Universidade de Aveiro Departamento de Electrónica,
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Susana Gonçalves Bento

Transceivers para TWDM-PON

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

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Dedico o presente trabalho aos meus pais, familiares e a todos os meus amigos que me acompanharam e que me inspiraram durante o meu percurso académico.

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palavras-chave Redes Ópticas Passivas, GPON, XG-PON, NG-PON2, TWDM-PON, Modo Burst, Payload, Guard time

resumo

A Internet tem vindo a assumir um papel fundamental no quotidiano de cada utilizador. A largura de banda exigida é cada vez mais alta, desta forma, as tecnologias actualmente disponíveis acabarão por deixar de satisfazer os requisitos emergentes. Nos últimos anos, as operadoras têm manifestado um interesse evidente no desenvolvimento de Redes Ópticas Passivas (PON), com o intuito de fornecer vários serviços e aplicações a uma taxa de fluxo elevada por cliente. Comparando com outras tecnologias de acesso, as redes PON são muito actrativas devido à sua baixa manutenção e aos custos/eficiência de operação. Como consequência, os sistemas PON foram padronizados e desenvolvidos em todo o mundo. No entanto, este tipo de tecnologia necessita de progredir ao longo do tempo, mantendo a satisfação dos requisitos de tráfego que lhe serão impostos. Assim, as tecnologias actualmente implementadas: GPON e XG-PON, necessitam de sofrer um *upgrade* para NG-PON2 (*Next-Generation PON 2)*. De modo a proteger o investimento inicial, reduzindo os custos de operação, as operadoras devem manter e reutilizer a ODN já implementada, possibilitando a coexistência das tecnologias na mesma fibra.

NG-PON2 é uma melhoria da capacidade, da compatibilidade na ODN, largura de banda e custo-eficiência das tecnologias anteriores. Em Abril de 2012, a FSAN selecionou a tecnologia TWDM-PON (*Time and Wavelength Division Multiplexing PON*) como solução do projecto NG-PON2. Um ano após a sua seleção, a norma ITU-T G.989.1 foi publicada, propondo alguns planos de comprimentos de onda. A coexistência de TWDM-PON com as PON anteriores na mesma ODN é o requisite mais importante.

A presente dissertação baseia-se no estudo de transmissão *upstream* de TWDM-PON. Ambos GPON e XG-PON operam em modo *burst* para a direção *upstream.* Uma vez utilizao este modo de transmissão, é necessário considerer determinados parâmetros como o tempo de separação *interburst – guard time,* tal como o comprimento de cada pacote, com o intuito de compreender o impacto da variação destes mesmos campos no desempenho do sistema.

No presente estudo, era susposto visualizar transientes em cada pacote de transmissão, no entanto foi comprovado experimentalmente, que uma vez que o tempo de vida dos portadores do EDFA selecionado é menor que o intervalo de cada *burst,* não se identificaram transientes. Verificou-se também que, o aumento da separação *interburst* degrada o desempenho do sistema.

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key-words Passive Optical Networks, G-PON, XG-PON, NG-PON2, TWDM-PON, Burst-Mode, Payload, Guard time

abstract

In recent years, Internet has been assuming a fundamental role in everyday life. Traffic demands are increasing in such a way that the available technologies will presumably no longer satisfy the raised requirements. For the last years, operators have expressed a clear interest in the implementation and development of Passive Optical Network (PON) to provide several services and applications to a high flow rate per client. Comparing to other access technologies, PON is very attractive mainly due to reduction of maintenance and to the operational cost efficiency. As a consequence, PON systems were standardized and developed in the whole world, but the ever-increasing bandwidth demand makes this type of network need to evolve. Therefore, the current standardized technologies Giga-capable PON and XG-PON need to be upgraded to Next-Generation PON2. In order to protect the initial investment and to reduce the operational costs, operators should keep the current optical distribution network, providing the technologies coexistence in the same fiber.

The principle of NG-PON2 is to improve previous technologies, in terms of capacity, ODN compatibility, bandwidth and cost-efficiency. In April 2012, Full Service Access Network (FSAN) selected the time and wavelength multiplexing PON (TWDM-PON) technology as the solution of choice for NG-PON2. Almost one year later, ITU-T G.989.1 came out, providing some wavelength plans proposals. The ability to operate on existing fiber ODN, coexisting with legacy PON is the most important requirement.

The current dissertation is based on the study of TWDM-PON upstream transmission. Both GPON and XG-PON work in burst mode for upstream direction, therefore in the current study also that type of data transmission is considered for upstream TWDM-PON. Once using this transmission mode, some parameters have to be taken into consideration, as the packets size and their separation length in order to understand which frame fits the best, considering the system performance.

In the actual study, it was supposed to visualize transients in each packet, however it was experimentally proved that once the lifetime of the carriers is less than the burst time, it was not possible to identify any of them. It was also verified that increasing the *guard time* will decrease the performance of the system.

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List of Acronyms

3DTV	3D television
A	
Alloc-ID	Allocation IDs
APD	Avalanche Photodiode
APON	Asynchronous Passive Optical Network
ATM	Asynchronous Transfer Mode
AWG	Array Waveguide Grating
B	
BER	Bit Error Rate
BIP	Bit-Interleaved Parity
BPON	Broadband Passive Optical Network
BWmap	Bandwidth Map
C	
CBU	Cell-site Backhauling Unit
CO	Central Office
CW	Continuous Wave
D	
DBA	Dynamic Bandwidth Allocation
DBRu	Dynamic Bandwidth Report upstream
DC	Direct Current
DSL	Digital Subscriber Lines
DSP	Digital Signal Processing
DS	Downstream
E	
EDFA	Erbium Doped Fiber Amplifier
EFM	Ethernet in First Mile
EPON	Ethernet Passive Optical Network
F	
FEC	Forward Error Correction
FP	Fabry-Perot
FSAN	Full Service Access Network
FTT	Fourier Time Transform
FTTB	Fiber to the Building
FTTCab	Fiber to the Cabinet
FTTCell	Fiber to the Cell
FTTC	Fiber to the Curb
FTTH	Fiber to the Home
FTTO	Fiber to the Office
FTTP	Fiber to the Permises
G	
GEM	GPON Encapsulation Method
GPON	Giga-Capable Passive Optical Network

GTC	Giga-Capable Passive Optical Network Transmission Convergence layer
H	
HDTV	High Definition Television
HEC	Header Error Control
I	
IEEE	Institute of Electrical and Electronics Engineers
IPTV	Internet Protocol Television
ITU-T	International Telecommunication Unit – Telecommunication Standardization Sector
M	
MAC	Media Access Control
MDU	Multiple Dwelling Unit
MIC	Message Integrity Checked
MMF	Multimode Fiber
MZM	Mach Zehnder Modulator
N	
NG-PON	Next Generation Passive Optical Network
NRZ	Non-return-to-zero
NT	Network Termination
O	
OAM	Operation and Management
OCDM	Optical Code Division Multiplexing
ODN	Optical Distribution Network
OFDM	Optical Frequency Division Multiplexing
OLT	Optical Line Terminal
ONU	Optical Network Unit
ONU-ID	Optical Network Unit Identifier
ONT	Optical Network Terminal
OOK	On-Off-Keying
P	
PCBd	Physical Control Block downstream
PCBu	Physical Control Block upstream
PHY	Physical
PLI	Payload Length Indicator
PLend	Payload length downstream
PLendu	Payload length upstream
PLOAMd	Physical Layer Operations, Administration and Management downstream
PLOAMu	Physical Layer Operations, Administration and Management upstream
PMD	Physical Medium Dependent
PON	Passive Optical Network
Port-ID	Port Identifier
PSync	Physical Synchronization
PSBd	Physical Synchronization Block downstream
PSBu	Physical Synchronization Block upstream
PTI	Payload Type Indicator

P2MP	Point to Multipoint
R	
RF	Radio Frequency
RS	Reed-Solomon
S	
SDU	Service Data Units
SMF	Single Mode Fiber
SOA	Semiconductor Optical Amplifier
T	
T-CONT	Transmission Container
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TWDM	Time and Wavelength Division Multiplexing
U	
UDWDM	Ultra Dense Wavelength Division Multiplexing
US	Upstream
V	
VoIP	Voice over Internet Protocol
W	
WDM	Wavelength Division Multiplexing
X	
XG-PON	10 Giga-Capable Passive Optical Network
XTC	10 Giga-Capable Passive Optical Network Transmission Convergence
XGEM	10 Giga-Capable Passive Optical Network Encapsulation Method

1 INTRODUCTION

1.1 Context and Motivation

In recent years, Internet has been assuming a fundamental role in everyday life. Beyond human geniality, consumers are the main reason of the development of the telecommunications industry.

After being demonstrated that the high-loss of optic fiber arose from impurities in the glass, it became possible to propagate light with low losses over high distances. However nowadays, the consumers' needs are the principal cause of optical networks evolution [1].

The consumption of bandwidth-intensive services is increasingly growing. The majority of these services contents are HDTV, 3D-TV, multiple image and angle video services, growth in unicast video, cloud computing, telepresence, multiplayer HD video gaming and more. However, it is expected that the highest bandwidth consumption will come from business users and mobile backhaul.

According to Cisco's Visual Networking Index, from 2012 until 2017 the total amount of data exchanged between mobile and users is expected to increase 66 percent annually. This will create a networked society, and consequently a tremendous growth in mobile data will place huge pressure on operators [2].

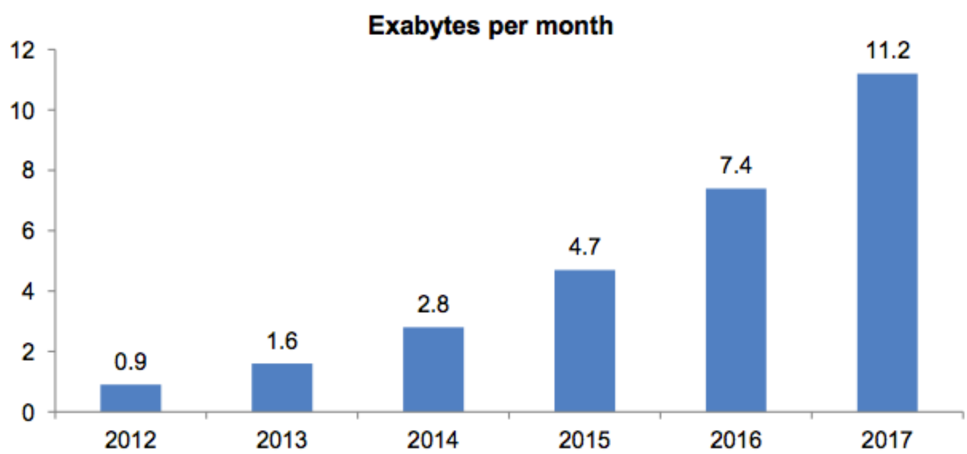

Figure 1.1 – Global Consumer Internet Traffic Forecast [2].

Therefore, bandwidth that copper based access networks can offer is not enough to support all these demands. This sets off the development and promotion of new technologies, such as Passive optical networks (PON).

Full Service Access Network (FSAN) [3] was the first group, to start working on Fiber to the Home (FTTH) architectures. It was a consortium of networks operators and equipment vendor cooperating together. Thus, over the last years several PON standards were developed, namely: Ethernet PON (EPON) [4] created by the Institute of Electrical and Electronics Engineers (IEEE) and Gigabit PON (GPON) [5] developed by International Telecommunication Union (ITU).

Though over time, the existing PONs will no longer meet the bandwidth needs of subscribers. To resist the overload of access network, operators have invested in the study and development of longer reaches technologies, providing more clients, satisfying the established demands, as the networks coexistence.

Operators also ambition larger split ratios, increased range and wavelength availability to serve more costumers with less investment. Next-generations PONs will enable the smooth migration from optical access networks, which are mainly residential, to converge access networks comprising residential, business and mobile backhaul.

This dissertation is mainly based on the basic specifications of the next-generation PON and its upstream performance.

1.2 Objectives

The purposes of the dissertation are:

- Study and analyze the structure of the communication protocol between the OLT and the ONU for GPON and XG-PON.
- Characterize the upstream transmission for TWDM-PON technology in the laboratory.
- Define and characterize several upstream frames for TWDM-PON.
- Analyse the impact of the EDFA in the upstream packets.

1.3 Structure

The dissertation is organized in five chapters:

- Introduction
- State of Art
- TWDM-PON
- Laboratory Results
- Conclusions and Future Work

The first chapter presents the context of the actual technology, the objectives and contributions of the dissertation.

The second chapter is based on the legacy PON, more particularly their evolution and continuity, their features and architecture. It has also presented each candidate technology to NG-PON2. Once the dissertation is mainly about upstream direction, it also based on TC layer, in order to present the frames lengths and how they are synchronized for both upstream and downstream direction.

Regarding the third chapter approaches TWDM selection, requirements, capacity, features and architecture.

The fourth chapter is based on the laboratory experiment, TWDM upstream transmission characterization, the analysis of the impact of the guard time variation and the threshold decision.

In the last chapter is presented the conclusions obtained through the research made for this subject. It is also suggested and briefly explained some future work that could be developed in order to continue the current research topic.

1.4 Major Contributions

The main contributions were:

- Characterization and main features of the current and future PON technology;

- Study of the TC layer of both GPON and XG-PON, in order to understand the formats and procedures of mapping between upper layer service data unit and the adequate bitstreams for the modulating carrier;

- Experimental characterization of upstream direction for TWDM-PON, considering burst mode transmission;

2 STATE OF ART

2.1 Introduction

PON architectures share point-to-multipoint architecture and the upstream/downstream transmission principles.

All the existing PON topologies were developed by two organizations and each standard correspond to two different approaches based on the requirements of the upper protocols such as Ethernet and Asynchronous Transfer Mode (ATM).

FSAN developed Broadband Passive Optical Network, which is an ITU standard (BPON) [7]. The other organization that developed PON standards was EFM, Ethernet in the first Mile, the standard presented is known as “Ethernet Passive Optical Network” (EPON) [4] and is an IEEE standard.

When the FSAN and ITU [6] proposed BPON, the transfer data protocol chosen was the Asynchronous Transfer Mode (ATM). When accepted, BPON specified bit rates of 0.155 Gbit/s at 1310 nm and 0.622 Gbit/s at 1490 nm for upstream and downstream directions, respectively.

However with the strong need of the Internet, it did not take long before ATM based BPON systems proved out to be very inefficient dealing with large, variable-sized IP frames, which composes the majority of traffic through the access networks. This led to the development of the Ethernet based PON. Ethernet is a data oriented protocol that transports IP packets over time.

Just after EFM started working on the EPON standard [4], the FSAN group become devoted to create a Gigabit-capable PON as well. The aim was to develop a technology that could handle better the changes toward the Ethernet and IP based network and its fast-growing bandwidth demand. Its name is “Gigabit-capable Passive Optical Network” (GPON) [5]. Both EPON and GPON basically support the same communication protocols, the way they are encapsulated and how the overhead is introduced. On the other hand, these technologies were created by different organizations. Both of these systems have the same wavelength plan [8], which means they cannot coexist in the same ODN, without prohibitive packet losses. However, the tendencies had indicated a greater development in GPON than in any previous technology.

In 2006, FSAN/ITU began to consider the system that would follow GPON. At the beginning, the main goal was to develop additional specifications for the GPON system, allowing a smooth migration to the following system. This resulted in the G.984.5 recommendation, which redefined the spectrum plan for GPON and defined blocking filters in the GPON optical network units (ONUs) to avoid crosstalk from non-GPON wavelengths.

In 2007, a long-term PON evolution started being developed, called “Next Generation Passive Optical Network” (NG-PON). The objective was to explore the post GPON system aspects, highlighting the reuse of the “legacy” fiber plant. Figure 2.1 presents the evolution of PON standards.

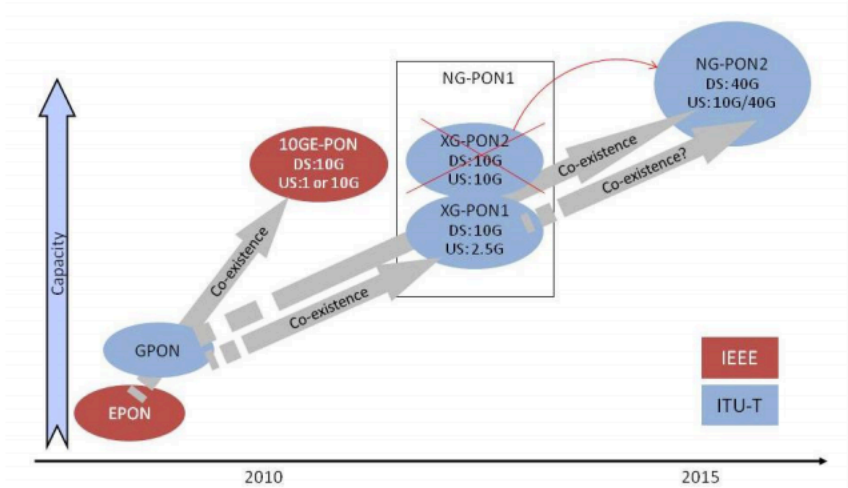

Figure 2.1 – Progress of PON systems [2].

NG-PON is divided in NG-PON1 and NG-PON2 and at the beginning its requirements were quite different from the actually ones. NG-PON1 was considered to be a mid-term upgrade, compatible with GPON ODNs, while NG-PON2 was supposed to be a long-term solution in PON evolution that could be deployed over new ODNs, thus ignoring GPON standards.

When the group finalized NG-PON1 basic specification – 10 Giga-capable PON (XG-PON1) [9], they started focusing on extending the applicability of XG-PON technologies.

Later FSAN members analyzed each proposal for NG-PON2, redefining posteriorly their true aims. Therefore the fundamental goal was to overcome all previous technologies in ODN compatibility, capacity, bandwidth and cost-efficiency. Finally, in April 2012, all eyes turned out to TWDM-PON as the most attractive solution for NG-PON2 [11].

2.2 PON General Architecture

Primarily, a passive optical network has point-to-multipoint architecture. There are three main elements that compose the PON – the optical line terminal (OLT), the optical distribution network (ODN) and the optical network unit (ONU). Each of them has a group of particular functions. Figure 2.2 presents each of the mentioned PON elements.

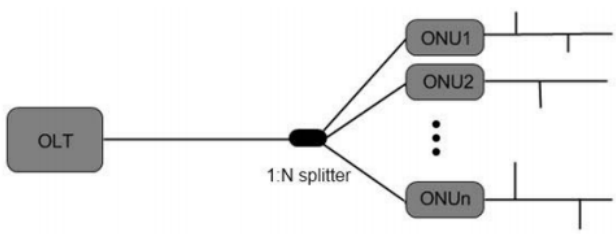

Figure 2.2 - PON architecture [41].

- The **ONU** or **ONT** are the same device. The first one is located outside the building of the subscriber and the second is located in the user's location. This device is the PON's termination and receives the broadcast signal coming from the OLT, and posteriorly selects the data that is intent to it.

- The **OLT** sends the broadcast signal to all ONUs, controlling and synchronizing the data exchange in the access network. It assigns the upstream bandwidth to the ONUs following a DBA algorithm. The OLT also charges the management and maintenance of the ODN.

- The **coupler/splitter** is an interface located between the OLT and the single mode fibers connected to each ONU. Considering the downstream link, the optical splitter divides the data stream coming from the Central Office, to individual links targeted to each ONU. In the upstream direction, this passive device can also function as a coupler, gathering all the upstream data packets relative of each ONU.

Both downstream and upstream transmission can take place on the fiber due to different wavelength assignment and multiplexing mechanisms or on separate fibers.

Considering the downstream direction, once the optical signal is broadcasted, when the travelling data arrives to the ONU, there is some data that has to be discarded. Therefore, the ONU filters the data that is not intended to it.

Regarding the upstream direction, each ONU sends its corresponding packets to the OLT. There is a point where the packets of all ONUs meet – the coupler. To preclude the packets collisions, there are two different mechanisms that multiplex several optical signals into the same fiber – *Time Division Multiplexing* (TDM) or *Wavelength Division Multiplexing* (WDM).

WDM is a non-standard PON that multiplexes several optical signals into a single mode fiber. Briefly, each wavelength is associated to one optical signal, which in turn is intended to one user. This can be achieved by an ***Array Waveguide Grating*** (AWG). It is seen as a passive router that selects each optical signal to each port, allowing bi-directional data flow through the single optical fiber. Figure 2.3 explains clearly how WDM-PON works, using an AWG.

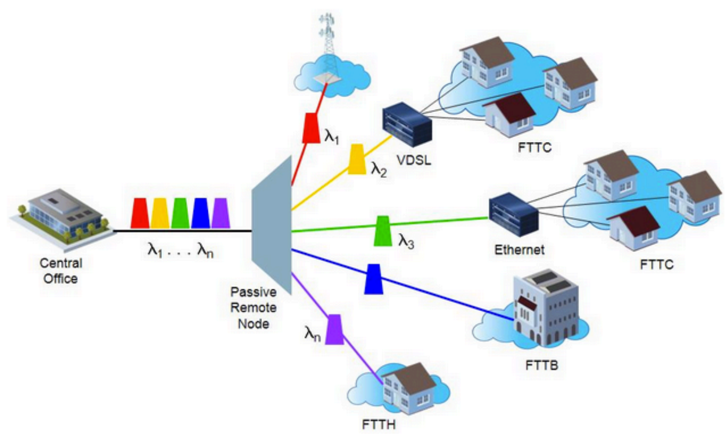

Figure 2.3 – WDM-PON non-standard protocol [12].

TDM is also a method of transmitting and receiving independent signals over a single fiber. The difference remains in the time domain, which is divided into several recurrent time slots of fixed length, one for each sub-channel. A TDM frame consists in one time slot per channel plus its error correction and synchronization. This mechanism only demands for one transceiver in the OLT, apart the number of ONUs, however it has to be synchronized to avoid packets collisions. WDM provides higher split ratios and longer reaches. MAC layer is simpler than it for TDM, because the system connections are made in the wavelength domain, thus do not need any use of P2MP media access control. However WDM elements have higher costs than TDM [15].

In addition, there is also other protocol of transmitting data, called Time Division Multiple Access (TDMA). It is used for upstream transmission, thus instead of having one transmitter connected to one receiver, there are multiple transmitters. This mechanism allows several users to share the same frequency channel by dividing the signal into different time slots. The users transmit fast and sequentially, one after another, each using its specific time slot. It is generally used in upstream traffic from the premises to the CO [16].

2.3 Gigabit-capable Passive Optical Network (GPON)

In 2003, the FSAN group launched "Gigabit-capable Passive Optical Network" (GPON) [5] standard. Considering the general PON concepts such as the ODN, the wavelength plan or the sub-layers functionalities, GPON was strongly based on BPON standard [9]. Both EPON and GPON basically support the same communication protocols, although once they had been developed by different organizations, not any of them had taken into account their wavelength plan or the even the possibility of coexisting together. Therefore, EPON and GPON cannot coexist in the same ODN, without prohibited packet losses [18].

The current technology easily meet the short-to-medium-term needs of residential consumers, such as commercial triple-play packages (Internet, HDTV and telephone) [19].

2.3.1 Architecture

GPON is based on a typical PON architecture. Its active elements only exist in the OLT and in each ONU. Between them there is the single mode fiber and the passive optical splitters 1:N. Figure 2.4 presents configurations for Fiber-to-the-X (FTTX).

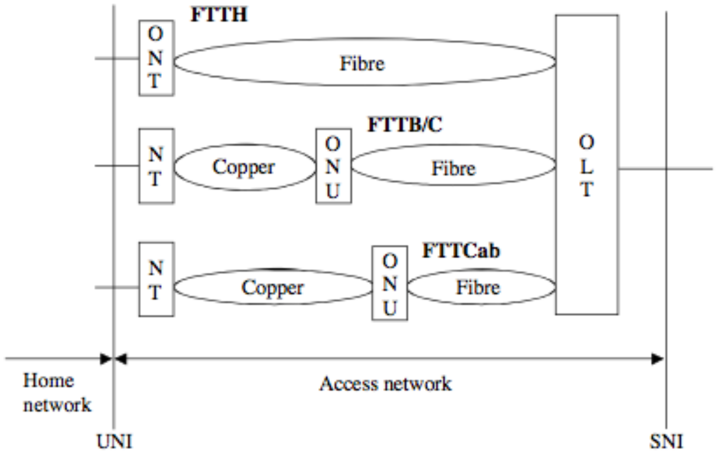

Figure 2.4 – GPON network architecture [5].

At the **OLT side**, there is an interface called Service Network Interface (SNI), and in the opposite side is the User Network Interface (UNI). The ODN remains in between those interfaces.

Considering the first configuration, the one that starts in SNI and goes forward until UNI is FTTH. Those, which are not directly connected to the UNI, correspond to different topologies. It is very important to identify where the optical/electrical conversion takes place, because it defines the topology.

In FTTCab/FTTCurb/FTTB topologies, the ONU and the NT are connected by cooper cables, which limit the bandwidth. The difference between these configurations relies on the supported services, as presented in Table 2.1.

Services	**Scenarios**	**FTTB**		**FTTCurb and FTTCab**	**FTTH**
		MDUs	Business		
Asymmetric broad-band services		Yes	No	Yes	Yes
Symmetric broad-band services		Yes	Yes	Yes	Yes
POTS and ISDN		Yes	Yes	Yes	Yes
xDSL		No	No	Yes	No
Private line		No	Yes	No	No

Table 2.1– The different services of FTTB, FTTC, FTTCab and FTTH topologies [5].

2.3.2 Features

Bit Rate

GPON standard has several transmission speed combinations, as the following table 2.2 presents:

Upstream (Gbit/s)	Downstream (Gbit/s)
0.15552	1.24416
0.62208	1.24416
1.24416	1.24416
0.15552	2.48832
0.62208	2.48832
1.24416	2.48832
2.48832	2.48832

Table 2.2 – GPON bit rate [19].

However, the most frequent bit rates are 1.24416 Gbit/s and 2.48832 Gbit/s for upstream and downstream directions, respectively. is the mainstream speed combination supported at current time, constituting nearly all the deployed and planned deployment of the GPON systems [5].

Line Code

The selected line code for GPON standard, in both transmission directions is NRZ code (*Non Return to Zero*) with scrambling. When using NRZ, situations without any transitions such as long sequences with consecutive identical bits, can cause a synchronization loss in the receiving clock. Thus, scrambling technique is applied. It randomizes the data stream, avoiding long sequences with identical digits [20].

Physical Reach

The physical reach is the maximum distance between the OLT and the ONU. In GPON standard there are two possibilities, 10 km and 20 km.

Split Ratio

Network operators intend to have the maximum number of subscribers as they can, to monazite their own networks.

The passive optical splitter can assume split ratios such as 1:32, 1:64 and 1:128. Although, higher the split ratio, higher the attenuation. Thus, the power budget to cover the physical reach has to be also higher [5].

Wavelength

As mentioned before, EPON and GPON have the same wavelength plan. For downstream direction, both standards define 1490 nm [1480; 1500] nm, and for upstream direction 1310 nm [1260; 1360] nm.

In addiction, there is a specific wavelength plan for RF video, in downstream direction; it goes from 1550 to 1560 nm [5].

Errors Correction

Forward Error Correction (FEC) is used by the transport layer communication systems to transmit data in an encoded format. The encoding inserts redundancy, allowing the decoder to detect and correct the transmission errors. Considering an input BER of 10^{-4}, the BER at the FEC's decoder wil assume a value of 10^{-15}. Through FEC technique, it is possible to achieve a better performance of the system, avoiding retransmissions [21].

2.3.3 Transmission

According to the standard, GPON method for data encapsulation is GEM. ITU-T G.984.3 recommendation identifies GPON encapsulation method as the unique data transport scheme in which specify GPON transmission convergence layer. GEM provides connection-oriented communication, a variable-length framing mechanism for transporting data services over the passive optical fiber. It is also independent of the type of service node interface at the OLT, as well as the types of UNI at the ONU [21] [22].

Downstream traffic is centralized. It is broadcasted from OLT to all ONUs through TDM. The OLT multiplexes the GEM frames onto the transmission medium using GEM Port-ID to identify which GEM frame is intended for each downstream logical connection. Each ONU filters the downstream GEM frames according to their GEM Port-IDs and processes only the GEM frames that belong to that ONU [21]. Figure 2.5 illustrates downstream GPON traffic.

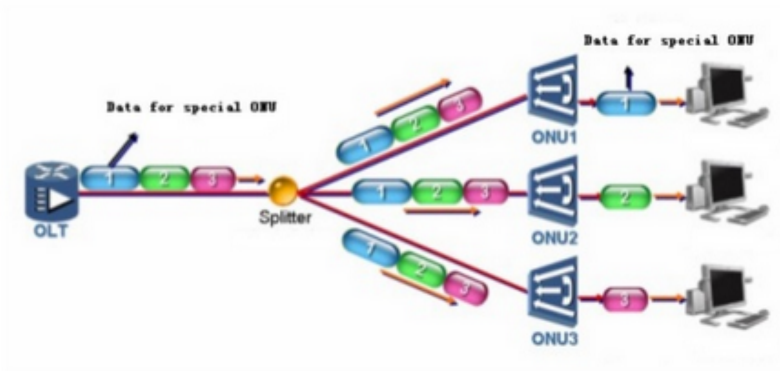

Figure 2.5– Downstream GPON traffic [19].

2.3.3.1 GPON Time Convergence Protocol

GPON Time Convergence (GTC) layer is located between the physical media dependent (PMD) layer and the GPON clients. It is responsible for traffic flows, security and operation and management (OAM) features. It also manages the user traffic [21].

GTC layer is composed of the GTC framing sublayer and the GTC adaptation sublayer. GTC adaptation sublayer supports the functions of user data fragmentation and de-fragmentation, GEM encapsulation, GEM frame delineation and GEM Port-ID filtering. GTC framing sublayer supports functions of GTC frame/burst encapsulation and delineation, embedded OAM processing and Alloc-ID filtering. The PMD layer defines the bit rate of uplink and downlink signals [21] [23].

GTC layer framing

The frame structure is defined in the GTC framing sublayer. GTC frame structure exists for downstream and upstream directions. The downstream GTC frame consists on the physical control block downstream (PCBd) and the GTC payload section. The upstream GTC frame has multiple transmission bursts. Each burst has variable-size and it is composed of the upstream physical layer overhead (PLOu) section and one or more allocation interval(s) associated with a specific Alloc-ID. Figure 2.6 shows the structures of GTC frame for both downstream and upstream directions [21] [22].

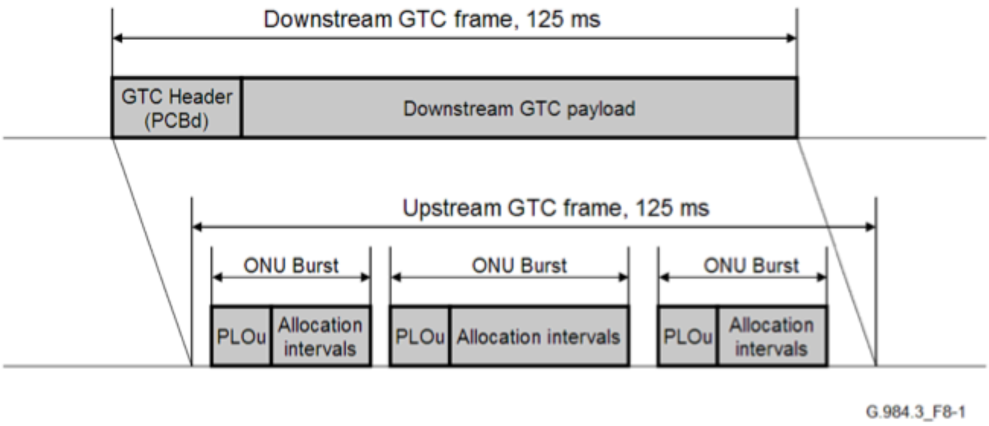

Figure 2.6 - GPON Time Convergence Layer for both directions [21].

Downstream GTC frame structure

The downstream GTC frame has duration of 125μs and has 38880 bytes, considering the downstream data rate of 2.48832 Gbit/s. The PCBd length range depends on the number of allocation structures per frame. Figure 2.7 presents the structure of downstream GTC frame.

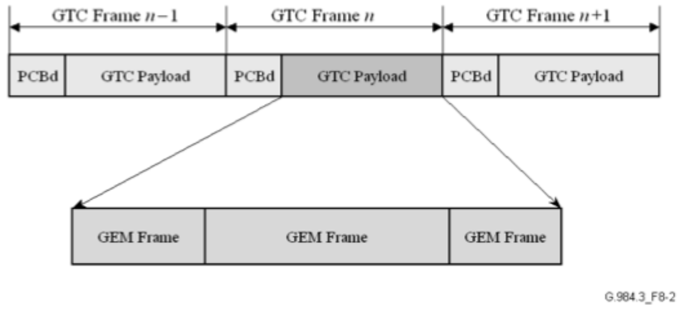

Figure 2.7 - Downstream GTC frame [21].

Each downstream frame can carry both Ethernet frames and TDM traffic in their native formats as well as asynchronous transfer mode (ATM). The transmission order of all fields is made from the most significant bit. For example, 0x03 indicates the sequence beginning with zero, and ending with one. The downstream GTC frame is scrambled using a frame-synchronous scrambling polynomial: $x^7 + x^6 + 1$.

It has two fields, the physical control block for downstream (PCBd) and the GTC payload. PCBd contains a variable part and a fixed part. The fixed part contains the physical synchronization (PSync), the ident field, the physical layer of operations and management for downstream (PLOAMd). These fields are protected by a 1-byte bit-interleaved parity check (BIP). The variable part is composed of the payload length (PLend) and the bandwidth mapping (BWmap). This fields protect the Each of one is be briefly described in table 2.3. The OLT sends the PCBd in a broadcast manner, and every ONU receives the entire PCBd. ONUs will operate according to the relevant information contained in the received PCBd. In Figure 2.8 is specified each field of PCBd [21] [24].

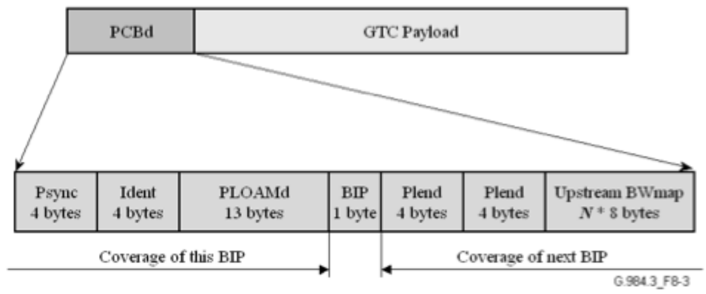

Figure 2.8 – GTC physical control block downstream (PCBd) [21].

PSync field	Ident field	PLOAMd field
Fixed 32-bit pattern that begins every PCBd. The ONU logic can use this pattern to find the beginning of every frame. The ONU implements a synchronization state machine to search for the PSync pattern.	It is used to indicate larger framing structures. It also indicates wether forward error correction (FEC) is used.	It contains information relative to TC-layer management functions, such as ONU activation and encryption configuration.

BIP field	PLend field	BWmap fields
Contains the bit-interleaved parity of all bytes transmitted since the last BIP, excluding FEC parity. The receiver shall compute the bit interleaved parity on all bytes received since the last BIP, and compare its result to the BIP transmitted in order to detect the number of errors on the link.	Payload length downstream field specifies the length of bandwidth map. It is sent twice to ensure error robustness.	Contais the allocation identifier (Alloc-ID) of a transmission container (T-CONT). The start time and end time to transmit that T-CONT in the upstream direction and a 12-bit flag indicating which allocation should be used.

Table 2.3 - PCBd description fields [21][24].

Following the BWmap there is the GTC payload section. It contains series of GPON encapsulation method (GEM) frames. It supports the fragmentation of the user data frames into variable-sized transmission fragments.

The downstream GEM frame stream is filtered at the ONU based upon the 12-bit port identifier (Port-ID) field contained in the header of each GEM frame. Each ONU identifies the Port-ID, which is intended to.

Upstream Traffic

In the upstream direction, it is used TDMA protocol in order to avoid packets collisions. The OLT grants the upstream bandwidth allocations to the traffic-bearing entities within the subtending ONUs. These entities that are recipients of the upstream bandwidth allocations are identified by their Alloc-IDs. The bandwidth allocations are multiplexed in time as specified by the OLT in BWmap transmitted downstream. Within each one, the ONU uses the GEM Port-ID to identify the GEM frames that belong to different upstream logical connections [25]. Figure 2.9 illustrates the upstream traffic of GPON.

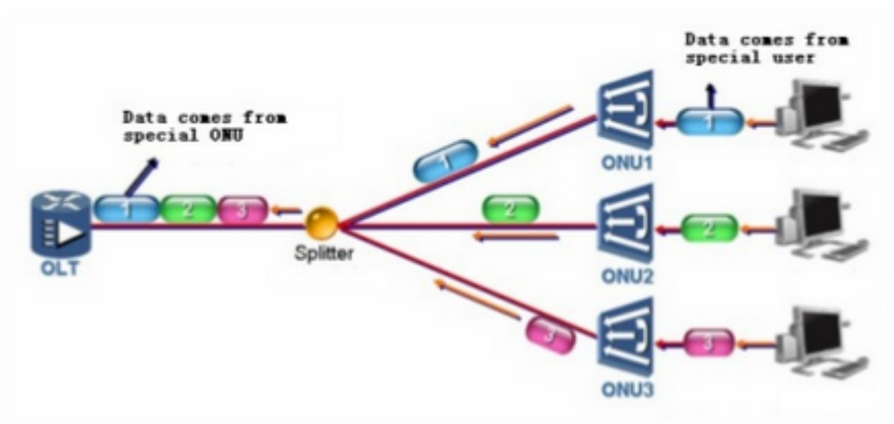

Figure 2.9 – Upstream direction schematic [15].

Burst Mode

In the upstream direction, GPON operates in burst mode. The transmission bursts from different ONU transceivers require isolation and delineation at the OLT receiver. A transmission burst is the interval during which the laser of an individual ONU transceiver remains turned on and is transmitting a pattern of zeros and ones into the optical fiber. Each burst contains the upstream physical layer overhead (PLOu) section and more allocation intervals. It is composed of preamble, delimiter, the burst header and the allocation intervals. The burst header is 3 bytes long and is composed of BIP, ONU identifier (ONU-ID) and Ind fields.

Burst Mode Overhead

The physical layer overhead (Tplo) time is used to accommodate five physical processes in the PON: Laser on/off time, Timing drift tolerance, level recovery, clock recovery, and start of the burst delimitation. Tplo can be divided in three sections, such as the guard time (Tg), the preamble time (Tp) and the delimiter time (Td). During Tg, the ONT transmits power at the nominal zero level. During the Tp, the ONT transmits a preamble pattern that provides the maximum transition density for fast level and clock recovery functions. Finally, during the Td, the ONT transmits a special data pattern with optimal autocorrelation properties that enable the OLT to detect the beginning of the burst. Td must provide sufficient data bits to provide a robust delimiter function in the face of bit errors. Its length must be at least 16 bits long [21].

There is other parameter related to the control logic on the PON – the total peak-to-peak timing uncertainly (Tu). This uncertainty emerges from variations of the time of flight caused by the fiber and component variations with temperature and other environmental effects [21]. Therefore, the recommended allocations for the physical layer overhead are presented in the given table 2.4.

Upstream data rate (Mbit/s)	Tx enable (bits)	Tx disable (bits)	Total time (bits)	Guard time (bits)	Preamble time (bits)	Delimiter time (bits)
155.52	2	2	32	6	10	16
622.08	8	8	64	16	28	20
1244.16	16	16	96	32	44	20
2488.32	32	32	192	65	108	20

Table 2.4 - Recommended allocations for the PLOu [21].

Threshold at OLT

The OLT receiver measures the incoming power level for a particular ONU and compares it the threshold. There will be an uncertainty on this measurement, due to implementation imprecisions, as current sources, linearity of receiver at high power, supply voltage variations, temperature effects on the electrical amplifier stages, etc. Thus, there are uncertainties on the effective threshold value when compared to its setting. The uncertainty range over which the threshold can vary over the operational range of the OLT is required to be 4 dB [21].

Power Detection

Regarding the initialization of the ONUs, the OLT periodically opens ranging windows during which a new ONU can send an upstream burst. The OLT must detect the attendance of any new ONU [21].

Burst structure

Since the upstream GTC frame has duration of 125 μs, for 1.24416 Gbit/s uplink the upstream GTC frame is 19440 bytes long. However, considering 2.48832 Gbit/s uplink, the GTC frame size will be 38880 bytes. Figure 2.10 presents the GPON upstream frame schematic.

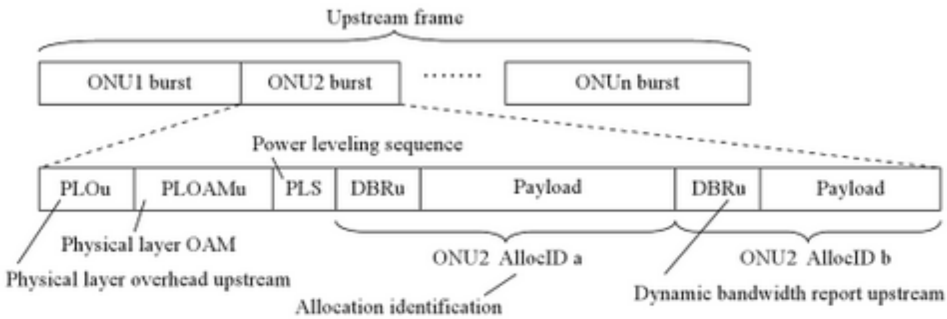

Figure 2.10 – GPON upstream frame format [26].

Each transmission contains a number of bursts coming from one or more ONUs. Its structure is based on the upstream physical layer overhead (PLOu) section and one or more bandwidth allocation intervals associated with individual Alloc-IDs. As it was refereed before, the BWmap dictates the arrangement of the bursts in the frame and the allocation intervals within each burst [21]. Figure 2.11 illustrates the GPON of upstream frame format. Figure 2.11 shows the diagram of the upstream GTC frame structure [21] [26].

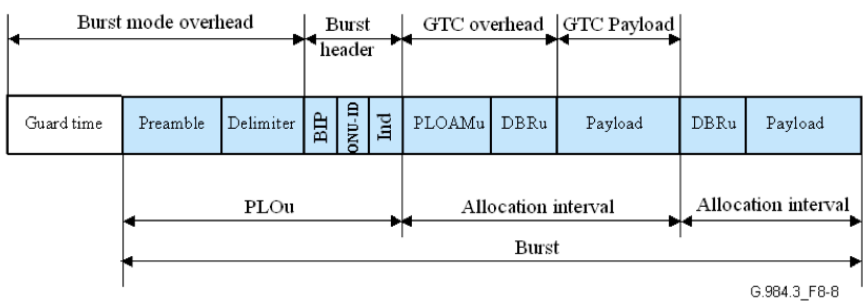

Figure 2.11 - Structure of GPON Burst [21].

A bandwidth allocation interval may contain two types of GTC layer overhead fields: upstream physical layer operations, administration and management

(PLOAMu) message and the upstream dynamic bandwidth report (DBRu) that indicates the T-CONT traffic status. The Flags fields of the allocation structure are used by the OLT, to indicate whether or not the PLOAMu and/or DBRu fields shall be included into the corresponding upstream allocation interval. The OLT should request PLOAMu transmission only in allocation intervals associated with the Default Alloc-ID of any given ONU [21] [26].

The physical layer overhead for upstream (PLOu) includes preamble, delimiter and the burst header, which contains the bit interleaved parity (BIP), the ONU-ID and the Ind. The ONU-ID field identifies the ONU that is transmitting, allowing the OLT to confirm if the correct ONU is transmitting. The Ind field reports to the OLT, the real-time ONU status (Note that the BIP field was described in the downstream GTC chapter) [21].

Each upstream allocation interval contains the GTC payload section, which carries the GEM-delineated frames. Figure 2.12 presents the GTC payload structure for upstream direction.

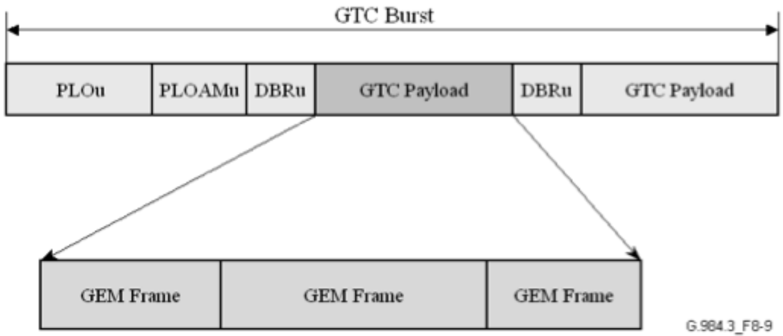

Figure 2.12 - GTC Payload structure for upstream direction [21].

The GEM protocol provides delineation of the user data frames and offers the port identification (Port-ID) for multiplexing. In the next figure is presented the GEM frames structure. The figure 2.13 specifies the fields of each GEM frame.

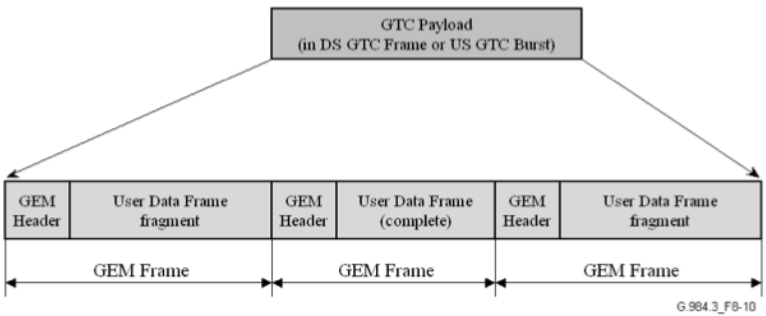

Figure 2.13 - Specification of the GEM frame [21].

The GEM header contains the payload length indicator (PLI), Port-ID, payload type indicator (PTI) and a header error control (HEC) field, as figure 2.14 presents. In table 2.5 is presented a briefly description for all the enumerated GEM header fields.

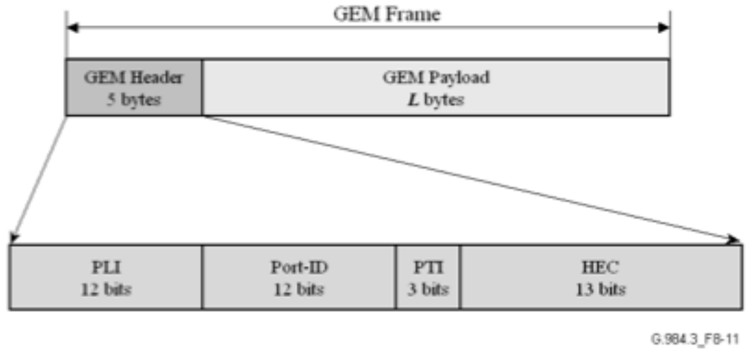

Figure 2.14 - GEM Header fields [21].

PLI	Port-ID	PTI	HEC
Indicates the payload length. It also finds the next header in the stream, providing delineation.	Provides 4096 unique traffic identifiers on the PON in order to provide traffic multiplexing. Each Port-ID contains a user transport flow.	Indicates the content type of the payload and its appropriate treatment. For example: PTI code of "000" means "user data fragment, not the end of a frame"; "001" means "user data fragment, end of a frame".	Provides error detection and correction functions for the header.

Table 2.5 - GEM header fields [21] [27].

GEM frame delineation and synchronization

The delineation process requires the GEM header at the beginning of every downstream and upstream GTC payload section. The receiver is in charge of finding the first head and posteriorly the subsequent headers through the PLI pointer. If some uncorrectable errors are detected in the header, the delineation process may lose the synchronization with the data stream. The receiver will try to reacquire synchronization by implementing a state machine. In the "Hunt" state the receiver searches for a GEM header HEC byte-to-byte. When it finds one, transits to the "Pre-sync" state, where it looks for the HEC at the location indicated in the previously found header. If that HEC matches, then the transition is made to the "Sync" state. If it does not, then the transition is made to the "Hunt" state.

To provide a data rate decoupling, an idle GEM frame is defined. If no user frames are being sent, the transmit process will generate these idle frames to fill the empty space. These frames will be used for the receiver to maintain synchronization. Once they have not data, they will not pass up to the GRM client. These idle GEM frames are defined to be all-zeros [21] [28].

Dynamic Bandwidth Allocation

The GPON network includes a mix of services. Some of them, such VoIP or native TDM, require constant upstream bandwidth, and the OLT may statically allocate the bandwidth for these services. Other IP-based services, such as Internet browsing, streaming video, file sharing and file download, are bursty by nature. For highest upstream bandwidth utilization, the OLT should allocate the upstream bandwidth for these services dynamically, using a dynamic bandwidth allocation algorithm (DBA). DBA improves the GPON upstream bandwidth use by reacting adaptively to the ONUs bursty traffic pattern. Therefore, the operators can add more subscribers to the PON. DBA is a process in which the OLT reallocates the upstream PON capacity between the traffic-bearing entities within the ONUs, based on the dynamic indication of their activity status. To initiate the process, the OLT needs to be aware about the status of each ONU. Each one of them has a T-CONT associated, which indicates the number of packets waiting in their buffer. The status is reported through DBRu (contains information tied to T-CONT) that notifies the MAC controller about the transmission attribution. Once the OLT possesses this information, it is able to determine how much traffic assigns to an ONU through management of grants accordingly. If the ONU is empty, it will notify that there is no data to transmit through an idle upstream cell. Figure 2.15 illustrates the DBA process.

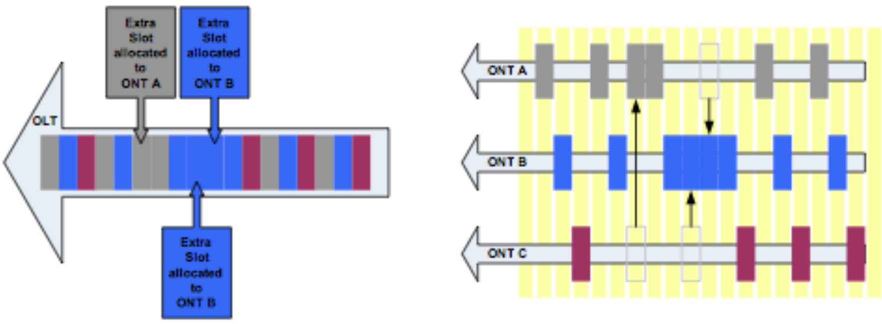

Figure 2.15 - DBA process.

Comparing with statically bandwidth allocation, the DBA process represents an improvement in the upstream transmission, once it adapts easily to ONUs traffic patterns of bursts. Besides providing more subscribers to the PON, due a better use of the available bandwidth, it also allows subscribers to take advantage of advanced services, like those which require variable rates, with peaks that exceed levels attributed statically [22][29].

2.4 Next Generation Passive Optical Network (NG-PON)

2.4.1 Introduction

Nowadays, commercial triple-play services provide typical bandwidths between 20 and 100Mbit/s to residential customers. Supposing that a high-end user's Internet connection increases 50 percent every year, it is expected that one subscriber who enjoys 58 Mbit/s in 2013, will demand for 130 Mbit/s by 2016 [2].
Current technologies, such as GPON, will easily satisfy short-to-medium needs of residential consumers. However, they will struggle over the ever-growing bandwidth services, such as HDTV, 3D-TV, multiple image and video services, cloud computing and more. Therefore, it is expected that PON technology will be improved and innovated, promoting low cost and high efficiency principles. Also, it is very important to take advantage of the existing ODN to the operators, in order to protect the investments. To fulfill this requirement, a system with WDM technology integrated, started to be developed – *Next Generation PON.*

FSAN group along ITU-T are the forum standardization with the greatest activity in the study of PON evolution. According to those entities, NG-PON system is divided into two stages; the first to emerge was NG-PON1, in 2012, specified as XG-PON1 [9]. The arrival of the second stage – NG-PON2 standard [12] came one year later. It is still being developed, however NG-PON2 already offers a clear path to higher capacities, and therefore is expected to better address the needs of operators in the future. It is expected to be concluding in 2015 [30].

2.4.2 NG-PON Roadmap

Both FSAN and ITU-T defined NG-PON1 as a mid-term evolution; it focuses on PON technologies, which are compatible with GPON standard, especially with its current optical distribution network (ODN). NG-PON1 is backwardly compatible with existing fiber installations, and tries to facilitate high bandwidth provision, large split ratio, and extended network reach.

NG-PON2 is considered to be the long-term term technology for PON evolution. At the beginning, the basic requirements for NG-PON2 deployment were at least 40Gb/s of capacity and 40 km of reach at a 64-way split. The backwards compatibility with existing ODN technology or even previous PONs were totally discarded. Based on these requirements, many different systems were proposed. However FSAN reformulated the requirements defined previously for the NG-PON2 project. The ability to operate on existing fiber ODN was the first requirement to crystalize followed by compatibility with video overlay. Coexistence with XG-PON was also made mandatory [13]. Figure 2.16 illustrates the PON evolution.

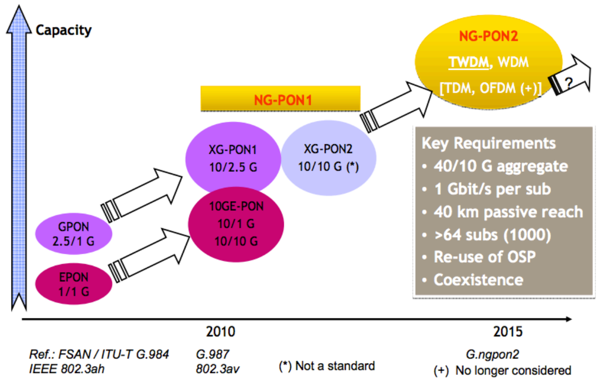

Figure 2.16 - NG-PON roadmap [31].

2.4.3 XG-PON

The specified NG-PON1 system is called XG-PON1. Its standard – G.987.1 [9] emerged in 2010, including the general requirements. The study and development of this technology lasted until 2012.

This system provides higher data transmission rates than GPON. The downstream bandwidth is four times of that of GPON, while the upstream bandwidth of XG-PON1 is twice as that of GPON. Particularly, the ODN in XG-PON1 entirely inherits that of GPON, implying that optical fibers and splitters in legacy GPON systems can be reused in XG-PON1. After a 10 Gb/s interface board is added to the OLT, smooth evolution from GPON to XG-PON1. Thus, this technology has become a cost-effective way to meet the performance in access networks. Although, the split ratio and the fiber reach didn't suffer any differences.

2.4.3.1 Architecture

XG-PON presents a typical PON architecture. In the outside plant XG-PON uses single mode fiber. The active elements are the OLT and the ONU. Between them there is the single mode fiber and a passive optical splitter that distributes the traffic into N separate paths to the users. This standard uses WDM technology to multiplex several optic carriers into a single optical fiber, by using different wavelengths. This also provides bidirectional data stream.

Besides supporting FTTH, FTTB/C and FTTCab architecures, G.987 standard also includes FTTCell (Fiber to the Cell) and FTTO (Fiber to the Office). In the first architecture, the ONU is called cell-site backhauling unit (CBU). It offers connectivity to wireless base stations. FTTO provides, in a flexible way, private line services at several rates and addresses each integrated business plan ONU into a small business costumer. The figures 2.17 and 2.18 help to understand clearly the previous services [9].

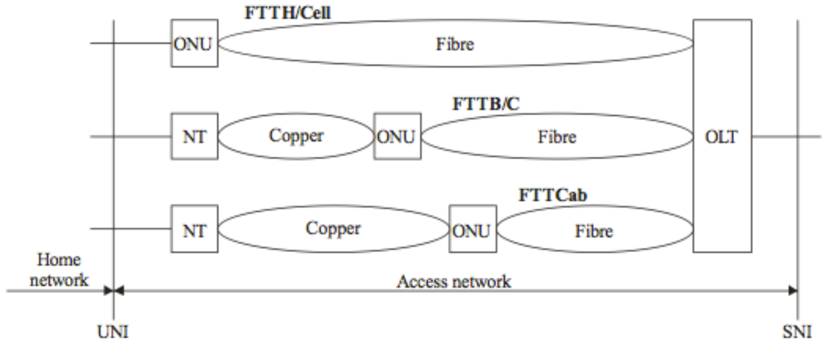

Figure 2.17 - Network architecture [9].

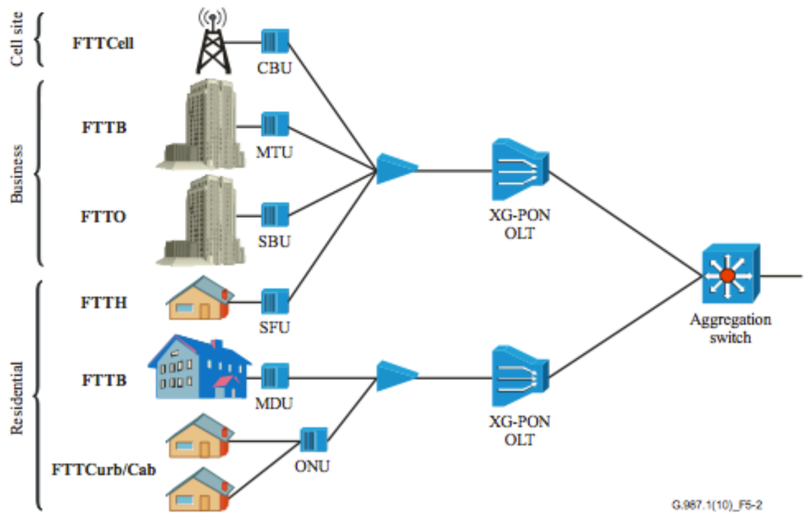

Figure 2.18 - XG-PON scenarios [9].

The table 2.6 presents the characteristics of different XG-PON architectures.

	FTTB MDU-served residential users	**FTTB MTU-**served business users	**FTTC and FTTCab**	**FTTH**	**FTTO**	**FTTCell**
Asymmetric broadband services	Yes	No	Yes	Yes	No	No
Symmetric broadband services	Yes	Yes	Yes	Yes	Yes	No
POTS	Yes	Yes	Yes	Yes	Yes	No
Private Line	No	Yes		No	Yes	No
xDSL backhaul	No	No	Yes	No	No	No
Symmetric TDM services	No	No	No	No	No	Yes
Symmetric/Asymmetric packet-based broadband services	No	No	No	No	No	Yes
Hot spots	No	No	No	No	No	Yes

Table 2.6 – Characteristics of different scenarios for XG-PON1 [9].

2.4.3.2 Features

Bit Rate

G.987.1 standard defined two transmission speeds, presented in table 2.7.

	Upstream transmission	Downstream transmission
XG-PON1	2.5 Gb/s	10 Gb/s
XG-PON2	10 Gb/s	10 Gb/s

Table 2.7 - XG-PON bit rate [9].

However, G.987.1 recommendation only focuses on the XG-PON1 bit rate. Due to the current technology challenges that need to be overcome to obtain low cost 10 Gb/s upstream burst mode building blocks, XG-PON2 will be specified later [9].

Line Code

The downstream and upstream line code employed in XG-PON1 is non-return to zero (NRZ) with scrambling. Using NRZ, the clock in the receiver can lose synchronization due to transitions lack in consecutive identical digits (CID). Thus, the scrambling technique is employed to pseudo-randomizing a data stream, avoiding long sequences CID [32].

Split Ratio

Many network operators have constructed their ODN infrastructure with 1:32 to 1:64 split for GPON, thus 1:64 split was defined the minimum requirement for XG-PON.

A single split architecture is a special case, where m = 64 and n = 1 and no splitter is needed at the access node. Extending the split is an interesting option to improve XG-PON overall economics compared with GPON. This extension would exceed 1:64 [9].

The higher splitter ratio allows extending PON in the backhaul section and to extend PON towards the end users to provide flexible splitter configurations and efficiently support a variety of deployment scenarios. Thus, the XG-PON TDMA control function should provide 1:256 split, considering the maturity and cost-effectiveness of optical devices [9].

Wavelength

To achieve a low cost implementation of such compatibility feature, the wavelengths selected are presented in the following table 2.8.

Upstream	1260 to 1280 nm (O band)
Downstream	1575 to 1580 nm (L band)

Table 2.8 – Optical wavelengths of XG-PON [9].

The selection of upstream wavelength was made according to a comparative study between C, L and O bands. C and L were excluded because of RF overlay and video overlaps, and also due insufficient guard band between respective wavelengths. The downstream wavelength was chosen according the band that was left in the system with RF overlay and video services. Besides the presented wavelength for downstream, it should be noted for outdoor there is a small extension until 1581 nm [32] [9].

Fiber Reach

G.987.1 standard defines the maximum fiber distance of at least 20 km.
XG-PON1 transmission convergence layer needs to support 60 km of maximum fiber distance [9].

Optical Power Budget

Coexistence of GPON and XG-PON on an ODN providing class B+ optical budget is the nominal requirement. The WDM device introduces an additional loss, thus two nominal power budget classes have been selected, Nominal1 (29 dB) and Nominal2 (31 dB) at BER 1E-12. In addiction, the coexistence an ODN with C+ optical budget drives the extended power budget requirement, allowing an additional split in the ODN with appropriate margins, or alternatively an increase in the supported system reach [9].

2.4.3.3 Transmission

2.4.3.3.1 XG-PON Transmission convergence (XGTC) layer

XG-PON transmission convergence layer is a part of XG-PON protocol stack, which specifies the formats and procedures of mapping between the upper layer service data units (SDU) and the bitstreams adequate for modulating the optical carrier.

There are three sublayers that constitute the current layer; the XGTC service adaptation sublayer, the XGTC framing sublayer and the XGTC PHY adaptation sublayer. XGTC layer is present in both OLT and ONU sides. There is a specific interface for each direction. For downstream direction, the interface between the XGTC layer and the physical medium dependent (PMD) layer is represented by a continuous bitstream at the nominal interface rate, which is divided in 125 μs frames. The interface between the XGTC layer and the PMD for upstream direction is represented as a sequence of precise timed bursts [40] [34].

XGTC service adaptation sublayer

XGTC service sublayer is responsible for upper layer SDU encapsulation, multiplexing and delineating in the optical carrier.

On the **transmitting side**, the XGTC service adaptation sublayer receives the upper SDUs (user data) and the ONU management and control interface (OMCI) divides SDUs into fragments, attributes to each of them a XGEM Port-ID and finally applies the XG-PON encapsulation method (XGEM). In the end, it was obtained the XGEM frame, which contains the XGEM payload (that can be optionally encrypted) and the XGEM Port-ID. All the XGEM frames together compose the XGTC payload, which will be sent to the XGTC framing sublayer [33].

On the **receiver side**, the XGTC service adaptation sublayer accepts the payload of the XGTC frames or bursts, performs XGEM frame delineation, filters the XGEM Port-ID, decrypts the XGEM payload if it was encrypted by the transmitter, and finally reassembles the fragmented SDUs, delivering them to the respective clients [33].

XGTC framing sublayer

The XGTC framing sublayer is responsible for the construction and analysis of the overhead fields, which support the necessary PON management functionality.

On the **transmitter side**, the XGTC framing sublayer accepts XGTC payload from the XGTC service adaptation sublayer, and constructs the downstream XGTC frame or the upstream XGTC burst by providing embedded OAM and physical layer operations, administration and maintenance (PLOAM) messaging channel overhead fields. In the upstream direction, an XGTC burst multiplexes XGTC payloads associated with the same Allocation IDs (Alloc-IDs) [33].

On **the receiver side**, the XGTC framing sublayer accepts the XGTC bursts or frames, analyses the XGTC overhead fields, extracting the incoming embedded management and PLOAM messaging flows, and delivers XGTC payload to adaptation sublayer. The incoming PLOAM messaging channel flow is delivered to the PLOAM processing engine. The embedded OAM belongs to the upstream bandwidth management (BWmap) and the dynamic bandwidth allocation (DBA) signaling is processed within the framing sublayer itself, providing partial controls over the PHY adaptation sublayer (PHY burst timing and profile control), and service adaptation sublayer (encryption key indication). The rest of OAM information is given to the control entities outside the framing sublayer [33].

XGTC PHY adaptation sublayer

The PHY adaptation sublayer includes the functions that modify the bitstream modulating the optical transmitter with the goal to improve the detection, reception and delineation properties of the signal transmitted over the optical medium.

On **the transmitter** side it accepts the XGTC frames or bursts from the XGTC framing sublayer, partitions them into FEC data blocks, computes and add the FEC parity field to each FEC data block, performs scrambling of the FEC protected data, precedes the specific physical synchronization block for downstream (PSBd) or upstream (PSBu) transmission, and provides timing alignment of the resulting bitstream.

On the **receiver side**, the PHY adaptation sublayer performs physical synchronization and delineation of the incoming bitstream, descrambles the PHY frame or burst data, executes FEC and extracts its parity symbols. Finally it delivers the resulting frames or bursts to the XGTC framing sublayer.
The line code employed in XG-PON1 is non-return to zero (NRZ) [33].

Downstream XGTC framing

For instance, if considered the transmitter side of the service adaptation sublayer, it behaves equally as for downstream and upstream directions. However when the XGTC payloads are received in the framing sublayer, there is a distinction for downstream and upstream direction. In the topic, the downstream XGTC frame is specified.

The downstream XGTC frame is 135432 bytes long. It is composed of XGTC header and XGTC payload section. Payload section is created on the transmitter side and is processed on the receiver side by the service adaptation sublayer. In Figure 2.19 is represented the structure of the downstream XGTC framing.

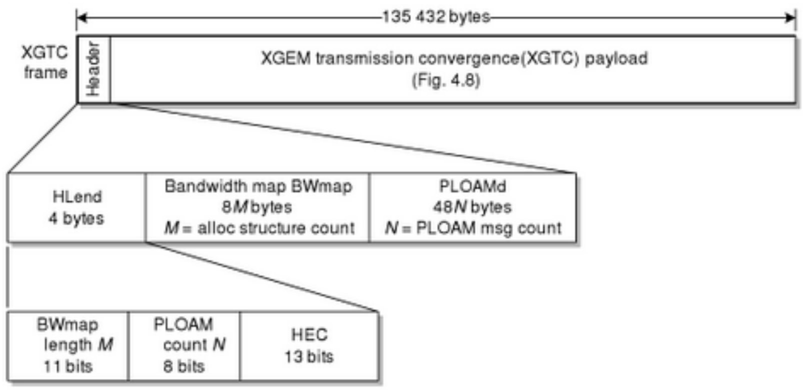

Figure 2.19 - Downstream XGTC frame scheme and header fields. [35]

A fixed size HLend structure and two variable size partitions, BWmap and downstream PLOAMd partition, compose XGTC header. HLend specifies the length of the other fields in XGTC header [35]. It is composed of the three fields presented in table 2.9.

BWmap length	PLOAM count	HEC
Indicates the number of allocations structures in the BWmap partition.	This field indicates the number of PLOAM messages in its partition.	Hybrid error correction is a field to detect and correct errors for the HLend structure.

Table 2.9 - HLend fields [33].

In the downstream frames, the OLT sends an authorization, through BWmap, to allow upstream transmissions from the ONUs. The BWmap contains allocations structures that specify a bandwidth allocation to a certain Alloc-ID. A sequence of one or more allocation structures associated with the Alloc-IDs that belong to the same ONU, and supposed to create a contiguous upstream transmission make a burst allocation series.

There is a field within each allocation structure, named BurstProfile that contains the index of the burst profile to be used by the PHY adaptation sublayer of the ONU to make the PHY burst. It is associated to the series of valid burst profiles that communicate to the ONUs by the broadcast or unicast transmissions over the PLOAM messaging channel [33] [34].

Upstream XGTC framing

The interface between the XGTC framing sublayer and the XGTC PHY adaptation sublayer is represented by an upstream XGTC burst. The XGTC burst transmitted by the ONU has a variable size. It is composed of a burst header, one or more allocation intervals and a XGTC trailer. Each allocation interval is related to a certain Alloc-ID and has a size dictated by the allocation structure of the BWmap.

The bandwidth allocation interval contains the overhead and then follows the XGTC payload section. The transmitting side forms the payload and then is processed on the receiving side, by the intended service adaptation sublayer entity. Figure 2.20 presents the XGTC burst format and its overhead fields [33].

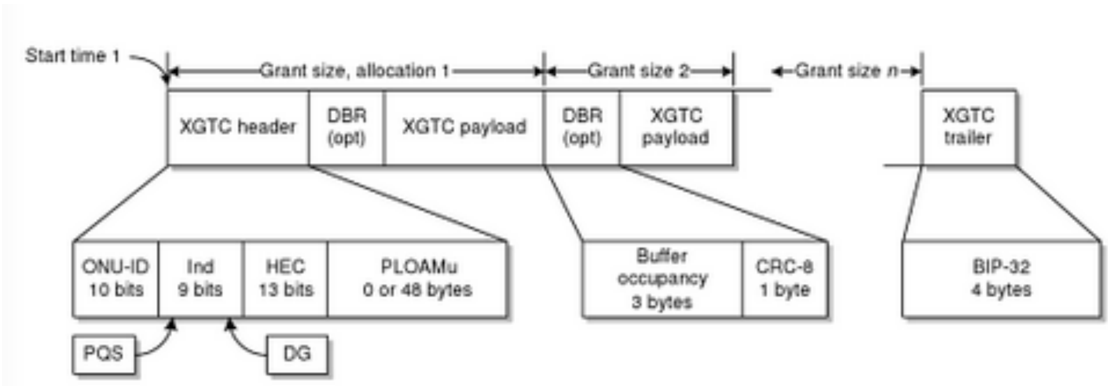

Figure 2.20 – XGTC upstream frame [35].

Table 2.10 have a briefly description of each XGTC header field.

XGTC header			
Fixed section			Non-fixed section
ONU-ID	Ind	HEC	PLOAMu
It identifies the ONU that is transmitting the actual burst. The OLT check this field to confirm that the correct ONU is the actual one, which is transmitting.	Bit 8 – provides an indication that the ONU's queue is non-empty, after the current burst is transmitted. Bit 7-1 – reserved. Bit 0 – indicates that the ONU has detected local condition that may prevent the ONU to respond to upstream bandwidth allocations.	Corresponds to the error detection and correction field for the upstream XGTC header.	It is the field, which contains one PLOAM message.

Table 2.10 – XGTC header fields description [33].

Besides the XGTC header, there is the DBRu and the XGTC payload. At the end of the upstream frame there is the XGTC burst trailer, which contains a BIP fields, that computes over the burst, providing the BER estimation of the upstream link to the OLT receiver. However the BER estimation is only possible when the FEC is turned-off [33].

Burst Structure

To detect an ONU burst is more difficult then receiving an ONU's regular transmission. Some ONUs may have higher power and be easier to detect, thus not needing FEC. The OLT establishes burst profiles and then requests for a specific burst profile for each burst transmission. A burst profile specifies the preamble pattern and length, the delimiter pattern and length and wether FEC parity shoud be sent. The OLT receiver is sensitive for the profile parameters and uses it to ensure proper response in its burst mode receiver.
In the ONU side some basic requirements should be respected, as the preamble and the delimiter patterns. These patterns can differ in each profile, and this difference could be used by the OLT receiver as an indication of the format of each burst. Figure 2.21 illustrates the interburst details and the preamble and delimiter patterns [32].

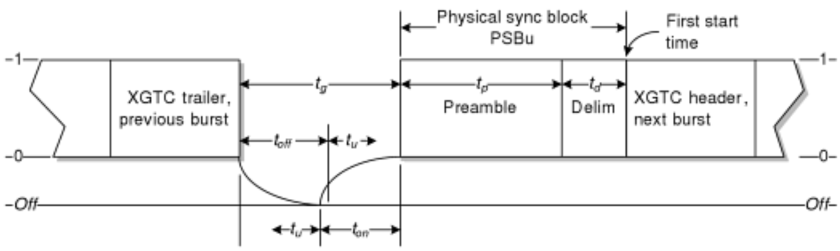

Figure 2.21 – Interburst detail [40].

XG-PON encapsulation method (XGEM)

XGEM is similar to GPON encapsulation method. It also supports SDU fragmentation, encapsulation and delineation and it is applicable in both upstream and downstream directions. Figure 2.22 presents the XGTC payload.

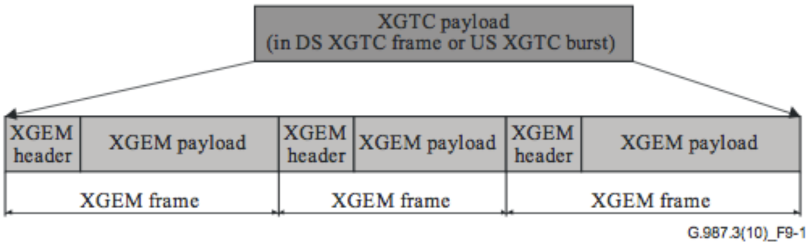

Figure 2.22 – XGTC payload [33].

The XGEM header has the PLI, key index field, XGEM port-ID, the last fragment indicator and the HEC fields. The key index field indicates the data encryption key used to encrypt each XGEM payload. Relatively to the XGEM frame, whenever a transmitter has no SDUs to send or when the length of the SDUs exceed the XGTC payload section, the transmitter has to generate an idle XGEM frame to fill the available payload [33]. SDU fragmentation is illustrated in figure 2.23.

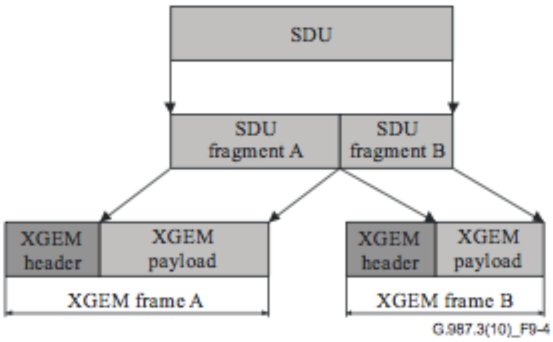

Figure 2.23 – SDU fragmentation [33].

2.4.3.4 Dynamic Bandwidth Allocation (DBA)

Dynamic bandwidth assignment (DBA) in XG-PON is the process by which the OLT allocates upstream transmission bursts to the traffic-bearing entities in the ONUs, based on dynamic indication of their activity and their configured traffic contracts.
Comparing DBA with static bandwidth assignment, its mechanism improves XG-PON upstream bandwidth utilization by responding in an adaptive way to the ONU's burst traffic patterns.

There are two benefits of using DBA: the network operator can add more subscribers to the access network due to the efficiency of the used bandwidth, and the subscribers can enjoy enhanced services, such as those requiring variable with peaks extending beyond the levels that can reasonably be allocated statically [9].

2.4.4 NG-PON2

In the last 10 years, the application and use of broadband technology enabled by optical networks has exploded. Nowadays, it is driven by push-pull effect of national communications priorities and ever-increasing consumer demand. A faster and more approachable system of communications with universal access is the main reason of the ever-increasing bandwidth.

Nowadays, costumers expect to have triple-play services, with voice, video and data by a single connection. Applications such as file sharing, online gaming, video on demand and HDTV, require higher bandwidth capacity that are struggling traditional technologies such as digital subscriber lines (DSL), cable and wireless. Only PON technology has the necessary requirements to deliver all of the services.

Therefore, operators are deeply devoted to fulfill the relevant requirements for a new solution for PON evolution.

On March 2013, the *Next-Generation PON2* – G.989.1 [10] recommendation was approved, addressing the some requirements.

2.4.4.1 Requirements

NG-PON2 system is expected to have high quality of service and high bit-rate capability. Therefore, its requirements are driven by the demand to fully support services for residential subscribers, business costumers, mobile and fixed backhauling, and other applications.

Therefore, NG-PON2 systems are expected to provide new revenue streams on implemented ODNs and supporting greenfield applications over the new ones [10]. The following topics refer to the system general requirements.

Bit Rate

NG-PON2 systems must have multiple wavelength channels TWDM architecture (4-8 TWDM channel pairs). Thus it shall be able to offer more capacity per customer than current GPON or XG-PON1 systems. NG-PON2 must be capable of supporting at least 40 Gbit/s and 10 Gbit/s for downstream and upstream directions, respectively. In other words, NG-PON2 supports bit rates as 10 Gbit/s per downstream channel and 2.5 Gbit/s per upstream channel. It is also expected to support symmetrical capacity such as 2.5 Gbit/s or 10 Gbit/s for both downstream and upstream directions [33].

Fiber Reach

NG-PON2 systems must be able to support at least 40 km of fiber reach without any reach extender. Although, if necessary it has also to be capable of reaching 60 km with reach extenders [10] [33].

Split Ratio

Nowadays ODNs are deployed typically with a split ratio in a range of 1:16 to 1:128. One of the aims of NG-PON2 technology is to overtake legacy power split ODNs. Therefore, NG-PON2 ODNs must support at least 1:256 of split ratio.

There are particular applications that may require higher split ratios, thus NG-PON2 OLT core design should not avoid higher split ratios [10] [33].

Power reduction

In telecommunications network systems, power saving has become a relevant concern to reduce operational costs, thus NG-PON2 must be design in the most energy-efficient way.

The primary goal of power saving in access networks is to maintain lifeline services, as long as possible, through a backup battery, when electricity service goes out [10].

Other requirements considering parameter combinations

The following topics are parameter combinations, once NG-PON2 requires flexibility to balance speed, distance and split ratios for specific applications:

- 40 Gbit/s downstream capacity and 20 km reach with at least 1:64 split
- 10 Gbit/s upstream capacity and 20 km reach with at leat 1:64 split
- Access peak rates of 10 Gbit/s and 2.5 Gbit/s for downstream and upstream directions, respectively.
- Longer distances with lower split ratios

NG-PON2 also supports:

- 40 Gbit/s upstream capacity, therefore 10 Gbit/s per upstream channel and 20 km fiber with at least 1:64 split.
- For both downstream and upstream directions 10 Gbit/s capacity, with 2.5 Gbit/s per channel, with 40 km reach and 1:32 split
- For both downstream and upstream directions 40 Gbit/s capacity, with 10 Gbit/s per channel, with 40 km reach and 1:32 split
- Access for peak rates of 10 Gbit/s and 10 Gbit/s for downstream and upstream directions.
- Tunable point-to-point WDM, supporting the coexistence with other PONs.

2.4.4.2 NG-PON2 architecture

One of the requirements for NG-PON2 is to ensure a smooth migration from the previous implemented standards, using the same ODN, thus protecting the investment made on the legacy PON systems. It also must operate in usable spectrum, in other words not occupied by legacy PONs.

In order to provide a flexible migration, NG-PON2 system must allow coexistence over the end-to-end ODN, including the coexistence over the feeder fiber.

The specified technology for NG-PON2 system – *Time Wavelength Division Multiplexing PON* (TWDM-PON) shall be compatible with splitting ODNs, which may contain power splitters and a coexistence element. According to the standard, technologies that require wavelength filtering in the ODN are not considered for this architecture. Figure 2.24 presents the network reference architecture [10].

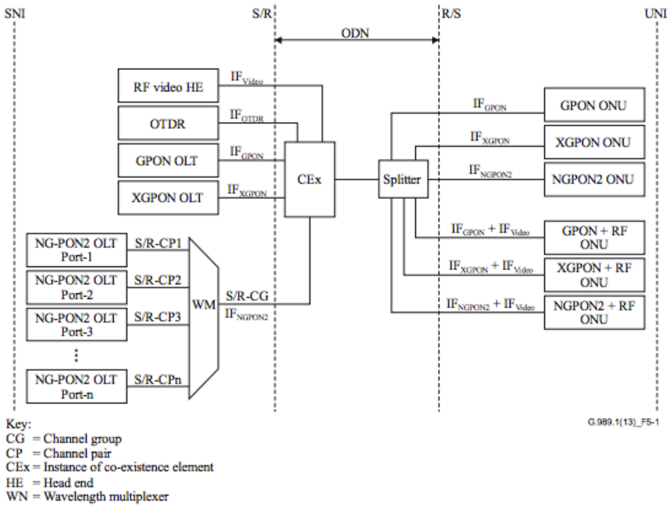

Figure 2.24 - Figure Network reference architecture for NG-PON2 [10].

In the previous figure, at the OLT side there are four different technologies, each one with a different wavelength plan. The technology below is NG-PON2, which has four or more channels, also with a specific wavelength. At the ODN, there is the interface coexistence element that combines/splits the several wavelengths, each one relevant to a specific technology. Then there is the passive optical fiber, which connects to splitter that distributes the signal to each ONU. The ONUs are colorless, allowing spectral flexibility. In each ONU should exist appropriate filters to eliminate interference between PON technologies. A non-wavelength selective ODN may be preferred to provide a system independent distribution network. Filters inside the ODN define wavelength spaces that limit flexibility and make the network more complex [10].

2.4.4.3 Optical spectrum

One of the most important requirements of NG-PON2 system is the coexistence with previous legacy PON, which is enabled through the wavelength band plan. Therefore, some matters should be considered, such as the linear and non-liner effects, the components limitations, considering their operating wavelengths, the fiber, etc.

Access networks employ single mode fibers, which are wavelength dependent. The figure specifies clearly the relation between the attenuation and the wavelength through a SMF [33]. Figure 2.25 presents the linear effects of the SMF.

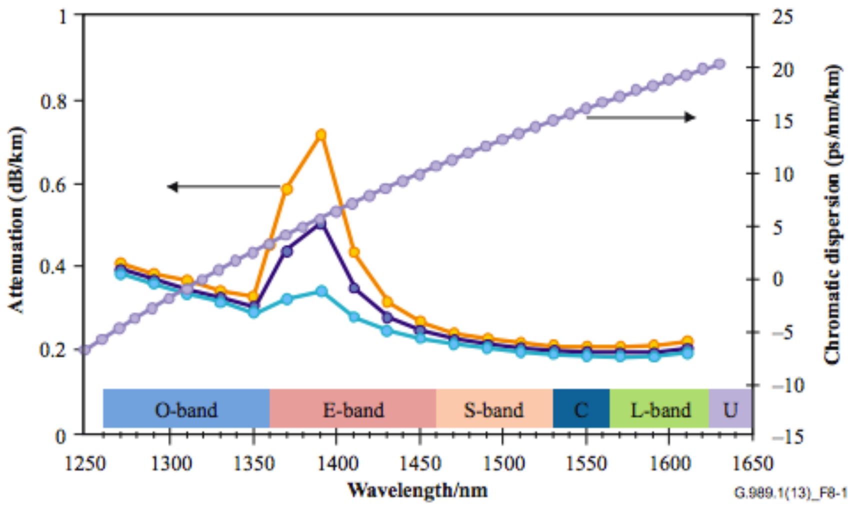

Figure 2.25 – SMF attenuation and chromatic dispersion effects [10].

The lowest verified attenuation is in C-band, however L-band also presents lower attenuation values.

Other observation, by adding fiber to the system causes the emergence of a well-known linear effect called chromatic dispersion. Unfortunately, increasing the bit rate can limit the system reach.

Once NG-PON2 system requires higher split ratios and reaches, the need to increase power should be considered. Therefore, to provide high level of power, some optical components such as tunable lasers and coherent receivers should be taken into consideration, however they can only operate for specifics wavelengths, such as of 1550 nm [36].

There is also the opto-electronic restriction, considering the as the Erbium doped optical amplifier (EDFA) it only operates in C and L bands. However, in cases of semi-conductor optical amplifiers (SOA), they can work in any of the desired bands. The performance optoelectronic components vary on the operating wavelength, laser temperature or photodiode responsivity [10].

Regarding the coexistence requirement, the further factor that limits available spectrum are the legacy filter characteristics build into current systems. Beyond BPON, GPON, 10GE/XG-PON systems, the most distinguished may be the RF-video filter, once requires guardbands that occupy most of the C-band. The wavelength plan of PON legacy system is presented in figure 2.26.

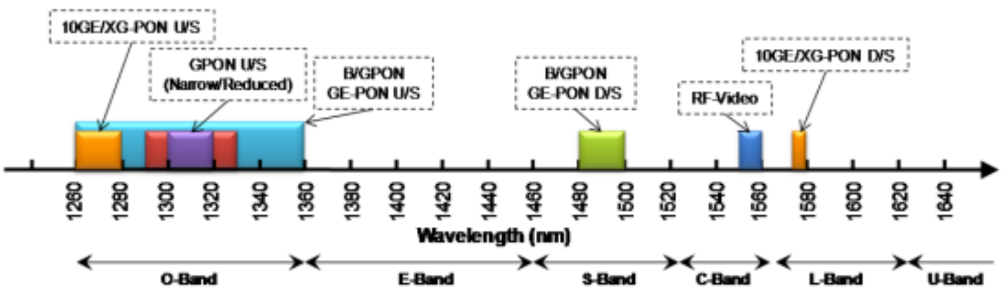

Figure 2.26 - Wavelength plan of legacy PON systems [10].

Considering the previous wavelength plan, C and L band are the most available wavelengths plan for NG-PON2.

2.4.4.4 Candidate Technologies

Immediately after XG-PON1 project was released for the ITU, FSAN began to work on at the beginning of NG-PON2 project, the principle requirements were a system with at least 40Gbit/s of capacity and 40km of reach at a 64-way split. The compatibility with implemented ODN technology or even previous PON systems were not a requirement. Therefore, based on these requirements, several systems were proposed such as "Time Division Multiplexed PON" (TDM-PON), "Time and Wavelength Division Multiplexing PON" (TWDM-PON), "Wavelength Division Multiplexed-PON" (WDM-PON) and "Orthogonal Frequency Division Multiplexed PON" (OFDM-PON), "Optical Code Division Multiplexing PON" (OCDM-PON) and "Ultra Dense Wavelength Division Multiplexing PON" (UDWDM-PON). The table 2.11 all the referred candidate technologies are briefly explained

Candidate PON Technologies	Characteristics and advantages
TDM	It has 40 Gbit/s of capacity, which comparing to XG-PON1, increases the single carrier serial downstream bit rate from 10 Gbit/s to 40 Gbit/s, while the upstream it supports 10 Gbit/s serial TDMA bit rate (see chapter 2.2) [11].
TWDM	It stacks multiple XG-PON1 flows, using WDM technology. Basically, this technology aggregates four pairs of wavelengths, each one with 10 Gbit/s of capacity, thus providing 40 Gbit/s for downstream direction. The upstream direction also works the same way, but with 2.5 Gbit/s each channel, thus providing a capacity of 10 Gbit/s [11].
WDM	It multiplexes several optical signals in one SMF, carried with a different wavelength. Each channel with a specific wavelength have a capacity of 1Gbit/s. (see chapter 2.2) [11].
OFDM	It applies quadrature amplitude modulation (QAM). A single transmission turns into multiple signals with lower spectral occupancy. Each one is spaced of the others in a way they can only overlap zeros of the other signals, thus avoiding inter-symbolic interference. To generate multiple digital OFDM signals from one signal, Fast Fourier Transform (FTT) arises several data blocks to be coded. It offers 40 Gbit/s to the upstream and downstream bit rates. Its great advantage relies on the operation cost [11] [37].
OCDM	It identifies all ONUs through a code word, represented by a specific pulses sequence in the optical domain. Therefore, it possible to take advantage from the available band frequency, where the subscribers can transmit all simultaneously with a lower latency and without any complex electrical components. Thus, it is able to transmit asynchronously. Its great advantage is security around the network and its content; also the equipment has a lower cost. Higher the number of users, higher will be the channels interference, demanding components to operate in higher rates – it deteriorates the signal, limiting the system performance [36].
UDWDM	It consists in a wavelength splitting and this allows the distribuition/sharing of a single downstream wavelength at 1Gbit/s for several ONU. The OLT dispose of one thousand individual wavelengths with 2.8GHz of channel spacing. It is capable to offer the necessary bandwidth for the next years, and allows the coexistence with legacy PON [38].

Table 2.11 - Candidate Technologies for NG-PON2 project.

Given the diversity of the proposals, FSAN operators reconsidered their true aims for NG-PON2 project. The ability to operate on existing fiber ODN was the first requirement to be fixed followed by compatibility with video overlay and with XG-PON1 system [11].

The FSAN group analyzed each of these system proposals, comparing functional complexity, achievable and loss budget, power consumption, technological challenges and components maturity. The requirement updates had a huge impact on the system selection. Some systems were discard due to the ODN compatibility and timeframe requirements. In April 1012, TWDM-PON was the selected solution for NG-PON2 project [11].

3 TWDM-PON

Operators are using GPON technology to extend fiber access to consumers. As it was referred before, GPON will satisfy the bandwidth needs of residential consumers for years to come. However, to obtain the most from their fiber network, operators have to go beyond the capabilities of GPON and develop strategies to monetize and maximize their fiber infrastructure investments. They want to have one flexible network that can support many revenue-generating services, providing efficient use of existing assets and decreasing the cost involves in deploying ultra-band on a large scale.

TWDM technology focuses on all aspects of this aim. It is a technology already standardized by the FSAN group and ITU. And according to its characteristics, TWDM can offer an efficient upgraded path to provide current PONs evolution. It can supply, manage and evolve to the best-fitting bandwidth for different services, for example, considering high-bandwidth symmetrical for business services or mobile backhaul will require sustained and symmetric 1 Gbit/s data rates, while residential consumers may be led bandwidth demanding, requiring the available pick bandwidths for durations only [2].

It is a hybrid system that combines time and wavelength. WDM technology has a fundamental role; it provides the aggregation of multiple XG-PON1 flows, through four pairs of wavelengths. Each of them provides a capacity of 10 Gbit/s, thus considering the whole four multiplexed channels is disposed 40 Gbit/s. Regarding upstream direction, it also works with four multiplexed wavelengths, offering 10 Gbit/s rate [11] [10].

3.1 Architecture

Figure 3.1 presents the architecture of TWDM-PON. In the diagram, there are four XG-PON1 stacked through four pairs of wavelengths. The channel spacing corresponds to 100 GHz. Options to the baseline architecture include more pairs of wavelength, such as eight and sixteen wavelength channels and different rates. The standard split ratio is 1:64.

Regarding to the OLT side, there is a WDM mux and a WDM demux, the first one serves to multiplex the XG-PON flows into the transmission fiber, and the second one demultiplexes each wavelength coming from the ONUs. Each upstream channel, apart supporting 2.5 Gbit/s rate, according to the standard, it also bear-out 10 Gbit/s. WDM technology is implemented through an AWG. Even at the OLT side, after the WDM mux (and before the WDM demux), it was added an optical amplifier to the system. Its aim is to achieve a higher power budget than XG-PON1. It boosts the downstream signals and pre-amplify the upstream signals as well.

Each ONU is equipped tunable receivers and transmitters. The transmitters are tunable to any of the upstream wavelengths and the receivers to any of the downstream wavelengths. In figure 3.1 is presented TWDM-PON architecture.

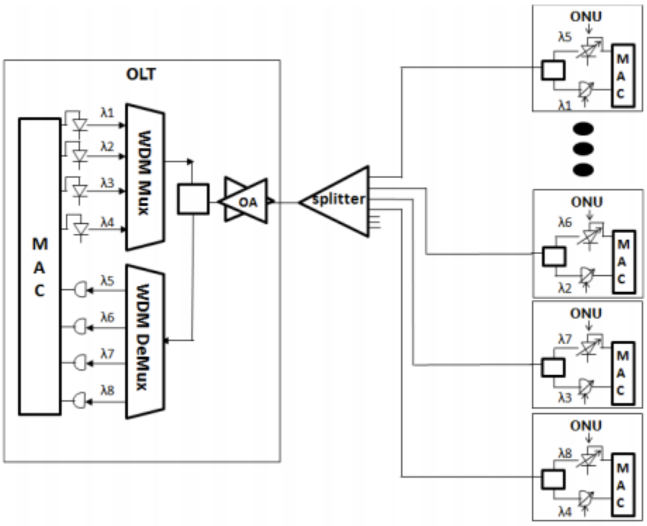

Figure 3.1 - TWDM-PON architecture [41].

The ODN remains passive, since the optical amplifier is placed at the OLT side. In figure 3.1 the TWDM-PON system represented does not use an AWG to select the optical signals to each port. Instead, it just uses a splitter to distribute the signal, and in each ONU there is a device that selects the optical signal, which intends to it.

3.2 Key Applications

Comparing TWDM and XG-PON technologies, the first delivers higher rates in both directions. The multiple wavelength feature of TWDM-PON could be applied for other applications.

TWDM could be developed beginning with a single wavelength pair, and then it could be upgraded by adding new wavelengths, thus increasing the system capacity. This would be considering as a pay-as-you-grow provisioning, therefore the operators can assign the bandwidth growth demand by investing for what is needed.

Other application is for local loop unbundling (LLU). Each operator would have their own OLT, containing a set of several wavelength channels. Then a wavelength selective device such a filter-base demultiplexer, would aggregate the OLT ports into a single fiber. This scheme provides the sharing of the infrastructure for several OLTs, remaining the possibility of each OLT belongs to an operator, or every operator's OLT being the same, thus possessing all the available wavelengths [39]. It is presented in figure 3.2.

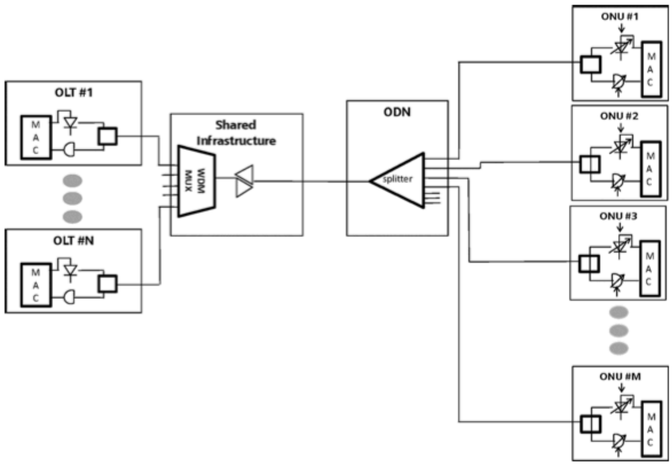

Figure 3.2 - TWDM-PON with multiples OLTs. [41]

3.3 Key Technologies

Most of the TWDM-PON components are commercially available in access networks today. As compared to previous generations of PONs, the main difference remains on the tunable receivers and tunable transmitters at each ONU.

The **TWDM-PON receiver** has to tune any downstream wavelength by following the OLT commands. There are several candidate technologies to be implemented such as:

- Thermally tuned Fabry–Perot (FP) filter
- Angle-tuned FP filter
- Injection-tuned silicon ring resonator
- Liquid crystal tunable filter
- Thermally tunable FP detector [41].

The **TWDM-PON transmitter** can also tune its wavelength to any of the upstream wavelengths. The candidate technologies are:

- The distributed feedback (DFB)
- Laser with temperature control (TC)
- DFB laser with partial TC
- Multi-section distributed Bragg reflector laser (electrical control) without cooling
- External cavity laser (ECL) with mechanical control without cooling
- ECL with thermo/electro/piezo/magneto-optic control without cooling [41].

The fact of TWDM-PON being essentially based on XG-PON1 technology takes advantage of all the development that has been made since G.987.x recommendations.

Therefore for the beginning, TWDM-PON tunable transceivers reuse the mature tunable optical transport network components, however if one technology does not work as it was expected, it will be necessary to turn to other options.

TWDM-PON technology does not strictly require specifications for tunable optical transmission components. Because the performance adjustment of TWDM-PON wavelength can be relaxed from the optical transport network, and the channel rates are far used, critical tuning requirements such as wavelength tuning range and channel spacing are quite relieved. This leads to some enhancements over components fabrication and cost reduction [11].

3.4 Supporting the legacy ODN

The total costs for FTTH deployment are directly related with the infrastructure investments. The majority of the implemented networks already use specific power splitter based in GPON ODNs. Some ODNs use connectors widely, for instance with as many as nine connectors between the OLT and the ONU.

Therefore, NG-PON2 systems must be able to support the arising reflections and connector loss. The network infrastructure lifetime is a matter that has to be taken into consideration, once it has 20 years it has to be improved to be reused.

NG-PON2 systems must be able to accommodate flexibility in order to, step by step, providing the split ratio increasing, either if the splitting technology is use is power or wavelength splitting or even the combination of both. To provide an independent distribution network, a non-wavelength selective ODN can be the option. Defining wavelength windows through introducing filters within the ODN will limit the ODN flexibility and may also increase its planning complexity [11].

3.5 Features

Bit rate

TWDM system mixes multiple XG-PON1 flows with a specific wavelength each. Table 3.1 presents the three bit rate options for each wavelength channel, considering upstream and downstream directions.

Bit rate for Downstream direction (Gbit/s)	Bit Rate for Upstream direction (Gbit/s)
10	2.5
10	10
2.5	2.5

Table 3.1 - Bit rate configurations of NG-PON2 [10].

This system requires flexibility to balance the speed, distance and split ratios for several applications. Table 3.2 presents a set of parameter combinations that the system must include.

Combinations Possibilities	DS capacity (Gbit/s)	US capacity (Gbit/s)	Range (km)	Split ratio	Capacity per channel (Gbit/s)	US peak rate (Gbit/s)	DS peak rate (Gbit/s)
C1	-	40	20	1:64	-	-	-
C2	10	-	20	1:64	-	-	-
C3	40	-	20	1:64	10	-	-
C4	-	-	40	1:32	2.5	-	-
C5	-	-	40	1:32	10	-	-
C6	-	-	-	-	-	2.5	10
C7	-	-	-	-	-	10	10

Table 3.2 - Set of parameter combinations [10].

NG-PON2 systems may also support an access to peak rates of 10/10 Gbit/s for downstream and upstream directions and a tunable point-to-point WDM with the capability to co-exist with other legacy PON [10].

Power Budget

Power budget is the allocation of available optical power launched into the considered network, among several loss-producing mechanisms such as splitting loss, fiber attenuation, connectors losses, in order to ensure that the optical signal at the receiver assumes an acceptable power. Therefore power budget requirement directly impacts optical component selection.

The introduction of optical amplifiers at the OLT side is directly related with the fact of achieving a higher power budget [39]. However, the transmitting power should not be too high because it can produce nonlinearity effects. The ODN must remains passive; therefore the given optical amplifier cannot be placed in the transmission link between the OLT and ONU.

In order to improve the power budget parameter, the signal has to have a higher sensitivity and that can be achieved applying pre-amplification at the receiver and using high sensitive receivers, such as Avalanche Photodiode (APD).

Wavelength Plan

As mentioned before, coexistence with previous PON generations in the legacy ODN is one of TWDM-PON main goals. It does not define any specific requirement of the wavelength allocation. One factor that may influence the wavelength plan choice is the space defined between each channel. It can be 50 GHz, 100 GHz and 200 GHz. It sort compromises the design complexity and components to the cost efficiency.

Therefore, some proposals were already defined. Between them, there is the first option, which consists in the reuse of XG-PON wavelength bands. This wavelength plan takes advantage of the developed work of XG-PON technology. It defines a finer grid inside from the previously defined bands in NG-PON1 study. It is compatible with G-PON and the 1555 nm radio frequency video overlay channel, but discards standardized XG-PON. The loss budget obtained is similar to that of XG-PON, assuming a value of 33 dB. It is difficult to achieve a 40 km reach, once it used the higher loss 1270 nm. In figure 3.3 is presented the wavelength plan described [11] [41].

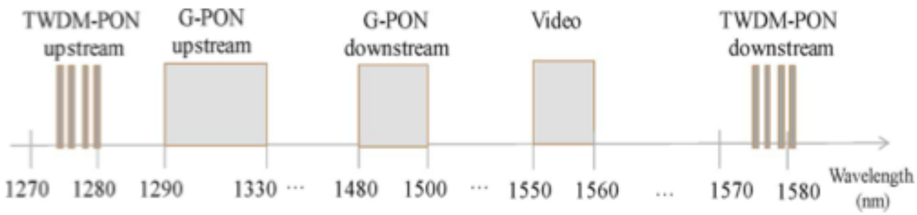

Figure 3.3 - XG-PON wavelength reuse [41].

The second option is the redefinition of an improved C-band, which contains both upstream and downstream wavelengths. Erbium-doped Fiber Amplifiers (EDFAs) fit perfectly on this wavelength plan, providing signal amplification and reducing transmission fiber loss. Such system also has a higher power budget and a longer reach, however RF video overlay channel is blocked. With EDFAs, this wavelength plan could achieve a loss budget around 38dB [11] [41]. Figure 3.4 presents the considered option.

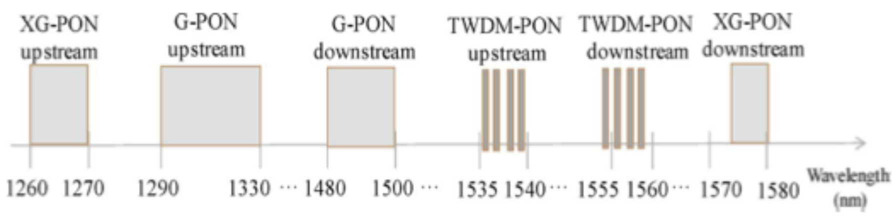

Figure 3.4 - C-band wavelength plan. [41]

The third option is a mixture of the described plans. The downstream channels would be design in L-band and the upstream channels are defined in C-band. It allows the coexistence with GPON and RF video channels. Relatively to the upstream plan, it is not only compatible with GPON, as the second plan, but also compatible with XG-PON system. It is expected to coexist with RF video overlay as well. Still considering the upstream transmission, C-band components could work with EDFA preamplifier, providing a higher power budget. Still a L-band amplifier is needed to offer a better improvement of the power budget. The loss budget of this option is about 38 dB, as the previous plan [11] [41]. Below, in figure 3.5 is presented the current wavelength plan.

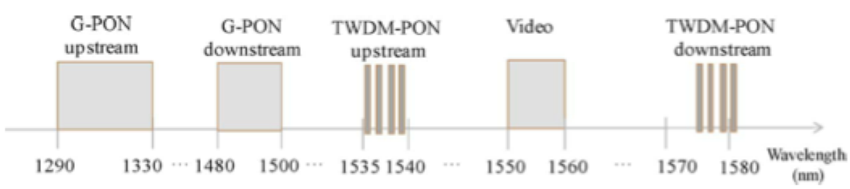

Figure 3.5 - C-band/L-band wavelength plan. [41]

The wavelength plan selection is still in study by the FSAN group and ITU. Once has not been defined any requirements for TWDM wavelength, operators can define plans according to their needs. The third option is considered the most favorable, having in advantage of the implementation of some devices, which perfectly fit on the selected wavelength plan.

4 LABORATORY RESULTS

4.1 Introduction

In the present chapter are presented the experiments performed in the laboratory.
It was only considered the upstream direction of TWDM-POM. Once the upstream packets transmissions operate in burst mode, the aim of the first experience is to test the efficiency of the transmitted burst packets, varying its size, separation length and bit rate. In the second part it was added an EDFA at the transmitter side (mapping the ONU side). The aim is to observe the impact caused in the performance of the upstream transmission.

4.2 Upstream Transmission

The duration of an upstream PHY frame defined in the standard is 125 μs, which at the upstream rate is 2.48832Gbit/s, corresponding to the size of 38880 bytes. Each ONU transmits a series of physical bursts and remains idle in between the bursts. Therefore, an upstream PHY frame is composed of several variable-size bursts.

As referred before, the upstream PHY burst is composed of an upstream physical synchronization block (PSBu) and a PHY burst payload. The aim of this study is to increase the size of payload, thus allowing the transmission of more data in one burst. It was also analyzed the performance of the system by varying the guard time between each burst.

Assumed Conditions

- The bit pattern created to fill both the payload and the PSBu section is composed by random sequences drawn from a uniform distribution.
- The bit rate for upstream direction TWDM-PON was 2.5 and 10Gbit/s.
- Each burst transmission packet is separated with an idle field – guard time.
- The guard time will also be varied.
- Payload size is variable between 50μs and 100μs.
- When the transmitted bit is “1” and the received one is “0”, or vice versa, a bit error is detected.
- The whole considered traffic comes from one ONU. Thus, it is only considered one wavelength.

4.2.1 Experimental Setup

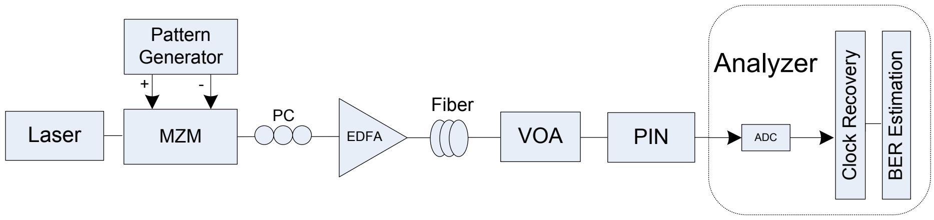

Figure 4.1 - Experimental Setup.

The experimental setup is presented in the figure 4.1. A tunable laser source (TLS) is used as optical source at 1550.116 nm. An external Dual Driver Mach-Zehnder Modulator (MZM) is then driven by a Pattern Generator (PPG) with an analog bandwidth of 20 GHz emulating the burst-mode upstream NRZ signal. A RF amplifier amplifies the electrical signal, therefore its defined amplitude in the PPG is 800mV. Then, a Polarization Controller (PC) is used to maximize the power of the signal for the X polarization and an Erbium Doped Fiber Amplifiers (EDFA) sets the appropriate feeder optical power.

The optical signal is transmitted over 20 or 40 km of a Standard Single-Mode Fiber (SSMF) with the following parameters: α=0.2 dB/km, D=16.5ps/nm/km, γ=80 μm^2. At the receiver side, a Variable Optical Attenuator (VOA) set the appropriate received power. The NRZ channel is then detected using a PIN PP-10G with an analog bandwidth of approximately 10 GHz. The electrical signal is then sampled by a 50Gsa/s real-time oscilloscope with analog bandwidth around 20 GHz (Tektronix DP072004B) and offline digital signal processing (DSP) is used to analyze the quality of the received signal. In the DSP side, clock recovery and synchronization algorithms are used in order to perform the BER measurements. The setup was tested for bit rates of 2.5Gbit/s and for 10Gbit/s. According to the TWDM-PON standard, the upstream wavelengths must belong to C-band; therefore the operating wavelength chosen is 1550.116 nm.

Once considered the upstream direction, PHY frames had to be create. The following six sequences presented in table 4.1 were defined, as:

Sequence	Guard time		Burst (PSBu + burst payload) [μs]
	For 2.5Gbit/s [s]	For 10Gbit/s [s]	
Red	25.6n	6.4n	50
Blue	25.6n	6.4n	100
Green	1μ	1μ	100
Magenta	12.8n	3.2n	100

(Note: To clarify the analysis, was attributed a name to each sequence that corresponds to the color, which represents them in the graphics.)

Table 4.1 – Guard time and Burst definition.

10 Gbit/s PIN Pre-amplified Receiver and decision

In Figure 4.2, is presented the PIN receiver schematic. It does not have any DC block inside, which is a required element for the receiver, in order to optimize the threshold bit decision of the network at the OLT side [13]. For instance, considering a system with multiples ONUs, at the OLT side the power of each received packet (corresponding to each ONU) can have different amplitude for the level '1' of the NRZ signal. This constitutes a problem for the threshold bit decision and one way to mitigate is to use a DC block. However, in the experimental setup of the current study this will not happen, since it is only used one modulator.

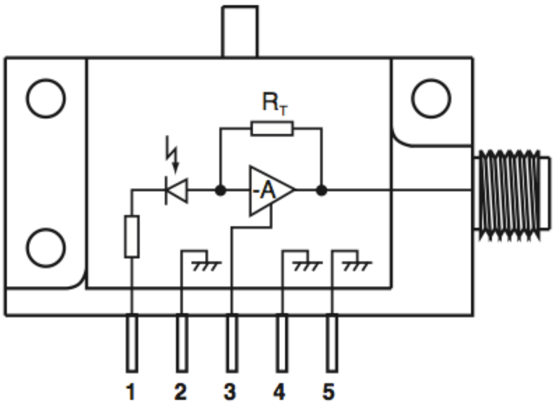

Figure 4.2 – PP-10G schematic. [39]

Beyond the benefit of the threshold optimization, DC block can cause problems for higher guard times. Once the guard is normally a long sequence of zeros, the DC block will cut this low frequency component of the signal.

4.2.2 Results capture

The capture of the results was performed through software developed in *Matlab*, called *Optical Coherent Receiver* (OCR) analyzer. Despite the name, it also works for direct detection using amplitude shift keying (ASK) modulation format, if we consider only the amplitude information of the signal (setting the quadrature component with zeros).

First of all, it has to be connected to the Real-Time Oscilloscope, which has four channels, but only one channel was used to capture the amplitude information of the received signal. The sample rate used was of 12.5 and 50Gsa/s for 2.5 and 10 Gb/s, respectively. Since this is a digital device, clock recovery was used in the digital signal processing (DSP) subsystems in order to find the ideal sampling instant. Bit error rate (BER) metric was used to evaluate the system performance using bit-by-bit comparison. Each estimated measure considers 25x25000 NRZ bits of resolution averaged over 25 independents windows. For BER synchronization, a correlation between the transmitted and the received data is performed in digital domain. The guard band is removed from the estimation. In a real-time system scenario, the synchronization is performed using a correlation the guard band.

BER corresponds to the number of bit errors divided by the total number of transmitted bits over a communication channel that has been altered due to noise, interference distortion, etc.

4.2.3 Setup without EDFA

System Sensitivity

Primarily, were studied the system sensitivities for back-to-back, 20 km and 40 km distances. The laser emits a power of 10.5dBm, following a polarization controller, which causes a loss of 1dB. In the modulator the optical signal looses approximately 5dB. Also considering the losses caused by the connectors, in the end, the transmitted power into the fiber was approximately 3dBm.

Figure 4.3 presents the sensibility for each considered sequence of bursts for a bit rate of 2.5Gbit/s.

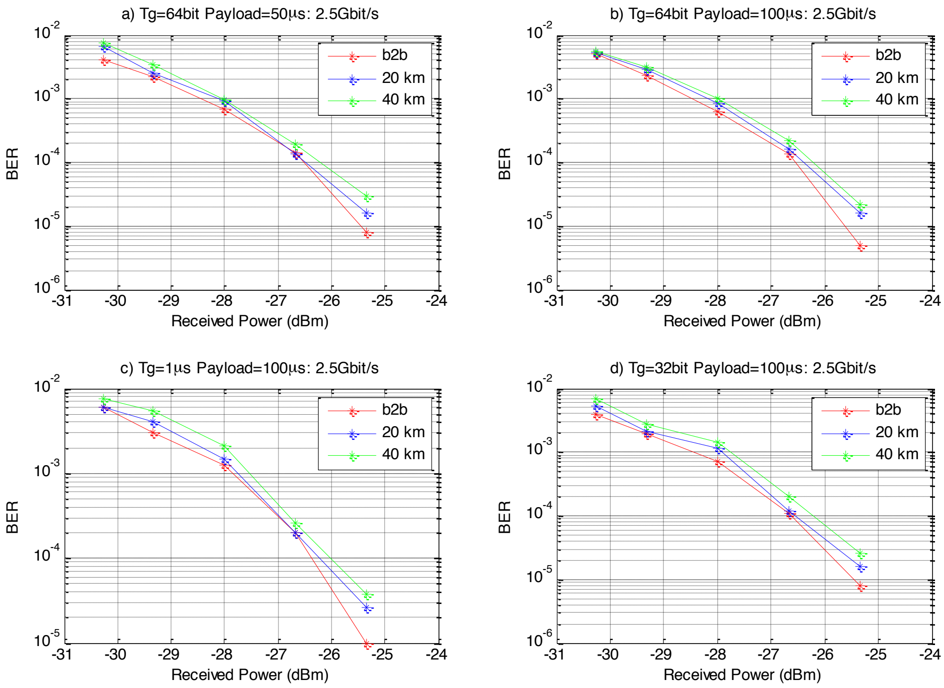

Figure 4.3 - System sensibility for each burst sequences at 2.5Gbit/s.

As the figure 4.3 present for all cases, the BER increases for higher fiber distances. For the burst sequences with 25.6ns of guard time and payload of 50 and 100μs, the minimum acceptable power to obtain the BER limit of 10^{-3}, considering all the fiber distances, is around -28dBm of received power. Regarding the third sequence, 1μs and 100μs of guard time and burst length, respectively, to get the minimum acceptable power, the received power increased around -27.8dBm. Finally, the last one (12.8ns of guard time and with a burst length of 100μs) assumes a lower value of minimum acceptable power than the previous, however still higher than the two first sequences.

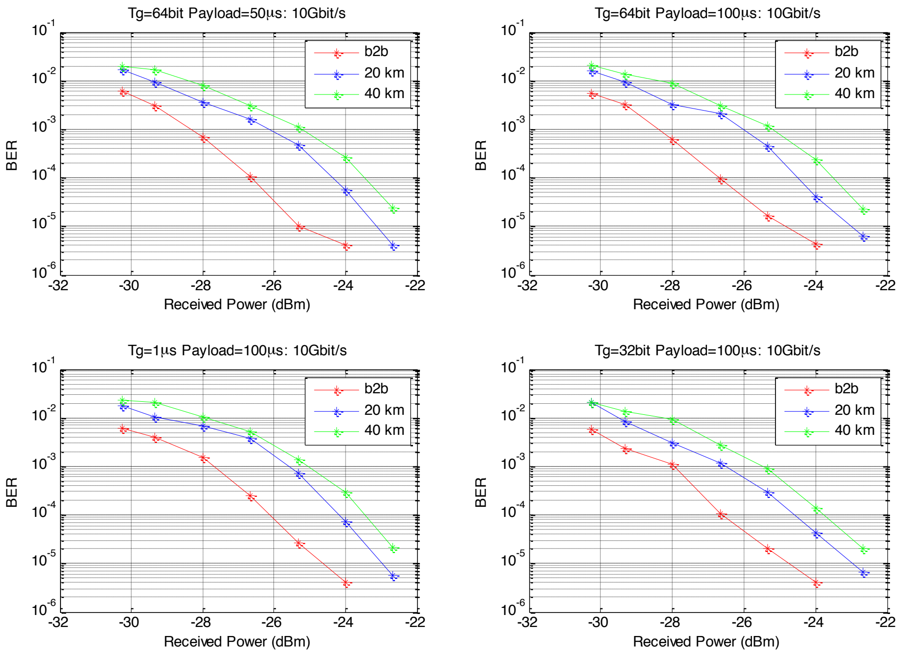

Figure 4.4 - System sensibility for each burst sequences at 10Gbit/s.

Also in these cases, as the distance gets higher, the BER increases, as well. However, there is a clear difference between the BER for 2.5Gbit/s signal and the current one. For instance, considering when the received power is -26.66dBm, the obtained values of BER are, 3.2E-4, 1.632E-3 and 4.548E-3 for back-to-back, 20 km and 40 km of fiber, respectively. This is due to chromatic dispersion linear effect, which becomes quite relevant in the performance of the system when the bit rate is increased, especially for higher distances of fiber.

4.2.3.1 Sequences comparison

In this section, the generated burst sequences are compared considering their sensibility and efficiency.

Once the guard time and payload are defined through time intervals, every time the signal bit rate changes, their lengths change as well. Table 4.2 presents the guard and payload lengths for 2.5Gbit/s.

Colour	Guard Time (s)	Burst (μs)
Red	25.6n (64-bit)	50 (125000-bit)
Blue	25.6n (64-bit)	100 (250000-bit)
Green	1μ (2500-bit)	100 (250000-bit)
Magenta	12.8n (32-bit)	100 (250000-bit)

Table 4.2 - Guard Time and Burst lengths for 2.5Gbit/s.

4.2.3.1.1 2.5Gbit/s scenario

The following figures 4.5a) and 4.5b) present the actual time domain burst sequences captured through the real-time oscilloscope, for back-to-back scenarios with a sensitivity of -14.63dBm. The bursts sequence presented in the following figures have a 25.6ns (64-bit) guard time and the burst has 50ns (125000-bit). Through the image observation it is possible to identify the guard region between the two bursts.

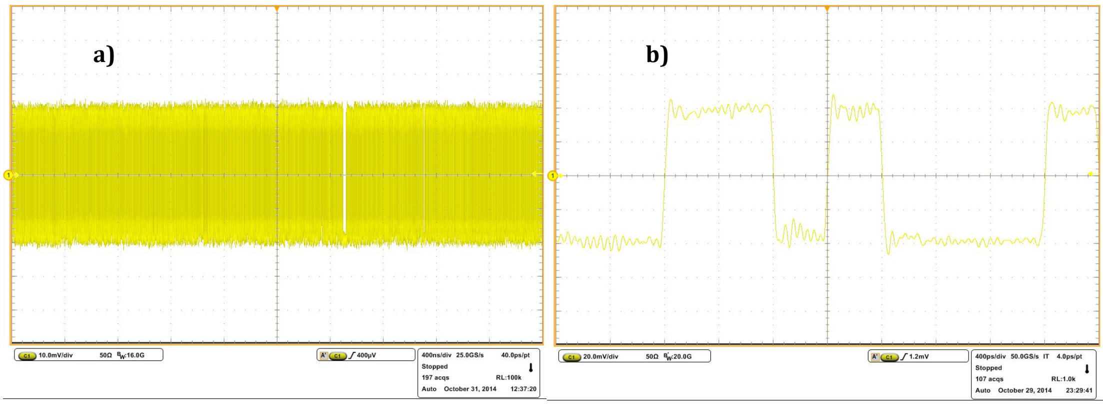

*Figure 4.5 - Burst sequence Tg = 25.6ns and Burst length = 50µs, for 2.5Gbit/s and without EDFA. **a)** [time scale = 400 ns/div; amplitude scale = 10mV/div; sample rate = 25Gsa/s]; **b)** [time scale = 40 ps/div; amplitude scale = 20 mV/div; sample rate = 50Gsa/s].*

The following sequence fragment, presented in figure 4.6, was taken from the burst sequence that has the largest guard time (1µs) considered in the experiment. Therefore, by observing figure 4.6 a) is very clear the zeros separation between the two packets.

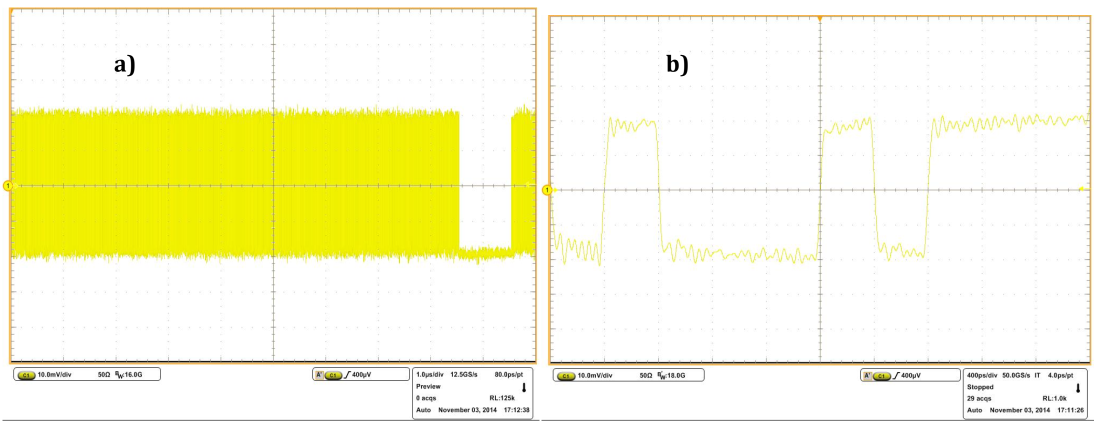

*Figure 4.6 - Burst sequence Tg = 1µs and Burst length = 100µs, for 2.5Gbit/s and without EDFA. **a)** [time scale = 1 µs/div; amplitude scale = 10mV/div; sample rate = 12.5Gsa/s]; **b)** [time scale = 400ps/div; amplitude scale = 20 mV/div; sample rate = 50Gsa/s].*

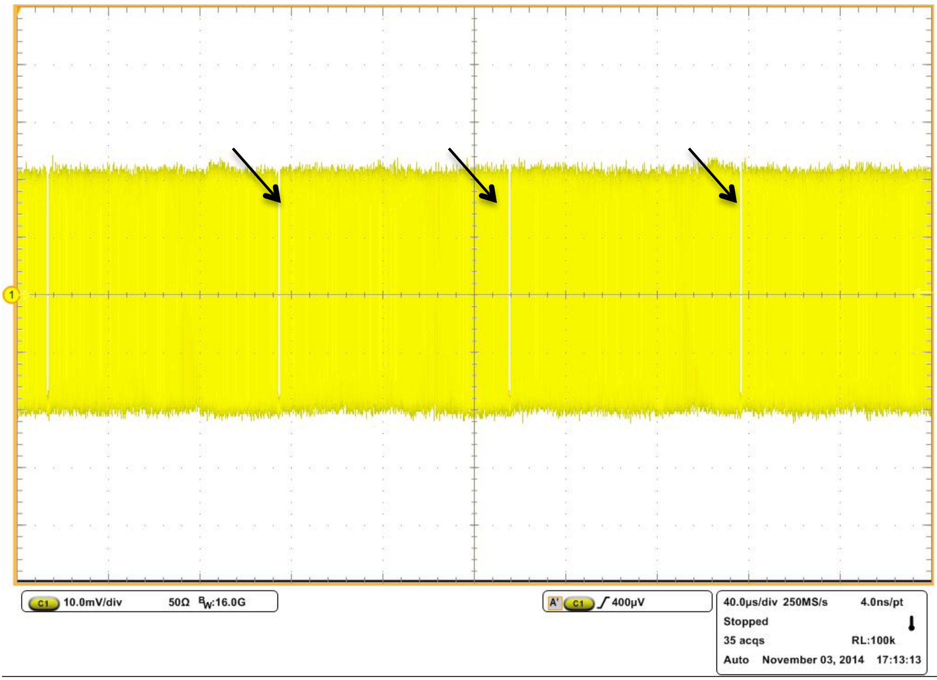

Figure 4.7 - Burst sequence Tg = 1μs and Burst length = 100μs, for 2.5Gbit/s and without EDFA [time scale = 40 μs/div; amplitude scale = 10mV/div; sample rate = 250 Msa/s].

The guard time is enough large to provide the visualization of each packet by increasing the time scale, as figure 4.7 presents. Each arrow indicates the guard regions.

The following figures 4.8 a) and 4.8 b) correspond to the burst sequence that has 12.8 ns of guard time and a burst length of 100 μs. Once the separation of zeros is much smaller than the burst itself, it is impossible to differentiate the packets separation at the considered time-scale, as it is presented in figure 4.8 a).

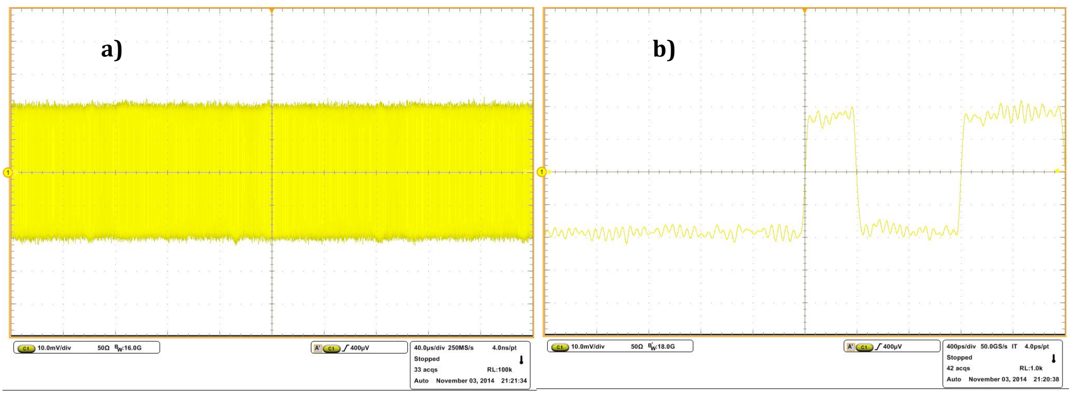

Figure 4.8 - Burst sequence Tg = 12.8ns and Burst length = 100μs, for 2.5Gbit/s and without EDFA. ***a)*** *[time scale = 40 μs/div; amplitude scale = 10mV/div; sample rate = 250 Msa/s];* ***b)*** *[time scale = 400ps/div; amplitude scale = 10mV/div; sample rate = 50Gsa/s]*

Figure 4.9 presents the receiver performance for **back-to-back** scenario and 2.5Gbit/s. To analyze each sequence results, the legend of each figure indicates the bursts sequence correspondent to each graphic. For instance, considering the red line, its legend is “64bit+50μs”, the 64-bit correspond to guard length in bits (25.6ns) and 50 μs is the burst length in time domain (see table 4.2). This applies for all cases of sequences comparison.

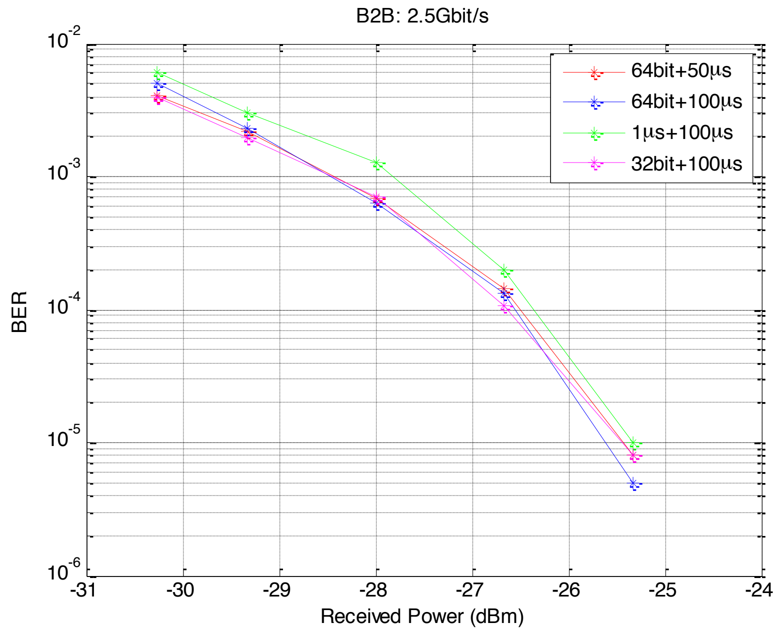

Figure 4.9 - All bursts sequences for back-to-back scenario at 2.5Gbit/s and without EDFA.

The burst sequence with 1μs of guard time presents the worse values. However, the remaining sequences assume a similar behavior. Both red and blue sequences behave practically the same, and yet they have different payload sizes. Regarding the magenta sequence, it shares the same payload size as the blue one; it only differs on the guard time size, which is 32 bits. And one more time, it assumes a similar behavior as the red and blue sequences. Therefore, while the guard time assumes relatively small lengths such as 32 or 64 bits, the system behaves as the red, blue and magenta sequences, achieving the receiver sensitivity around -28.5dBm. However, if increasing it until a considerable length, such as 1μs, which in 2.5 Gbit/s correspond to 2500 bits, it starts presenting some penalty. For the case of the green line, the minimum acceptable power is about -27.8dBm.

In the output of the PIN receiver was introduce a DC block in order to approximate the system to a real scenario. Once the DC block acts as a serial capacitor, behaving like a high pass filter, it cuts the low frequencies of the signal. This fact can justify the BER performance decay of the green line case, once it has a lower frequency in the guard region.

After adding a 20 and 40 km fiber into the system, the obtained sensitivity for each sequence is represented in the following figures.

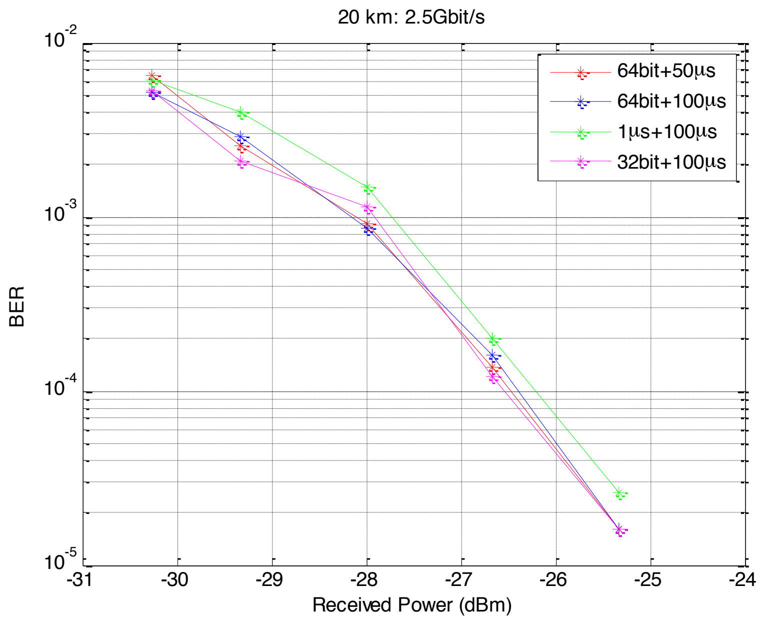

Figure 4.10 - All bursts sequences for 20 km fiber distance at 2.5Gbit/s and without EDFA.

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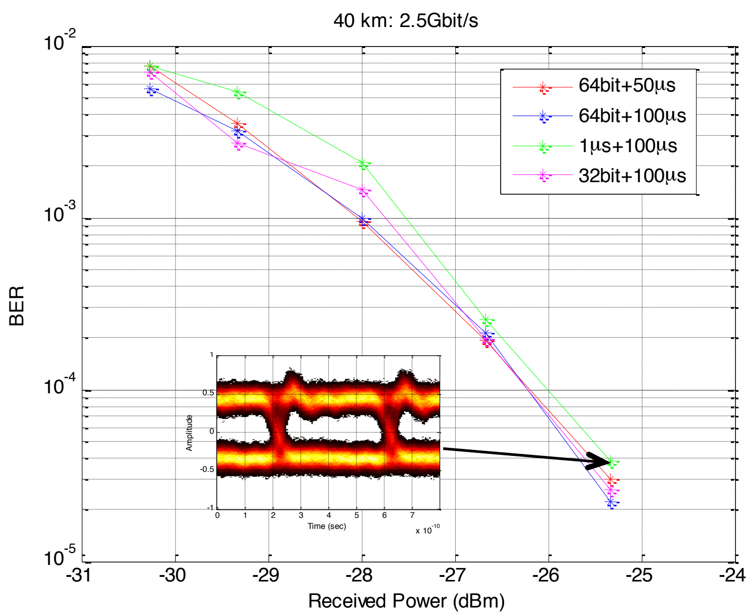


Figure 4.11 - All bursts sequences for 40 km fiber distance at 2.5Gbit/s and without EDFA.

Both figures present similar values of BER for the same received power, for 20 and 40 km fiber, respectively. Table 4.3 presents the values of BER for a sensitivity of -28 dBm, for bot 20 and 40 km distances.

Sequences	BER (20 km)	BER (40 km)
Tg=25.6ns; burst length=50μs	9.16E-4	9.6E-4
Tg=25.6ns; burst length=100μs	8.52E-4	1.0E-3
Tg=1μs; burst length=100μs	1.496E-3	2.08E-3
Tg=12.8ns; burst length=100μs	1.132E-3	1.456E-3

Table 4.3 - BER comparison between both distances.

In table 4.3, considering the estimated values for 20 and 40 km fiber, they are very close to each other, for all burst sequences. Although, the burst sequence with 1μs of guard time has the worst performance, its differences are not accentuated; actually the values of the green signal are close to the others. Regarding the remaining sequences, they assume a similar behavior. Comparing with back-to-back scenario, the receiver sensitivity decreases. It happens because of the fiber penalty, essentially due to some residual dispersion. The average receiver sensitivity is around -28 and -27.5dBm for 20 and 40 km of fiber, respectively. Also in these cases the red and the blue sequences present a similar behavior, still with different burst sizes, but with the same guard time length. Regarding the magenta sequence, it shares the same burst length as the blue and the green lines, however it differs on the guard time, which is 12.8ns. And once more, it behaves similarly to the red and blue sequences. As it was concluded for the back-to-back scenario, the existing DC block in the PIN output cuts the signal for low frequencies, and it can be related with the lower performance of the green sequence.

4.2.3.1.2 10Gbit/s capacity

NG-PON2 standard (G.989.1 2013) also supports a capacity of 40Gbit/s for upstream direction, implying 10Gbit/s per channel. The current experience was tested for a capacity 10Gbit/s as well, to analyze the system performance. Varying the bit rate will also vary the guard time and the burst length. Table 4.4 presents the lengths of guard and burst for 10Gbit/s.

Sequence	Guard Time (s)	Burst(μs)
Red	6.4n	50
Blue	6.4n	100
Green	1μ	100
Magenta	3.2n	100

Table 4.4 - Guard time and payload lengths for 10 Gbit/s.

The following figures 4.12 a) and 4.12 b) present the burst fragments of each sequence, at different time scales. The figures correspond to back-to-back scenario with a received received power is -14.63dBm.

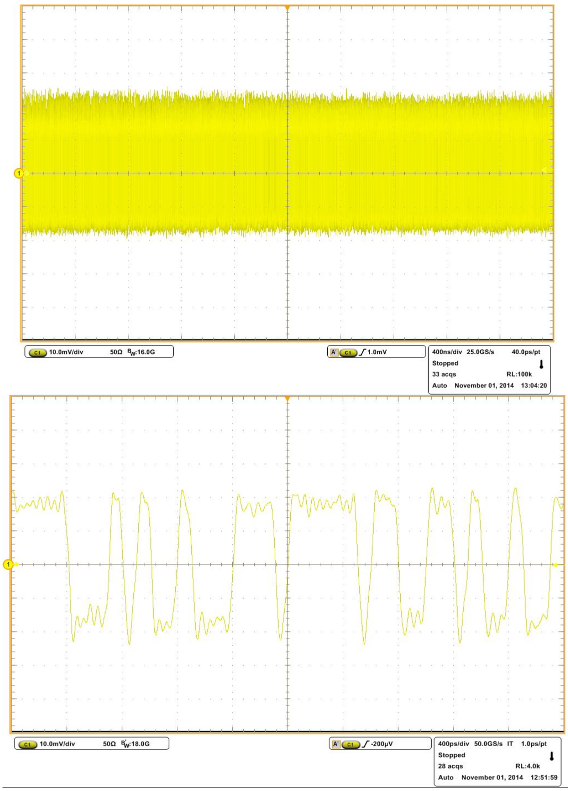


Figure 4.12 - Bursts sequence Tg = 6.4ns and Burst length = 50µs, for 10Gbit/s and without EDFA. ***a)*** *[time scale = 400 ns/div; amplitude scale = 10mV/div; sample rate = 25Gsa/s];* ***b)*** *[time scale = 400ps/div; amplitude scale = 10mV/div; sample rate = 50Gsa/s]*

It is impossible to visualize the guard time at the considered time scale. Once the bit rate has increased to 10Gbit/s, the burst length increased as well, however despite the variation of guard time, it always assumes a fixed number of bits (64 bits) for the current bursts sequence.

Figure 4.13 a) and b) were captured from the burst sequence that has the largest guard time (1μs). Therefore, through its figure the guard region between the two packets is very clear.

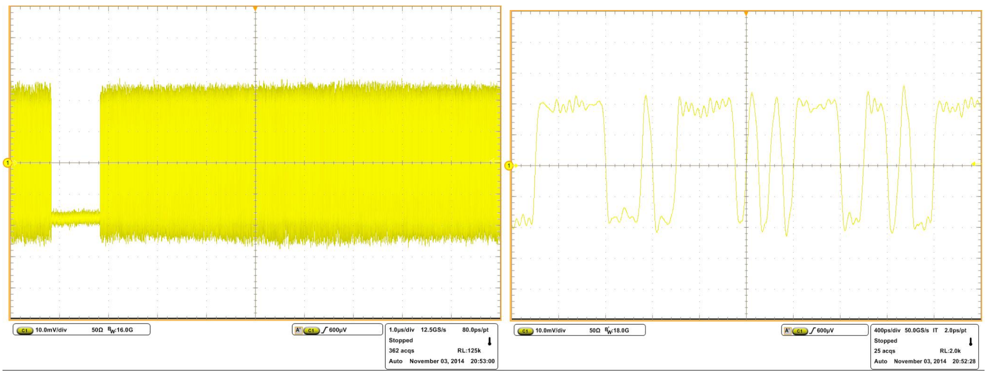


Figure 4.13 - Bursts sequence Tg = 1µs and Burst length = 100µs, for 10Gbit/s and without EDFA. ***a)*** *[time scale = 1µs/div; amplitude scale = 10mV/div; sample rate = 12.5 Gsa/s];* ***b)*** *[time scale = 400ps/div; amplitude scale = 10mV/div; sample rate = 5 Gsa/s]*

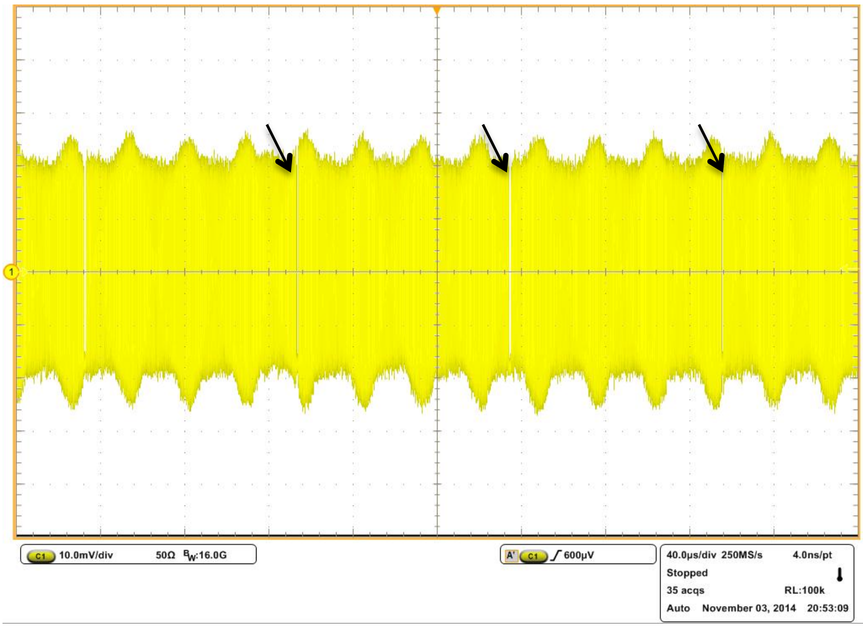


Figure 4.14 - Bursts sequence Tg = 1μs and Burst length = 100μs, for 10Gbit/s and without EDFA [time scale = 40 μs/div; amplitude scale = 10mV/div; sample rate = 250Msa/s].

Firstly, the amplitude fluctuations that appear in the signal of figure 4.14 are related with an oscilloscope representation error, due to Aliasing effect. This happens because the sample rate does not satisfy the Nyquist criteria, which says that an analog signal is correctly represented if the sample rate is higher than the double of the maximum frequency of signal. In this case, the 10GHz signal was sampled at 250Msa/s in the current representation. Also for figure 4.13a), although the sample rate is higher than the previously discussed one, it still does not respect the Nyquist criteria. The current signal was obtained through the analysis of the sequence with the largest guard time 1μs (10000-bit). Through figure 4.14 observation, the guard regions are easy recognizable and consequently the bursts as well.

The fragments of the remaining bursts sequences, both with 100μs of burst length and 6.4ns and 3.2ns of guard time, are not presented because, once their guard lengths are too small compared to the burst size, it is not possible to identify them in the captured fragments.

The following figures 4.15, 4.16 and 4.17 present the system sensitivity of each considered bursts sequence, for 10 Gbit/s. Each graphic is for **back-to-back, 20 and 40 km** scenarios.

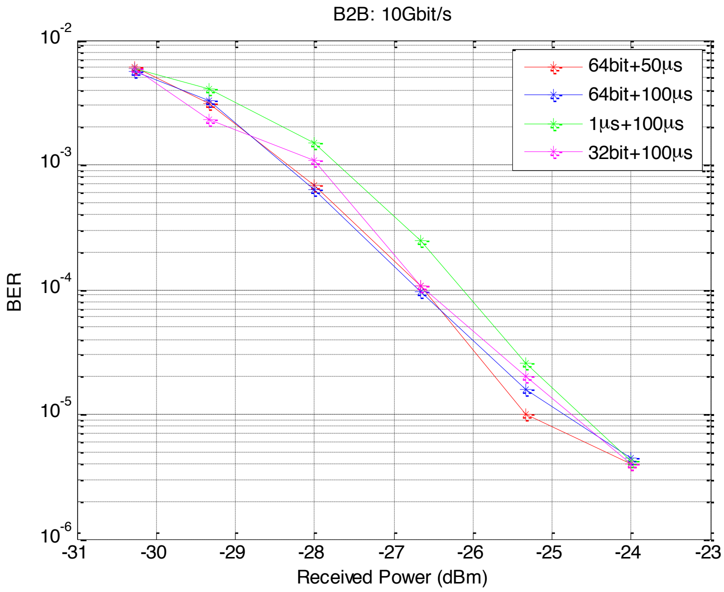


Figure 4.15 - All bursts sequences for back-to-back scenario at 10Gbit/s and without EDFA.

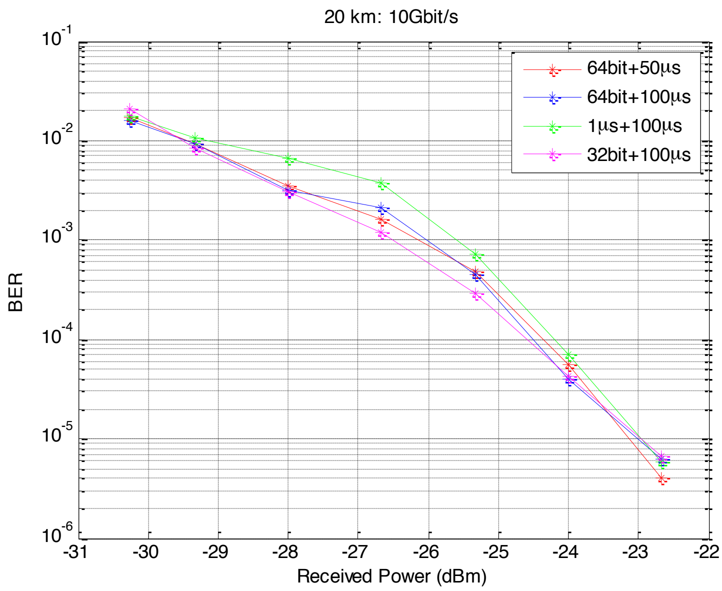


Figure 4.16 - All bursts sequences for 20 km fiber distance at 10Gbit/s and without EDFA.

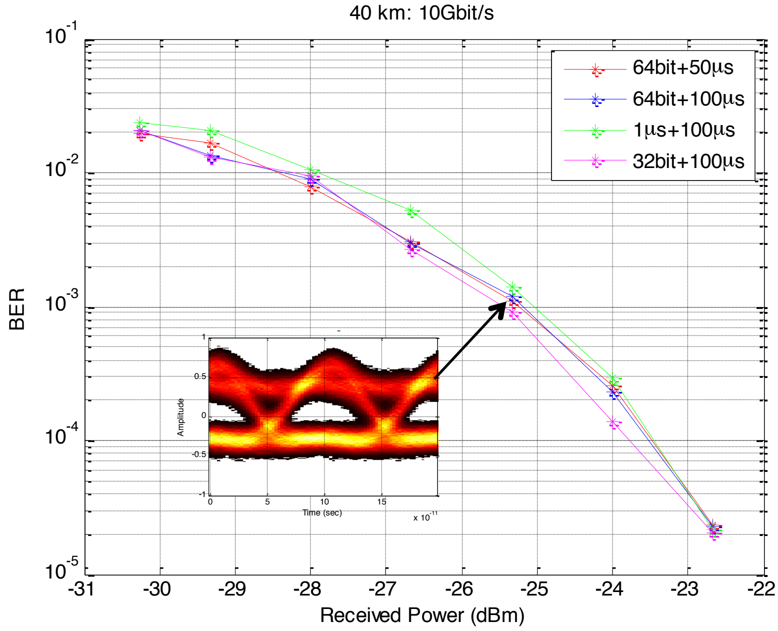


Figure 4.17 - All bursts sequences for 40 km fiber distance at 10Gbit/s and without EDFA.

Once again the conclusions to be drawn from the current scenario are the same as the obtained ones from 2.5Gbit/s scenario. However, comparing the receiver sensitivities of each sequence for 10Gbit/s and 2.5Gbit/s of capacity, it is noticeable that the ones obtained from the system with higher capacity have a worse performance.

Regarding table 4.5, it presents the differences between 2.5Gbit/s and 10Gbit/s systems, for 20 and 40 km fiber distance.

Sequences	20 km		40 km	
	2.5Gbit/s [dBm]	10Gbit/s [dBm]	2.5Gbit/s [dBm]	10Gbit/s [dBm]
Green	-27.00	-25.60	-27.50	-25.00
Blue	-28.10	-26.00	-28.00	-25.30
Red	-28.10	-26.10	-28.00	-25.30
Magenta	-27.9	-26.50	-27.80	-25.50

Table 4.5 - Average receiver sensitivities (BER = 10^{-3}) for 20 and 40 km.

As it is presented, for 10Gbit/s of capacity, the system presents a decrease in the average receiver sensitivity. For higher bit rates, the introduction of fiber in the system will cause chromatic dispersion. For the back-to-back case, there is almost no significant difference between 2.5Gbit/s and 10Gbit/s capacity. When the bit rate increases it also can degrade the system performance, because the equipment provides a better response to lower bandwidth systems. However in this case the equipment response is similar to both bit rates, this means the equipment is offering a good bandwidth response for 10Gbit/s, as well.

4.2.4 System with EDFA

The current topic is based on the analysis and characterization of the considered system with an EDFA. Once the amplifier is introduced in the system, it is expected to achieve better sensibilities, improving the system power budget.

System sensitivity

In the current topic, it was also studied the sensitivities for back-to-back, 20 and 40 km fiber. The selected pump current in the EDFA was 140 mA and the transmitted power was 10dBm. Figure 4.18 presents the sensibility for each bursts sequence for 2.5Gbit/s.

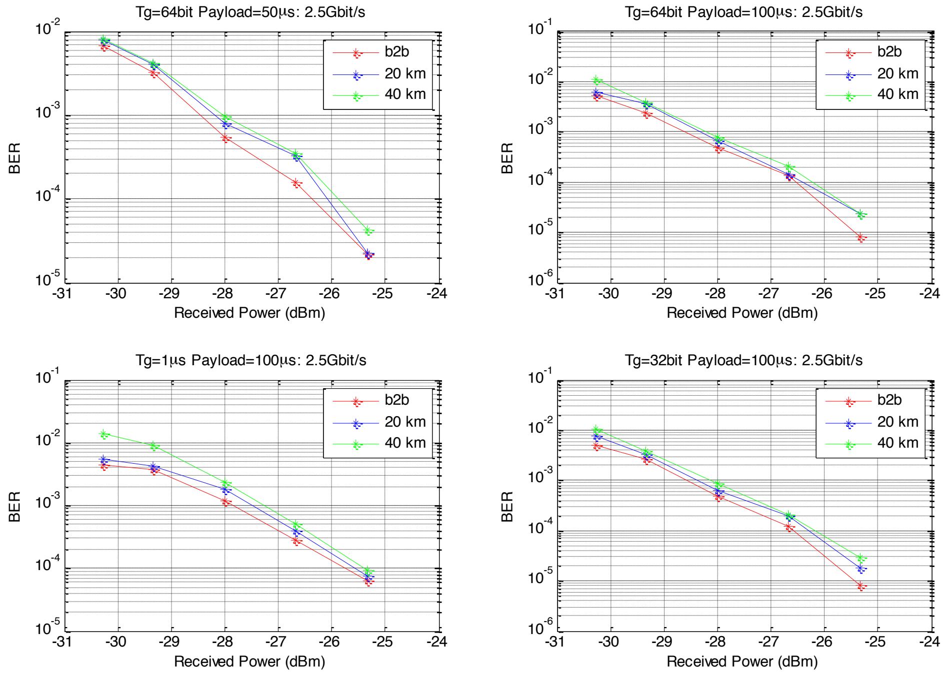


Figure 4.18 - System sensitivity for each bursts sequence at 2.5Gbit/s with EDFA.

The BER increases for higher fiber distances. Regarding the 2.5Gbit/s systems without and with EDFA there are no significant differences. Once the EDFA amplifies the transmitting power, it is expected that it will improve the power budget. Table 4.6 presents the average receiver sensitivity (BER = 10^{-3}) for 2.5Gbit/s capacity system with and without the EDFA.

Fiber distances	**Without EDFA [dBm]**				**With EDFA [dBm]**			
	Red	Blue	Green	Magenta	Red	Blue	Green	Magenta
B2B	-28.50	-28.50	-27.90	-28.50	-28.50	-28.60	-28.00	-28.60
20 km	-28.10	-28.10	-27.70	-28.00	-28.10	-28.30	-27.60	-28.30
40 km	-28.00	-28.00	-27.50	-27.80	-28.00	-28.20	-27.40	-28.00

Table 4.6 - Average receiver sensitivity (BER = 10^{-3}).

Including the EDFA system for 2.5Gbit/s, causes a smooth increase in the sensitivity results. Figure 4.19 presents the system sensitivity for 10Gbit/s of capacity.

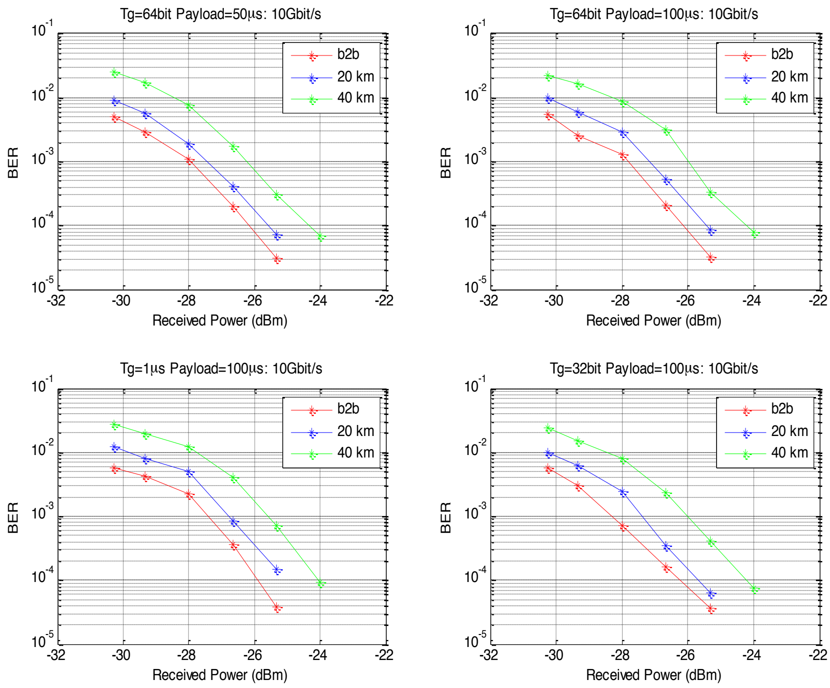


Figure 4.19 - System sensitivity for each bursts sequence at 10Gbit/s with EDFA.

Comparing the current case with the 2.5Gbit/s results with EDFA, there is a noticeable difference between each considered distance due to chromatic dispersion effect. For instance, considering the first burst sequence [guard time = 6.4ns and burst length = 50 μs] for 40 km case, the average receiver sensitivity (BER = 10^{-3}) is about -26.20dBm, while for 2.5Gbit/s, it achieves sensitivity around -28dBm. Table 4.7 presents a comparison between the average receiver sensitivities for both cases at 10Gbit/s – with and without EDFA.

Fiber distances	**Without EDFA [dBm]**				**With EDFA [dBm]**			
	Red	Blue	Green	Magenta	Red	Blue	Green	Magenta
B2B	-28.30	-28.50	-27.80	-28.00	-28.00	-27.90	-27.50	-28.40
20 km	-26.20	-26.20	-25.60	-25.60	-27.50	-27.20	-26.80	-27.40
40 km	-25.20	-25.30	-27.50	-25.20	-26.20	-26.00	-25.50	-26.00

Table 4.7 - Average receiver sensitivity (BER = 10^{-3}).

Through the explicit values, the conclusion is that including an EDFA in the system, the system performance remains similar. However, it provides an improvement in the power budget.

4.2.4.1 2.5 Gbit/s capacity

The following figures present the burst fragments of the bursts sequence with the higher separation zeros, at different time scales, for 2.5Gbit/s. The others were not considered in this section, because they are very similar to the previous sequences fragments presented.

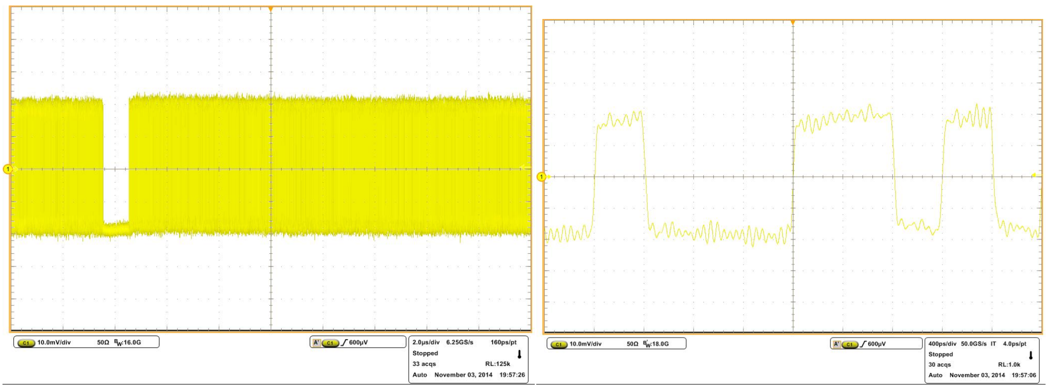


Figure 4.20 - Burst sequence Tg = 1µs and Burst length =100µs, for 2.5Gbit/s and with EDFA. ***a)*** *[time scale = 2 µs/div; amplitude scale = 10mV/div; sample rate = 6.25 Gsa/s];* ***b)*** *[time scale = 400 ps/div; amplitude scale = 10mV/div; sample rate = 50Gsa/s]*

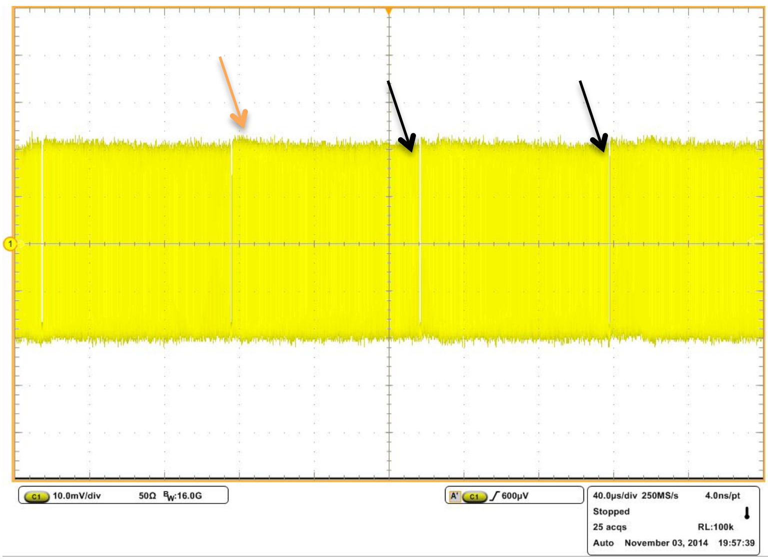


Figure 4.21 - Burst sequence Tg = 1µs and Burst length =100µs, for 2.5Gbit/s and with EDFA. [time scale = 40 µs/div; amplitude scale = 10mV/div; sample rate = 250 Msa/s].

Through the figure observation it is possible to identify a small "ripple" at the beginning of the burst packet marked with an orange arrow. The considered payload is based on a random signal and has a very long length. It means the payload signal has a higher frequency then the guard time, therefore in the guard region, the DC block attenuates the signal due to its low frequency. This situation creates some problems to the threshold bit decision.

The following figures 4.22, 4.23 and 4.24 present the system sensitivities for each bursts sequence, considering a bit rate of 2.5Gbit/s.

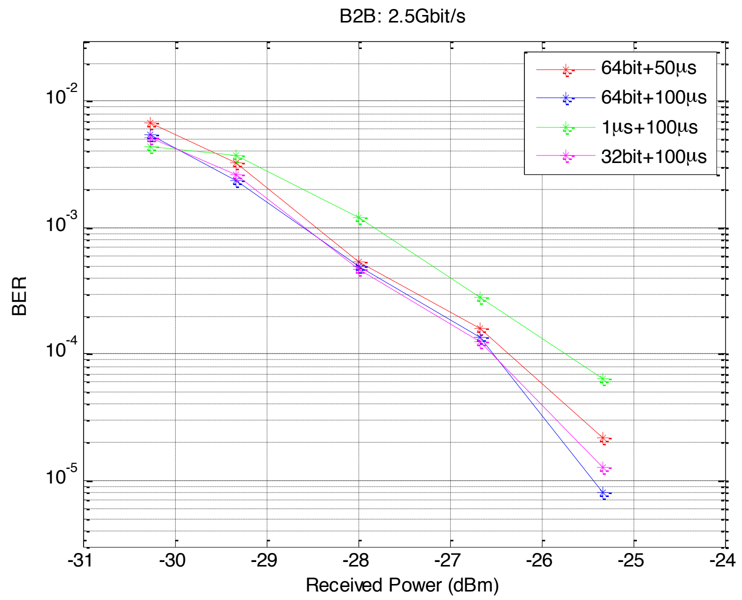


Figure 4.22 - burst sequences comparison for back-to-back with EDFA.

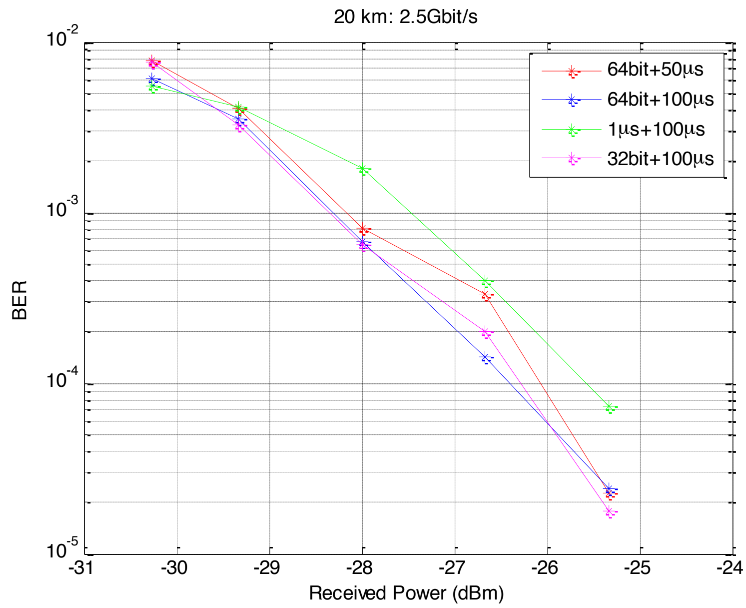


Figure 4.23 - burst sequences comparison for 20 km with EDFA.

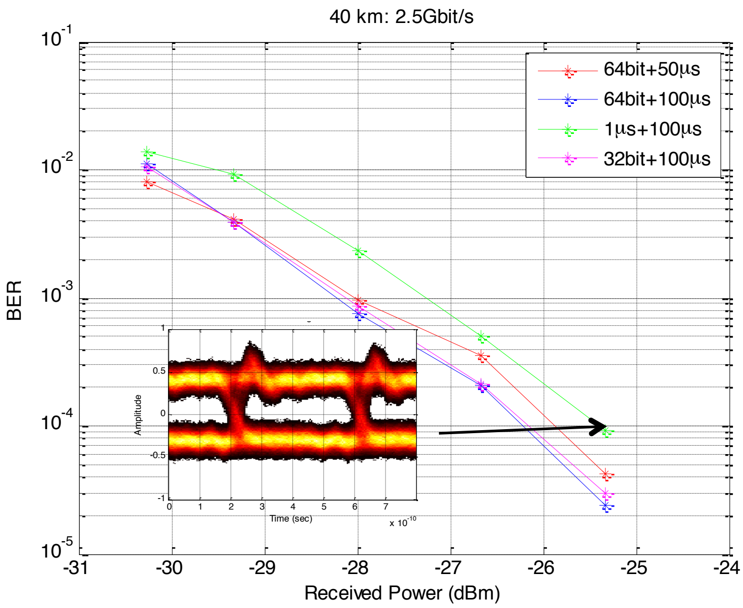


Figure 4.24 - burst sequences comparison for 40 km with EDFA.

As for the 2.5Gbit/s case without EDFA, the sequence with the longest guard time has the worst performance, while the remaining sequences generally present similar values of BER. Regarding when some values of BER assume a value that does not satisfy what was expected, it can be related with the BER estimation resolution.

In the previous subchapter, the systems sensitivities comparison for both cases, with and without EDFA, was briefly described. The system can achieve higher sensitivities, by adding an EDFA. Also for the cases of 20 and 40 km fiber, the system follows the same logic – with EDFA, it achieves better a minimum acceptable values than without.

4.2.4.2 10 Gbit/s capacity

Figures 4.25 and 4.26 present the burst fragments of the bursts sequence with a guard time of 1μs and a payload of 100μs for different time scales at 10Gbit/s.

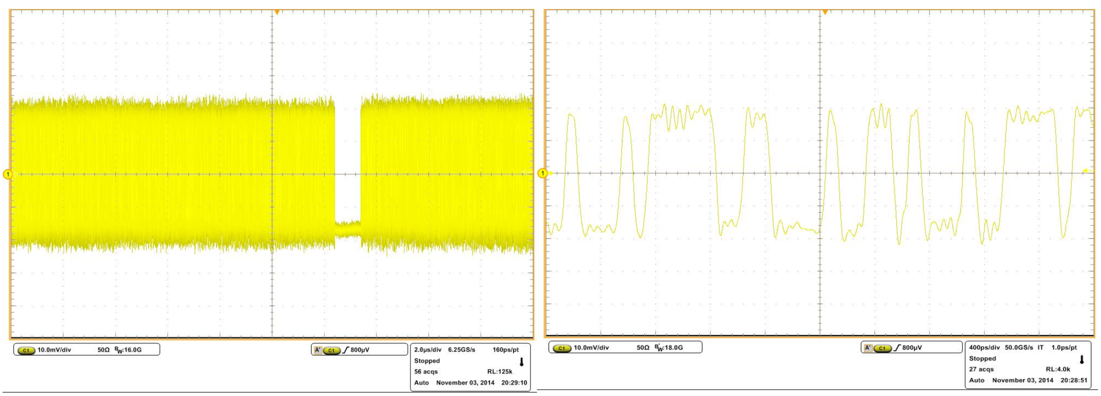


*Figure 4.25 - Burst sequence Tg = 1µs and Burst length = 100µs for 10Gbit/s and with EDFA. **a)** [time scale = 2 µs/div; amplitude scale = 10mV/div; sample rate = 6.25 Gsa/s]; **b)** [time scale = 400ps/div; amplitude scale = 10mV/div; sample rate = 50Gsa/s].*

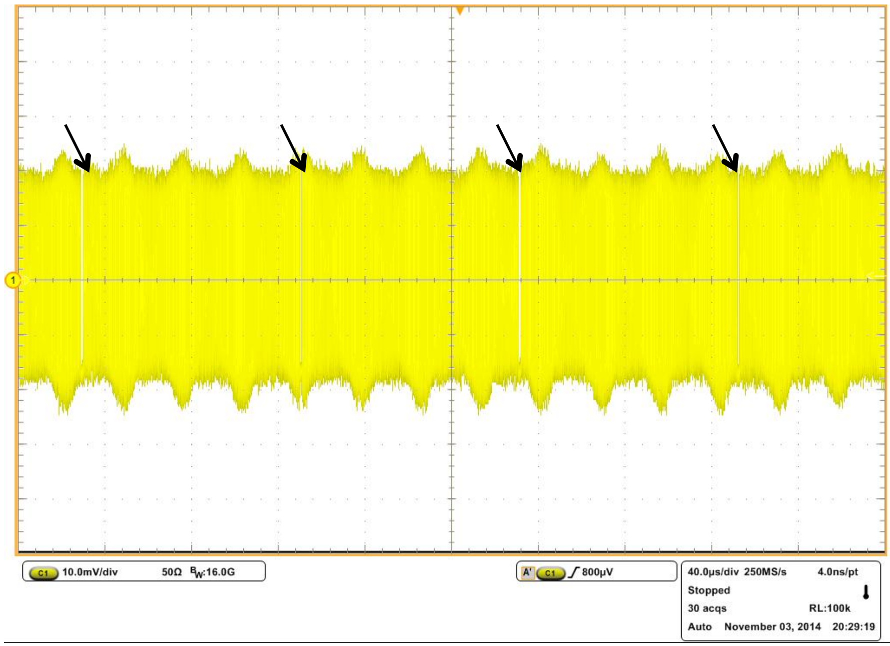


Figure 4.26 - Burst sequence Tg = 1µs and Burst length = 100µs for 10Gbit/s and with EDFA. [time scale = 40 µs/div; amplitude scale = 10mV/div; sample rate = 250Msa/s].

Considering figure 4.26 a), it is visible a smooth tendency in the guard region, while it gets closer to the burst region. Once again, this tendency is due to the guard time low frequency, causing the attenuation of signal through the DC block. The fragments of the remaining bursts sequences, both with 100µs burst length and 3.2ns and 6.4ns of guard time, are not presented because their guard lengths are too small compared to the burst length.

In the following figures 4.27, 4.28 and 4.29 are presented the comparison of the system sensitivities, considering all bursts sequences.

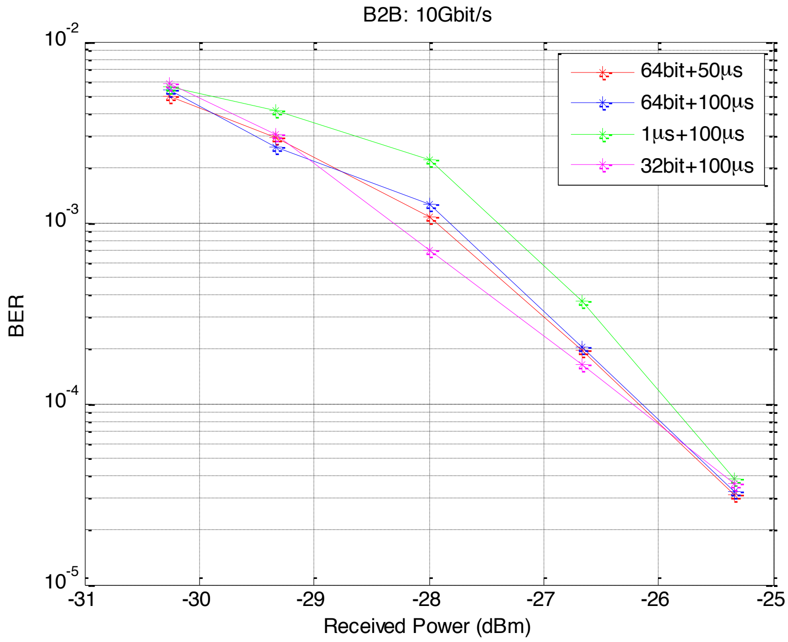


Figure 4.27 - burst sequences comparison for back-to-back.

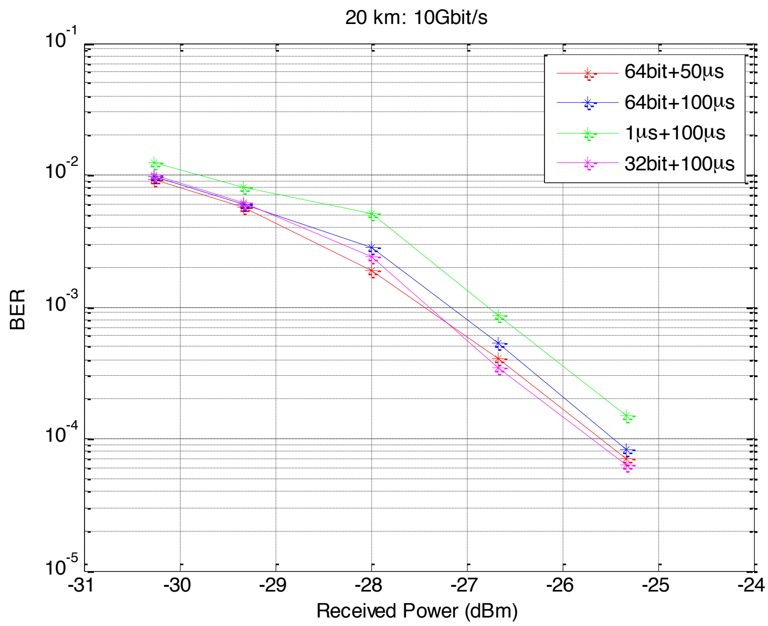


Figure 4.28 - burst sequences comparison for 20 km.

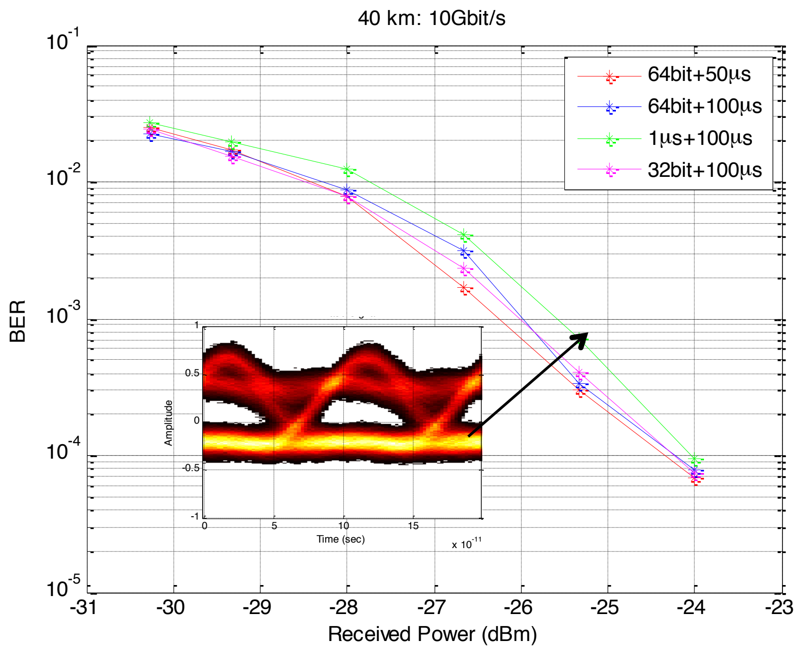


Figure 4.29 - burst sequences comparison for 40 km.

Once more, as for the 10Gbit/s case without EDFA, the sequence with the longest guard has the worst performance, while the remaining sequences generally share similar values of BER.

In the previous subchapter, the systems sensitivities comparison for both cases – with and without EDFA, were briefly described. The system can achieve higher sensitivities, by adding an EDFA. Also for the cases of 20 and 40 km fiber, it follows the same logic – with EDFA, it achieves better a minimum acceptable values than without. Table 4.8 provides the average receiver sensitivities of the system for 2.5 and 10 Gbit/s capacity, with EDFA.

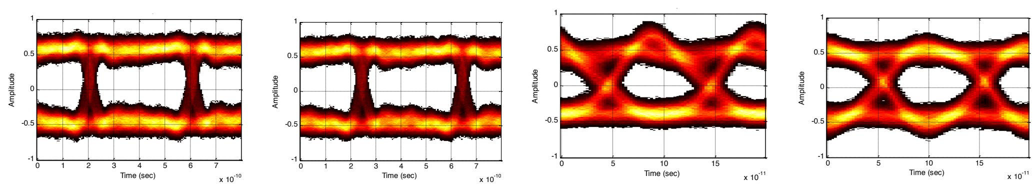
Sequences	**2.5 Gbit/s – Sensitivities [dBm]**			**10 Gbit/s – Sensitivities [dBm]**		
Distances	B2B	20 km	40 km	B2B	20 km	40 km
Red	-28.50	-28.20	-28.05	-27.90	-27.50	-25.30
Blue	-28.60	-28.40	-28.20	-27.80	-27.20	-26.00
Green	-27.90	-27.50	-27.30	-27.45	-26.80	-25.60
Magenta	-28.60	-28.41	-28.10	-28.40	-27.45	-26.00

Table 4.8 - Average receiver sensitivities obtained from the EDFA scenario, for 2.5 and 10Gbit/s rates.

Increasing the bit rate decreases the system sensitivities, especially for the cases that have 40 km fiber due to the chromatic dispersion.

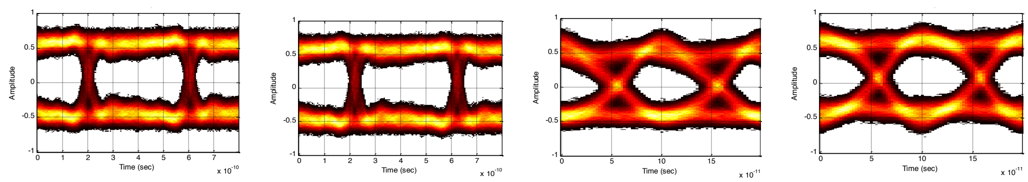
4.2.5 Eye Diagrams

Figures 4.30, 4.31, 4.32 and 4.33 present the eye diagrams for each analyzed case. They were taken for -24.00 dBm (BER = 0) and for back-to-back scenario.



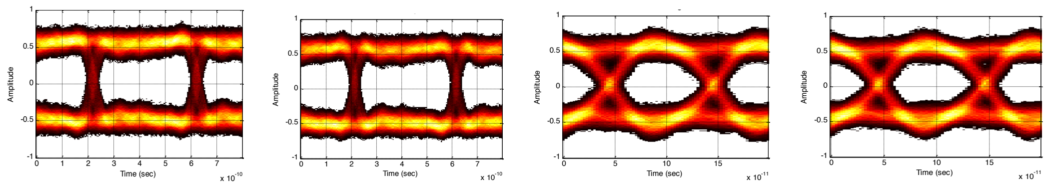
a) b)

Figure 4.30 - Tg=64-bit; Payload=50µs; a) for 2.5Gbit/s with and without EDFA; b) for 10Gbit/s with and without EDFA.



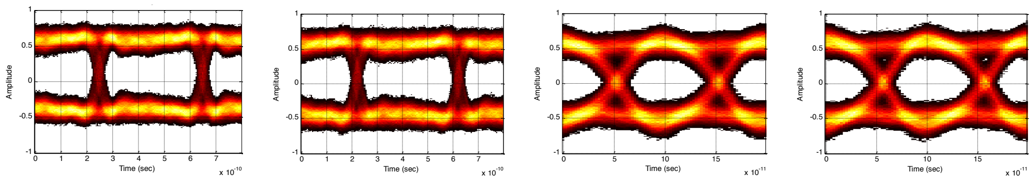
a) b)

Figure 4.31 - Tg=64-bit; Payload=100µs; a) for 2.5Gbit/s with and without EDFA; b) for 10Gbit/s with and without EDFA.



a) b)

Figure 4.32 - Tg=1µs; Payload=100µs; a) for 2.5Gbit/s with and without EDFA; b) for 10Gbit/s with and without EDFA.



a) b)

Figure 4.33 - Tg=32-bit; Payload=100µs; a) for 2.5Gbit/s with and without EDFA; b) for 10Gbit/s with and without EDFA.

The rise times of each signal sequence were verified and as it is possible to visualize, each bit rate, all rise times assume practically the same value. Increasing the bit rate of the signal to 10Gbit/s and considering the fact that the PIN receiver bandwidth is 10GHz, the eye diagram will be attenuated. In terms of BER, the differences between 2.5Gbit/s and 10Gbit/s are not so significant, because regardless of the bit rate, the eye is still open.

Regarding the EDFA cases, the eye diagrams are also very similar to those that were obtain without the optical amplifier.

5 CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

During the last decade, the emergence of new broadband services through optical fiber has exploded. The ever-growing consumer demand for high bandwidth applications has caused a push-pull effect. This leads operators to develop faster, more affordable delivery system of communications. PON technology is continuously evolving and consequently it has lead to the emergence of the next generation access networks. NG-PON2 is the long-term solution in PON evolution, providing higher capacities and the coexistence with legacy PON through the same ODN. Beyond these requirements, some other parameters must be defined, such as the upstream wavelength for the physical layer, tuning time for the ONU laser, power budget, line coding, etc.

The current dissertation is focused in the upstream traffic, considering a part of the protocol stack that specifies the formats and procedures of mapping between the service data unit, and the proper bitstreams for modulating the optical carrier. Both G-PON and XG-PON systems use burst mode to transmit the data through the optical carrier. This study is focused also on burst mode transmission for TWDM-PON.

At first were defined four sequences of bursts, with different guard times and burst lengths. The aim was to test the impact of the lengths variation on the receiver performance. The first conclusion is increasing the guard time till considerable lengths such as 1μs, the system performance in terms of BER starts to decrease. This happens due to the presence of a DC block in the PIN output, which cuts the low frequency component (guard time) of the received signal. However, in a real system scenario an electronic device with a similar frequency response to a DC block can be required in order to optimize the threshold bit decision of the different ONUs packets.

The system was tested for different fiber lengths and bit rates. Logically, increasing the fiber length, it will degradate the system performance. This was verified for all bursts sequences. Relatively to the bit rate variation, it is noticeable that increasing the bit rate, the BER increases, due to chromatic dispersion effect. The most evident case was for 40 km fiber, since increasing the fiber length for higher bits, the dispersion will also increase.

The inclusion of the EDFA in the transmission side, does not cause a significant improvement in the power budget of the system.

The eye diagrams obtained from each sequence with and without EDFA are very similar and its rise times assume practically the same value. The only relevant difference is that increasing the bit rate of the signal, the eye will be attenuated due to the equipment bandwidth, especially because of the PIN receiver. However, in terms of BER, the differences between the two bit rates are not so significant, because the eye diagram keeps open for the different cases.

5.2 Future Work

Once the threshold decision is a fundamental parameter to provide a good performance of the system, it is an interesting topic to give continuity. Therefore, it is important to analyze the effects caused by the DC block, since it assumes a significant role to the threshold bit decision. The main goal is to improve the slope that it causes to the low frequency component of the received signal. Thus the purposed future work is:

- Experimental validation of TWDM system for upstream transmission, with four different modulators

The system would consist in four different wavelength channels, each one with a different bitstream. Each of them would simulate the ONU traffic. Then the modulated signals would be multiplexed into a WDM. At the ODN there would be placed the fiber and then a 1:4 splitter followed by a waveshapper, in order to select each wavelength. At the OLT side (receiver) there would be the receiver connected to the output filter. Then through the real-time oscilloscope it would be possible to take the amplitude of each ONU, and posteriorly the amplitudes comparison would be taken place. It is very important the presence of a DC block in the system, in order to observe and study its behavior, every time there is a transition from guard time to the burst and vice-versa. In the created sequences, the guard time should be accentually varied.

- Assess synchronization methods of TDM between bursts using physic delays

Other option would be the creation of the previous setup, but instead of coupling all the modulated signals, connecting each of them to a different fiber length. For instance, the first modulator would be directly connected to the coupler, the second would be followed by 10 km fiber, the third by 20 km and the last one would be followed by 40 km fiber. Then all of them would be coupled together and after connected to the receiver. The real-time oscilloscope would present the traffic from all “ONUs”. It is optional, but if the fiber distance does not attenuate enough the power of its correspondent signal, the transmitted powers of each signal should assume different values. This experiment would provide to study the threshold behavior through the amplitudes variation.

- Burst mode coherent receiver for TWDM-PON

In this experience the only difference between the current setup and the previously ones, is that in the OLT side (receiver) would not be necessary the optical filters (waveshappers) in order to select each WDM channel and instead of having a PIN or an APD receiver, it would be a coherent receiver working without DSP detecting only the power of the signal (I^2+Q^2). The idea would be also to improve the receiver sensitivity increasing the system power budget.

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