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Departamento de Electrónica, Telecomunicações e Informática (DETI)

Bárbara Salomé Ribeiro de Almeida

Redes ópticas passivas avançadas e de cobertura estendida

Advanced passive optical networks and of extended coverage

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

Dedico este trabalho ao meu irmão Bernardo e aos meus pais Dina e Manuel.

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palavras-chave

Redes Ópticas Passivas, GPON, EPON, Reach Extension.

resumo

A grande procura por largura de banda acompanhada pelas preocupações económicas tornaram as Redes Ópticas Passivas o foco das operadoras de telecomunicações. A intensificação dos trabalhos nesta área levou à criação de vários standards e intensificou a investigação na área.

Ao longo deste trabalho os requisitos definidos na norma EPON e GPON foram analisados bem como algumas das futuras alternativas. Seguiu-se a caracterização dos sistemas EPON e GPON existentes no laboratório. Finalmente um protótipo para um Reach Extender previamente desenvolvido é analisado e testado tendo em vista provar o seu funcionamento com tráfego GPON.

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keywords

Passive Optical Networks, GPON, EPON, Reach Extension.

abstract

The high demand for bandwidth accompanied by economic worries has made the passive optical networks the focus of telecommunication operators. The intensification of works on this area has led to the creation of several standards and intensified the researches.

Throughout the work, the requirements defined in the standard EPON and GPON are analyzed as well as future alternatives. Later, EPON and GPON systems are characterized, and finally a prototype previously developed is adjusted, analyzed and tested in order to prove its operation in GPON.

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List of Acronyms

AWG	Arrayed Wavelength Grating
APD	Avalanche Photodiode
APON	Asynchronous Passive Optical Network
ATM	Asynchronous Transfer Mode
ASK	Amplitude Shift Keying
BPON	Broadband Passive Optical Network
CAPEX	Capital Expenditure
CD	Chromatic Dispersion
CO	Central Office
CWDM	Course Wavelength Division Multiplexing
DBA	Dynamic Bandwidth Allocation
DD	Direct Detection
DWDM	Dense Wavelength Division Multiplexing
EAM	Electroabsorption Modulator
EDF	Erbium Doped Fiber
EDFA	Erbium Doped Fiber Amplifier
EPON	Ethernet Passive Optical Network
EVOA	Electrically Controlled Variable Optical Attenuator
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction

FSK	Frequency Shift Keying
FTTC	Fiber To The Corn
FTTB	Fiber To The Building
FTTH	Fiber To The Home
FSAN	Full Service Access Network
GEPON	Gigabit Ethernet Passive Optical Network
GPON	Gigabit Passive Optical Network
HFC	Hybrid Fiber Coax
IM	Intensity Modulation
IEEE	Institute of Electrical and Electronics Engineers
ITU-T	International Telecommunication Union
MAC	Media Access Control
MZM	Mach Zehnder Modulator
NGN	Next Generation Networks
NG-PON	Next Generation – Passive Optical Networks
OOK	On Off Keying
OPEX	Operational Expenditure
OLT	Optical Line Termination
ONU	Optical Network Unit
OFDM	Orthogonal Frequency Division Multiplexing
OFDM-CO	OFDM- Coherent Detection
OFDM-DD	OFDM. Direct Detection

ODN	Optical Distribution Network
PSK	Phase Shift Keying
PON	Passive Optical Network
P2P	Point-to.Point
P2MP	Point-to-Multipoint
PMD	Physical Medium Dependent
PM	Phase Modulator
PER	Physical Medium Dependent
QoS	Quality of Service
RN	Remote Node
SOA	Semiconductor Optical Amplifier
SMF	Single Mode Fiber
TDM	Time Division Multiplexing
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
VOA	Variable Optical Amplifier
WDM	Wavelength Division Multiplexing
XGPON	X-Gigabit Passive Optical Network

1 Introduction

The globalization, one of the most experienced phenomena of recent decades, affects all areas of society, allowing a flow of exchange of information without criteria in mankind history. In result, the world of telecommunications has been obviously growing quite fast causing a huge demand for bandwidth. Nowadays, in between telecommunications actors, next generation networks (NGN) are the main focus. These NGN aims to achieve more bandwidth, capable of support the today's services and also new and future services.

1.1 Motivation

The world is moving so fast that the bandwidth today enough to surf web pages, watch streaming video, down and upload songs, etc, will not be enough to support the growing demand for new applications, more and heavy change of data all over. The so desired HDTV, which requires about 20Mbit/s per channel, online gaming, interactive E-learning, new business models, next generation 3D TV, and so on, will dramatically increase bandwidth demand, as represented in the figure 1.1 [2].

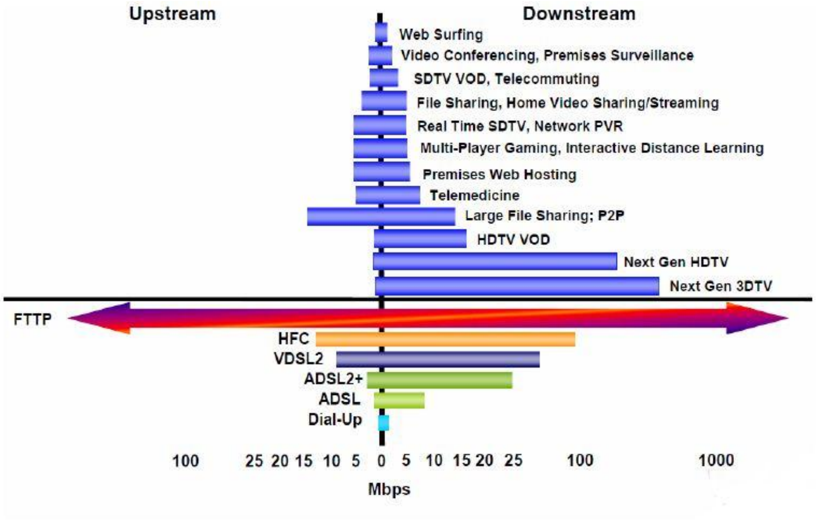

Figure 2.1: Today's services and futures needs of bandwidth

The quasi-continuous increase from residential and business customer applications make the service providers deliver more broadband capacity to end subscribers, an important issue in this scenario and a question to be answered is: how and where can the economic efficiency be found. Which makes the fiber access technology the most future-proof alternative available on the market, more specifically, the Passive Optical Networks, PONs.

1.2 Structure

This dissertation is organized in six chapters as presented:

- 1. Introduction;
- 2. State of Art;
- 3. E/G PON characterization;
- 4. Extender Box;
- 5. Conclusions and Future Work;
- 6. Appendices;

In the Introduction is presented the context of the project, the organization and also the main contributions.

In the chapter two, State of Art, the passive optical networks technologies are presented, specifically targeting the access network. The standards evolution is then briefly explained: - the requirements, special of EPON and GPON presented, and some future paths referred.

In the third chapter, the EPON and GPON systems are characterized in order to check their characteristics and requirements at light of the standard. Also a comparison between both standards is made with the goal of showing the GPON practical advantages.

In the fourth chapter, the previous work and the Extender Box status is presented. Using GPON it is presented the characterization of the Reach Extender identifying the best operation point. Finally a monitoring solution for the Extender that adapts itself for the GPON scenario is done.

The chapter five, conclusion and future work, presents the conclusion and some future work directions in order to close the Extender Box developments.

1.3 Contributions

The main contributions of this work are:

- Characterization of an EPON systems in terms of: maximum line rate, maximum reach and maximum power budget;
- Characterization of a GPON system in terms of: maximum line rate, maximum reach and maximum power budget;
- Generation of a GPON OLT and ONU utilization manual;
- Configuration of the GPON for the tests and extension characteristics;
- Characterization of Extender Box power budget boundaries with a GPON system;
- Extender Box monitoring in a GPON environment;
- Extender Box software debugging and improvements;
- Extender Box Datasheet;

2 State of Art

2.1 Introduction

PON standardization work began in 1990"s when carriers anticipated fast growth in bandwidth demands. The real push to the PON standardization was taken when the necessity to lower the cost of optical access systems and create a reliable economic solution appeared.

Nowadays Passive optical networks are intensively being deployed all over, initially BPON and EPON and then as a result of FSAN effort, Gigabit PON (GPON), offering unprecedented high bit rate support while enabling the transport of multiple services.

One of the next steps in PON systems will be the implementation of WDM-PONs, which are already being study and some vendors already have working equipments. In these chapter the PON systems are presented and also some of the features presented

With the eyes on future new standards have recently came up, XG-PON and 10G-EPON belong to the next generation of passive optical networks (NG-PON), these new standards show improvements when compared with the previous ones. A brief description of next generation of passive optical networks are made. And also WDM and OFDM technologies are presented as technologies capable of support the future challenges.

2.2 Telecommunication network

The general structure of a modern telecommunication network consists of three main sub-networks: backbone or core network, metro or regional network, and the access network. A simple scheme of a telecommunication network is presented in the figure 2.1.

The core network, interconnects all the metro/regional (urban/rural area) networks of a country. These, metropolitan networks aggregate high tributary traffic from the central offices, pass that traffic addressed to other metro/regional areas to the core network and delivers to the respective central office the remaining traffic.

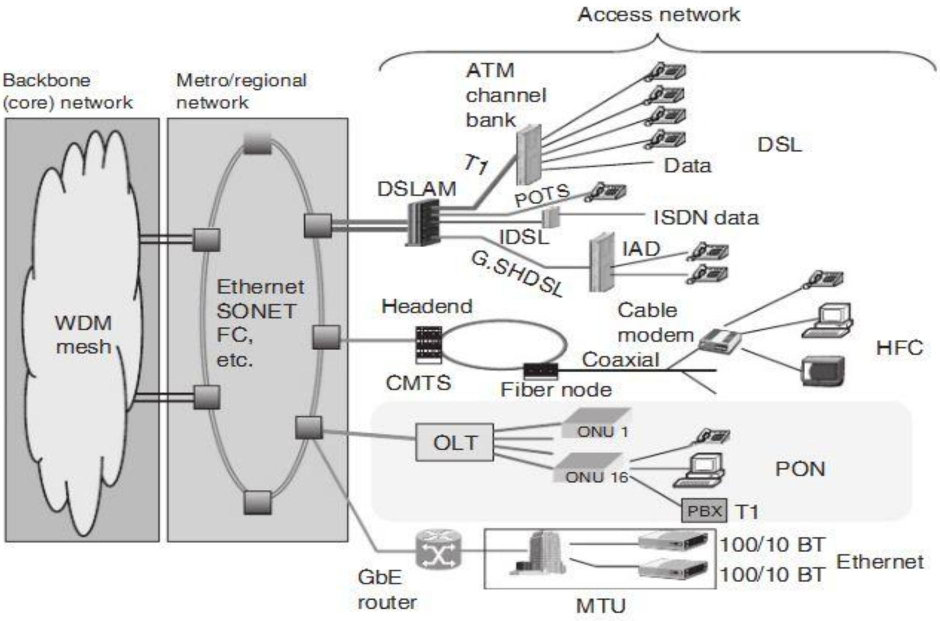

Figure 2.1: Architecture of a telecommunication network [11]

The structures of core and metro networks are usually more uniform than access networks and their costs are shared among large numbers of users. Finally, the access network is the one that provides end-user connectivity, this is, connects the service provider with its home or business subscribers.

Table 2.1: Characteristics of the several layers of a telecommunication network.

Optical network layer	**Characteristics**
Core	. Have active elements; . Low granularity; . Low variation in traffic flow; . Operate with a lower number of protocols than metro networks; . Transport traffic over long distances; . Use a irregular mesh topology;
Metropolitan	. Have active elements; . Medium granularity; . Medium fluctuation in traffic flow; . Covers high density population areas; . Use ring topologies;
Access	. Passive optical network (PON); . High granularity; . High fluctuation in traffic flow; . Operate with a variety of protocols (IP, ATM, Ethernet); . Covers small distances; . Have a wide variety of topologies implemented

2.3 Access Network

Being fiber access one of the most important technologies in the next generation network, it's fundamental to understand what Access Network is. Nowadays, the most cost efficient solution in access networks is the passive optical networks. They are constituted of an optical line terminator (OLT) located at the Central Office (CO), remote nodes (RN), and a set of associated optical network terminals (ONT), also known as network interface units (NIU) to terminate the fiber.

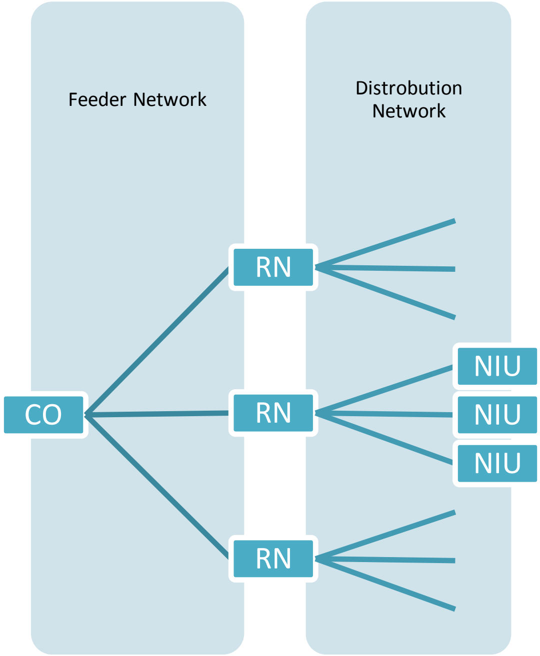

Figure 2.2: High-level architecture of an access network

In a simple perspective, an access network can be seen as two different networks, the distribution and the feeder network. One connects the RNs with the NIUs and the other connects the CO with the RNs, respectively, as it can be seen in figure 2.2. And, it’s the last segment of the operator network before reaching the subscriber, being made up of their three major components that enable the connection between subscribers and service provider.

2.4 FTTx Network Model

Optical Access Network has several applications model, the FTTx. Unlike HFC, optical fiber is used in both feeder and distribution networks. Figure 2.3, represents the different types of FTTx architectures, based on the ONU location and the fiber length according to [8]. Citing, FTTC (Fiber to The Curb), FTTB (Fiber to The Building) and FTTH (Fiber to The Home).

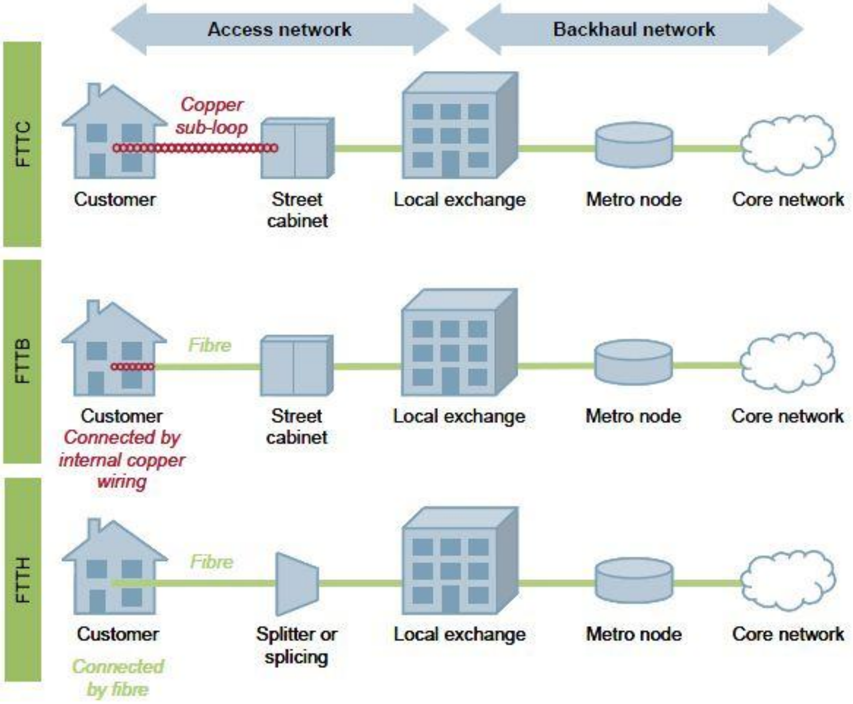

Figure 2.3: FTTx application model in PON [8]

The optical fiber is terminated with a node, ONU. On the feeder side, the CO end is terminated with Optical Line Terminal (OLT), with the purpose of multiplex transmission of all ONUs belonging to the same network and provide as interface from the access network to either a large network or some services.

At FTTH deployment, the ONU is located at the costumer's premise but in the other FTTx solutions, ONUs are located in an intermediate point between the CO and the end users.

FTTH are receiving a special attention because of the fundamental question, “Can our current last-mile bandwidth capabilities handle the future needs?” and because of the knowledge that connecting homes directly to fiber optic cable can enable enormous improvements in the bandwidth that can be provided to consumers.

2.5 Passive Optical Network

The remote node of a network can be either passive or active, and the FTTx architectures can be based on both. Regarding to the nomenclature, a network that makes use of an active RN is referred to as an active optical network (AON). An active RN requires constant power supply, backup power, and additionally, a cabinet for its placement, raising the CAPEX and OPEX.

When using a passive RN, FTTx access network is referred to as a passive optical network (PON), figure 2.4. Due to the use of the passive element, that does not requires power supply, climate, cabinet etc. Passive optical networks are considered the most cost effective solution in the access network, as it is referred before.

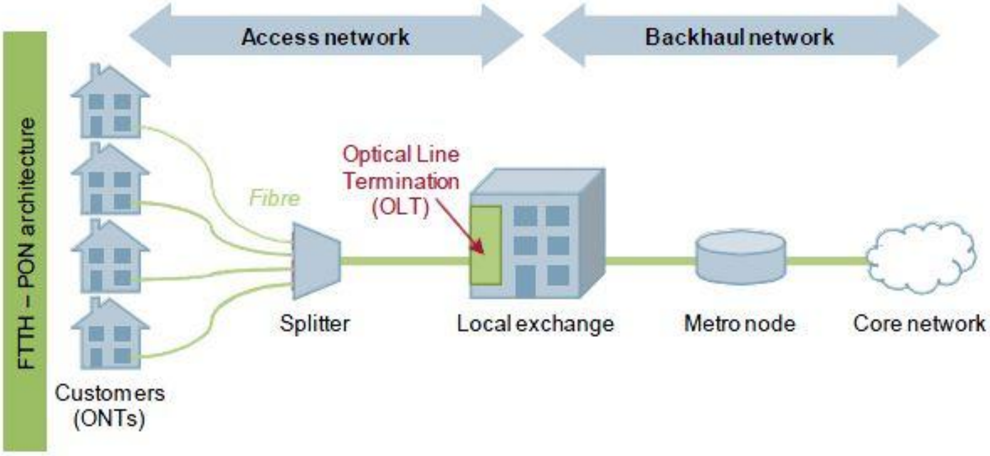

Figure 2.4: Passive optical network architecture [8]

PON is generally referred in the literature to be a P2MP system. Some authors also argue that being the connection between the OLT and the ONU completely passive, P2P optical access network can also be considered a PON. However, the most common and widespread definition to PON is P2MP.

The feature of passiveness makes the network deployment flexible and advantageous:

- Both, equipment and fiber in the CO are shared (smaller number of fibers in feeder), providing lower cost than in a P2P solution. Above all, equipment room and power supply are not needed, greatly reducing the CAPEX;
- Trough the removal of the active equipment, there is a reduction in the electromagnetic interference, decreasing the failure rate of the line and the external equipment. This provides easy maintenance, lower CAPEX and also lower OPEX;

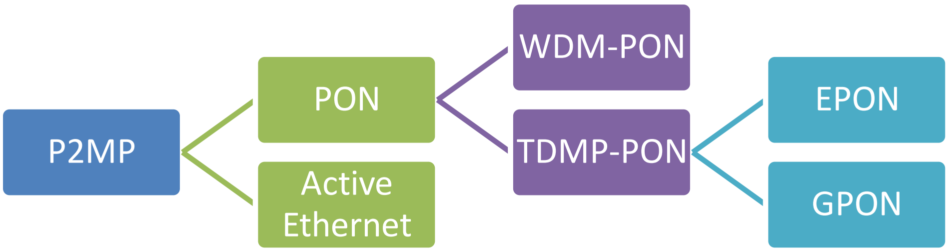

Figure 2.5: Architectures and Technologies of FTTH network P2MP

2.6 PON Standards Development

The foundation of Full Service Access Network (FSAN) working group by seven global network operators, in 1995, was one of the most important events in the PON development. So, it’s acceptable to say that the history of PON dates back to the early 90s. Since that time standardization has never stopped, figure 2.6 shows the past and ongoing IEEE and ITU-T standardization activities for various PON system generations, together with reference to actual deployments and their major coverage areas [13].

The mission of FSAN is to drive applicable standards, where they already exist, into the services and products in the industry, while simultaneously advancing its own specifications into the appropriate standard bodies to provide further definition to the Full Service Access Network [12].

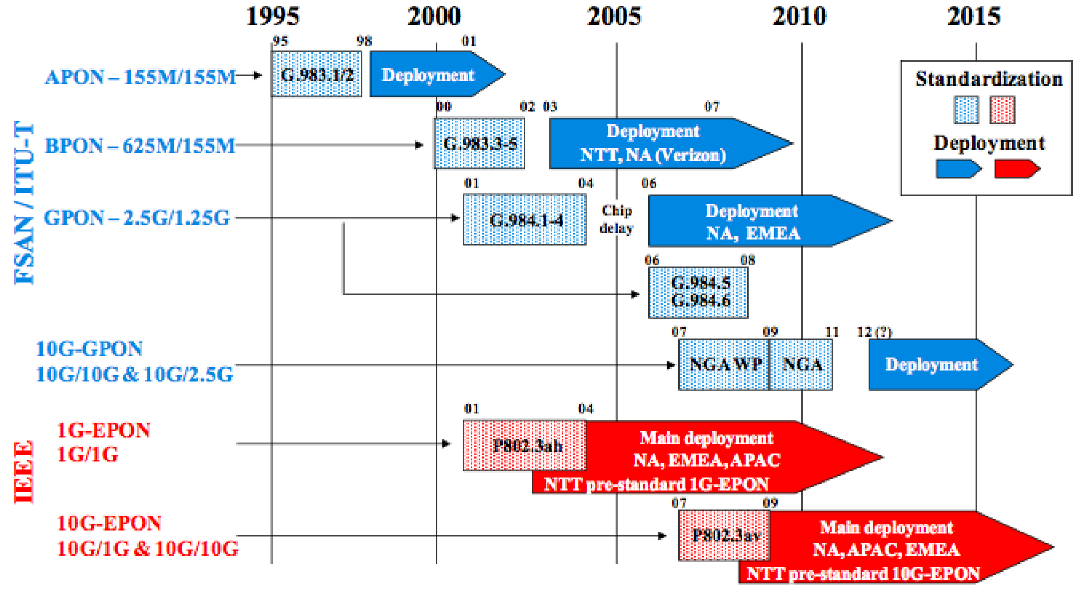

Figure 2.6: IEEE and FSAN/ITU-T PON systems and their standardization status [13]

2.6.1 ATM and Broadband PONs

ATM-based PON, APON, is the first standardized PON solution, officially, APON was first proposed in 1995 by FSAN, and later transferred to ITU-T SG15, as the G.983 standards. Mixing ATM and PON, APON seemed to be a good multiservice broadband option, by supporting the legacy of ATM protocols at 622 Mb/s of downstream and 155 Mb/s of upstream bandwidth. However, it has not full field the expectations and did not become the universal network protocol. Instead, IP and Ethernet also gained attention. The name APON led users to believe that only ATM services could be provided to end-users, so ITI-T SG15 decided to change it to broadband PON, BPON [11].

The first BPON standard was published in 1998 in the ITU-I G.983.x series of ITU-T recommendations. The G.983 series recommendation have been refined several times, reaching the last update recommendation in 2005 which specifies higher aggregate transmission rates, for up to, 1.24416 Mbps in the DS and 622.08 Mbps in the US direction.

2.6.2 Gigabit PONs – GPON and EPON

A task force called 802.3ah was initiated by IEEE 802.3 working group in 2001 from the need of draft a standard to address Ethernet. The result of their activities was Ethernet PON, EPON, standardized in 2004 with bit rates of 1,25Gb/s and a maximum split ratio of 32.

Also in 2001, FSAN began to move in order to bring out standards for networks operating at bit rates of above 1Gb/s, i.e., increased nominal rate and also enhanced security. Subsequently, in 2003, FSAN proposed the first recommendation for gigabit capable PON, GPON, described in the G.984.x series. With bit rates of 2,5Gb/s for downstream, 1,5Gb/s for upstream, and a maximum spilt ratio of 64 [14]. EPON and GPON are known as TDM PONs because they are both based in time division multiplexing technology in contrast to technologies based on WDM.

TDM-PON, Time Division Multiplexed Passive Optical Network, is the most common commercial PON architecture, the principle is illustrated in the figure 2.7 below.

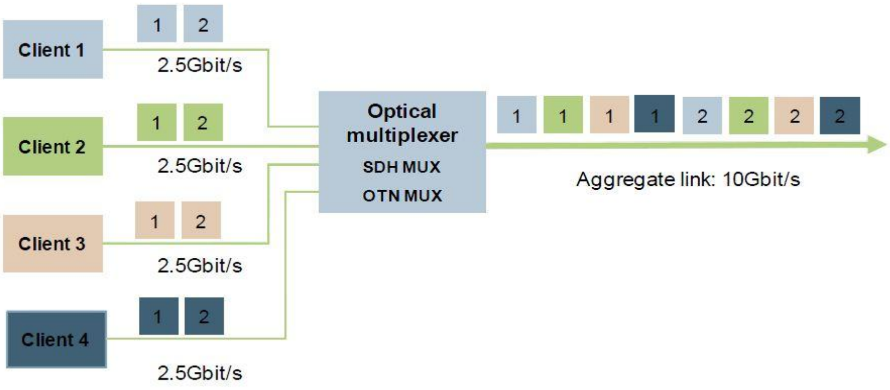

Figure 2.7: TDM principle [8]

By using the TDM technique is possible to interleave various signals in the time domain, as depicted in the figure for a scenario with four clients, each one at 2,5Gbit/s (as example), the resulting will be 10Gbit/s in the aggregate link. TDM add value to itself because makes use of low OPEX and CAPEX by passive infrastructure and high capacity provided by optical fiber. But from the other side, the advantage is that because all the subscribers share the optical carrier through the same splitter and working bit rate of transceivers, the number of ONUs is limited.

As a better solution for TDM-PON, WDM-PON solution can overcome some limitations by supporting multiple wavelengths over the same fiber infrastructure. Furthermore, it's transparent to the channel bit rate, and it does not suffer power splitting losses, this solution have been proposed as early as the mid-1990s but the interest has intensified in recent times, these solution is present later in this chapter.

2.6.2.1 EPON

2.6.2.1.1 EPON main features

EPON, Ethernet PON, system is translated into two classes, 1000BASE-PX10 and 1000BASE-PX20, which are sub-layers of PMD (physical medium dependent) that enables point-to-multipoint connection, for 10km and 20km respectively.

EPON handles physical broadcasting of 802.3 frames, by that fact upstream and downstream can coexist in the same fiber, but at different wavelengths. The wavelength assigned for downstream transmission is 1490nm (S band), for upstream 1310nm (O band) and also a wavelength for video overlay is assigned, 1555nm (C band), figure 2.8.

Figure 2.8: Wavelength allocation for EPON [adapted from 18].

EPON adopted a fixed line rate, configurable preamble and it can provide downstream and upstream transmission at lines rates of 1.25Gbps, but due to the 8B/10B line encoding the bit rate for data transmission is 1Gbps. As referred before, EPON is able to reach up to 20km and it allows a maximum of 32 users [27].

Forward error correction, FEC, is a mathematical signal-processing technique that allows the detection and error correction. With FEC the optical link budget (from 3 to 4dB), splitting ratio or fiber length can be increased. As can be seen in table 2.2, when FEC is used the chosen code is RS(255,239). These key features are presented in table 2.2 below.

Table 2.2: EPON main features.

Standard	IEEE803.2ah
Bit rates	Downstream: 1250Mbps (1Gbps Eth) Upstream: 1250Mbps (1Gbps Eth)
Optical wavelengths	Downstream: 490nm Upstream: 1310nm
Supported ODN classes	A and B (15 and 20dB)
Split ratio	1:32/1:64 typical
Fiber Length	10/20Km
Transmission Format	Ethernet
FEC	RS(255,239) optional

2.6.2.1.2 EPON traffic transmission

In downstream transmissions the data is broadcasted from the OLT to the ONUs in packets (from 64 to 1518 bytes), this is, the Ethernet frames (802.3 frames) are transmitted from the OLT to every ONU.

Each packet contains a header that contains the recipient identification, after the signal pass the splitter the packets are not divided, i.e., all the paths still contain the same packets, once the packets reach the ONUs, each one of them accepts their respective packets and discard the others, this can be seen in figure 2.9.

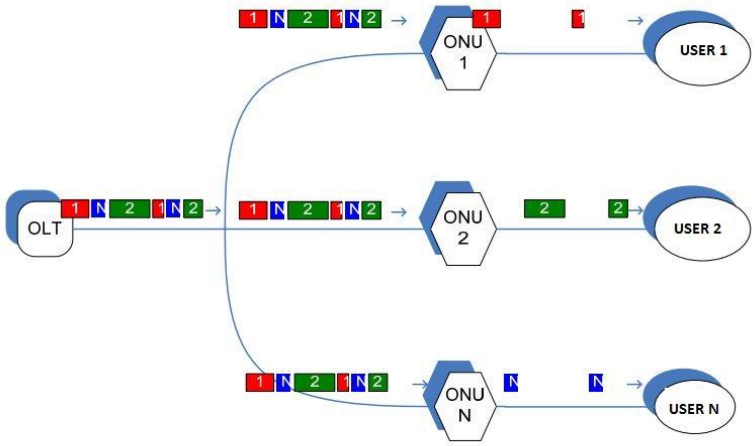

Figure 2.9: Downstream traffic in EPON [adapted from 24].

In upstream transmissions, the Ethernet frames from each ONU only reach the OLT and not another ONUS. By performing point-to-point transmission, collisions may occur between frames from different ONUs, so, to efficiently guarantee upstream transmissions the transmissions are arbitrated.

By mean of MPCP, Multi-Point Control Protocol in the Medium Access Control, MAC, the ONUs transmissions are arbitrated. Each ONU just transmit in its respective time slot avoiding on that way the collisions, the upstream transmission process is represented in figure 2.10.

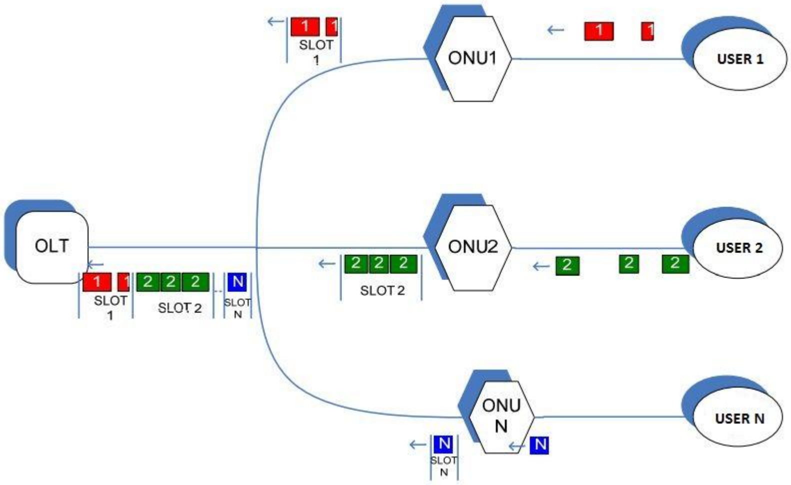

Figure 2.10: Upstream traffic in EPON [adapted from 24].

2.6.2.1.3 EPON frame

In EPON the TC, transmission convergence layer, is carried out by a Ethernet frame very similar to the common Ethernet frame. The difference is: the replacement of the 8-byte Ethernet preamble by the LLID, logical link identifier and a 8-bit cyclic redundancy check (CRC-8). By means of the LLID, the ONUs filter the received packets, forwarding to the upper layer only packets carrying the LLID value assigned to each one of them by the OLT. The frame is shown in figure 2.11.

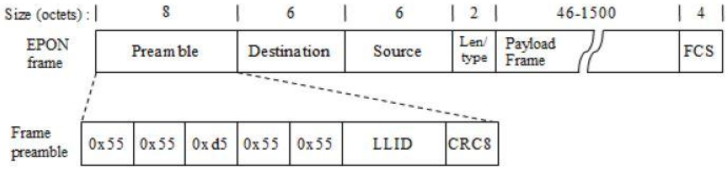

Figure 2.11: EPON frame. [28]

2.6.2.1.4 Requirements

To ensure that the system keeps transmitting with acceptable values of bit error rate, signal noise to ratio, and others, the definitions of boundaries is extremely important. The channel characteristics are presented in table 2.3.

Table 2.3: Channel characteristics for 100oBASE-PX20 [adapted from18]

Parameter	**Units**	**Value**
Maximum range	Km	0.5m to 20
Available power budget	dB	26
Minimum channel insertion loss	dB	10

Regarding the maximum and minimum values for optical launch power of transmitter and receiver and also sensitivity range the standard definitions are presented in table 2.4.

Table 2.4: EPON 1000BASE-PX20 receiver and transmitter power levels.

OLT		
Parameter	**Units**	**Value**
Maximum optical launch power	dBm	+7,0
Minimum optical launch power	dBm	+2,0
Received sensitivity	dBm	-27,0
Maximum receive power	dBm	-6,0
ONU		
Parameter	**Units**	**Value**
Maximum optical launch power	dBm	+4.0
Minimum optical launch power	dBm	-1.0
Received sensitivity	dBm	-24.0
Maximum received power	dBm	-3.0

2.6.2.2 GPON

2.6.2.2.1 GPON main features

The wavelength plan for GPON defines 1310nm for upstream direction, 1490nm for downstream direction, and also assigns a wavelength for video overlay, 1555nm, as represented in figure 2.12.

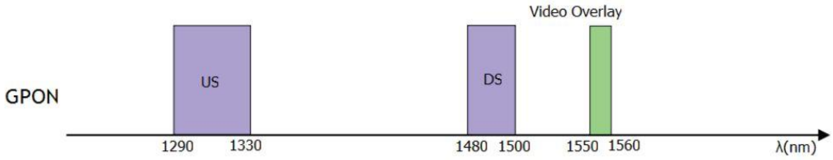

Figure 2.12: Wavelength allocation for GPON

GPON can support different speed cases, being the most popular option 2,4Gbit/s for downstream and 1,2Gbit/s for upstream, also symmetric 2,4Gbit/s is supported (among others), on that way both residential and business customers can be covered as desired for that technology.

In terms of maximum reach, the physical limitation imposes a limit of 10km or 20km depending on the equipment, anyway, the logic limit imposed by the standard is 60km. In terms of splitting ratio a maximum of 64 costumers is recommended, but after overcome some limitation due to the equipment the desired is to achieve 128 costumers.

As mentioned the widespread GPON implementation by the service providers is the pair 1.2Gbps/2.4Gbps, with equipments class B+ which imposes a limit of 20km of fiber. This class B+ is the equipment considered in the scope of this work (as will be seen in future tests - chapter 3 and 4).

The GPON main features are summarized in table 2.4.

Table 2.4: GPON main features.

Standard	ITU G.984
Bit rates	Downstream: 2.5Gbps Upstream: 1.25/2.5Gbps
Optical wavelengths	Downstream: 490nm Upstream: 1310nm
Supported ODN classes	A, B and C (15/20/25dB)
Split ratio	1:32/1:64 /1:128
Fiber Length	20Km
Transmission Format	Ethernet,ATM,TDM

2.6.2.2.2 GPON transition and frame structure

In downstream direction, the data is transmitted to all subscribers by the OLT, on the subscriber's side, all the ONUs receive the same data. Then, each ONU selects their respective packets and discard the others. For the upstream case, the system assigns time slots for each specific user to send data, since the bandwidth is shared between all costumers in the time domain [8]. As for what was said the GPON mode of operation is identical to EPON, however GPON differs in the transmission frames and has its own frame encapsulation

The downstream transmission starts when the OLT receives the Ethernet traffic from the Service Network and checks the destination MAC address, and then the lookup table to get related Port-ID according to the MAC address. The OLT encapsulates the traffic to a GEM (GPON encapsulation method) frame by adding the GEM header. The OLT packs several frames together and adds these GEM frames to the PCBd (physical control block downstream) filed that has related a control plane message, upstream bandwidth allocation map and other frame control fields. All of this constructs a GTC frame, GPON transmission convergence frame. When the GTC frames arrive to the ONU, this extracts the GEM frame that are directed to it through a Port-ID identifier. How the GEM frame maps into the GTC frame is represented in figure 2.13.

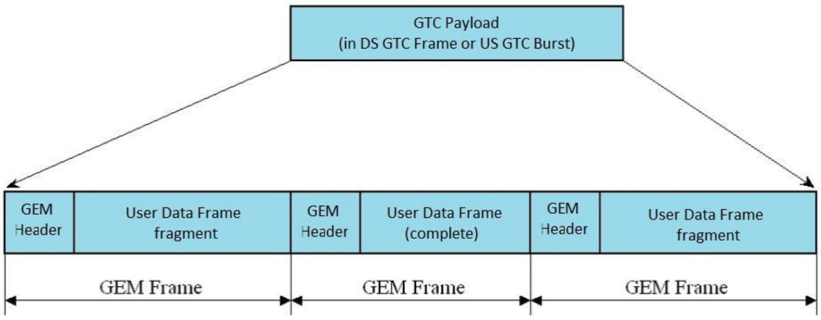

Figure 2.13: How GEM frame maps into the GTC frames [adapted from 29]

In both directions, the GTC have the same duration, 125us. But the structures are different as represented in figure 2.14 for downstream and figure 2.15 for upstream.

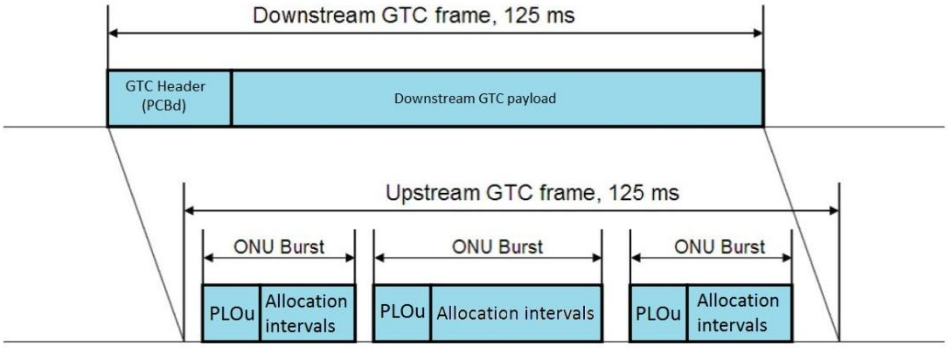

Figure 2.14: GTC frame for downstream and upstream [adapted from 29].

As can be seen in figure 2.14, the downstream frame consist of a PCB, physical control block and the GTC payload, the upstream GTC frame consist of various burst, each containing a PLOu, physical layer overhead and one or more allocation intervals.

When upstream is intended, the ONUs get Ethernet traffic, check the bandwidth allocation map which is contained in PCBd field from a previous downstream. By mean of the T-CONT and allocation map, the ONU knows how much bandwidth has been allocated to it and the related time-slot. The ONU should pack the Ethernet traffic into GEM payload and add the necessary GEM header. The ONU attaches the PLOu field which is mandatory. PLOAMu, PLSu and DBRu fields might be attached as well according to the different requirements including sending the PLOAM response, power level related information and dynamic bandwidth report information. The packet frame is sent by the ONU to the splitter. All these ONU frames will be packed into an upstream frame and transmitted to the OLT side. When the OLT gets this frame, it will split the frame to several units according to the ONU-ID in the PLOu fields. OLT will check the PLOAMu, PLSu and DBRu fields and send a response if necessary. The OLT gets the GEM frames, checks the OMCI messages in the GEM headers, updates the related managed entities if needed and checks the lookup table to get related destination MAC address according to the Alloc-ID. Finally, the OLT gets the GEM payloads which are Ethernet frames from the User Networks. The Ethernet frames will be transmitted to the Service Network according to the destination address [27]. The details of physical and GTC layer upstream overhead are represented in figure 2.15.

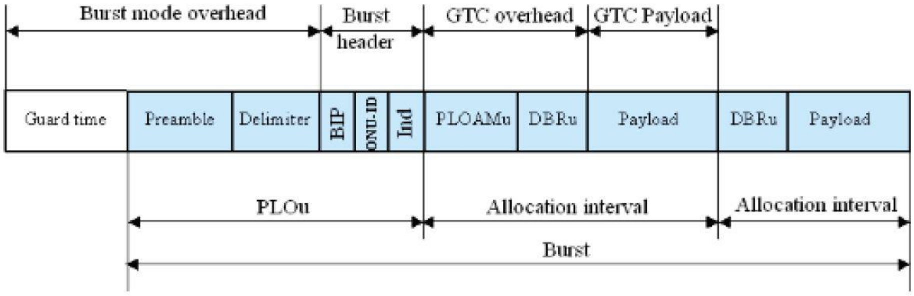

Figure 2.15: Details of physical and GTC layer upstream overhead [18]

FEC is also defined for GPON, by using FEC, redundant information is transmitted together with the original information. The amount of redundant information is reduced, so, FEC does not significantly increase the overhead. Thus, results in a increased link budget by about 3/4 dB, and therefore, higher bit rates and distances from the OLT to the ONUs can be supported, as well as higher splitting ratios.

2.6.2.2.3 Requirements

As mentioned before, class B+ is the equipment considered in the scope of this work. The power levels defined for that kind of equipment, are presented in the table 2.6. For low power the noise can overlap the signal, for high powers, nonlinear effects can occur causing degradations in the signal. In both cases the implication is the increase in the number of errors. Thus, the power values defined aim to ensure that the BER is always lower than 10^{-10}.

Table 2.6: GPON receive and transmit characteristics (class B+ 2,4/1,2 Gbit/s).

OLT		
Parameter	**Units**	**Value**
Maximum optical launch power	dBm	+5,0
Minimum optical launch power	dBm	+1,5
Received sensitivity	dBm	-28,0
Maximum receive power	dBm	-8,0
ONU		
Parameter	**Units**	**Value**
Maximum optical launch power	dBm	+5.0
Minimum optical launch power	dBm	+0.5
Received sensitivity	dBm	-27.0
Maximum received power	dBm	-8.0

2.6.2.2.4 Reach Extender

Due to the need of a extended reach and higher number of clients supported in the same PON, ITU outlined the recommendation G.984.6, Gigabit-capable passive optical networks (GPON): Reach extension, describing the architecture and interface parameters for GPON with extended reach using one active extension node placed in the middle of the optical network. Two options are considered for that device, opto-electronic regeneration and optical amplification, architecture is presented in figure 2.16 Hybrid solutions are also possible by using both of the techniques at the same time, this is, using OEO regeneration in downstream and amplification in upstream or vice-versa.

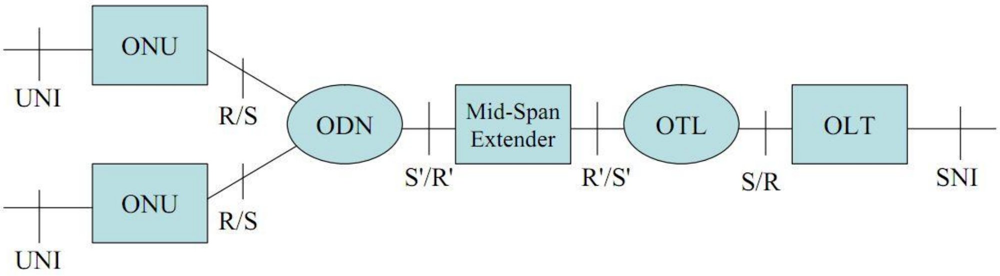

Figure 2.16: Mid-Span Extender [26].

The extender device is placed in between the OLT and ONUs. The path between ONUs and the mid-span extender is named ODN (Optical Distribution Network), and between the mid-span extender and OLT OTL (Optical Trunk Line) [26].

The G.984.6 standard defines characteristics for the two options, optical-electrical-optical (OEO) regeneration and optical amplification. In the scope of these work only the characteristics of a extender based in optical amplification are presented in the summarized table 2.7. These definitions are of great importance principle because the extender box must remain compatible with existing equipment.

Table 2.7 Relevant parameters of an extender box based in optical amplifiers [adapted from26]

			Value	Units
Downstream	Transmitter	Maximum power	+5 - minimum ODN attenuation + maximum gain	dBm
		Minimum power	+1,5 - minimum gain – OLT loss	
		Maximum ASE output @ -28dBm input	5	dB
	Receiver	Minimum sensitivity	-23	dBm dBm
		Maximum power	-5	
Upstream	Transmitter	Maximum power	+5 – maximum gain – OLT loss	
		Minimum power	+0,5 – maximum ODN attenuation + minimum gain	
		Maximum ASE output @ -28dBm input	7	dB
	Receiver	Minimum sensitivity	-28	dBm
		Maximum power	-8	

One important parameter when defining characteristics to a Extender Box based on optical amplifiers the Amplified Spontaneous Emission, ASE, because its capable of degrade the signal and not just significantly.

2.6.3 Comparison of standardized BPON, GPON and EPON

These three standards, they all use two wavelengths, one for downstream and one for upstream data traffic, these wavelengths are time-shared among users, making them Time Division Multiplexed PONs (TDM-PONs). Table 2.8 below presents a summary of operation parameters for BPON, GPON and EPON.

Table 2.8 BPON, GPON and EPON parameters [adapted from 11]

	BPON	EPON	GPON
Standard	ITU G.983	IEEE 802.3ah	ITU G.984
Maximum/diff reach	20km / 20km	20 km / 20 km	60 km / 20-40 km
Maximum split ratio	128	---	128
Line rate (up/down)	155.52-622.08/ 155.52 - 1244.16 Mb/s	1250/1250 Mb/s	1244.16/2488.32 Mb/s
Coding	NRZ + scrambling	8b10b	NRZ + scrambling
Data rate	Equals to line rate	1000 Mb/s	Equals to line rate
ODN loss tolerance	20/25/30 dB 28dB (best practice)	20/24 dB 29 dB (actual systems)	20/25/30 dB 28dB (best practice)
US tolerance	Fixed 3 bytes 154ns (155.52Mb/s) 38.4ns (622.08 Mb/s)	Guard: 2 µs Laser on/off: 512 ns AGC/CDR: 400ns	Guard: 25.7 ns Preamble: 35.4 ns Delimiter: 16.1 ns
Estimated cost	Low	Lowest	Medium

2.6.4 10Gbit/s PONs

The obvious need for new higher capacity access architectures, make both, IEEE and FSAN/ITU-T work on PONs with at least 10 Gb/s data rates. In September of 2006, IEEE 802.3ah 10 Gigabit Ethernet Passive Optical Network (10GEPON) Task Force was formed. Later, in September of 2009, the standard was published, with a development strategy of co-existence with EPON, being the operation mode a combination of 1G down/1G up, 10G down/10G up and 10G down/10G up over a single fiber. A share of infrastructures between the new and legacy EPON is expected, allowing both systems to serve over the same physical infrastructure.

On the other side, since November of 2009, FSAN was working on next-generation PON standard, referred to as 10 Gigabit-capable Passive Optical Network, (XGPON). The goal is to perform the evolution towards XGPON in two phases, the first phase planned to achieve transmission rates of 10Gbps in downstream and 2,5 Gbps in the upstream direction, referred to as XGPON1. The symmetric option, 10 Gbps in both up and downstream direction, referred to as XGPON2, is the second phase. This XGPON2 system, may be considered as the ultimate version of TDMA by FSAN and supported by IEEE [14] [11]. A detailed explanation of both standards, 10G-EPON and XG-PON, their architectures, migration scenarios, requirements, etc, can be found in [15].

2.6.5 Comparison of 10GE-PON, XG-PON1 and XG-PON2

Table 2.9 below presents a summary of operation parameters for 10GE-PON, XG-PON1 and XG-PON2 (XGPONs).

Table 2.9: Comparison of 10GE-PON and XGPONs [adapted from 14]

	10 GE-PON	**XG-PON1**	**XG-PO2**
Standard	IEEE 802.3av	FSAN	FSAN
Framing	Ethernet	GEM	GEM
Maximum Bandwidth (up/down)	10 Gb/s	2,5 / 10 Gb/s	10 Gb/s
User per PON	≥ 64	≥ 64	≥ 64
Bandwidth per user	≥ 100Mb/s	≥ 100Mb/s	≥ 100Mb/s
Line coding	64b66b	Scramble NRZ	64b66b
Video	RF/IP	RF/IP	RF/IP
Cost	High	High	High

2.7 Next Generation PON

The today's solutions to optical access networks will have to migrate into higher bandwidth alternatives, and this is why the interest in more capable generations comes. Currently, the trend is shifting towards the New Generation Networks, NGN, always bearing in mind the protection of legacy investments by ensuring a smooth migration towards Next Generation PON, (NG-PON). Being the main organization leading with the future generation of access networks, the activity of defining Next Generation PONs is taking place in FSAN consortium. The main goal of FSAN with NG-PON is to provide a substantial increase of today's available bandwidth to end-users when compared with GPON and EPON. FSAN NG-PON taxonomy is presented in figure 2.17 [13].

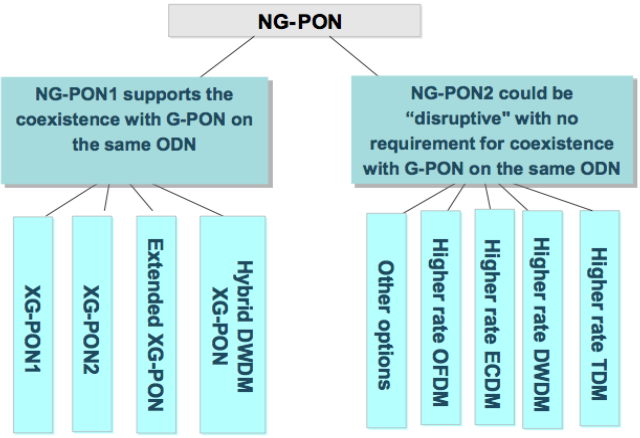

Figure 2.17: NG-PON taxonomy [21]

2.7.1 NG-PON Roadmap

Based on co-existence characteristics, NG-PON can be divided into two groups, NG-PON1 and NG-PON2. The figure 2.18 represents the roadmap of NGPON, leading us to better understand of this evolutionary scenario.

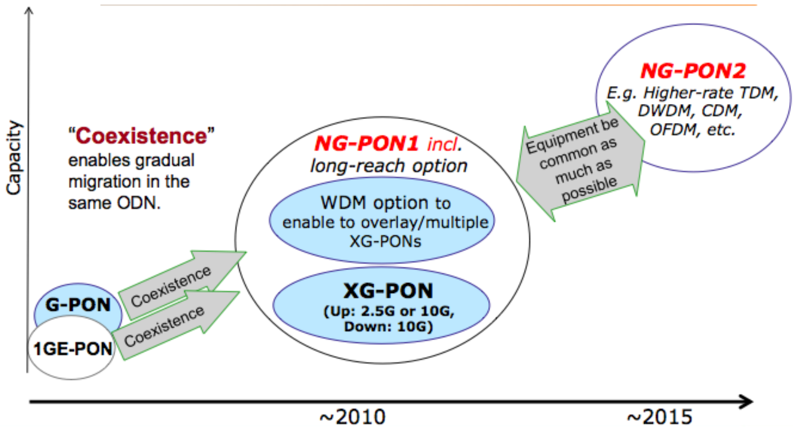

Figure 2.18: NG-PON roadmap.

NG-PON1 supports co-existence with GPON in the same ODN, i.e, this solution leverages the existent infra-structures without the need to disrupt the existing services for customers served over GPON. NG-PON1 is also divided into two sub-categories, the already described, XG-PON1 and XG-PON2. This migration scenario is referred to as Service-Oriented, and it is a middle term solution. General requirements are:

- Co-existence in the same ODN with GPON and NG-PON;
- Not disrupting the existing services for costumers server over GPON;
- Capacity of emulating all GPON services in case of a complete migration;

On the other hand the second generation, NG-PON2, the long-term solution, presents a major investment by renewing the infrastructure of the access network. Because NG-PON2 doesn't have any requirements of co-existence with GPON in the same ODN, this scenario is referred to as Service-independent.

NG-PON2 should be the long-term solution for service providers by the time NG-PON reaches the maturity, presenting a higher bandwidth and lower economic solution (from the point of view of service providers) as it is represented in figure2.18.

NG-PON2 has no constraints of coexistence with GPON, which increases the number of technology candidates. At this time without a preferred technology, panoply of solutions ranging from higher capacity multi channel TDM PON passing through WDM-PON and OFDM have been studied and are candidates, as it's represented in figure 2.6 [15] [16].

2.7.2 Requirements and contributions for NG-PON2

In order to increase the lifetime of actual TDMA-PON systems several solutions have been proposed in recent years. Such as, the reach extender by ITU with the purpose to extend the reach of GPON to the limit of its protocol, 60km, as mentioned in previous sections. Also other medium/long term solution had appeared, as those mentioned 10GEPON and XGPONs.

Factors to take into account when developing the new requirements are the necessity of keep the ratio per user of more than 1Gbit/s, the possibility to use a single platform for residential, business and backhaul, and also to minimize the active equipments in the field.

This way the requirements for NG-PON2 which are intended to meet until 2015 are presented:

- 40Gbit/s of aggregate capacity
- 1:64 splitting ratio
- 20km of minimum reach
- 60km of extended reach
- More security
- Cost-efficiency design for both up and downstream
- Reduction of energy costs

Also another future service should be supported, as:

- Games;
- Online virtual environments;
- Grid computing;
- Video services: 3D+HS+Ultra HD;
- Real time applications;

2.7.3 Technologies for NG-PON2

2.7.3.1 WDM-PONs

A passive optical network employing wavelength division multiplexing is known as a WDM-PON and has been considered as one of the promising fiber-to-the-home (FTTH) solutions to carry multiple broadband services to costumers due to its high data bandwidth. Quickly became apparent that WDM had advantages over TDM, particularly in the capacity, low level of latency and transparent services.

In WDM, the various signals are multiplexed in a single fiber by using different wavelengths, this way it’s possible to perform a two-way communication in the same fiber, thus increasing the capacity of the transmission link.

One of the major technological challenges for the WDM-PON networks is to avoid the need for expensive components capable of made the selection of wavelength in each ONU, which would imply an enormous expenditure. In practice, this is not possible with the actual lasers for transmission in DWDM without WDM-PON, the figure 2.19 illustrates an example of a WDM transmission.

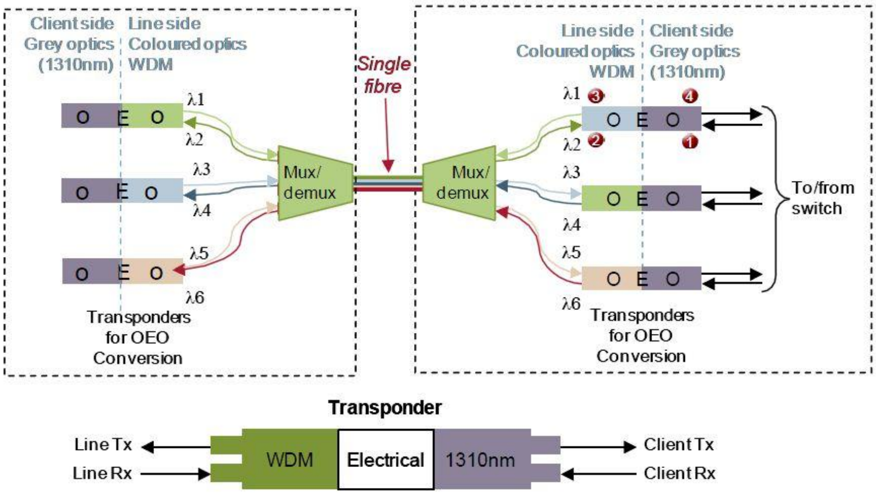

Figure 2.19: WDM System [8]

Each channel is modulated at a different wavelength, and then multiplexed with wavelengths independents from each others. A main component of that technologies is shown in the figure 2.19, is the transponder, the device that performs the optical-electrical-optical conversions. Another important component is the mux/demux, with the function of multiplex all the wavelengths coming from the CO or from the users allowing the use of one single fiber. This process is possible through the use of an AWG, arrayed wavelength grating, based in the constructive and destructive interference between waves.

The operation principle of an AWG: the incoming light received by the wavelengths passes through the free space, and then enters in the waveguide series. Each waveguide has its own space because they are made for different wavelengths, implying that the wavelengths must have different phases. Them, the incoming signals from the waveguides goes to the new free space and after, based on the interference principle each port receive only one wavelength, this process is the demultiplexing. In the opposite, this is, to multiplex the signals, the process is the same but with the port reversed. The AWG is device in shown in figure 2.20.

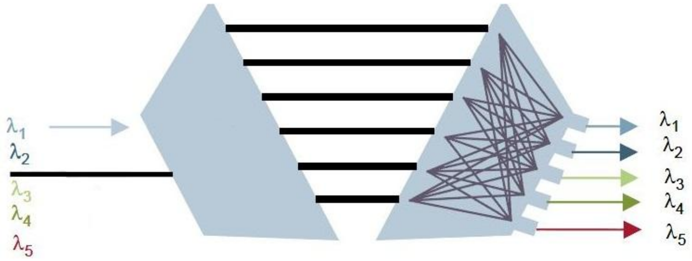

Figure 2.20: AWG [adapted from 8]

The WDM systems can be divided into two types, Coarse WDM (CWDM) that supports fewer than 16 multiplexed wavelengths per fiber, and Dense WDM (DWDM) that can support up to 320 multiplexed wavelengths per fiber.

One f the CWDM characteristic is that wavelengths have bigger spaces in between them, and by that reason CWDM is less expensive than DWDM. Another advantage is the absorption of water peak, once the E band is used. CWDM is typically used in lower-level infrastructure such as metropolitan or access applications.

Oppositely, DWDM is typically used at higher level infrastructures since they have greater capacity compared to CWDM systems, particularly for long haul and metro networks. This greater capacity is related with the capacity of support a wider range of wavelengths depending on the spacing among channels used. As the space between channels is significantly lower than in CWDM, the use of high quality lasers is implied, requiring more control on the wavelength. It have to be noted that the lasers should also have a precise temperature control to avoid the dispersion of the central wavelength. As a natural consequence, DWDM is much expensive because it requires greater precision devices. By the other side, as advantage its possible to support a high number of wavelengths as higher bandwidth. [8]

Based in the same principle of DWDM there is the Ultra Dense WDM, UDWDM, here the spacing among channels is very low. Typically, 3GHz between channels, implying more expenditures than technologies mentioned before, also as even more precise equipments to minimize the interference that nature comes with the proximity of channels.

2.7.3.2 OFDM-PON

The history of orthogonal frequency division multiplexing, OFDM, dates back to 60’s, when the concept was first introduced. However the use of frequency division multiplexing, FDM, goes back over a century where more than one low rate signal, such as telegraph, was carried over a relatively wide bandwidth channel using a separate carrier frequency for each signal. The arrival of broadband digital applications and maturing of very large-scale integrated CMOS chips in the 90’s brought OFDM into the spotlight. After, OFDM has been adopted by various standards in recent years, including DSL and 802.11a wireless LAN standards, ensuring importance and heralding a new era of OFDM success in a broad range of applications [1] [2].

In FDM, Frequency Division Multiplexing, the main signal is divided into a set of independent signals, called subcarriers in the frequency domain, i.e., the original data stream is divided into many parallel streams one for each subcarrier. After the modulation and subsequent combination of each subcarrier, a FDM signal is obtained. To prevent the spectrum of one subcarrier from interfering with another, a guard band between modulated subcarriers may be required, and therefore the resulting spectral efficiency is low. To overcome this limitation one appellative option emerged, the OFDM, Orthogonal Frequency Division Multiplexing [6].

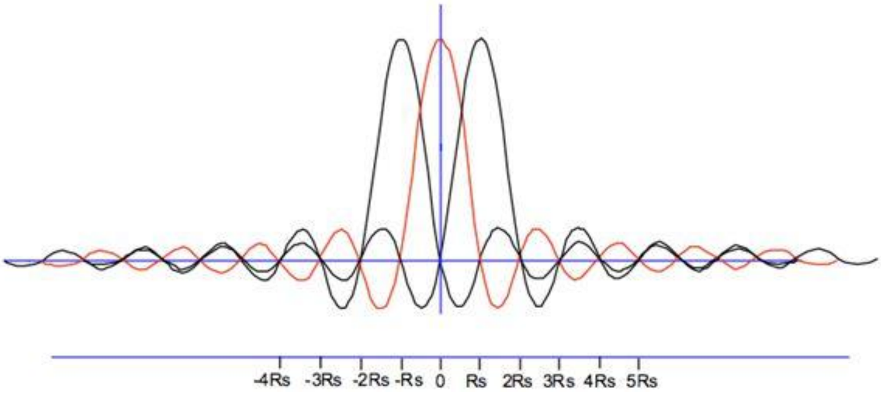

Figure 2.21: Distribution of 3 carriers using OFDM [adapted from 3].

In a simply way, OFDM is just a form of multi-carrier modulation where a high bit rate stream is divided between the sub-carriers and then each low bit rate stream is transmitted in each sub-carrier using a conventional modulation. Such as, quadrature amplitude modulation (QAM) or quadrature phase shift keying (QPSK). Hereupon, OFDM is a combination of modulation and multiplexing making it very efficient in data delivery systems over the phone line, digital radio and television, and wireless networking systems, as referred before [4].

An OFDM symbol spectrum is shown in the figure 2.21, this consists of overlapping *sinc* functions, each one representing a subcarrier where at the frequency of the *kth* subcarrier all other subcarriers have zeros. As desired, the use of orthogonal subcarriers would allow the subcarrier's spectra to overlap, thus increasing the spectral efficiency.

The choice for OFDM as transmission technique could be justified by comparative studies with single carrier systems. And is often motivated by two of its many attractive features, it offers an elegant way to deal with equalized of dispersive slowly fading channels and it is considered to be spectrally efficient.

Main advantages:

- reduces the symbol rate which makes optical OFDM robust against chromatic dispersion (CD) and polarization mode dispersion (PMD); (resilience to dispersive effects);
- Subcarrier frequencies are selected so that signals are mathematically orthogonal over one OFDM symbol period. The spectra of individual subcarriers are partially

overlapped, ensuring that even through the subchannels overlap they do not interfere with each other resulting in high optical spectral efficiency;

- Fast and efficient (de)modulation of the OFDM signal by the implementation of FFT algorithm. Making electronic compensation dispersion possible (EDC);

Main disadvantages:

- Sensitivity to nonlinear effects;
- High peak to average power ratio;

There are two main techniques with several differences in optical OFDM, the direct detection optical OFDM (DDO-OFDM) and the coherent optical OFDM (CO-OFDM).

In case of DDO-OFDM a photodiode is used in the receiver, resulting in simple receiver architecture. Due the use of a guard band between the OFDM band and carrier to overcome the intermodulation, the spectral efficiency is reduced. Another option is to reduce the optical power, but this will limit the reach, so, DDO-OFDM is more suitable for short reach or cost-effective applications.

CO-OFDM, makes use of a local oscillator in the receiver to do the conversion from optical to electrical by coherent detection. This technique requires a laser at the receiver, to generate the carrier locally. The advantages over DDO-OFDM, are the, higher sensitivity, better spectral efficiency/reach trade-off and the electrical compensations more effective. What has been said, leads to the conclusion that, CO-OFDM is better suited for ULH transmissions than DDO-OFDM.

2.7.3.2.1 Block diagram of an OFDM system

The use of an FTTI/FTT pair for modulation and demodulation make it computationally efficient, being the major contribution to the OFDM complexity problem. So, a block diagram of a classical OFDM transmission system scheme using FFT (Fast Fourier Transform) is presented in Figure 2.14.

The technique involves assembling the input information into blocks of N complex numbers, one for each sub-channel. An inverse FFT is performed on each block, and the resultant transmitted serially. At the receiver, the information is recovered by performing an FFT on the receiver block of signal samples. This form of OFDM is often referred to as Discrete Multi-Tone (DMT).

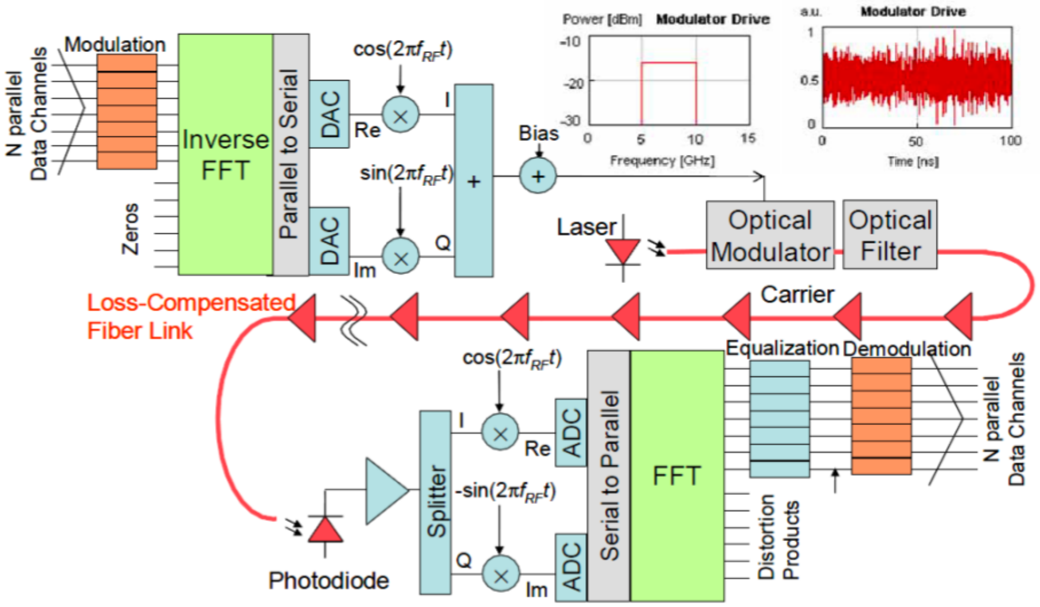

Figure 2.19: OFDM Block diagram [5]

On that OFDM system, each block represents N possible channels of sent data to the OFDM transmitter. The N input signals are modulated into N sub-carriers with the same spacing using Quadrature Amplitude Modulation (QAM) (or in other cases, QPSK). Then, an inverse FFT (IFFT) is performed on each block, and the resultant transmitted serially, on that way, each QAM channel it’s represented by a IFFT input (IFFT block brings the signal into the time domain).

The output of the process explained before, is the summation of all N sinusoids. This output is now modulated by a RF carrier, through a IQ modulator. After, the signal was modulated by a optical carrier using a linear optical modulator. In the output of the optical modulator the signal is filtered to take off all the frequencies except the upper sideband, and the carrier is attenuated. When this is done, the resultant signal is transmitted across the channel.

Now, the signal is converted with I and Q components, and brought to the frequency domain using an FFT block, ie, the information is recovered by performing an FFT. Once in the frequency domain, each channel is equalized to compensate the phase and amplitude distortions. After the demodulation of each QAM channel, N parallel data channel are obtained. Ideally, the FFT output will be the original symbols that were sent to the IFFT at the transmitter.

2.7.4 Advantages and disadvantages of each technology

WDM:

Advantages:

- Extends the capability of transmission as it combines several wavelengths in a single fiber;
- Supports all services in a transparent manner, ATM, Ethernet, TDM, etc;
- With the technology CWDM allows low costs;
- With the technology DWDM allows a better use of the spectrum
- Allows multiplicity of rates and independence of systems;
- Enables the increase of bandwidth used in a fiber without structural changes;

Disadvantages:

- Additional costs in the equipment to generate and filter different wavelengths,;
- Do not have QoS acceptable to the next access generation;
- The technology CWDM is limited in number of channels, so, with low scalability;
- The DWDM technology presents high costs, mainly due to requirements of stability of lasers;

OFDM

Advantages:

- A high speed channel is transformed into a set of independent sub-channels with low bit rate;
- OFDM channels can achieve good performance;
- IFFT and FFT can be performed using digital signal processing techniques, which makes the implementation of OFDM very easy, ensuring that the subcarriers do not interfere with each other;
- High efficiency of bandwidth;
- Energy savings;
- Enables dynamic allocation of bandwidth that cost-effectively increases data rates and flexibility of access networks;
- Tolerance to dispersion, useful for long-haul PONs;
- Allocation bandwidth is performed in the electrical field;

Disadvantages:

- Phase noise of the laser and frequency offset of the carrier can lead to performance degradation;
- OFDM is affected by fiber nonlinearities;
- High energy is required to correctly recover the information;

3 E/G PON tests

The objectives of this chapter is verify the operational points of both technologies, EPON and GPON in what regards their respective standards, so, in this section EPON and GPON systems are characterized. The subsequent test, in chapter 4, relates the extension of any of the technologies by the extender box previously developed in [18] and [19], this box is transparent to the traffic passing, as long as it is not simultaneously bristly and multichannel.

For this purpose, ONUs, optical network units and OLTs, optical line terminations from both technologies, the traffic generator IXIA and some extra optical components are used in the tests.

Within the capabilities of the laboratory, the IXIA is the best and most realistic way to have traffic flowing in the system that is intended to simulate. The tests were made using the 'IxNetwork' software which is remotely connected to the IXIA equipment. The IXIA card used has several copper Ethernet ports that support up to 1Gbps in Full Duplex mode. Any of these ports works bidirectional, allowing the generation and reception of traffic. The application which allows the access to these capabilities is the 'IxNetwork', where the settings will be entered, the traffic configured and the results analyzed.

Figure 3.1 below represents the generic test setup where OLT, ODN and ONUs are connected. The OLT and ONUs are connected through two routes, ODN (optical path) and IXIA generator, allowing transmissions in both directions, upstream and downstream.

When downstream is intended, the IXIA generates traffic and inserts it into the OLT through the 1Gbps Ethernet cable, then the OLT directs the traffic to the ONUs by the ODN. On the ONUs side, depending on the technology different top speeds are received as will be discussed later in this document.

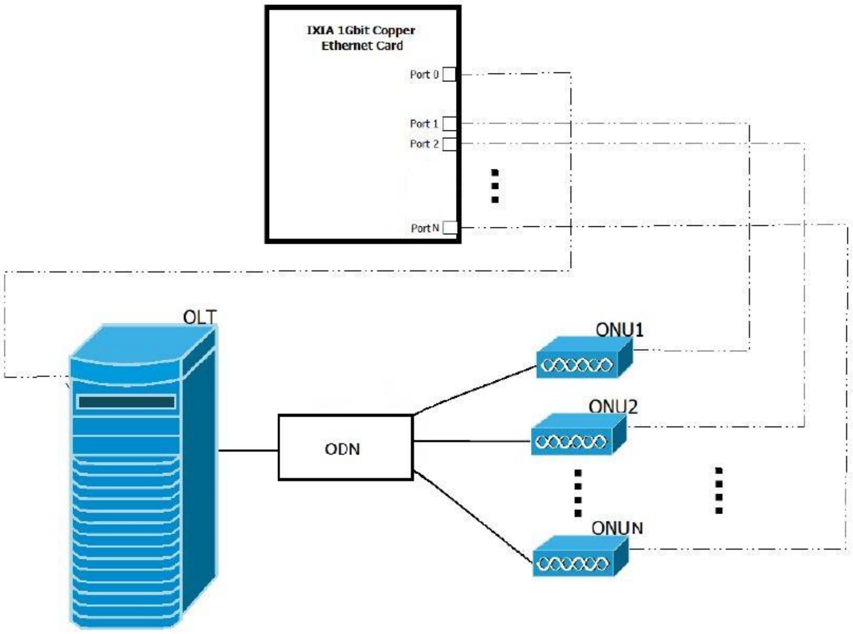

Figure 3.1: Generic test setup [adapted from 17]

When upstream transmission is intended, the traffic generated by IXIA is introduced in the ONUs and then directed to the OLT side by the ODN. Depending on the technology different top speeds are allowed as will be discussed later in this document.

Only after configuring all the ports and the traffic model, the OLT and ONUs are capable of performing traffic transmission, and the result analysis can be done. How to configure the ports and the traffic for each specific case will be explained in sections 3.1 and 3.2 respectively for EPON and GPON.

The results are presented on the form of statistics in the program 'IxNetwork', where the following statistics can be highlighted:

- Frames Sent – total number of packets sent
- Valid Frames Received – total number of valid packets received
- Bits Sent – total number of bits sent
- Bits Received – total number of valid bits received
- PER – Packet Error Rate

The analysis made in this work was based in the Packet Error Rate, PER, which is given by the equation 3.1, being a relation between valid received packets and transmitted packets, the optimum value to PER is zero (in a generic case scenario), this is, the smaller the better PER. A packet is considered valid when all the bits are correctly received.

$$\boldsymbol{PER = 1 - \frac{Valid\ Received\ Packets}{Transmitted\ Packets}} \tag{3.1}$$

For simplicity, from now on the IXIA will not be represented, but will always be used to analyze the system performance.

3.1 EPON measurements

The EPON equipments used here, OLT-AN5116-02 and ONU-AN5006-074 are from Fiberhome. The detailed description is presented in figure 3.3 and table 3.1 for OLT and table 3.2 for the ONU.

By using the OSA, Optical Spectrum Analyzer, the spectrum of the EPON OLT was measured, as represented in figure 3.2. The same measure is not possible for the ONU as will be explained.

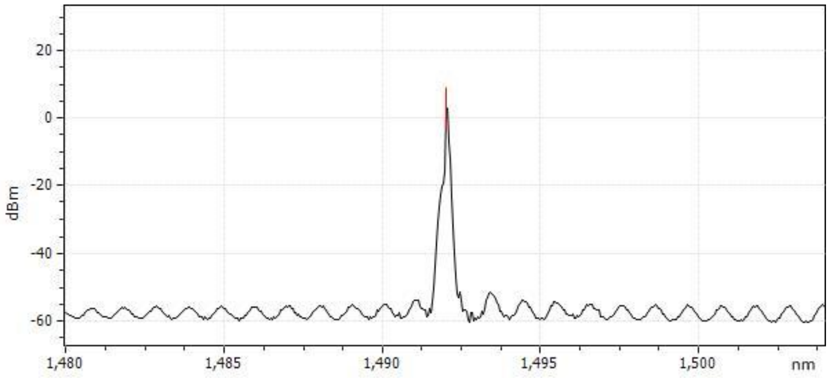

Figure 3.2: EPON OLT spectrum.

Figure 3.3: (left) OLT-AN5116-02 rack and power supply (right) ONU – AN5006-074

Table 3.1: EPON OLT characteristics

Manufacturer	FiberHome
Model	AN5116-02
Transmitter wavelenght	1490 nm
Receiver wavelength	1310 nm
Trasmit power (standard)	+2 to +7 dBm
Trasmit power (measured)	+3 to +5 dBm
Maximum receive power	-6 dBm
Receive sensitivity (standard)	-27 dBm
Receive sensitivity (measured)	-27 dBm
Transmit rate	1.25 Gbps
Receive rate	1.25 Gbps
Connector type	SC-PC
Power supply	DC -48V
Working temperature	0ºC to 45ºC

Table 3.2: EPON ONU characteristics

Manufacturer	FiberHome
Model	AN5006-05
Transmitter wavelenght	1310 nm
Receiver wavelength	1490±10 nm
Trasmit power (standard)	-1 to +4 dBm
Trasmit power (measured)	+4 dBm
Maximum receive power	-3 dBm
Receive sensitivity (measured)	-24 dBm
Receive sensitivity (measured)	-28 dBm
Transmit rate	1.25 Gbps
Receive rate	1.25 Gbps
Connector type	SC-PC/SC-APC
Power supply	DC +12V
Working temperature	-10ºC to 45ºC

NOTE: The ONU sensitivity has shown a variance with time (temperature) and also hysteresis with the input power.

3.1.1 ONUs Maximum Line Rate

To characterize the EPON ONUs and to be sure the traffic is sent at speeds that introduces no errors, i.e., without any packet loss. It is essential to test the effective maximum rate bearable at the ONUs side.

In case of EPON there are six ONUs available in the laboratory, so, the maximum line rate tests were based in the setups of figure 3.4, (a) for downstream traffic and (b) for upstream traffic. With this test we are investigating if it is possible to assign the maximum line rate allowed by the ONUs Ethernet port (100Mbps). Within the capabilities of the laboratory, this is, with the ONUs available, we are not able to test the OTL capacity. By joining the six ONU the maximum rate that can be achieved is 600Mbps (theoretically).

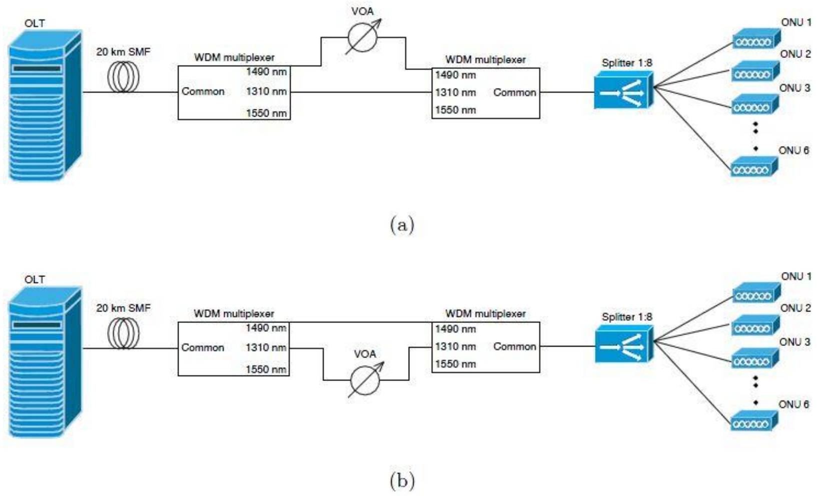

Figure 3.4: EPON line rate setup (a) downstream, (b) upstream [18]

To separate the traffic for down and upstream two WDM multiplexers (Add/Drop filters) were used and a VOA was placed in between to control the power, thus emulating different power budgets. To connect the six ONUs a 1x8 optical splitter was used, and finally, to have some dispersion in the system, 20km of SMF fiber were placed after the OLT. Before the tests the Add/Drop Filters were characterized as presented in the table 3.3, and the fiber and splitter losses were measured. These measurements are very important because the total loss should not exceed the loss budget, otherwise error-free transmission would not be possible.

Table 3.3. Add/Drop Filters characteristics.

Parameter	**Units**	**Value**
Passband	nm	1490±10
Reflection band 1	nm	1310±10
Reflection band 2	nm	1550±10
Insertion loss @ 1490nm	dB	0.63
Insertion loss @ 1310nm	dB	0.75
Insertion loss @ 1550nm	dB	0.88
Isolation @ 1490nm	dB	≥ 30
Isolation @ 1310nm	dB	≥ 20
Isolation @ 1500nm	dB	≥ 15
Return losses	dB	≥ 50
Operating temperature	°C	-40 ~ +85

For the splitter 1:8 a average loss of about 11dB was obtained and for the 20km a fiber attenuation of about 7dB@3100nm, 5dB@1490nm and 4dB@1550nm. As can be seen in table 3.3, the loss of each WDMs is around 0.6 to 1 dB.

For the tests, in both cases up and downstream, the traffic introduced was unidirectional. When testing the upstream link the downstream link must remain connected to allow the OLT and the ONUS to complete the acknowledgement process and setup links.

The setups used for the two measurements are similar, but the attenuation between end points has to be measured in different ways. In case of downstream it is trivial to gauge the power budget by measuring the optical power coming from OLT and arriving to the ONUs with a power meter and then calculate the difference, i.e., |POLT-PONU| dB. However, the upstream transmission is made in bursts, meaning that a packet takes a little time in the US frame, making the power too small to be measured in the same way as for downstream. The solution is to place an auxiliary laser emitting at 1310nm in each iteration instead of the ONUs, and then measure the power at the OLT, obtaining the difference, |POLT-PONU| dB.

The relation between PER and different line rates for downstream at different attenuation values is represented in figure 3.5, this PER is the average value between the PER of the six ONUs.

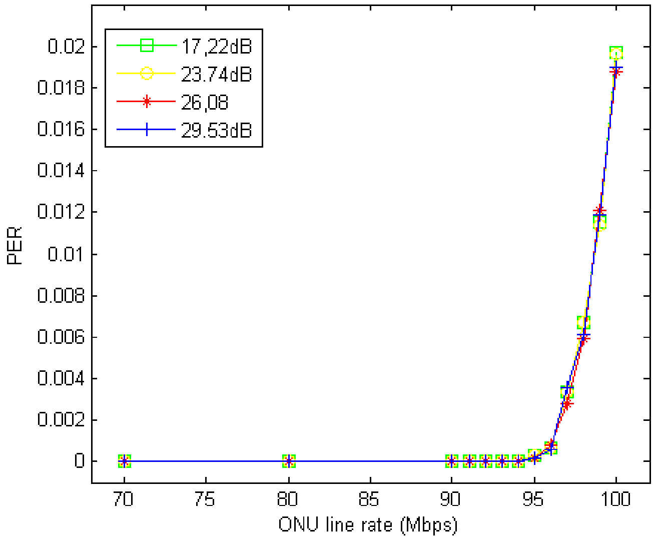

Figure 3.5: Downstream packet error rate for different line rates at different attenuations of EPON ONUs.

The line rate varies in the same way independently of the applied attenuation as can be seen in figure 3.5. Up to 91Mbps the PER remains zero, but after, it starts to rise with the increasing line rate until it gets the maximum 100Mbps imposed by the Ethernet ports. The differences between all the ONU are minimal so the representation is dispensable.

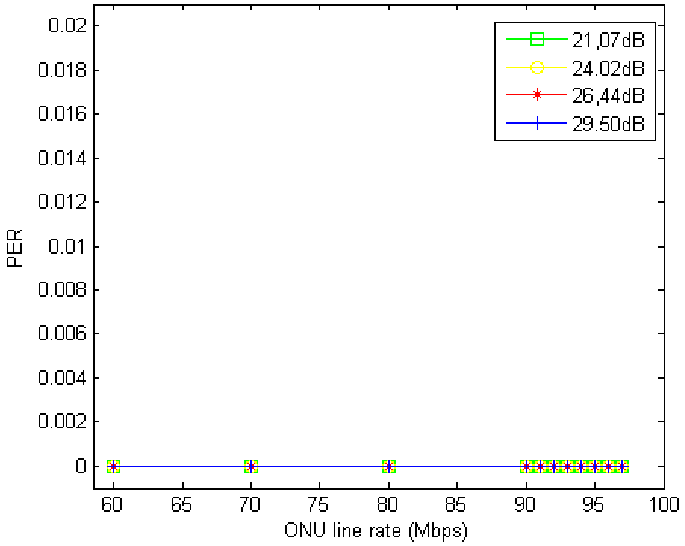

Figure 3.6: Upstream packet error rate for different line rates at different attenuations of EPON ONUs

In upstream, for the line rate tests the PER is always zero, figure 3.6. The maximum rate reached was 97Mbps, because the ONUs are limited to about 100Mbps. As explained before, by using six ONUs should be possible to send 600Mbps to the OLT (six ONUs each transmitting at 100Mbps), but with the 97Mbps limitation and without more ONUs, the maximum attainable value will be less, ~582Mbps.

Analyzing the two results together, figure 3.5 and 3.6, the line rates with operation without errors should be lower than 91Mbps. So, from now on we are setting by software the line rate to 90Mbps, assuring in this way that the tests performed further are not due to line rate.

3.1.2 Maximum Power Budget

This section aims to characterize the EPON system in terms of maximum power budget. In a real system, the total loss should never exceed the loss budget, otherwise error-free transmission is not possible.

In order to realize these measurements, the setup was the same as for the previous test, figure 3.4, with the difference that only one ONU was used. The VOA is also used to vary the attenuation, obtaining different power budgets. But unlike the test before, here is used a fixed rate, 90Mbps.

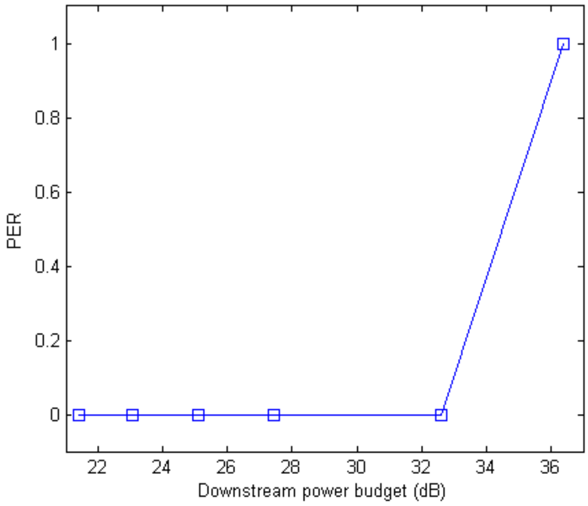

Figure3.7: Downstream packet error rate for different power budgets of EPON.

For downstream the maximum power budget obtained was about 32.6dB and for upstream of about 31.1dB, as represented in figure 3.7 and 3.8 respectively.

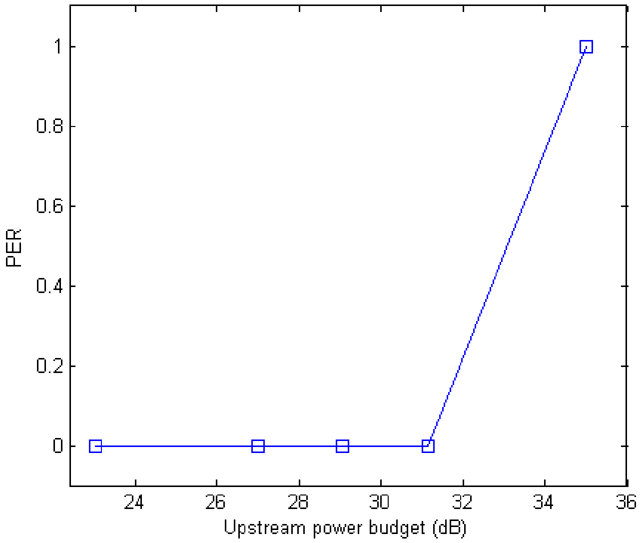

Figure3.8: Upstream packet error rate for different power budgets for EPON.

For higher values, i.e., higher than 32.6 for downstream and higher than 31.1 for upstream, the PER starts to increase until it gets the maximum (1, all the packets are lost) and the ONUs did not registered, a 100% of packet loss correspond to 36dB for downstream case and 35dB for the upstream.

As a matter of convenience and to simplify the results, rounded values are considered, so it is assumed that the maximum power budgets are 32dB and 31dB for downstream and upstream respectively.

3.1.3 Maximum Reach

To determine the maximum reach, the setup represented in figure 3.9 was used. Once the values of maximum rate and maximum power budget are known, for the maximum reach test it’s possible to set a value of attenuation and rate not susceptible to errors.

The insertion loss of the Splitter is approximately 11dB which added with the VOA attenuation, about 7dB, and the 20km of SMF, about 5dB (@1490nm), cannot go close the limit. Thus, the amount of fiber can be varied without exceeding the maximum attenuation allowed.

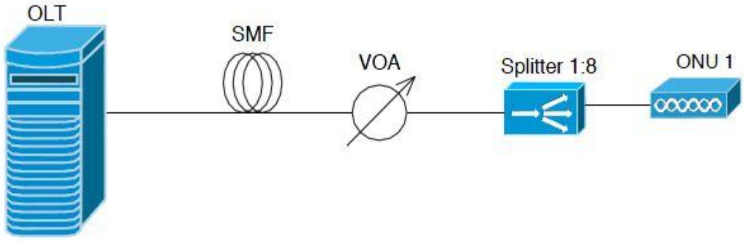

Figure3.9: EPON maximum reach setup [18]

The standard defines the maximum achievable reach as 20km, so, to it would be the starting fiber length to be introduced in the system. At this distance, it can be seen in figure 3.10, there are no packet losses.

Then the fiber length was successively increased of every hundred yards by using different amounts of fiber from the fiber rack. The length of fiber was increased until there is a packet loss of 100%, i.e., a PER of 1. Thus by doing this it was found the maximum length, i.e., the maximum length for which the PER is null.

The values obtained are represented in figure 3.10, because at 23,7km some packets start getting lost. This reads as the EPON system has a tolerance of 3km to the standard. With 26km the ONU is not registered, therefore no transmission is achieved leading to a PER of 1 as can be seen in figure 3.10.

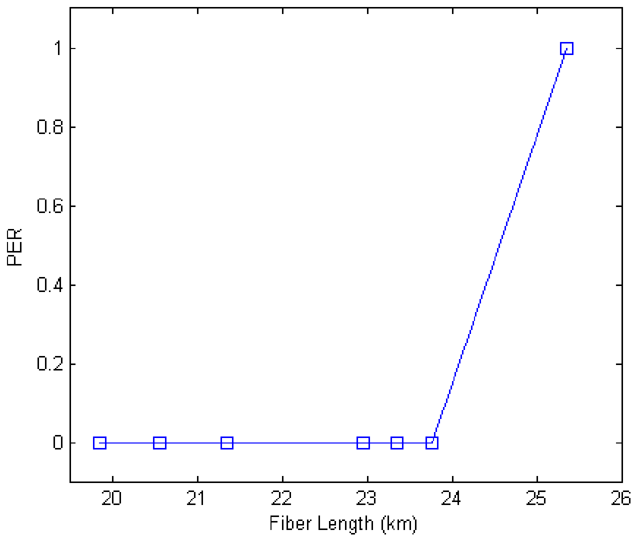

Figure3.10: Packet error rate for different fiber lengths for EPON.

3.2 GPON

The GPON equipments used here, OLT7-8CH and ONT7RF1GE are from ‘PT Inovação’. The detailed description is presented in figure 3.12 and table 3.4 for OLT and 3.5 for ONU. The characteristics relative to measurements were obtained only when completed this section, however, are already presented.

By using the OSA, Optical Spectrum Analyzer, the spectrum of the EPON OLT was measured, as represented in figure 3.11. The same measure is not possible for the ONU, because it transmits in bursts.

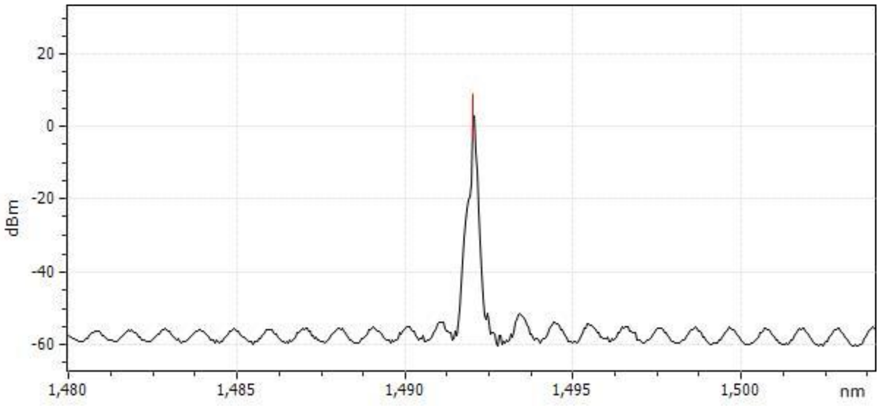

Figure 3.11: GPON OLT spectrum

Figure 3.12: (left) OLT- OLT7-8CH (right) ONT7RF1GE

Table 3.4: GPON OLT characteristics

Manufacturer	PT Inovação
Model	OLT7-8CH
Transmitter wavelenght	1490 nm
Receiver wavelength	1310 nm
Trasmit power (standard)	+1,5 to +5 dBm
Trasmit power (measured)	+3 to +4 dBm
Maximum receive power	-8 dBm
Receive sensitivity (standard)	-28 dBm
Receive sensitivity (measured)	----
Transmit rate	2.5 Gbps
Receive rate	1.25Gbps
Connector type	SC-PC
Power supply	DC -48V
Working temperature	-5 to +85 ºC

Table 3.5: GPON ONU characteristics

Manufacturer	PT Inovação
Model	PTINONT7RF1GE
Transmitter wavelenght	1310 nm
Receiver wavelength	1490 nm
Trasmit power (standard)	+0,5 to +5 dBm
Trasmit power (measured)	------
Maximum receive power	-8 dBm
Receive sensitivity (standard)	-27 dBm
Receive sensitivity (measured)	-31 dBm
Transmit rate	1.25 Gbps
Receive rate	2.5 Gbps
Connector type	SC-APC
Power supply	DC +12V

3.2.1 ONU Maximum Line Rate

The first, and essential, test that has to be done is the effective maximum line rate that can be achieved for both directions, downstream and upstream. In case of GPON it is crucial because there is not enough information about the ONUs, this is, there are no previous results to make comparisons.

As mentioned in table 3.4, the maximum speed the OLT can receive, 1.25Gbps, cannot be achieved in practice with the number of ONUs available in the laboratory. For the ONUs the expectations are 1.25Gbps for upstream and 2.5 for downstream, however, by using IXIA 1Gbps card we are limited.

The figure 3.13 below shows the setup used for the maximum line rate tests, (a) for downstream and (b) for upstream. To clarify the ONUs operation and to understand how and if the conditions vary for different numbers of ONUs, the setups 3.13(a) and 3.13(b) were twice implemented. Once with only one ONU connected on the network and another time with the two ONUs connected at the same time.

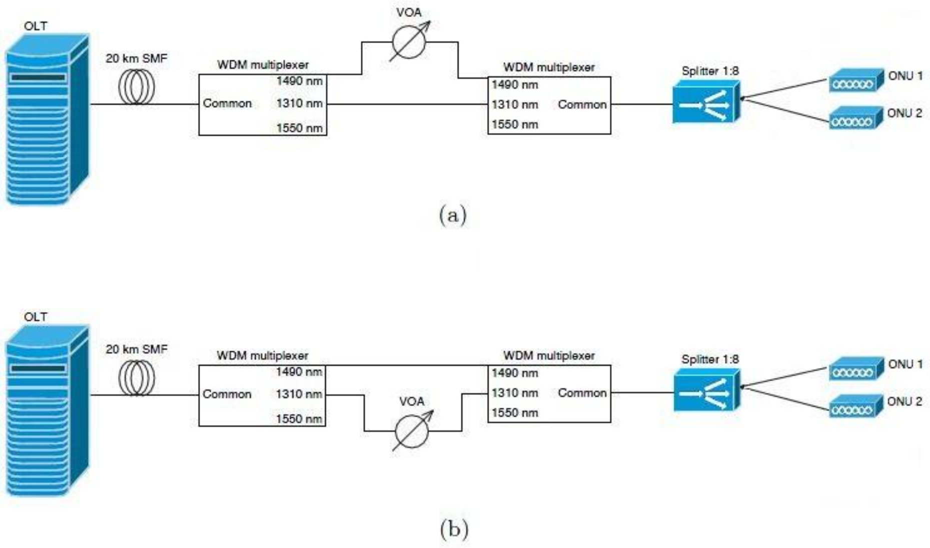

Figure 3.13: GPON line rate setup (a) downstream, (b) upstream.

The result of the first test, maximum downstream rate with only one ONU connected, figure3.14, shows that is possible to go almost until 1Gbps (the IXIA card maximum capacity) l maintaining a PER of 0 (at least until 975.43Mbps error-free transmission is possible). The limit of 975.43Mbps is imposed not because there is some packet loss in the network, but because of the IXIA 1G card. In practice, a warning message appeared in the IxNetwork software not letting go beyond this rate.

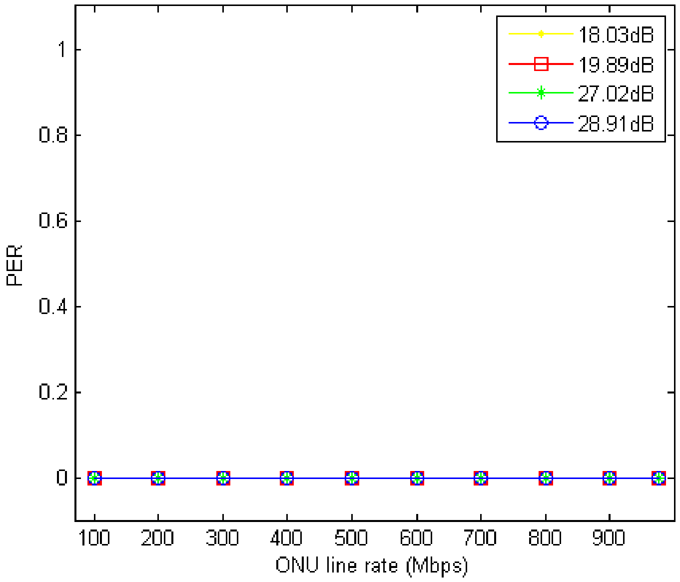

Figure3.14: Downstream packet error rate for different line rates at different attenuation values in the ODN for GPON with one ONU.

After, when testing the two ONUs at the same time, figure 3.15, it was realized that the system behaved in the same way but having a different limit to the maximum rate, in this case 487,.71Mbps, i.e., a value half of the previous result (975.43Mbps).

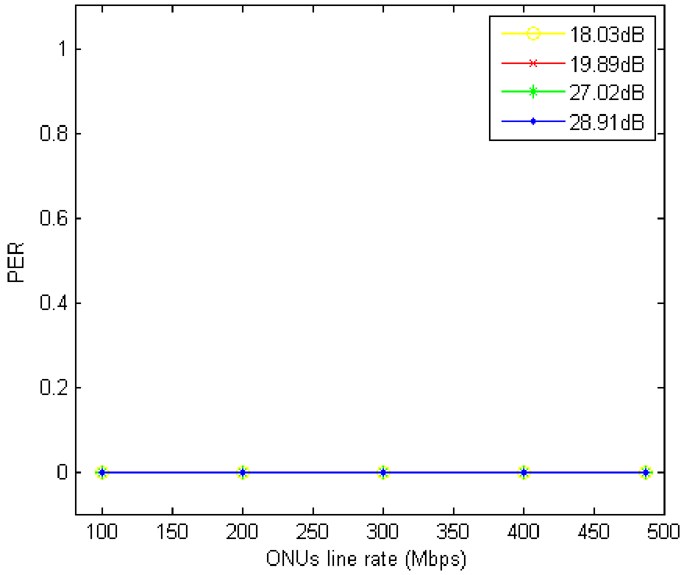

Figure3.15: Downstream packet error rate for different line rates at different attenuation values in the ODN for GPON with two ONUs.

By those two tests some conclusions can be drawn:

- Within the tested limits, the attenuation does not affect the rates, at least the ones tested (from 100Mbps till 973Mbps), so, the rates are imposed by hardware limitations and not by the attenuation;

- When using more than one ONU the rate is symmetrically separated, this is, with one ONU connected the rate received is 100% of 975.43Mbps (IXIA card limitation), with two 50% of 975.43Mbps and so one, this is because the capacity of 1G card is equally shared by all the terminals by default. However, the 'PT inovação' provides an interface where different profiles can be created for each client;

- There is no limitation concerning to the ONUs at least for the rates tested (less than 975.43Mbps), so, any conclusion about the downstream top speed of the ONUs can not be made.

For the upstream transmission the same two tests were made, with only one ONU connected and with two ONUs connected. By looking at the results of the two ONUs tested separately, figure 3.16, it can be seen a little difference among the ONUs behavior, the ONU1 is able to send upstream traffic at speeds slightly higher than ONU2 without errors.

The ONU1 achieved 700Mbps and the ONU2 800Mbps with a packet loss of zero, the ONUs are sensitivity to temperature variations, so, this difference could be due to that fact. The worst case should be taken as reference, therefore it is assumed that the top rate for upstream is 700Mbps.

With the two ONUs connected and transmitting at the same time, a similar behavior was observed, figure3.17, the differences among them are almost negligible and error-free transmission (PER of 0) for rate values of about 450Mbps were achieved with success.

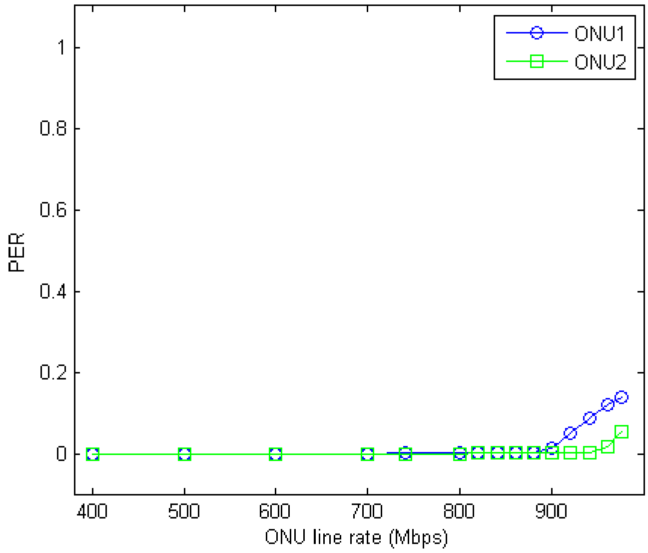

Figure3.16: Upstream packet error rate for different line rates for each one of the two ONUs

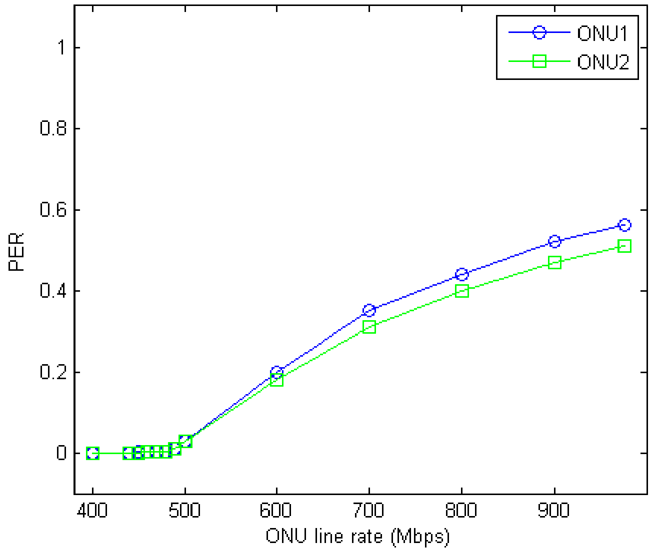

Figure3.17: Upstream packet error rate for different line rates for two ONUs.

3.2.2 Maximum Power Budget

This section aims to characterize the GPON system in terms of maximum power budget. As referred before, in a real system, the total loss should never exceed the loss budget, otherwise error-free transmission is not possible and this is why the measurement is so important.

In order to realize these measurements, the setup used was the same as for the previous test, figure 3.13. Some differences were found between the two ONUs in the rate tests (section 3.2.1). So, unlike the EPON maximum power budget measurements where only one ONU is used, in case of GPON the two ONUs were used in order to investigate if the ONUs also differ in terms of maximum power budget.

For the downstream transmission, the maximum power budget obtained was, 34,45dB for ONU2 and 35,09dB for ONU1, as represented in figure 3.18 below. At this points the PER was zero, henceforth for higher attenuation values the packets start to be lost. For attenuation values of 36.6 and 35.9 respectively for ONU1 and ONU2, the ONUs can't register, which translates into inability to make transmissions.

Analyzing the results, the worst case is 34.45dB (ONU2), so, it's assumed that the maximum downstream power budget is the rounded value of 34dB.

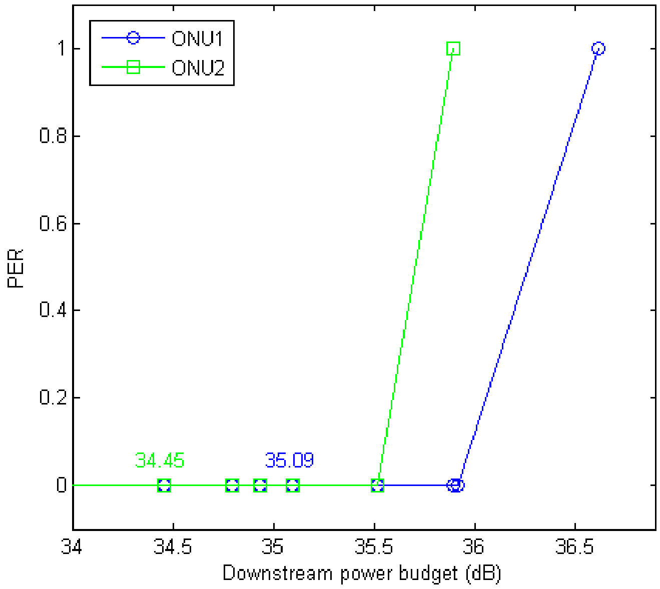

Figure3.18: Downstream packet error rate for different power budgets for GPON.

For the upstream maximum power budget measurements, as noted above, an external laser was used which caused distortion to the setup, making the upstream measurement more suitable for errors.

As can be seen in figure 3.19, the maximum power budget obtained was 32.54dB for ONU2 and 32.63dB for ONU1. For higher attenuations the PER starts to increase until it reaches the maximum (100% of errors), about 33.8dB for ONU2 and 35dB for ONU1. By rounding and taking into account the worst case, the maximum upstream power budget is considered to be 32dB.

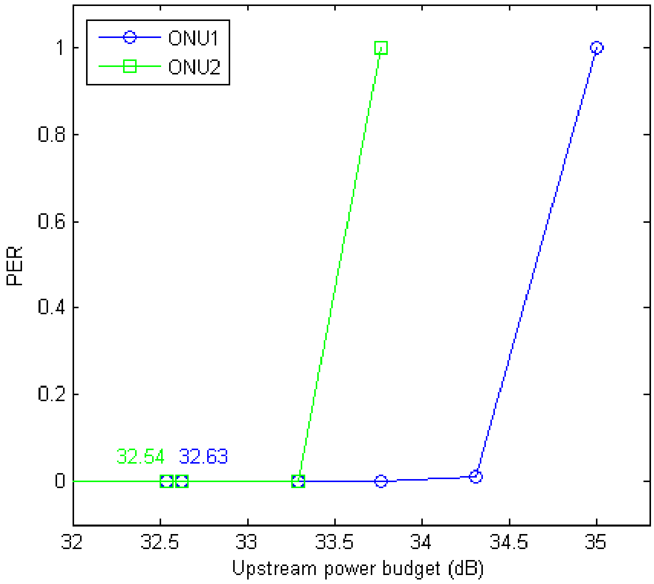

Figure3.19: Upstream packet error rate for different power budgets for GPON.

3.2.3 Maximum Reach

With GPON network subsystems, the setup of figure 3.9 was implemented, with a total attenuation of about 24dB between the end points. While sending the packets at 500Mbps the length of fiber was varied, starting with 19,80km until getting values where PER is 1.

The total attenuation and the line rate were set at safe values, i.e., at values that introduce no errors as tested in previous sections, 3.2.1 and 3.2.2.

The result shown in figure 3.20, a maximum packet error value of about 21.5km was obtained. For greater values the ONU is unable to register so the PER is one.

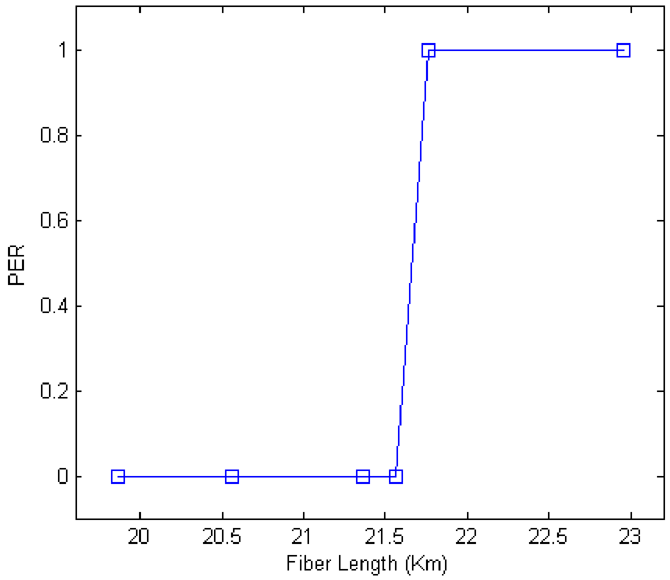

Figure3.20: Packet error rate for different fiber lengths of GPON.

3.3 Comparison

In order to simplify the comparison of results, the table 3.6 below contains the values obtained in the previous tests for both EPON and GPON technologies.

Table 3.6: Summary table for EPON and GPON.

	EPON		**GPON**	
	DS	US	DS	US
Maximum rate (Mbps)	91	>97	>975	700
Maximum power budget (dB)	32	31	34	32
Maximum reach (km)	23		21	

For maximum rate not all the results are conclusive. In any case one hint can be taken, supposing that the maximum upstream rate for EPON will not pass the 700Mbps, can be assumed that the ONUs from GPON are better in both directions. In downstream the maximum rate is at least ten times greater than those of the EPON ones int the lab, a substantial advantage.

In terms of power budget, GPON overcomes the EPON in both directions, for downstream transmission by 2dB and for upstream by 1dB.

The last test, maximum reach, is the only one unfavorable for GPON, and where the EPON overcomes it by a difference of 2km. Anyway this GPON overcomes the standard by 1km.

Apart from the results presented, GPON have more relaxed ranges for the sensitivity, the OLT is 3dBs better and the ONU 8dB as discussed before in chapter 2. As expected, led us to the conclusion that GPON system as several technical advantages when compared with a EPON system.

4 Extender Box

In almost all the cases GPON technology is able to satisfy all the costumers with no big changes, but in some specific cases, as dispersed and rural scenarios the standard equipment cannot provide service. One way to solve the problem could be the installation of new equipments, this is, equipment of superior class, but this, sometimes may not be enough.

The necessity to reduce resources for GPON installation led the equipment developers to put on the market, available for the service providers, devices capable of increasing the physical reach of the signal.

In this context, this chapter presents an extender box previously developed and the tests results in a GPON environment studied in the previous chapter.

After being designed and proven to work in [18] and [19], in this chapter the extender box is detailed and more exhaustively tested for GPON technology. The extender is characterized in terms of power budget boundaries, the best operation point found, the monitoring and control done and finally the main functionality is tested, this is, a error-free transmission for 60km and 128 clients.

4.1 Previous Developments

In previous developments three different devices were studied, the PON.ext of Alphion, GPON Extender v1.1 of Telnet and the Intelligent Pon Node of Teknovus. The three are based in different technologies, namely optical amplifiers, electrical repeaters and a conjugation of electrical repeaters and WDM. The advantages and disadvantages of each of the reach extender, led the author of -[17] to the conclusion that the best option would be based the solution on optical amplifiers, as an all optical solution was desired.

The next step was to evaluate the possibilities regarding the option based on optical amplifiers. Three types were studied, the doped fiber amplifiers, DFA, the semiconductor optical amplifiers, SOA and Raman amplifiers. In GPON technology O and S band are used. In these bands, SOAs have an acceptable noise figure, high gain and rapid response to changes in input signal. Also have the advantage of being small and cheaper when compared with other amplifiers for the desired bands. Within the market options, the amplifiers chosen in [17] were the SOAs, their capability was proved and besides the referred additional control to operate in burst mode is not needed [19].

For S band the amplifier chosen was the CIP SOA-S-OEC-1550, its large bandwidth allows its use at 1490nm and for O band the amplifier chosen was the Alphion SOA29p. Results from [17] and [18] proved that the minimal values for noise figure are obtained for 145mA of bias current for the CIP and for the Alphion of about 445mA.

Then, a prototype designed, as depicted in figure 4.1, considering the best operation point for the SOAs.

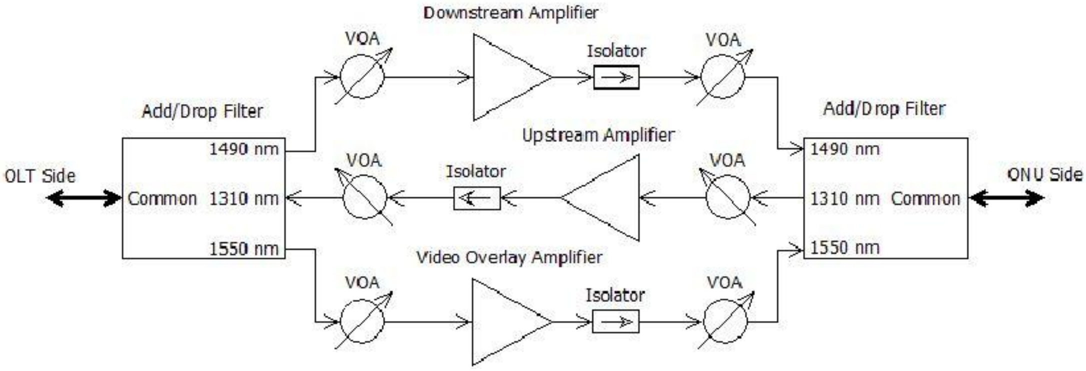

Figure 4.1: Extender prototype, first proposal [17]

The channels are separated and then added by add/drop filters, acting as noise filters too. The isolators after each amplifier protect the amplifiers from reflections.

In [18] the author discussed that the implementation of isolators as depicted in figure 4.1, could not be the most efficient choice, and by testing the different options, isolator before the SOA and isolator after the SOA. It was concluded that if placed before the SOA the reflections and noise figure can be reduced, thus leading to a more efficient amplification at the specified wavelength. The change is done for both upstream and downstream.

Monitoring photo-detectors to measure the input and output power of the amplifiers through the use of 1%:99% couplers were considered in [18]. The results would then be parsed by a controller. This device would also be responsible for setting of the variable attenuator, the initial configuration or further adjustments, as well as for displaying the monitoring values.

Based on the previous consideration some chances were done and a new prototype was proposed, as represented in figure 4.2.

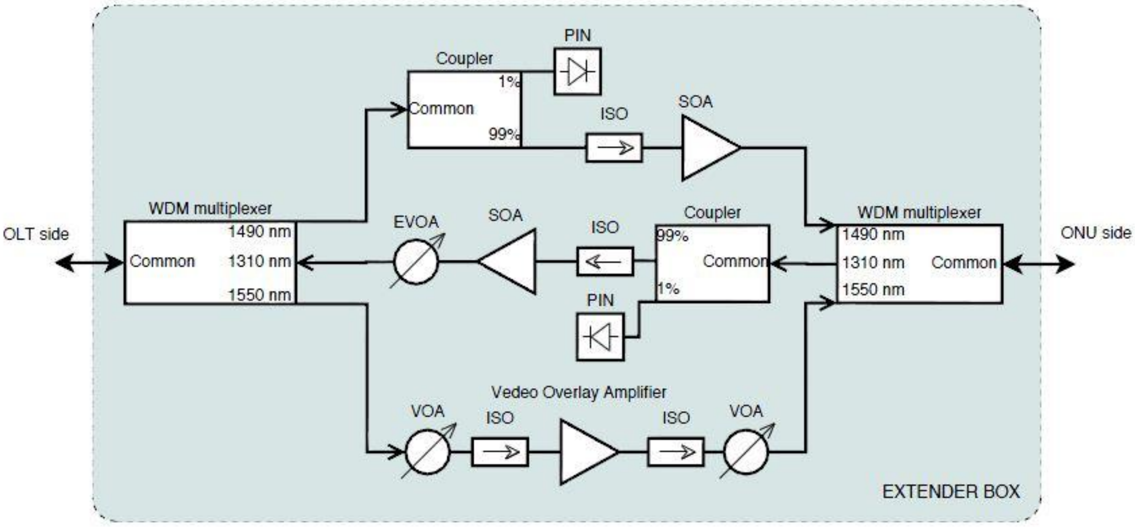

Figure 4.2: Extender prototype, last proposal [18]

4.2 Status

These prototype tested in [18] did not have the video overlay amplifier, the components were not assembled together in the box and self configuration was still under construction. Also, the tests were done in a EPON scenario and not GPON as desired.

Meanwhile all the extender box optical components and the microcontroller were assembled together following the suggestions in [18], but the video channel was still not included in the box. The function diagram followed illustrated in figure 4.3, is the same as presented in [18] with different input power range. The actual front view of Extender Box is presented in figure 4.4 and a view of the box inside in figure 4.5.

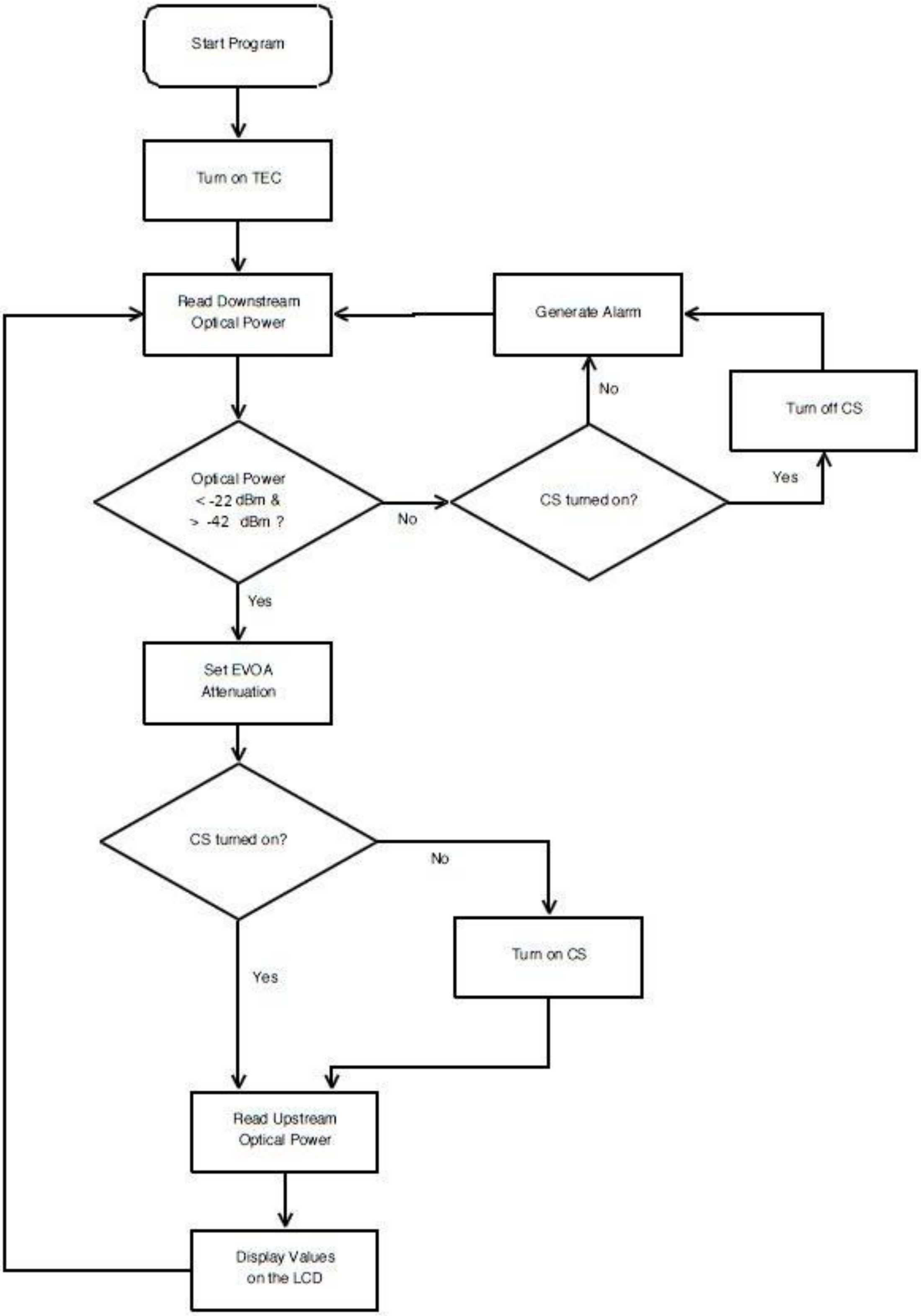

Figure 4.3: Functional diagram [adapted from 18].

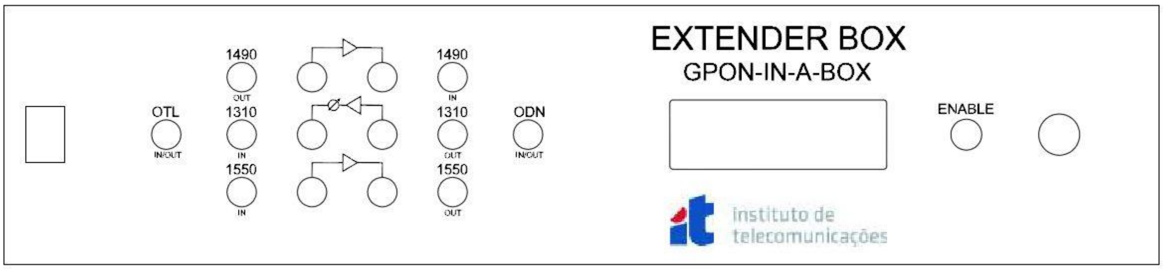

Figure 4.4: Front view design.

As can be seen in figure 4.4, from the outside it is possible to access to the add/drop filters input(s) and output(s) and also to the input and output of the amplification path.

The power supply is placed in the back side and a switch in the front side, also a enable button is included and the program sequence only starts after pressing it, then followings the functional diagram, figure 4.3. The video channel was not developed but the box is prepared to this upgrade.

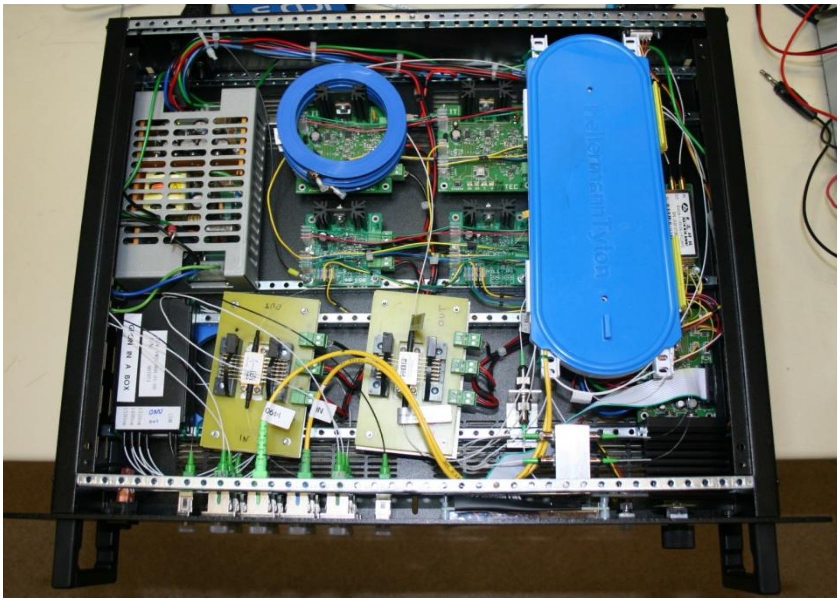

Figure 4.5: Extender Box inside view.

From figure 4.5 can be seen that inside the box there is still some free space to include the video amplifier.

In the scope of this work we tested the Reach Extender with the referred interfaces as depicted in figure 4.6, with all improvements from [18] and the microcontroller included.

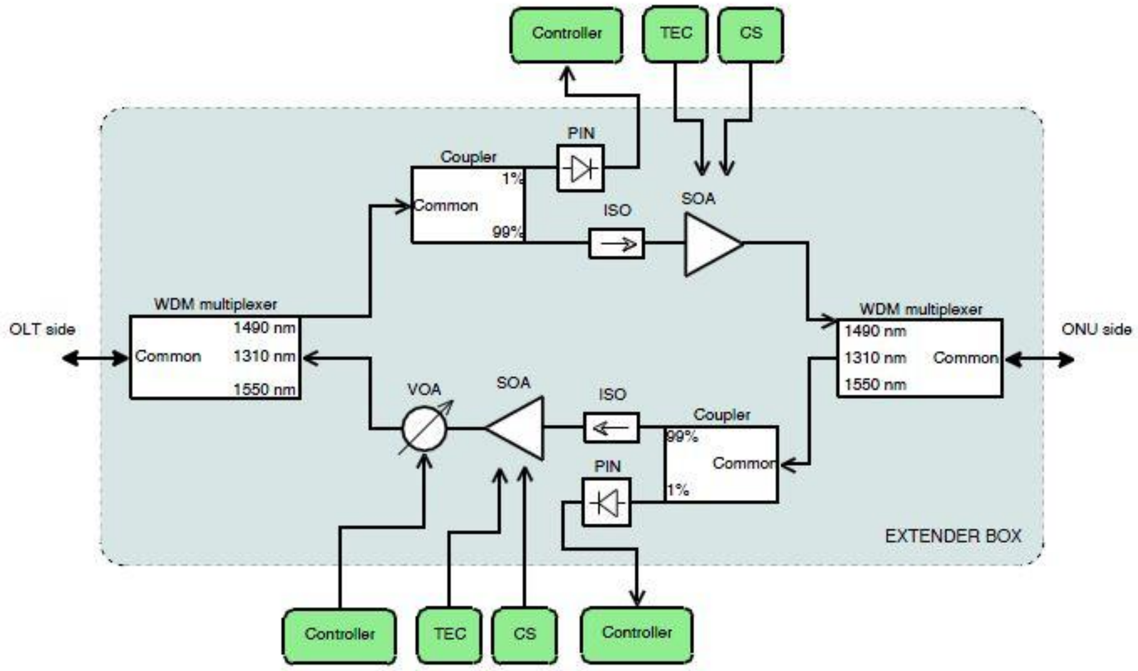

Figure 4.6: Extender BOX and interfaces

Further developments were to characterize the Extender Box with all the components assembled, find the best operation point in the GPON environment and to perform the monitoring tests, to enable the Extender to automatically configure itself independently from the input.

4.3 Power Budget Boundaries in a GPON environment

This section aims to define the power budgets imposed by the extender box in different scenarios, by inserting it in a real network. Two questions have to be answered, how far from the OLT can the Extender be placed and what is the achievable splitting ratio.

In order to analyze the possible scenarios two variables were changed, the attenuation between OLT and Extender Box, this is, the power budget in the OTL (optical trunk line) and the attenuation between Extender Box and ONUs, this is, the power budget in the ODN (optical distribution network).

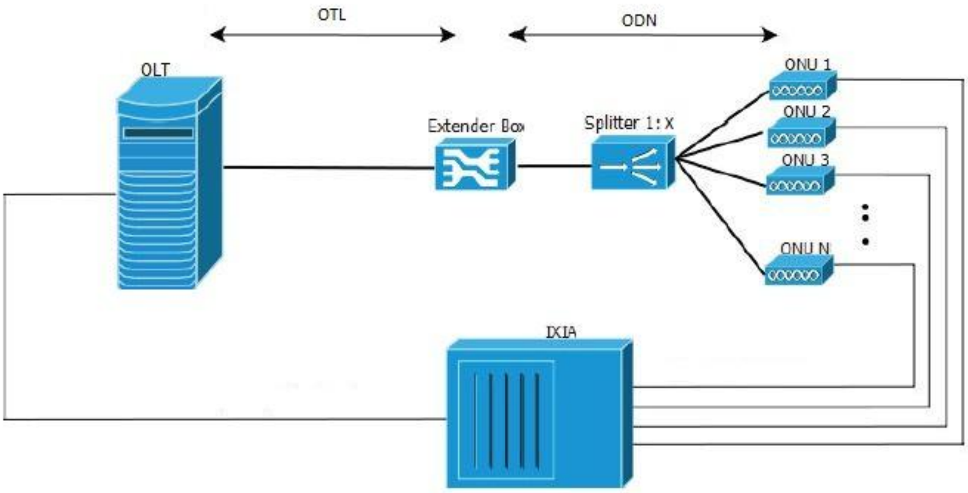

Figure 4.7: Extender Box general setup test.

The schematic of figure 4.7 represents the general but not realistic setup implemented in the laboratory. For the tests, in reality we emulate the splitting ratio using a tunable attenuator and not a splitter. The IXIA was always used in these power budget boundaries measurements, so in future schemes the generator will not be represented to simplify the figures.

4.3.1 Downstream

The setup used is shown in figure 4.8, as mentioned before, for the previous tests done in [17] and [18] the Extender Box wasn't assembled in a closed box unlike the current version, where strategic points are accessible from the outside of the box as seen before (subchapter 4.2).

To perform the desired variations in the power budget two VOAs are placed in different sides of the extender box. Because these two attenuators are not part of the extender box and are placed in the path, i.e. after and before the add/drop filters (VOA1 and VOA2 respectively), in the figure 4.8 they are surrounded by dashed traces. In the upstream link the extender is not performing any amplification, i.e., a patch core is placed to connect the 1310nm ports of the WDM multiplexers just to have the up and downstream traffic separated.

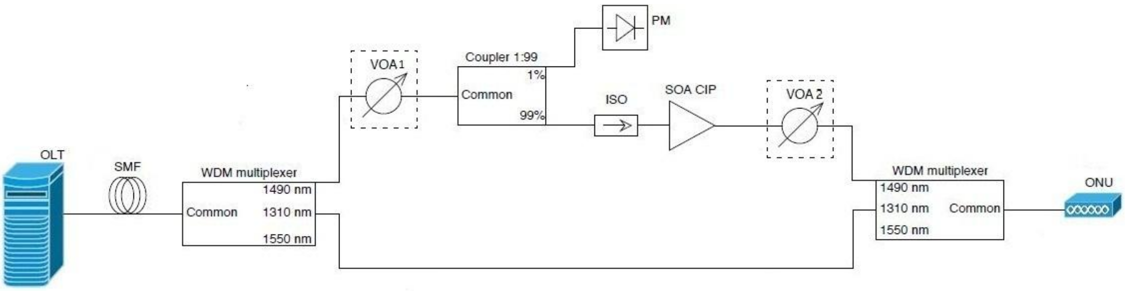

Figure 4.8: Experimental setup to test downstream power budget boundaries.

With VOA1 different values were fixed for the OTL power budget, then with VOA2 the attenuation in the ODN was varied for each value fixed in the OTL. For each of these fixed attenuation values in the OTL, variations from 13dB until the maximum allowed with PER zero were done.

The standard defines a maximum of 23dB in the OTL and between 13dB and 28dB in the ODN. As can be seen in figure 4.9 for all the values of OTL power budget the standard is fulfilled. For 25dB OTL, the power budget in the ODN goes till 31dB overcoming the defined by 3dB. Higher values in the OTL weren't used, due to the limited attenuation of VOA1.

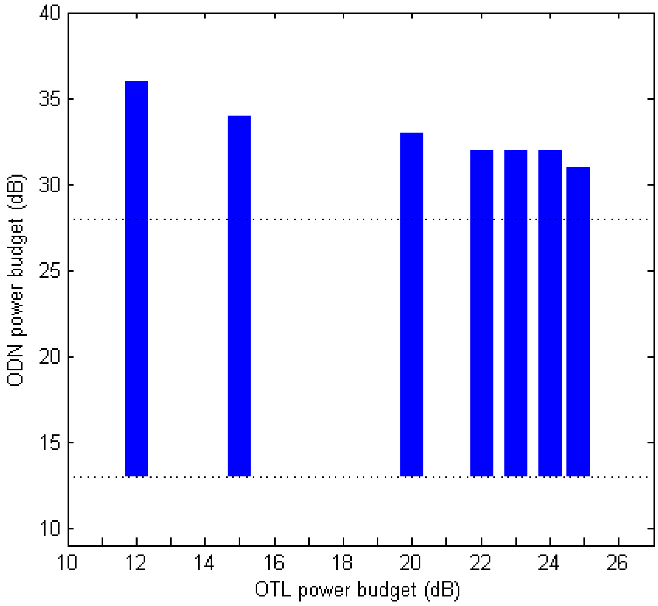

Figure 4.9: Maximum downstream power budget range.

4.3.2 Upstream

The setup for upstream is similar to the one used in the downstream, however in this case the downstream link must remain connected, otherwise the test is not possible. Could be possible to separate the downstream traffic without amplification and register the ONU, but then the upstream would not perform any amplification, in practice the SOAs are not turned on, this is due to the extender box operation mode, a detailed description can be found in appendix C (function diagram).

The setup implemented is represented in figure 4.10, the dashed traces surrounding the VOAs have the same justification as referred before and the same procedure is used. The results are presented in figure 4.11.

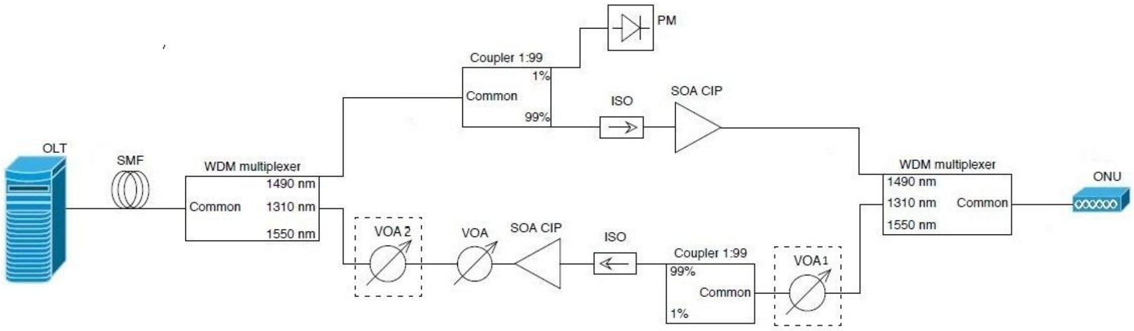

Figure 4.10: Experimental setup to test upstream power budget boundaries.

The standard defines a maximum power budget in the OTL of 28dB and between 13 and 28dB in the ODN. For 28dB in the OTL on the ODN side the standard is not fulfilled, only 27dB is achieved. The case in which the ODN range is higher is when OTL power budget is 27dB.

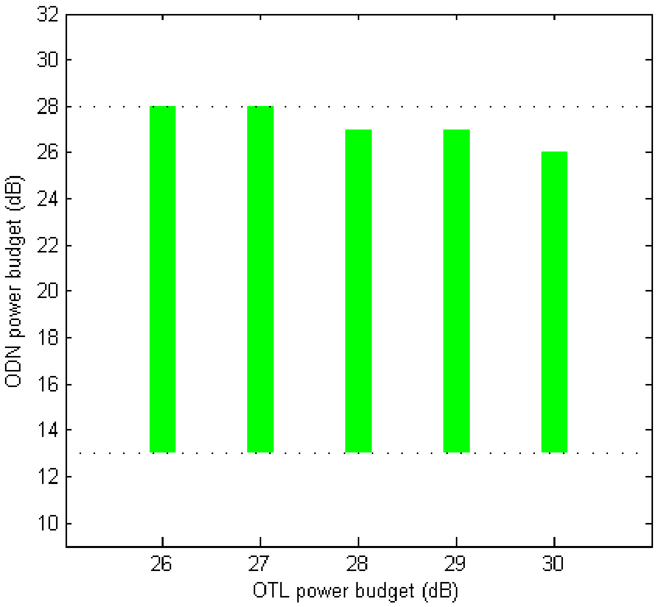

Figure4.11: Maximum upstream power budget range.

4.4 Monitoring

Based on the results of earlier tests a optimum operation point for the Extender Box was found, when the ODN has the best upstream range that is for an OTL power budget of 27dB. To ensure that Extender Box is operating at the optimum point, the upstream output power should be always the same.

Analyzing the upstream link, there is an isolator, a coupler 1:99, a SOA and a VOA. Any kind of control can be done in the ISO or in the coupler, the options are the SOA and the VOA. Change the SOA's gain is not a good option, because to do that it is necessary to change its bias current, taking it out from the best operation point. So, the way is to control the attenuation in the VOA, (and that is the reason why the VOA was there as discussed in the previous developments). This control is made in terms of input power at the extender box in the downstream link.

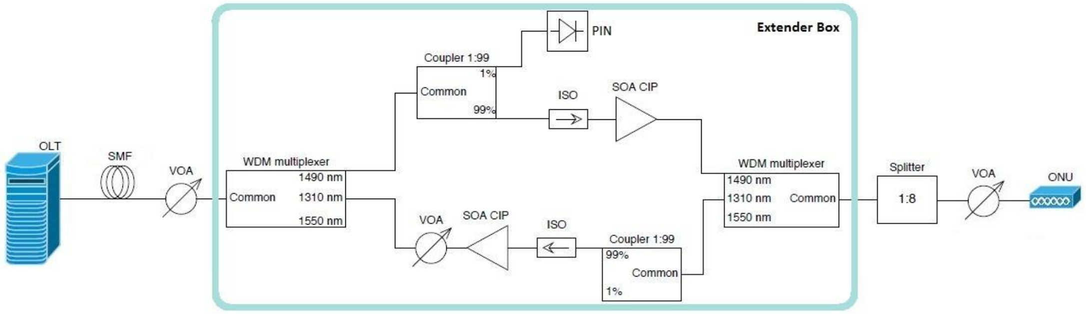

Figure4.12: Monitoring setup.

Observing figure 4.12 from the OLT side, a VOA is placed before the extender and another before the ONU. The first one is used to control the input power, allowing the simulation of different input powers at the extender. The second one is used to control the ONU input power, so that it is always within the range of ONU sensitivity.

The input power is varied and the VOA attenuation changed to guarantee a power budget in the OTL of 27dB. For each of input power, a attenuation value is taken and the relation traced as represented in figure 4.13.

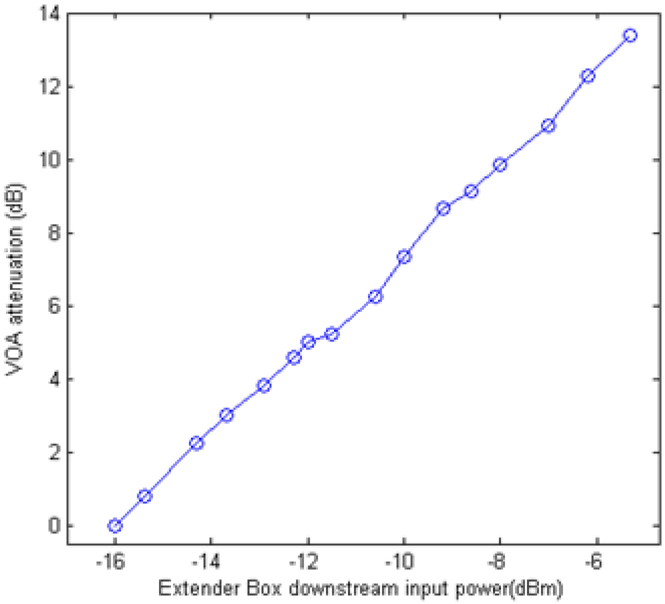

Figure4.13: VOA attenuation as a function of extender box input power.

The microcontroller is associated with the 1% port of the coupler, so, these values represented]-18,-4[are far from the ones the microcontroller needs, but the relation is the same. After entering the Extender, the signal passes through the add/drop filter and through the coupler, and after that is read by the PIN. In the add/drop approximately 1.4dB is lost and in the coupler about 0.6. The difference between the 1% and 99% port is 20dB. So, for each value of input power in the extender box, 22dB has to be added. Afterwards, by knowing this PIN input power, the microcontroller is able to control the VOA attenuation as desired. Through this procedure, the new graphical representation is shown in figure 4.14.

The input power range represented in figure 4.13 and thus also in figure 4.14, was due to the minimum attenuation allowed by the VOA and to accomplish the defined in the standard (table 2.4 in chapter 2).

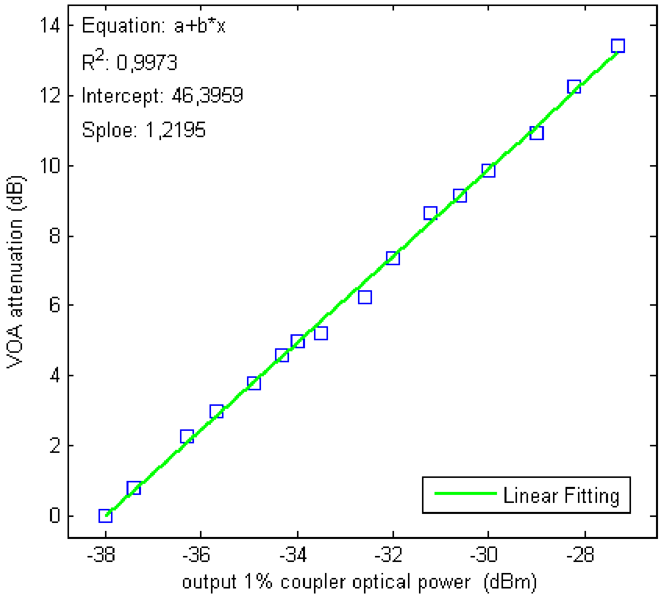

Figure 4.14: VOA attenuation as a function of output optical power of coupler at 99% output.

The result is linear and the result of the linear regression is:

$$y = 1{,}2195x + 46{,}3959 \tag{4.1}$$

With this equation, by reading the input power at the extender box, the microcontroller is able to set the attenuation in the VOA according to the relation, thus ensuring that in any implementation in the field the extender has the same output power, this is, the power arriving at the OLT will be always the same.

Figure 4.15 shows the VOA attenuation as a function of OTL downstream power budget.

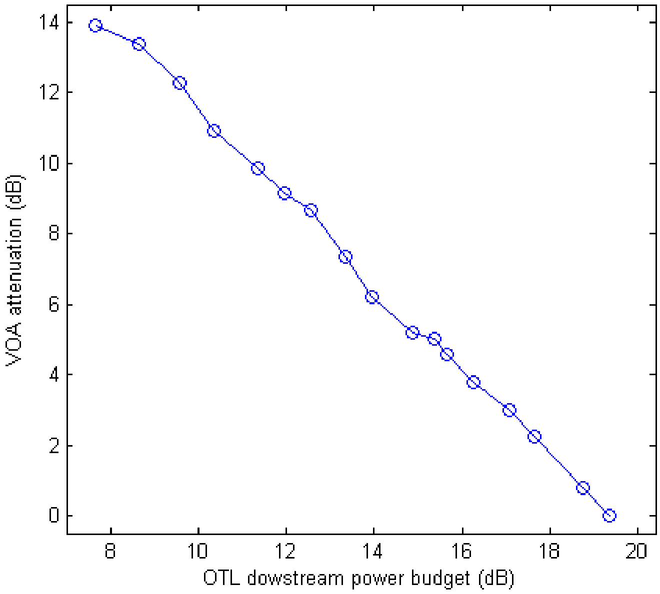

Figure 4.15: VOA attenuation as a function of OTL downstream power budget.

The monitoring PIN located at the downstream link not only gives information about the downstream input power but also allows to obtain some extra data. Based on the input data, the microcontroller is capable of calculating another outputs.

Directly through the downstream PIN is possible to calculate:

- Downstream output power;
- Upstream output power;
- Downstream input power;

Here, only the relation between input power and downstream output power and the relation between input power and upstream output power are presented, in figure 4.16 and 4.17 respectively, and equation 4.2 and 4.3.

The relation between the extender box and PIN input powers is not presented. As referred before the difference is considered to be 22dB, by approximation, because with all components closed in the box there is no way to access and to measure the exact PIN's input power.

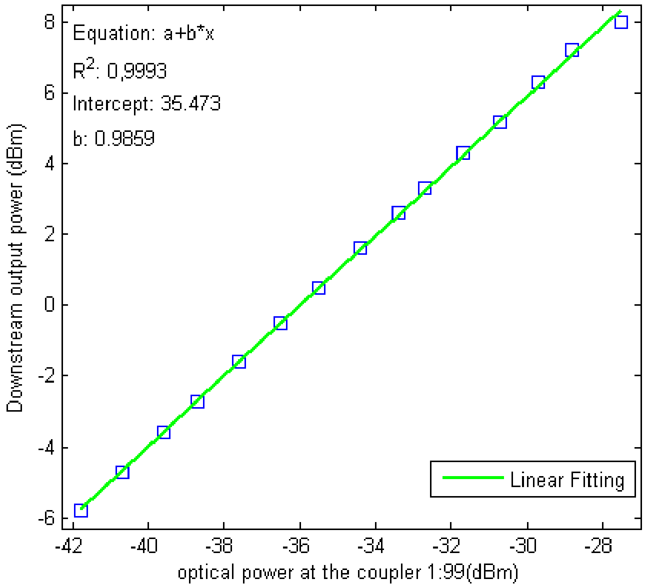

Figure 4.16: Downstream output power as a function of output optical power of coupler at 99% output.

$$y = 0.9859x + 35{,}473 \tag{4.2}$$

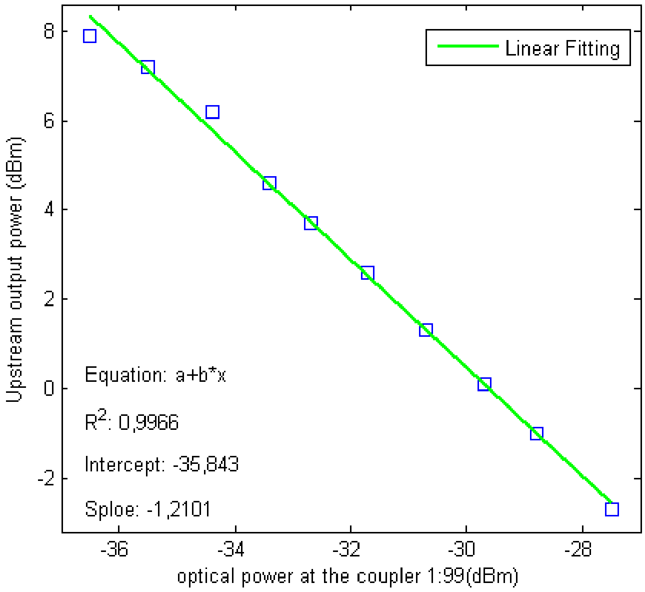

Figure 4.17: Upstream output power as a function of output optical power of coupler at 99% output.

$$y = -1{,}2101x - 35{,}843 \tag{4.3}$$

4.5 Checking the feasibility

During the preceding subchapters the Extender Box was described, it's power budget boundaries defined, the optimal operation point found and the monitoring equation introduced. Thus, the extender should be able to amplify the signal allowing to achievement of maximum distances and splitting ratios higher than those initially defined in the GPON standard.

The Extender characterization was made in terms of power budget, but the effectively goal in untested, that is, the Extender was not tested by using different fiber lengths and different splitters, and by emulating different attenuation with attenuators.

To check the viability of the prototype presented in this work, the setup of figure 4.18 is implemented. The ideal would be have as many clients as desired, but this is not possible, because there is only two ONUs available in the laboratory.

As in previous tests, the IXIA is used, so, traffic is upstream and downstream traffic is introduced. 1 million of packets uniformly distributed between 128 and 1500 bytes are sent, the line rate is 400Mbps for both directions, in total, 4 millions of packets at 400Mbps flow in the network.

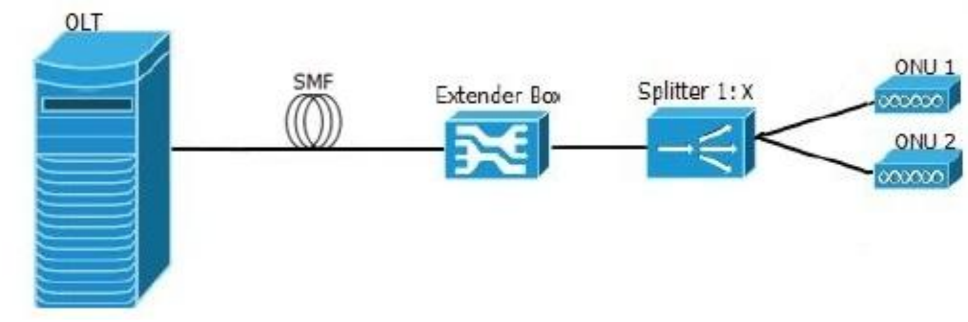

Figure 4.18: Final test setup

Due to the laboratory capabilities the splitters used were, a 1:4, a1:8 and a 1:16 splitter. Due to that fact it was necessary to make some combinations of splitters to perform the required measurements (1:32, 1:64 and 1:128). Previously, all splitters were characterized to ensure the insertion loss of each splitter do not exceed the expected.

The insertion losses obtained were, <7dB for the 1:4, <11dB for the 1:8 and <14dB for the 1:16.

To have different lengths of fiber several rolls of fiber were interconnected, so, also multiple connectors were needed. For example, when testing the 60km, at least four connector was inserted in among the fiber, which may be significant for borderline cases. Thus, the results could have been even better if there was a full material availability.

The summary of the results are presented in table 4.1, where + means that error-free transmission was achieved with success, and – that the ONUs weren't capable to register. Therefore, only two results were obtained, a PER of 0 meaning a error-free transmission and the ONUs being unable to register.

Table 4.1: Relation between maximum fiber length and maximum splitting ratio.
(+ error-free transmission; - ONUs did not registe)

		Splitting Ratio				
		1:8	1:16	1:32	1:64	1:128
SMF length (km)	20	+	+	+	+	+
	30	+	+	+	+	+
	40	+	+	+	+	+
	50	+	+	+	+	+
	60	**+**	**+**	**+**	**+**	**+**
	62	+	+	+	+	+
	62.5	+	+	+	+	-
	65.7	+	+	-	-	-
	66	+	-	-	-	-

The IXIA also has a 10Gbps card which was used to test the Extender Box compatibility with higher line rates. The card has two receivers and two emitters working at 1550nm. The Extender Box downstream link has a port which allows passing this wavelengths. It was verified that the downstream link extension has a good response at 10Gbps performing error-free transmission at least up to the tested 20km. Based on that, the Extender Box could be considered capable of supporting the data rates characteristics of the XG-PON.

4.5 Result Analysis

When testing the power budget boundaries, for the downstream power budget the standard fulfilled, this is, in the OTL is possible to go until 25dB always with ODN power budgets higher than the ones defined in the standard. From 13dB to 31dB overcoming the standard by 31dB. In the upstream direction, the results are not as good as for downstream, the standard is not totally fulfilled. To guarantee between 13dB and 28dB on the ODN, on the OTL is not possible to go over 27dB (standard is not fulfilled by 1dB).

Ensuring the best operation point, this is, 27dB in the upstream OTL power budget the power budget values of OTL are presented and compared with the standard in table 4.2. As can be seen, only for upstream the standard is not fulfilled. But only by a difference of 1dB

Table 4.2: Differences between Extender Box OTL power budgets and the standard.

	Downstream (dB)	**Upstream (dB)**	**Difference**
Measured	23	27	4
Standard	23	28	5
Difference	0	1	

As was seen in previous section (4.5-table 4.1) the main goal was reached with success. This is, for 60km of fiber and 1:128 of splitting ratio, error-free transmission was obtained. Beyond the main goal, 60km, 62km were achieved with packet error rates of 0 for both directions for all the splitting rates tested.

5 Conclusions and Future Work

5.1 Conclusions

In this thesis the main EPON and GPON characteristics and requirements were presented. The real scenarios were tested and characterized in terms o maximum line rates, maximum power budgets and maximum reach. Leading to the expected conclusion that GPON system have many advantages.

EPON main features are, a wavelength plan of 1480-1500nm for downstream and 1260-1360 for upstream, a symmetric 1.25/1.25Gbps line rate with splitting ratios of 1:16 and 1:32. Depending on the link loss budget and splitting ratio, it can transmit at maximum distances of 10 or 20km. When employing FEC it gives an extra supported splitting ratio of 1:64.

GPON main features are, bit rates of 2.5/1.25Gbps or 2.5/2.5Gbps for DS/US, which ensures asymmetric and symmetric bit rate options. It supports 1:32, 1:64 and 1:128 splitting ratios. Also depending on the link loss budget and splitting ratio, can reach a maximum fiber distance of 20km. The wavelength plan is the same as for EPON.

In the characterization, chapter 3, a brief comparison between the EPON and GPON was also made, leading to the conclusion that GPON have several practical advantages when compared with EPON. As concluded, in terms of maximum line rates and power budgets.

In the scope of this work, the requirements for the GPON reach extender solution for GPON was presented. And also a prototype for the Extender Box previous developed. The lack of resources forced the previous tests (in [17] and [18]) to be done with a EPON system and the authors assumed that the Extender Box would work in a GPON. But always showed the need to test the device in accordance with the correct assumptions, this is, using a real GPON system.

Being now a GPON system available in the laboratory on of the final goals could be achieve, so, the Extender Box power budget boundaries were characterized, the optimal operation point found and the monitoring done.

The main goal for the Extender Box was, achieve at least a 60km of maximum reach and support 128 clients. The objective was successfully achieved, as discussed in section 4.5 and 4.6.

5.2 Future Work

In the near future, in order to optimize the operating mode of the Extender Box some changes at the programming level might be made. For example, make the Extender capable of working for both scenarios, EPON and GPON, the two monitoring equations should be included and the input condition will change depending if the operator chose EPON or GPON operation mode.

Also some warning messages can be added, in case of failure, overheating, too high or too low powers on the ONU side is case of splitting ratios to low or too high respectively.

One of the main and first improvements for the future, the CATV amplifier should be included in the prototype.

As mentioned in [18] the need to find a way of usefully interpret the incoming upstream power still exists, twice mentioned, one way can be to isolate the ONU and make it transmit at a certain line rate, if possible at the highest.

A future challenge will be to adapt the proposed extender box in order to use wavelength division multiplexing to allow even more supported clients. For it, methods to convert wavelength have to be investigated, thus the operation could be transparent to the OLT and ONUs. The amplifiers would also have to be reevaluated since the SOA may have nonlinear effects when operating with WDM.

In addition, the wavelength conversion can be also useful to make the Extender Box capable of support the new access standards of 10Gbit/s, having on that way a device supporting 10Gbit/s PONs and the legacy ones.

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