Universidade de Aveiro 2011

Departamento de
Electrónica, Telecomunicações e Informática,

José Pedro
Oliveira Rodrigues

Estudo e teste de uma rede EPON

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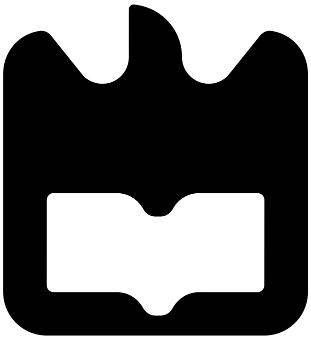

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Estudo e teste de uma rede EPON

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

Dedico este trabalho ao meu pai Zeca, à minha mãe Rosa, à minha irmã Catarina e à minha namorada Maria.

o júri / the jury

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Palavras Chave

Redes Ópticas Passivas, GPON, EPON, 10G-EPON, XG-PON, *Reach Extension*.

Resumo

O rápido crescimento do acesso a internet de banda larga, e o consumo de novos conteúdos tem levado os operadores a apostarem fortemente nas redes ópticas passivas de acesso. Essa aposta pretende chegar ao maior numero e diversidade de utilizadores possível. Para aumentar a capacidade das redes existentes, bem como diminuir o seu custo, foram criadas normas que regulam a criação de equipamentos para esse efeito.

Ao longo deste documento são abordadas as normas e respectivos requisitos para implementação deste tipo de redes, quer da tecnologia EPON quer da tecnologia GPON, bem como ainda das tecnologias mais recentes que sucedem as primeiras, as redes 10G-EPON e XG-PON. Com base num protótipo apresentado numa dissertação de 2010 vai ser caracterizado o dispositivo, apresentados melhoramentos e vai ser comprovado o seu funcionamento em diversos cenários.

Key words

Passive Optical Networks, GPON, EPON, 10G-EPON, XG-PON, Reach Extension.

Abstract

The rapid growth of broadband internet access, and the consumption of new services, has led the operators to strongly bet in optical passive networks. This commitment aims to reach as greatest number and diversity of users as possible. To increase the capacity of the existing networks, while decreasing its cost, standards were created to regulate the creation of devices for this purpose.

Throughout this document it is discussed the standards and their requirements for the implementation of this kind of networks, whether EPON or GPON technology, as well as the latest technologies which replace the former, 10G-EPON and XG-PON. Based on a prototype presented in a dissertation of 2010 the device will be characterized, improved and it will be proved its operation in various scenarios.

Contents

List of Figures

List of Tables

List of Acronyms

ADSL	Asymmetric Digital Subscriber Line
APON	Asynchronous Passive Optical Network
ARPANET	Advanced Research Projects Agency Network
ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
BPON	Broadband Passive Optical Network
CATV	Community Antenna Television
CO	Central Office
CS	Current Source
DARPA	Defense Advanced Research Project Agency
DBA	Dynamic bandwidth assignment
DFA	Doped Fiber Amplifier
DSL	Digital Subscriber Line
EPON	Ethernet Passive Optical Network
EVOA	Electrically Controlled Variable Optical Attenuator
FEC	Forward Error Correction
FP-SOA	Fabry-Perot SOA
FSAN	Full Service Access Network
FTTB	Fiber To The Building

FTTC	Fiber To The Curb
FTTH	Fiber To The Home
GPON	Gigabit Passive Optical Network
HFC	Hybrid Fiber Coax
HID	Human Interface Device
IP	Internet Protocol
ISP	Internet Service Provider
ITU	International Telecommunication Unit
ITU-T	ITU – Telecommunication standardization sector
LA	Limiting Amplifier
LLID	Logical Link ID
MAC	Media Access Control
MPCP	Multi-Point Control Protocol
MSDSL	Multi-rate Symmetric Digital Subscriber Line
NF	Noise Figure
OAM	Operation, Administration and Maintenance
ODN	Optical Distribution Network
OLT	Optical Line Termination
ONU	Optical Network Unit
OTL	Optical Trunk Line
OSA	Optical Spectrum Analyser
P2MP	Point-To-Multipoint
P2P	Point-to-Point
PER	Packet Error Rate
PMD	Physical Medium Dependent

PON	Passive Optical Network
PSTN	Public Switched Telephone Network
QoS	Quality of Service
SMF	Single Mode Fiber
SNR	Signal to Noise Ratio
SOA	Semiconductor Optical Amplifier
SONET	Synchronous Optical Network
SMF	Single Mode Fiber
TC	Transmission Convergence
TCP	Transmission Control Protocol
TEC	Thermoelectric Controller
TIA	Trans-Impedance Amplifier
TV	Television
TW-SOA	Travelling-Wave SOA
VDSL	Very high bit rate Digital Subscriber Line
VOA	Variable Optical Attenuator
WDM	Wavelength Division Multiplexing

Chapter 1

Introdution

1.1 Context

The Ultra Broadband access market (FTTH/B - Fiber To The Home/Building and VDSL - Very high bit rate Digital Subscriber Line) is expected to grow steadily in the upcoming years, to reach close to 150 million subscribers around the globe by 2014. It is expected that by the same year, 18 countries will have deployed optical fiber networks to more than 50% of homes, which is 10 times more than at the end of 2009. And beyond these figures, that reflect the current and future situation, there have been several announcements from private operators and governments confirming the interest in very high-speed access in most parts of the world [1].

Additionally, the inexorable increase in bandwidth demand by the subscribers, which fuels the investment aforementioned, will eventually cause the existing PON (Passive Optical Network) technologies, GPON (Gigabit PON) and EPON (Ethernet PON), to exhaust in perhaps 2 to 4 years [2]. So, to give solution to the possible bandwidth overload, the standardization groups have started studying and regulating the next generation access networks to replace, or complement the legacy ones, such as: WDM (Wavelength Division Multiplexing), 10 Gbps based networks - 10G EPON, XG-PON -, and longer reach/higher splits [3].

The general increase on the interest in broadband internet also reflects in areas where the broadband access is not much developed, mainly due to cost-effectiveness of the solutions. In most urban scenarios, the existing standards covers the majority of the users, but in semi-urban or rural scenarios, where the subscriber may be far from the OLT (Optical Line Termination), the limits of the standards may not be enough to assure their link and QoS. Both, distance and splitting ratio, can be insufficient to reach those particular regions.

To overcome this problem, a device that increases the physical reach of the signal, either in amplitude, either in quality can be installed. This solution consists in optical amplification, compatible with the legacy equipment (OLTs and ONUs — Optical Network Unit), capable of increasing the basic capabilities of the GPON standard. This device is called a mid-span extender, reach extender or extender box. This dissertation focus on characterizing an extender box for GPON, using an EPON system, based on a prototype already designed in a dissertation presented in 2010.

1.2 Structure

This document is organized in five chapters and is structured as shown:

- Introduction;
- Standards for Access Networks;
- State of Art;
- Extender Box;
- Conclusions and Future Work;
- Appendices

The second chapter, the most theoretical one, starts with an introductory section, where is described the origins of the broadband networks, and then, it is described the main characteristics and requisites of the standards of EPON, GPON, 10G-EPON and XG-PON. In this chapter, the objective is to study the standards, and comprehend how the environment on which the extender box is inserted, works. The description of the 10 Gigabit standards are included for a possible compatibility in the extender box.

In the third chapter are presented the main results obtained in the theses of *J. Girão* in 2010, which are the characterization of the extender box amplifiers, the prototype proposal and the proof that the extender box works (extends the reach to 60 Km and the splitting ratio to 1:128), that constituted the starting point for this theses.

The fourth chapter starts with a characterization of the EPON used in the laboratory, which was used for tests of the Extender box. Then, it is evaluated the necessity of some components of the prototype. It is presented the characterization of the extender device, identifying the conditions and scenarios of operation, as well as its best operating point. It is also presented a solution for automatic adaptation of the extender box to the scenario where it is inserted. A performance monitoring solution is described too. Finally it is evaluated the capacity of amplifiers to deal with 10 Gigabit signals, and a new prototype is proposed.

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

1.3 Contributions

The main contributions of this work are:

- Description of the characteristics of Passive Optical Networks standards, EPON and GPON, as well as the requirements for the construction of a reach extender for GPON;
- Description of the characteristics of the new 10 Gigabit Passive Optical Networks, 10G-EPON and XG-PON;
- Analysis of the main characteristics and functional principals of the Semiconductor Optical Amplifiers;
- Characterization of the maximum power budget and maximum reach of an EPON;
- Improvement of a previously proposed prototype for a reach extender device;
- Characterization of the operating range of the extender box;
- Add of the functions of automatic configuration and performance monitoring to the prototype;
- Experimental demonstration of the extender box operation at line rates characteristic of new 10 Gigabit PONs;
- Description of the electronic interfaces of the prototype;
- A Publication on the SEON 2011 conference with the title: *"Reach Extender Based on Semiconductor Optical Amplifiers (SOA)"*;

Chapter 2

Standards for Access Networks

2.1 Broadband History

Broadband access is the link between service providers and the end-users of their broadband services [4].

To understand the origins of the, so common known, broadband access, we may have to look back in time, to the late 1950's, when the United States military were researching methods to improve their communication networks. This led to a project developed by the United States Defense Advanced Research Project Agency (DARPA) in the late 1960's, called "Advanced Research Projects Agency Network" (ARPANET) [5] which claims to be the world's first operational packet switching network and the core network of a set, that came to compose the global Internet. The idea was to use the computer's potential as an interactive device and create new networking technologies so that research centers and universities could link each other.

However, the internet was only available to the public in 1983, when the first Transmission Control Protocol and Internet Protocol (TCP/IP) — based wide-area network — was operational. Since then, the costumer has faced an exponential evolution and growth in the internet access.

2.1.1 Dial-up

Dial-up modems were the first widespread form that allowed residential users to connect to the internet. This technology uses the Public Switched Telephone Network (PSTN) to establish a connection to the Internet Service Provider (ISP) through the telephone lines. But this 56 *kbps* technology was slow, as the sites got bigger in number and content. In addition, the internet popularity and the number of paying costumers was growing as well, and demanding for diversified applications such as music and video.

This expansion in the traffic and users attracted the ISPs to compete and invest in developing faster rates of data transmission, and the broadband access was introduced in 2000. Although the term “broadband” is relative to its context, it became familiar in the telecommunication’s vocabulary when the Digital Subscriber Line (DSL) technology was available to the costumers.

2.1.2 Digital Subscriber Line

DSL became very popular and different types were deployed over the world such as Multi-rate Symmetric Digital Subscriber Line (MSDSL), High bit rate Digital Subscriber Line (HDSL), among others, but the most wide common variety is Asymmetric Digital Subscriber Line (ADSL). Asymmetric DSL was built assuming that the users would require more bandwidth in the downstream direction rather than in the upstream direction.

2.1.3 Community Antenna Television

Along with DSL, another widespread broadband service that emerged was Community Antenna Television (CATV). The CATV networks were originally designed to deliver analog broadcast television (TV) signals in areas where they were not received in an acceptable manner by an antenna [6]. It was built in a tree topology and most of its spectrum was used to allocate downstream analogue signals, as no interaction by the user and the headend was needed. With the competition from the telecommunication operators in providing internet access, cable television operators, after a slow start, invested substantially in network upgrades and became an alternative to DSL [7]. This brought the arrival of new services that integrated television, telephone and internet access, commonly known as triple play.

2.1.4 Hybrid Fiber Coax

Some alternatives were created to upgrade the existing solutions in the access network, such as VDSL, which offers up to 50 Mbps [8], upgrading the DSL networks. Other was improving the CATV networks to Hybrid Fiber Coax (HFC) networks, where coax cable was limited to the drop network [1] and fiber running between a video head-end and the optical node, providing a shared bandwidth up to 36 Mbps. Although, this seems acceptable speeds,

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[1] The network between the curb-side optical node and the subscriber.

due to the shared nature, this could result in frustrating low speed during peak hours. Thus, optical fibers and nodes have been extended deeper into the access network.

2.1.5 Passive Optical Network

Optical fiber is a mean of data transmission capable of carrying large amounts of data, with low loss and immunity to magnetic interference. Even though, optical fiber has been deployed in backbone networks by some time, taking advantage of that large capacity, it took a while until it became cost-effective[2] to deploy it in the access networks, where the traffic volume per link is lower. To that, contributed the development of new optical networks architectures, capable of supporting Gigabit per second speeds, at costs comparable to DSL and HFC networks [8].

Different ways are possible to deploy optical fiber in the access network, each differing in the number of transceivers and/or in the amount of fiber used. The simpler is using a Point-to-Point (P2P) topology, with dedicated fiber from the Central Office (CO) to each subscriber, being possible to address each one the maximum speed. However, this topology may be cost prohibitive due to the large amount of fiber and transceivers needed. Other possibility is deploying fiber using a Point-to-Multipoint (P2MP) topology, placing a remote node (switch) close to the neighbourhood reducing, significantly, the fiber needed. On the other hand, it increases the number of transceivers needed and it requires electrical power supply as well. If the remote switch is replaced by an optical splitter, both Capital Expenditure (CapEX) and Operational Expenditure (OpEX) can be reduced [8, 10], which makes it an attractive solution.

The absence of active elements within the access network, except the CO and the subscriber endpoint, gives the name to this specific topology – Passive Optical Network (PON). Each PON can be classified in different architectures depending on the network arrangement including ring, bus and tree. Independently of the architecture, the transmission is held between the OLT, located at the central office, and the ONU that can be located, for example, at the costumer's home — fiber to the home (FTTH), building — fiber to the building (FTTB) and curb — fiber to the curb (FTTC).

An example of a tree topology PON scheme is shown in figure Figure 2.1

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[2] Determined by the simplicity of the technology, affecting installation, operation and maintenance costs and scalability

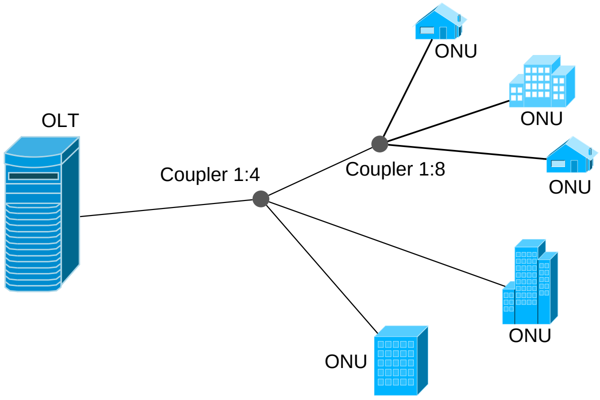

Figure 2.1: Example of a tree topology PON.

2.2 Standardization Activity

The increased interest in PON technology as an important and attractive solution, reflected in the standardization introduced by the Full Service Access Network (FSAN), a group of the International Telecommunication Unit – Telecommunication standardization sector (ITU-T) and the Ethernet in the First Mile (EFM) a group of the Institute of Electrical and Electronics Engineers (IEEE).

FSAN (Full Service Access Network) came up with an Asynchronous Transfer Mode (ATM) based solution named APON (Asynchronous Passive Optical Network) and lately renamed to BPON (Broadband Passive Optical Network) when they realized that it did not have significant cost advantages against new access-oriented SONET (Synchronous Optical Network) based platforms.

In 2000, claiming that current technology offerings at that time for that market were found to be lacking, the necessity to decrease the cost of optical access systems and create a reliable economical solution became a priority and the EFM group was created, initially called Ethernet in the last mile and then renamed to Ethernet in the first mile, to symbolize the importance of access portion of the network [11]. Ethernet was chosen because of the advantage of its maturity and success in computer communications networks.

In 2004, The Ethernet based PON (EPON) standard was made available to the world. The publication of the standard marked the culmination of four years of effort by industry leaders and innovators to address the broadband subscriber access network market. At that time, 1 Gbps was reached [12]. ITU-T was also working on another standard, the gigabit PON (GPON). The GPON standard reaches a higher downstream speed than EPON, but the basic physical features are close to each other with the bigger difference being the encapsulation method: GPON typically uses the GEM (Generic Encapsulation Method) while EPON uses pure Ethernet frames.

Although the currently dominating technologies, and with the major deployment, are GPON and EPON, the standardization bodies, anticipating an increase in bandwidth demand, driven by the user consumption of more bandwidth demanding applications and services, such as HD-IPTV, cloud computing, PiP TV, High Definition TV, online interactive gaming, remote storage, etc, have already been working on the next generation networks (NGN) of 10 Gigabit-class PON systems. Both ITU-T and IEEE wanted to upgrade the current technologies to achieve higher bit-rates and coexistence with legacy technologies, allowing smooth migration, and they came up, recently, with XG-PON[3] (10 Gigabit GPON) and 10G-EPON (10 Gigabit EPON), respectively.

In 2006, IEEE started to develop of the 10G-EPON specifications through the standard 802.3av, and in 2009 the work was completed with the definition of 10GBASE-PR10, 20, 30 for symmetric 10G systems and 10G/1GBASE-PRX10, 20, 30 for asymmetric 1G/10G (upstream/downstream) systems. Due mainly to the larger bandwidth of GPON, the FSAN/ITU-T took a longer time to react to the market and, in 2007, started studying XG-PON. However, in late 2006, FSAN began to contemplate the system that would follow after GPON, particularly G.984.5, which refined the spectrum plan for GPON, to enable a smoother migration to whatever system came later [24–27]. The work of ITU is nearly completed and resulted in G.987 series, with general requirements (G.987.1), physical media dependent layer (G.987.2) and transmission convergence (G.987.3) specifications already approved.

2.3 Ethernet Passive Optical Network

The EPON standard was published by the IEEE and approved in 2004 with the name 802.3ah [12]. The goal was to extend Ethernet into the subscriber access area, focusing on both, residential and business access network. The standard defined physical layer specifications for EPON as 1000BASE-PX10 and PX20 (which stands for 1000 Mbps single-fiber point-to-point and 10km or 20km version), multipoint Media Access Control (MAC) and MAC control sub-layers as well as Operation, Administration and Maintenance (OAM) functions and optional Forward Error Correction (FEC).

The reference configuration of a simplified P2MP PON network is depicted in Figure 2.2

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[3] X stands for the Roman number 10.

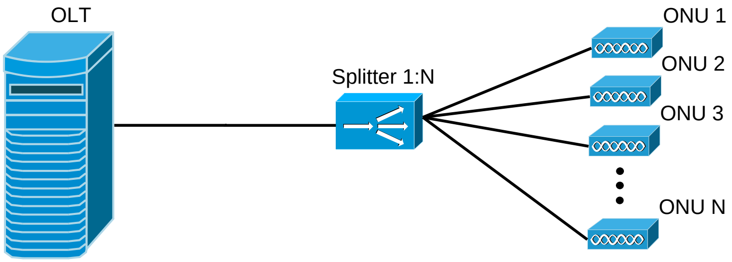

Figure 2.2: Simplified P2MP PON configuration .

The basic components of an EPON network are the OLT (on the left side of the figure), the splitter(s) (on the middle) and the ONUs (on the right side) and the optical fiber:

- The OLT is located at the CO and is responsible for connecting the users from the access network to the transport network. The OLT is also responsible for managing and operating the PON.
- The splitter is a passive device, usually with one input and “N” outputs. Its function is to split the signal that comes from the OLT so that it is divided to reach all the ONUs (each ONU receives approximately 1:N of the power that reaches the splitter), and combine them when flowing from the ONUs to the OLT. The location of the splitter depends on the strategy, that involves population density, optical fiber saving, initial investment and also other factors.
- The ONU does the interface between the client side and the PON and terminates it. It delivers the services required from the client; they may include voice, data and video. The location of the ONU depends on the architecture adopted as mentioned above (FTTH, etc…).
- Optical fiber is the medium that carries the information in the network.

2.3.1 Downstream

In downstream direction, an EPON behaves as a shared medium, with Ethernet frames transmitted from the OLT to every ONU, i.e., EPON handles physical broadcasting of 802.3 frames. So that downstream and upstream can coexist in the same fiber, the standard defines a different wavelength for each direction of the transmission and also an additional wavelength assigned to video overlay. In the downstream direction the wavelength assigned is $1490\,nm$ (S band) and at line bit rate of $1.25\,Gbps$, shared amongst the population of ONUs attached to the P2MP topology [12]. Yet, due to the 8B/10B line encoding, the line rate is 1.25 Gbps but the bit rate for data transmission is 1Gbps.

Figure 2.3 shows a scheme of downstream traffic:

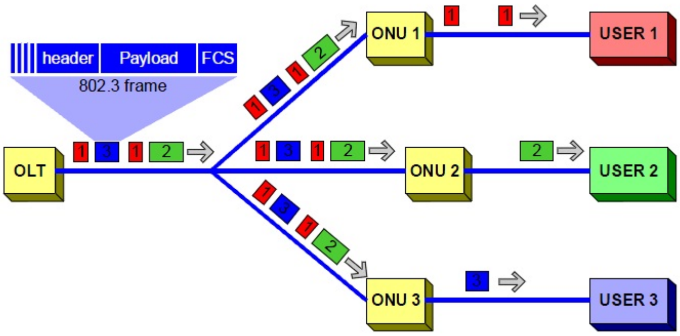

Figure 2.3: Downstream traffic in EPON [9].

The data is broadcasted from the OLT to the multiple ONUs in packets of 64 to 1518 bytes. Each packet contains a header that identifies to which ONU the packet is designated, for example, in the Figure 2.3, red packets (identified with number 1) are intended to ONU 1, green packets (number 2) to ONU 2 and blue packets (number 3) to ONU 3. At the splitter, the signal is divided, but each signal after the splitter carry all of the packets intended to every ONUs. Once the packets reach the ONU, it accepts the packets that are intended to it and discards all the others. For example, in Figure 2.3, ONU 1 receives packets 1, 2 and 3, but only delivers two packets to the user 1, which are the packets addressed to it.

2.3.2 Upstream

In the upstream direction the wavelength assigned is 1310 nm (O band). The line speed is also 1.25Gbps, which, due to the encoding referred above, corresponds to 1Gbps of data transmission. This similarity to the downstream confers to the EPON a symmetrical characteristic in bandwidth.

In upstream direction, because of the splitters characteristics, Ethernet frames from an ONU only reach the OLT and not any other ONU. The logical behaviour of an EPON is to an emulated point-to-point network. But unlike a real point-to-point network, collisions may occur among frames transmitted from the ONUs. To avoid data collisions and increase the efficiency of the subscriber access network, by means of a Multi-Point Control Protocol (MPCP) in the Medium Access Control (MAC) layer, ONU's transmissions are arbitrated. This arbitration is achieved by allocating a transmission window (grant) to each ONU, which defers the transmission until the arrival of the grant. When the grant arrives, the ONU transmits frames during its assigned time slot [12]. Thus, the upstream transmission efficiency is guaranteed through a Time Division Multiplexing Access (TDMA).

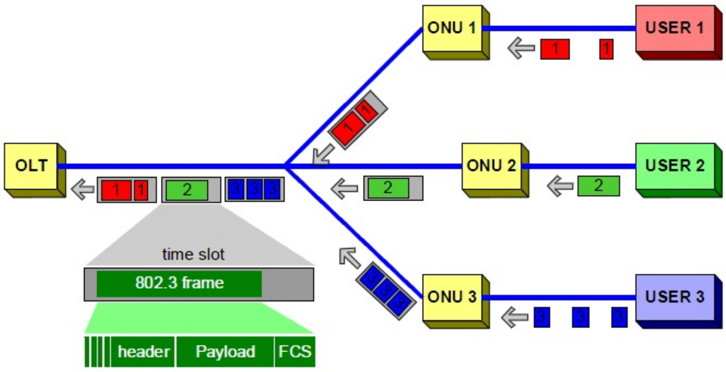

Figure 2.4: Upstream traffic in EPON [9].

In Figure 2.4 is shown an example of an upstream transmission. Each ONU has its own time slot to transmit. In this example, ONU 1 transmits its packets in the first time slot, ONU 2 transmits in the second ant ONU 3 in the third.

To avoid spontaneous emission noise from near ONUs obscuring signal from a distant ONU, the standard defines that the ONUs' lasers should be turned off between their transmissions. Therefore, unlike OLTs that transmit continuously, ONUs have a burst-mode operation.

2.3.3 Multipoint MAC Control Protocol

The Multipoint MAC Control Protocol (MPCP) uses messages, state diagrams, and timers, as defined in Clause 64 of the 802.3ah standard [12], to control access in a P2MP topology. The MPCP located at the OLT is responsible for timing the different transmissions allowing a MAC client to participate in a point-to-multipoint optical network as if it was connected to a dedicated link.

The MPCP is a frame-oriented protocol based on 64-byte MAC control messages. There are GATE, REGISTER and REPORT control messages. The first two are used to control the auto-discovery process and the last is used for Round Trip Time (RTT) calculation, allocate upstream bandwidth and also as keep-alive from ONU to OLT to maintain link health.

The discovery process is the process whereby newly connected or off-line ONUs are provided access to the PON. The OLT initiates the process by broadcasting, periodically, discovery GATE messages to the ONUs in a discovery time window during which newly connected or off-line ONUs are given the opportunity to make themselves known to the OLT. The off-line ONU responds with a REGISTER request message containing the ONU's MAC address.

The OLT, after receiving a valid request message, registers the ONU, allocating and assigning new port identities (LLIDs – Logical Link IDs), bonding corresponding MACs to the LLIDs and sends a REGISTER message to the newly discovered ONU. The REGISTER message contains the ONU's LLID and the OLT's required synchronization time.

The discovery handshake is completed when the OLT sends a GATE message and then receives a REGISTER acknowledge by the ONU. Finally, the ONU is registered and normal traffic can begin. Figure 2.5 depicts and resumes the process described above.

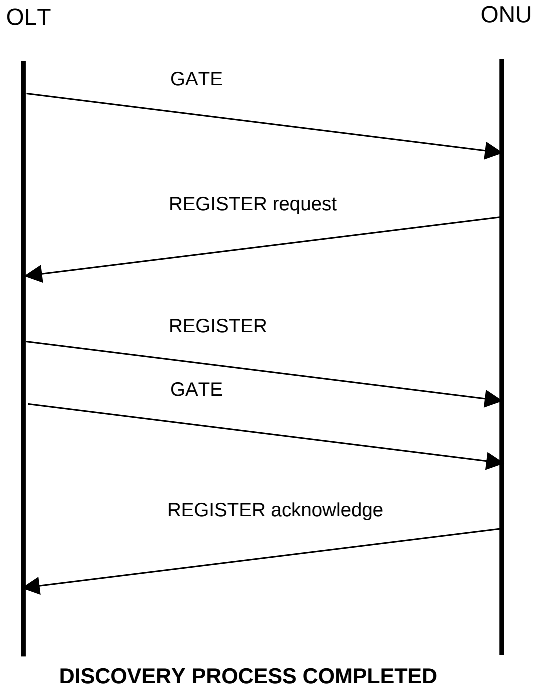

Figure 2.5: Auto discovery process of an ONU in an EPON (adapted from [12]).

2.3.4 Forward Error Correction

Forward error correction (FEC) is an optional mechanism to increase the optical link budget[4], the fiber distance or splitting ratio (according to the standard, with FEC the power budget is increased by 2.5dB). The FEC appends to the Ethernet frame additional data, algorithm [RS(255, 239)], which encodes 239 information symbols by adding 16 parity symbol. It is used to detect and correct data errors at the receiving end points [12].

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[4] Optical link budget or optical power budget is defined by the maximum available attenuation between two points.

2.3.5 EPON Ethernet frame

The transmission format in EPON, as the name indicates, is Ethernet, and the Ethernet frames flowing in an EPON network are very similar to the common Ethernet frame, with differences on the preamble: the EPON Ethernet frame's preamble contains the LLID that identifies the ONU and a 8-bit Cyclic Redundancy Check (CRC-8). Thus, the frame is as shown in Figure 2.6.

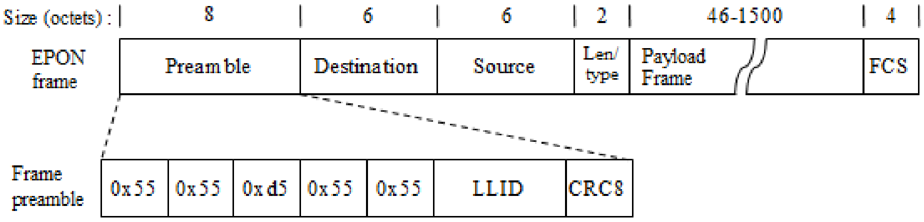


Figure 2.6: EPON Ethernet Frame structure (adapted from [13, 14]).

2.3.6 Requirements

To deploy an EPON network there are several requirements that need to be well defined. This imposes, for example, limits in the optical power flowing in the networks, low optical power values lead to high bit error rates (BER) as the signal to noise ratio (SNR) is low. High optical power values, besides damaging equipment risk, generates nonlinear effects that degrades de SNR and compromises the BER too. The IEEE standard assumes optical power values that leads to a BER greater or equal to 10^{-12}. The optical fiber cable is a single mode fiber and shall meet the dispersion specifications defined in IEC 60793-2 and ITU G.652. The standard defines a target nominal maximum range of 20 km and typical 1:16 split ratio, but the maximum length is not limited by the protocol and the split ratio can go up to 32 clients.

Table 2.1: Channel characteristics for 1000BASE-PX20 [12]

Description	**Downstream**	**Upstream**	**Units**
Nominal transmit wavelength	1490	1310	nm
Maximum range	0.5 m to 20		km
Available power budget	26.0		dB
Minimum channel insertion loss	10		dB

The maximum and minimum optical power values for transmitters and receivers for both the OLT and ONU are presented in Table 2.2.

Table 2.2: 1000BASE-PX20 receive and transmit characteristics [12]

Transmitter			
Description	**Downstream**	**Upstream**	**Units**
Wavelength range	1480 to 1500	1260 to 1360	nm
Maximum optical launch power	+7	+4	dBm
Minimum optical launch power	+2	-1	dBm
Receiver			
Description	**Downstream**	**Upstream**	**Units**
Wavelength range	1260 to 1360	1480 to 1500	nm
Maximum bit error ratio	10^{-12}		–
Maximum receive power	-6	-3	dBm
Damage threshold	+4	+7	dBm
Receive sensitivity	-27	-24	dBm

2.4 Gigabit Passive Optical Network

GPON is, along with EPON, a solution for passive optical networks in the access portion of networks. It is specified by International Telecommunication Union – Telecommunication Standardization Sector (ITU-T) G.984 series. GPON has improved capabilities compared to APON and BPON and is backwards compatible. It is also similar to EPON in the physical level.

Depending on the class of equipment, the physical reach of GPON, i.e. the maximum physical distance between the ONU and the OLT, can be 10 km or 20 km. However, the standard defines that besides the physical reach limitation, the maximum distance between the ONU and the OLT – the logical reach – can go up to 60 km. Regarding the splitting ratio, it is obvious that, for operators, the largest the split ratio, the best, and given the current technology, the recommended splitting ratio is 64 users per PON. Still, the TC (Transmission Convergence) layer considers splitting ratios up to 1:128, which is a factor favouring GPON [15].

The reference configuration of a GPON network is the same as for the EPON (Figure 2.2), and the network is also constituted of an OLT, splitters, ONUs and fiber optical cables. The terminal equipment's type is now GPON's. Bidirectional transmission is accomplished by using WDM on a single fiber using the same wavelengths as in EPON: 1490 nm (S band) in downstream and 1310 nm (O band) in upstream direction, the upstream access is made in TDMA as well as EPON [15, 16].

2.4.1 GPON frame

In the physical layer, the GPON technology is very similar to the EPON, and the mode of operation in both downstream and upstream is identical, however GPON differs in the transmission frames and has its own frame encapsulation. In the downstream direction GEM (GPON Encapsulation Method) frames are carried in the GTC (GPON Transmission Convergence) payload in a broadcast way, this means, the GTC frames, sent by the OLT, arrive at all the ONUs. The ONU extracts the GEM frames that are directed to it, through a Port-ID identifier (a 12-bit number assigned by the OLT to the individual logical connections). Figure 2.7 shows how the GEM frame maps into the GTC frames.

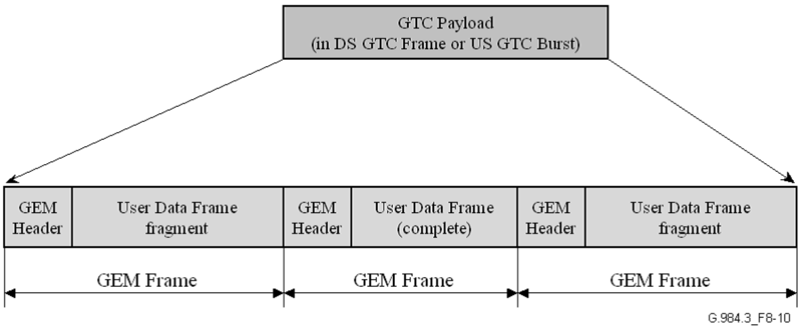


Figure 2.7: Mapping of GEM frames into GTC payload [17].

Both in downstream and upstream, each GTC frame has a duration of 125 μs, which corresponds in the downstream direction (2.48832 *Gbps*) to 38880 bytes long frame and in the upstream direction (1.24416 *Gbps*) to 19440 bytes. The downstream frame consists of the physical control block downstream (PCBd) and the GTC payload. The upstream transmission is made, as in EPON, in burst mode. Each burst contains the upstream physical layer overhead upstream (PLOu) section and one or more allocation intervals. Figure 2.8 shows the frame structure for downstream and upstream directions.

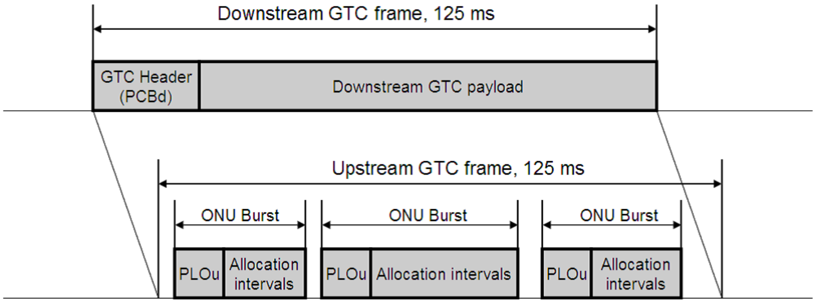


Figure 2.8: GTC frame for downstream and upstream [17].

In the GTC header or PCBd, the OLT sends pointers for the upstream bandwidth map. These pointers indicate when starts and ends each ONU transmission, or in other words, indicates and assigns each allocation interval. This way, only one ONU is transmitting at any time. To assure that there are not lasers turned on at the same time, it is defined a gap between bursts with the duration of $26.67\,ns$ (32 bits assuming $1.25\,Gbps$) called guard time. The upstream bursts begin with the PLOu that includes preamble, delimiter and the burst header, and is completed with one or more allocation intervals. When one or more allocation intervals are assigned to one ONU they can be either adjacent, and there is not necessary to transmit the guard time and the PLOu again, or separated and the time of the burst mode overhead and burst header have to be taken in account. The next figure illustrates the detail of an upstream burst.

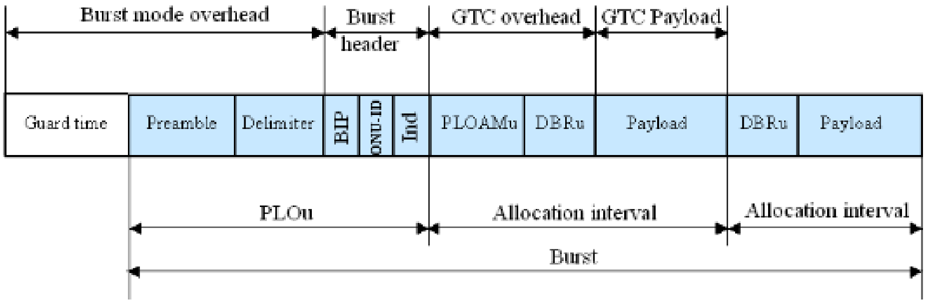


Figure 2.9: Details of physical and GTC layer upstream overhead [17].

2.4.2 Dynamic Bandwidth Assignment

Dynamic bandwidth assignment (DBA) is the process by which the OLT (DBA compatible) reallocates the upstream transmission opportunities to the ONUs based on their activity status and their configured traffic contracts. Although DBA is possible in EPONs it is not defined in the standard, but in GPON it is. The goal of DBA is to effectively and efficiently perform fair scheduling of time slots between ONUs improving GPON upstream bandwidth utilization, and it has practical benefits for both operators and subscribers: the operators can add more subscribers due to a more efficient bandwidth use and the subscribers can enjoy enhanced services, such as those requiring variable rate with peaks beyond levels that were contracted or that can be reasonably static allocated.

Unlike static fashion, using DBA algorithms the OLT can react adaptively to the ONU bursty traffic patterns. The DBA method can be either based on ONU buffer occupancy reports that are solicited by the OLT and submitted by the ONUs in response (status reporting DBA) or based on the OLT's observation of the idle GEM frame pattern and its comparison with the corresponding bandwidth maps (traffic monitoring DBA) [17].

2.4.3 Forward Error Correction

As in EPON, FEC is defined in GPON standard, and allows an increased link budget of approximately 3-4 dB. The encoded data format introduces redundancy, and allows the decoder to detect and correct transmission errors. For example, for an input BER of 10^{-4}, the FEC decoder's output BER will drop to 10^{-15}. Therefore, longer distance from OLT to ONUs and higher splitting ratios can be achieved [17].

2.4.4 Requirements

Even though the standard defines different approaches in the implementation of the GPON technology, the market choice [16] has fell on 2.488 $Gbps$ and 1.244 $Gbps$ on downstream and upstream rates, respectively, over a single fiber. The main channel characteristics are shown in Table 2.3.

Table 2.3: Channel characteristics for GPON [16]

Description	**Downstream**	**Upstream**	**Units**
Nominal transmit wavelength	1490	1310	nm
Maximum range	up to 60		km
Available power budget	28.0		dB
Minimum channel insertion loss	13		dB

The maximum and minimum optical power values for the transmitters and receivers of OLT and ONU are shown in Table 2.4. The parameters are specified relative to an optical section design objective of a BER not worse than 10^{-10} and the optical fiber utilized to be the monomode defined in G.652.

Table 2.4: GPON receive and transmit characteristics [16]

Transmitter			
Description	**Downstream**	**Upstream**	**Units**
Wavelength range	1480 to 1500	1260 to 1360	*nm*
Maximum optical launch power	+5	+5	*dBm*
Minimum optical launch power	+1.5	+0.5	*dBm*
Receiver			
Description	**Downstream**	**Upstream**	**Units**
Wavelength range	1260 to 1360	1480 to 1500	*nm*
Maximum bit error ratio	Less than 10^{-10}		–
Maximum receive power	−8	−8	*dBm*
Damage threshold	–	–	*dBm*
Receive sensitivity	−28	−27	*dBm*

2.4.5 Extender Reach

The need to extend the physical reach or the number of clients in a GPON led the ITU outline the architecture and interface parameters to achieve that goal. The standard [18] defines two general classes of extender devices. The first class, is based on the use of optical-electrical-optical (OEO) regeneration, that can be 2R or 3R. The 2R receives an optical signal, reshapes and reamplifies the signal. The 3R reshapes, retimes and reamplifies the signal. These processes are done in the electrical domain and then the signal is again converted to the optical domain and is retransmitted. The second is using an optical amplifier, which provides gain in optical domain. Hybrid schemes are also possible, using regeneration in upstream and optical amplification in downstream or vice-versa.

The insertion of the extender device is recommended to be between the ODN (Optical Distribution Network) and an Optical Trunk Line (OTL) as shown in the Figure 2.10.

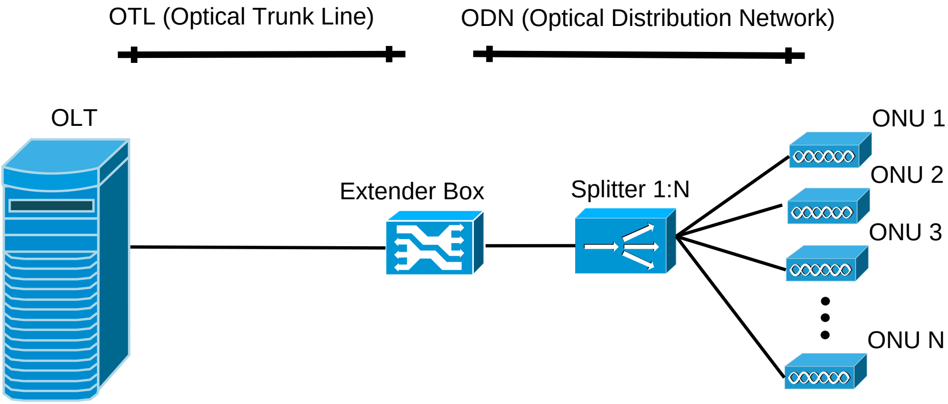


Figure 2.10: Mid-span extension.

The standard defines the essential parameters for the design of a mid-span extender for both using opto-electronic regeneration and optical amplification, but, as the choice fell on using optical amplification in the design the extender box, the parameter here presented are focused just in the recommendations for optical amplification.

The system with the insertion of the extender box must remain compatible with the existing terminal equipment, and thus, new power budgets are defined. With the introduction of the extender box, in the OTL, the power budget is now 23 dB in downstream and 28 dB in upstream, and in the ODN, between 13 and 28 dB for both downstream and upstream. One problem of using optical amplifiers is the insertion of Amplified Spontaneous Emission (ASE), which will degrade the signal, so, in [18] were defined limits for ASE in the extender devices.

Table 2.5 summarizes the recommended characteristics for an extender box based in optical amplifiers.

Table 2.5: Relevant parameters of an extender box based in optical amplifiers [18]

Transmitter			
Description	**Downstream**	**Upstream**	**Units**
Maximum power output	+1.5 – minimum gain – OLT loss	+5 – minimum ODN attenuation + maximum gain	*dBm*
Minimum power output	+0.5 – maximum gain – OLT loss	+0.5 – maximum ODN attenuation + minimum gain	*dBm*
Maximum ASE output @ −28 dBm input	+5	+7	*dB*
Receiver			
Description	**Downstream**	**Upstream**	**Units**
Maximum receive power	−5	−8	*dBm*
Minimum sensitivity	−23	−28	*dBm*

The standard also makes recommendations for the management of the extender box. It is recommended that the reach extender must support full management of its configuration, performance monitoring and fault reporting. As it is an electrically supplied equipment, it requires power, therefore, the standard recommends to have protection against failures of the primary source.

2.5 10G-EPON – 10 Gigabit Ethernet Passive Optical Network

10G-EPON is the successor of EPON and was targeted to achieve a tenfold leap to data rates of 10 *Gbps*. The standard (IEEE 802.3av [29]) provides both, symmetric and asymmetric rates of 10 *Gbps* downstream and upstream and 10 *Gbps* downstream and 1 *Gbps* upstream, respectively, as well as compatibility and coexistence with the backwards equipment in previous system, EPON, specified in [12]. To achieve a smooth upgrade, it is assumed that the two technologies can coexist in the same PON and, therefore, not forcing neither the clients to upgrade to a system that they may not need yet, neither the carriers to invest all at once.

The standard 802.3ah adds new Physical Layers characteristics for 10 *Gbps* operation on point-to-multipoint passive optical networks and achieving backwards compatibility with 1 *Gbps* EPON equipment and ODN imposed several hurdles and challenges. Among the changes, the main are in wavelength allocation, dual-rate burst-mode operation at the OLT and achieving higher power budget.

2.5.1 Wavelength Allocation

One of the challenges faced was choosing the wavelengths that would be compatible with legacy EPON upstream, downstream and analogue video overlay maintaining economic and practical feasibility. In the downstream, choosing a wavelength shorter than the 1260 *nm* would be a problem regarding the wavelength cutoff in the already deployed SMF (Single Mode Fiber). Between 1360 *nm* and 1480 *nm* and between 1500 *nm* and 1550 *nm* the ONUs would not be able to cut the 10 *Gbps* signal, which would cause crosstalk penalty. Therefore, the band chosen was between 1575 *nm* and 1580 *nm*, as shown in Figure 2.11b and Figure 2.11c, 15 *nm* after 1560 *nm* to assure a good isolation from the video overlay.

In upstream, due to economic reasons, the band near zero dispersion around 1310 nm was chosen (1260—1280). As it is used by the 1G-EPON, a dual-rate mode operation was the solution at the OLT to accommodate both speeds. Figure 2.11 depicts the allocated wavelengths in all three architectures, Figure 2.11a shows the wavelength allocation in the legacy EPON, Figure 2.11b shows the wavelength allocation for asymmetric 10G-PON, note that as the upstream link data rate is 1 *Gbps*, the operation is the same as in EPON, Figure 2.11c shows the wavelength allocation for symmetric 10G-EPON.

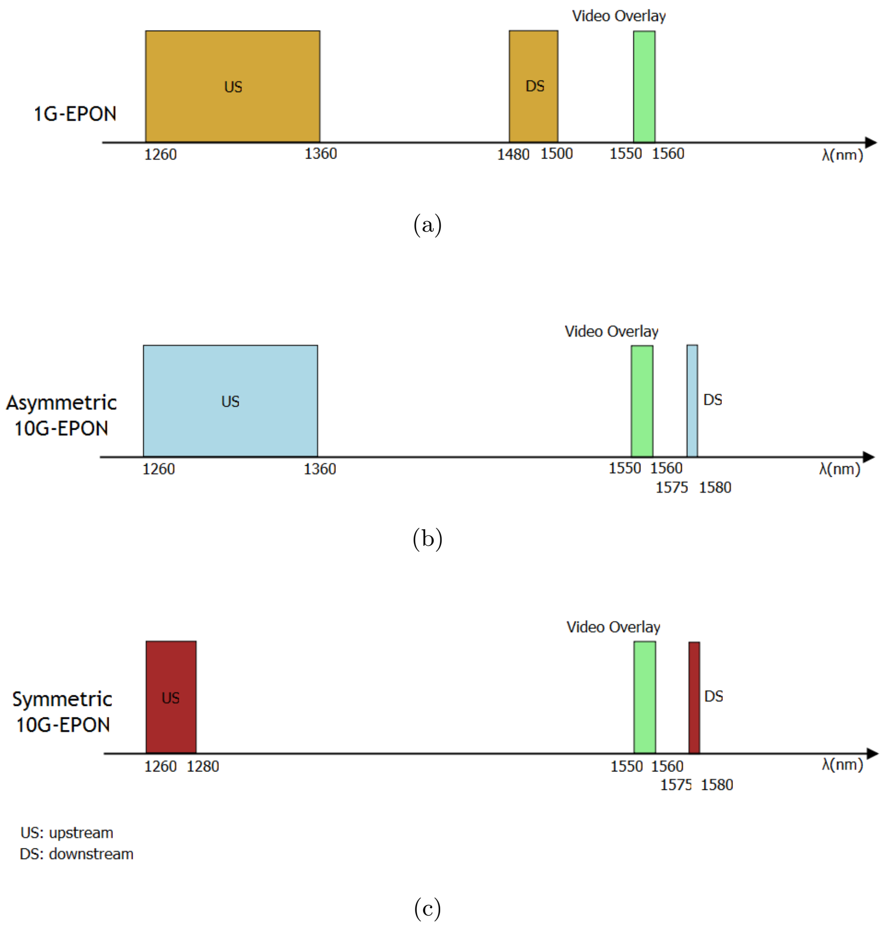


Figure 2.11: Wavelength allocation in (a) EPON, (b) 10/1G-EPON, (c) 10/10G-EPON (adapted from [28]).

2.5.2 Power Budget

Following backwards compatibility requirements, there were defined combinations of classes of power budget to support at least $10\,km$ and $20\,km$ and split ratios of 1:16 and 1:32 both on symmetric and asymmetric rates. Each power budget class is represented by PR-type power budget and PRX-type power budget. PR-type describes symmetric-rate physical layer specifications for PON operating at $10\ Gbps$ downstream and upstream over a single SMF and PRX-type describes asymmetric-rate physical layer specifications for PON operating at $10\,Gbps$ downstream and $1\,Gbps$ upstream. The lower power budget class is represented with the value 10, PR10/PRX10, and supports a P2MP media channel insertion loss $\leq 20\,dB$ for a PON with split ration of at least 1:16 and the distance of at least 10 Km. The medium power budget class is represented with the value 20 supports insertion loss $\leq 24\,dB$, which is characteristic of PR20/PRX20 with a split ratio of at least 1:16 and a distance of at least

20 km or 1:32 split ratio at least, and distance of 10 km at least. The high power budget class is represented with the value 30 supports loss $\leq 29\, dB$, characteristic of PR30/PRX30 with a split ratio of at least 1:32 and the distance of at least 20 km. Table 2.6 a summarizes the relation between split ratio and distance for symmetric and asymmetric power budget classes.

Table 2.6: Physical Medium Dependent (PMD) combinations for both symmetric 10/10G-EPON (PR) and asymmetric 10/1G-EPON (PRX).

Split ratio \ Distance	**10** km	**20** km
1:16	10GBASE-PR10/PRX10	10GBASE-PR20/PRX20
1:32	10GBASE-PR20/PRX20	10GBASE-PR30/PRX30

Tables 2.7 and 2.8 present the main characteristics of the optical transceivers of OLT and ONU respectively, for each power budget class. The OLT transmitter characteristics are the same for PR and PRX classes, both line rates are 10.3125 $Gbps$, the same is not true for the upstream link, where a dual-rate mode receiver is implemented, which is more detailed in the section (2.5.3), and accepts both line rates, 10.31 $Gbps$ and the 1.25 $Gbps$. In the case of PRX-10 and 20, in the ONU transmitter and OLT receiver, the values for receiver can be found in [12], as they are the same for 1000BASE-PX10 and 1000BASE-PX20, respectively. The parameters listed are on the condition of a BER inferior to 10^{-3} before FEC decoding[5], except for the PRX receivers at the OLT that impose a BER smaller than 10^{-12} that is characteristic of the 1.25 $Gbps$ rates without FEC.

---

[5] The standard imposes FEC for 10 Gigabit rates. Therefore, the BER limit before the signal is submitted to error correction, is more relaxed.

Table 2.7: PR and PRX type OLT transmit and receive characteristics [12, 29]

Transmitter				
Description	**PR/PRX10**	**PR/PRX20**	**PR/PRX30**	**Units**
Wavelength range	1575 to 1580			*nm*
Maximum optical launch power	+5	+9	+9	*dBm*
Minimum optical launch power	+2	+5	+2	*dBm*
Receiver				
Description	**PR10**	**PR20**	**PR30**	**Units**
Wavelength range	1260 to 1280			*nm*
Maximum bit error ratio	Less than 10^{-3}			–
Maximum receive power	−1	−6	−6	*dBm*
Damage threshold	0	−5	−5	*dBm*
Receive sensitivity	−24	−28	−28	*dBm*
Description	**PRX10**	**PRX20**	**PRX30**	**Units**
Wavelength range	1260 to 1360			*nm*
Maximum bit error ratio	Less than 10^{-12}			–
Maximum receive power	−1	−6	−9.38	*dBm*
Damage threshold	+4	+4	−5	*dBm*
Receive sensitivity	−24	−27	−29.78	*dBm*

Table 2.8: PR and PRX type ONU transmit and receive characteristics [29]

Transmitter				
Description	**PR10**	**PR20**	**PR30**	**Units**
Wavelength range	1260 to 1280			*nm*
Maximum optical launch power	+4	+4	+9	*dBm*
Minimum optical launch power	−1	−1	+4	*dBm*
Description	**PRX10**	**PRX20**	**PRX30**	**Units**
Wavelength range	1260 to 1360			*nm*
Maximum optical launch power	+4	+4	+5.62	*dBm*
Minimum optical launch power	−1	−1	+0.62	*dBm*
Receiver				
Description	**PR/PRX10**	**PR/PRX20**	**PR/PRX30**	**Units**
Wavelength range	1575 to 1580			*nm*
Maximum bit error ratio	Less than 10^{-3}			–
Maximum receive power	0	0	−10	*dBm*
Damage threshold	+1	+1	−9	*dBm*
Receive sensitivity	−20.5	−20.5	−28.5	*dBm*

2.5.3 Dual-rate Mode

To support coexistence of 10G–EPON and 1G–EPON ONUs on the same outside plant, the OLT may be configured to use a dual-rate mode. Dual-rate mode supports transmission and/or reception of both 10 *Gbps* and 1 *Gbps* data rates, and can be introduced as options for 10G–EPON OLTs, functionally combining PMDs supporting 10 *Gbps* and 1 *Gbps* data rates [29].

Figure 2.12 illustrates the coexistence of signals between an OLT and ONUs operating in EPON and 10G-EPON architectures.

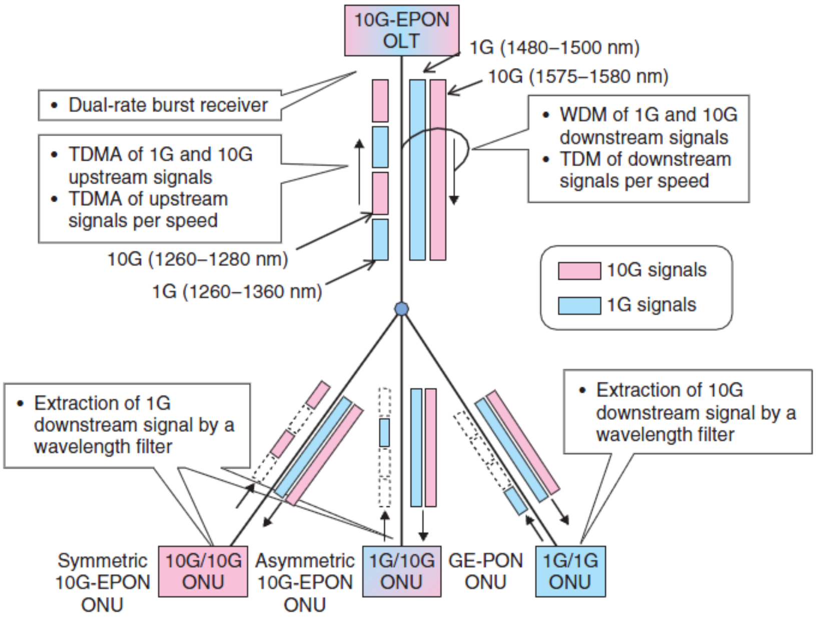


Figure 2.12: Schematic of EPON and 10G-EPON signals coexistence [27].

In the downstream both 10 *Gbps* and 1 *Gbps* are transmitted by the OLT and separated by two different wavelengths. When the signal reaches the ONU, it is filtered by a wavelength filter and only one wavelength is received by the ONU, either a 10 *Gbps* or 1 *Gbps* signal. In the upstream direction, the signals are multiplexed in the time domain (TDMA) and are within the same/overlapped wavelength band (1260—1360 EPON upstream and 1260—1280 10G-EPON upstream), but they arrive at different times at the OLT. To divide the two signals at different speeds, the OLT needs a dual-rate burst receiver.

The receiver can separate the two signals of different line-rate in two ways: in an optical domain or in an electrical domain.

- In the optical domain, the incoming signal is divided in the optical domain and fed into two, independent photodetectors operating one in 10 *Gbps* and the other in 1 *Gbps*, and then each separated signal follow the electrical path that consists of a trans-impedance amplifier (TIA) to overcome the loss of the 1:2 splitter and a limiting amplifier (LA), as depicted in Figure 2.13a.
- Alternatively, the signal can be detected by a photodetector and then separated in the electrical domain after a dual-rate TIA block, as shown in Figure 2.13b. The standard leaves the choice of signal splitting as an implementation choice [29].

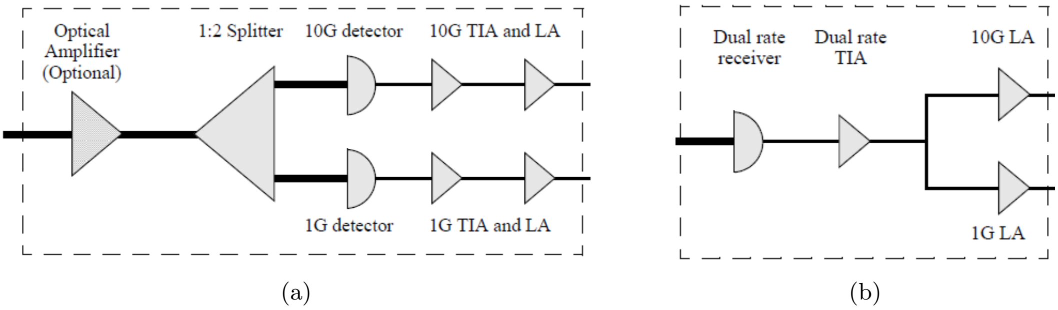


Figure 2.13: Dual-rate topologies with split in (a) optical domain, (b) electrical domain [29].

2.5.4 Forward Error Correction

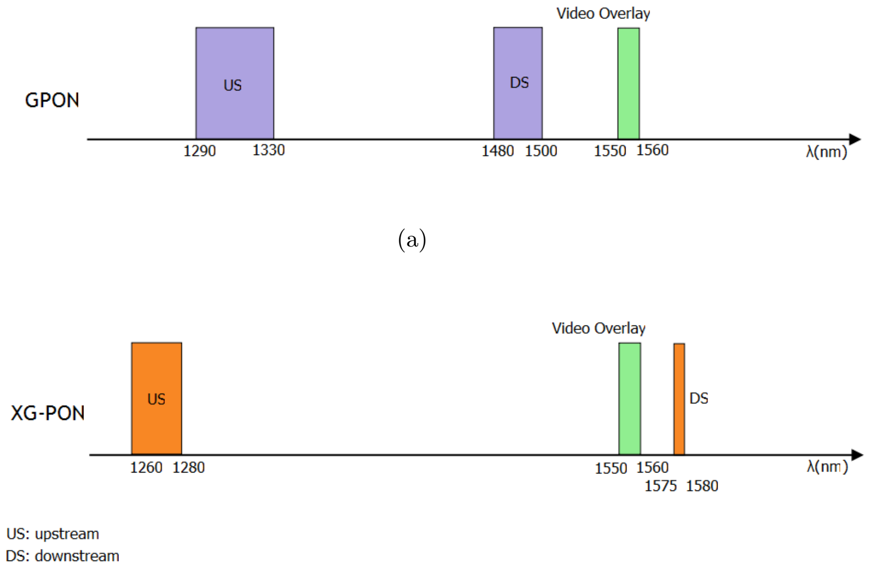
As in EPON (see 2.3.4), FEC is used to increase the optical link budget or the fiber distance, with the difference that in 10G-EPON its use is mandatory. It is also used a Reed-Solomon code (255, 223), but different from (255, 239) of EPON, this encodes 223 information symbols and adds 32 parity symbols. The line coding is different too, in 10G-EPON it is used a 64B/66B encoding, which means that are transmitted 66 bits for every 64 bits of information, which reduces the coding overhead from 20% to 3%, when compared to EPON, increasing the efficiency.

2.6 XG-PON – 10 Gigabit Passive Optical Network

XG-PON is the successor of GPON and, as well as 10G-EPON, introduces 10 Gigabit rates to the PON. The ITU-T G.897 series are the standards for the new 10 Gigabit PON, some are already complete and available — XG-PON: General requirements (G.897.1 [30]) and XG-PON: Physical media dependent (PMD) layer specification (G.897.2 [31]). The preparation work for the upcoming PONs begun with the recommendation G.984.5 [32], where are defined wavelength ranges reserved for additional service signals to be overlaid via WDM. This refined spectrum plan allowed a smoother migration to the wavelengths chosen for XG-PON, defining parameters for discrete WDM filters for combining and isolating the GPON signals at the OLT side.

2.6.1 Wavelength Allocation

The operating wavelength for XG-PON agree with choices made for 10G-EPON, discussed in 2.5.1, with the difference that XG-PON does not contemplates symmetric 10 Gigabit rates, which is considered for XG-PON2 [30]. Therefore the choice for downstream range was from 1575—1580 nm and for upstream was the range from 1260—1280 nm. In this case it does not overlaps with the GPON upstream band, due to the its narrowing considered in G.984.5. Figure 2.14 shows the wavelength allocation for both GPON and XG-PON.



(a)

(b)

Figure 2.14: Wavelength allocation in (a) GPON and (b) XG-PON.

When compared to Figure 2.11 it is possible to verify that the wavelength chosen for XG-PON is the same of symmetric 10G-EPON for upstream and downstream. In the case of XG-PON, the non-overlapping upstream wavelengths eliminate the requirement for dual-rate receivers at the OLT side. The two systems can coexist with a WDM combiner/splitter installed at the CO. An example of a migration scenario is depicted in Figure 2.15.

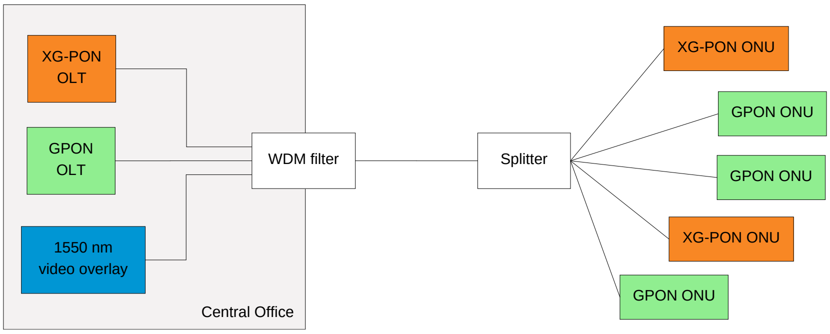


Figure 2.15: Example of a coexistence scenario between GPON and XGPON

2.6.2 Power Budget

Due to the introduction of the WDM filter and the deviation of some operators from the previous standard, there were defined new classes for optical power budgets featuring class B+ equipment: Nominal 1 (29 *dB*) and Nominal 2 (31 *dB*) at a BER of 10^{-12} and also two extended classes: Extended 1 (33 *dB*) and Extended 2 (35 *dB*). The standard also contemplates higher logical split ratios above 1:128 to improve the economical benefits compared to GPON, as some operators have shown interest in extending the split above 1:64. The bit rates adopted for XG-PON were: downstream line rate of 10 *Gbps* and upstream of 2.5 *Gbps*. Table 2.9 resumes the OLT main characteristics and Table 2.10 the ONU main characteristics, N1 stands for Nominal 1, N2 for Nominal 2, E1 for extended 1, E2 for extended 2, *a* and *b* refers to the reception in the ONU being made by an APD (Avalanche Photodiode) or a PIN diode respectively. The BER at the receivers presume the using of FEC in both downstream and upstream.

Table 2.9: XG—PON OLT transmit and receive characteristics [31].

Description	**Value**						**Units**
Transmitter							
Nominal rate	9.95328						*Gbps*
Wavelength range	1575 to 1580						*nm*
ODN Class	N1	N2a	N2b	E1	E2a	E2b	
Maximum optical launch power	+6	+8	+12.5	+10	+12	+16.5	*dBm*
Minimum optical launch power	+2	+4	+10.5	+6	+8	+14.5	*dBm*
Receiver							
Wavelength range	1260 to 1280						*nm*
Maximum bit error ratio	10^{-4}						
ODN Class	N1	N2		E1	E2		
Receive sensitivity	−27.5	−29.5		−31.5	−33.5		*dBm*
Maximum receive power	−7.0	−9.0		−11	−13		*dBm*

Table 2.10: XG—PON ONU transmit and receive characteristics [31].

<table>
<tr><th>Description</th><th colspan="6">Value</th><th>Units</th></tr>
<tr><td colspan="8">Transmitter</td></tr>
<tr><td>Nominal rate</td><td colspan="6">2.48832</td><td>Gbps</td></tr>
<tr><td>Wavelength range</td><td colspan="6">1260 to 1280</td><td>nm</td></tr>
<tr><td>ODN Class</td><td>N1</td><td colspan="2">N2</td><td>E1</td><td colspan="2">E2</td><td></td></tr>
<tr><td>Maximum optical launch power</td><td>+7</td><td colspan="2">+7</td><td>+7</td><td colspan="2">+7</td><td>dBm</td></tr>
<tr><td>Mimum optical launch power</td><td>+2</td><td colspan="2">+2</td><td>+2</td><td colspan="2">+2</td><td>dBm</td></tr>
<tr><td colspan="8">Receiver</td></tr>
<tr><td>Wavelength range</td><td colspan="6">1575 to 1580</td><td>nm</td></tr>
<tr><td>Maximum bit error ratio</td><td colspan="6">10^{-4}</td><td></td></tr>
<tr><td>ODN Class</td><td>N1</td><td>N2a</td><td>N2b</td><td>E1</td><td>E2a</td><td>E2b</td><td></td></tr>
<tr><td>Receive sensitivity</td><td>–28.0</td><td>–28.0</td><td>–21.5</td><td>–28.0</td><td>–28.0</td><td>–21.5</td><td>dBm</td></tr>
<tr><td>Maximum receive power</td><td>–8.0</td><td>–8.0</td><td>–3.5</td><td>–8.0</td><td>–8.0</td><td>–3.5</td><td>dBm</td></tr>
</table>

2.6.3 Additional Features

Although not yet specified in [30], there are already some features mentioned when compared to legacy GPON. One of them is power saving and energy efficiency for two objectives. First, saving power so that a backup battery would last longer when electricity service goes out. Second, saving power at all times, without penalizing the QoS. Another feature is stronger authentication mechanism with strong encryption algorithms to protect against spoofing. The mechanisms intend to be optional but standard.

Chapter 3

State of Art

3.1 Fiber Deployment

"Fiber networks can make a vital contribution to sustainable economic development" [19]. It is widely accepted that fiber optics play now a vital role in access networks market. This attracted investors, vendors and manufactures to develop networks and equipment suitable to attend the subscriber needs and expectations. To promote a balanced equipment market, with interoperability and coexistence between manufactures, ITU and IEEE created a set of standards to guide the deployment of optical networks. Both sides, industry and regulators, have been working and cooperating for the sustainable growth of optical networks, particularly, the optical access networks.

Data of the end of 2009[1] shows that, around the world, Asia is still the largest market in the distribution of FTTH/B with 72% of total FTTH/B deployment, followed by North America and Western Europe. In Eastern Europe, the FTTH/B market is being spurred by a healthy growth momentum in several countries like Lithuania, Slovenia and Estonia. Lithuania stands out for having the highest percentage (40%) of households that subscribe to an FTTH/B access service of anywhere in Europe, East or West, and Slovenia the highest percentage of homes passed [1,20]. However, Russia and Sweden lead in the total number of subscribers, due to the higher population.

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[1] The results of 2009 are the last up to date IDATE statistics.

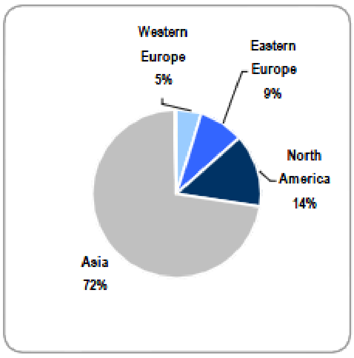

Figure 3.1: FTTH/B subscriber distribution around the world at the end of 2009 [1].

Portugal, particularly, is highly investing in optical access networks, expecting to be the 10^{th} country with higher percentage (above 80%) of homes passed in 2014:

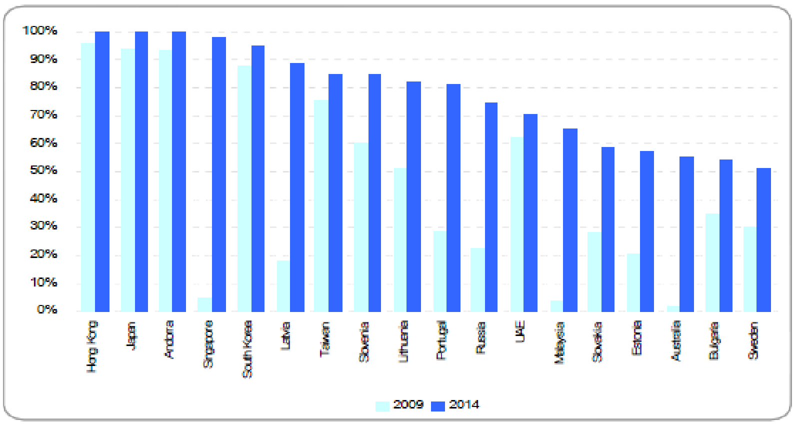

Figure 3.2: Countries with more than 50% of homes passed in 2014 [1].

Regarding the optical access technologies, EPON and GPON dominate the market. EPON is the most deployed technology (55%), benefiting of almost exclusive adoption by the Asian market. A technology initially backed by Japanese and South Korean carriers, EPON was also the first choice for Chinese operators.

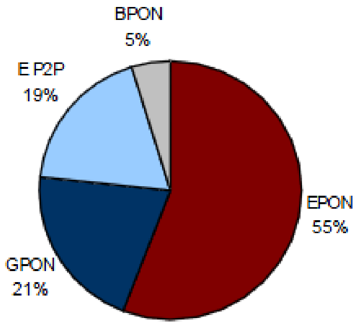

Figure 3.3: Breakdown of the FTTx technologies worldwide – end of 2009 [1].

GPON trial announcements in 2009 could change technological trends as some of the players are expected to increase their use of GPON substantially. According to the industry, this trend will spread up to 2011, following a period of coexistence for EPON and GPON. Other industry experts say that GPON will be the number one technology by 2013 [1]. With this, Figure 3.3 may be a bit outdated to the current year of 2011, where a two years gap may be reflected in a reduced EPON percentage and an increased GPON percentage.

3.2 Extender Box Status

The steadily increasing demand for bandwidth is clear, which generates high interests in deploying and operating cost-efficient broadband access networks. To keep the costs of the network investment and installation as low as possible, the manufacturers place on the market devices capable of increasing the range of optical access networks, giving the opportunity for operators to achieve a reach increase maintaining the same technology and the network previously deployed.

In this section will be presented and described the prototype developed in other dissertation [21]. The focus was to design a device capable of extending the reach of the existing PONs maintaining compatibility and all the features of the network with a low cost of production. The reach extender designed, is based on optical amplification, with individual SOAs (Semiconductor Optical Amplifier) amplifying each band, $1310\,nm$, $1490\,nm$ and $1550\,nm$ for upstream, downstream and analogue video respectively[2]. The choice was based on the availability, performance and price of each amplifier and between SOAs, Raman amplifiers and Doped Fiber Amplifiers (DFA), the SOAs, for this purpose, have proven to be the best option [21].

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[2] The video overlay amplification was intended to be included in the extender box, but its study was not completed and a solution was not presented.

3.2.1 SOA Basic Principals

As the choice in the design of the extender box fell on using SOAs, it is important to study and understand their behaviour.

The first studies on SOAs were carried out in the 60s around the time of the invention of the semiconductor laser. These devices were initially based on GaAs homojuntions operating at low temperatures. In the late 80s studies on InP/GaAsP SOAs began to appear, designed to operate in the 1300 nm and 1500 nm regions [22].

An SOA is an optoelectronic device that under certain conditions can amplify an input light signal. The schematic of a semiconductor optical amplifier (SOA) is shown in Figure 3.4.

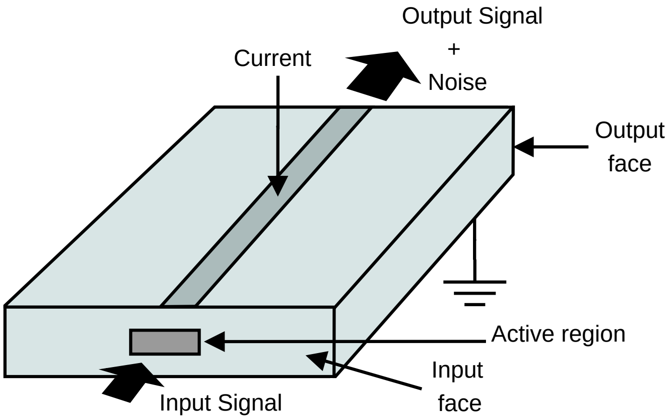
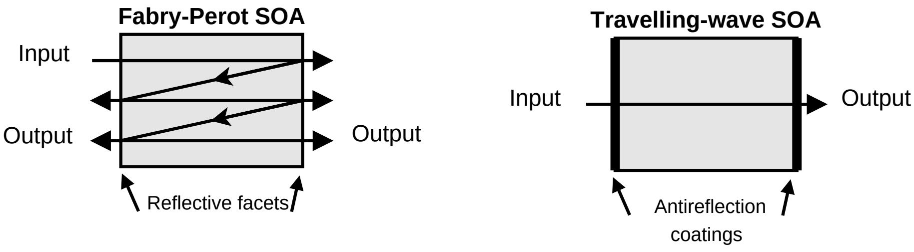


Figure 3.4: Schematic diagram of an SOA [22].

The active region is responsible for the gain of the input signal, enabled by an external electric current source. The propagating signal wave is confined to the active region through an embedded waveguide, which is weak, so some of the signal leaks into the surrounding lossy cladding regions. A drawback of the process itself is the additive noise at the output signal, that cannot be entirely avoided [22].

SOAs can be classified into two main types: The Fabry-Perot SOA (FP-SOA) and travelling-wave SOA (TW-SOA). The two differ in the reflections from the end facets. In the FP-SOA, reflections from the end facets are significant (the signal undergoes many passes through the amplifier), in the TW-SOA, reflections are negligible (the signal undergoes a single-pass in the amplifier). Both types are described in Figure 3.5.



(a) (b)

Figure 3.5: SOA types: (a) Fabry-Perot SOA and (b) Travelling-wave SOA [22].

To occur amplification, electrons from the external current source are injected into the active region. This electrons, or carriers, occupy energy states in the conduction band leaving holes in the valence band. The gain is produced through radioactive transitions between those two bands, conduction and valence. The three possible radioactive transitions are spontaneous emission, stimulated emission and stimulated absorption. Considering a two discrete energy levels model, these transitions are illustrated in Figure 3.6.

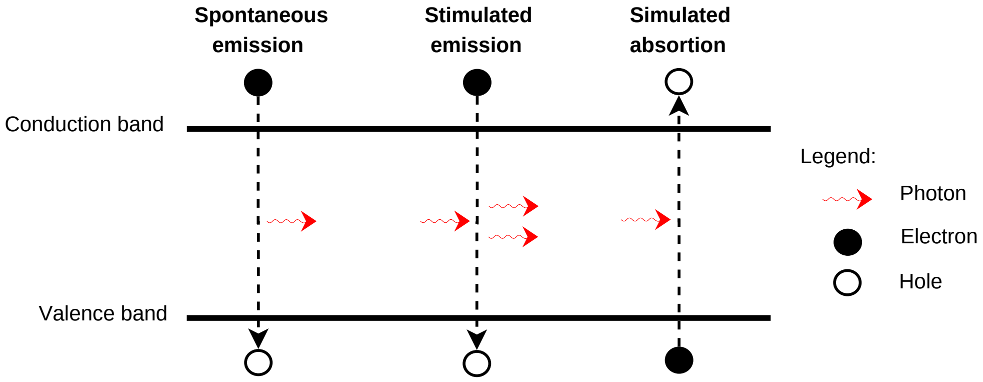


Figure 3.6: Transitions between valence and conduction band in a SOA [22].

In the gain region, the electrons and holes recombine to produce photons through both spontaneous and stimulated emission process [23]. In Figure 3.6 the first process depicted is spontaneous emission, which results from a non-zero probability of a carrier in the conduction band to spontaneously recombine with a hole in the valence band and, switching to a lower energy state, emitting a photon. This photon has random phase, direction and frequency. This process, that cannot be avoided, is responsible for generating noise, called ASE, and reduces the carrier population available for optical gain.

When injected a current to the active region of the SOA, if a photon is incident on the semiconductor, with suitable energy, it may cause a carrier in the conduction band to recombine with a valence band's hole, losing its energy in the form of a photon identical to the incident, i.e., with identical phase, direction and frequency. The process is illustrated in the middle region of Figure 3.6.

In the right side of Figure 3.6 is the transition of a carrier from the valence band to the conduction band. This occurs when the injected current is low and the photon energy is superior to the energy gap. This is a loss process as the incident photon is extinguished [22].

The three processes occur simultaneously and, in the desired gain case, stimulated emission is greater than stimulated absorption and spontaneous emission. The amplification process is repeated along the active region and the semiconductor will exhibit optical gain.

The main advantages of using SOAs for PON applications are their great availability in the market, at low prices, when compared with other amplifiers for the considered bands, the acceptable noise figure, high gain and fast response to variations of the input signal.

3.2.2 CIP SOA-S-OEC-1550

In the S band the amplifier chosen was the CIP SOA-S-OEC-1550, designed to operate in the C band, but its large bandwidth allows its use in the 1490 nm region. In this section are presented experimental tests to characterize the downstream amplifier and evaluate its performance in the extender box.

In Figure 3.7 is presented the gain as a function of bias current. It can be seen that the gain is greater for higher bias current. The gain is also higher for smaller signals, as expected.

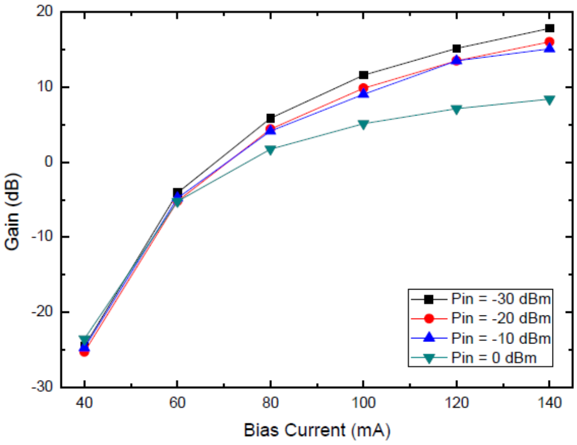


Figure 3.7: Gain as a function of bias current for different input power at 1490 nm [21].

In Figure 3.7 is presented the gain as a function of the input power for different bias current.

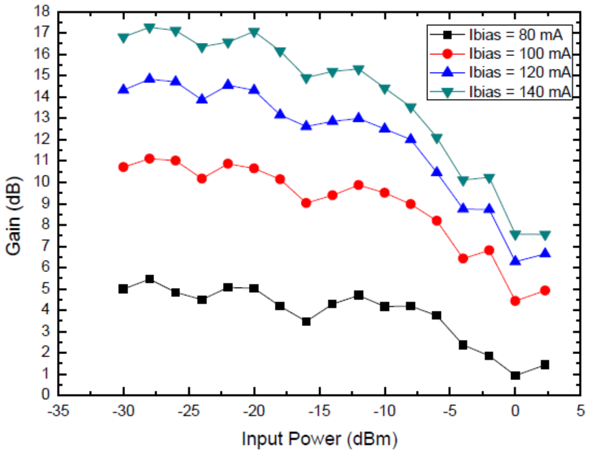


Figure 3.8: Gain as a function of input power for different bias current at 1490 nm [21].

In Figure 3.9 is presented the gain as function of the wavelength at a fixed input power and bias current. This shows that, even though the CIP SOA is designed for the C band, it can also operate in the 1490nm region, reaching almost 20dB as shown in Figure 3.8.

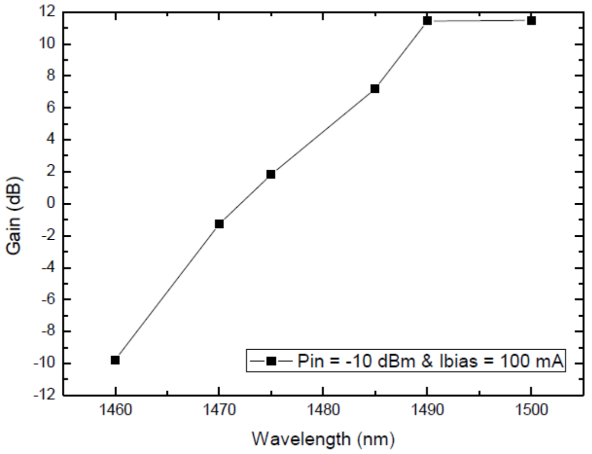


Figure 3.9: Gain as a function of wavelength for input power of $-10\,dBm$ and bias current of $100\,mA$ [21].

The noise analysis is presented in the next two figures, in the first, Figure 3.10, is depicted the NF of the amplifier and in Figure 3.11 the ASE power, both as a function of the bias current. The objective of these measures is to identify the best region of operation of the SOA.

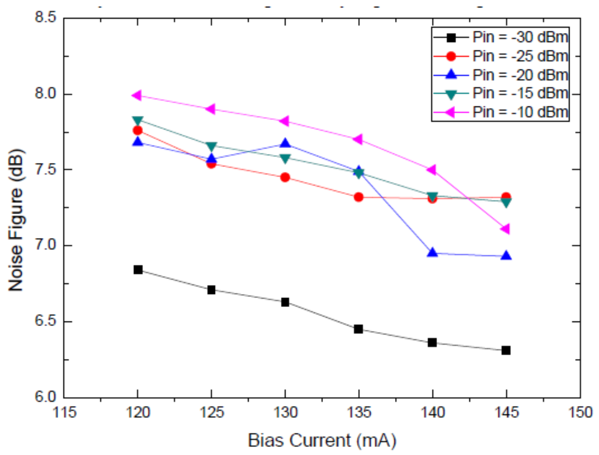


Figure 3.10: Noise figure as a function of bias current at 1490nm for different input power [21].

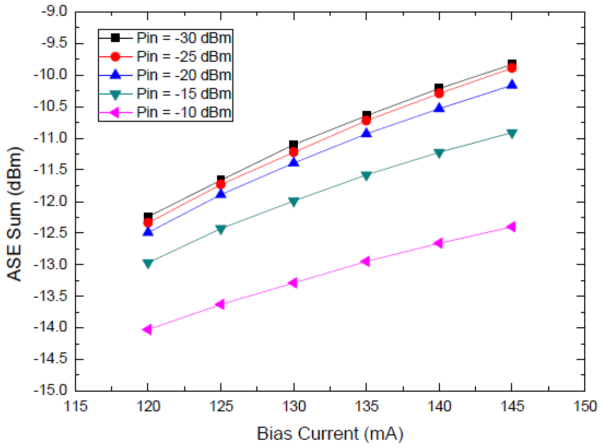


Figure 3.11: ASE power as a function of bias current at 1490nm for different input power [21].

These figures show that the minimal values for noise are obtained for 145 mA of bias current. Thus, a detailed analysis of gain at that region is presented in Figure 3.12:

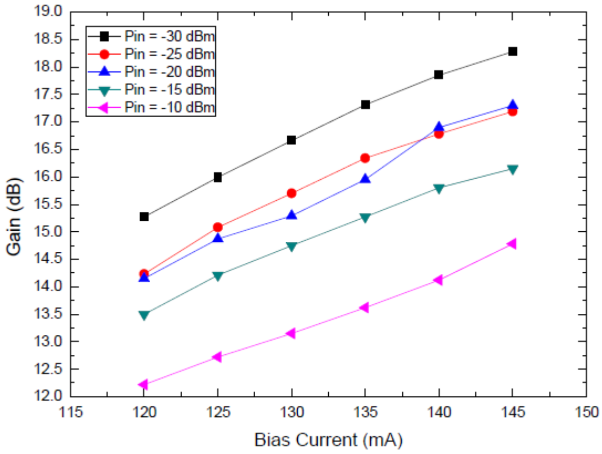


Figure 3.12: Gain as a function of bias current (in the region of 130 mA) for different input power at 1490 nm [21].

The point of lower noise (6.25 to 7.5 dB) coincides with the higher gain (14 to 18 dB) and higher ASE (-12.5 to -9.75 dBm). Working at 1490 nm, close to limit of bandwidth of amplification, the noise figure appears to be higher than the recommended, exceeding in 2.5 dB the maximum recommended in the standard (5 dB).

Were made tests with the SOA in the EPON available in the laboratory with a bias current of 145 mA (the procedures for the tests are detailed in section 3.2.4). The results shown that the SOA allows an increase of the power budget to 51 dB.

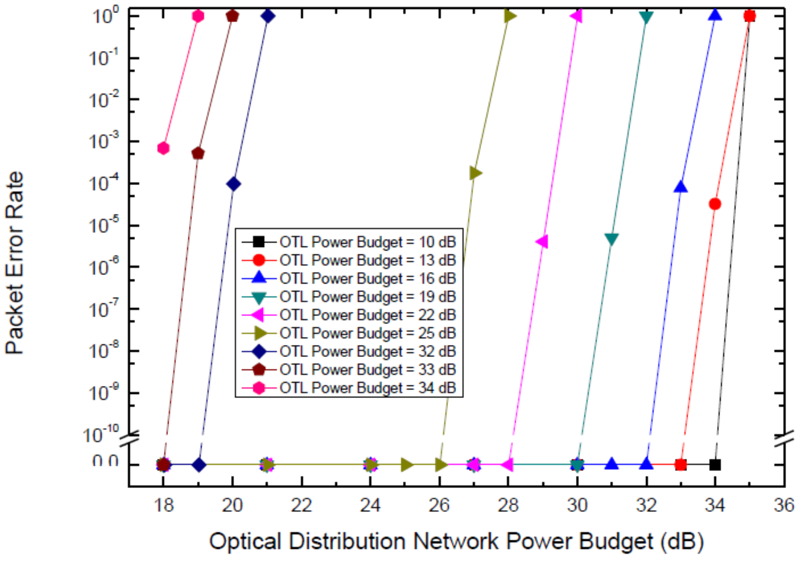


Figure 3.13: Packer error rate for power budget combinations of ODN and OTL with CIP SOA-S-OEC-1550 [21].

In Figure 3.13 it is verified that it is not possible to achieve the maximum values recommended in standard, [18], of 23 dB in OTL for all range of ODN (13 to 28 dB), its only possible with an OTL power budget of 22 dB (pink line), at least in the EPON environment, as it is expected that with GPON equipment we will have a greater power budget.

3.2.3 Alphion SOA29p

In the O band the amplifier chosen was the Alphion SOA29p which was designed to operate in access networks. In this case, it was not done the characterization of gain as a function of wavelength, because there was not any tunable laser available in the O band. Figure 3.14 presents the gain of the SOA as a function of the bias current.

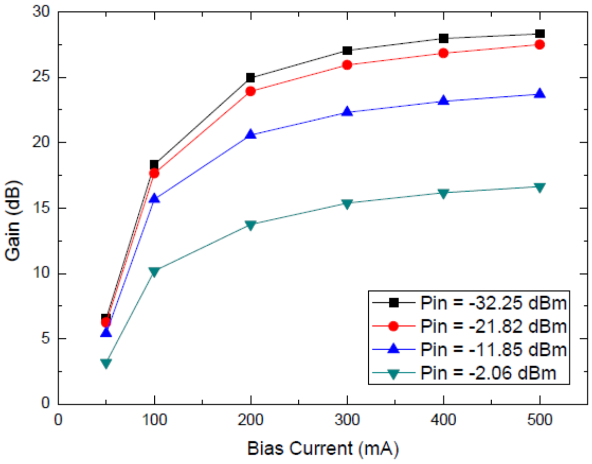


Figure 3.14: Gain as a function of bias current for different bias current at 1310 nm [21].

In Figure 3.15 is presented the gain as a function of input power for different bias current which shows a higher gain than the CIP SOA, about 28 dB.

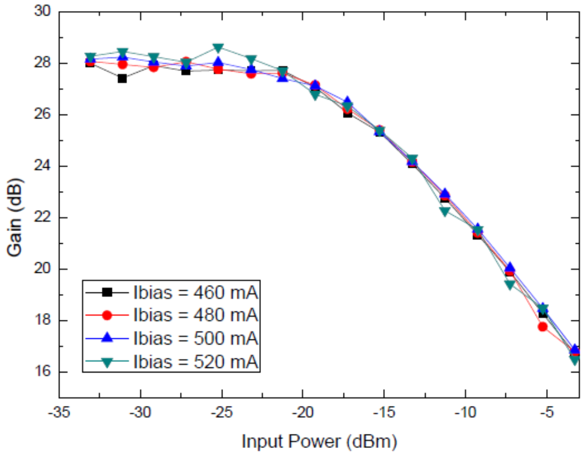


Figure 3.15: Gain as a function of input power for different bias current at 1310 nm [21].

In Figure 3.16 and Figure 3.17 is presented the noise figure and the ASE power, respectively, of the amplifier.

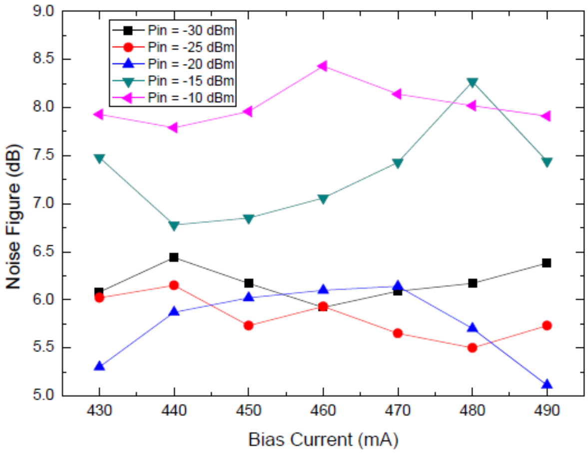


Figure 3.16: Noise figure as a function of bias current at 1310nm for different input power [21].

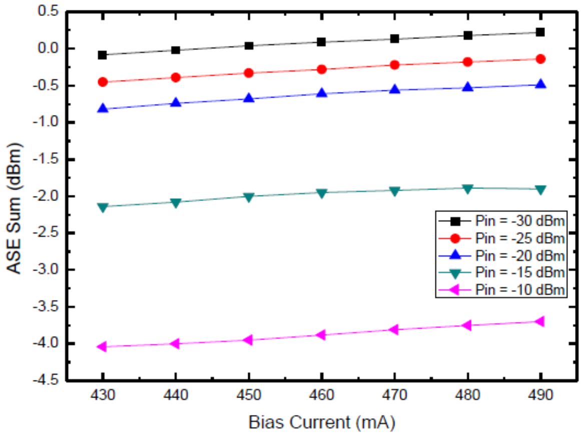


Figure 3.17: ASE power as a function of bias current at 1490 nm for different input power [21].

The noise, in the presence of signal, can reach 8.5 dBm , which is 1.5 dB greater than the recommended in the standard [18]. The point of less noise seems to be in the 440–445 mA of bias current, where the noise figure is from 5.75 to 8 dB, the ASE about -4 to 0 dBm and the gain 21 to 27 dB, as depicted in Figure 3.18.

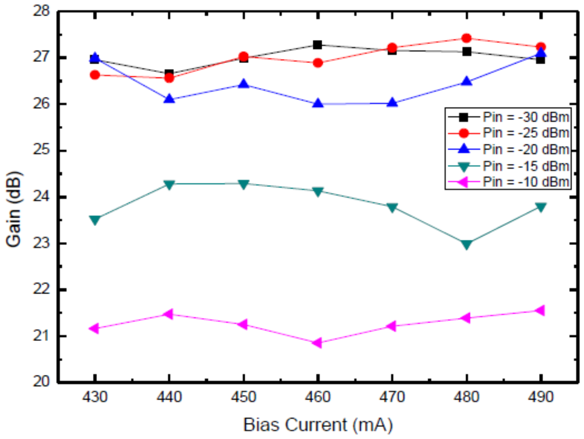


Figure 3.18: Gain as a function of bias current (in the region of 460 mA) for different input power at 1310 nm [21].

Were made tests in the laboratory, with the Alphion SOA inserted in the EPON, with a bias current of 450mA. The results shown that the SOA allows an increase of the power budget to 55 dB. The results for all the combinations tested are presented in Figure 3.19.

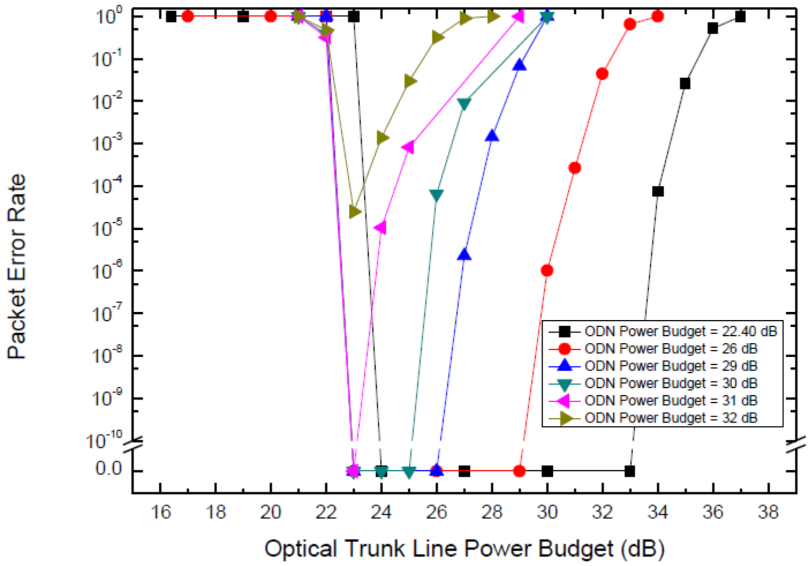


Figure 3.19: Packer error rate for power budget combinations of ODN and OTL with Alphion SOA29p [21].

In Figure 3.19 is possible to verify that is not possible to achieve the maximum values recommended in standard [18] of 28 dB in OTL for all range of ODN (13 to 28 dB). It is possible to obtain 29 dB in the ODN in a range of 23 to 26 dB in the OTL (blue line). This is 2 dB lower than the standard recommendation (28 dB), this occurs because of the noise that the SOA introduces in the line.

3.2.4 Extender Box Prototype

In Figure 3.20 is presented the prototype proposed for the extend box in [21].

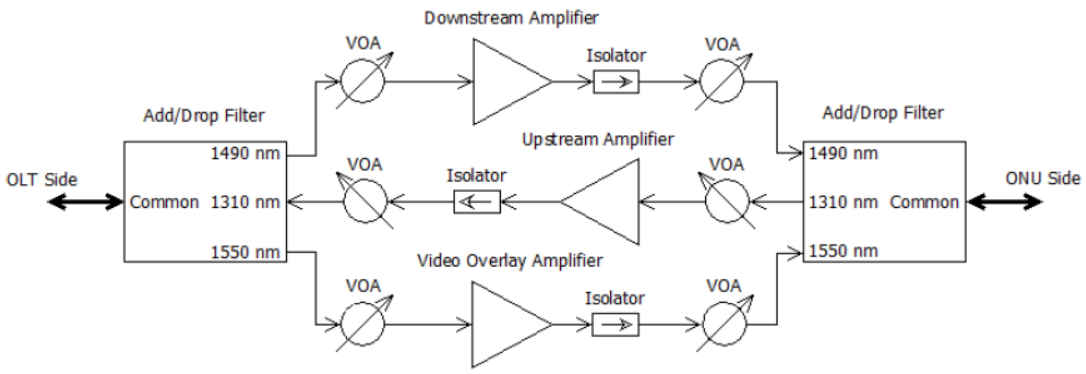


Figure 3.20: Extender box prototype [21].

The goal is to extend the reach of the optical access network, amplifying each channel separately. Even though the traffic of downstream data and video overlay are in the same direction and in adjacent bands (C and S), the CIP SOA having a gain of $20\,dB$, in the presence of the video channel could saturate. As such, the channels are amplified separately. The three bands (O, S and C) are separated and joined using add/drop filters, which act as noise filters too. The isolators make sure there are no reflections that could reach the amplifier and damage it, or cause decrease in signal quality.

The objective is that the extender can adapt itself to the environment in which it is inserted, so to operate in the range admitted by the standard — $23\,dB$ in OTL downstream and 28 upstream, 13 to $28\,dB$ in ODN upstream and upstream — the extender will act in the variable optical attenuators (VOAs) to put the SOAs in their best operating point, adapting the gain. This way, we get the best out of the amplifier without compromising the noise figures. Whenever it is needed to reduce the gain, we can attenuate the signal to the desired values. Despite not being depicted in the scheme, it is necessary to the extender box to give some feedback. The possibility of including monitoring photodetectors to measure the input and output power of the amplifiers trough 1%:99% couplers have also been considered. The results would then be parsed by a controller. This device would also be responsible for the configuration of the variable attenuator for the initial configuration or further adjustments, as well as display the monitoring values.

The SOAs for downstream and upstream were tested simultaneously in a simulation of a real scenario. The considered scenario was $60\ km$ of fiber serving 128 clients. The OTL represents $55\ km$ of the total network and the other $5\ km$ is of ODN, that connects two splitters of 1:8 an 1:16, in cascade, to the clients. This scenario was to represent a rural scenario or of consolidation of central offices where the clients were at a considerable distance from the OLT.

The tests were made with EPON equipment which is the available at the laboratory. As EPON only allow a $20\ km$ reach, the GPON's $60\ km$ were emulated using a VOA which add the attenuation corresponding to $40\ km$ of SMF. Although there are 128 outputs available for the clients, the tests were reduced to only 6 ONUs, the available at the laboratory.

The tests were performed using a traffic generator and parser from IXIA. The traffic is IP, generated at the IXIA equipment and sent to the OLT through a $1\,Gbps$ Ethernet port, having as IP destination another IXIA's port, at $100\ Mbps$ connected to one ONU and vice versa. Figure 3.21 depicts the setup used to perform the traffic tests.

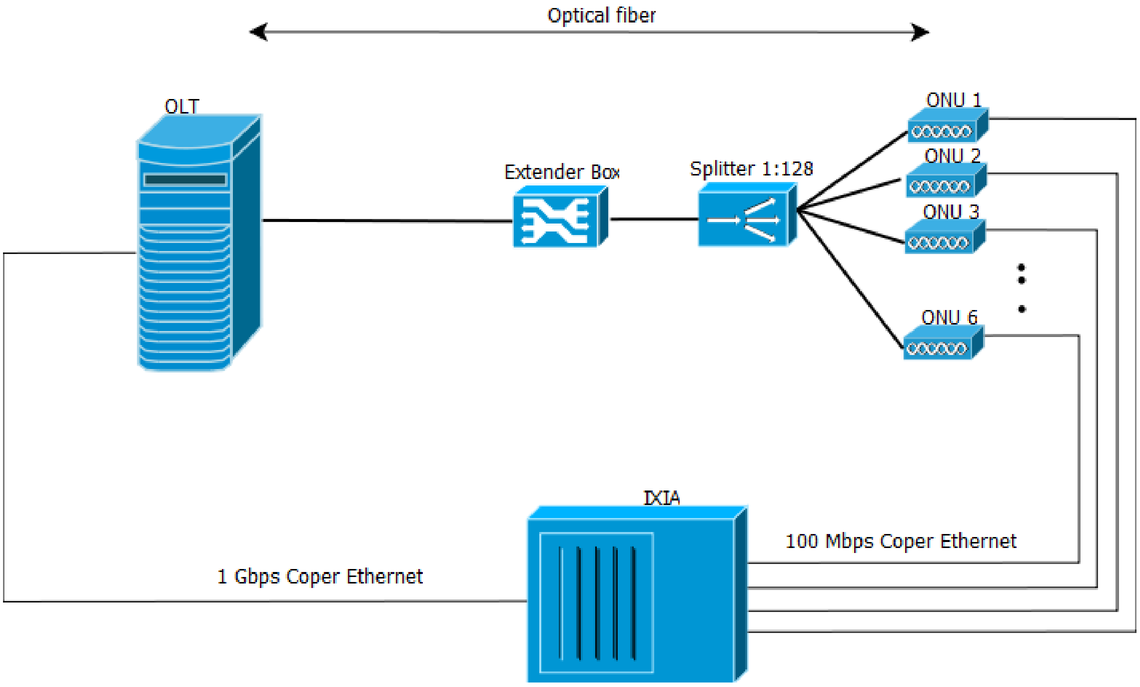


Figure 3.21: Network traffic testing setup.

The simulation was done with IP traffic, evenly distributed between 128 and 1500 bytes with random payload. The line rate was 90 $Mbps$ to each channel (totals 540 $Mbps$ between the OLT and the first splitter) and were sent 2 million packets from the OLT to each ONUs and 10 million packets from the ONUs to the OLT, totalling 72 million. Figure 3.22 shows the experimental setup used to test the extender box integrated in the EPON environment.

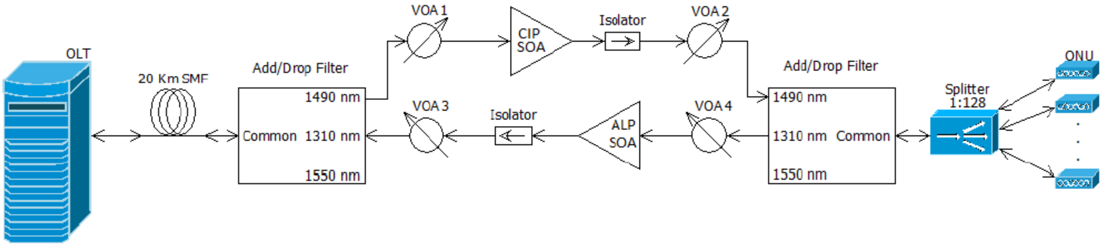


Figure 3.22: Experimental setup emulating a GPON scenario with 60 km and 128 clients [21].

The experiment resulted in the transmission of the 72 million packets in the network without errors, which shows that it is possible, using the solution proposed, to increase the reach of the optical access network. The emulation of the 60 km due to the limitation of the EPON excludes the dispersion and propagation delay introduced by the remaining $40\,km$, thus, in this test they are not included. If a GPON equipment was available, the problem would be eliminated.

Chapter 4

Extender Box

After being designed and proven to work, the extender box needs to be detailed and tested more exhaustively, with wider scenarios. The controlling and monitoring needs also to be implemented and the box need to be built. To test the prototype is also necessary to test its surrounding environment to assure that the results are transparent and its analysis clear. It is important to characterize the elements that belong to the system where the extender box is inserted. The tests are made using the IXIA equipment, generating Ethernet traffic evenly distributed between 128 and 1500 bytes, with random payload. Then it is analysed the Packet Error Rate (PER), which follows the equation 4.1. A packet is considered valid when all of its bits are received correctly. The PER accepted depends on each case, but in most, the lower, the better.

$$PER = 1 - \frac{Valid\ Received\ Packets}{Transmitted\ Packets} \tag{4.1}$$

The traffic is generated at the IXIA equipment and is sent through a 1 Gbps Ethernet card connected by Ethernet cables to the OLT and ONU(s). Between both is the ODN, an optical path. In the downstream direction, the traffic is introduced in the OLT at the maximum speed of 1 *Gbps* and is received on the ONU(s) side at a maximum speed of 100 *Mbps*[1]. In the upstream, the traffic is introduced at the ONU(s) at the same 100 *Mbps* maximum in each ONU and received in OLT side, that, if combined from several ONUs can reach up to 1 *Gbps*. The PER calculated at IXIA is what determines the condition of the ODN being tested.

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[1] 100 *Mbps* is the maximum rate of the Ethernet card in the ONUs.

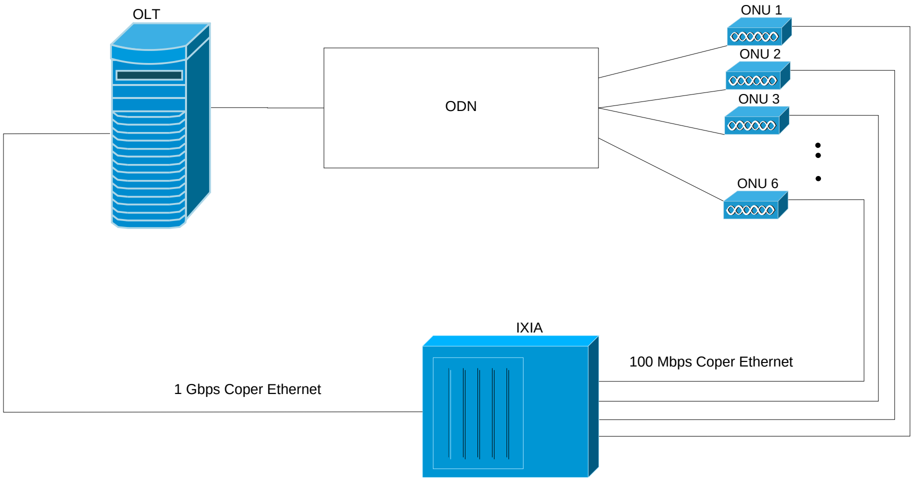


Figure 4.1: Generic setup of an experience with IXIA network analyser.

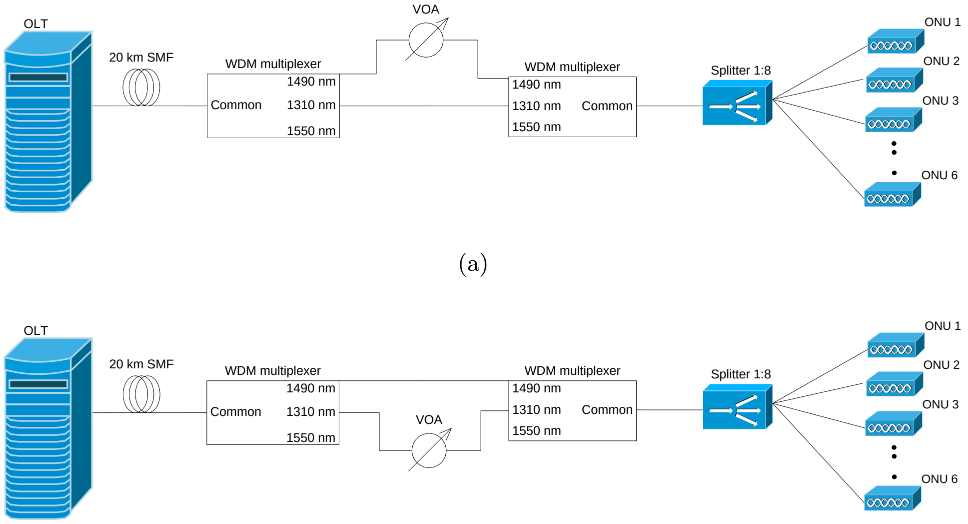
Figure 4.1 depicts a generic testing setup. The use of IXIA traffic generator is an asset to reliable results as it allows a very good approximation to a real network, with real traffic flowing in the ODN. In the further figures, for convenience, will be omitted the IXIA equipment and the links from it to the OLT and to the ONUs. Unless mentioned, should be assumed that, when performing tests with the OLT and the ONUs, it is used the IXIA equipment.

4.1 EPON Characteristics

4.1.1 ONU Maximum Line Rate

One basic, but essential, test that have to be done is the effective maximum rate that can be achieved at the ONU side, so that we are sure that the tests are done at speeds that introduce no errors. The test is performed to investigate if it is possible to assign the maximum line rate allowed by the ONUs Ethernet ports (100 $Mbps$). The same test is not done to the OLT because the maximum speed that the OLT can reach, 1.25 $Gbps$, can not be achieved with only six ONUs at the laboratory. The maximum speed that, in practice, can be achieved in the ODN is 600 $Mbps$, which is the combination of six ONUs, operating at their maximum Ethernet ports' speed, each.

The experimental setup used was based on Figure 4.2 with the ODN constituted by a splitter to serve 6 ONUs, a VOA to emulate power budgets, 20 km of fiber to introduce dispersion and two add/drop multiplexers to join/separate the upstream and downstream, so that the variable attenuation is introduced only in the channel that is being analysed. The setup is depicted in Figure 4.2. Were used auxiliary lasers, operating in the correspondent wavelength of the channel being analysed, instead of the lasers from OLT and ONUs. In the case of the downstream signal it is possible to measure the optical power with a power meter, but in the upstream it is not, as the time that a packet from the ONU occupies in the upstream frame is very little, making the mean power very small and not measurable by a power meter. Therefore, the attenuation (that corresponds to the power budget) between OLT and ONU, in downstream and upstream is measured, in each iteration, using a continuous wave laser in one end point and with a power meter in the other end point.



(a)

(b)

Figure 4.2: ONUs speed test setup (a) downstream, (b) upstream.

The traffic introduced is unidirectional, in Figure 4.2a is downstream traffic (from OLT to the ONUs) and in Figure 4.2b is upstream (from the ONUs to the OLT), but, even though it is tested just one link, the other must be maintained so that the OLT and ONUs can complete the acknowledge process, which is necessary for any traffic transmission between the two end points. In each transmission is sent 1 million packets.

Figure 4.3 shows the packet error rate for different line rates at different attenuation between end points in the downstream direction. It is shown that until 91 $Mbps$ the transmission is done without any packet loss, but after there are packet lost, and increases with the line rate, this can be verified in more detail in Figure 4.4. For each attenuation were used the 6 ONUs and were used the mean values of PER between them for each line rate applied. It is shown that the PER shows independence from the ODN attenuation, as long as we do not reach the limit of sensitivity of the receiver. Figure 4.5 shows that there is little difference between ONUs concerning the PER for different line rates.

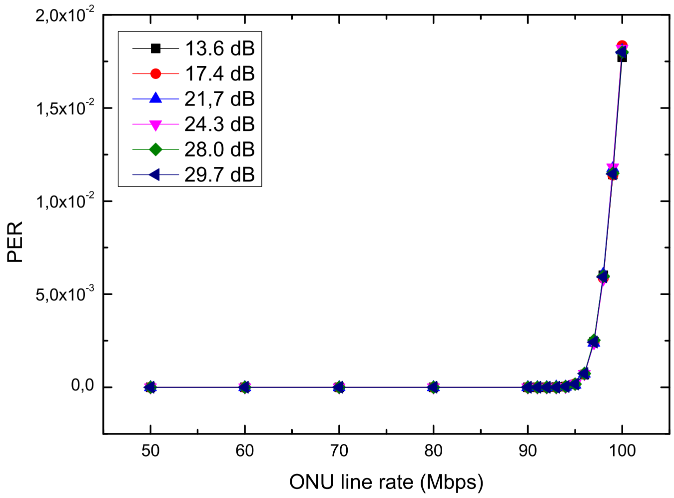


Figure 4.3: Downstream packet error rate of the ONUs for different line rates at different attenuation in the ODN.

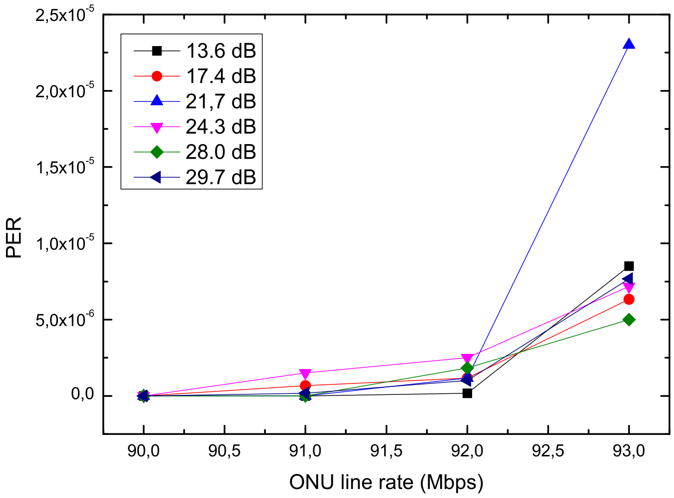


Figure 4.4: Downstream packet error rate of the ONUs for different line rates at different attenuation in the ODN (narrower range).

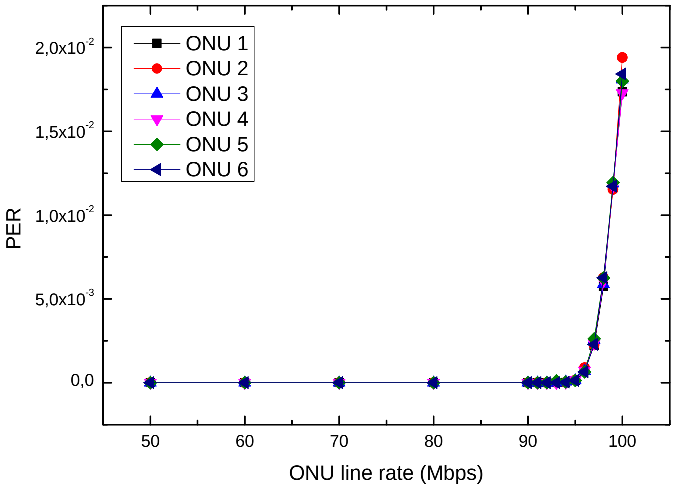


Figure 4.5: Downstream packet error rate of the ONUs for different line rates.

For upstream was used the setup shown in 4.2b. Figure 4.6 shows the packet error rate for different line rates at different attenuation between end points in the upstream direction.

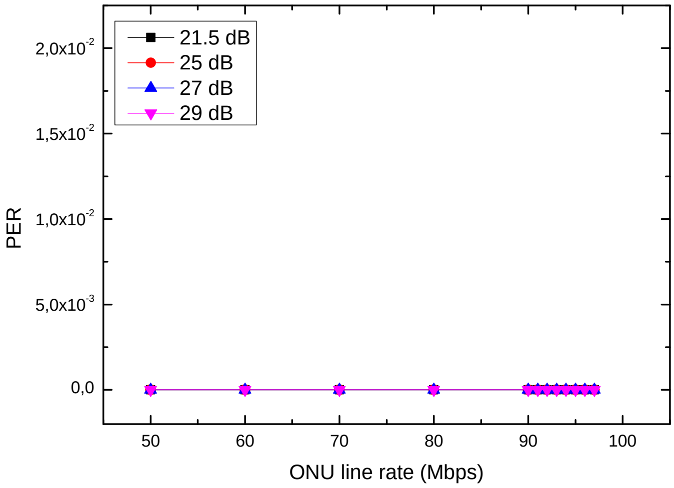


Figure 4.6: Upstream packet error rate of the ONUs for different line rates at different attenuation in the ODN.

In the upstream direction there is no packet loss, and the line rate is limited by the traffic generator to 97 $Mbps$. The difference between downstream and upstream, may be in the receiver electrical circuit of the 100 $Mbps$ Ethernet port of the ONU. The same does not happen in the upstream direction because the Ethernet port of OLT operates at 1 $Gbps$, far from the combined 600 $Mbps$ that arrives at it. Even though the upstream exhibits no packet loss, the dependence of PER with line rate in the downstream direction advises to perform tests at line rates below 90 $Mbps$.

4.1.2 Maximum Power Budget

In this section is characterized the maximum power budget of the EPON system. The objective is to characterize the EPON system without the reach extender. The experimental setup used is the same of Figure 4.2a and Figure 4.2b for the downstream an upstream, respectively, with the difference that only one ONU was used. In each iteration is varied the VOA to emulate different power budgets.

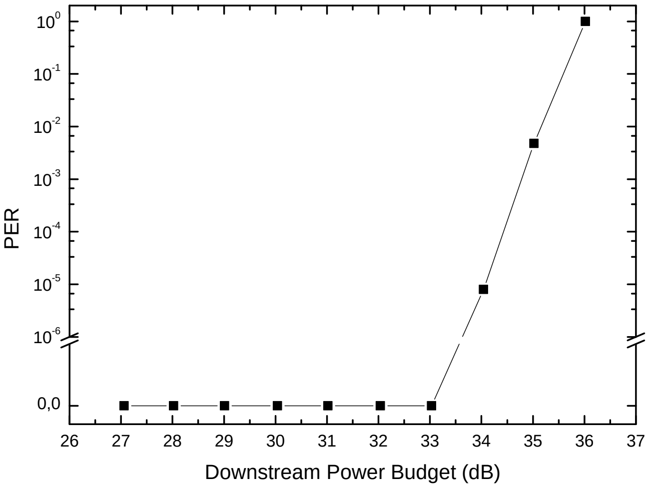


Figure 4.7: Downstream Packet error rate of the EPON for different power budgets without the extender box.

In the downstream case the maximum power budget obtained was 33 dB as shown in Figure 4.7. With 34 dB there are some errors, and at 36 dB the ONU lights the alarm of Loss of Signal, which means, that the ONU does not receive any correct packet. In the upstream case, the maximum power budget obtained is 31 dB as shown in Figure 4.8. At 34 dB the ONU lights the alarm that indicates that the ONU is not registering, which means that it receives the signal from the OLT, in the downstream channel, but it is not able to register in the OLT as the upstream link is too degraded.

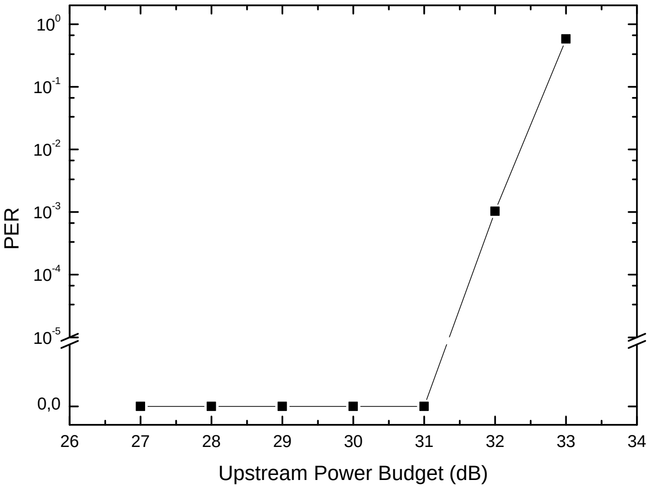


Figure 4.8: Upstream Packet error rate of the EPON for different power budgets without the extender box.

4.1.3 Maximum Reach

Following the characterization of the maximum power budget available is the maximum achievable reach, which is defined in the standard as 20 km. The experimental setup used is shown in Figure 4.9. In this case what is varied is the SMF length. The VOA is set at 7 dB, which, summed with the splitter attenuation (11 dB) and the SMF, is far from the maximum attenuation. This way we are sure that the errors are due to the maximum reach. The length was varied using different reels of different lengths. As the unit unit of magnitude is km, the size of patch cords that connect the components can be unvalued.

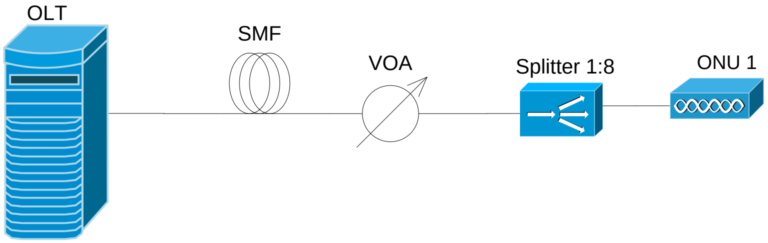


Figure 4.9: Downstream Packet error rate of the EPON for different power budgets without the extender box.

The maximum reach obtained was km as shown in Figure 4.10, which is 3 km

more than the defined in the standard. This limit is imposed by the time delay[2] in the transmission which, in this case, is achieved with 24 *km* of fiber.

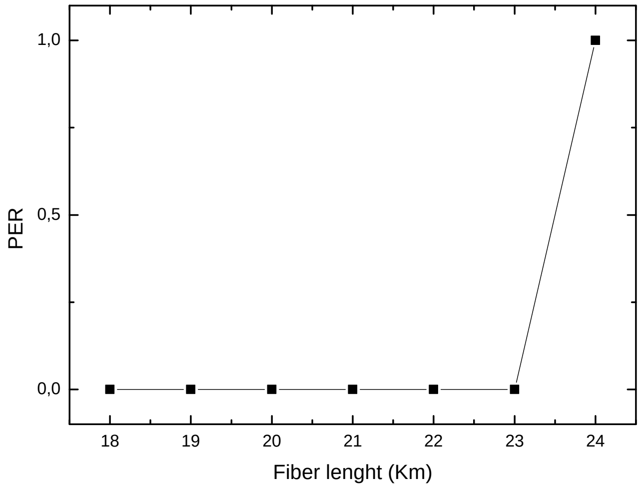


Figure 4.10: Packet error rate of the EPON for different fiber lengths without the extender box.

4.2 Isolators

As referred in section 3.2.4 the isolators are used to protect the SOAs from reflections coming from ahead and their implementation is shown in Figure 3.20. However, in practice, their implementation as in Figure 3.20 may not be the most efficient, and this is what is discussed in this section.

In section 3.2.1 is discussed the SOA Basic principles and one of their characteristics is spontaneous emission. This phenomenon, called ASE, is depicted in Figure 3.6 and is responsible for generation noise. The noise has random phase, direction and frequency, as so, it is generated in both directions of the SOA. Therefore, the noise generate towards the OLT, in the downstream case, for example, has to be studied and, possibly, taken into account. The following tests were done with SOA CIP, since it is easier to test the downstream link. The conclusions taken can then be extrapolated to the upstream SOA (Alphion).

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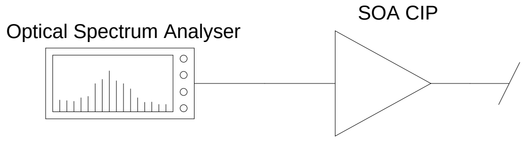
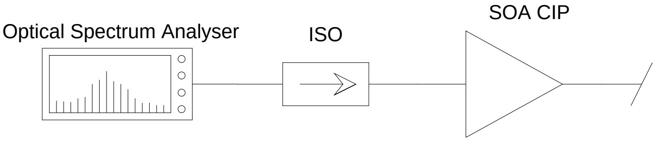
[2] The OLT through the MPCP (section 2.3.3) can calculate the Round Trip Time. When the RTT reach a certain limit, it discards the transmission.

4.2.1 Isolator Before the SOA

In this section is evaluated the necessity of an isolator before the SOA. The first test done was to characterize the SOA ASE emission into the opposite direction of amplification, with the experimental setup show in Figure 4.11a and compare to the case where an isolator is used before the SOA Figure 4.11b.



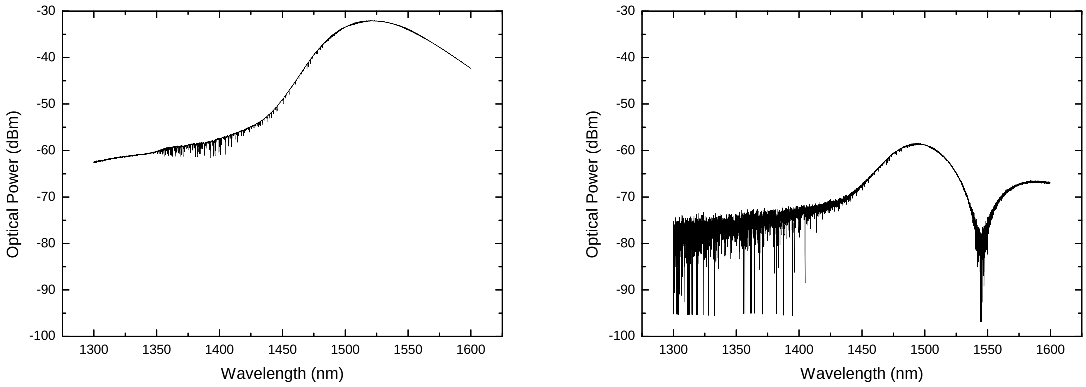
(a)



(b)

Figure 4.11: Experimental setup for ASE characterization of the SOA, in the opposite direction of amplification, (a) without an isolator, (b) with an isolator before it.

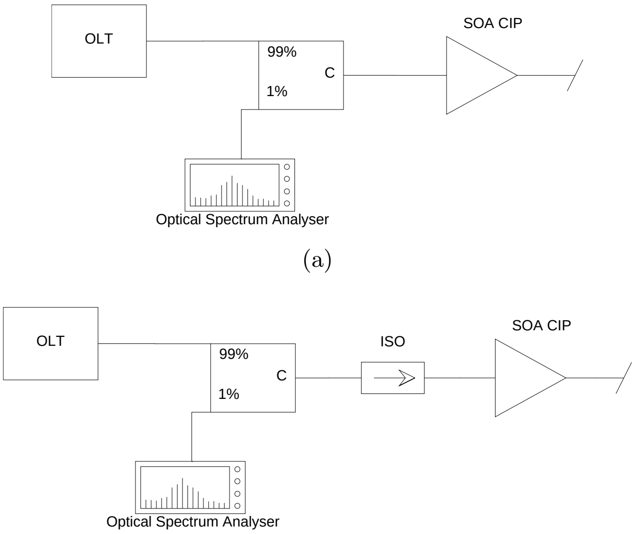
The results are shown in Figure 4.12. Figure 4.12a corresponds to the results obtained in the optical spectrum analyser (OSA) using the setup of Figure 4.11a and Figure 4.12b to the results obtained using the setup of Figure 4.11b.



(a) (b)

Figure 4.12: Results of ASE characterization of the SOA, in the opposite direction of amplification, (a) without an isolator, (b) with an isolator before it..

Then, it was characterized the backwards ASE emission of SOA similar to the previous test but with traffic on the line, sent by the OLT. The experimental setups are depicted in Figure 4.13

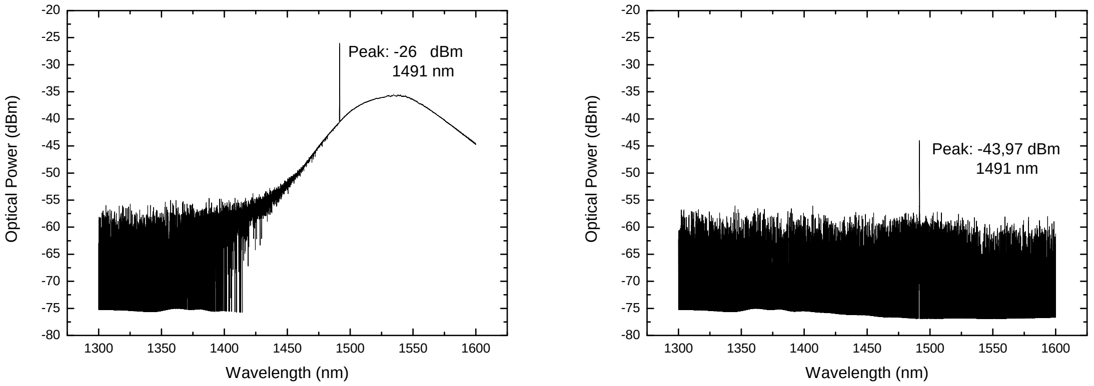


(a)

(b)

Figure 4.13: Experimental setup for ASE characterization of the SOA, in the opposite direction of amplification and with traffic in the link, (a) without an isolator, (b) with an isolator.

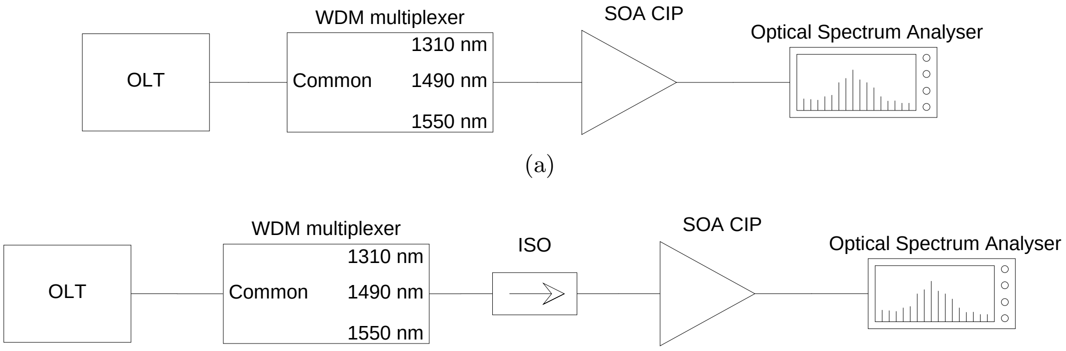
The results observed in the OSA for both setups are depicted in Figure 4.14. Again, Figure 4.14a shows the results that correspond to setup of Figure 4.13a, and Figure 4.14a corresponds to the setup of Figure 4.13b.



(a) (b)

Figure 4.14: Results of ASE characterization of the SOA, in the opposite direction of amplification and with traffic in the link, (a) without an isolator, (b) with an isolator..

Finally, it was analysed the impact of the isolator in the signal, after the SOA. The setups, with and without the isolator, are shown in Figure 4.15. It was introduced the WDM coupler as part of the extender box, which influences the spectral analysis in this case.

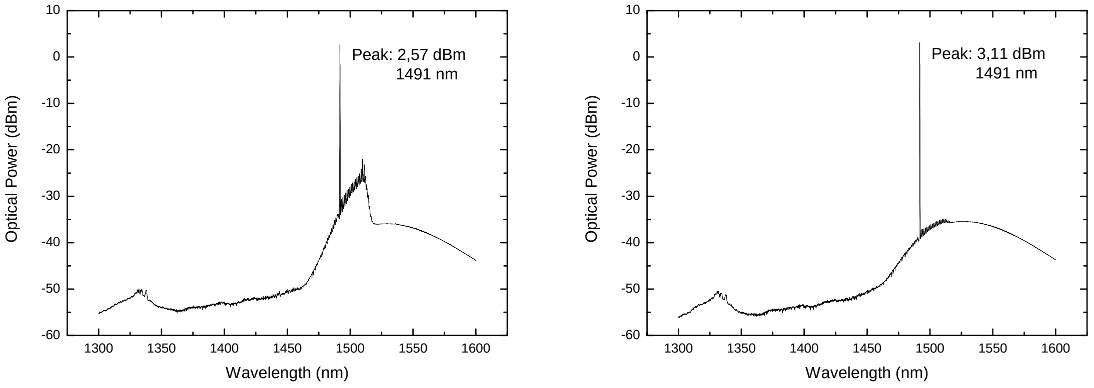


(a)

(b)

Figure 4.15: Experimental setup for characterization of the signal after the SOA, (a) without an isolator, (b) with an isolator before it.

The results observed in the OSA are shown in Figure 4.16 and correspond in the same way as before to the setups presented in Figure 4.15



(a) (b)

Figure 4.16: Results of the characterization of the signal after the SOA, (a) without an isolator, (b) with an isolator before it..

Comparing each graphic (a) and (b) in Figure 4.12, Figure 4.14 and Figure 4.16 is clear that the isolator before the SOA has a positive impact both in limiting the noise going backwards the SOA and improving the signal quality after it. The first two experiences prove the first sentence. In both cases the noise is reduced by approximately 20 *dB*, which is significant. In addition, the graphic in Figure 4.14a exhibits a peak of -26 *dBm* in the wavelength of transmission going towards the OLT that cannot be ignored. This also contributes to a degradation of the signal transmitted and this is verified when it is introduced the isolator, as shown in Figure 4.16, where the peak, in the wavelength of transmission, is improved by about 0.5 *dB* when compared to the situation without it, which is important when dealing with power budgets. In this case, the isolator reduces the reflections of caused by the SOA, reducing the noise, and therefore, leaving more amplification for the wavelength of transmission. For these reasons, the introduction of an isolator before the SOA, in the band of transmission, is included on the extender box.

4.2.2 Isolator After the SOA

The isolator after the SOA was in the initial prototype, but its real necessity is evaluated in this section. Due to its characteristics, the isolator lets pass the entire signal through it in the direction of transmission, so it is not necessary to evaluate the impact on the signal after it, as it will not show any changes, apart from an insertion loss. On the other hand, the signal flowing in the opposite direction[3] is the one that can justify its use. The

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[3] As the SOA tested in this case is the SOA from CIP, the forward direction being analysed is the downstream.

signals that flow in this direction are the upstream signal, coming from the ONU, however, this signal is filtered at the WDM coupler and does not reach the downstream link; and the reflections that may occur at the WDM coupler, and those are analysed next.

The experimental setup tested is depicted in Figure 4.17. The signal seen at the OSA is the reflection occurred at the WDM coupler of the signal amplified in the SOA. It is already included the isolator before the SOA as it was previously demonstrated that its use is recommended.

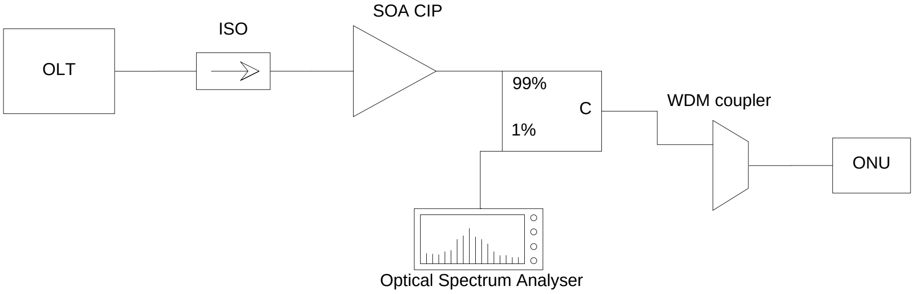


Figure 4.17: Experimental setup to analyse the reflections seen at an SOA in the extender box.

The results observed at the OSA are shown in Figure 4.18. It is clear that the signal reflected towards the SOA is negligible and the use of an isolator after the SOA can be dispensed.

Thus, the isolator after the SOA is removed and it is added before it. The same procedure is adopted for the upstream link.

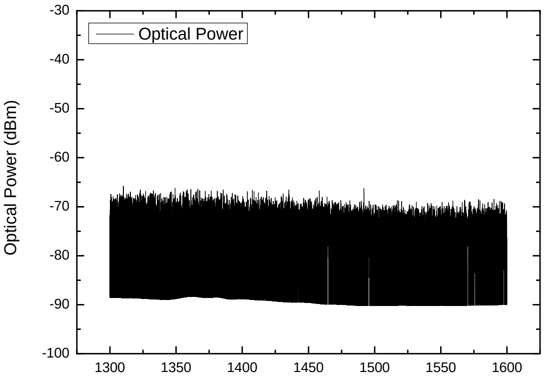


Figure 4.18: Results of the characterization of the reflections seen at an SOA in the extender box.

4.3 Power Budget Boundaries

In sections 3.2.2 and 3.2.3 is described the SOAs capability in increasing both downstream and upstream links' power budget and in section 3.2.4 is proven that the extender box works and allows such a reach extension. However it is also important to clearly define its boundaries, limitations and, as most as possible, to cover all the possible scenarios. The next tests intend to define these boundaries in power budget that the extender box imposes.

As mentioned in section 2.4.5 the GPON standard G.984.6, [18], defines the following power budgets when it is introduced in a GPON a mid-span reach extender:

Table 4.1: OTL and ODN power budgets

Max loss	**Downstream** (dB)	**Upstream** (dB)
GPON OTL	23.00	28.00
GPON ODN	13 to 28	

To cover, as most as possible, the most cases that can occur in an optical access network, was varied, using VOAs, the OTL power budget and verified the range of ODN power budget that could be achieved. This variation in the OTL simulates, in practice, different distances of placement of the extender box from the OLT and the variation of ODN simulates different split ratios and ONU distances from the extender box. The procedure was done for both downstream and upstream separately.

4.3.1 Downstream

To test the downstream link were used two ONUs, one was fixed at the lowest power budget (13 dB) and the other one is variable to try to achieve the maximum range possible. The experimental setup concept is described in Figure 4.19, the idea is to separate the downstream channel from the upstream before it enters the extender box, so that it is possible to vary the attenuation in only the link that is being analysed. However, the real setup executed is more complex and is shown in Appendix A.

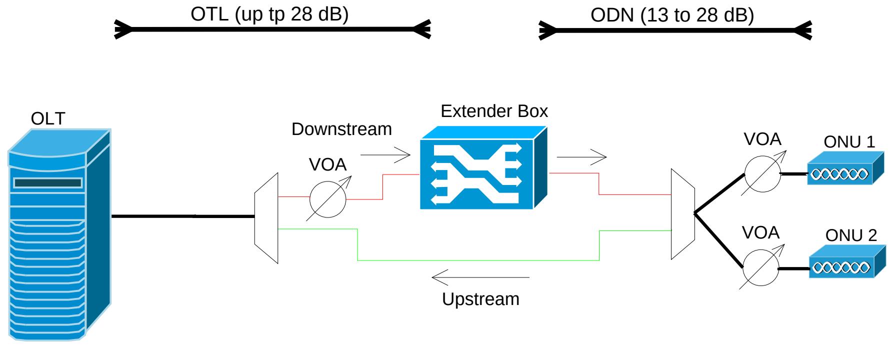


Figure 4.19: Experimental setup to test the downstream power budget limits.

In Figure A.1 of Appendix A, the downstream signal is separated from the upstream signal in the WDM multiplexer, and then is attenuated by a VOA, that is responsible for the OTL range simulation, then, the signal is amplified in the extender box, divided into two and each one is attenuated by a VOA, simulating different ODN power budgets. The upstream signal that is send by the ONUs, flow into the two WDM couplers and then into one coupler that joins them. Then, they are added in the WDM coupler, on the left side, to the downstream signal, this way, its guaranteed that only the downstream signal is affected by the variation on the attenuation.

The procedure was fixing different values in the OTL power budget (using the VOA) and vary the ODN range for each OTL power budget, maintaining one ODN VOA with such attenuation that the ODN power budget sum $13\,dB$ and the varying the other VOA until the highest values of power budget are achieved. The highest value is the highest value of ODN attenuation that allows traffic transmitting from the OLT to the ONU without packet loss. For that, was used the traffic generator IXIA sending 1 million packets at 80 *Gbps* to each ONU in each combination of power budgets.

The results are shown in Figure 4.20.

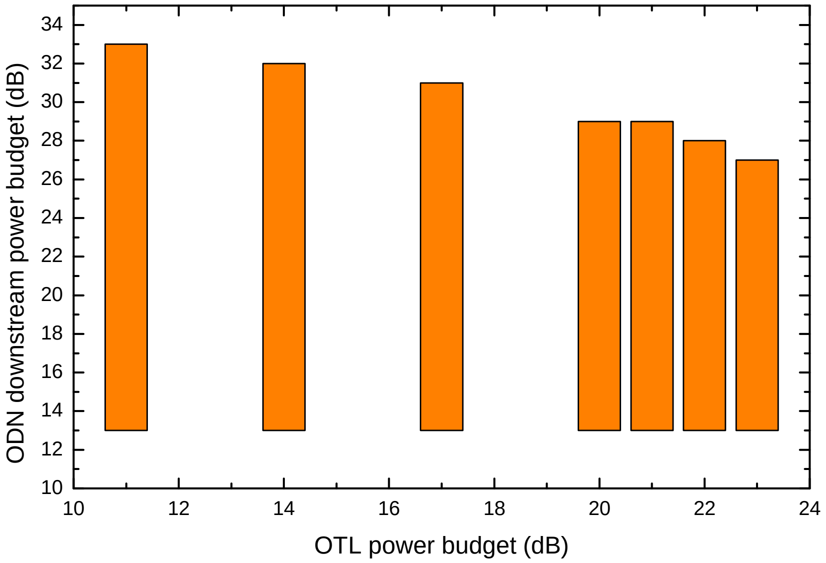


Figure 4.20: Downstream maximum OTL and ODN power budget range.

The results show that it is achieved until 22 dB in the OTL, a range from 13 to 28 dB in the ODN. Only for 23 dB in the OTL the range is limited to 13 to 27 dB in the ODN. These values are acceptable as the extender box is being tested in an EPON environment and it is expected that when inserted in a GPON system, the limits would be more relaxed. Nevertheless, in this case, only at 23 dB in the OTL is not fully completed the standards recommendations.

4.3.2 Upstream

In the upstream link the idea is the same, separate the upstream from the downstream and attenuate the upstream link to cover the power budget combinations of OTL and ODN. Figure 4.21 illustrates the concept of the upstream measurements. In AppendixA is depicted a more detailed setup.

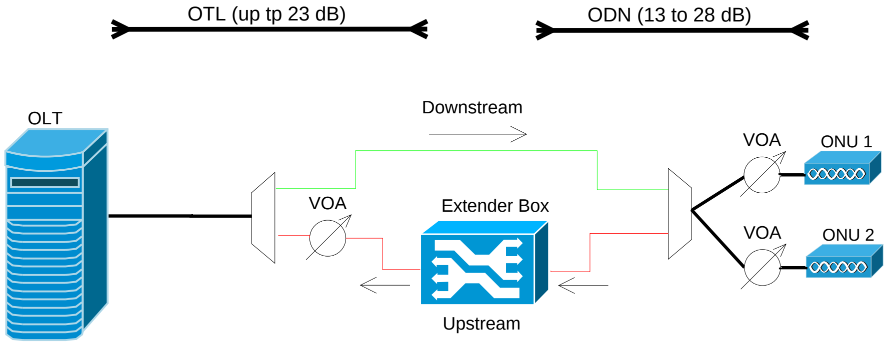


Figure 4.21: Experimental setup to test the upstream power budget limits.

In the upstream case, the signal coming from an ONU is separated from the downstream in a WDM multiplexer and then is attenuated in a VOA, joined with the upstream signal from the other ONU and both are joined in a splitter. Then, the signal is amplified in the extender box, again attenuated (to simulate different OTL power budgets) and joined with the downstream signal to reach the OLT. Before it, it passes through a 20 Km fiber reel to insert some dispersion to the signal.

The test procedure is the same as for the downstream link as well as the traffic characteristics.

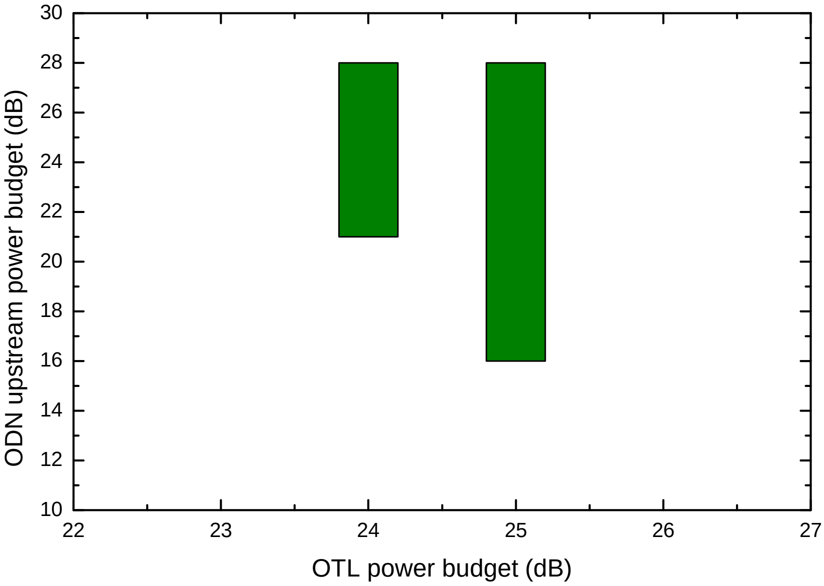


Figure 4.22: Upstream maximum OTL and ODN power budget range.

The results are shown in Figure 4.22. The graphic shows that the case in which the ODN range is bigger is when the OTL power budget is $25\,dB$ (between $16\,dB$ and $28\,dB$). After that there is not any ODN power budget where the transmission can be done with success, neither before 24 dB. At an OTL power budget of 24 dB the range is narrower, between $21\,dB$ and $28\,dB$.

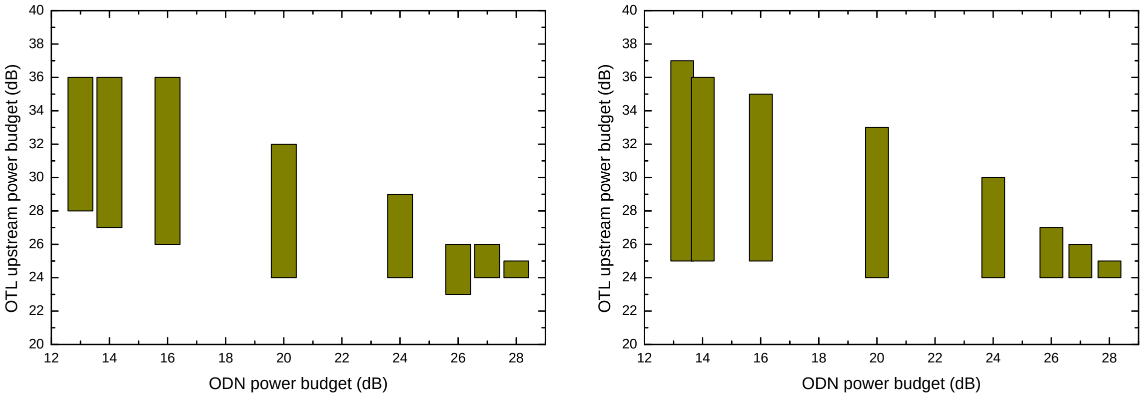
4.3.3 Results Analysis

In both downstream and upstream the results do not meet the recommendations of Table 4.1. However, in the downstream case, the results are very close to them, only in the limit of the OTL power budget, $23\,dB$, the ODN range does not meet the requirements. So, given the higher margin that GPON can achieve, it is possible to say that the downstream power budget range covers the required in the standards.

In the upstream case, the results are a little far from the range of the OTL power budget recommended. Yet, there is a OTL power budget point where the ODN range is close to the desired and this can be explored in acting in upstream amplification or in the power of the signal after amplification. This contributes to the necessity of the extender box to automatically configure itself which is the issue of section 4.4.

Despite the results can be considered sufficient, there are other factors that contribute to the degradation of them that cannot be avoided due to limitations in the laboratory equipment. One of them was already mentioned, which is the use of an EPON system, another is the quality of the ONUs that, for example, reduce their performance with temperature, in the course of time.

The ONUs are also different among them and one of them can penalize the results. For example, the upstream test is done with two ONUs and tests to each one individually show that the same tests to the upstream link with the extender box, but only with one ONU, can be different depending on the ONU. This is illustrated in Figure4.23.



(a) (b)

Figure 4.23: Upstream maximum OLT and ODN power budget for two ONUs tested individually.

The graphics 4.23a and 4.23b represent the results correspondent to the setup of Figure 4.21 but with only one ONU at a time. Even though the ONUs are of the same model, the results are quite different, especially when the ODN power budget is lower. For easier interpretation, the axis are swapped comparing to the previous graphics, and its possible to verify that its only possible to achieve (in both graphics) 28 dB in the ODN when the OTL power budget is 24 dB or 25 dB, which is in accordance with the results in Figure 4.22.

As the ONU that produces the results of 4.23a can achieve lower ODN power budgets with 25 dB in the OTL it was chosen to be varied (the ODN power budget) and the other, that cannot reach such results, to stay fixed with 28 dB of ODN power budget. Thus, the results of Figure 4.22 were achieved.

4.4 Performance Monitoring

4.4.1 Variable Optical Attenuator Controller

The results obtained in the upstream tests in section 4.3.2 allow identifying an optimal operational point for the extender box, that is when the upstream OTL power budget is 25 dB. In this point, the extender has its best upstream ODN range. As the OTL power budget depends on the components and fiber distance of the link, it is unlikely that every implementation in the field of the extender box would have those OTL loss characteristics. Therefore, it is necessary to act, somehow, on the output power of upstream signal of the extender box, so that the upstream optical power arriving at the OLT would be the same independently of the OTL power budget.

This control of the upstream output power in the extender can be done in two different ways. One is controlling the bias current of the upstream SOA, and, therefore, adjust the gain — the drawback of this option is that it would take the SOA out of its best operation point, discussed in the section 3.2.3 — another option is to introduce an attenuator after the SOA and adjust it as a function of the power budget of the OTL link, which means in practice, as a function of the input power of the extender box in the downstream link.

To "read" the input power of the downstream link, it is introduced a coupler and a monitoring PIN in the downstream link of the extender box. The coupler is 1:99 to be the less intrusive as possible and the PIN connects to a microcontroller that acts in the electrically controlled VOA that is introduced after the upstream SOA.

This is illustrated in Figure 4.24. It is also the experimental setup for analysing the downstream monitoring results. Instead of a PIN, it is used a power meter.

The attenuation that the VOA has to have as a function of the power measured in the power meter is shown in Figure 4.25.

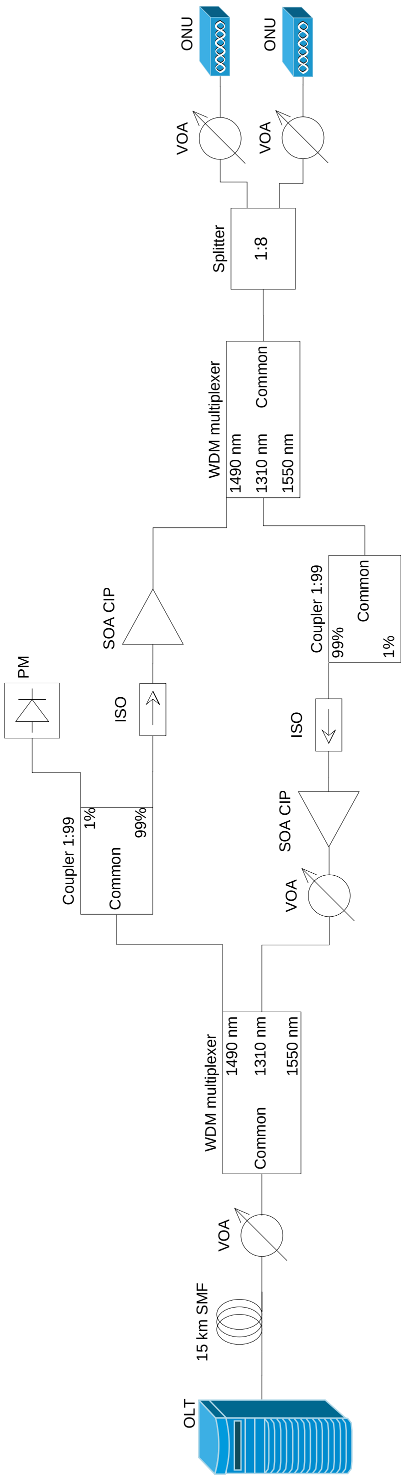


Figure 4.24: Experimental setup for downstream monitoring.

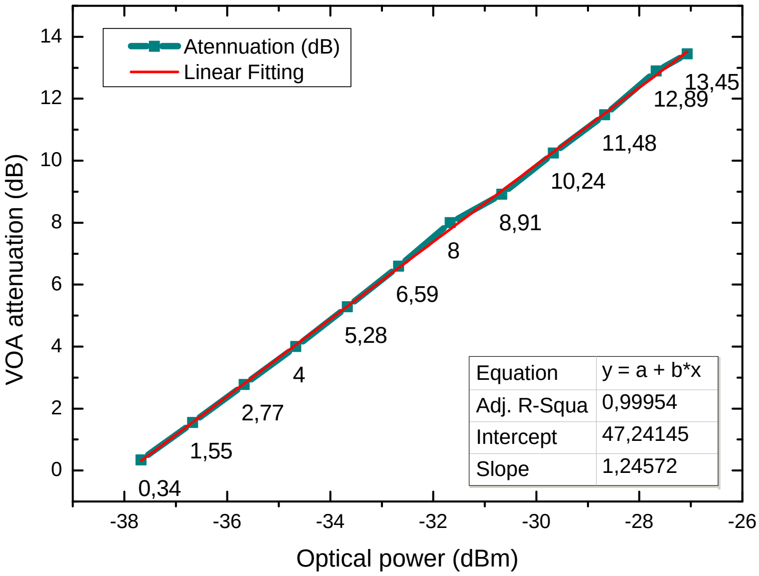


Figure 4.25: VOA attenuation as a function of power monitored in the downstream link.

The results are linear (with an adjusted *R-square*[4] close to 1) in a logarithmic scale and the resultant function is:

$$y = 1.24572x + 47.24145 \tag{4.2}$$

This function is to the microcontroller set the attenuation on the VOA, as a function of the data received from the monitoring PIN. For a better understanding of the results, Figure 4.26 and Figure 4.27 illustrate the VOA attenuation as a function of the extender box input power and downstream OTL power budget, respectively.

The extender box input power limits in Figure 4.26, are due to, at the right side, the maximum input power defined by the standard, and, at the left side, to the minimum attenuation possible at the VOA. Figure 4.27 show that the downstream OTL power budget is limited to 20 dB which is consistent to the differences between downstream and upstream OTL power budgets, 5 dB, and between the standard and the extender box, 3 dB, as shown in Table 4.2.

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[4] The adjusted *R-square* is a modification of the Coefficient of Determination with the difference that it attempts to make an estimate of value of *R-square* in the population (rather than in the sample). Unlike *R-square*, adjusted *R-square* increases only if the new term improves the model more than would be expected by chance [33].

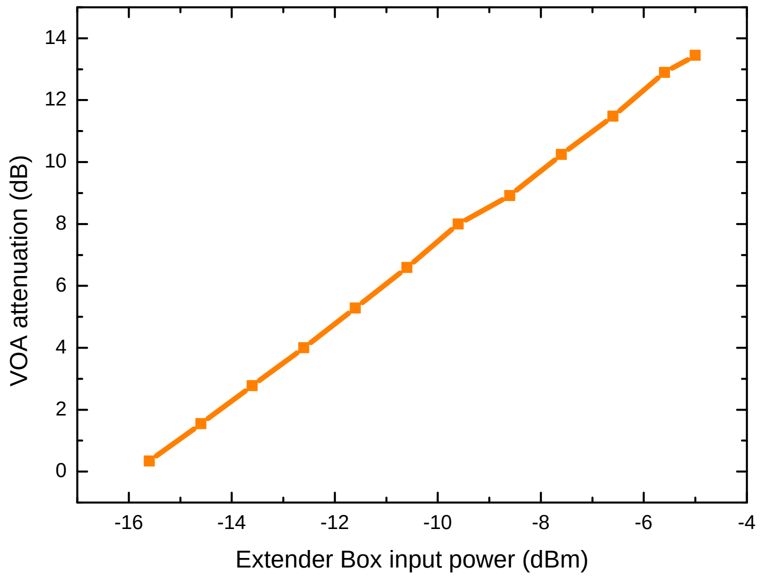

Figure 4.26: VOA attenuation as a function of the Extender Box input power.

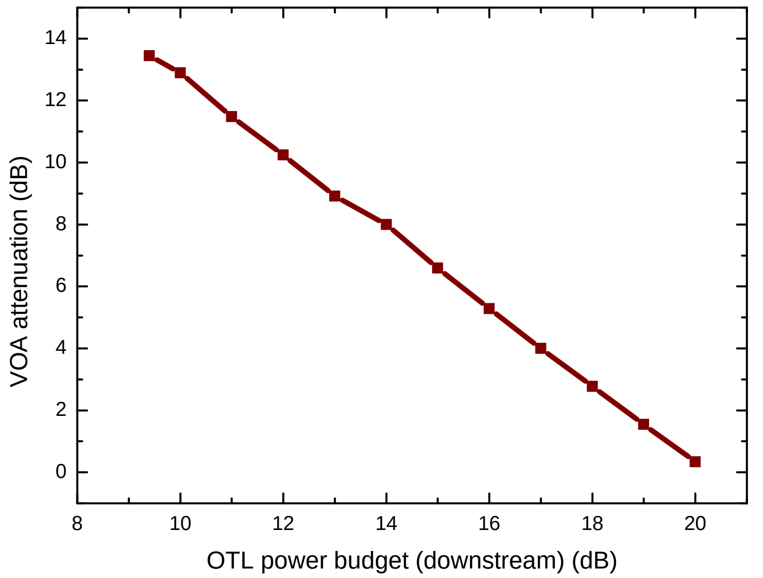

Figure 4.27: VOA attenuation as a function of the downstream OTL power budget.

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

	Downstream (dB)	**Upstream** (dB)	**Difference** (dB)
Extender Box	20	25	5
Standards	23	28	5
Difference	3	3	

4.4.2 Downstream PIN Outputs

Besides giving information for controlling the VOA, the monitoring PIN, located in the downstream link, can also provide information for performance monitoring, which is a required requisite for the extender box. Based on that data, the microcontroller can then, with the appropriate functions, calculate the outputs.

From the downstream PIN data is possible to calculate the extender box's:

- Downstream output power;
- Upstream output power;
- Downstream input power;
- Available upstream power budget;

The curves that characterize each item as a function of the power read at the 1% exit of the coupler 1:99 are depicted in Figure 4.28, 4.29, 4.30 and 4.31, respectively.

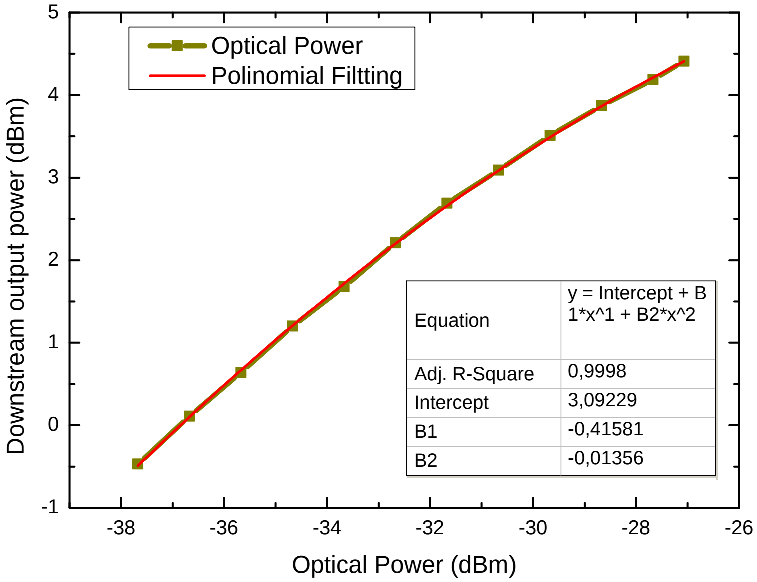

Figure 4.28: Extender box downstream output power as a function of the power at the coupler 1:99.

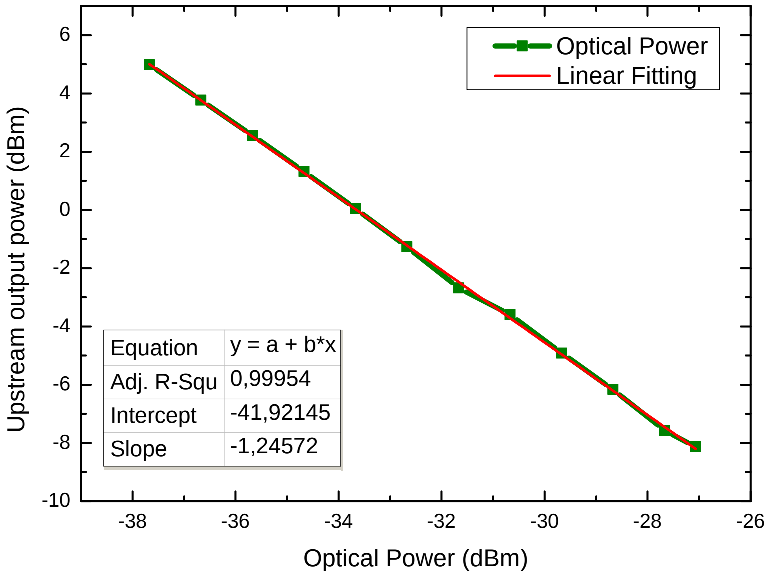

Figure 4.29: Extender box upstream output power as a function of the power at the coupler 1:99.

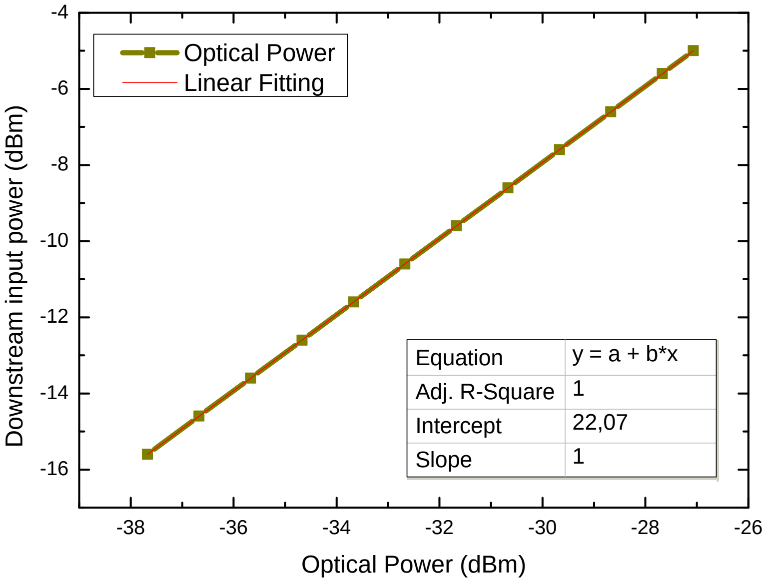

Figure 4.30: Extender box downstream input power as a function of the power at the coupler 1:99.

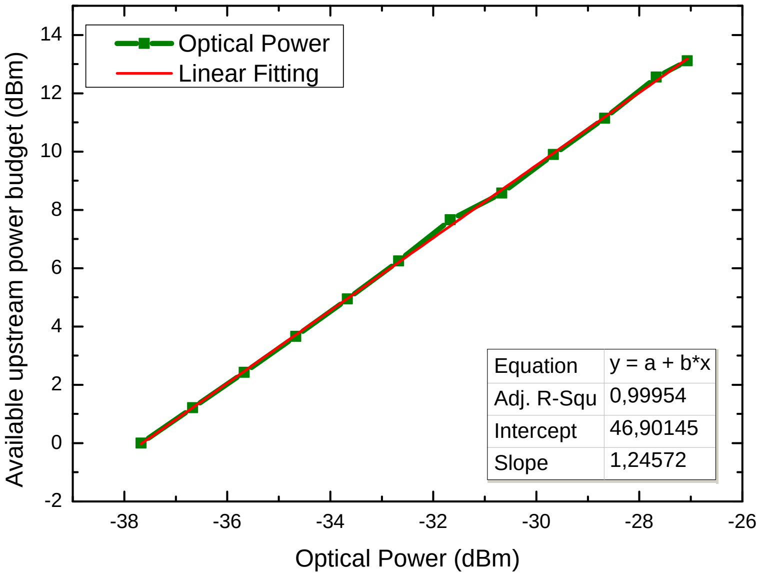

Figure 4.31: Extender box available upstream power budget as a function of the power at the coupler 1:99.

The polynomial equation of second degree that characterizes the curve of downstream output power with an adjusted *R-square* of 0.9998 is equation 4.3.

$$y = -0.01356x^2 + -0,41581x + 3.09229 \tag{4.3}$$

Equation 4.4 with an adjusted *R-square* of 0,99954, defines the upstream output power as a function of the power read at the coupler 1:99.

$$y = -1.24572x - 41.92145 \tag{4.4}$$

Figure 4.30 shows the downstream input power as a function of the power read at the coupler 1:99 that is the same power plus 20 dB which is the difference between the 1% and 99% outputs, plus the coupler and WDM multiplexer insertion losses. The equation that describes the relation between optical powers is equation 4.5. As expected, the slope and associated adjusted *R-square* is 1.

$$y = x + 22.07 \tag{4.5}$$

The available optical power as a function of the optical mean power read on the PIN is illustrated in Figure 4.31 which is similar to Figure 4.25, this is because the available power budget is as much as the VOA has to compensate and to attenuate, with an offset that is the VOA minimum attenuation. Therefore, the equation that characterizes the available upstream power budget is equation 4.6. The associated adjusted *R-square* is 0,99954.

$$y = 1.24572x + 46.90145 \tag{4.6}$$

4.4.3 Upstream PIN Outputs

The performance monitoring parameters that are still missing are the upstream input power and the available downstream power budget. However, retrieving data from the upstream link is not as simple as in downstream. In the upstream link, as mentioned before, the ONUs transmit in bursts, that may vary in length and amplitude, and the time between burts is low (26.67 ns), so fast electronics may be necessary. This solution would introduce high complexity in development so another options must be considered. In the downstream case, the OLT is continuously emitting and it is easy to measure the mean power with the power meter. One option for measuring the mean power coming from the ONU is to create a scenario similar to the downstream. As there is a traffic generator available, one solution is: fill, as much as possible, the upstream link with traffic and measure the power. However, it is not possible to measure the power in an intrusive way as it is in downstream (the IXIA wont transmit unless OLT–ONU connectivity is guaranteed), and here the tap coupler is a solution.

Then, there is the possibility of monitoring the power after and before the SOA. At first sight, the better solution would be monitoring after the SOA, because of the higher power, however, the experimental results showed that even though the power is greater, the reduction in resolution is too significant. Thus, the implementation of the coupler is before the SOA.

As mentioned before, the maximum line rate of each ONU is limited to the Ethernet port, $100\,Mbps$, and tests showed that to transmit without packet loss, line rate should be limited to $90\ Mbps$. $90\ Mbps$ is less than 10% of the full capacity of the upstream link ($1\,Gbps$). Therefore it is necessary to use all ONUs available, that are 6, reaching $480\ Mbps$ when their signal is combined, near a half of the full capacity of the upstream link. The experimental setup is depicted in Figure 4.32.

The variation of optical power measured with the power meter in the coupler as a function of the line rate for different ODN power budgets is shown in Figure 4.33 and the variation of the optical power as a function of the ODN power budget for different line rates is show in Figure 4.34.

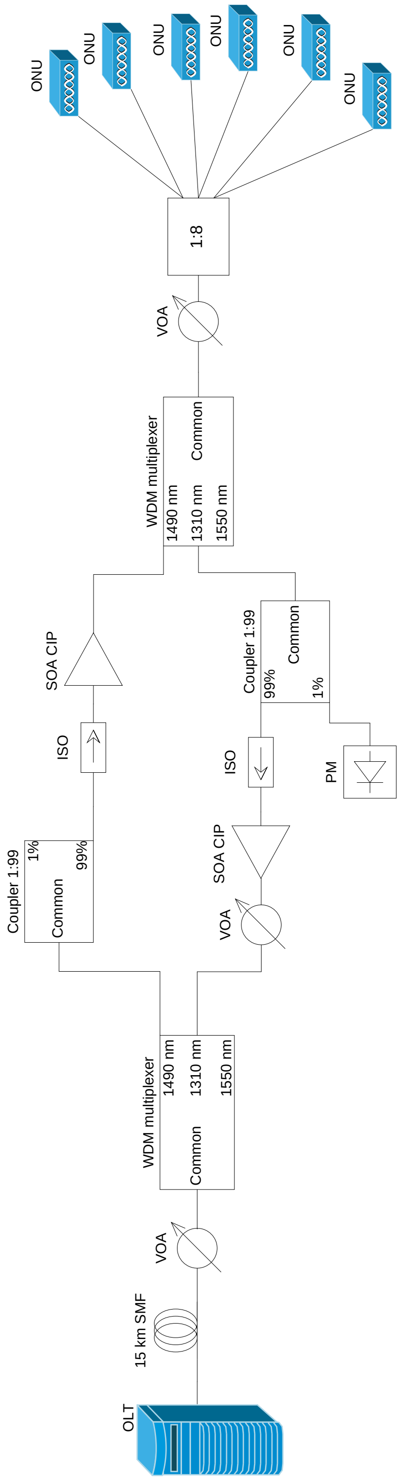

Figure 4.32: Experimental setup for downstream monitoring.

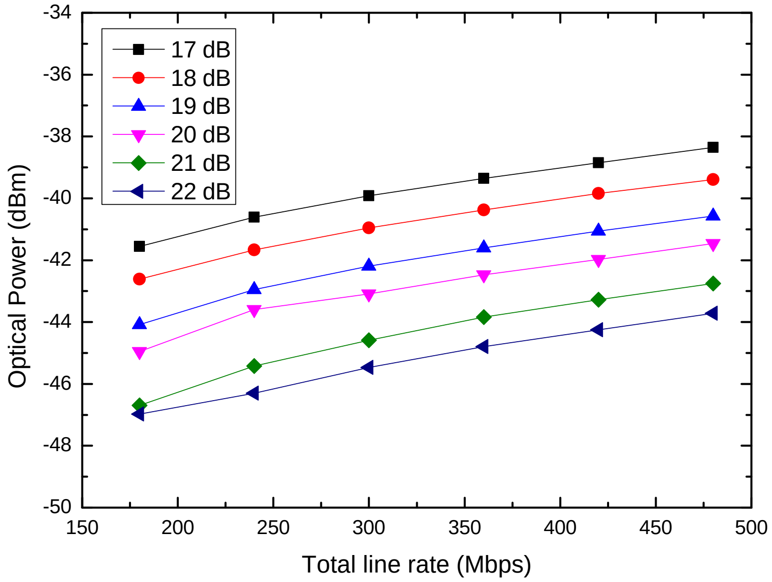

Figure 4.33: Variation of the optical power in the tap coupler as a function of the line rate for different ODN power budgets.

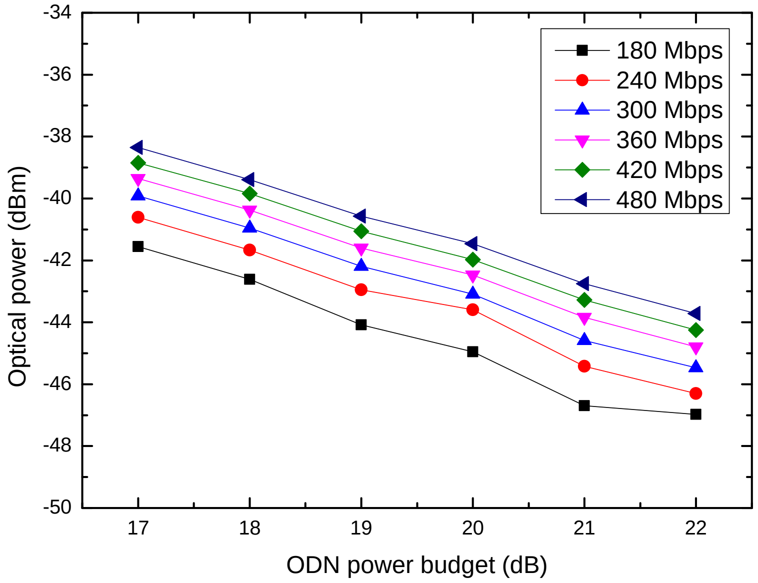

Figure 4.34: Variation of the optical power in the tap coupler as a function of the ODN power budgets for different line rates.

The results show that it is possible to measure the mean power of the upstream link with this method. However, in a real scenario, measuring the optical power in the upstream link, nothing can be said about the power budget before the extender box, because it depends on the number of ONUs, each distance to the extender box, line rates of each and it depends on how many and which are transmitting. For example, considering Figure 4.33, if a optical power received was -44 dB several scenarios are possible, an ODN power budget of 19 dB at a line rate of 180 Mbps or an ODN power budget of 21 dB at a line rate of 425 Mbps and so on, the combinations are many. So, concerning the automatic calculation of ODN power budget available in the extender box, it is not possible and thus, it is considered out of the scope for the extender box.

Still, if the operator could isolate each ONU and make it transmit at a certain line rate for a period of time, with the data gotten from the extender box would be possible to know the ODN power budget.

4.5 10 Gigabit Coexistence

One important characteristic and a surplus value is that the extender box could support data rates characteristic of the XG-PON. That possibility is attractive as the evolution is towards the 10 gigabit signals. The 10G-PON signals, described in section 2.6, are divided in downstream and upstream, and the upstream signal has 2.5 Gbps line rate which does not constitutes a significant difference in the upstream SOA operation. However, the 10 Gbps characteristic of the downstream link, is considerably higher than the GPON's downstream 2.5 Gbps. Therefore, it was verified that the downstream SOA has a good response at 10 Gbps.

The experimental setup is shown in Figure 4.35.

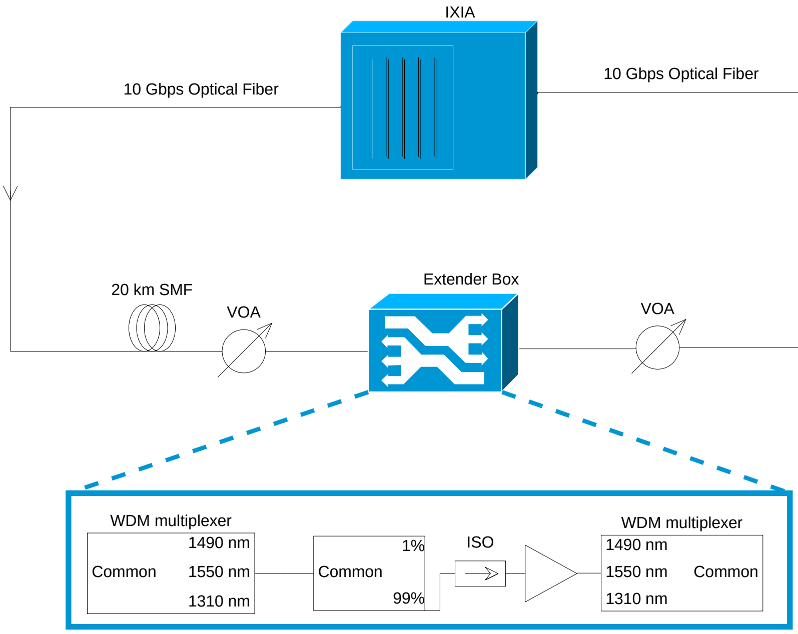

Figure 4.35: Experimental setup for the 10 Gigabit signal compatibility in the downstream link.

Besides the 1 Gigabit Ethernet cards of IXIA, the IXIA equipment has a 10 Gigabit optical card that has optical line rates up to 10 $Gbps$ and, this way, it were possible to run tests at these rates in the extender box. The card has two emitters and two receivers, working in 1550 nm. The transmitter is connected to a 20 km reel to introduce dispersion, and then, the signal enters the extender box, that is constituted only by the downstream part. Before and after the extender box is a VOA, the first is to vary the input power, and the second is to control the output power of the extender box.

There were generated 100 million packets for each input power and the results for the packet loss are shown in Figure 4.36.

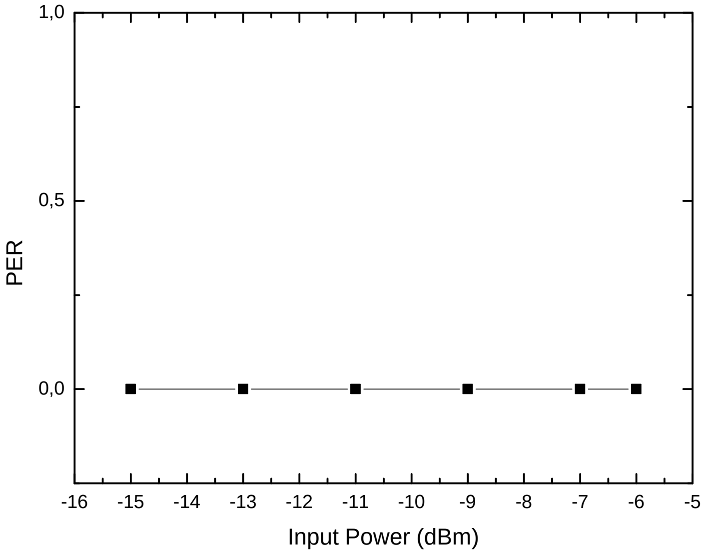

Figure 4.36: Packet error rate for the 10 Gigabit signal compatibility in the downstream link as a function of the input power.

It was verified that the SOA put no obstacles the transmission of 10 Gigabit signals. However, to make this extender box fully compatible with the new XG-PON, some modifications should be made, as for example, using another WDM multiplexer to include the 1260–1280 nm and 1575–1580 nm bands as well using more two SOAs for the downstream and upstream signals.

4.6 Extender Box New Prototype

Based on the considerations taken in the previous sections, it is presented the new prototype for the extender box in Figure 4.37.

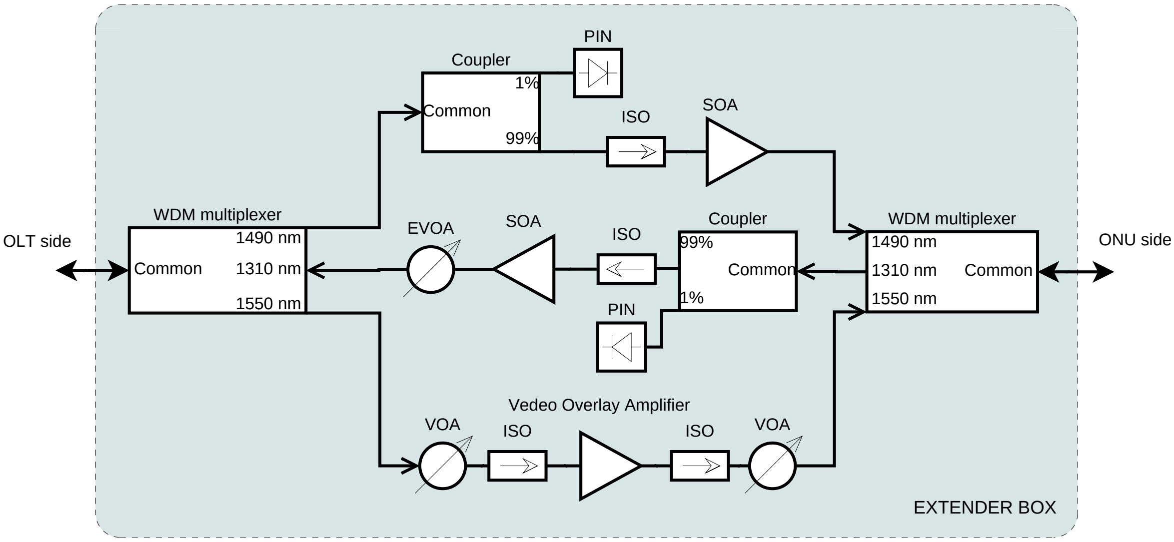

Figure 4.37: Extender Box new prototype.

In the downstream channel was removed the VOAs and the isolator after the SOA, and was added the coupler and PIN for monitoring. In the upstream link was also removed the VOA and the isolator that were before the SOA, the VOA after it was replaced by an Electrically controlled Variable Optical Attenuator (EVOA) and was also added the coupler and PIN for monitoring. Note that the video overlay channel is maintained as in the original prototype, as this channel, for lack of time and equipment was not evaluated yet. Details on the interface and interoperability of the extender components with a microcontroller are given in Appendix B.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

With the growth of the internet appetite by the generality of the users, and the increase in bandwidth demand, it is necessary to deliver broadband services to areas not covered by the optical access networks. In addition, operators can benefit from a solution that could increase the cost-effectiveness of their networks, increasing the splitting ratios of a single PON. Thus, the market began to seek a solution to fill these needs, and a mid-span extender device is presented as a suitable option.

In this thesis was characterized the operation range of an extender device capable of increasing the range and the splitting ratio of a GPON to 60 km and 128 users. Some modifications to the initial prototype were made, and were added the capabilities of self configuration and performance monitoring. All tests were performed using a traffic generator and in similar conditions of a real scenario, which grants the reliability of the results.

The evaluation of the downstream and upstream channels in real scenarios showed an improvement of power budgets up to 48 dB and 53 dB, respectively, which are enough to contemplate the extended reach desired in a wide range of scenarios. This evaluation was made using an EPON, and as the GPON power budgets are larger, it is expected that the extender box will also work in a GPON. However, this needs to be verified, as in the downstream channel was used a SOA with a noise figure greater than the recommended in the standard. The power budgets evaluation also allowed identifying the best operating point of the extender box. The extender box operation on its optimal point is achieved through the control of an electrically controlled VOA, which gives the extender box the capability of self adaptation when introduced in a GPON on the field. The need for performance monitoring was filled with the introduction of monitoring PINs in a low intrusive way, using 1:99 couplers.

The prototype includes a video overlay amplifier that due to lack of time and equipment (video generators) was not yet implemented.

5.2 Future Work

Firstly, the work that should be done is to find a suitable amplifier for the video overlay as soon as there is a video transmitter available for testing.

Another improvement could be exploring the results of the upstream monitoring PIN and find a way of usefully interpret the incoming upstream power. One way, which was already mention, is isolating the ONU and make it transmit at a certain line rate, if possibly, at the highest line rate, for higher optical mean power.

The next step in the reach extension would be to study ways of wavelength conversion. It can be useful for using, for example, just one amplifier for downstream and upstream, converting the upstream signal to the band of amplification of the downstream amplifier. The wavelength conversion could also be useful for other applications such as stacked PON, converting several PONs into adjacent wavelengths to be amplified in the same extender box; or for compatibility with the 10 Gigabit standards, building an extender box that could support both standards, 10 Gigabit PONs and the legacy ones.

Appendices

Appendix A

Power Budget Experimental Setups: Downstream and Upstream — detailed

In this Appendix are detailed the experimental setups shown as a concept in 4.3.1 and 4.3.1.

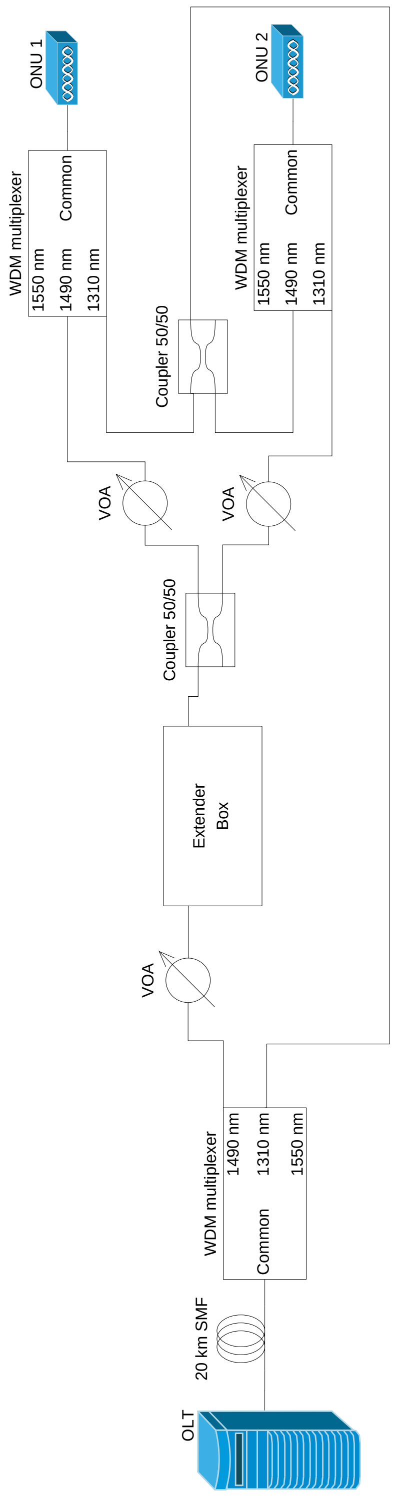

Figure A.1: Experimental setup to test the downstream power budget limits — detailed.

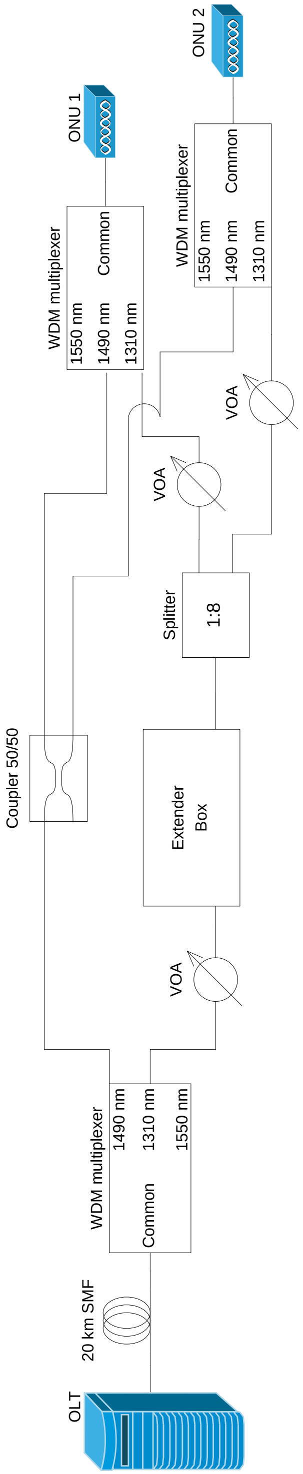

Figure A.2: Experimental setup to test the upstream power budget limits — detailed.

Appendix B

Extender Box Interfaces

After designing the prototype it is necessary that extender box components are assembled together. Apart from the optical components, there are other that are also part of the extender box. These components and the interface between them and the optical components are presented in this Appendix.

B.1 Extender Box Interfaces Prototype

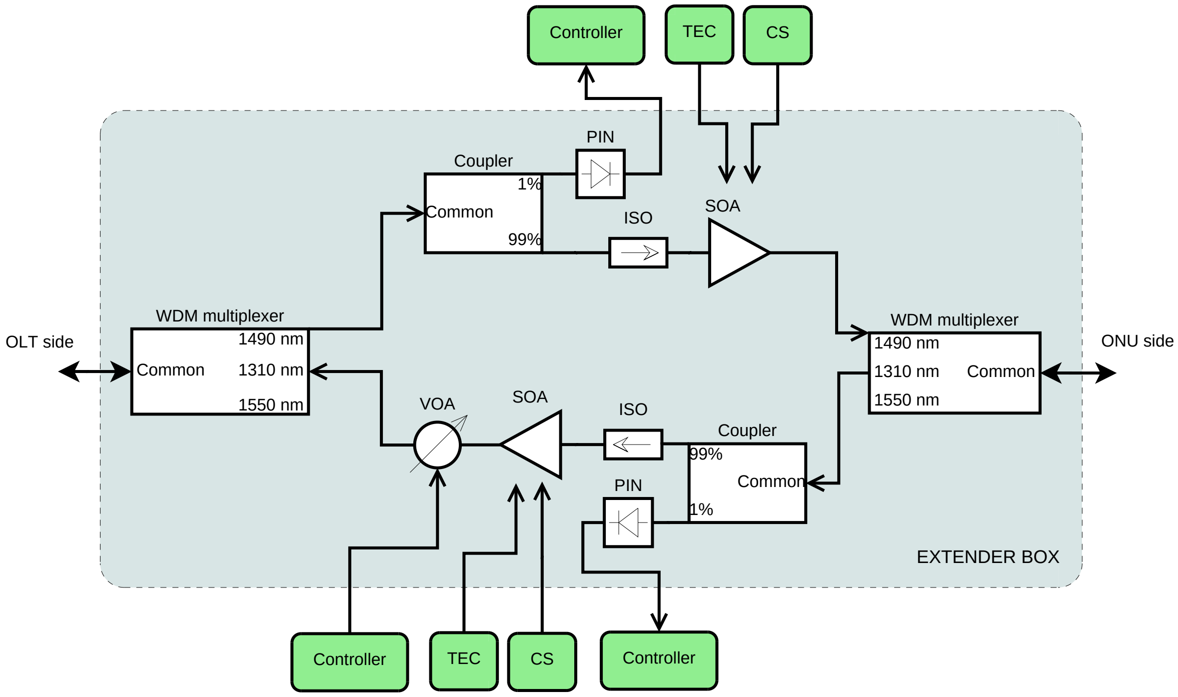

Figure B.1: Extender Box new prototype including interfaces.

In Figure B.1 is shown the optical components that have to give feedback or that need some kind of control. It is the case of the two PINs that give data to the performance monitoring and for the controlling of the EVOA. The SOAs have to be controlled by TECs (Thermoelectric Controller) and CSs (Current Source). The EVOA needs to be configured using the data received on the downstream PIN. To receive the data, process it and control the other components is used a microcontroller. This microcontroller will also have three peripherals, one Human Interface Device (HID) for manual adjustments, a LCD to display the outputs discussed in the performance monitoring section, 4.4 and a serial interface for reconfiguration if needed. These outputs are based on the graphics of that section and can be introduced in the microcontroller as linear functions of the power measured in the monitoring PINs, given by the equations 4.3, 4.4, 4.5 and 4.6. The control of the EVOA is also done with a linear function, equation 4.2. These equation parameters can be modified with the HID.

A scheme of the interfaces between components is shown in Figure B.2.

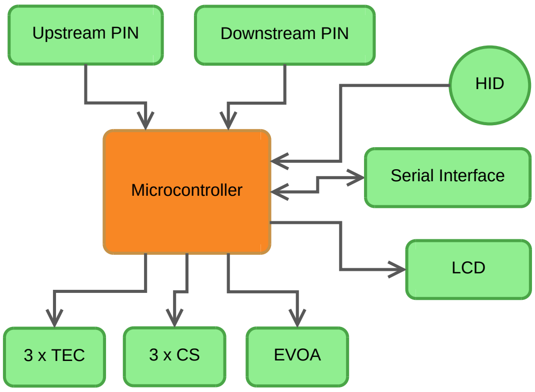

Figure B.2: Microcontroller interfaces and communication.

Note that, even though the video overlay amplifier is not yet evaluated, its necessity has to be taken into account and the microcontroller has to have interfaces reserved for it.

B.2 Extender Box Functional Diagram

As the extender device is to be automatically configured when installed, it is supposed that when it is turned on for the first time it is ready to work. Figure B.3 shows a functional diagram of what will be the extender box functional states since the moment it is turned on.

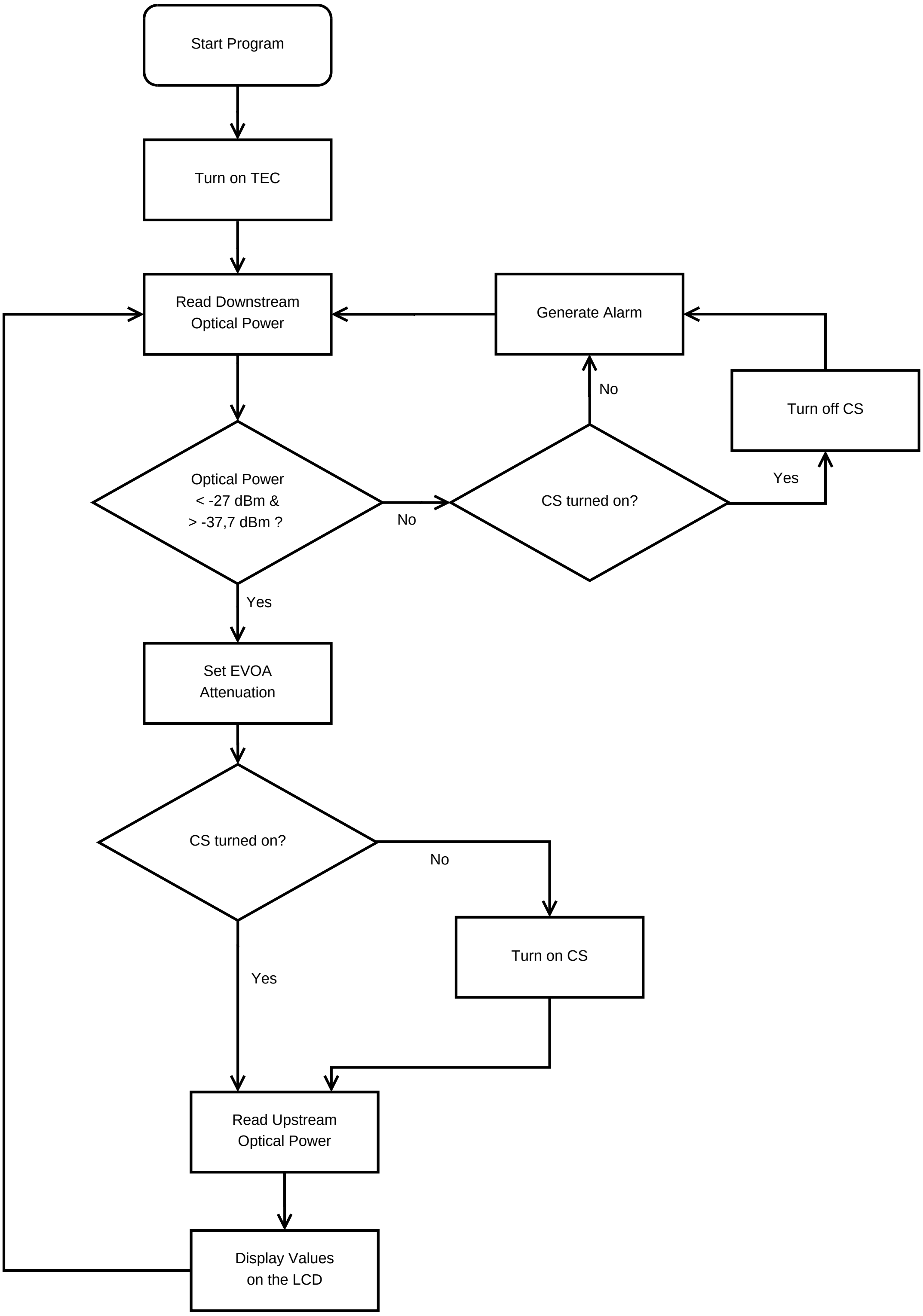

Figure B.3: Extender Box functional diagram.

The functional diagram is a high–level view of the extender box functioning. After the extender is turned on, the first thing turned on are the TECs, as they may take some time to be at the right temperature. Next is read the downstream optical power in the downstream monitoring PIN, and, whether the optical power is within the margins defined or not, the SOAs are turned on or not. This is to assure that there is not optical power arriving from the OLT is not crossing the boundaries defined. If the optical power is not within that margins it is generated an alarm, and depending on the state of the CS, they can be turned off or not. If the received optical power is within the margins, it is set the attenuation in the VOA depending on the optical power. Then, again, depending on whether the current sources are already turned on or not, they can be turned on. Then it is read the optical power in the upstream. Using the equations defined for monitoring results, those outputs are displayed on the LCD. Then to continuously check the condition of the link, and if necessary, adjust the VOA again, or even turn of the system (of the power read crosses the boundaries), the optical power is read in the downstream PIN again, which restarts the loop.

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