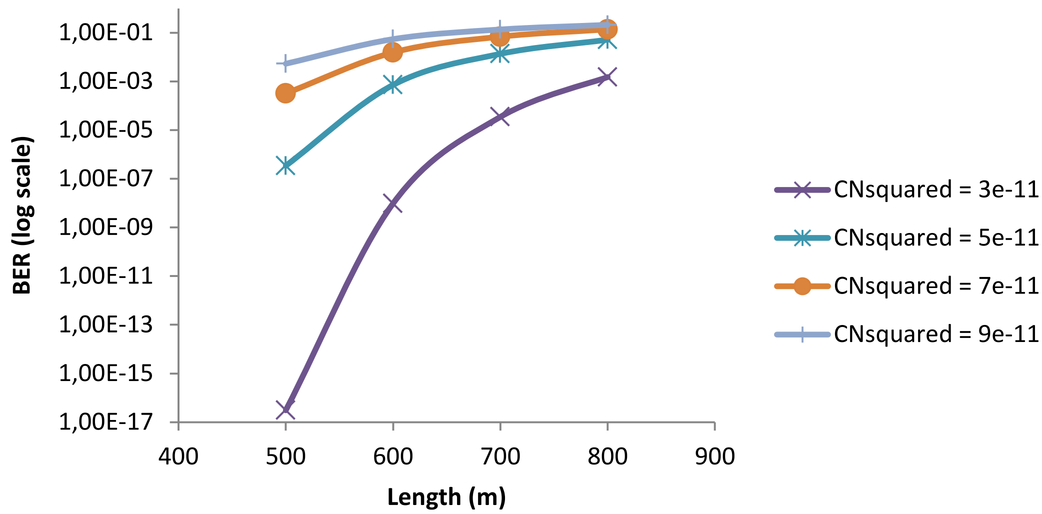

Figure 4.43 - BER variation with the length

Figure 4.42 and Figure 4.43 shown that losses increase with the length, but the BER value remains more or less the same when the C_n^2 have small values; since a certain value, BER increases significantly. It means that, for favorable weather conditions, BER value doesn't have many changes, but, if the atmosphere is turbulent, it only works for smaller link lengths.

It is important to refer that all the BER values were estimated by Gaussian analysis method.

5 Conclusions and Future Work

5.1 Conclusions

This document has been structured in a set of six chapters. The first one has the context and motivation, objectives, structure and contributions.

The second chapter is a study of the optical networks, where are presented the architectures used, its characteristics and the standards for communication. Also in this chapter are presented the video emission techniques: cable, satellite and terrestrial. It presents the main features of each one.

The chapter number three is a description of the free space optics systems. Here explains the influence of atmospheric effects in the optical beam. It also has a study about FSO systems and its components.

In the fourth chapter are presented the laboratory and simulation results. In laboratory results, comparing the setups with and without FSO section, it was possible to conclude that there are no substantial differences in terms of packet losses and CNR of video signal. So, the only weakness of indoor FSO systems is the attenuation, because the results were very satisfactory. In this tests was not included the effects of atmospheric conditions, because it was executed indoor.

About the simulations, they included the effects of turbulence in the losses and in the BER, as well as the effects of the increase of link length. For a 10 Gbps NRZ signal it was possible to conclude that, in small distances, FSO have a good performance, even in adverse weather conditions. For larger distances but with good weather conditions, BER values keep low, so the link keeps the good performance. With the increase of turbulence, BER increases a lot, for any distance. So, the factor that most affects the FSO link is the turbulence, and distance by itself only increases the losses, and not BER.

5.2 Future Work

This dissertation uses GPON and video over FSO. In the future, it would be interesting to use signals with other type of modulation format over the same medium.

Another interesting thing to do would be a practical test of a longer FSO link; in the laboratory, the conditions only allowed for a 2,29 m link, but it would be great to do it outside and maybe link two buidings, because atmospheric conditions have a big impact in this type of communication, and also because it would be interesting to observe if the increase of length doesn’t really increase BER.

To improve the SNR and reduce scintillation index it is possible to use an array of detectors [**23**], which would be also an interesting subject to analyze.

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