**Universidade De Aveiro** Departamento Electrónica, Telecomunicações e Informática

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**Bruna Patrícia Rodrigues Paredes**

# Contextos de Convergência em Redes de Acesso de Nova Geração

# Contexts Requirements in New Generation Access Networks

**Universidade De Aveiro** Departamento Electrónica, Telecomunicações e Informática

**2014**

Integrated Master Degree in
Telecommunication and Electronics Engineering
2014

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# Contextos de Convergência em Redes de Acesso de Nova Geração

# Contexts Requirements in New Generation Access Networks

Dissertation presented to the University of Aveiro for fulfillment of the necessary requirements to the attainment of the degree of Master in Electronic and Telecommunication Engineering, accomplished under the scientific orientation of Prof. Dr. António Teixeira and Prof. Dr. Mario Lima, both of the Department of Electronic, Telecommunications and Informatics (DETI) and of the Institute of Telecommunication (IT) of Aveiro's University.

I want to dedicate this work to my family, in particular to my parents and sister who had supported me tireless and unconditionally. Also to my dated one, for all the patience, all the strength and for never let me to give up. I also dedicate to my truly friends, especially to Susana Bento and Sir Master Engineer Simão Brandão, who had always believed me and had directed me in the right way.

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**Gratefulness**

These past years at university, kind were the best years I had. I met new people, had new experiences, grew up and got matured. I became a new person with new feelings and new perspectives of life. Now it is time to take another step forward and I will never forget everyone who helped me at this stage.

First of all, I want to give a deep thanks to my parents and my sister for all the support and for believing in me throughout my academic career. I love them and I'm proud of them every day.

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*"The only limit to our realization of tomorrow will be our doubts of today. Let us move forward with strong and active faith."*

(Franklin Delano Roosevelt)

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**Keywords**

Passive Optical Networks, G-PON, XG-PON, NG-PON2, Raman, TWDM-PON, Advanced Modulation Formats, QPSK, 16QAM

**Abstract**

The Internet is increasingly becoming part of everyday life. Once the traffic demands are growing much more rapidly than the available revenue, it is visible the gradual increase of the need for broadband services. In recent years, telecom operators have shown a great interest in providing various services to residential customers, using the Passive Optical Network (PON) topology. This strong investment has led to several standards in order to achieve the potential subscribers and nowadays is being developed the next generation. The future goal is clear - NGPON2 must overcome previous technologies in ODN compatibility, capacity, bandwidth and cost-efficiency. After several studies, in April 2012, FSAN (Full Service Access Network) defined TWDM (Time-Wavelength Division Multiplexing) as the more attractive solution to fulfill the necessary requirements. On March 2013, was approved the ITU-T G.989.1 recommendation addressing possible wavelength plans, according operator's needs. The most important requirement for this new access generation is to provide an environment of coexistence with the legacy PON and others. In this order, it is necessary new allocation in the spectrum and further interference studies, to preserve all the systems intact.

In this scope, the following document presents a study over the new technology TWDM separately, including general features and limitations. Both simulated and experimental results were obtained. Afterward, it is introduced within several coexistence scenarios, with the legacy and signals with different modulation formats, to observe the effect created on its performance. Were taken into account some parameters as channel spacing, transmitted power and high bit rates. The aim is to create a heterogeneous network with high data rate formats coexisting in the same access network to study and help defining the next generation max occupancy of a given network.

**Palavras-Chave** Redes Ópticas Passivas, G-PON, XG-PON, NG-PON2, Raman, TWDM-PON, Formatos Modulação Avançada, QPSK, 16QAM

**Resumo**

A Internet está a ter um papel cada vez mais activo no quotidiano actual. As exigências de tráfego estão a aumentar consideravelmente mais do que a receita disponivel, sendo que se torna visível a extrema necessidade por servicos de banda larga. Recentemente, os operadores de telecomunicações tem demonstrado um vasto interesse em providenciar serviços a clientes residenciais, usando Redes Ópticas Passivas (PON). Este forte investimento levou ao desenvolvimento de vários *standards*, estando actualmente a ser desenvolvida a nova geracão da rede. O novo objectivo é bastante claro – NGPON2 deve superar as tecnologias anterioes relativamente à compatibilidade ODN, capacidade, largura de banda e custo-eficiência. Após vários estudos, em Abril de 2012, FSAN ((Full Service Access Network) definiu TWDM (Time-Wavelength Division Multiplexing) como sendo a solução mais atractiva para preencher os requisitos necessários. Em Março de 2013, foi aprovada a norma ITU-T G.989.1 endereçando novos planos de comprimentos de onda, de acordo com as exigências dos operadores. O requisito mais importante para esta nova rede de acesso centra-se em garantir uma possível co-existência com as redes PON já desenvolvidas. Para esse efeito, torna-se essencial uma nova alocação de espectro e posteriores estudos de interferência, garantindo, assim, a preservação de todos os sistemas.

No âmbito do referido acima, o presente documento expôe inicialmente um estudo acerca da nova tecnologia TWDM, incluindo caracteristicas gerais e suas limitações. Foram obtidos, para tal, resultados experimentais e simulados. Posteriormente, é efectuado um estudo da tecnologia TWDM em co-existência com redes PONs anteriores e, também, com sinais modulados com diferente formatos. Estes cenários tem o propósito de observar os efeitos gerados no seu desempenho. Alguns parâmetros, como espaçamento entre canais, potência de transmissão e taxas de transmissão de bits foram tidos em consideração. O objectivo é criar uma única rede heterogénea onde vários formatos de alta transmissão de dados co-existem, por forma a optimizar e definir a máxima ocupação da rede de acesso de nova geração.

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# Acronyms list

| | |
|---|---|
| 3DTV | *3D Television* |
| 40 Gbps TDM | *40 Gbps Time Division Wavelength* |
| **A** | |
| APD | *Avalanche Photodiode Detector* |
| APON | *Asynchronous Passive Optical Network* |
| ASK | *Amplitude-Shift Keying* |
| ATM | *Asynchronous Transfer Mode* |
| AWG | *Array Waveguide Grating* |
| **B** | |
| BER | *Bit Error Rate* |
| BPON | *Broadband Passive Optical Network* |
| BPSK | *Binary-Phase-Shift Keying* |
| BWmap | *Bandwidth Map* |
| **C** | |
| CBU | *Cell-site Backhauling Unit* |
| CO | *Central Office* |
| CW | *Continuous Wave* |
| **D** | |
| DBA | *Dynamic Bandwidth Allocation* |
| DBm | *Decibel miliwatt* |
| DBRu | *Dynamic Bandwidth Report upstream* |
| DFB | *Distributed Feedback* |
| DML | *Directly Modulated Laser* |
| DRof | *Digitized Radio over Fiber* |
| DS | *Downstream* |
| DSL | *Digital Subscriber Line* |
| **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 de Curb*
FTTH *Fiber to the Home*
FTTO *Fiber to the Office*
FTTP *Fiber to the Premises*
FWM *Four-Wavelength Mixing*

**G**
Gbps *Giga bits per second*
GEM *GPON Encapsulation Mode*
GHz *GigaHertz*
GPON *Gigabit-Capable Passive Optical Network*

**H**
HDTV *High Definition Television*
HEC *Header Error Control*
HFC *Hybrid-Fiber Coaxial*

**I**
IEEE *Institute of Electrical and Electronics Engineers*
IPTV *Internet Protocol Television*
ITU-T *International Telecommunications Unit – Telecommunication Standardization Sector*

**J**
JDSU *JDS Uniphase*

**K**
KM *Kilometer*

**L**
LLID *Logical Link ID*

**M**
MAC *Media Access Control*
Mbps *Mega bits per second*
MMF *Multi-Mode Fiber*
Ms *Milliseconds*
MZI *Mach-Zehnder Interferometer*
MZM *Mach-Zehnder Modulator*

**N**
NGPON *Next Generation Passive Optical Network*
NGA *Next Generation Access*
NM *NanoMeter*
NRZ *Non-Return-to-Zero*
NT *Network Termination*

**O**

| | |
|---|---|
| OA | *Optical Amplifier* |
| OCDM | *Optical Code Division Multiplexing* |
| ODN | *Optical Distribution Network* |
| OFDM | *Orthogonal Frequency Division Multiplexing* |
| OLT | *Optical Line Terminal* |
| ONU | *Optical Network Unit* |
| ONT | *Optical Network Terminal* |
| OOK | *On-Off Keying* |
| OSA | *Optical Spectrum Amplifier* |

**P**

| | |
|---|---|
| PLI | *Payload length indicator* |
| PMD | *Physical Medium Dependent* |
| PON | *Passive Optical Network* |
| PSK | *Phase-Shift Keying* |
| PTI | *Payload type indicator* |
| P2MP | *Point to Multipoint* |

**Q**

| | |
|---|---|
| QAM | *Quadrature Amplitude Modulation* |
| QPSK | *Quaternary-Phase-Shift keying* |

**R**

| | |
|---|---|
| RF | *Radio Frequency* |
| RoF | *Radio over Fiber* |
| RS | *Reed-Solomon* |
| RTD | *Round-trip delay* |
| RTT | *Round-trip time* |

**S**

| | |
|---|---|
| SBS | *Stimulated Brillouin Scatering* |
| SiP | *Silicon Photodiode* |
| SLA | *Service Level Agreement* |
| SMF | *Single Mode Fiber* |
| SOA | *Semiconductor Optical Amplifier* |
| SPM | *Self-Phase Modulation* |
| SR | *Status Reporting* |
| SRS | |

**T**

| | |
|---|---|
| TC | *Transmission Convergence* |
| T-CONT | *Transmission Container* |
| TDM | *Time Division Multiplexing* |
| TDMA | *Time Division Multiple Access* |
| THz | *Tera-Hertz* |

| | |
|---|---|
| TM | *Traffic Monitoring* |
| TTA | *Tunable Transmitter Assembly* |
| TWDM | *Time and Wavelength Division Multiplexing* |

**U**

| | |
|---|---|
| UDWDM | *Ultra Dense Wavelength Division Multiplexing* |
| US | *Upstream* |

**V**

| | |
|---|---|
| VOD | *Video-on-Demand* |
| VoIP | *Voice over Internet Protocol* |

**W**

| | |
|---|---|
| WBF | *Wavelength Blocking Filter* |
| WDM | *Wavelength Division Multiplexing* |

**X**

| | |
|---|---|
| XGPON | *10 Gigabit-Capable Passive Optical Network* |
| XPM | *Cross-Phase Modulation* |

**Z**

| | |
|---|---|
| ZWP | *Zero Water Peak* |

# 1 INTRODUCTION

## 1.1 Motivation

Internet is increasingly becoming part of everyday life. This means that data networks, distributed throughout the world, have a remarkable growth in traffic. Once the traffic demands are growing much more rapidly than the available revenue, it is visible the gradual increase of the need for broadband services. In recent years, telecom operators have shown a great interest in providing various services to residential customers requiring high bandwidth, including a service called “triple-play”, which means, video, voice and data on the same network. This offer of services, such as IPTV, collects a high bandwidth due to higher quality formats such as HDTV (*High Definition Television*). Over time, IPTV tends to evolve to support ultra HDTV and 3DTV, which requires a bandwidth not provided by current access networks. Once arose the possibility to increase the network capacity, also appeared solutions for distribution of radio signals like RoF (*Radio over Fiber*) and DRof (*Digitized Radio over Fiber*). These solutions have reduced the complexity of the equipment and the operating costs, which created a bigger number of users and turnover.

In June 2011, it was predicted that the volume of the Internet traffic worldwide would grow sevenfold between 2010 and 2015.

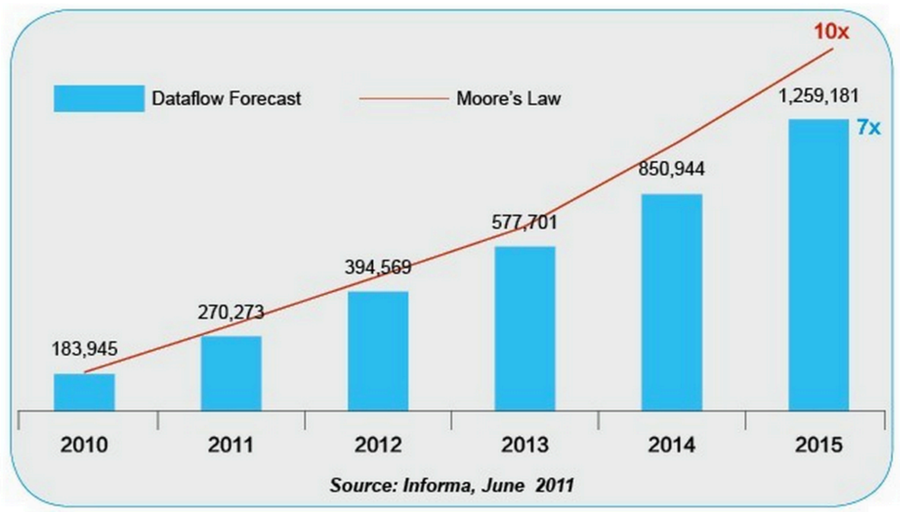



*Figure 1.1 - Bandwidth available to users [1]*

All this continued need for bandwidth, leads to the main idea that a new transmission technology is mandatory. To meet this end, operators seeking to launch fiber deeper into the access network as far as subscriber premises – FTTP. Several studies have shown that Fiber to the Premises network is the most favorable solution in this regard, being based on the Passive Optical Network (PON) topology. [2]

The FSAN (*Full Service Access Network*) [3] was the first group, in 1995, working on Fiber to the Home (FTTH) architectures, which is formed by major telecommunications service providers and system vendors.

Nowadays, the most widely deployed PON standards organizations are the Institute of Electrical and Electronics Engineers (IEEE) [4] and the International Telecommunication Unit (ITU-T). [5] Have been approved some standards, currently in use, like 802.3ah EPON in 2004 [6] and G.984.1 GPON in 2008 [7], but rapidly they will not be able to satisfy the needs of the costumers. In this regard, several studies continue to be developed in order to provide higher bandwidth, higher reach and higher number of users, promoting the coexistence between each other.

These new technologies are called NGPON – *Next Generation PON* - which are divided in mid-term and long-term solutions, NGPON1 and NGPON2, respectively. In the first one emerged the XGPON technology, ITU recommendation G.987 in 2012 [8], which is compatible with existing GPON, to reduce the cost. For the second one have been studied several technologies.

NGPON2, standard G.989.1 [9], has set some operator requirements which wants to full fill by adopting the best technology between some proposed, such as WDM, 40 Gbps TDM, OFDM, UDWDM, TWDM. The goal is clear – NGPON2 must overcome previous technologies in ODN compatibility, capacity, bandwidth and cost-efficiency. In April 2012, FSAN organization reconsidered their true aims, selecting TWDM-PON as the most attractive solution to be integrated as future technology. The prospective is to have the compliant systems ready for deployment in 2015.

## 1.2 Goals

The main purposes of this dissertation are:

- Study the rules of access networks for signal distribution of GPON, XGPON and TWDM.
- Characterize the technologies GPON, XGPON and TWDM, separately, through the VPI simulator.
- Characterize the coexistence scenario for GPON, XGPON and TWDM, also in VPI simulator.
- Demonstrate and characterize TWDM system in the laboratory.
- Characterize the coexistence scenario of TWDM and advanced modulation formats.

## 1.3 Structure

This dissertation is organized in 5 chapters:

- Introduction
- State of Art
- Simulation Results
- Laboratory Results
- Conclusions and Future Work

The first chapter is written to present the framework, goals and contributions of the
Dissertation and, also, how it is structured for a better understanding.

In the second chapter, it is available the PON legacy till the present, as well the new standard to be implemented, in the near future, and its candidate technologies. It contains the features and requirements of each one, allowing the respective discussion for the migration scenarios and coexistence. At the end, it is presented some interesting acknowledgement of modulation formats and their relevance.

The third chapter has the aim of bring forward the simulation results obtained with VPIphotonics [10], starting with the characterization of each technology PON separately, including general features and limitations. After is created several coexistence scenarios to simulate the coexistence of the respective technologies between each other.

The fourth chapter is regarding the laboratory experiments. Keeping the line, it is firstly characterized the TWDM system, separately and in different conditions. Posteriorly, it is carried a study about the coexistence scenarios between the TWDM system and some modulation formats available in the laboratory.

For the last one, fifth chapter, it is discussed some possible future work to develop in this research area and, also, the conclusions obtained through this investigation.

## 1.4 Main Contributions

The main contributions were:

- Characterization and main features of available PON standards till the present, as well the next generation to be implemented;
- Standards requirements and coexistence issues between each one;
- Description of candidate technologies for NG-PON2, such as WDM, 40 Gbps TDM, OFDM, UDWDM and TWDM;

- Presentation, validation and comparison between GPON, XGPON and TWDM technologies;
- Coexistence scenario between each technology and fulfilled requirements;
- Static Raman study in the coexistence scenario of PON systems;
- Experimental study and validation of TWDM system;
- Coexistence scenarios of TWDM and different modulation formats.

Besides, a paper under the name “Context Requirements in Future Access Networks” will be submitted in the 16th International Telecommunications Network Strategy and Planning Symposium. It addresses the study about coexistence scenarios between TWDM and high data rate formats, as QPSK and 16QAM modulation formats. Authors: Susana Bento, Simão Brandão, Ricardo Ferreira, Ali Shaphari, António Teixeira e Mário Lima.

# 2 STATE OF ART

## 2.1 Introduction

Since 1995, the Passive Optical Networks have been studied and improved, by several groups, to provide better conditions and satisfy the users needs. This fame creates the necessity to consolidate the important role of those networks for the telecommunication operators.

The big demand started with the idea of getting video, voice and data on the same network. Over the years, several standards have been approved, creating an evolution path till the present, leading to the need to go forward and upgrade the access network.

In the early days of the organization, FSAN [3] developed the APON, standard G.983.1 approved in 1998, based on Asynchronous Transfer Mode (ATM) protocol. The gradual decline of ATM use leaded to the final version of ITU-T G.983.3, in 2001, being referred as Broadband PON (BPON). [11] This standard, the first one accepted, specifies a bit rate of 0.155 Gbps of uplink traffic, at 1310 nm and 0.622 Gbps of downlink traffic, at 1490nm. It is important to underline the addition of a video/RF service to this PON system, as a benefit well granted, what contributed to the history to follow this path. Figure 2.1 presents the wavelength range at this moment in the legacy.

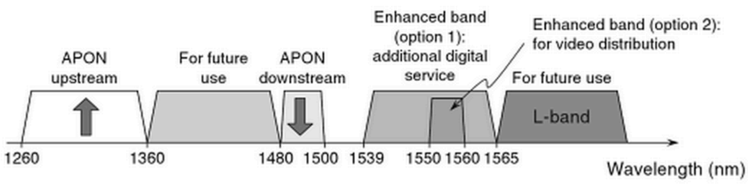



*Figure 2.1 - Wavelength allocation plan in ITU-T G.983.3[12]*

The wavelength chosen for RF-video (1550 nm) was tight to some reasons, such as:

- Smaller attenuation loss which allows better transportation conditions and cheaper signal transmission;
- Video amplification using EDFA (relatively cheap);
- High guard band between the downstream wavelength for data and the wavelength for video, making possible the use of lasers and common filters with higher bandwidth.

The transmission was improved over the years (2002), but BPON is now an outdated technology, giving place to other.

In 2001, born the EFM task force giving place to the full standard IEEE 802.3ah [6] in 2004. At the same time, FSAN [3] started a new effort to develop new patterns with higher capacity, so in 2003 emerged the GPON technology giving place to the full-approved recommendation G.984.1 [7] in 2008. Following the line of the history, due to the fast growing of bandwidth demand, in 2012 was approved the G.987 standard [8] as a smooth upgrade of the previous one. Hereupon, it is possible to advertise the PON legacy – EPON, GPON, XGPON – and focus in the deployment of the Next Generation PON2.

Nowadays, the researchers are targeted to respond to the bandwidth need and bring to the world the long-term solution. Thus, after the investigation around all the candidate technologies, it appeared the one that covers the specified requirements and allows the coexistence with past technologies – TWDM-PON.

To finalize the segmentation, it is noteworthy the incoming solutions of radio signals distribution (RoF and DRoF), derived by this increase in adherence by operators to FTTH and FTTB services, and, consequently, by the development of technologies in the optical domain.

## 2.2 Passive Optical Networks

The major concern of the telecommunication operators relies in implementation costs of the access network. The aim is to create a positive balance between cost and bandwidth. The PON is revealing to be a technology with large-scale acquisition in the access networks market, since it can reduce the cost of equipment compared to point-to-point architectures.

PON is a point-to-multipoint, fiber to the premises network architecture in which unpowered optical splitters are used to enable a single optical fiber to serve multiple premises. It is a form of broadband access.

Figure 2.2 addresses the several possible architectures of a Passive Optical Network.

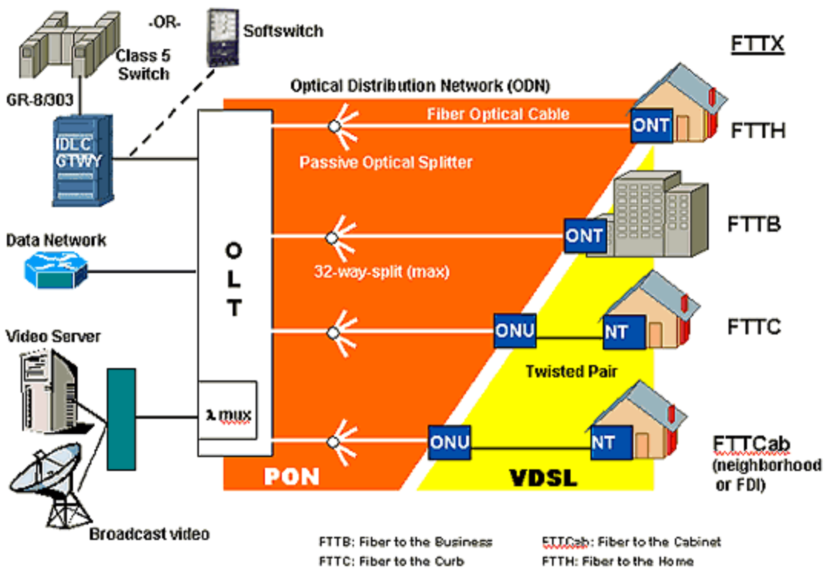



*Figure 2.2 - Typical architectures of a PON network [13]*

A PON consists of an OLT (optical line terminal) at the service's provider central office (CO) and a number of ONUs (optical network units), also called ONTs (optical network terminals), near end users. Between those two nodes, which are the only points with active elements, there is the passive network, called Optical Distribution Network (ODN). By means of elimination of the active elements, it consists of one single mode fiber (SMF) and passive splitters 1:N. These four basic components have specific performance functions.

- The OLT has, as main functionality to adapt the network traffic of operator (data, voice and video) to the access network. It is responsible for management and maintenance of the ODN.
- The ONU or ONT are the same device. The first one is located in mediations of the subscriber, outside of the building and the second is located in user location. This device terminates the PON and presents customer service interfaces to the user. It can be placed in a home, office, business, and more, emerging, that way, some distinct network designations like FTTH, FTTB, and FTTC. Some ONUs implement a separate subscriber unit to provide services such as telephony, Ethernet data, or video.
- The optical fiber is the way used to diffuse the information.
- The beam splitter divides the data stream, from de CO, into the individual links to each costumer (downstream link) or connect the data sequences from all the users (upstream link).

The splitter, used to distribute the signal, cannot provide any switching or buffering capabilities, so the ONTs at the end users must perform some special functions. Once the ONUs share the same fiber, is necessary to control the multiple access channel, in the upstream transmission.

In first place, to compensate the first absence, each signal leaving the central office must be broadcast to all served users where the ONTs have to filter out signals intended for other costumers. In order to compensate the second absence, each ONT should be coordinated in a multiplexing scheme to prevent signals sent by costumers from colliding with each other. For this purpose, it can be used the WDM (Wavelength Division Multiplexing) or TDM (Time Division Multiplexing) technologies.

Wavelength Division Multiplexing is a non-standard type of PON with the aim to multiplex several optical signals in one single fiber. Thus, as it is possible to visualize in Figure 2.3, it is used several wavelengths, through lasers with different colors to carry different signals.

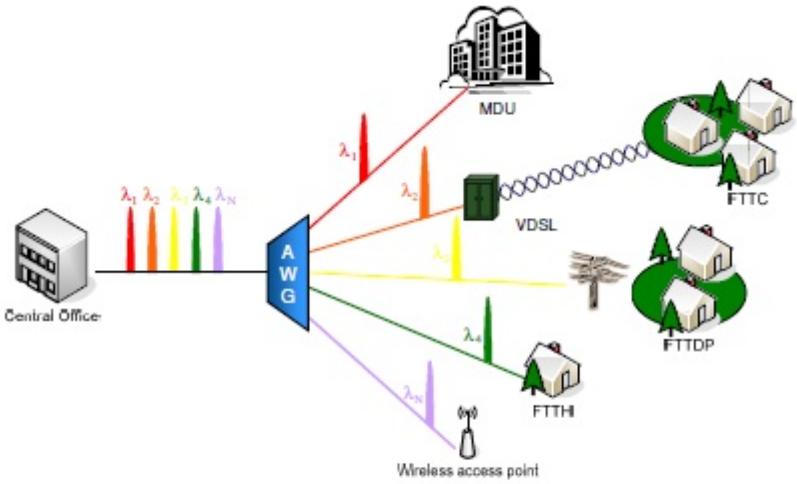



*Figure 2.3 – WDM-PON non-standard protocol [14]*

The multiple wavelengths of a WDM-PON are used to separate ONUs into several virtual PONs co-existing on the same physical infrastructure, which means that each costumer transmits their signal using a unique wavelength. This can be achieved using an Array Waveguide Grating (AWG), seen as a passive router, which will determine each optical signal to send to each port, allowing a bi-directional data flow through a single optical fiber.

Summarizing, it provides a virtual point-to-point connection between the subscriber and the central office, thereby providing many advantages of point-to-point Ethernet approach.

Being possible to use one wavelength for downstream traffic and another for upstream traffic, on a single non-zero dispersion-shifted fiber, is a great advantage. Alternatively, the wavelengths can be used collectively through statistical multiplexing to provide efficient wavelength utilization and lower delays experienced by the ONUs. [15]

In case of TDM, the costumers, with power splitters, transmit the information. On Figure 2.4, is possible to observe the data sending procedure using TDM protocol.

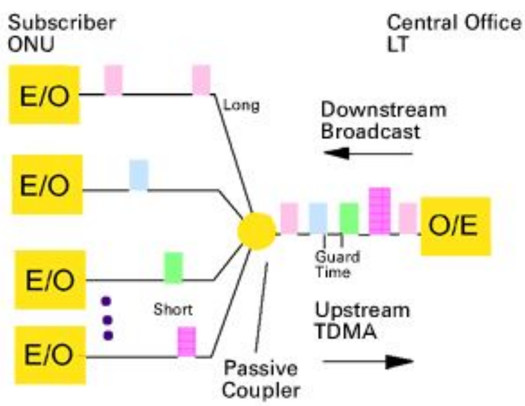



*Figure 2.4 – TDM-PON non-standard protocol [16]*

Substantially, the signals or bit streams, in this kind of digital multiplexing, are physically taking turns on the channel, once they are transferred appearing at the same time as sub-channels on a single communication channel. Each sub-channel has a recurrent time slot of fixed or variable length from the division of the time domain, exploring the entire bandwidth. The bandwidth available for each ONU can be established based on the need, which is checked periodically, or based on service contracts (Service Level Agreement - SLA).

Both PON approaches offer a single fiber operation in Optical Distribution Network for operational and cost reasons. The first equipment in the market was the TDM. This technique only needs one transceiver at the OLT, independent of the number of ONUs (low cost), but it means that it needs to be synchronized to avoid the signals collision. However, WDM allow longer reach and larger split ratios and the mac layer is simplified because connections realized in wavelength domain do not need the P2MP media access control. Once the transmission uses different wavelengths, it does not need any security tools. In disadvantage, the WDM components have higher costs and the wavelengths tend to drift with environment temperatures. [17]

## 2.3 Ethernet PON (EPON)

In November 2000, was announced a study group called Ethernet in First Mile, created by IEEE [4], which aimed to extend Ethernet to the area of the user access. In June 2004, it was improved becoming the standard IEEE 802.3ah (EPON) [6]. This network is based on Ethernet traffic transportation, working with packets of variable size, unlike the previous network, becoming very efficient.

### 2.3.1 Architecture

EPON architecture is based on a typical access network PON. In this way, it is considerable to say that it is a fiber access technology with no active elements in the outside plant. Between the OLT and the ONU, the active elements, are the single mode fiber and the passive optical splitters 1:N to distribute the traffic to the costumers. The EPON splitter, being a passive element, does not require powering, so it is extremely stable and it never fails in virtual mode. This architecture is characterized for using WDM, to multiplex several optical carriers, in a single optical fiber, through different wavelengths.

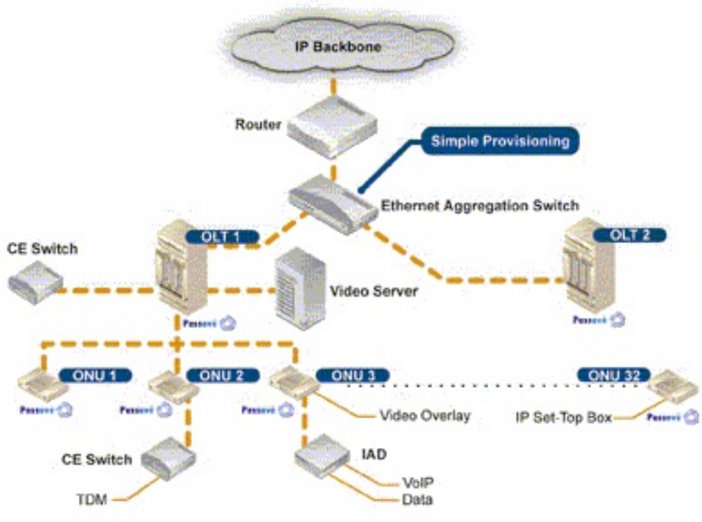



*Figure 2.5 – EPON architecture [18]*

### 2.3.2 Features

**Bit Rate**

EFM introduced a family of Physical Layer signaling systems, derived from 1000BASE-X, including extensions like FEC (Forward Error Correction) capability. EPON specifies two physical layers for a point-to-multipoint link over one single mode optical fiber: 1000BASE-PX10 and 1000BASE-PX20. In both cases, the transmission rate is 1.25 Gbps for upstream and downstream link. [6]

**Line Code**

The PMD sub-layer service interface uses a coding line 8b/10b. It maps 8-bit symbols to 10-bit symbols to maintain the DC-balance, bounded disparity and also to allow a reasonable clock recovery. In advantage, this helps to reduce the demand for the lower bandwidth limit of the channel, necessary to transfer the signal.

However, using this line coding confine the transmission rate, in reality, to symmetric 1 Gbps for both upstream and downstream traffic [6, 19].

**Physical Reach**

The physical reach depends on the physical layer specifications. The 1000BASE-PX10 layer uses a PIN receiver and achieves a 10 km range, whereas the 1000BASE-PX20 uses a APD receiver and achieves 20 km maximum range. [6]

**Split Ratio**

The standard 802.3ah defines a typical split ratio of 1:16. However, it can be extended to 1:32, if it is used FEC [19].

**Wavelength Range**

In this architecture, it is reserved for downstream traffic the 1510 nm wavelength, to send data to the users. Regarding the upstream direction, data sent by users, it is used the 1310 nm wavelength. In addition, there is another wavelength reserved for downstream video - 1550 nm wavelength. The video is encoded as MPEG2 and is carried over Quadrature Amplitude Modulated (QAM) carriers. On Figure 2.6 is presented the wavelength range for EPON data and video technologies.

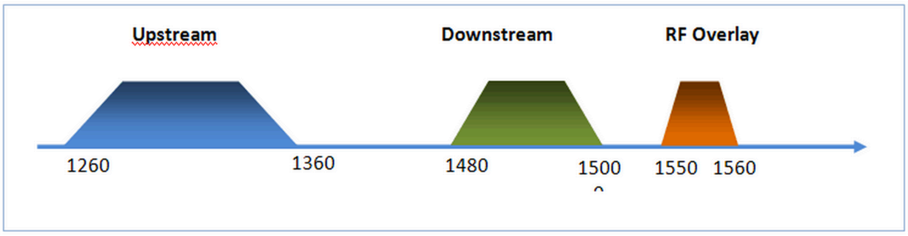



*Figure 2.6 - Range of wavelengths for EPON standard [20]*

**Error Correction**

The FEC functionality was defined as optional for some implementations, like EPON standard. Nevertheless, it is still necessary to code and decode the data flow.

This mechanism has the meaning of detect and correct errors, at the receiving end of the link that may occur when data is transferred through the link. For this purpose, when the signal is decoded, FEC uses additional data, created by a set of non-binary arithmetic functions, attaching it to the Ethernet frame.

Its usage may increase the optical link budget, making possible to have higher transmission rates and fiber distances, as well an increase of the split ratio.

In 802.3 PON standard it is recommended the use of a linear Cyclic Block code – the Reed-Solomon Code (255,239,8) – which allows the correction of 8 bytes. It can encode 239 information symbols, adding 16 parity symbols, then creating the 255 information symbols of the coded word, without any disturb. [6]

### 2.3.3 Transmission

**Downstream and Upstream Traffic**

The Ethernet PON has different techniques to send data from the OLT to multiple ONUs – downstream transmission – and to send from multiple ONUs to the OLT – upstream transmission.

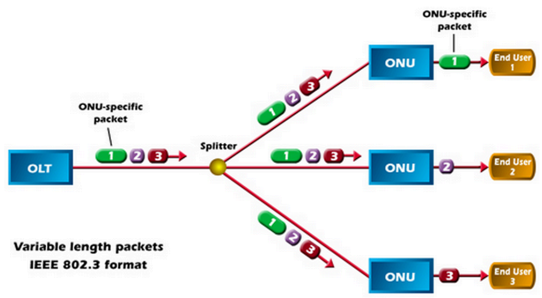



*Figure 2.7 – Downstream traffic flow in EPON [21]*

Observing Figure 2.7, it is possible to understand that several packets, with variable length, are broadcast to the ONUs, in downstream transmission. According to 802.3ah protocol, the load size reaches from 46 to 1518 bytes. Each packet carries a header with information about the addressee, as is possible to verify in Figure 2.8. All the ONUs receive the same packets, each one accepting only the ones that are intended for the respective user and discarding the others. This is accomplished through the field LLID, embedded in the frame.

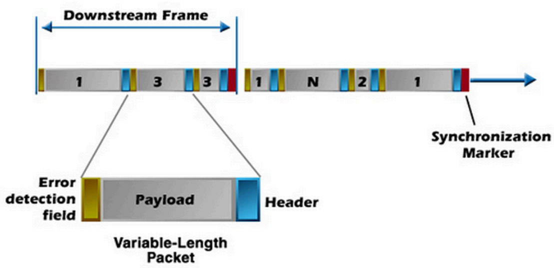



*Figure 2.8 – Downstream frame format EPON [21]*

Regarding to the upstream traffic, it is used a multiple access protocol – TDMA: Time Division Multiple Access – where transmission time slots are dedicated to each ONU. Thus, all the information is multiplexed and sent to the OLT.

In this order, once the data is coupled on the same fiber, the time slots must be synchronized to avoid collisions between packets from each ONU. Figure 2.9 presents the schematic oh the referred procedure.

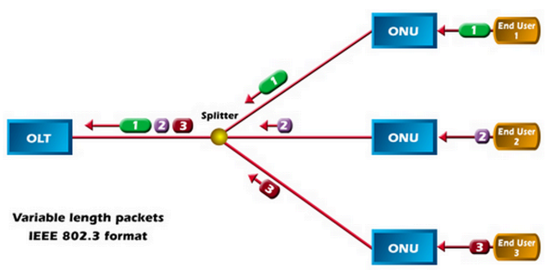



*Figure 2.9 – Upstream traffic flow in EPON [21]*

The upstream traffic is divided into frames, identified by a header with a transmission interval of 2ms. This can be observed in Figure 2.10. Each frame has the ONU-specific time slots, which are dedicated to the transmission of the variable-length packets from the time slots of the respective ONU. The OLT and the TDM controller of each ONU control the transmission timing of the packets jointly.

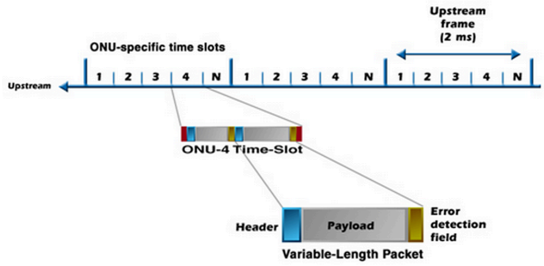



*Figure 2.10 – Upstream frame format EPON [21]*

**Ranging**

Ranging is the necessary mechanism to guarantee the synchronization between every ONUs slot and the assigned OLT slot, by calculating the RTT (round-trip time).

From the point of view of the OLT, it is possible to occur transmission overlap of upstream data, due to the different distances of each ONU. This could lead to changes in the RTT, by changes of time and environment.

In order to avoid the collision of upstream data, RTT is measured, based in time stamps, and inserted with the corresponding equalization delay to put the same virtual distances between OLT and ONUs.

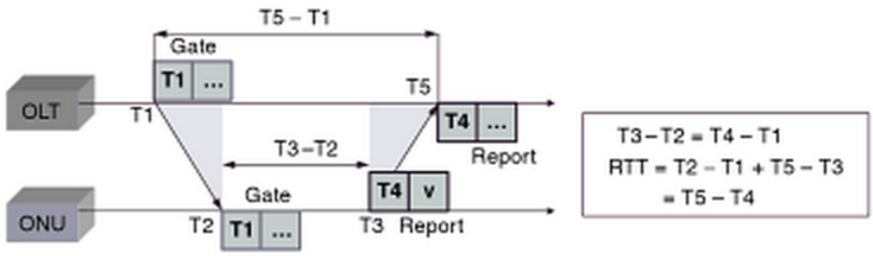



*Figure 2.11 – EPON ranging process [22]*

The ranging process, illustrated on Figure 2.11, involves one single phase, with changes at the OLT side, and is described in the following steps:

1) The OLT sends a GATE message with the timestamp T1, to inform the ONU when to start the transmission;

2) The ONU receives the GATE message at local time T2, after the transmission delay - $T_{downstream}$, and resets its timer to T1.

3) The ONU sends, after some time – $T_{WAIT}$, a REPORT message at local time T3, with timestamp T4 – T1 = T3 – T2. In practice, it corresponds to a change in the value of the local clock;

4) The OLT receives the report at local time T5 and calculate RTT, which is simply RTT = T5 – T4 (difference between the local watch value, when received REPORT message T5, and the value of the timestamp received in that message).

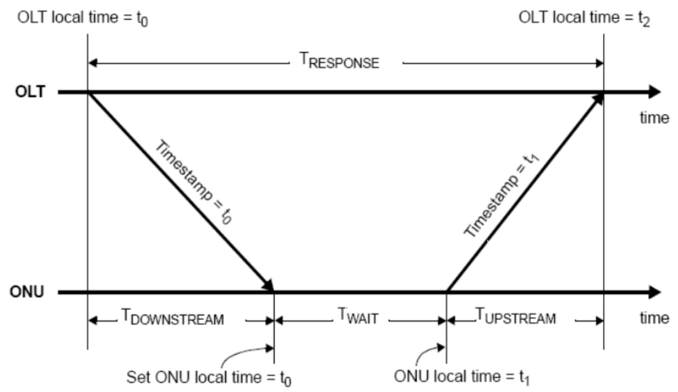



*Figure 2.12 – RTT calculation (IEEE 802.3ah) [23]*

**Auto Discovery**

The auto discovery process allows newly ONUs entrance and register in the system, without manual intervention and without affecting other ONUs. This is possible because the OLT periodically propagates discovery Gate frames, granting a discovery window, where each ONU can provide independently some parameters, like LLID and RTT. The process of auto discover is presented in Figure 2.13.

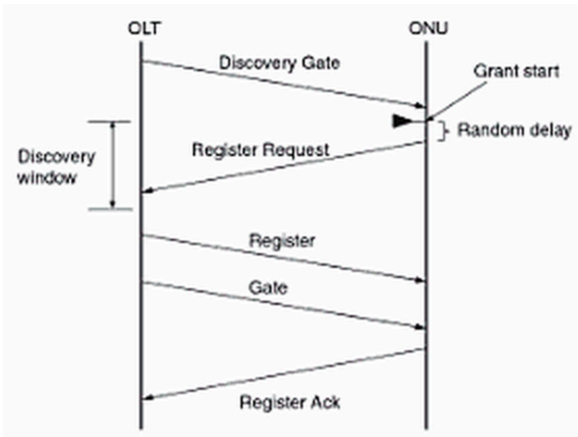



*Figure 2.13 – Auto Discover Process [22]*

When an ONU intends to register, in first place, it receives the discovery gate message and responds with a register request, after a random delay. Then, the OLT allocates the ONU with the LLID, sending a gate frame to grant the upstream time slot for transmission. At last, the ONU sends a register acknowledgement frame to the OLT, establishing the communication channel and finishing the process.

It is possible to have requests from multiples ONUs at the same time, because it is added, to each one, a random delay, before sending the register frame in order to avoid the possible collision.

## 2.4 Gigabit PON (GPON)

There are more and more people using Internet nowadays, what is generating more demand for very high bandwidth. In 2001, became necessary to study a technology capable of incorporate an important feature feed by the needs of operators, which is the ability to upgrade legacy deployments without interrupting service for existing users.

In 2003, emerged the standard GPON (Gigabit-Capable Passive Optical Network), becoming the full recommendation ITU-T G.984.1 [7] in 2008. Seen as an upgrade from BPON [11], it represents an improvement in bandwidth efficiency by the use of larger and variable length packets. GPON, also called “triple play”, allows having Internet, Image in high definition and telephone, replacing the current cooper network IPTV and ADSL. It allows to the consumers the possibility to see all channels in high definition and at three dimensions.

### 2.4.1 Architecture

GPON architecture is based on a typical access network PON. In this way, it is considerable to say that it is a fiber access technology with no active elements in the outside plant. Between the OLT and the ONU, the active elements, there is the single mode fiber and the passive optical splitters 1:N to distribute the traffic to the costumers. The GPON splitter, being a passive element, does not require powering, so it is extremely stable and it never fails in virtual mode. It is characterized for using WDM, to multiplex several optical carriers, in a single optical fiber, through different wavelengths.

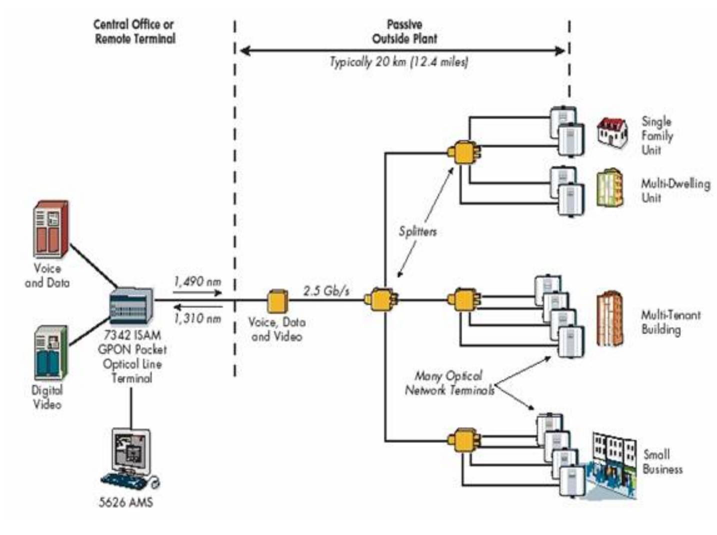



*Figure 2.14 – Scheme of GPON network [24]*

As observed in Figure 2.14-15, GPON network can embrace multiple architectures where the differences between each one are the services supported. The typical architecture is FTTH however, operators seeking to launch fiber deeper into the access network either to a short copper drop (FTTC/FTTB) or as far as subscriber premises (FTTP).

- FTTB - Fiber to the Building - refers to installing optical fiber from the telephone company central office to a specific building such as a business or apartment house and FTTB.

- FTTC – Fiber to the Curb - refers to the installation and use of optical fiber cable directly to the curbs near homes or any business environment as a replacement for "plain old telephone service".

- FTTP – Fiber to the Premises - networks are based on the passive optical network (PON) topology with a passive optical fiber power splitter deployed close to the end user.

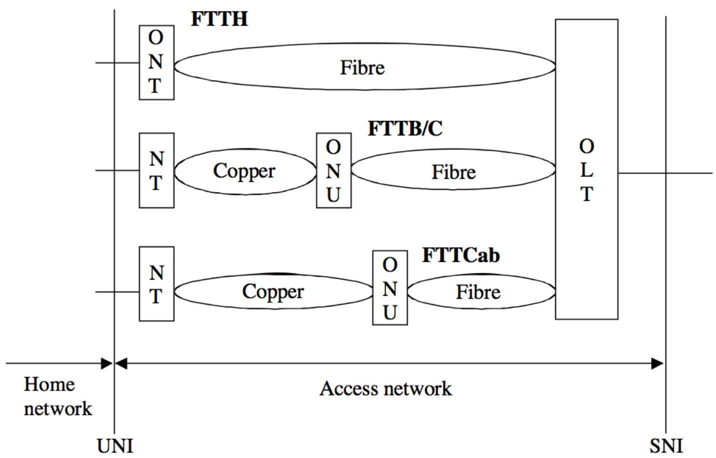



*Figure 2.15 – Different GPON architectures [7]*

On table 2.1, available services and characteristics of different GPON architectures are presented in other to make a better comparison.

| | FTTB Companies | FTTB for MDU | FTTC | FTTCab | FTTH | Provided services |
|---|---|---|---|---|---|---|
| Asymmetric broadband services | × | ✓ | ✓ | ✓ | ✓ | Digital radio diffusion services, Video on Demand (VoD), online games, files download. |
| Symmetric broadband services | ✓ | ✓ | ✓ | ✓ | ✓ | Content transmission, email for files exchange, distance learning, telemedicine. |
| POTS and ISDN | ✓ | ✓ | ✓ | ✓ | ✓ | Must be capable to provide narrow band services by telephone, in a flexible way, with the right moment for introduction. |
| Private line services | ✓ | × | × | × | × | Must be capable to provide private line services and multiple rates, in a flexible way. |
| xDSL backhaul | × | × | ✓ | ✓ | × | |

*Table 2.1 – Provided services by GPON different architectures [25]*

### 2.4.2 Features

**Bit Rate**

This standard is able to define several transmission speed combinations, like is presented in table 2.2:

| | Bit Rate (Gbps) | | | | | | |
|---|---|---|---|---|---|---|---|
| Upstream | 0.155 | 0.622 | 1.244 | 0.155 | 0.622 | 1.244 | 2.488 |
| Downstream | 1.244 | 1.244 | 1.244 | 2.488 | 2.488 | 2.488 | 2.488 |

*Table 2.2 – Possible combinations of GPON Rate transmission*

However, it has the aim to achieve values of 1.2 Gbps or higher. So, the most common bit rate, which is currently supported, is 1.244 Gbps upstream and 2.488 Gbps downstream, shared among users. [7]

**Line Code**

The line code, used in G.984 in both ways of transmission, is NRZ (non-return-to-zero) with scrambling. With NRZ, the receiving clock can lose synchronization due to the lack of transitions in consecutive identical digits (CID). In this way, it is used the scrambling technique, to pseudo randomizing a data stream and trying to avoid long sequences of identical digits. [7]

**Physical and Logical Reach**

The physical reach corresponds to the maximum physical distance between the OLT and an ONU. The GPON technology defines two possible values for this parameter: 10 and 20 km. In case of use a Fabry-Perot laser diode, which is a low cost solution, it is assumed 10km as the maximum distance.

The logical reach corresponds to the maximum distance between the OLT and ONU, except for the limitation of the physical layer. It can achieve values till 60 km, in the maximum. [7]

**Split Ratio**

The passive optical splitter can be in the order of 1:32, 1:64 and 1:128. However, higher the split ratio higher is the optical splitting and, consequently, higher is the power budget needed to cover the physical reach.

In this order, 1:64 is the normal split ratio defined for the current GPON technology. Despites the 1:128 is still not in use, it is an option for the continued evolution of the optical modules. [7]

**Wavelength Range**

With the WDM protocol, the G.984.1 standard uses different wavelengths for upstream and downstream traffic, with a single fiber. The wavelength plan enables the co-existence of ITU-T standards compliant PONs.

EPON and GPON have the same basic wavelength plan. For the downstream traffic, it is defined the 1490 nm wavelength (1480 to 1500) and for the upstream traffic the 1310 nm wavelength (1260 to 1360).

An additional wavelength plan, 1550 to 1560 nm, is reserved for optional overlay services, typically RF (analog) video, in downstream direction. [20]

**Error Correction**

The FEC functionality was defined as optional for some implementations, like GPON standard. In case of being disabled, an ordinary data is transmitted. Nevertheless, it is still necessary to code and decode the data flow.

In G.984 PON standard it is recommended the use of a linear Cyclic Block code – the Reed-Solomon Code (255,239,8) – which allows the correction of 8 bytes. It is able to encode 239 information symbols, adding 16 parity symbols, then creating the 255 information symbols of the coded word, without any disturb.

Forward Error Correction is used in GPON to improve optical link budgets, giving about 3-4 dB extra margin, and to reduce user data in 6%. While without FEC the G.984 requires BER not worst than $10^{-10}$, with FEC it is possible to improve it to $10^{-4}$. [26]

### 2.4.3 Transmission

**Upstream and Downstream Traffic**

For the downstream transmission, the traffic is broadcast from the OLT to ONU in fixed GEM (GPON Encapsulation Mode) frames of 125 μs. Every ONU receives the same data, so they need to distinguish which traffic is destined to each one. This is accomplished through the field GEM port ID, embedded in the frame, allowing the filtering data that is not addressed. This procedure is presented in Figures 2.16-17.

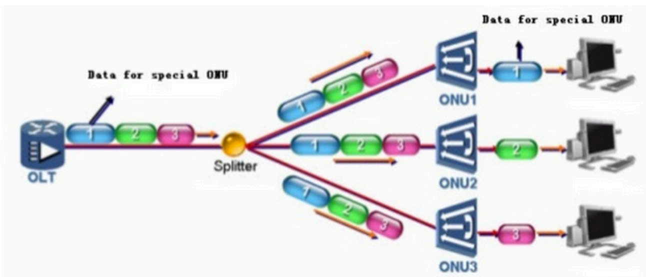



*Figure 2.16 – Downstream transmission traffic [27]*

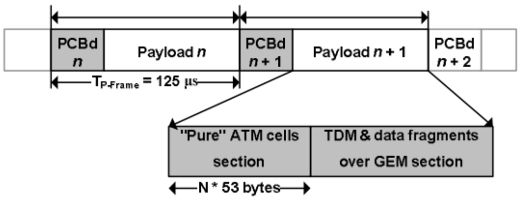



*Figure 2.17 – Downstream GPON frame [28]*

Regarding the upstream traffic, to avoid collisions between packets, it is used the TDMA protocol. The OLT assigns variable length time slots to each ONU with the aim to synchronize the data bursts transmission, as shown in Figure 2.18. The field Upstream Bandwidth Map (BWmap) sent in the downstream frame, dictates, according to its content, the attribution of the time slots.

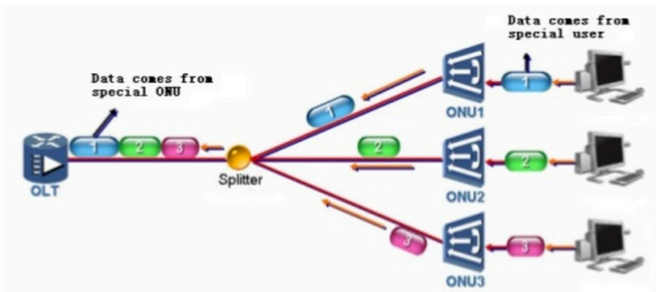



*Figure 2.18 - Upstream transmission traffic [27]*

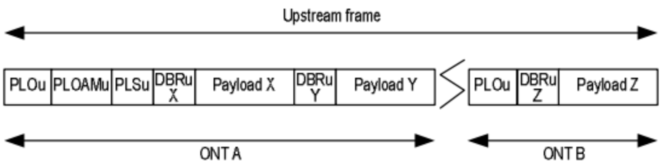



*Figure 2.19 – Upstream GPON frame [28]*

**Ranging**

In the upstream direction, the PON is a multipoint-to-point network, multiplexing data with TDMA. Giving that the distance from the OLT to each ONU is different, if every ONU start to transmit itself, the signal may overlap, since the delay propagation is different. Thus, to achieve an exact synchronization between the elements of the network, the standard G.984.1 uses the ranging mechanism.

Ranging is the process of measuring or calculating a specific delay for every ONU. This method can operate in two ways:

- Initial ranging: performed at ONU boot-up or upon ONU discovery, before the ONU transmits first time.
- Continuous ranging: performed continuously to compensate for delay changes.

In GPON, this mechanism it is preceded in two phases, where the changes are made in the ONU side. In the first step, demonstrated in Figure 2.20 it is attributed and registered a unique serial number, ONU-specific ID, for new ONUs.

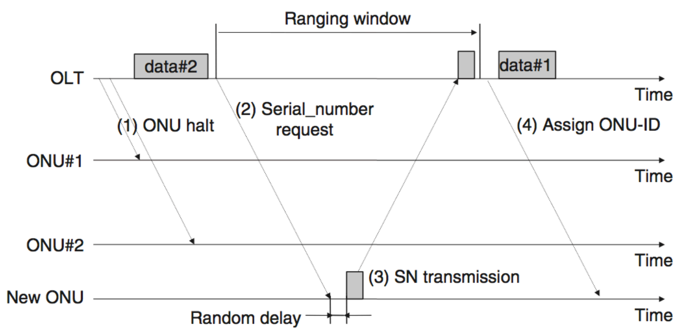



*Figure 2.20 – GPON ranging phase 1: serial number process [29]*

For the second phase, shown in Figure 2.21, the OLT measures the round-trip delay (RTD) to the ONU. Then, the signal transmission timing of each ONU is adjusted according to this RTD so that the signals from individual ONUs arrive at different times and do not overlap.

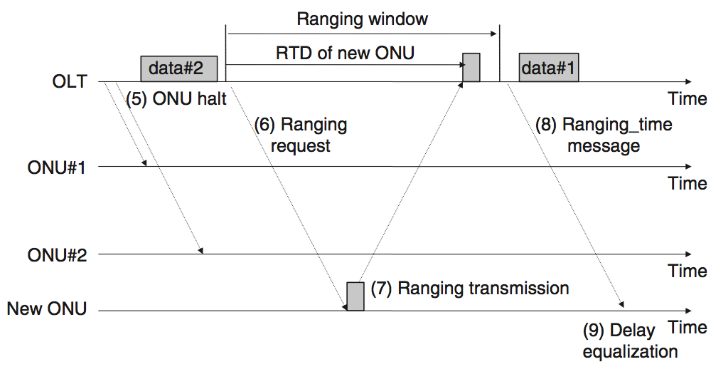



*Figure 2.21 – GPON ranging phase 2: delay measurements [29]*

### Dynamic Bandwidth Allocation

Dynamic bandwidth allocation (DBA), as focused on Figure 2.22, is used to reassign bandwidth volume to ONUs, based on current traffic requirements. This methodology, which is controlled by the OLT, only works in upstream transmission.

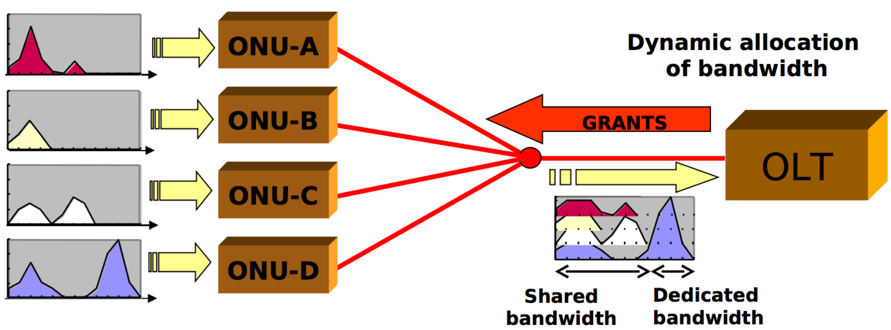



*Figure 2.22 – Dynamic Bandwidth Allocation [30]*

To start the process, the OLT needs to have information about the traffic status of each ONU. In this regard, each ONU has associated a transceiver T-CONT to indicate how many packets are waiting in its buffer. The status is reported in a field called DBRu, which is used to notify to MAC controller a transmission attribution. When the OLT has this information, it is able to determine how much traffic to assign to an ONU, through a management of grants accordingly.

In case of an ONU being empty, it will inform that there is no data to be sent, with an idle cell upstream and the T-CONT grant can be provided to others. [28]

Figure 2.23 presents a scheme of DBA in order to understand better the process.

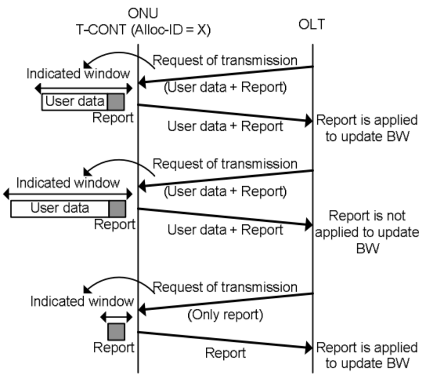



*Figure 2.23 – DBA process [28]*

**Data Encapsulation Method**

The standard G.984.1 defined the GEM, as an encapsulation method for data transportation. It provides the Generic Frame, constituted by 5 headers:

- 12-bit Payload length indicator (PLI) – specifies payload length in bytes;
- 12-bit Port ID – gives the port numbers for traffic multiplexing;
- 3-bit Payload type indicator (PTI) – indicates if the payload has user data frame or OAM frame;
- 13-bit Header Error Control (HEC) – maintains frame synchronization and integrity protection;
- L-byte GEM fragment Payload

GEM frame encapsulation has the function of multiplex ports and payload data fragmentation. In this way, it became very efficient because enables GPON to transport TDM and variable length packets, both carried in the Generic Frame, over fixed data-rate channels, without ATM. [29]

### 2.4.4 Wavelength Coexistence Issues

In recommendation G.984.5 [31], approved in 2007 by ITU-T Study Group [5], was redefine the wavelength ranges, reserved for additional service signals, to be overlaid in future with next generation services – NGA and video. For this purpose, it is presented the tolerance to signals interference from GPON ONUs.

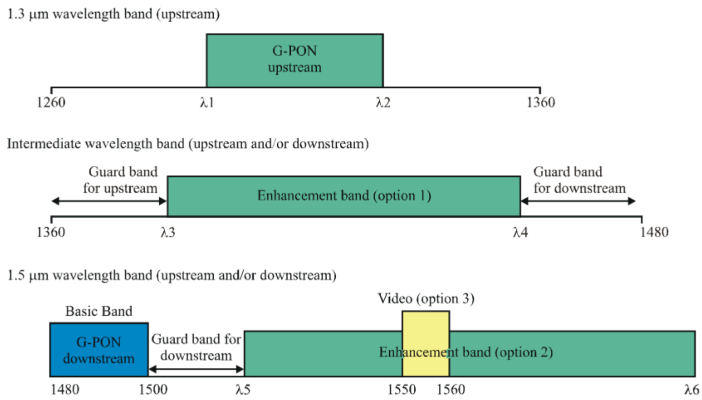


*Figure 2.24 – Wavelength allocation [31]*

In first place, outward in Figure 2.24, the operating wavelength is redefined as basic band to downstream signal and enhancement band for reserved bands, with a guard band between each other. It is used a WBF (Wavelength Blocking Filter) to provide isolation outside the guard band, due to the signal degradation caused by the interference between the two bands.

Notice that, the wavelength range for video and downstream transmission remains the same as defined previously.

Secondly, regarding to the upstream wavelength band, this can occupy three possible options in O band, with width of 20 nm, 40 nm or 100 nm, named as narrow, reduced and regular, respectively. This is possible to visualize in Table 2.3.

| Limit | Notation | Unit | Nominal Value | Application examples |
|---|---|---|---|---|
| 1.3 µm wavelength band | | | | For use in GPON upstream. |
| - Regular wavelength band option | | | | e.g., ONUs based on Fabry-Perot lasers. |
| Lower limit | λ 1 | nm | 1260 | |
| Upper limit | λ 2 | nm | 1360 | |
| - Reduced wavelength band option | | | | e.g., ONUs based on ordinary DFB lasers. |
| Lower limit | λ 1 | nm | 1290 | |
| Upper limit | λ 2 | nm | 1330 | |
| - Narrow wavelength band option | | | | e.g., ONUs based on wavelength selected lasers. |
| Lower limit | λ 1 | nm | 1300 | |
| Upper limit | λ 2 | nm | 1320 | |

*Table 2.3 – Parameters for wavelength allocation of GPON upstream [32]*

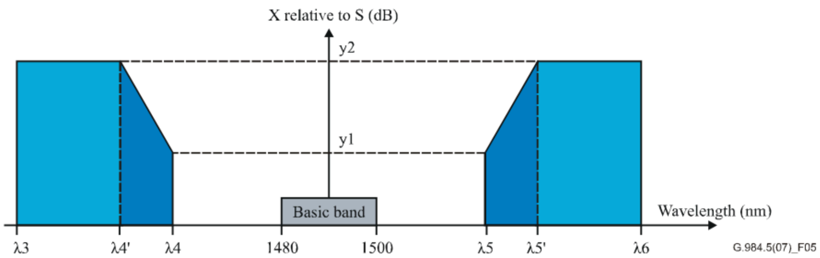
At last, concerning to the next generation services, presented in Table 2.4, were also defined three possible options, two in E+ band and the other in C and L band.

| Bands for Next Generation Services (NGA) | | | | |
|---|---|---|---|---|
| Limit | Notation | Unit | Nominal Value | Application examples |
| Enhancement band (option 1-1) | | | | Applicable for low-water-peak fibers (informative values). |
| Lower Limit | λ 3 | nm | 1415 | |
| Upper Limit | λ 4 | nm | 1450 | |
| Enhancement band (option 1-2) | | | | Applicable for low-water-peak fibers only (informative values). |
| Lower Limit | λ 3 | nm | 1400 | |
| Upper Limit | λ 4 | nm | 1450 | |
| Enhancement band (option 2) | | | | Upper limit determined by choice of the operator considering some factors. |
| Lower Limit | λ 5 | nm | 1530 | |
| Upper Limit | λ 6 | nm | 1580 to 1625 | |

*Table 2.4 - Parameters for wavelength allocation of NGA [32]*

Even with the coexistence of NGA and video, the signals interference in the enhancement band must allow to be known the minimum optical sensitivity. In this order, the ONUs must isolate the interference between signals, using filters with specific isolation characteristics, to guarantee minimum interference effect.

Following, the recommendation G.984.5 presented the X/S tolerance mask – Figure 2.25 - (X – maximum power of interference signal, S – received power of basic band signal) of the GPON ONU, without exceeding the limit for the sensitivity of the basic band receiver. The signal is measured in NRZ pseudo-random format, which can be coded in two options: with the same bit rate as GPON downstream signal or a lower rate within the bandwidth of the basic band receiver. [31]




| Wavelength (nm) | λ3 | λ4' | λ4 | λ5 | λ5' | λ6 |
|---|---|---|---|---|---|---|
| | 1415/1400 *(Informative)* | 1441 *(Informative)* | 1450 *(Informative)* | 1530 | 1539 | 1580 to 1625 |
| X relative to S (dB) | y2 | y2 | y1 | y1 | y2 | y2 |
| | 22 *(Informative)* | 22 *(Informative)* | 7 *(Informative)* | 7 | 22 | 22 |

S Received power of basic band.
X Maximum total power of NGA and video received in the blocking wavelength range.
X/S in the mask (hatching area) should not cause the sensitivity of the basic band receiver to fail to meet the specified limit.
NOTE – λ3 value of 1400 *(Informative)* may be applicable for low-water-peak fibre only.

*Figure 2.25 – S/X tolerance mask for ONU [31]*

Another coexistence scenario, allowing the coexistence between GPON, video and NGA services is shown in Figure 2.26. It takes into consideration the possible video CNR performance degradation that may be caused by interference. With the aim to avoid that, arise the idea of introduce guard bands in both sides of the video band, which will have ranges dependent on filter characteristics of the video band pass filter and video receiver performance.

This situation leads to a wavelength range, between the basic band and video, which cannot be used for NGA downstream signals.

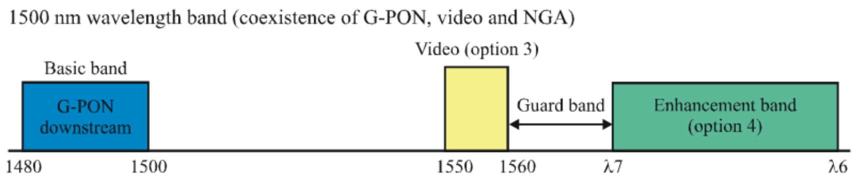



*Figure 2.26 – Wavelength allocation for coexistence between GPON, video and NGA [31]*

The spectrum occupation for the several coexistence scenarios of GPON with NGA and video services is shown in figure 2.5.

| | | 1260 | 1270 | 1280 | 1290 | 1300 | 1310 | 1320 | 1330 | 1340 | 1350 | 1360 | 1370 | 1380 | 1390 | 1400 | 1410 | 1415 | 1420 | 1430 | 1440 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Option 1 | Wdm1rn | | | | | Up narrow | | | | | | Guard Band | | | | | | Option 1-1 | | | 9nm |
| | Wdm1r | | | | Up reduced | | | | | | | | | | | | | | | | 9nm |
| | wdm | Up Regular | | | | | | | | | | | | | | | | | | | 9nm |
| Option 2 | Wdm1rn | | | | | Up narrow | | | | | | Guard Band | | | | Option 1-2 | | | | | 9nm |
| | Wdm1r | | | | Up reduced | | | | | | | | | | | | | | | | 9nm |
| | wdm | Up Regular | | | | | | | | | | | | | | | | | | | 9nm |
| Option 1 + video | Wdm1rn | | | | | Up narrow | | | | | | Guard Band | | | | | | Option 1-1 | | | 9nm |
| | Wdm1r | | | | Up reduced | | | | | | | | | | | | | | | | 9nm |
| | wdm | Up Regular | | | | | | | | | | | | | | | | | | | 9nm |
| Option 2 + video | Wdm1rn | | | | | Up narrow | | | | | | Guard Band | | | | Option 1-2 | | | | | 9nm |
| | Wdm1r | | | | Up reduced | | | | | | | | | | | | | | | | 9nm |
| | wdm | Up Regular | | | | | | | | | | | | | | | | | | | 9nm |
| | | O Band | | | | | | | | | | E Band | | | | | | | | | |

| | | 1450 | 1460 | 1470 | 1480 | 1490 | 1500 | 1510 | 1520 | 1530 | 1535 | 1540 | 1550 | 1560 | 1565 | 1570 | 1575 | 1580 | 1590 | 1600 | 1610 | 1620 | 1625 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Option 1 | Wdm1rn | Guard Band | | | DS GPON | | Guard Band | | | 9nm | | Option 2 | | | | | | | | | | | |
| | Wdm1r | | | | DS GPON | | | | | 9nm | | | | | | | | | | | | | |
| | wdm | | | | DS GPON | | | | | 9nm | | | | | | | | | | | | | |
| Option 2 | Wdm1rn | | | | DS GPON | | | | | 9nm | | | | | | | | | | | | | |
| | Wdm1r | | | | DS GPON | | | | | 9nm | | | | | | | | | | | | | |
| | wdm | | | | DS GPON | | | | | 9nm | | | | | | | | | | | | | |
| Option 1 + video | Wdm1rn | Guard Band | | | DS GPON | | Guard Band | | | 9 | 15nm | | video | 15nm | | | Option 4 | | | | | | |
| | Wdm1r | | | | DS GPON | | | | | 9 | 15nm | | | 15nm | | | | | | | | | |
| | wdm | | | | DS GPON | | | | | 9 | 15nm | | | 15nm | | | | | | | | | |
| Option 2 + video | Wdm1rn | | | | DS GPON | | | | | 9 | 15nm | | | 15nm | | | | | | | | | |
| | Wdm1r | | | | DS GPON | | | | | 9 | 15nm | | | 15nm | | | | | | | | | |
| | wdm | | | | DS GPON | | | | | 9 | 15nm | | | 15nm | | | | | | | | | |
| | | E | S Band | | | | | | | C Band | | | | | L Band | | | | | | | | U |

*Table 2.5 – Wavelength bands for coexistence between GPON and additional services [32]*

Through analysis, the GPON technology gives allocation possibilities in E, C and L band for video and NGA services.

In a scenario of coexistence between GPON and video service, the available spectrum for NGA allocation is restricted to the E and L band and only 5 nm of the C band.

### 2.4.5 Reach extender

In March 2008, arise the recommendation G.984.6 [33], defining architecture and interface parameters to extend the physical layer reach up to 60 km.

To achieve this higher reach, and possibly an increase of the beam splitter, it is allocated a mid-span extender device in the fiber link between the OLT and ODN, which can be a regenerator or an optical amplifier.

However, it brings some negativity, such as the increase of the loss budget and the management of optical impairments. Besides that, there are some needed requirements, like compatibility with existing equipment and electrical power supply.

In the tables 2.6-8, it is possible to check the specifications for mid-span extenders relative to OLT and ONU elements and the power balance in ODN and OLT.

| OLT Transmitter | | |
|---|---|---|
| Transmission Rate | 2488.32 | Mbps |
| Wavelength | 1480-1500 | nm |
| Line Code | NRZ | |
| Minimum Power | 1.5 | dBm |
| Maximum Power | 5 | dBm |
| Extinction Ratio | > 8.2 | dB |
| Dispersion reach at 1 dB penalty | 60 | Km |

| OLT Receiver | | |
|---|---|---|
| Transmission Rate | 1244.16 | Mbps |
| Wavelength | 1290-1330 | Nm |
| Line Code | NRZ | |
| Sensitivity | -28 | dBm |
| Maximum Power | -8 | dBm |
| BER | $10^{-10}$ | |

*Table 2.6 – Defined specifications for OLT [34]*

| Maximum Attenuation | Downstream (dB) | Upstream (dB) |
|---|---|---|
| OLT | 23 | 28 |
| ODN | 13 to 28 | |

*Table 2.7 – Power Balance in OLT and ODN [34]*

| ONU Transmitter | | |
|---|---|---|
| Transmission Rate | 1244.16 | Mbps |
| Wavelength | 1290-1330 | nm |
| Line Code | NRZ | |
| Minimum Power | 0.5 | dBm |
| Maximum Power | 5 | dBm |
| Extinction Ratio | > 10 | dB |
| Dispersion reach at 1 dB penalty | 60 | Km |

| ONU Receiver | | |
|---|---|---|
| Transmission Rate | 2488.32 | Mbps |
| Wavelength | 1480-1500 | Nm |
| Line Code | NRZ | |
| Sensitivity | -27 | dBm |
| Maximum Power | -8 | dBm |
| BER | $10^{-10}$ | |

*Table 2.8 – Defined specifications for ONU [34]*

## 2.5 Next Generation PON (NGPON)

### 2.5.1 Introduction

The bandwidth demand has a significant raise over the years, meaning that the current PON networks, like GPON, are not able to cover the users needs. This growth of Internet and the competition between telecommunication operators are leading to further investigation.

The future involves innovation and improvement to the existing technology, which means, even better P2MP technology, through an upgrade plan. The research that has been developed tackles the dual lower cost / higher quality. The new research in the area is focus to allow an increase in bandwidth, data rates and reach, and better splits with the capability of smooth migration system between generations and the reuse of the fiber plant. [35] To meet this end, a new architecture, that incorporates the WDM technology, started to be developed.

This research is today known as NGPON – Next Generation Passive Optical Network, divided in two stages. In 2012, emerged the NGPON1, approved as G.987 [8] by ITU-T Incorporation, and in 2013 appeared the NGPON2, approved as G.989.1 recommendation [9], still in development expected till 2015.

### 2.5.2 Roadmap

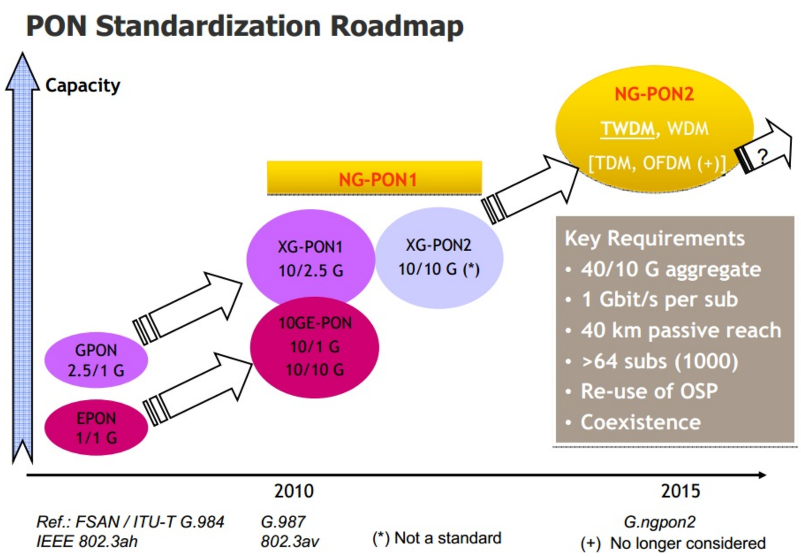



*Figure 2.27 – NGPON roadmap [36]*

Studies conducted by organizations, ITU-T and FSAN, always try to meet the future need of users. As such, as noticeable in Figure 2.27, the new technology is divided into two phases, by the maturity of growth: NGPON1 and NGPON2.

- NGPON1, being a mid-term update, is compatible with GPON technology in the same ODN, making use of existing structures. Thus, it is possible to make a smooth migration while new users are served, to control the associated cost.
- NGPON2, as a long-term update, can take advantage of new elements and technology, to full fill the desired requirements, like higher capacity, longer reach, higher bandwidth and more users.

Still in development, despite the several candidate technologies to be adopted, TWDM was the winner.

## 2.6 10 Gigabit PON (XGPON)

Concerning to the GPON system, the upgrade is achieved by wavelength overlapping of generations, leading to the next generation standard.

Thus, in 2010, arose the G.987.1 standard [37] – 10 Gigabit Passive Optical Network (XGPON also known as 10GPON or NGPON1), with general requirements. The research of this stage one in the new generation of access networks lasted until 2012, when the recommendation G.987 [8] was finally approved.

This technology has become a cost-effective way to meet performance demands in access networks. However, in terms of spit ratio and target distance, it will not present significant differences.

### 2.6.1 Architecture

XGPON architecture is based on a typical access network PON. In this way, it is considerable to say that it is a fiber access technology with no active elements in the outside plant. Between the OLT and the ONU, the active elements, are the single mode fiber and the passive optical splitters 1:N to distribute the traffic to the costumers. The XGPON splitter, being a passive element, does not require powering, so it is extremely stable and it never fails in virtual mode. This technology is characterized for using WDM, to multiplex several optical carriers, in a single optical fiber, through different wavelengths.

Like the previous technology, the G.897 standard can support architectures, such as FTTH, FTTC and FTTB. In addition, despite these scenarios, it is able to support two more: FTTCell (Fiber to the Cell) and FTTO (Fiber to the Office). Each one has different services supported and different locations for the ONU, what can be better understood through Figures 2.28-29.

- Fiber To The Office: has the aim to address each ONU integrated in a business plan to a small business costumer;
- Fiber To The Cell: provides connectivity between a wireless base station and the ONU, called a cell-site backhauling unit (CBU).

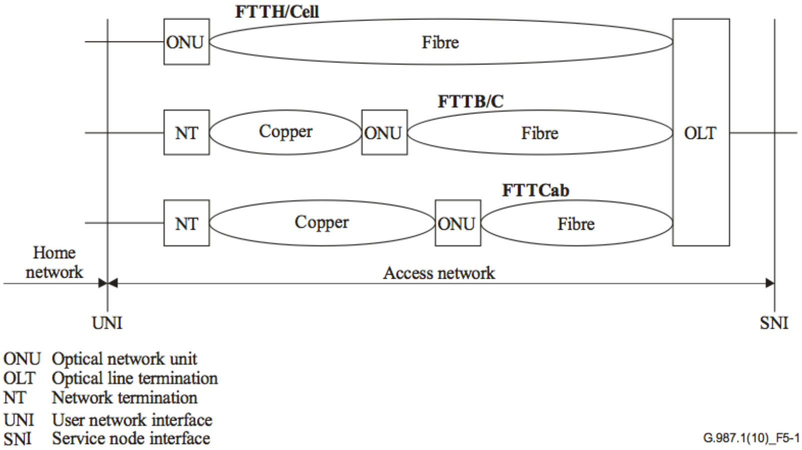



*Figure 2.28 – Different FTTx architectures [37]*

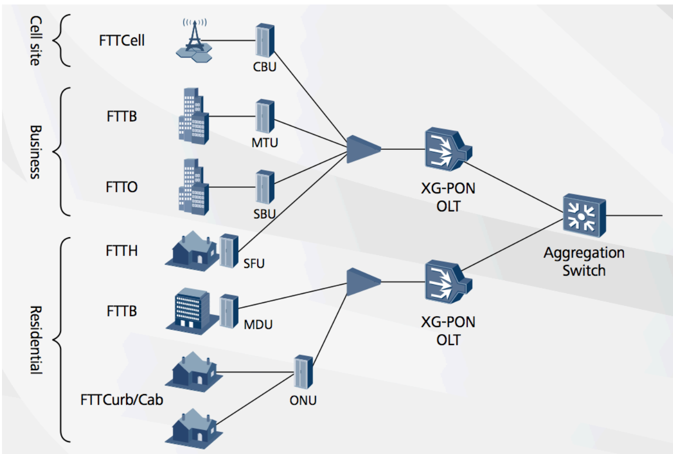



*Figure 2.29 – Architectures supported by XGPON [37]*

On table 2.9, available services and characteristics of different XGPON architectures are presented in other to make a better comparison.

| | FTTB Companies | FTTB for MDU | FTTC and FTTCab | FTTO | FTTCell wireless | FTTH |
|---|---|---|---|---|---|---|
| Asymmetric broadband services | × | ✓ | ✓ | × | × | ✓ |
| Symmetric broadband services | ✓ | ✓ | ✓ | ✓ | × | ✓ |
| POTS | ✓ | ✓ | ✓ | ✓ | × | ✓ |
| Private line services | ✓ | × | × | ✓ | × | × |
| xDSL backhaul | × | × | ✓ | × | × | × |
| Asymmetric/Symmetric Broadband services based in packets | × | × | × | × | ✓ | × |
| Symmetric TDM services | × | × | × | × | ✓ | × |
| Hot Spots | × | × | × | × | × | × |

*Table 2.9 – Provided services by XGPON different architectures [38]*

### 2.6.2 Features

**Bit Rate**

The G.987.1 recommendation defined two transmission velocities, with changes only in the upstream traffic, as presented in Table 2.10:

| | Bit Rate (Gbps) | |
|---|---|---|
| | Downstream | Upstream |
| XGPON1 | 10 | 2.5 |
| XGPON2 | 10 | 10 |

*Table 2.10 – Transmission speeds for XGPON [37]*

Nevertheless, in a first stage, the attention goes through XGPON1 due to technology challenges, like low cost, which need to be overtaken. The nominal values for this standard are a downstream line rate of 9.95328 Gbps and an upstream line rate of 2.48832 Gbps.

In this way, XGPON2 technology will just have focus later, in a second phase.

**Line Code**

The line code, used in G.987 standard in both ways of transmission, is NRZ (non-return-to-zero) with scrambling. With NRZ, the receiving clock can lose synchronization due to the lack of transitions in consecutive identical digits (CID). In this way, it is used the scrambling technique, to pseudo randomizing a data stream and trying to avoid long sequences of identical digits. [39]

**Split Ratio**

Since the typical split ratios, already defined in previous technologies, were 1:32 and 1:64, it was expected a higher split ratio as a requirement for XGPON.

Some network operators were interested in increase the splitter to 1:128 and 1:256, in order to improve economics and support a diversity of deployment scenarios. Thus, it should support 256-way, or more, logical split taking into consideration the maturity and cost-effectiveness of optical devices. [37]

**Wavelength Range**

The operators discussed the wavelength plan in order to provide the better solution, maintaining the coexistence with GPON technology and video services.

Toward downstream wavelength range, the choice was made looking to the band that was left in the system with RF overlay video services. Respecting to the upstream wavelength range, the process implied a comparative study between C-, L- and O- bands. C and L band were excluded because of overlap with RF overlay video channel and insufficient guard band between wavelengths, respectively. The selection either took into consideration the complexity and costs associated. [40]

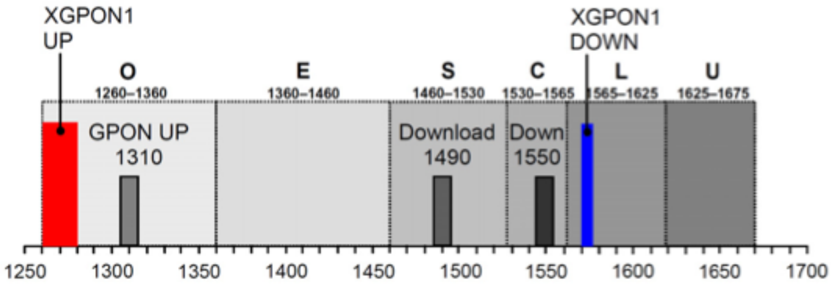



*Figure 2.30 – XGPON wavelength allocation coexisting with GPON and video [40]*

In conclusion and visualizing Figure 2.30, for the upstream traffic was defined the range of 1260 to 1280 nm in the O- band. For downstream traffic, it was selected the 1575 to 1580 nm wavelength range, in the L band. [37]

**Fiber Reach**

The XGPON1 recommendation is capable to support a fiber distance of 20 km, at least.

Furthermore, the TC layer must be able to support 60 km of maximum fiber distance and up to 40 km of maximum differential fiber distance. [37]

**Optical Power Budget**

There were selected two nominal power budget classes, Nominal1 – 29 dB and Nominal2 – 31 dB, at BER of $1^{-12}$. These classes were defined due to additional loss added by the WDM1r device, which comes from the coexistence between GPON and XGPON, expected as a nominal requirement. [37] Besides, the limit of the maximum power loss was defined in another class called Extended with value of 35 dB. [39]

**Error Correction**

Contrary to previous technologies, the FEC (Forward Error Correction) is now obligatory in the G.987 recommendation, in both ways, to be possible to achieve the required power budgets and to handle with higher transmission rates.

Concerning to the downstream way, the code used is a truncated version of Reed-Solomon (255,223), named RS(248,216), necessary to allow the insertion of an integer number of code words into the 125 μs downstream frame. It is constituted by 32 parity bytes added to the 223 bytes of data, making the 255 bytes of coded word and it allows the correction of 16 bytes.

For the Upstream transmission, was selected a truncated version of RS(255,239), called RS(248,232). This code consists in 232 data bytes, with 16 added parity bytes, making the 248 bytes of coded word and allowing the correction of 8 bytes. [41]

### 2.6.3 System Requirements

**Dynamic Bandwidth Allocation**

The upstream transmission of the G.987.1 recommendation appeals to a DBA - Dynamic Bandwidth Allocation – method, in order to improve utilization of the capacity, which means better efficiency.

DBA has the aim of allocate bandwidth to each connected ONU, taking into account the upstream traffic demand and requirements. This dynamic activity can be indicated based on two methods: [37]

- Status reporting (SR): the OLT requires reports with information about buffer occupancy;
- Traffic monitoring (TM): the actual traffic amount is compared with the allocated upstream transmission.

Due to the better bandwidth efficiency brought with the DBA mechanism, network operators are able to introduce more subscribers to a PON, where each one can enjoy of advanced services with variable rates.

However, the DBA must be appropriately designed, for the required specifications, to avoid high delays or deteriorated bandwidth usage efficiency.

### 2.6.4 Migration Scenarios

The standard XGPON G.987.1 was specified to be compatible with GPON deployments, in order to sustain the GPON operator's investments and dedicated time. In this purpose, it can reuse the existing optical fibers and splitters but with different wavelengths for upstream and downstream. Besides that, it allows a smooth migration, being possible to serve new clients while GPON clients are getting the update over time.

The FSAN/ITU-T Incorporations came up with two different and possible evolution scenarios: Greenfield and Brownfield PON scenarios.

- Greenfield scenario does not require the co-existence with the GPON deployments, as it seeks to renew the entire access network, deploying new PON systems. This scenario becomes a possibility to replace the pre-existing infrastructure based on cooper or to be implemented in more favorable areas covers, being capable to provide better features.

- Brownfield scenario makes use of already existing PON systems, by allocating these infrastructures for greater bandwidth. The migration process will depend on the number of present subscribers, since they can remain in or migrate to XGPON system, not being necessary to migrate all at once. After some time, when the coexistence of the two standards became unjustified, due to a substantial decrease of the GPON users number, the operators can force the migration to XGPON.

Taking in consideration these two scenarios, the first one is not the best option, since it requires more investment from the operators. The second one, once it uses de coexistence of GPON with XGPON, is more favorable. However, it is dependent on the time that GPON and XGPON will coexist in the same ODN, which is normally a long period, leading to a very slow migration. [37]

For the coexistence with GPON and to assure the smooth migration, XGPON standard has to incorporate a WDMA technology, in the upstream way, to separate different wavelengths for each costumer.

With the aim to combine and isolate the GPON signals and the next generation service bands, it is constituted by an optical filter WDM1r implemented in the central office and WBF (Wavelength Blocking Filter) on the user side. The explained migration scenario is visible in Figure 2.31.

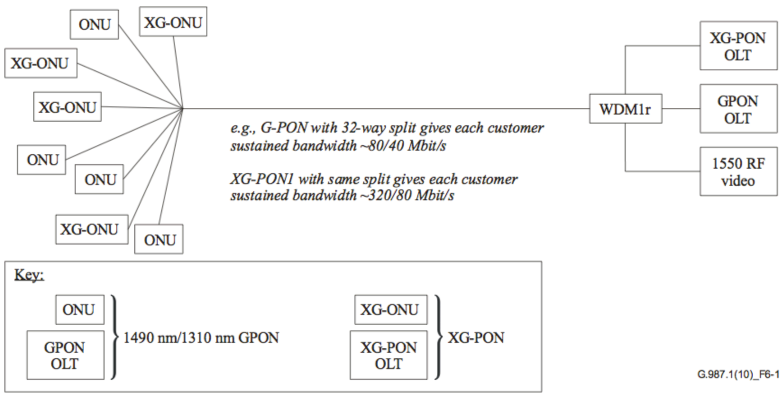



*Figure 2.31 – Migration scenario from GPON to XGPON [37]*

### 2.6.5 Co-existence issues

In recommendation G.987.1 was redefined the reserved wavelength range and the tolerance for interference signals of the ONUs, with the purpose to generate the coexistence plan between GPON, XGPON and video services, through Figure 2.32.

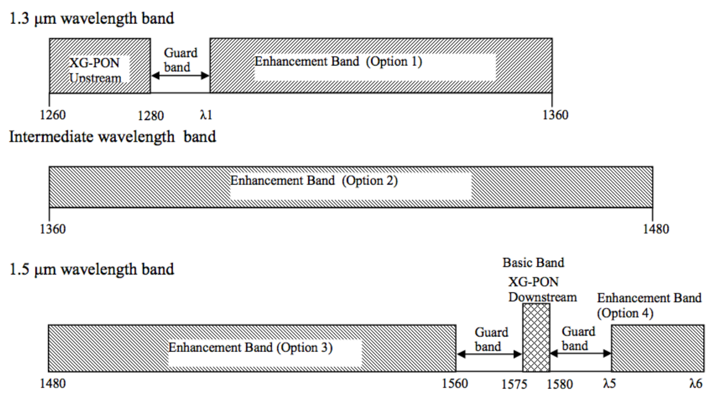



*Figure 2.32 – Wavelength allocation [37]*

As in Recommendation G.984.5, referred in section 2.4.4, the operating wavelength is redefined as basic band to downstream signal and enhancement band for reserved bands, with a guard band between each other. It is used a WBF (Wavelength Blocking Filters) to provide isolation outside the guard band, due to the signal degradation caused by the interference between the two bands.

Notice that, the wavelength range for video and downstream transmission remains the same as defined previously.

The Table 2.11 presents the new allocation plan, including wavelength bands reserved for additional services, to ensure the required coexistence.

| Limit | Notation | Unit | Nominal Value | Application Examples |
|---|---|---|---|---|
| XGPON1 upstream | | | | For use in XG-PON1 upstream. |
| Lower Limit | - | nm | 1260 | |
| Upper Limit | - | nm | 1280 | |
| Enhancement band (option 1) | | | | For use in XG-PON1 upstream (Reduced option: 1290-1330 nm). |
| Lower Limit | λ 1 | nm | 1290 | |
| Upper Limit | - | nm | 1330 | |
| Enhancement band (option 2) | | | | For future use. |
| Lower Limit | - | nm | 1360 | |
| Upper Limit | - | nm | 1480 | |
| Enhancement band (option 3) | | | | For use in GPON downstream (1480-1500 nm) and/or video distribution service (1550-1560 nm) |
| Lower Limit | - | nm | 1480 | |
| Upper Limit | - | nm | 1560 | |
| XGPON downstream (Basic band) | | | | For use in XGPON downstream. |
| Lower Limit | - | nm | 1575 | |
| Upper Limit | - | nm | 1580 | |
| Enhancement band (option 4) | | | | For future use. |
| Lower Limit | λ 5 | nm | 1590 | |
| Upper Limit | λ 6 | nm | 1625 | |

*Table 2.11 – Wavelength bands allocation [37]*

The spectrum occupation for the several coexistence scenarios of XGPON with GPON and video is shown in Table 2.12.

| | 1260 | 1270 | 1280 | 1290 | 1300 | 1310 | 1320 | 1330 | 1340 | 1350 | 1360 | 1370 | 1380 | 1390 | 1400 | 1410 | 1415 | 1420 | 1430 | 1440 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| XGPON | UP XGPON | | G.B. | Option 1 | | | | | | | Option 2 | | | | | | | | | |
| XGPON, GPON | UP XGPON | | G.B. | UP GPON | | | | Option 1 | | | Option 2 | | | | | | | | | |
| XGPON, XGPON, video | UP XGPON | | G.B. | UP GPON | | | | Option 1 | | | Option 2 | | | | | | | | | |
| | O Band | | | | | | | | | | E Band | | | | | | | | | |

| | 1450 | 1460 | 1470 | 1480 | 1490 | 1500 | 1510 | 1520 | 1530 | 1535 | 1540 | 1550 | 1560 | 1565 | 1570 | 1575 | 1580 | 1590 | 1600 | 1610 | 1620 | 1625 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| XGPON | Option 2 | | | Option 3 | | | | | | | | | Guard Band | | | DS | G.B. | Option 4 | | | | |
| XGPON, GPON | Guard Band | | | DS GPON | | Guard Band | | | Option 3 | | | | Guard Band | | | DS | G.B. | Option 4 | | | | |
| XGPON, GPON, video | | | | DS GPON | | | | | | 15 nm | | Video | 15 nm | | | DS | G.B. | Option 4 | | | | |
| | E | S Band | | | | | | | C Band | | | | L Band | | | | | | | | | U |

*Table 2.12 – Wavelength bands for coexistence between XGPON and additional services [32]*

It is noteworthy that C band can be totally available for the coexistence scenario of XGPON with GPON, with the absence of the video service. Besides that, are available the E band and some nm of the O and L band.

In case of the coexistence scenario between XGPON, GPON and video, is available just some nm of the O and C band. Regarding to the L and E band, they are almost entirely available.

## 2.7 Next Generation PON 2 (NGPON2)

All the previous technologies have been standardized and deployed worldwide. Despite the several improvements to monetize the optical networks, over the years become necessary new revenue to minimize operation costs and full fill relevant requirements. Nowadays, the network operators are deeply involved with one main requirement for a future PON: be able to supply higher bandwidth, sufficient to cover business applications and the growth of consumer's demand.

On March of 2013 was approved the ITU-T G.989.1 recommendation [9] – Next Generation Passive Optical Network 2 – addressing the general requirements.

NGPON2, being a robust and flexible optical access network, is structured to handle efficiently with numerous applications, such as mobile backhaul, residential and business.

### 2.7.1 Requirements

With the technological advance that has come to notice, it is important to continually work on technologies that support higher transmission rates and hailing higher bandwidth. The ideal is to compress everything into a single platform without active elements and reuse existing structures to reduce operating costs. These needs are boosted by the progressive evolution of video services, provided by unicast platforms that will lead to a higher traffic volume, which is driven by future trends: [42]

- Virtual on-line environments and video games;
- Network of virtual computers;
- Evolution of actual TV formats: Super HD, Ultra HD and 3D;
- Higher number of connected devices in one home;
- Higher traffic due to a video calls.

In order to respond to the future demands, the NGPON2 technology seeks to fulfill the following requirements till 2015: [9] [42]

- 10 Gbps aggregate capacity for upstream;
- 40 Gbps aggregate capacity for downstream;
- 1:256 passive splitter (minimum);
- Basic 40 km range;
- 60 km range, at least, with reach extender;
- Increased security and data integrity;
- Design cost-efficiency for downstream and upstream;
- Colorless ONUs to allow spectral flexibility;
- Reuse of already implemented infrastructures;
- Reducing energy costs without losing service quality.

### 2.7.2 Spectral Options

About NGPON2, overcame a relevant issue that predominates over the exact wavelength range to be used. Despites the large offer of spectrum capacity, there are some factors, which may influence some wavelengths to be used, such as lasers, receivers, amplification, existing standards, coexistence issues and costs considerations.

One main restriction to take into consideration is the use, by mostly operators, of the conventional single mode fiber (SMF), in some access networks. Once the SMF represent a good operation, recently, between 1260-1360 nm and 1480 nm forward, the restriction felt in the use of those windows, in order to manage cost issues.

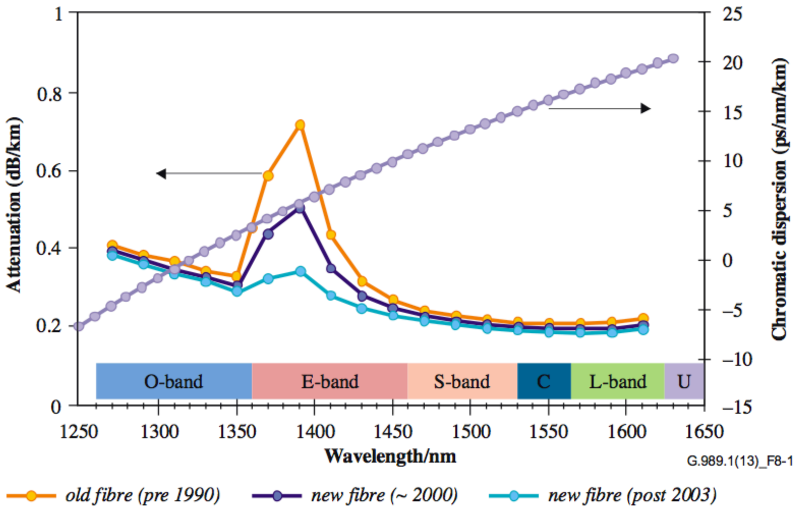



*Figure 2.33 – Attenuation of SMF over wavelength range [9]*

Observing Figure 2.33, the lower attenuation of an optical signal is verified for C-Band and lower L-Band. Also it is possible to visualize the chromatic dispersion dependency with the wavelength, where it has a zero value at 1310 nm for SMF.

Another wavelength limitation is referred to the opt-electronic components availability. The use of Semiconductor Optical Amplifiers (SOAs) does not furnish any particular restriction, since it can work in any pretended bands. However, commonly available Erbium Doped Fiber Amplifiers (EDFAs) are just able to work in C and L bands. [9]

This aspect is manly due to the NGPON2 requirement for increasing power in order to obtain high reaches and splits. Thus, the optical components, like tunable lasers and coherent receivers, capable of provide that high level of power, can only operate, in a reasonable way, at 1550 nm. [43]

One further aspect concerns to the coexistence issue, falls in the NGPON2 requirement of reuse the already installed infrastructures. The existing standards like GPON and XGPON use separated frequency bands whereas Video overlay uses 1550 nm wavelength. The problem relies in the use of large spectrum from previous standards that is now difficult to recover, as manifested in Figure 2.34. Moreover, the standards also defined some guard bands that must be respected, due to the filters characteristics. The most considerable one is the used for video overlay which covers almost the entire C band, where the fiber loss is lower.

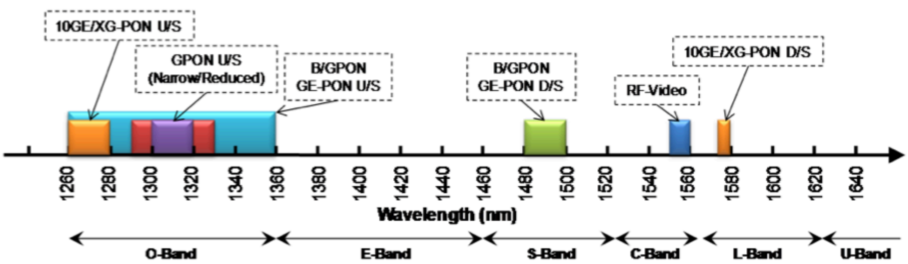



*Figure 2.34 – Wavelength plans of legacy PON systems [9]*

In this way, it is noteworthy that NGPON2 wavelength allocation will be defined according operators needs, in a variety of possible ways, for several possible scenarios enumerated on Figure 2.35. Mainly scenarios allowing coexistence with legacy PONs and signals with different modulation formats, creating heterogeneous networks with high data rate formats.

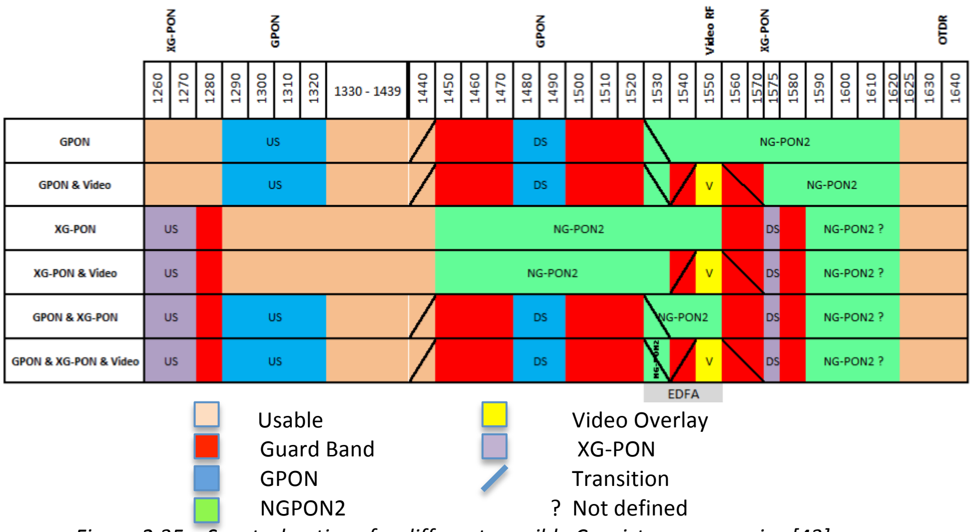



*Figure 2.35 – Spectral options for different possible Coexistence scenarios [43]*

Considering all the possible scenarios of coexistence and the mentioned limitations driven by pretended requirements, the available wavelengths band for NGPON2 is just the L band and some nm of the C band (1530-1539 nm).

### 2.7.3 Candidate Technologies

In the beginning of the research for NGPON2 by ITU-T, were considered only basic requirements, so it was not required compatibility with existing ODN or previous PON systems. Adopting this approach, were proposed several different technologies, highlighting:

- OFDM – Orthogonal Frequency Division Multiplexing;
- OCDM – Optical Code Division Multiplexing;
- WDM – Wavelength Division Multiplexing;
- 40 Gbps TDM – Time Division Multiplexing;
- UDWDM – Ultra Dense Wavelength Division Multiplexing;
- TWDM – Time Wavelength Division Multiplexing.

With the development of research, was reached the conclusion that each system has specific characteristics, so it became necessary to decide what the most important and which is ideal to meet NGPON2 requirements. [44]

Some features and network concepts of each technology, which were taken into account, are shown below.

**OFDM**

OFDM technology subdivides a single transmission into multiple signals with lower spectral occupation, spaced in a manner that each carrier can overlap with the zeros of the other signals in order to avoid inter-symbolic interference. To generate the division of data into digital OFDM signals, it apply FTT (Fast Fourier Transform) arising several data blocks to be coded. This can be observed in Figure 2.36.

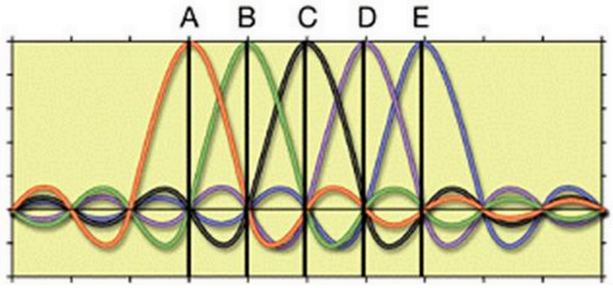



*Figure 2.36 – Concept of signal OFDM [42]*

This technique is capable of getting a good performance with high broadband efficiency, because it allows dynamic broadband allocation, becoming more flexible. Besides that, it offers a method to increase the system performance and gives 40 Gbps to the upstream and downstream bit rates what is very attractive. The fundamental advantage of OFDM relies on the operational cost, where it reveals to be economically profitable. [42]

**OCDM**

The OCDM concept is based on the identification of all ONUs through a code word, which is represented by a specific pulses sequence, represented in the optical domain. In this way, is possible to use the entire frequency band available, where all the subscribers are able to transmit at the same time. Its based architecture is shown in Figure 2.37.

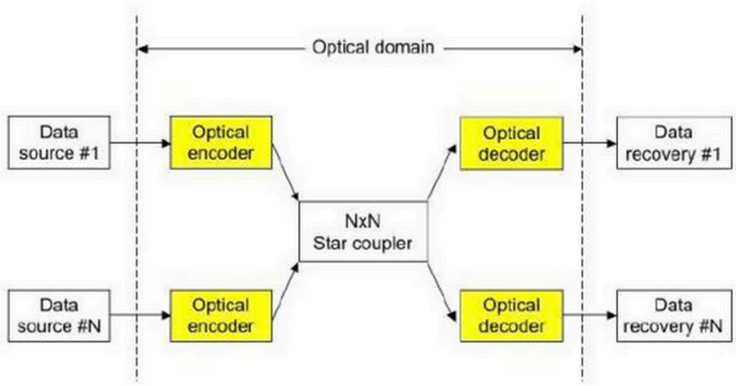



*Figure 2.37 – OCDM base architecture [42]*

The greater advantage of the OCDM technology is the reliable security around the network and the information, leading to higher spectral efficiency and equipment cost reduction. Thus, it is able to support an asynchronous transmission with lower latency and without complex electrical components. Besides, it does not define any fixed limit of the supported users number.

However, a large increase of the users in the system can originate higher interference between channels, making necessary the physical components to operate with higher rates, comparative with the data rates of the users. This has the disadvantage of deteriorate the signal, limiting the system performance. [42]

**WDM**

WDM-PON technology is used to multiplex several optical signals in one single fiber, carried by different wavelengths. Each wavelength provides a dedicated wavelength channel at the rate of 1Gbps to each ONU.
(See section 2.2.)

**40 Gbps TDM**

This technology, also called XLG-PON is base on TDM-PON (See section 2.2). It is capable to provide 40 Gbps in the single carrier serial downstream bit rate, necessary in XGPON1. Regards to the upstream bit rate, it provides a 10 Gbps serial TDMA. [45]

Due to this high range of choices, FSAN operators reformulated their true aims for NGPON2. One of the main goals felt in the idea of operate on the existing ODN, so many options were eliminated by their leak of compatibility. The next two firm requirements were the capability to support till 8 independent operators and maintain coexistence with video overlay.

The shifted requirements, over time had a remarkable effect in the selection. By this way, in the FTTH European consortium, realized in February 2012, were distinguished two technological solutions that were best positioned for this responsibility: TWDM-PON and UDWDM-PON.

**UDWDM**

UDWDM uses power splitters and filters, like AWG, becoming a universal technology for existing ODNs and future deployments. In this system, each ONU receives its respective wavelength and sends an upstream one, of about 1 GHz, with fixed distance to the downstream wavelength. Thus, it allows the OLT to provide till 1000 individual wavelengths with short spacing of 2.8 GHz. Its network concept is display on Figure 2.38.

This technique was formulated to be able to address future challenges, joining an intelligent system design with some technologies and innovations, such as: [46]

- A 10 wavelengths plan, generated by advanced IQ modulation, to receive unwanted reflections that can be ignored;
- Coherent detection, introduced in the light of performance, to decrease some design criteria and increase optical performance;
- Silicon Photonics (SiP) to reduce efforts packaging, integrating individual components in optical modules and moving much of the complexity into the electronic domain, enabling cost reduction;
- Paired-Channel technology which allows to hide the expensive wavelength locking and thermo-electric cooling, given the relationship between upstream and downstream channels directly adjacent and with a fixed off-set;
- Sub-wavelength splitting able to share a single downstream wavelength of 1Gbit/s by multiple ONUs, achieving scalability from 100Mbps to 10 Gbps.

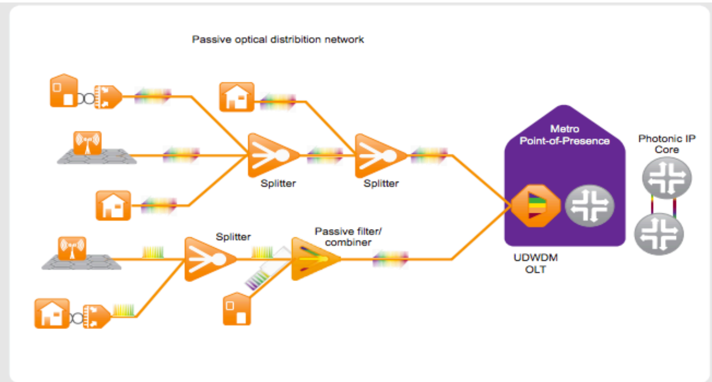



*Figure 2.38 – High level UDWDM network concept [46]*

In this regard, UDWDM is an innovative technology, capable of give the necessary bandwidth for the next years, solving the lack of effectiveness in scalability, at a reduced cost. Other great advantage is to allow the coexistence with standardized systems, providing a smooth migration. It is ideal to obtain new network projects, allowing to overlay the connectivity scenarios effectively, both present and future, without increasing the investment in hardware path and consolidating a new operational vision.

**TWDM**

TWDM technology is a hybrid system combining time and wavelength division multiplexed. WDM is used to attach multiple XGPON1s, through four pair of wavelengths being capable of supporting 40 Gbps and 10 Gbps bit rates in downstream and upstream, respectively. [45] (See section 2.7.4 for further information)

### 2.7.4 TWDM-PON selection

Comparing all the features and advantages of each proposed technology, it did not take much long for all the attention be directed to TWDM-PON, which was selected in April 2012 as the architecture for NGPON2. [44]

**Architecture**

TWDM technology, in contrary to the previous standardized PONs that use only TDM, adds multiple wavelengths (WDM) to stack XGPON flows.

The basic configuration of its architecture, exhibit on Figure 2.39, shows four pair of wavelengths, to provide 40 Gbps bit rate in downstream and 10 Gbps in upstream, with a split ratio of 1:64. Although, can be also considered 8 and 16 wavelengths channels.

The optical amplifier is introduced in the scheme, at the OLT block, with the aim to increase the power budget, in comparison with XGPON1. It has two functions: stimulate the downstream signals and pre-amplify the upstream signals.[44]

Also at the OLT side, are the multiplexer to multiplex the different XGPONs in the transmission fiber and the demultiplexer to isolate the wavelengths came from the ONUs, both implemented through an AWG (Array Waveguide Grating).

In order to create a simple network deployment, are used colorless ONUs, each one able to provide peak rates of 10 Gbps downstream and 2.5 Gbps upstream or symmetric 10 Gbps. This way, the tunable transmitters and receivers are able to tune upstream and downstream wavelengths, respectively. [47]

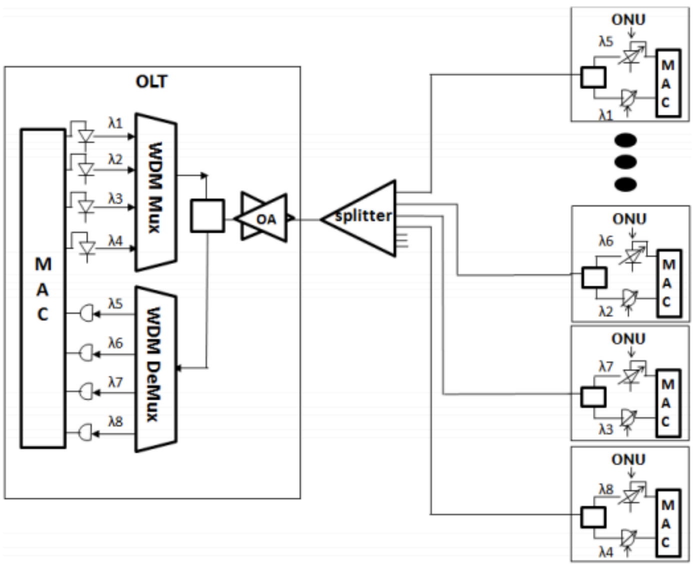



*Figure 2.39 – TWDM system architecture [44]*

Notice that, once the OA and mux/demux are at the OLT side, the ODN remains passive. All the changes occur in the OLT and ONU terminals, allowing operators to increase network capacities without transform the ODN, which makes TWDM an attractive technology. [47]

**Features**

As it was mentioned in the previous topic, TWDM technology combines multiple XGPON systems with distinct wavelengths, where for a number of used wavelengths will lead to that number times the XGPON bandwidth. Thus, the G.989.1 recommendation [9] defined some configurations that must be supported as in Table 2.13:

| | Bit Rate (Gbps) | | |
|---|---|---|---|
| Upstream | 10 | 2.5 | 2.5 |
| Downstream | 10 | 10 | 2.5 |

*Table 2.13 – Bit Rate configurations supported by NGPON2.*

Moreover, it must support a set of combinations, being flexible in a way that some features like speed, distance and split ratios can be balanced. So, the system must include: [9]

| | | Features | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | US capacity (Gbps) | DS capacity (Gbps) | Range (km) | Split Ratio | Gbps/channel | US Peak Rate (Gbps) | DS Peak Rate (Gbps) |
| Combinations | 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 |
| | C8 | Higher transmission distances + lower split ratios | | | | | | |
| | C9 | Tunable WDM point-to-point connection + coexistence with other PONs | | | | | | |

*Table 2.14 – Set of combinations supported by NGPON2.*

**Power Budget**

Power budget is an important parameter, used to evaluate the network performance. Features like the split ratio and the maximum transmission distance, which characterize the coverage of a PON technology, are limited by the power budget of the upstream and downstream ways.

This parameter is obtained through measurements of the transmitting power and received signal sensitivity. Regarding to the power launched into the transmitting fiber, it is necessary to be careful with the quantity that cannot be too high, to avoid fiber nonlinearities. Besides, the ODN must remain passive so it is not possible to add an amplifier in the transmission link between the OLT and ONU. Thus, the power budget parameter can just be optimized by higher signal sensitivity, which can be achieved through APD (Avalanche Photodiode) and pre-amplification employed at the receiver.

The research about this topic has an interesting relevance. NGPON2 operators are determined to extend PON reach and split, in order to decrease the number of central offices – concentrate the OLTs - and server a larger geographic area from each OLT. This way, the objective of reduce costs can be achieved, since the monetary value can be split by a larger number of subscribers. [48]

**Wavelength Range**

TWDM does not define any specific requirement relative to the wavelength allocation. In this order, there are several options available, providing, or not, coexistence with previous employed technologies.

The first option is to reuse the already existing wavelength bands for XGPON, defining a smaller grid inside of it. The main idea is to not through way the developed work dedicated to that standard. Thus, XGPON technology is blocked in this option, but it is possible to maintain coexistence with GPON and RF video overlay, obtaining a typical loss budget of about 33 dB.

In disadvantage, once it uses the higher loss 1270 nm band, it is difficult to achieve 40 km of passive reach. [44]

One factor that may influence the spectrum choice is the wavelengths spacing, which can be 50 GHz, 100 GHz or the most relaxed 200 GHz. It creates a tradeoff between hardware design complexity/cost and spectral efficiency.

Figure 2.40 shows the wavelength plan for this option, with 200 GHz wavelengths spacing.

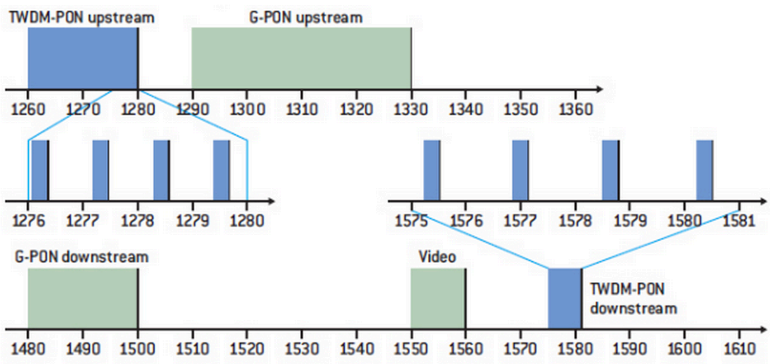



*Figure 2.40 – Wavelength allocation reusing XGPON wavelength [49]*

The second option, exhibit in Figure 2.14, relies on de C band, in a way to use it for both downstream and upstream wavelengths allocation. This system is attractive because the signal is amplified through EDFAs, allowing long distance transmission with low transmission losses and high power budget, able to achieve 38 dB of loss budget. [45]

In this regard, it is possible to obtain coexistence with GPON and XGPON, but RF video overlay channel will be blocked.

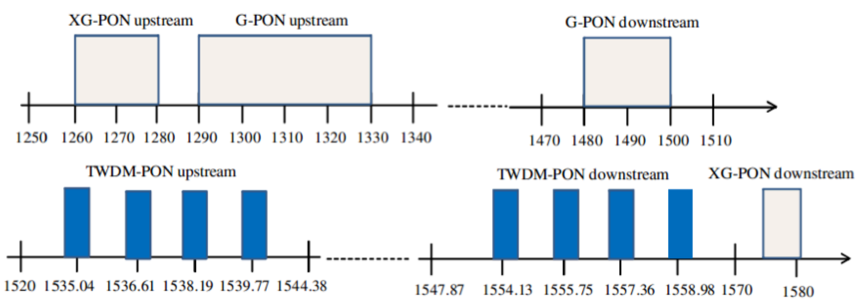



*Figure 2.41 – Wavelength allocation redefining the C band (Based on [49])*

The third option is a mixture of the above two plans, where the upstream channels are allocated in the C-minus band, while the downstream channels are allocated in the L-minus band. Its wavelength plan is visible on Figure 2.42.

This system is similar to the second option, being thereby compatible with GPON and RF Video Overlay technologies but blocking XGPON. Furthermore, it also takes advantage of the EDFA preamplifier to provide higher power budget, whereas the L band needs another amplifier to improve it. Thus, it is able to achieve 38 dB of loss budget.

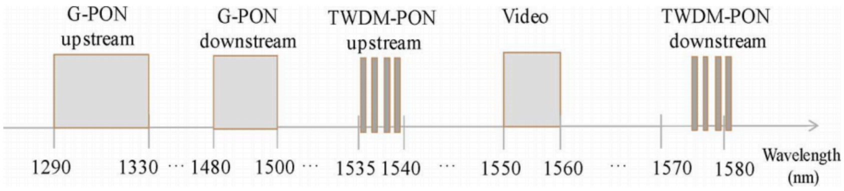



*Figure 2.42 - Wavelength allocation using C-minus/L-minus band [50]*

Finally, the fourth option for the TWDM-PON wavelength plan, demonstrated on Figure 2.43, came out on May 2013, with the aim to allow coexistence between the previous standardized technologies, such as GPON, XGPON and RF Video Overlay with NGPON2. This system defines de use of the O, E, S, C and L bands. This scenario is possible in a manner that the spectrum already allocated is not reused for other PON technology.

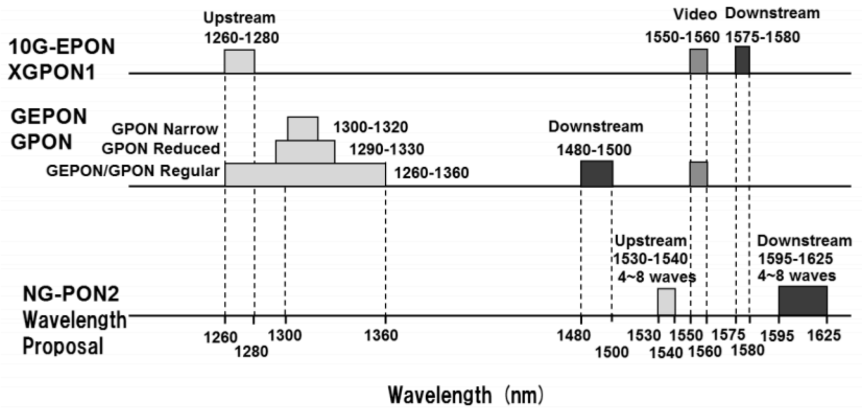



*Figure 2.43 – Wavelength plan for coexistence between GPON, XGPON, Video and TWDM [51]*

This topic is still an active study by FSAN [3] and ITU-T Recommendation [5]. As TWDM does not present specific requirements for the wavelength plan, it can be defined according operators needs. Anyway, the option should be defined taking into consideration the coexistence with previous PONs and the reuse of the commercial components. The most favorable option in this regard is to use the L band for downstream and the C band for upstream transmission.

**Migration and Co-existence Scenarios**

One huge requirement for NGPON2 is the capability to ensure a smooth migration from previous installed standards, on the same ODN in order to protect the investments made to deploy these legacy PON systems, including the fiber infrastructure.

G.989.1 recommendation specifies two migration scenarios, PON brownfield migration scenario and PON greenfield migration scenario, like in section 2.6.4 for the migration from GPON to XGPON. [9]

With the aim to facilitate the process and enable a flexible migration, coexistence between PONs should exist. Thus, it is possible to proceed to migration, without the subscribers waiting too much long to move their services and without service interruption.

The best scenario would be the coexistence with PON legacy, creating maximum flexibility, to characterize NGPON2 as a coexistent system over the whole, end-to-end ODN including over the feeder fiber. In this regard, the technology should reuse existing PON optical power splitters and operate on usable but available spectrum. The required coexistence scenario is demonstrated on Figure 2.44.

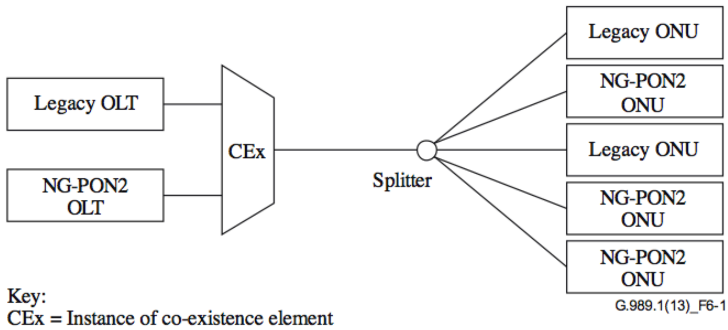



*Figure 2.44 – ODN coexistence scenario [9]*

With the purpose to create an easy migration on existing infrastructure without any prolonged service interruption, NGPON2 must support a migration path from GPON to NGPON2 and another from XGPON1 to NGPON2. In this order, came out three possibilities with different level of flexibility:

1. Straight migration
2. Flexible migration
3. All-embracing migration

In the first migration scenario, it is only possible to migrate from one PON to another followed in the line of the Legacy, like from GPON to XGPON and then XGPON to NGPON2. Thus, it is necessary to first complete the upgrade to XGPON before starting evolving to NGPON2. One solution to allow coexistence between the two last technologies could be removing GPON from the ODN and reuse that wavelength window.

The flexible migration scenario provides migration from GPON to NGPON2 without the middle process. The requirement need to allow this process is the coexistence between GPON and NGPON2.

The third migration scenario is the most challenging one. All-embracing migration enables coexistence between GPON, XGPON and NGPON2, creating a greater flexibility on the upgrades from one technology to another. Furthermore, it allows direct migration from GPON to NGPON2, requiring a large range of optical wavelength band. Besides the offer of large flexibility, it makes the legacy ODN future proof, making this scenario the most desirable one.

It is noteworthy that, independently of the chosen scenario, is required the reuse of the ONUs and OLTs already deployed without any changes or insert additional filters. In addition, the attenuation of additional devices – CEx referred on figure 2.44 - must be kept similar to those introduced by wdm1r with the aim to maintain the legacy optical budget. [9]

## 2.8 Modulation Formats

Fiber-optic communication systems became a revolutionary high-capacity infrastructure able to furnish broadband data services and advanced Internet applications. Along the time, the optical networks were routed with high spectral efficiencies, due to the constant need for higher transmission capacities and lower costs. Thus, the key to the design of flexible and cost-effective WDM fiber systems, operating at high bit rates, falls in the optical modulation formats.

The different modulation formats are distinguished through some parameters, such as, the number of symbols representing the binary transmitted data and the physical characteristic of the CW light wave. In this order, they can be divided into three modulation categories: intensity, phase and polarization. However, the last one has received less attention for use in high-speed optical systems [52]. On other hand, amplitude combined or not with phase modulation results in multi-level signaling, offering benefits in line of the high data rate transmissions.

Intensity modulation formats, also known as ASK (Amplitude Shift Keying) allows, in addition to a very simple transmitter, the use of a simple receiver for detection because semiconductor lasers are electrically pumped, having short photon lifetimes. Two examples of this type of modulation are: NRZ-OOK (Non-Return to Zero On-Off Keying) and RZ-OOK (Return to Zero On-Off Keying).

Phase modulation, known as PSK (Phase Shift Keying), means that the information is carried on the optical phase, shifting the phase between consecutive bits to recover the information in the reception. This group includes BPSK (Binary-Phase-Shift Keying) and QPSK (Quaternary-Phase-Shift keying) modulation formats.

Over time, research has been focused on a hybrid multilevel intensity/phase modulation, called QAM (Quadrature Amplitude Modulation), which become a good candidate for high capacity and high spectrally efficient optical systems [53].

By relevance, this work only addresses the study of NRZ-OOK, QPSK and 16QAM modulation format. It is presented some characteristics and comparisons between them.

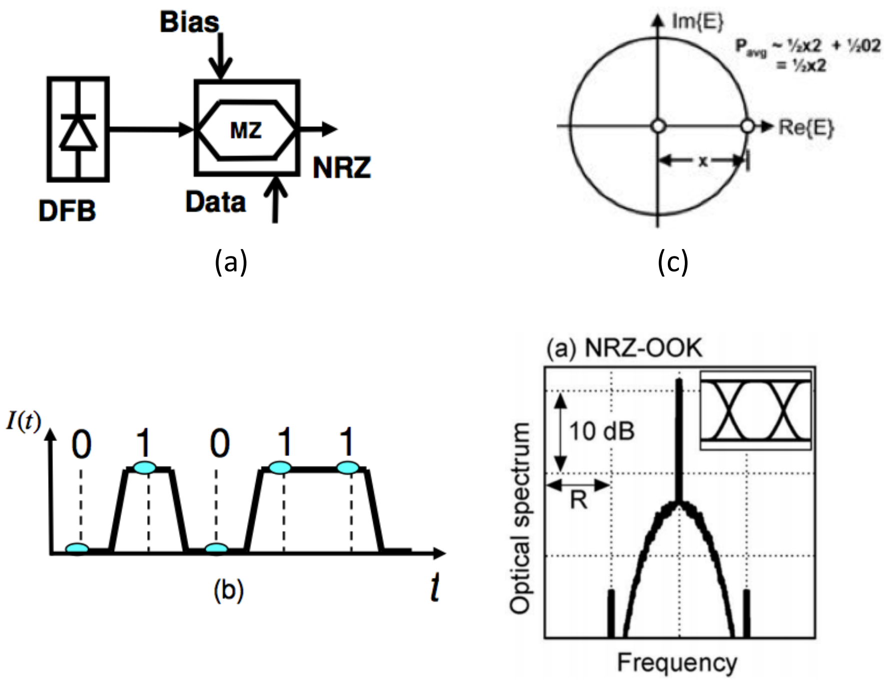
### 2.8.1 NRZ-OOK

NRZ is a simple technique used to convert from electrical to optical binary information, where a quantity of pulses are transmitted by data stream of 0's and 1's.

Figure 2.45 (a) presents a block diagram of a NRZ transmitter with a DFB (Distributed feedback) laser and an external intensity modulator that can be a MZM or an electro-absorption modulator. Its function is to convert an electrical signal into an optical signal at the same data rate [54]. In this case, the modulator is normally biased at 50% transmission, known as quadrature point, and is managed from minimum to maximum transmission. At the receiver is used a simple photodiode to detect the signal and convert the optical power into electrical current.

Looking at Figure 2.45 (c) is easy to understand that OOK formats only encode 1bit/symbol, meaning that it is necessary twice the bit rate to guarantee the required bandwidth to avoid symbols interference and the symbol rate is the same as the bit rate.

As observed in Figure 2.45 (d), NRZ presents an optical spectrum more compact in comparison with other modulation formats. However, that fact does not validate higher resistance to linear and nonlinear effects.




(d)

*Figure 2.45 –Transmitter Block diagram (a); waveform for intensity (b); ideal constellation diagram (c) and optical spectrum (d) [52, 54].*

NRZ modulation format has some advantages, like low electrical bandwidth for transmitters and receivers, not sensitivity to laser phase noise and it has the simplest system configuration. In disadvantage, it is very sensitive to fiber impairments with the increase of the bit rate. Also, increasing the power will trigger nonlinear effects.

Despites NRZ format not present the best choice for future high capacity networks, it has been already widely deployed, being now used in most of the terrestrial long-haul transmission systems.

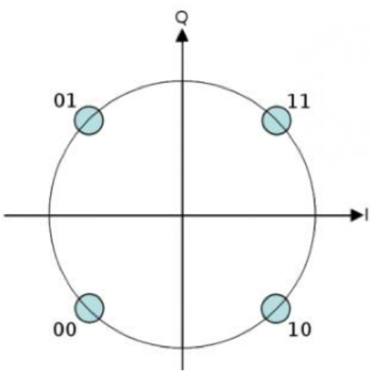
### 2.8.2 QPSK

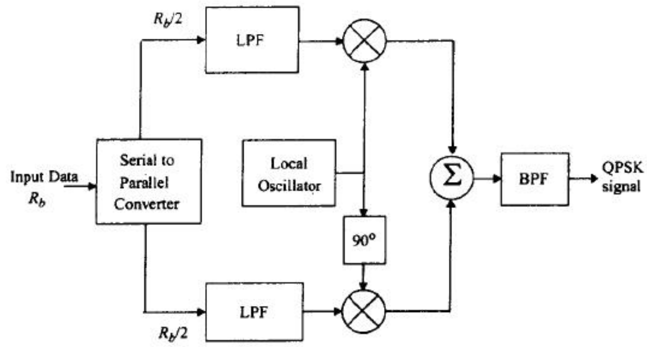
In recent years, advanced modulation formats won a considerable focus in the area of high data rates per channel in WDM networks to increase robustness of transmission lines.

QPSK, also known as 4-PSK, is based on the phase carrier modulation, belonging to the multi-level format that encodes 2bits/symbol. So, the required bandwidth to avoid symbols interference is the bit rate and the symbol rate is half the bit rate, making it more efficient and robust against chromatic dispersion. From Figure 2.46 (a) it is possible to deduce that for each 2-bit combination corresponds a different phase, as shown in table 2.15 [55].

| Symbol | 11 | 10 | 00 | 01 |
|---|---|---|---|---|
| Phase | $\pi/4$ | $3\pi/4$ | $5\pi/4$ | $7\pi/4$ |

*Table 2.15 – Phases corresponding to each symbol.*




(a) (b)

*Figure 2.46 – Ideal Constellation Diagram (a); QPSK Modulator (b) [55, 56].*

The Figure 2.46 (b) presents the structure of a QPSK Modulator. At first, the signal is divided into two branches being after mixed with a local oscillator to move the baseband signal to the desired frequency. At the output, a delay of $\pi/2$ is added to one of the branches and, then, the two signals are combined, originating the different phases [55].

An advantage of QPSK modulated signals over OOK falls in the higher spectral efficiency and twice lower symbol rate to obtain an equivalent overall bit rate. However, in disadvantage, to guarantee the success of the transmission, the OSNR requirements must increase and the receiver is much more complex [52].

### 2.8.3 16QAM

QAM is a hybrid multi-level modulation format, combining the ASK and PSK, providing a square configuration of the symbols constellation. In this case are encoded 4bits/symbol, leading to a decrease of the channel spacing, applied in WDM, in four times lower compared with OOK [55].

To generate 16QAM signals have been proposed a few techniques. The most prevalent one uses two 4-level signals to conduct the IQ modulator arms. Two electrical signals, equally spaced in amplitude, conduct the IQ modulator over the linear part of its transfer function, after converted into optical signals, creating two 4-ASK. These signals are phase shifted by $\pi/2$ inside the IQ modulator, leading to interference at the output of the MZI (Mach-Zehnder Interferometer). This way is created the 16QAM signal.

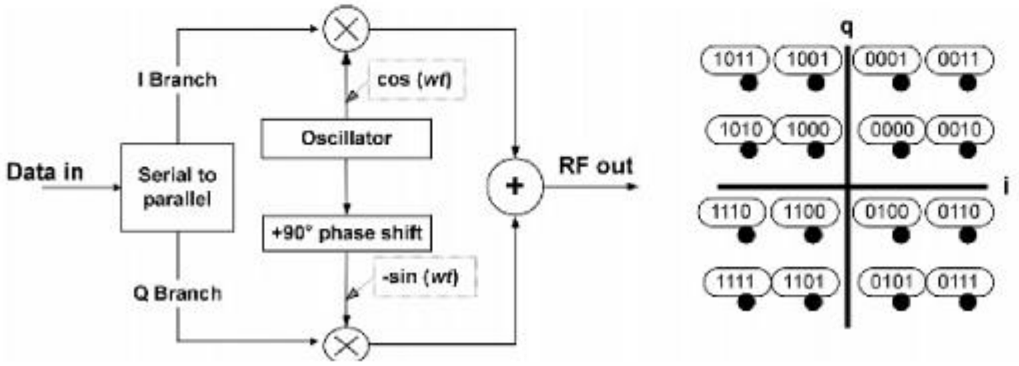



*Figure 2.47 – Structure of a QAM Modulator (left) and constellation diagram of a 16QAM signal (right) [57].*

In advantage, 16QAM modulation offers twice higher spectral efficiency than QPSK and decreases the required symbol rate to obtain the equivalent bit-rate. Nevertheless, it needs a higher OSNR and behaves with worse performance in the linear and nonlinear transmission. In other way, the spectral efficiency approaches the Shannon limit closer than QPSK, being larger for the same SNR and M [52].

# 3 Simulation Results

## 3.1 PON System Characterization

### 3.1.1 Introduction

In this section, it is used a simulation software called VPI [10], with the purpose to obtain results relative to Passive Optical Networks. In order to compare some results between technologies and take conclusions, some parameters in the schematic were defined the same.

- BitRateDefault = 2.5 Gbps
- SampleRateDefault = 32*BitRateDefault
- TimeWIndow = 512/BitRateDefault

Besides, all the schematic were implemented with an attenuator in the end of the fiber, attenuation value 18 dB, with the aim to simulate a splitter 1:64 and another attenuator in the receiver part, to be able to obtain values of BER between the established.

### 3.1.2 GPON System Characterization

GPON system was simulated with 2.5 Gbps for the downstream traffic and 1.25 Gbps for the upstream traffic. The setup used for this simulation is presented in Figure 3.1.

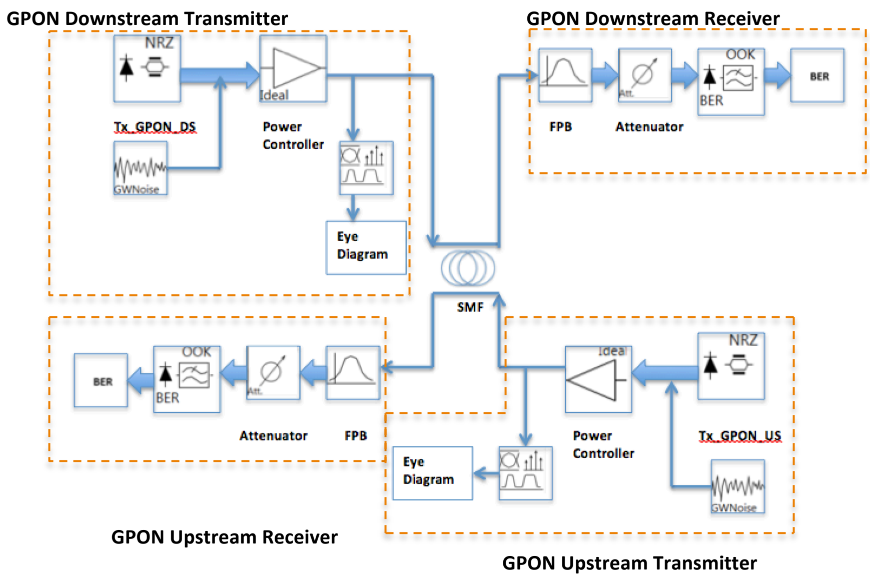



*Figure 3.1 – Simulated setup of GPON in VPI.*

#### Optical Spectrum

The wavelength plan used in the setup was chosen, according the standard G.984.5 [31], as 1490 nm for downstream traffic and 1310 nm for upstream traffic.

In this way, the first step was to visualize the optical spectrum of each correspondent channel, with 3 dBm of transmitted power, as exhibit in Figures 3.2-3.

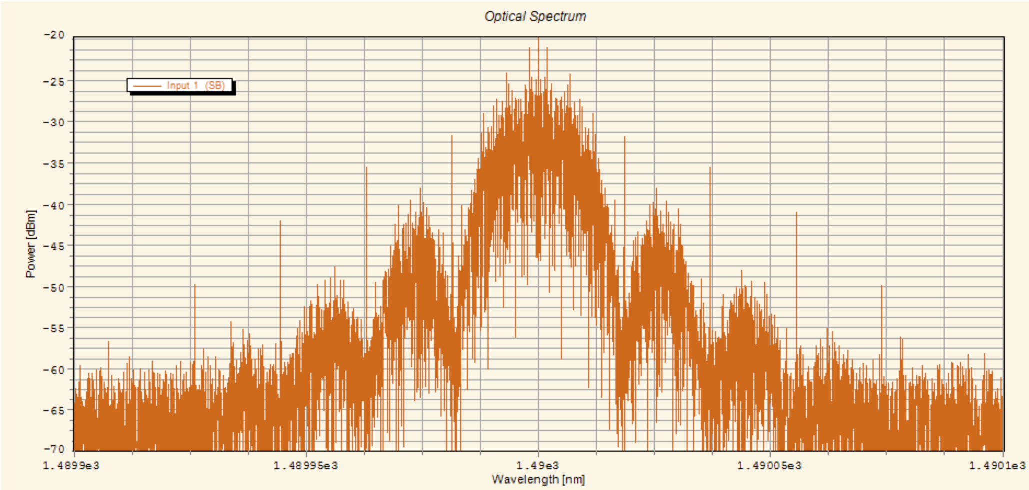



*Figure 3.2 - Optical Spectrum for downstream.*

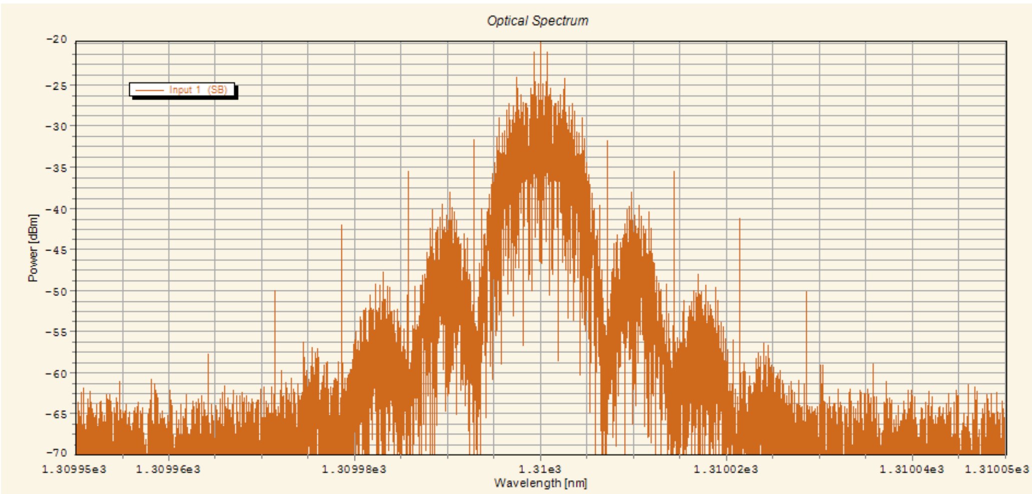



*Figure 3.3 - Optical Spectrum for upstream.*

### System Sensitivity

To characterize the system, the sensitivity was measured for downstream and upstream traffic. Thus, the transmitted power was fixed in 3 dBm and was created a sweep with the attenuator varying the received power to obtain values of BER between the established. The result is presented in Figure 3.4.

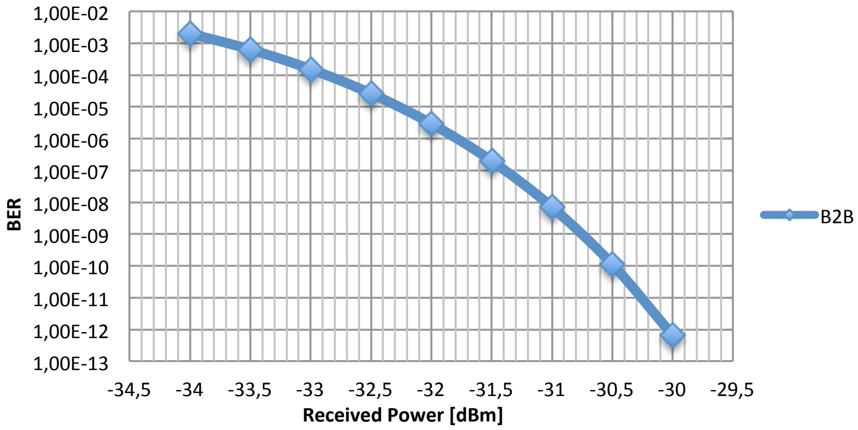



*Figure 3.4- BER vs Received power for downstream.*

For downstream way, the minimum acceptable power in the receiver, for the limit of BER 1E-3, is around -34 dBm. The performance of the system was studied, in the same conditions, introducing fiber of 20, 40 and 60 km, for comparative evaluation. In the three cases were not observed any differences, as expected, due to the low bit rate.

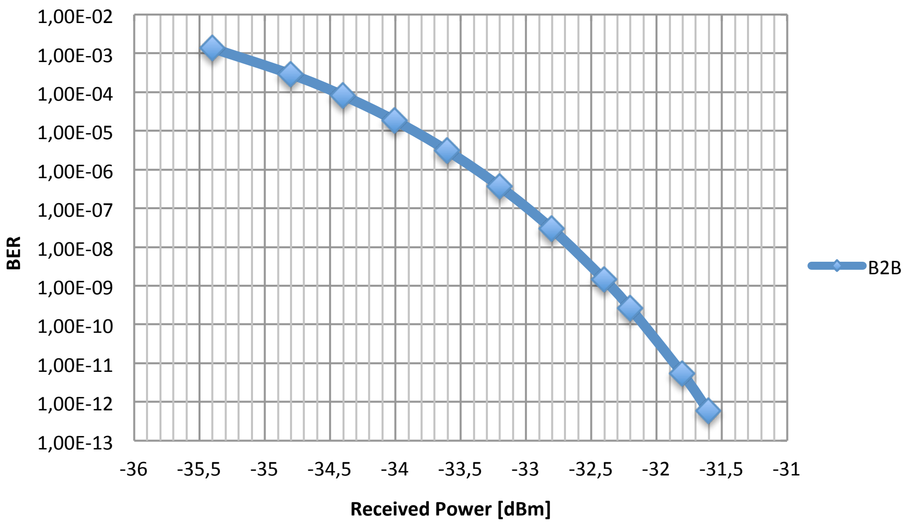



*Figure 3.5 - BER vs Received power for upstream.*

Regarding the GPON upstream, the minimum acceptable value is -35.5 dBm, as visible on Figure 3.5. It is expected to be lower than the above situation, once the bit rate is lower. Also the obtained result for the setup with 20, 40 and 60 km fiber was similar, by the same reason explained in the downstream.

**Maximum Reach**

The next study was about the maximum distance that could be obtained with different transmitted power. For this situation was necessary to adjust the attenuation to be able to get values of BER between the defined ranges. The transmitted power was chosen according the power defined in the standard [58]. The results are shown in Figures 3.6-7.

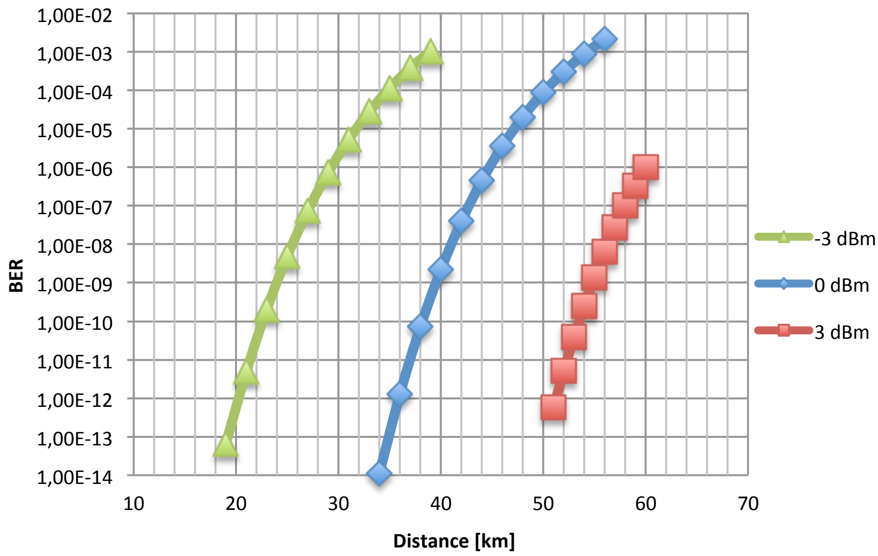



*Figure 3.6 – Downstream maximum reach obtained for different transmitted power.*

In downstream, the system can reach 40 km with -3 dBm of transmitted power and 55 km with 0 dBm. Once the distance is determined by the attenuation, it is possible to say that with +3 dBm the system will be improved in 15 km, reaching 70 km. It's noteworthy that was not used any amplifier in this setup.

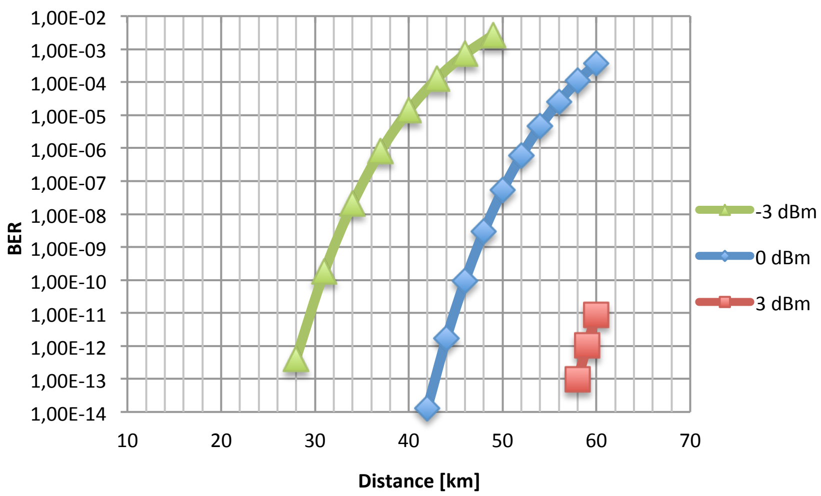



*Figure 3.7 – Upstream maximum reach obtained for different transmitted power.*

For the upstream, was possible to get results for -3dBm and 3 dBm. In the first case, the maximum reach was 45 km and for the second case is expected a distance of 75 km, for the same reason explained above.

### 3.1.3 XGPON System Characterization

XGPON system was simulated with 10 Gbps for the downstream traffic and 2.5 Gbps for the upstream traffic. The setup used for this simulation is presented in Figure 3.8.

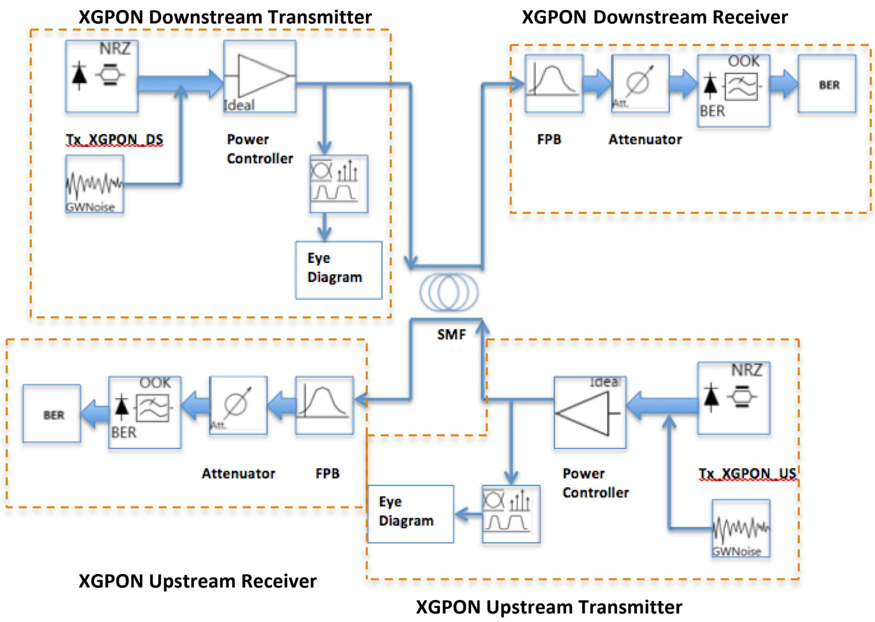



*Figure 3.8 – Simulated setup of XGPON in VPI.*

## Optical Spectrum

The wavelength plan used in the setup was chosen regard the standard G.987.1 [37] as 1577 nm for downstream traffic and 1270 nm for upstream traffic. In this way, the first step was to visualize the optical spectrum of each correspondent channel, with 3 dBm of transmitted power, through Figures 3.9-10.

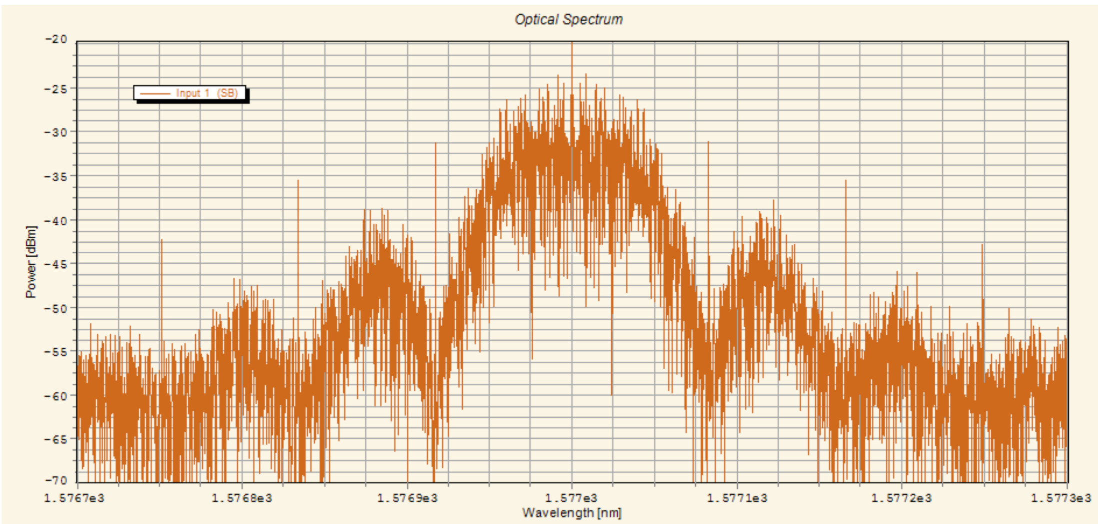



*Figure 3.9 - Optical Spectrum for downstream.*

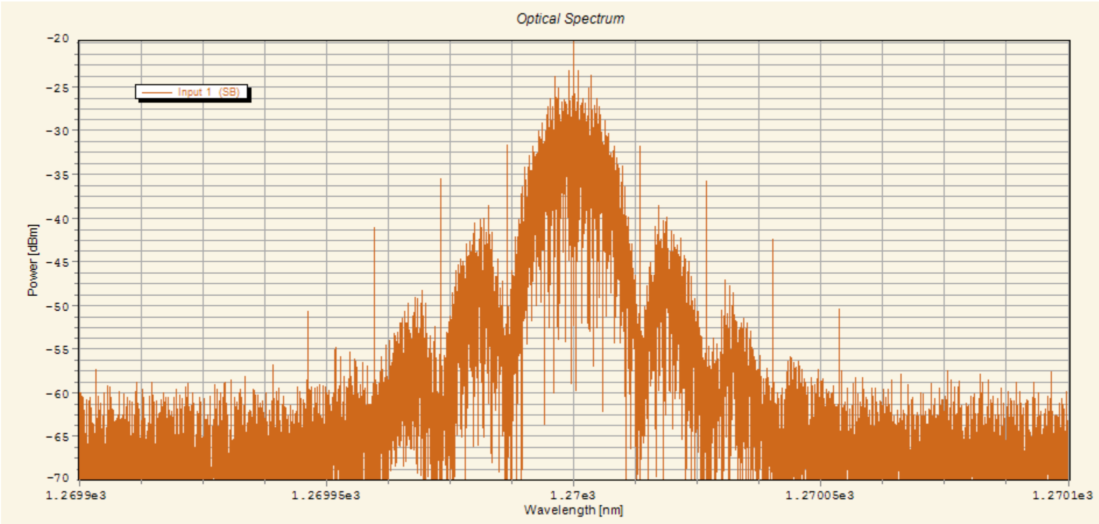



*Figure 3.10 - Optical Spectrum for upstream.*

### System Sensitivity

To achieve the sensitivity of the system, the BER according the received power in the receiver, was measured for downstream and upstream traffic. The conditions were the same as in 3.1.2 and the results are presented in Figures 3.11-12.

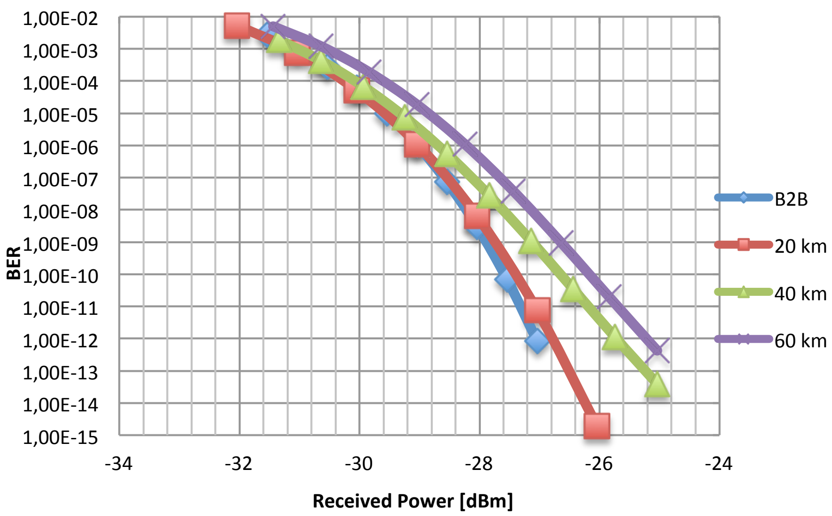



*Figure 3.11 - BER vs Received power for downstream.*

The system was tested in Back-to-Back situation and with some kilometers of fiber. The result obtained for downstream without any fiber, was -31 dBm for the limit of BER 1E-3. When it was add fiber to the setup, the sensitivity of the system increased. So, XPON has a considerable bit rate to be noted some differences in the value of the received power.

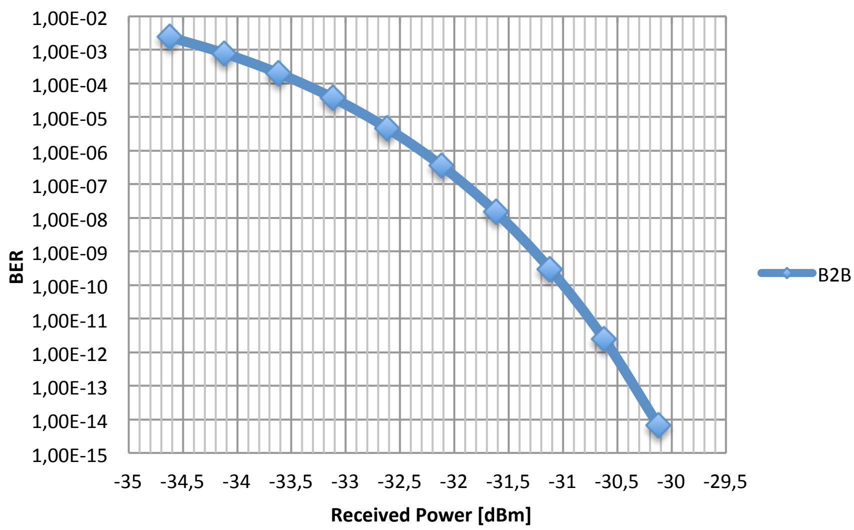



*Figure 3.12 - BER vs Received power for upstream.*

Regarding the upstream traffic, the minimum value admissible in the receiver, to obtain results of BER till 1E-3, is -34 dBm. In this situation, there were not get any differences for the received power in case of Back-to-Back or with fiber.

**Maximum Reach**

To study the maximum distance in XGPON system, were used the same conditions as for the previous technology. For the upstream, the transmitted power and the attenuation were the same. In case of downstream, the transmitted power was chosen according the classes defined in the standard [59].

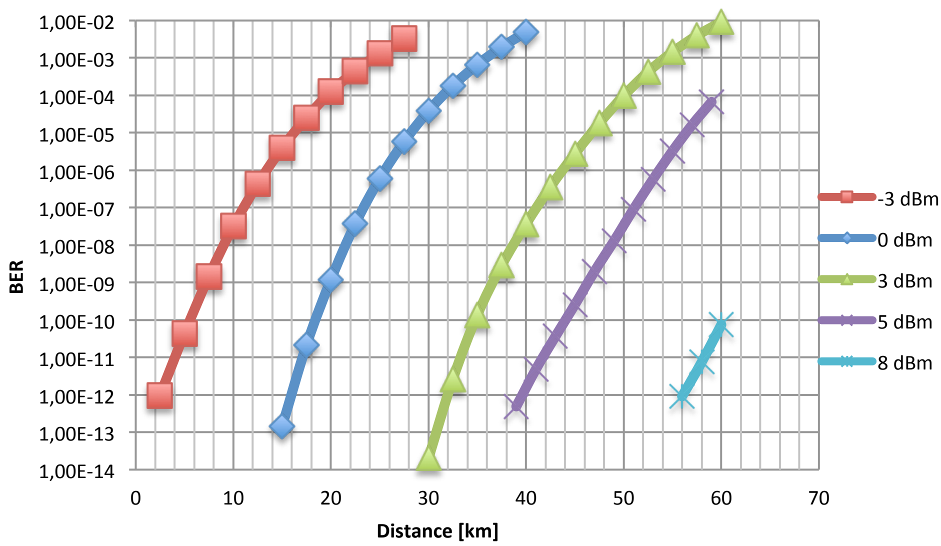



*Figure 3.13 - Downstream maximum reach obtained for different transmitted power.*

By observation of the figure 3.13, with -3dBm in the transmitter the system can reach 25 km and with +3 dBm around 55 km. Notice that, with higher transmitted power, which is supported by its standard, XGPON can reach over 60 km.

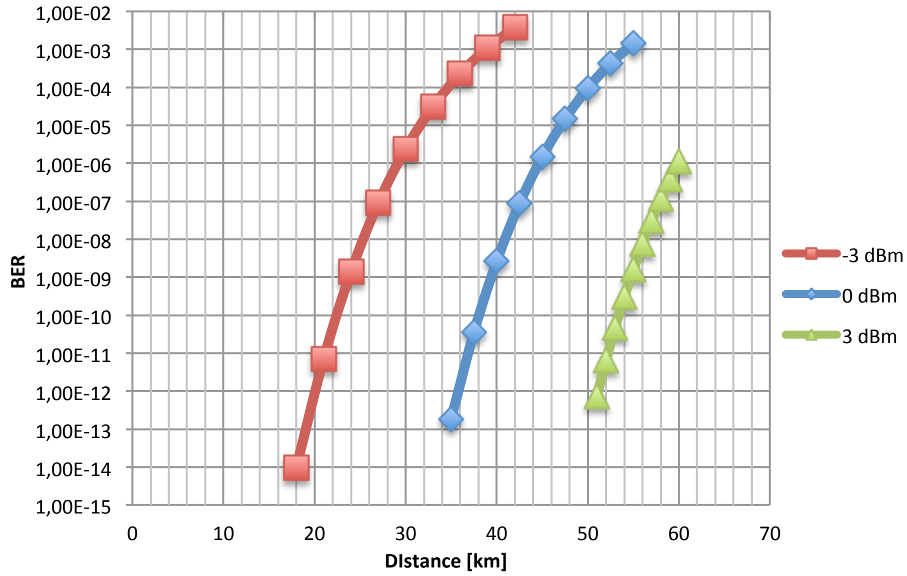
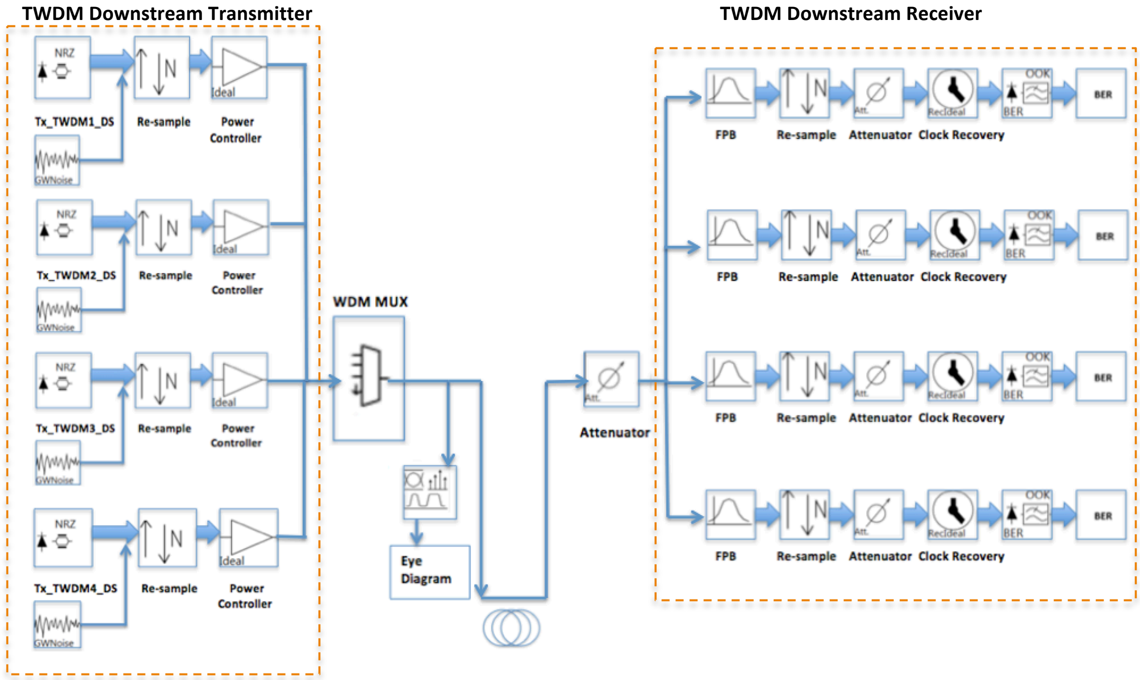



*Figure 3.14 - Upstream maximum reach obtained for different transmitted power.*

For the upstream transmission, demonstrated on Figure 3.14, a maximum reach of 40 km for -3 dBm of transmitted power and 55 km for 0 dBm was acquired.

### 3.1.4 TWDM System Characterization

TWDM system was simulated with 40 Gbps (4x10Gbps) for the downstream traffic and 10 Gbps (4x2.5Gbps) for the upstream traffic. The setup used for this simulation is presented in figure 3.15.



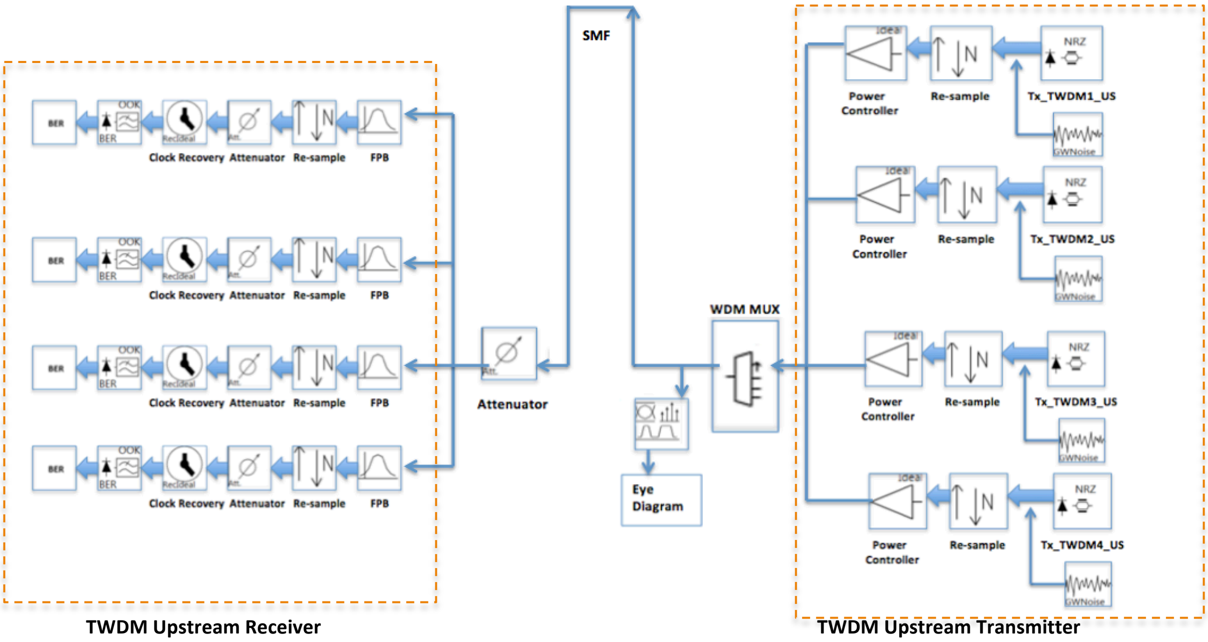



*Figure 3.15 – Simulated setup of TWDM in VPI.*

## Optical Spectrum

The wavelength plan used in the setup was chosen regarding the standard G.989.1 [9], option mentioned in point 2.7.2, using L-band for downstream and C-band for upstream with 100 GHz of channel spacing between each of them, as is noticeable in Table 3.1.

| | Downstream | Upstream |
|---|---|---|
| λ1 | 1595.49 | 1530.33 |
| λ2 | 1596.34 | 1531.12 |
| λ3 | 1597.19 | 1531.90 |
| λ4 | 1598.04 | 1532.68 |

*Table 3.1 – Wavelength plan of TWDM.*

According the chosen wavelength plan, the optical spectrum of each correspondent channel was visualized, as in Figures 3.16-17.

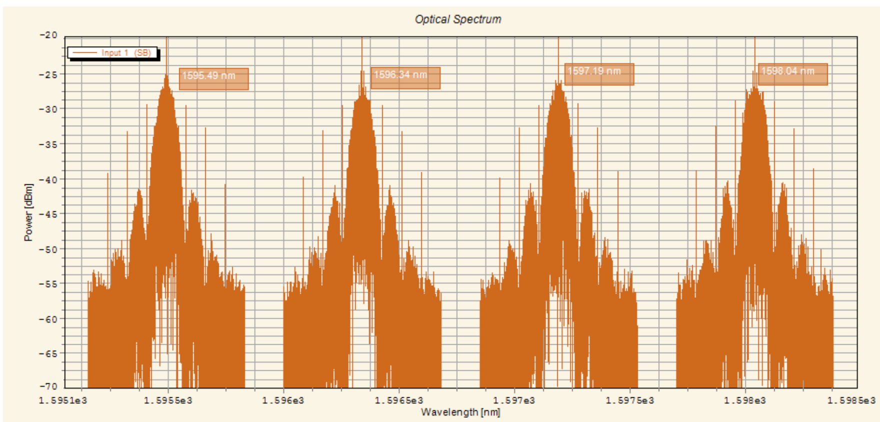



*Figure 3.16 - Optical Spectrum for downstream.*

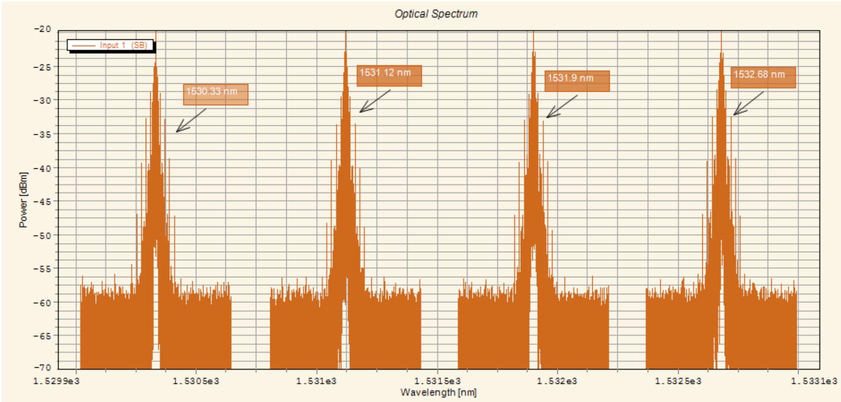



*Figure 3.17 – Optical Spectrum for upstream.*

**System Sensitivity**

To achieve the sensitivity of the system, the BER according the received power in the receiver, was measured for downstream and upstream traffic. The transmitted power was 3 dBm. For a way of comparison, the system was tested in Back-to-Back situation and with some kilometers of fiber. Results are presented in Figures 3.18-19.

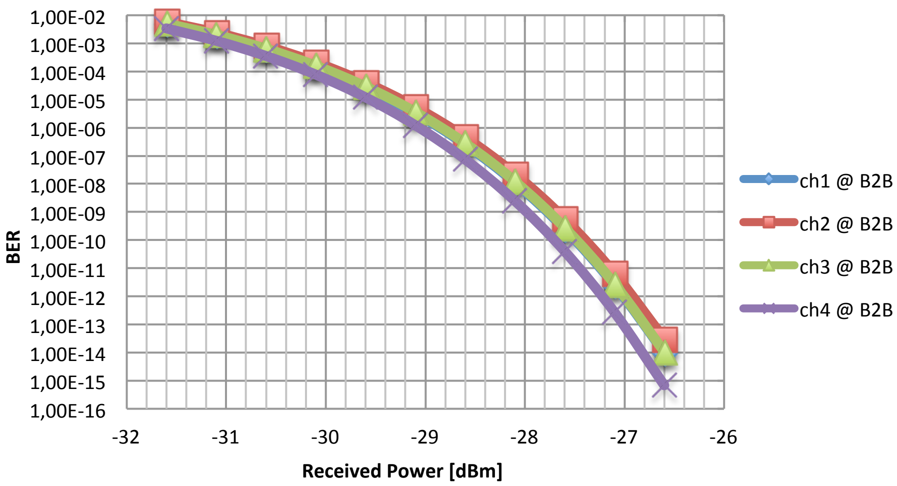



*Figure 3.18 - BER vs Received power for downstream without fiber.*

In downstream transmission, for back-to-back, the minimum received power necessary to obtain values of BER till the limit of 1E-3, was -31 dBm.

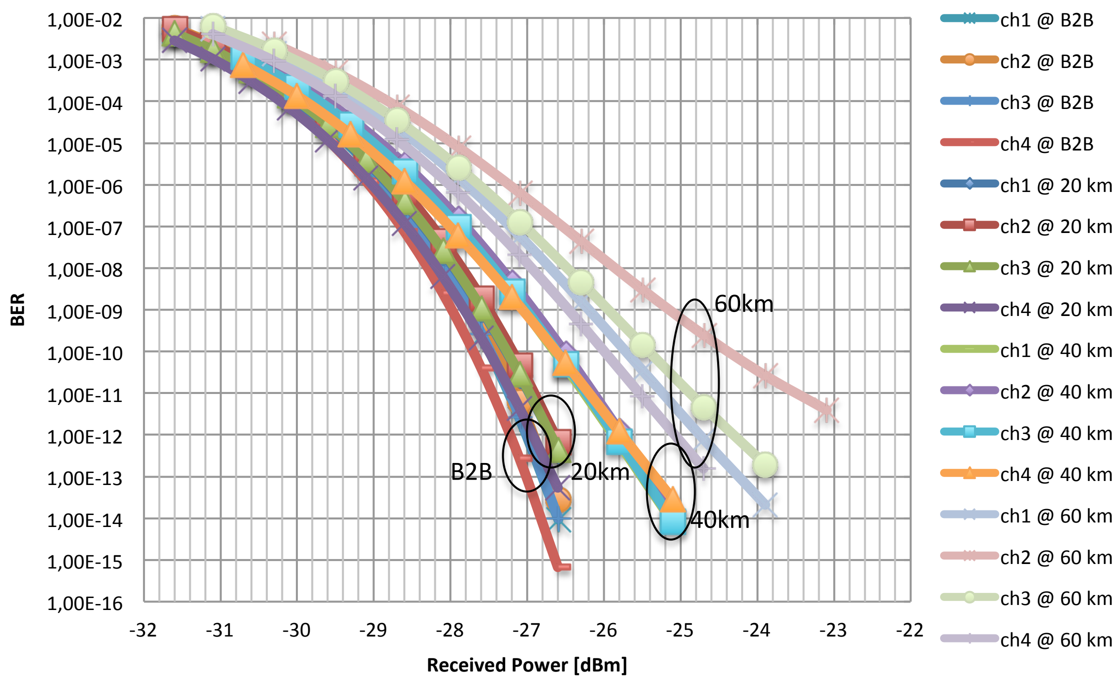



*Figure 3.19 - BER vs Received power for downstream with fiber.*

Observing Figure 3.19 is possible to take some conclusions. When it is added fiber to the system, comparing with the B2B situation, it is necessary a higher in the receiver to obtain the same conditions of BER. However, if it is connected only 20 km of fiber, the variation is not much considerable. This setup has the same performance as XGPON downstream transmission.

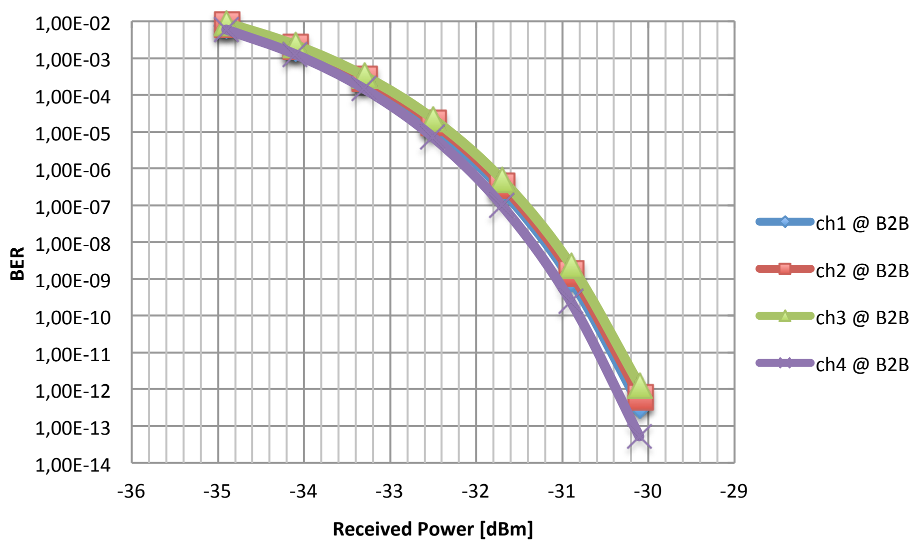



*Figure 3.20 - BER vs Received power for upstream without fiber.*

In this case, the minimum power acceptable in the receiver is of –34 dBm. For the same reason as above in 3.1.2, there is no difference in the received power for back-to-back or with fiber.

**Maximum Reach**

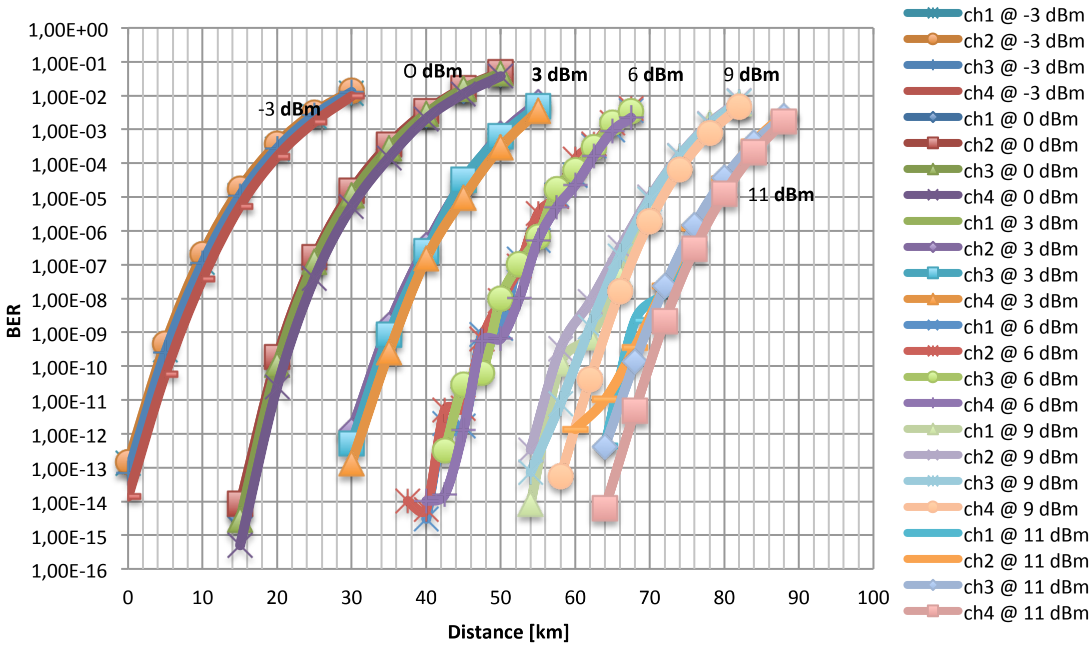



*Figure 3.21 - Downstream maximum reach obtained for different transmitted power.*

For TWDM downstream transmission, cases within a wither range of transmitted power were studied according the established. So, transmitting -3 dBm, the system can reach around 25 km and with 3 dBm around 55 km. Again it is notice the improvement of 15 km for each increment of 3 dBm transmitted power. After 6 dBm, this relation is no longer noted due to some linear and nonlinear effects, mainly SPM and XPM, which become to manifest for high powers (Appendix A).

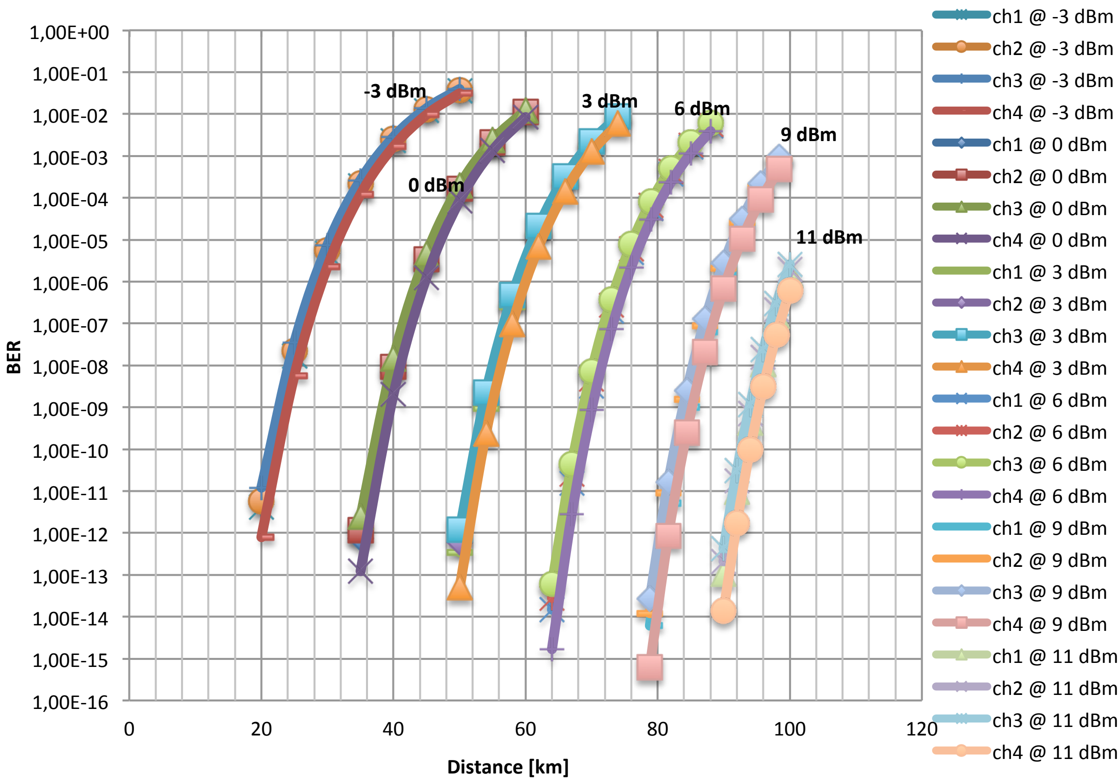



*Figure 3.22 - Upstream maximum reach obtained for different transmitted power.*

Regarding the upstream transmission, with -3dBm it is possible to reach 40 km and with 3 dBm, 65 km. If the transmitted power is increased even more, the system can go further denoting the same problems explained for Figure 3.21.

### 3.1.5 Conclusions

The aim of this section was to characterize each technology separately, studying their limitations for the maximum distance that each one can reach and the sensitivity of each system.

Regarding the sensitivity, comparing the three technologies, the upstream transmission of GPON, with 1.25 Gbps bit rate, can admit the lower power in the receiver, of -35.5 dBm. After, comes GPON downstream and XGPON/TWDM upstream transmission, with 2.5 Gbps bit rate, admitting -34 dBm. XGPON and TWDM downstream, 10 Gbps bit rate, have the worst value of minimum power acceptable in the receiver, of -31 dBm. These values are identical due to the same bit rate. So, the first conclusion is that higher the bit rate, higher is the necessary power in the receiver to obtain the same BER, decreasing its sensitivity. This fact is demonstrated on Figure 3.23. This means that, for the same value of power, increasing the bit rate, the BER increases and the performance of the system gets worst.

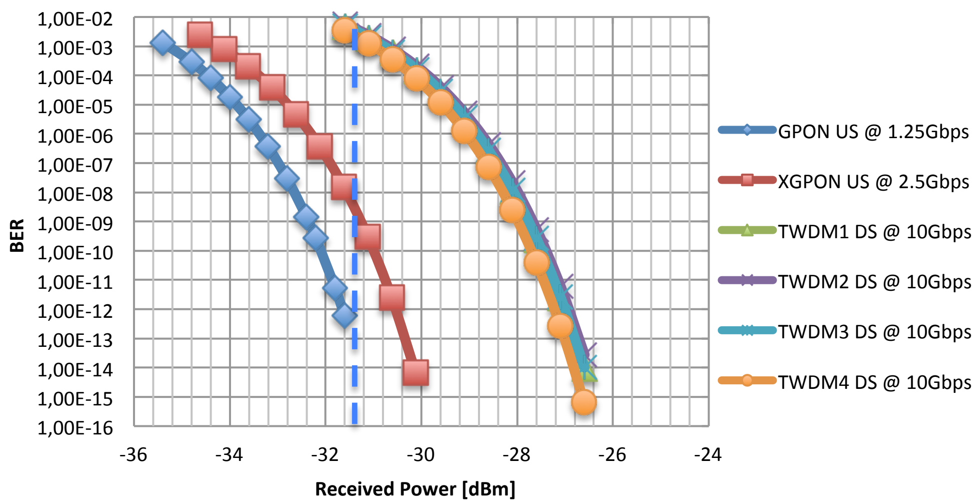



*Figure 3.23 – Comparison of sensitivity for each technology.*

Another conclusion is that for 10 Gbps bit rate, adding fiber to the system increases the minimum value in de receiver, deteriorating its performance. The reason is in the chromatic dispersion, which becomes quite relevant in the performance of the system, for this bit rate.

About the distance reached for each technology, it is possible to observe that, for a same transmitted power between -3 and +3 dBm, GPON upstream can achieve a higher distance. In other words, lower the bit rate further can go the system, for the same BER. If comparing the same transmitted power for a value of distance, concludes that decreasing the bit rate the performance improves, as visible on Figure 3.24.

Studying the downstream transmission of TWDM in case of 6 dBm or higher transmitted power was reached a higher distance. However were denoted nonlinear effects in the fiber, such as SPM and XPM present for high powers (See Appendix A) and the linear Chromatic dispersion became more intense.

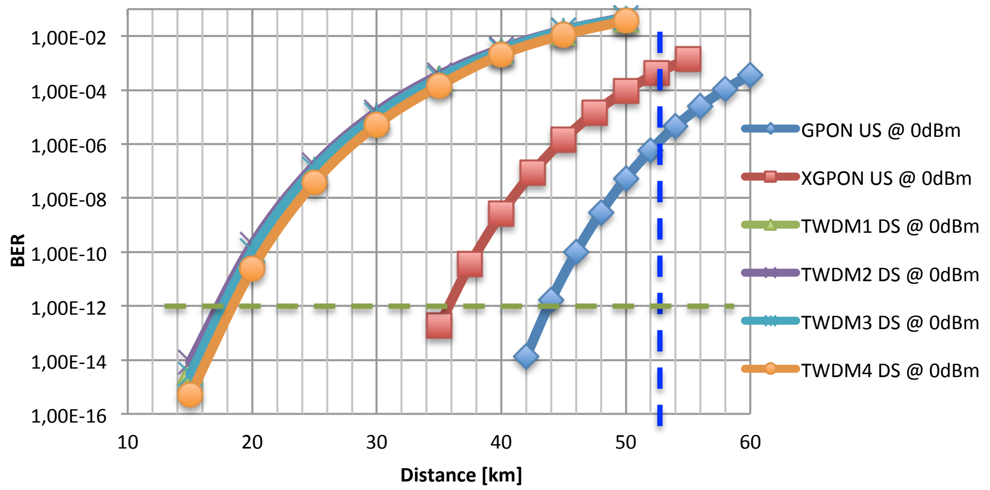



*Figure 3.24 – Comparison for the same transmitted power.*

## 3.2 Coexistence Scenarios

In this section, a coexistence scenario between the previous technologies is studied with focus on the effect of GPON in the performance of TWDM. In addition, other coexistence scenarios, between the technology TWDM and signals with different modulation formats are also studied.

In a way of comparison, some parameters were defined in common for all the scenarios and presented in Table 3.2.

| Parameters | Value | Units |
|---|---|---|
| BitRateDefault | 2.5e9 | Bit/s |
| SampleRateDefault | 32*BitRateDefault | Hz |
| TimeWindow | 512/BitRateDefault | s |
| Attenuator | 18 | dB |
| NoiseDensity | 1e-16 | $A/Hz^{(1/2)}$ |

*Table 3.2 – Common Parameters.*

Each technology has a second attenuator in order to obtain values between the acceptable and the same conditions for all the case studies.

### 3.2.1 Coexistence GPON, XGPON and TWDM

For this coexistence scenario were chosen some different parameters for the technologies, according the defined ones in each respective standard, as explained in section 3.1.

| Parameter | Value | Units |
|---|---|---|
| br_gpon_down | BitRateDefault | Bit/s |
| br_xgpon_down | BitRateDefault*4 | Bit/s |
| br_twdm_down | BitRateDefault*4 | Bit/s |
| br_gpon_up | BitRateDefault/2 | Bit/s |
| br_xgpon_up | BitRateDefault | Bit/s |
| br_twdm_up | BitRateDefault | Bit/s |

*Table 3.3 – Defined parameters.*

| Parameter | Value | Units |
|---|---|---|
| c | 299792458 | m/s |
| freq_gpon_down | c/1490e-9 | Hz |
| freq_xgpon_down | c/1577e-9 | Hz |
| freq_twdm_down1 | c/1595.49e-9 | Hz |
| freq_twdm_down2 | c/1596.34e-9 | Hz |
| freq_twdm_down3 | c/1597.19e-9 | Hz |
| freq_twdm_down4 | c/1598.04e-9 | Hz |
| freq_gpon_up | c/1310e-9 | Hz |
| freq_xgpon_up | c/1270e-9 | Hz |
| freq_twdm_up1 | c/1530.33e-9 | Hz |
| freq_twdm_up2 | c/1531.12e-9 | Hz |
| freq_twdm_up3 | c/1531.9e-9 | Hz |
| freq_twdm_up4 | c/1532.68e-9 | Hz |

*Table 3.4 – Wavelength plan.*

**VPI Setup**

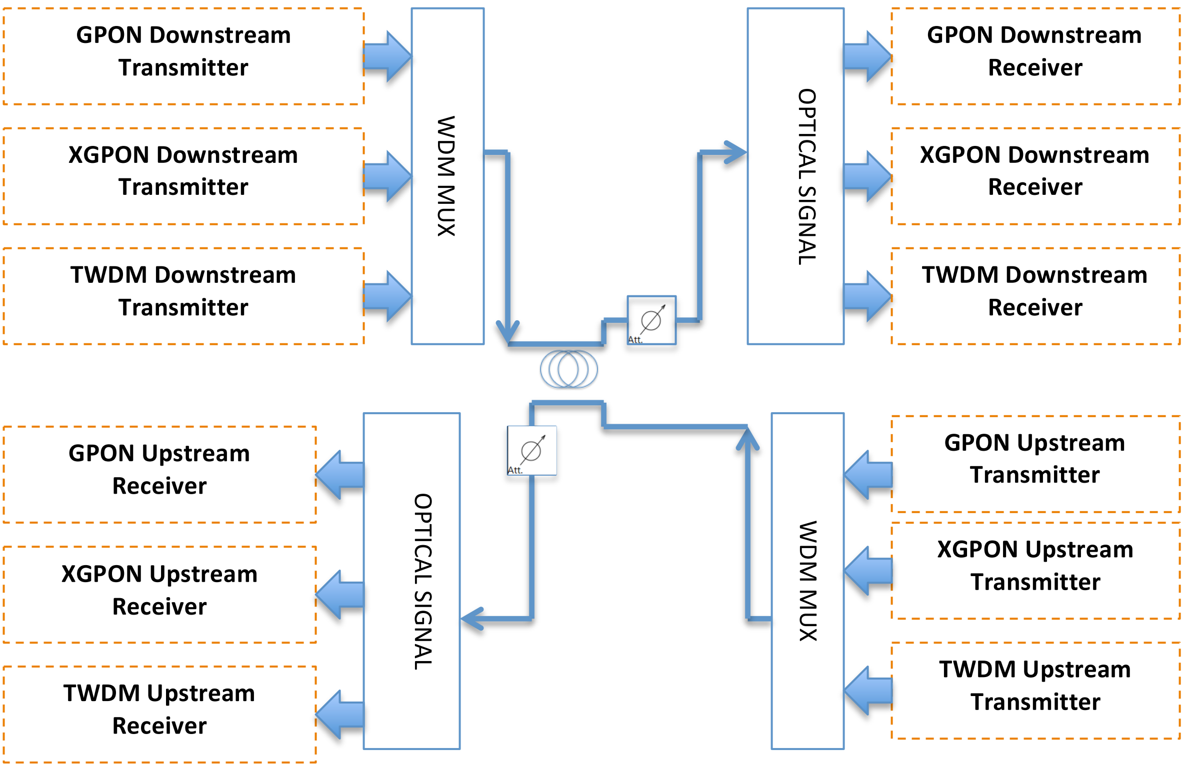


*Figure 3.25 – Coexistence scenario considered.*

## Results

The figures 3.26-27 present the optical spectra for downstream and upstream transmission obtained for this coexistence scenario.

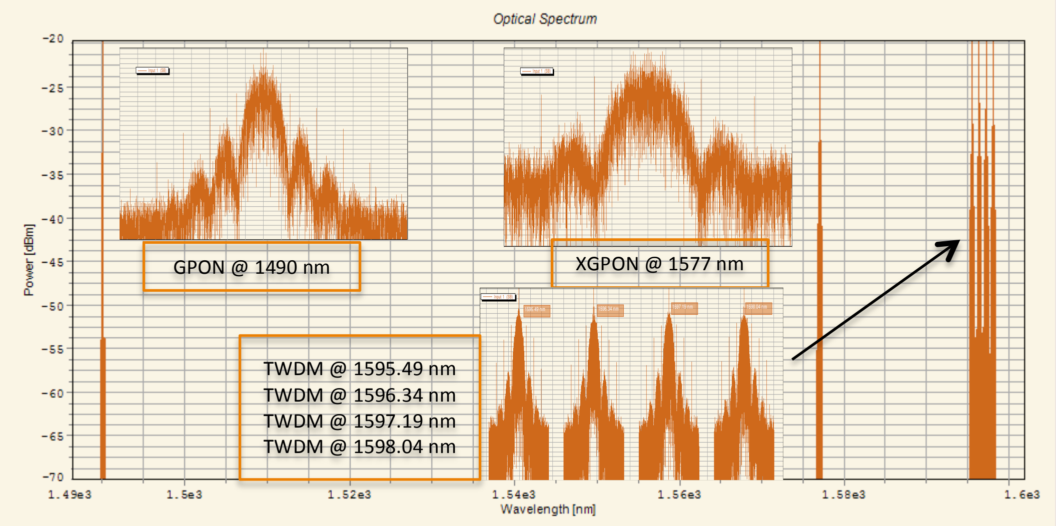



*Figure 3.26 – Optical spectrum for downstream transmission.*

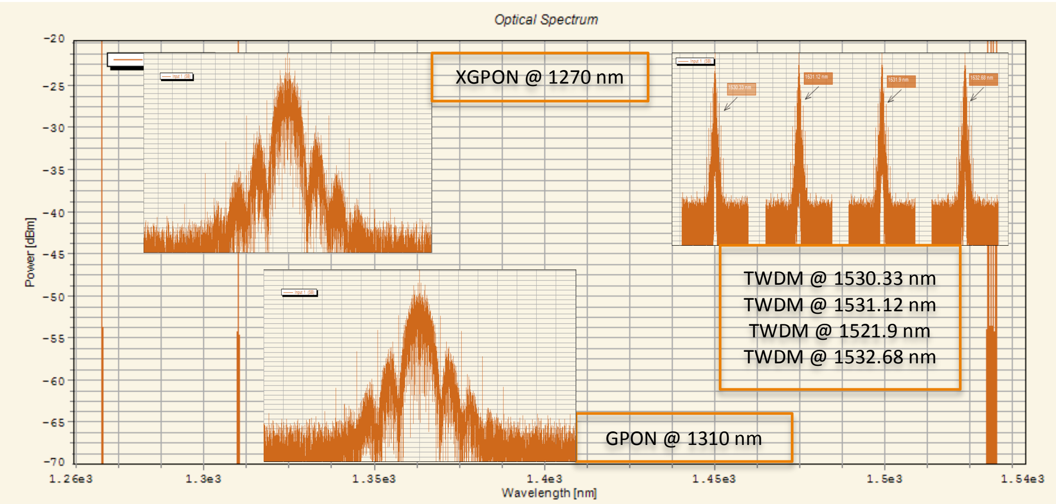



*Figure 3.27 - Optical spectrum for upstream transmission.*

In the same line of analysis, the sensitivity of the coexistence scenario was studied, in order to meet the acceptable power in the receiver for both sides of transmission and the results are shown on Figures 3.28-29.

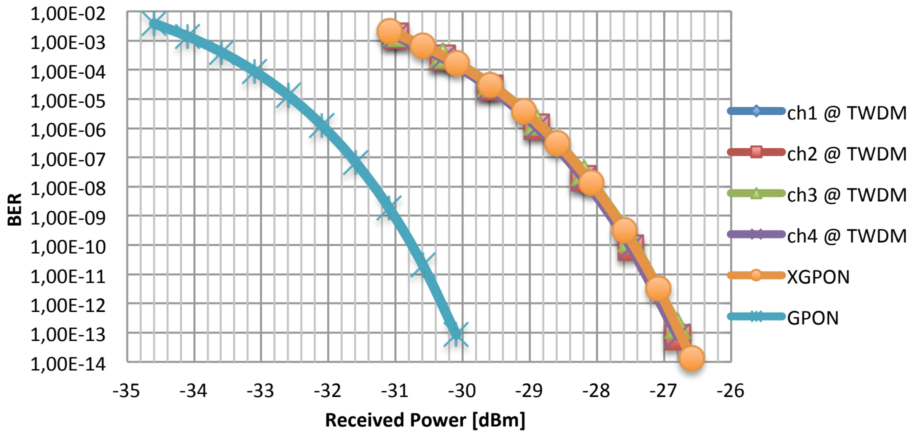



*Figure 3.28 - BER vs Received power for downstream.*

About the downstream transmission, was obtained the value of -34 dBm for GPON and -31 dBm for TWDM/XGPON channels.

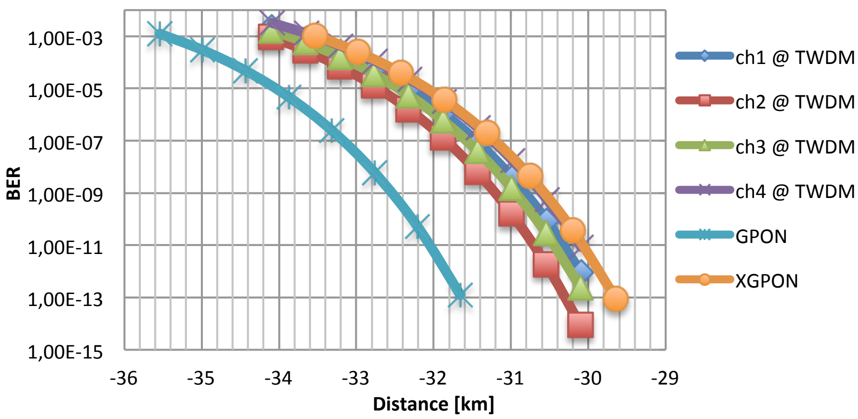



*Figure 3.29 - BER vs Received power for upstream.*

Regarding the upstream transmission, TWDM and XGPON channels need -34 dBm of power in the receiver, whereas GPON accepts -35.5 dBm.

Figures 3.30-31 demonstrate a study about the maximum reach obtained by each technology within the coexistence scenario. The transmitted power was chosen equally for the three PONs with the aim to observe each one would limit the distance.

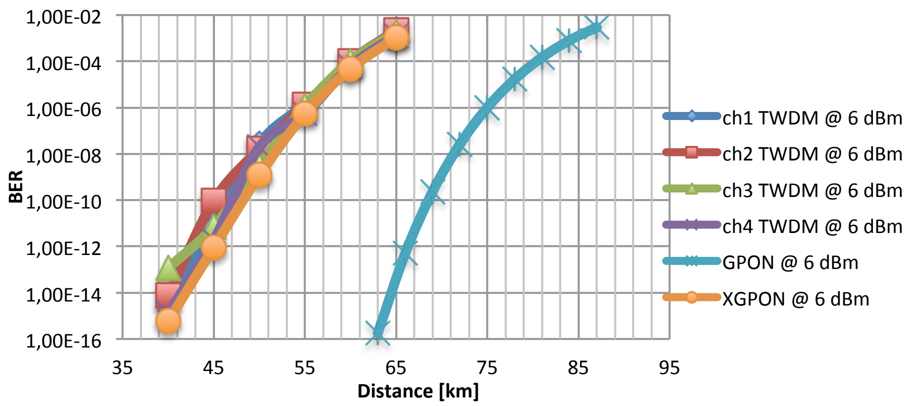



*Figure 3.30 - Downstream maximum reach for transmitted power of 6 dBm.*

As visualized in Figure 3.30, TWDM and XGPON channels limit the maximum reach for downstream transmission in 65 km.

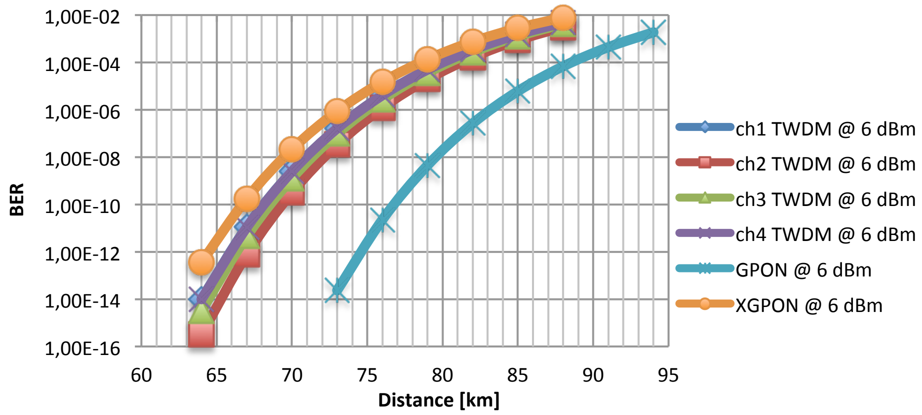



*Figure 3.31 - Upstream maximum reach for transmitted power of 6 dBm.*

Also in upstream transmission the maximum reach is limited by TWDM and XGPON technology, imposing 85 km.

The following study is about the effect of GPON transmitted power on the performance of the other technologies, XGPON and TWDM, within the coexistence scenario considered. Due to the allocation in the spectrum of each PON, the GPON channel will induce the Raman effect in the others. Notice that in VPI simulator it is only possible to observe the static behavior of the phenomenon.

Firstly, the acceptable power in the receiver was measured for different transmitted power of GPON, exhibit on Figures 3.32-33. Thus, the transmitted power of the other channels was fixed in 3dBm for downstream and 0 dBm for upstream. For GPON, was created a sweep varying between -12 to +22 dBm.

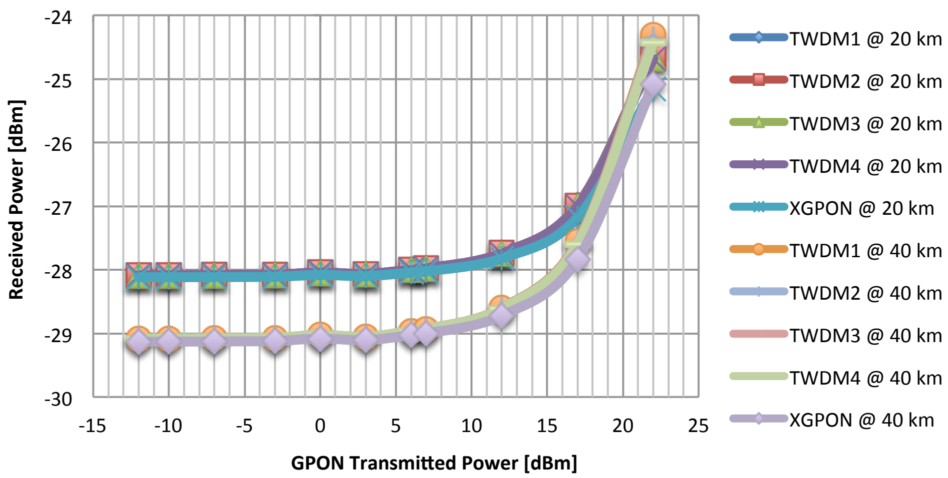



*Figure 3.32 – Effect of GPON transmitted power on the received power of each downstream channel.*

Regarding downstream transmission, both XGPON and TWDM channels suffer an increase of the power in the receiver induced by the increase of GPON transmitted power. This is justified by GPON channel that works as a pump, causing transference of power to the other channels.

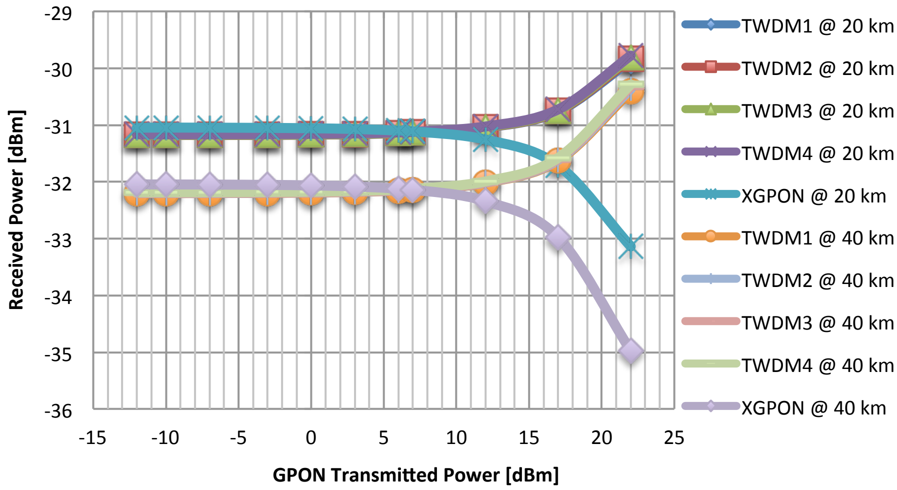



*Figure 3.33 - Effect of GPON transmitted power on the received power of each upstream channel.*

Upon the upstream transmission, TWDM channels denote the same trend but XGPON suffers the opposite effect. In this case, since XGPON is behind the pump channel, the power transference occurs from the first to GPON.

The Figure 3.34 presents the static Raman induced on TWDM and XGPON downstream channels, for 20 and 40 km of fiber.

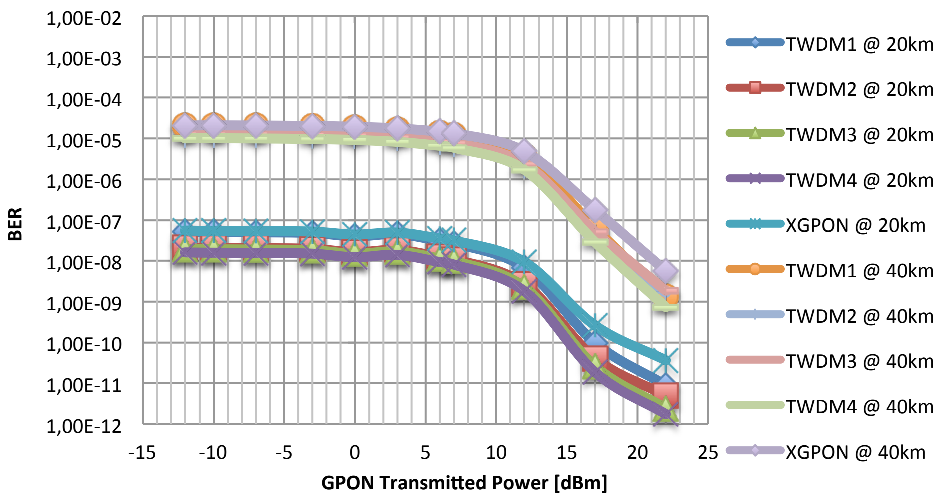



*Figure 3.34- Static Raman effect of GPON in the others downstream channels.*

As expected, increasing the transmitted power of GPON improves significantly the performance of the other channels, due to the power transference referred in Figure 3.32.

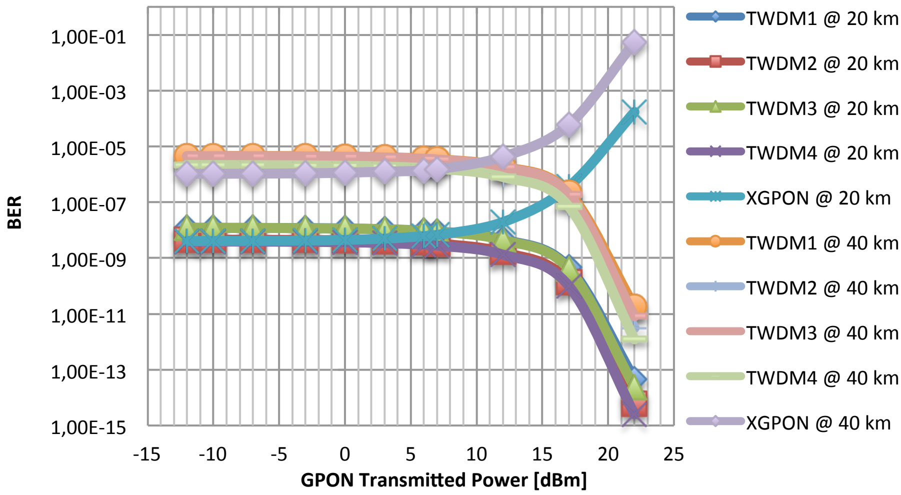



*Figure 3.35 - Static Raman effect of GPON in the others upstream channels.*

Regarding upstream transmission, displayed on Figure 3.35, TWDM keeps improving its performance with the increase of GPON transmitted power. However, XGPON channel suffers an opposite effect, caused by the power transference explained in Figure 3.33 (See Appendix A)

**Conclusions**

About the sensitivity it is possible to conclude that GPON upstream has the higher value. So, increasing the bit rate it is obtain worst sensitivities.

The second analysis relies on the maximum reach obtained for the coexistence scenario. In both upstream and downstream transmission, the distance is limited by the XGPON and TWDM technologies, in 85 and 65 km, respectively. Signals with higher bit rate present worst reaches due to dispersion phenomenon. Thus, it is possible to conclude that the maximum reach is limited by the signal with higher bit rate, if compared within the same transmitted power. Increasing the transmitted power may not always mean an improvement on the performance, due to the nonlinear effects present in the fiber.

Regarding the static Raman effect induced by GPON technology it is justified to say that it has a substantial influence on the performance of the other channels (See Appendix A). Raman effect become to notice after ~20nm of channel spacing, working as an amplifier. It causes power transference from one channel of behind to other in front on the spectrum allocation. By this way it is concluded that, on the coexistence scenario, Raman effect improves the performance of TWDM and XGPON downstream channels but degrades the XGPON upstream transmission.

### 3.2.2 Coexistence TWDM and QPSK signal

The second coexistence scenario studied in VPI was between TWDM technology and a signal modulated with QPSK format. The purpose of this setup is to observe the effect of the QPSK signal on TWDM. It was only performed simulations for downstream transmission in order to compare the laboratory results.

Regarding the TWDM technology, it was simulated with 40 (4x10) Gbps bit rate, 100 GHz of channel spacing and the transmitted power was fixed in 7 dBm/channel.

For the signal modulated with QPSK format were used bit rates of 20 and 40 Gbps dual polarization. It was supposed to used 100 Gbps but, due to TWDM bit rate, it is only possible to introduce bit rates with the same value 10 GBit/s or multiplied by $2^n$, with n=1,2,3,4,etc. The transmitted power was changed from -15 to 15 dBm, in order to observe the desired effect.

Besides that, were executed measurements for different channel spacings, from 50 GHz to 100 GHz, between QPSK and the first wavelength of TWDM, which was fixed. The aim is to meet the limitations of the coexistence, regarding the spectrum allocation. The first wavelength plan used, with 50 GHz channel spacing, is presented in the table 3.5.

| | Wavelength (nm) | |
|---|---|---|
| | TWDM | QPSK |
| λ1 | 1549.72 | 1549.32 |
| λ2 | 1550.52 | -- |
| λ3 | 1551.32 | -- |
| λ4 | 1552.12 | -- |

*Table 3.5 – Wavelength plan considered.*

### VPI Setup

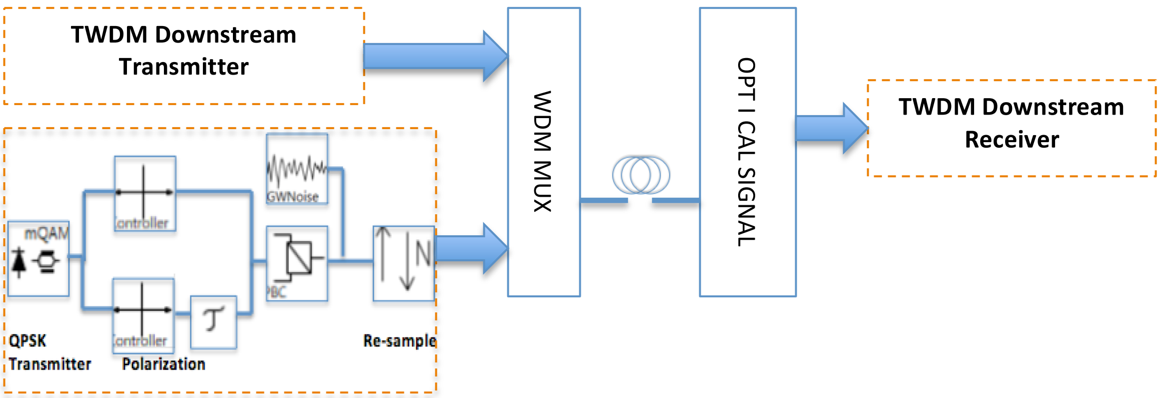



*Figure 3.36 – Coexistence scenario considered between TWDM and QPSK.*

At the OLT side, the QPSK signal is transmitted with 2bits/symbol and dual polarization after interconnected with a polarization combiner. The two signals are joined in the ODN, with the WDM multiplexer, passing through a 40 km SMF. For the receiver part, the used four filters BPF (Band Pass Filter) have a Gaussian response order 5, approximately square, with 100GHz of bandwidth.

### Results

In figures 3.37-38,the optical spectra with only QPSK signal and for the coexistence scenario with bit rate 40 Gbps, are presented with 50 GHz channel spacing.

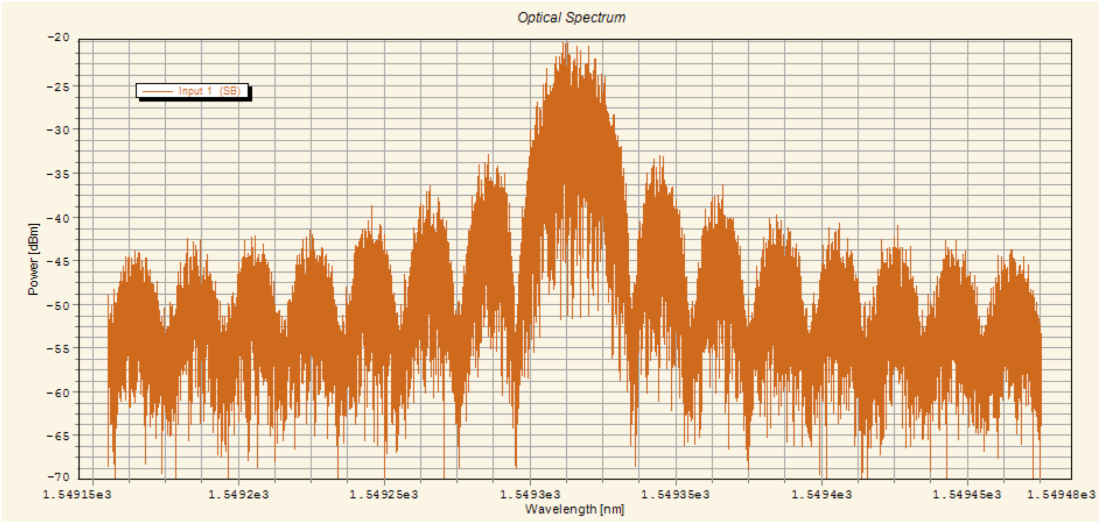



*Figure 3.37 – Optical spectrum of QPSK signal.*

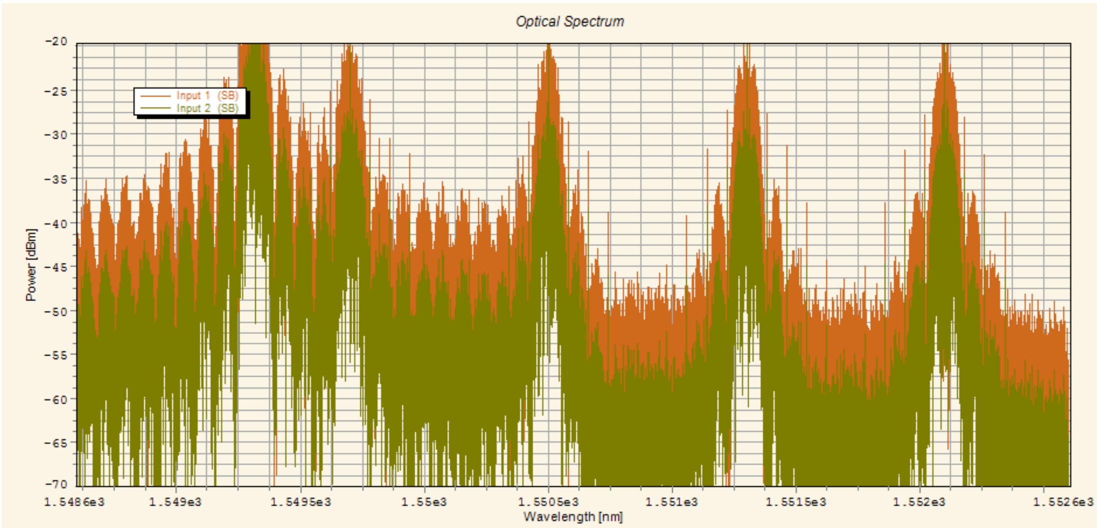



*Figure 3.38 - Optical spectrum of the coexistence scenario.*

In the first simulation, the effect of the signal modulated with QPSK format on TWDM performance was study for 20 Gbps bit rate.

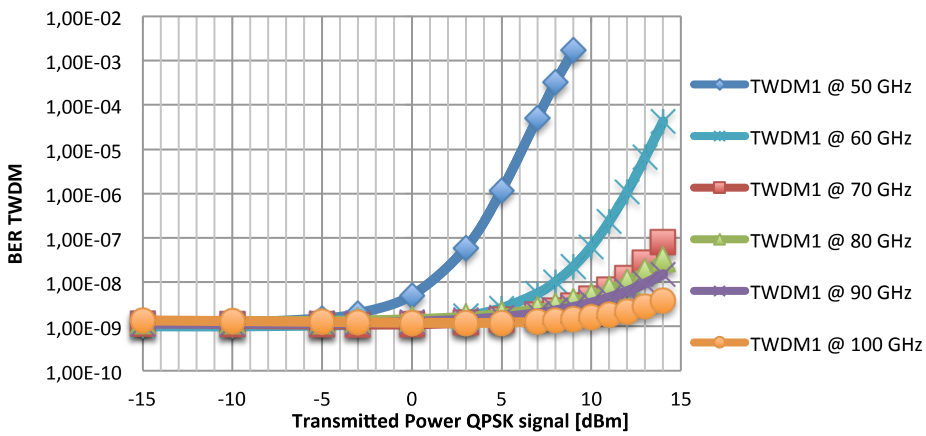



*Figure 3.39 – Effect of QPSK signal at 20 Gbps.*

Analyzing some results of Figure 3.39, for 50GHz the effect on TWDM is very accentuated after 0 dBm of QPSK transmitted power and transcends the limit of 1E-3 with 9dBm. Looking to 100GHz, the effect is already very low, and after this channel spacing TWDM does not suffer any degradation.

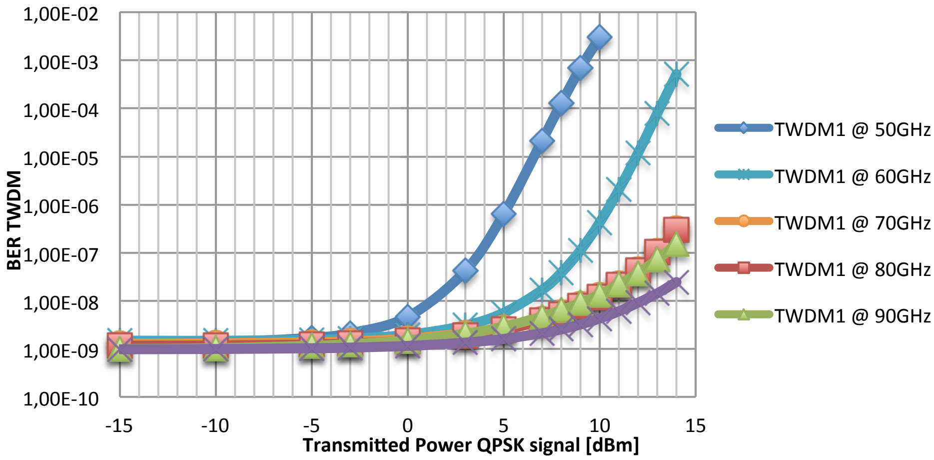



*Figure 3.40 - Effect of QPSK signal at 40 Gbps.*

In case of 40Gbps bit rate, results indicated on Figure 3.40, the line of effect is the same but with some penalty. With 100GHz, the performance is worst than in 20 Gbps, but nevertheless QPSK still does not create degradation after this channel spacing.

**Conclusions**

This coexistence scenario addresses some limitations for the TWDM technology, through some relevant factors for the chosen parameters.

The first conclusion to withdraw is about the transmitted power. If the power of the modulated signal with QPSK is increased, the performance of TWDM will degrade, due to linear crosstalk interference. It is the main existing effect between the signals, since they are very close one to another. Also are present in the fiber nonlinear effects, such as XPM (Cross-Phase Modulation), which contribute to the degradation of the signal.

Another observation is about the channel spacing. Increasing the channel spacing between the two signals creates lower effect on TWDM, improving its performance, because the crosstalk gets lower.

Regarding the bit rate of QPSK modulated format, it was verify that increasing it substantially will increase the BER of TWDM, which means will diminish its performance. This happen because the optical spectrum of QPSK gets wider, increasing the interference level within TWDM signal.

In final conclusion, a signal modulated by QPSK must be allocate in the spectrum with more than 100GHz of channel spacing from TWDM, in order to not degrade its performance. This equates to 0.8 nm.

### 3.2.3 Coexistence TWDM and 16QAM signal

The last coexistence scenario studied in VPI was between TWDM technology and a signal modulated with 16QAM format. It has the same purpose as the scenario studied in 3.2.2 and it was performed within the same characteristics.

**VPI Setup**

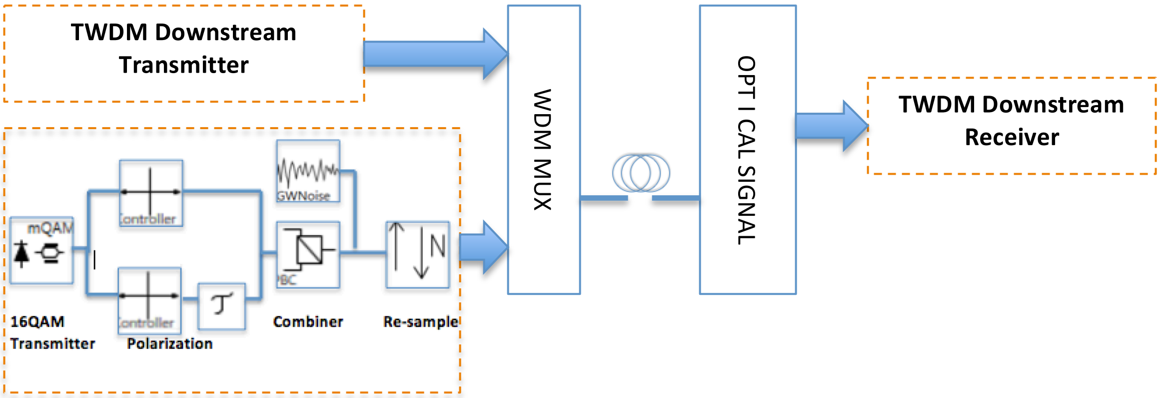



*Figure 3.41 - Coexistence scenario considered between TWDM and 16QAM.*

The setup presented on Figure 3.41 was simulated with the same parameters, also. The only difference is at the 16QAM transmitter, which sends 4Bits/symbol, being a more efficient format. It will be notice in the level of degradation caused on TWDM performance, which is expected to be lower.

**Results**

In figures 3.42-43, the optical spectra with 16QAM signal and for the coexistence scenario with bit rate 40 Gbps are presented with 50 GHz channel spacing.

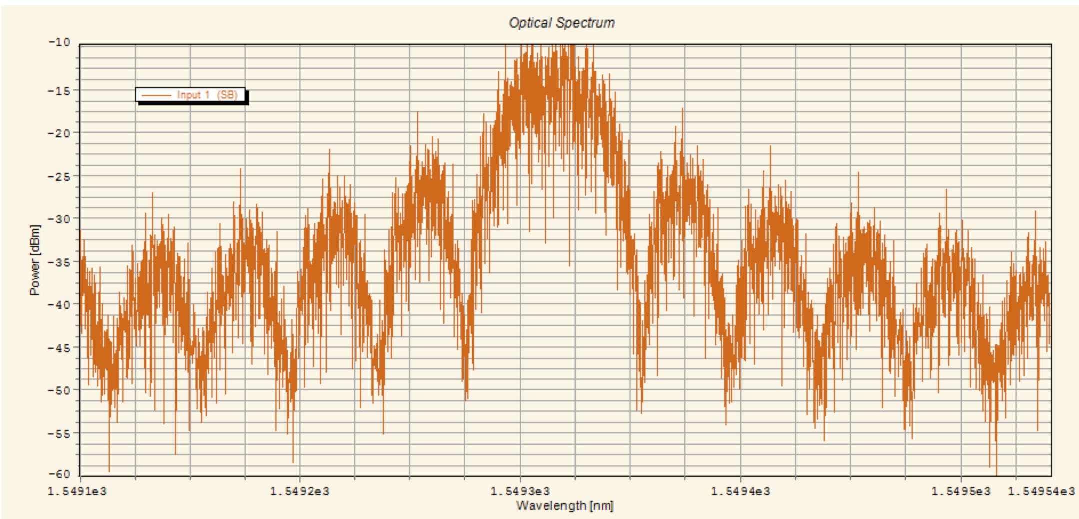



*Figure 3.42 - Optical spectrum of 16QAM signal.*

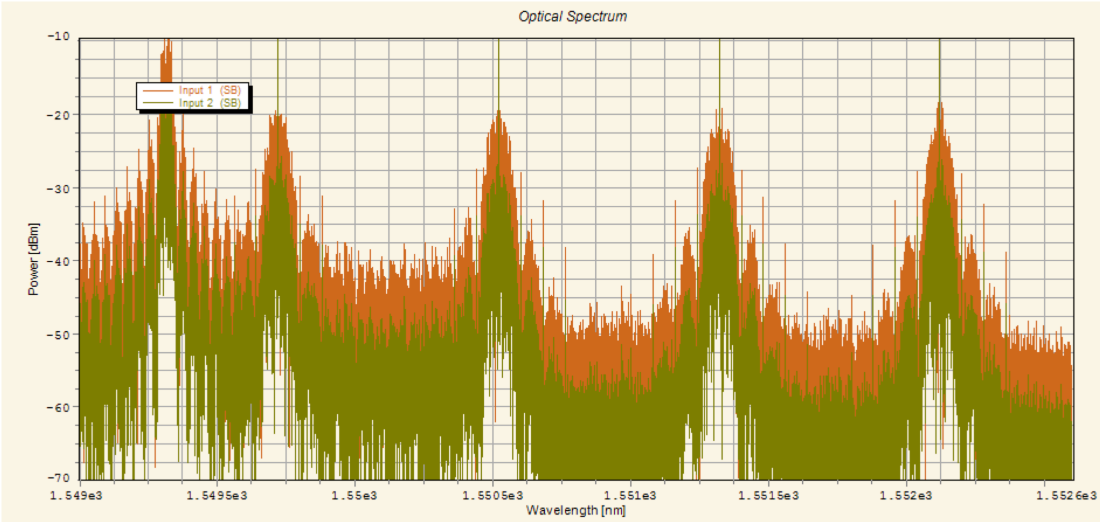



*Figure 3.43 - Optical spectrum of the coexistence scenario.*

Following the guideline, firstly was study the effect of the signal modulated with 16QAM format on TWDM performance, for 20 Gbps bit rate. The obtained results are revealed on Figures 3.44-45.

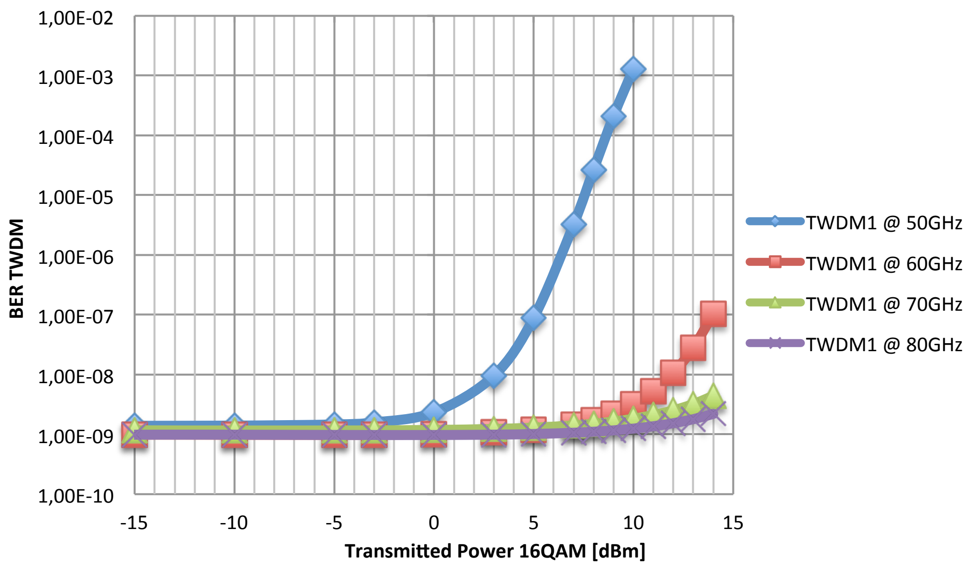



*Figure 3.44 - Effect of 16QAM signal at 20 Gbps.*

16QAM format has the same effect as QPSK in the performance of TWDM, degrading it, but with less intensity. Also for 50GHz the limit of BER 1E-3 is transceeded but with 10dBm, which means with less 1dB penalty. In this case, after 80 GHz of channel spacing, the performance of TWDM remains intact.

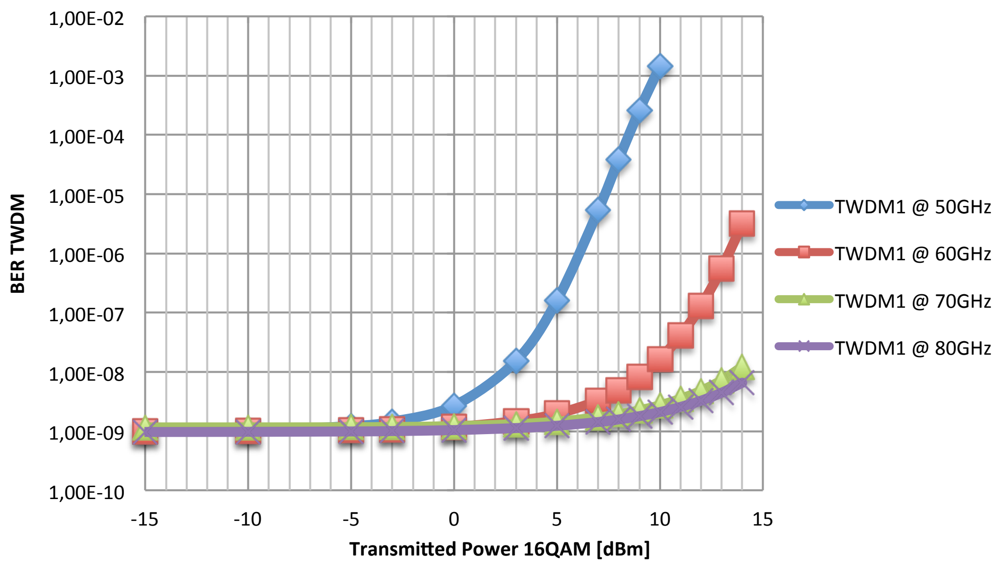



*Figure 3.45 - Effect of 16QAM signal at 40 Gbps.*

About 40Gbps bit rate, the line of effect is the same but with some penalty. With 80GHz, the performance is worst than in 20 Gbps, but nevertheless 16QAM still does not create degradation after this channel spacing.

**Conclusions**

As concluded above in 3.2.2 for the coexistence scenario between TWDM and QPSK, also this scenario addresses some limitations for the TWDM technology, through some relevant factors for the chosen parameters.

Regarding the 16QAM transmitted power, bit rate and channel spacing between the two signals, the conclusions observed are the same. This means that increasing the 16QAM transmitted power and bit rate, the performance of TWDM degrades, but increasing the channel spacing between them, it improves.

Another conclusion relapses in the comparison between the coexistence scenario with QPSK signal and this one with 16QAM signal. The simulation results shows that the second coexistence scenario is better in a way that the degradation of TWDM performance is lower and existent for lower channel spacing. The reason lies in the fact that the 16QAM modulation allows sending more bits/symbol, in this case 4, against 2 bits/symbol of QPSK modulation (See 2.8). By this reason, 16QAM modulation is more efficient and robust.

The final conclusion is about the possible allocation in the spectrum of a signal modulated by 16QAM, which must be distanced of more than 80GHz of channel spacing from TWDM, in order to not degrade its performance. This equates to 0.64 nm.

# 4 LABORATORY RESULTS

## 4.1 Introduction

In this chapter will be presented the study performed in the laboratory. In order to meet some limitations and understand further analysis was created a setup with TWDM technology. In a second step, were created heterogeneous networks with high data rate formats coexisting in the same access network. So, three coexistence scenarios were studied, one between TWDM and a NRZ signal and the other two with a signal modulated with QPSK/16QAM format. The aim is to observe the effect of each signal of the performance of TWDM and make a comparative assessment with the simulation results. In this way, it will be possible to study and help defining the next generation max occupancy of a given network.

## 4.2 TWDM characterization

First of all, the TWDM setup was created to study its limitations about the minimum power acceptable in the receiver. It was only performed simulations for downstream transmission due to laboratory limitations.

TWDM technology was simulated with 40 (4x10) Gbps bit rate and 100 GHz of channel spacing. For the wavelength plan was used the C-band due to the available spectrum and material in the laboratory. It is presented in the table 4.1.

| | Wavelength (nm) |
|---|---|
| λ1 | 1549.72 |
| λ2 | 1550.52 |
| λ3 | 1551.32 |
| λ4 | 1552.12 |

*Table 4.1 – Wavelength plan for TWDM experimental setup.*

**Setup**

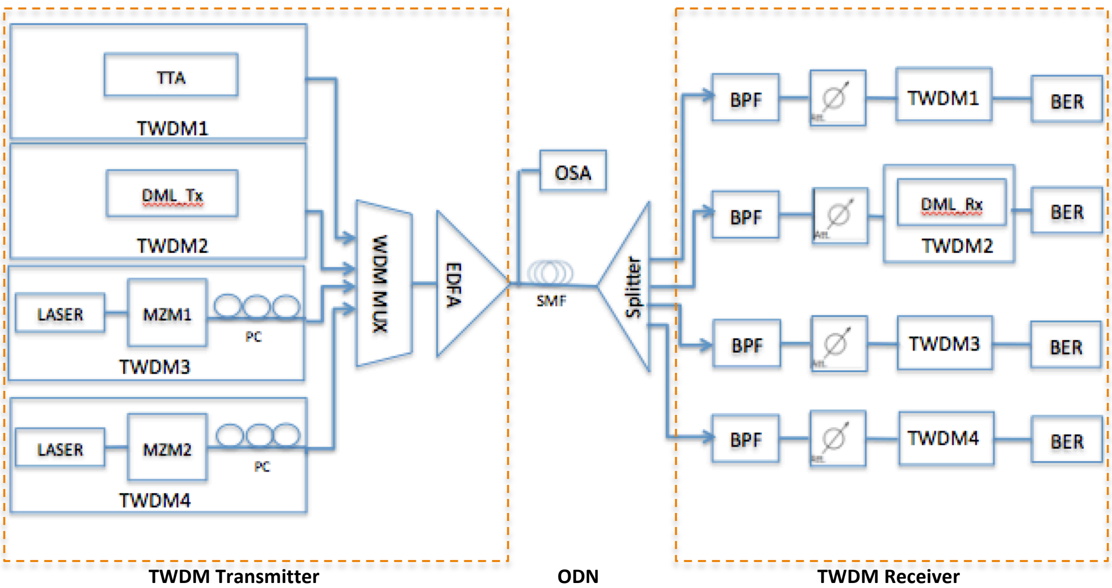



*Figure 4.1 – Experimental TWDM scenario considered.*

The OLT side is constituted by the TWDM technology, with 4 XGPON wavelengths multiplexed in a WDM, each one with different modulation and amplified by an EDFA (Erbium Doped Fiber Amplifier). The first channel is transmitted by a TTA (Tunable Transmitter Assembly) which is a high performance continuous wave (CW) tunable laser combined with an InP Mach-Zehnder [60]. The second is a tunable DML (Directly Modulated Laser) integrated in the JDSU tunable optical XFP transceiver [61]. The third and fourth channels are lasers modulated with external 10 Gbps MZM (Mach-Zehnder Modulator) with the difference that the last one is a Dual Driver MZM [62]. In the end of the EDFA it is connected an OSA (Optical Spectrum Analyzer) to visualize the four channels. At ODN is used a 20 and 40 km fiber and a waveshapper with a BPF (Band Pass Filter) to filter each channel. For the receiver part, is used the receiver present in the JDSU XFP optical transceiver which integrates a transimpedance amplifier to recover the signal.

**Optical Spectrum**

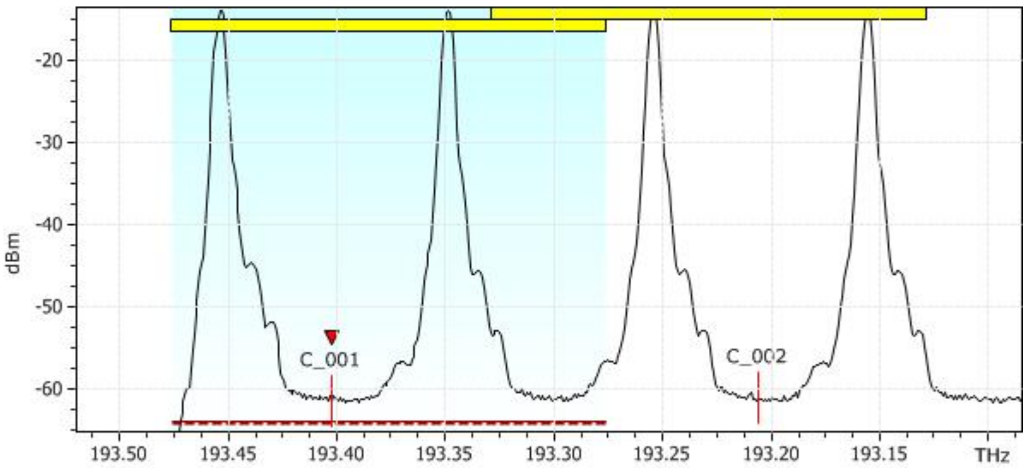



*Figure 4.2 – Optical spectrum of TWDM technology.*

**System Sensitivity**

Firstly, the system sensitivities for the back-to-back scenario and with 20 and 40 km of fiber were studied. The transmitted power for downstream transmission was 6dBm. For the sake of simplicity, it is only presented the results for the second channel, on Figure 4.3.

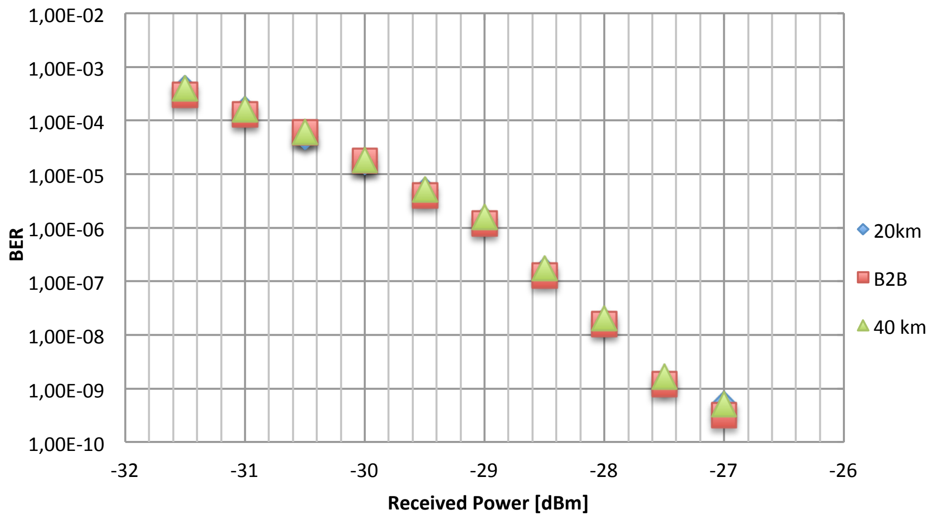



*Figure 4.3 – Sensitivity of TWDM downstream transmission.*

The minimum acceptable power to obtain values of BER between the established was around -32 dBm in the three cases.

In a further study, the minimum acceptable power in the receiver was measured for higher transmitted power and with 40 km fiber, as indicated on Figure 4.4.

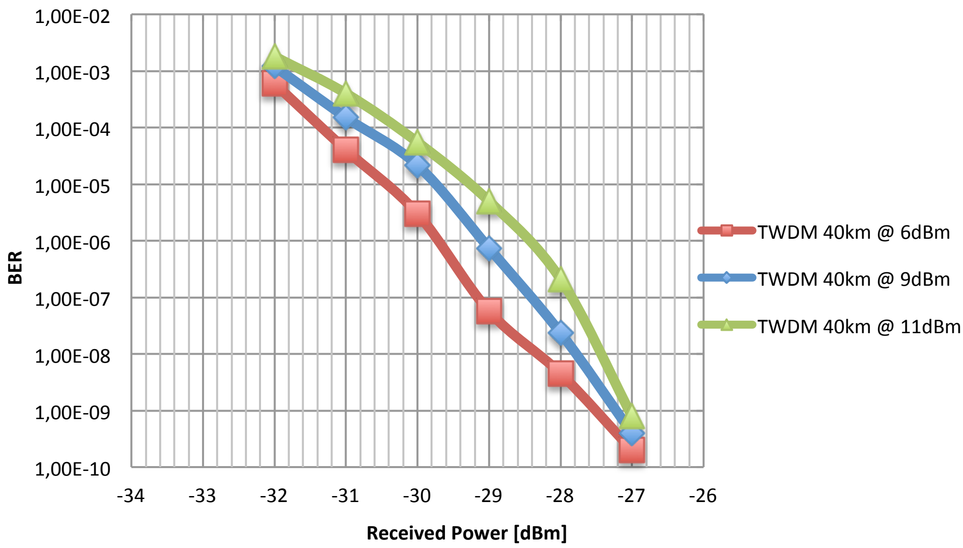



*Figure 4.4 - Sensitivity of TWDM for high-transmitted power.*

Increasing the power in the transmitter, it will be necessary a higher power in the receiver to obtain acceptable values. In case of 11dBm of transmitted power, the receiver accepts -31.5dBm.

## Conclusions

Regarding figure 4.3, it is noteworthy that comparing the necessary power in the receiver between B2B and the setup with fiber, the difference is not significant. This happen due to the receiver has an amplifier, which improves the signal [61].

Another conclusion to take is about the transmitted power. As expected, the sensitivity of the system increases if the transmitted power is increase.

Comparing the simulation and laboratory results, they are very similar. In fact, the experimental setup should provide better values due to the JSDU board receiver, already explained, as revealed in Figure 4.5.

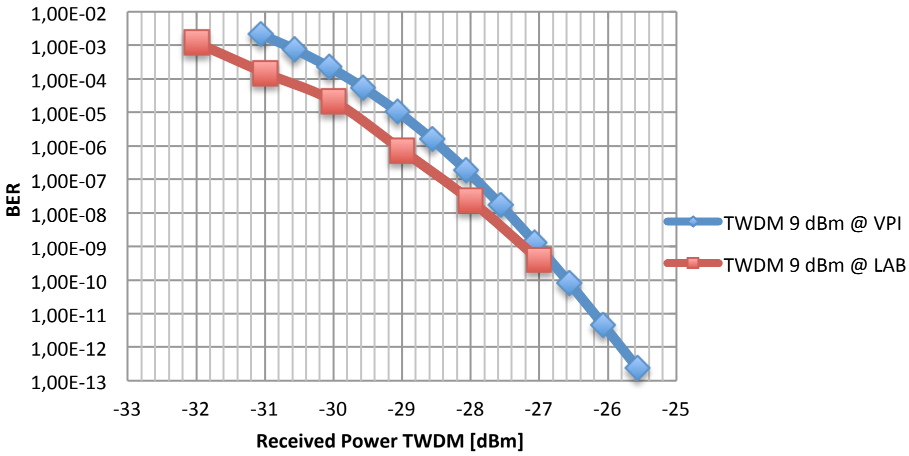



*Figure 4.5 – Experimental vs Simulation results.*

## 4.3 Filter Characterization

In order to understand better each effect will be present on the TWDM performance, was made a study taking into consideration the filter characteristics. For this purpose, its transfer function is exhibit in figure 4.6.

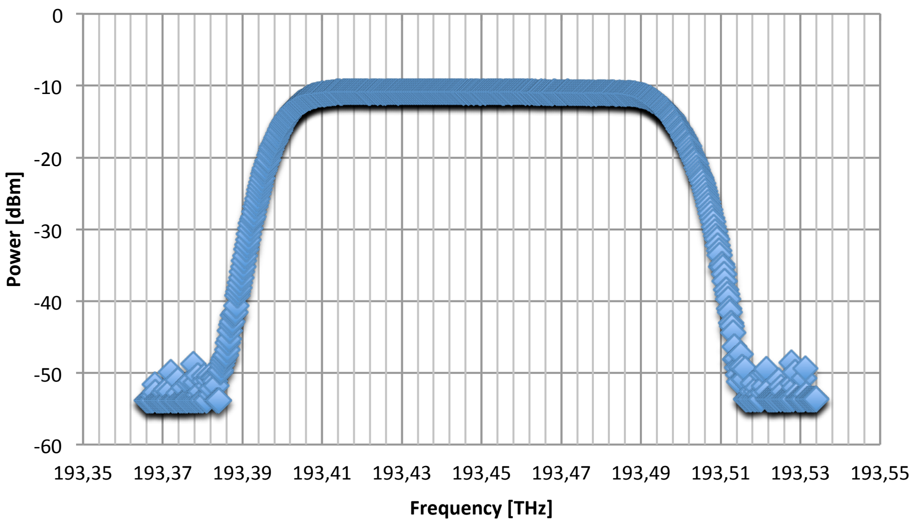



*Figure 4.6 – Band Pass Filter used in the experimental setup.*

It has a Gaussian response, approximately square, with 100GHz of bandwidth and it is centered on the first wavelength of TWDM signal.

The aim is to overlap the BPF on the optical spectrum, obtained in each coexistence scenario, to determine the level of crosstalk between the two coexistent signals.

Each value of crosstalk in dB, is obtained through the below equation (1) where the Area_TWDM is the area of the first channel and the Area_signal is the area of interference of each signal inside the filter.

$$Crosstalk = 10 * log_{10}\left(\frac{Area_{TWDM}}{Area_{signal}}\right)\ (dB) \qquad (1)$$

## 4.4 Coexistence TWDM and NRZ signal

TWDM technology was defined as in point 4.2 with the transmitted power fixed in 7 dBm/channel. Regarding the NRZ signal were used bit rates of 10, 20 and 40 Gbps. The transmitted power was changed from -15 to 15 dBm, in order to observe its effect on the performance of TWDM. Also were executed measurements for channel spacings between the two different signals, from 50 GHz to 250 GHz. The first wavelength plan used, with 50 GHz channel spacing, is presented in the table 4.2.

| | Wavelength (nm) | |
|---|---|---|
| | TWDM | NRZ |
| λ1 | 1549.72 | 1549.32 |
| λ2 | 1550.52 | -- |
| λ3 | 1551.32 | -- |
| λ4 | 1552.12 | -- |

*Table 4.2 – Wavelength plan for the coexistence scenario considered.*

### Setup

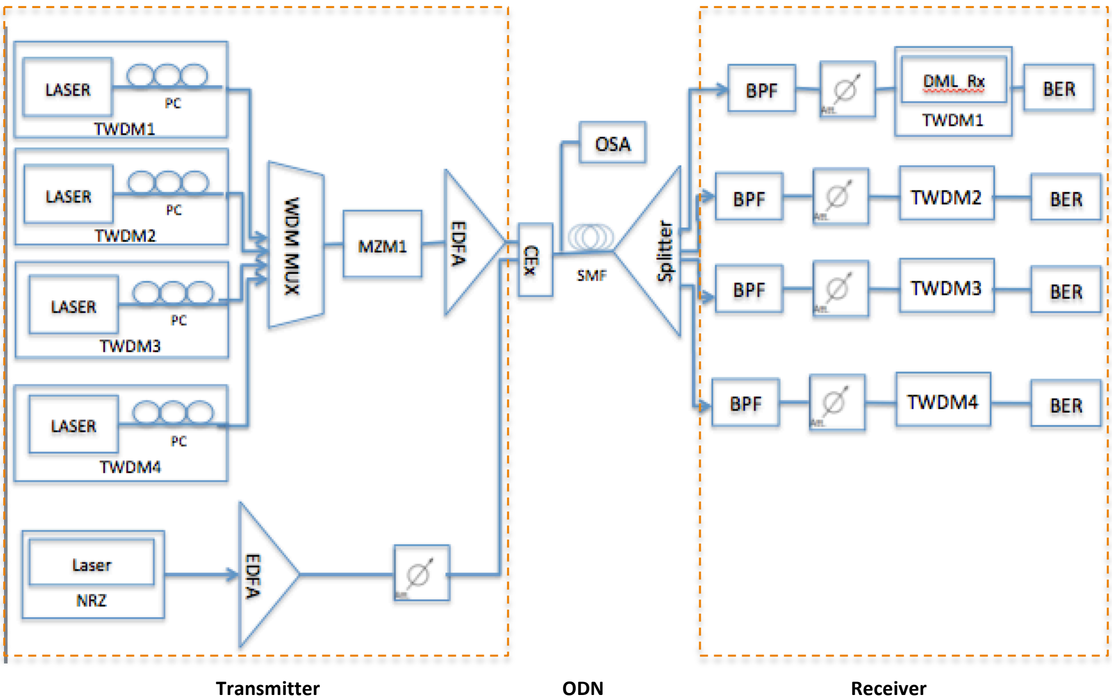



*Figure 4.7 – Experimental coexistence scenario considered between TWDM and NRZ signal.*

### Results

After the coexistence element, an OSA was used to visualize the optical spectrum of the coexistence scenario for each bit rate and channel spacings. In a sense of relevance, are presented the situations with the limits of the level of interference of the NRZ signal inside the filter, on Figures 4.8-9.

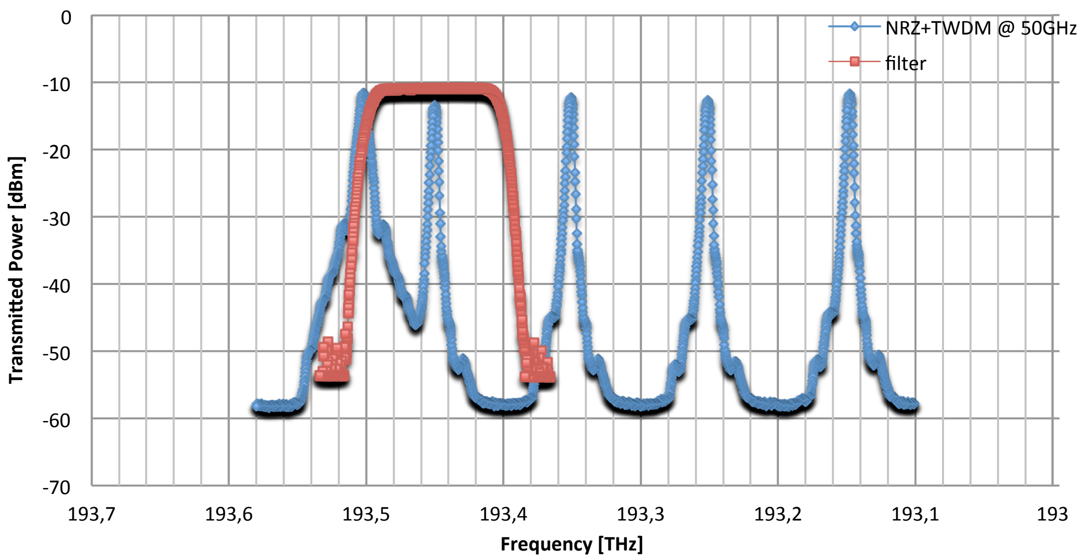



*Figure 4.8 – Optical spectrum for NRZ bit rate 10 Gbps.*

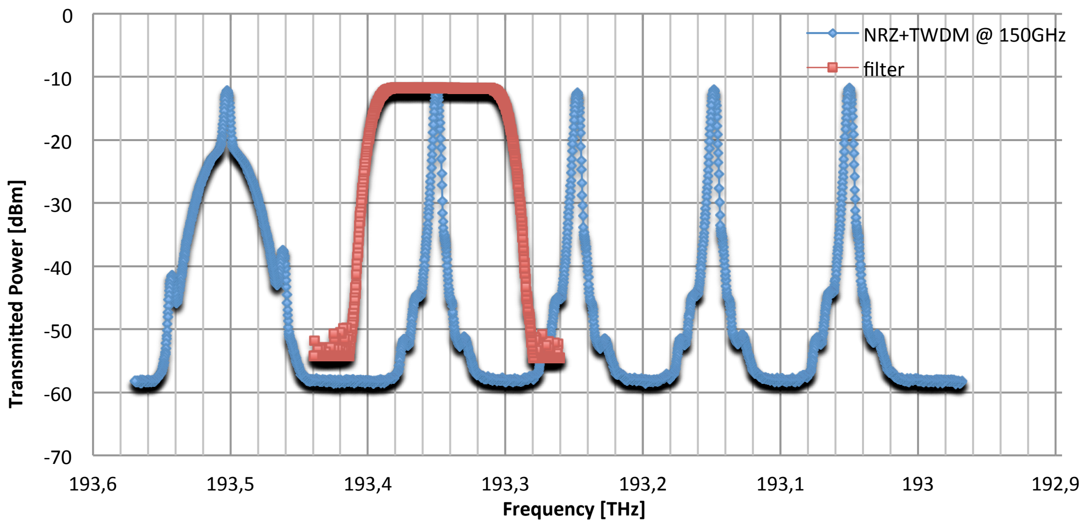



*Figure 4.9 - Optical spectrum for NRZ bit rate 40 Gbps.*

The Figures 4.10-12 present the effect created on the TWDM performance for each bit rate of NRZ and for different channel spacing.

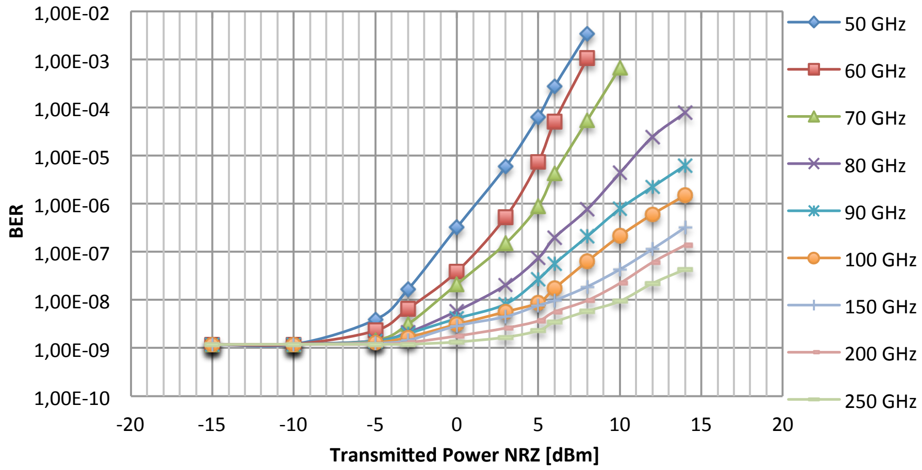



*Figure 4.10 – Effect of NRZ at 10Gbps on TWDM performance.*

It was verified that increasing the transmitted power of the NRZ signal, the TWDM performance is degrading. Looking to the 50 and 60GHz, both exceed the limit of BER of 1E-3 with 8dBm. Increasing the channel spacing the effect is getting lower but keeps present.

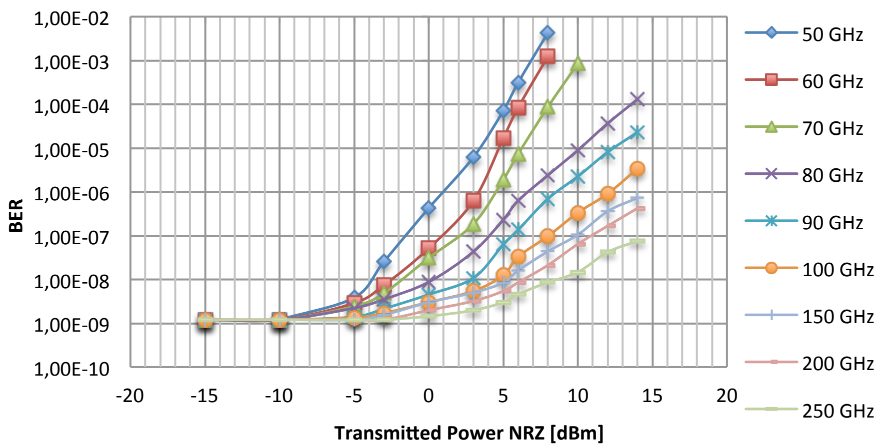



*Figure 4.11 – Effect of NRZ at 20Gbps on TWDM performance.*

The Figure 4.11 presents de influence of the transmitted power of the NRZ signal at 20 Gbps. Comparing with the results of Figure 4.10, the line of effect is the same but with a small penalty.

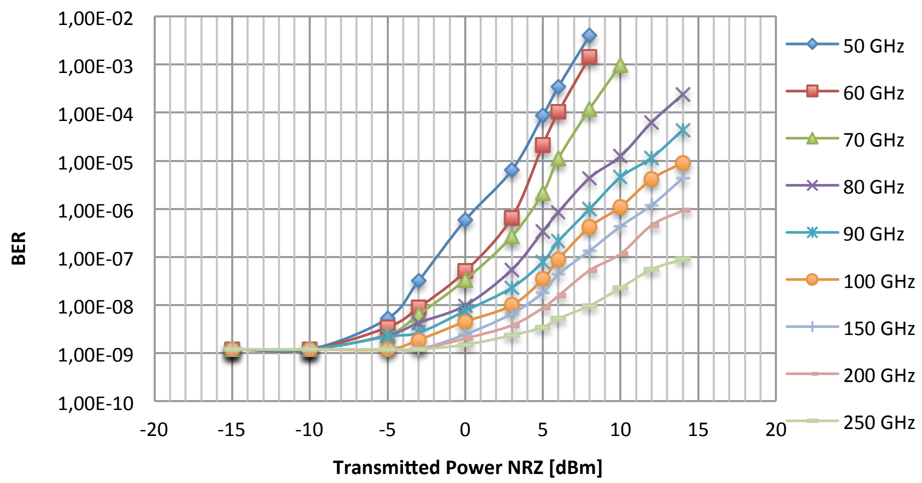



*Figure 4.12 - – Effect of NRZ at 40Gbps on TWDM performance.*

At 40 Gbps bit rate, the impact on TWDM performance is more significant, but still only for 50 and 60 GHz the limit of BER is transcended.

**Conclusions**

As explained in 4.3 was possible to determine the level of crosstalk between the two coexistent signals. Thus, in the figure 4.13, is presented the calculated crosstalk for the effect of NRZ in TWDM performance.

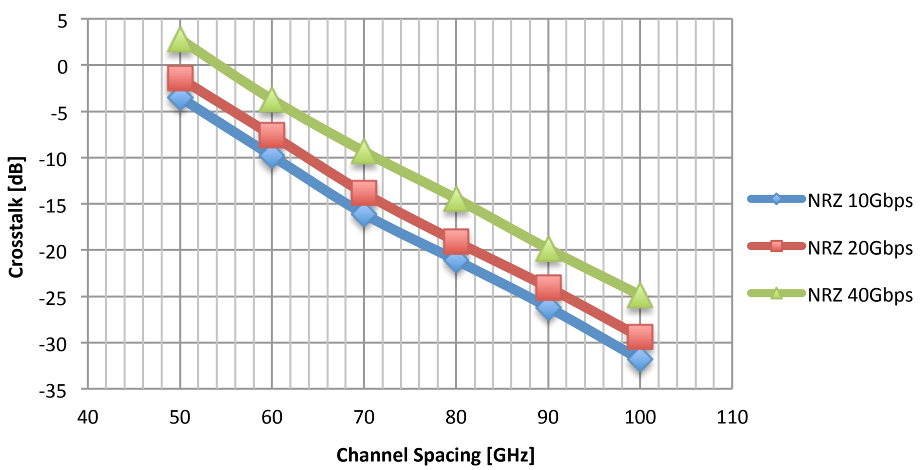



*Figure 4.13 – Linear Crosstalk for the NRZ effect.*

In a first analysis, was verified that the increase of the transmitted power of the NRZ signal creates a notorious degradation effect on the TWDM performance, mainly due to high level of Crosstalk. Thus it is possible to conclude that higher the crosstalk, higher degradation suffers the TWDM channel. Also, was verified that after 100 GHz it keeps degrading, even without direct crosstalk interference. This happen due to XPM nonlinear effect, always present in the fiber and considerable for low channel spacings and SPM induced by TWDM channel itself. Both of them are significant for high transmitted powers.

Observing Figure 4.13, is relevant to say that higher the bit rate, higher the crosstalk and higher is the BER of TWDM. It is expected to get higher crosstalk for the higher bit rate once the spectrum of the NRZ signal gets wider.

Looking in other perspective, it is possible to verify that the value of crosstalk is getting lower as it is increased the channel spacing. So, higher the spacing between the two coexisting signals, lower is the value of crosstalk and lower is the degrading of TWDM performance.

## 4.5 Coexistence TWDM and QPSK signal

TWDM technology and the characteristics of the coexistence scenario were defined as in point 4.4. Only there were changes in the bit rate used for QPSK modulated signal which were 20, 40 and 100 Gbps dual polarization and channel spacings were varied from 50 GHz to 100 GHz.

### Setup

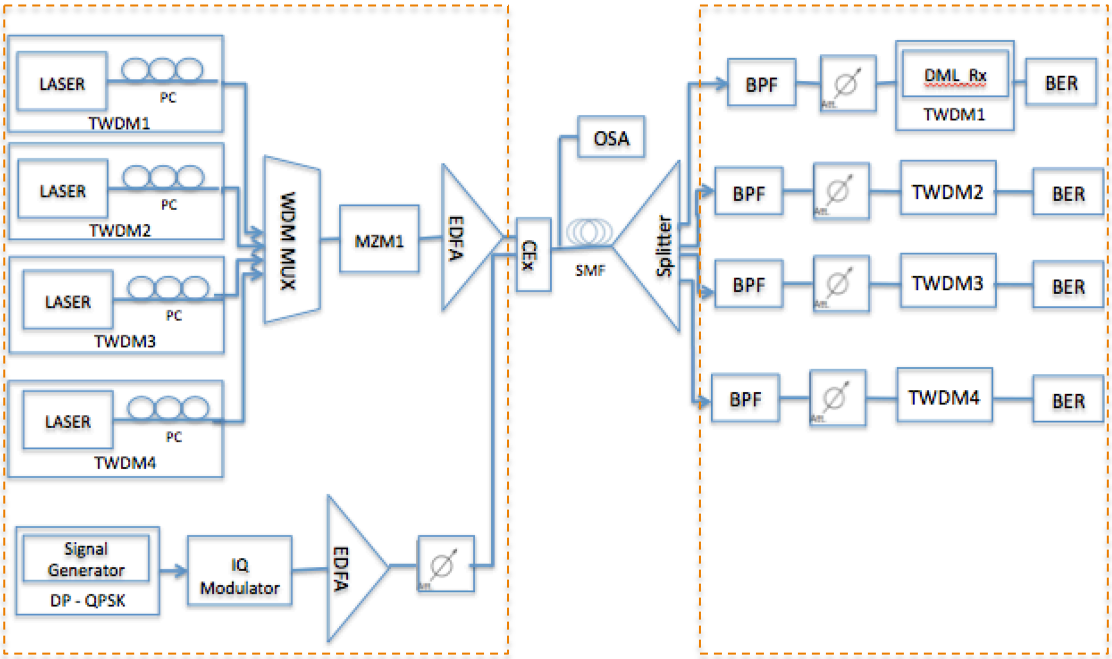



*Figure 4.14 – Experimental coexistence scenario considered between TWDM and QPSK signal.*

### Results

Figures 4.15-16 present the optical spectra of the coexistence scenario for 20 Gbps and 100 Gbps bit rate with 50 GHz and 100 GHz channel spacings, respectively.

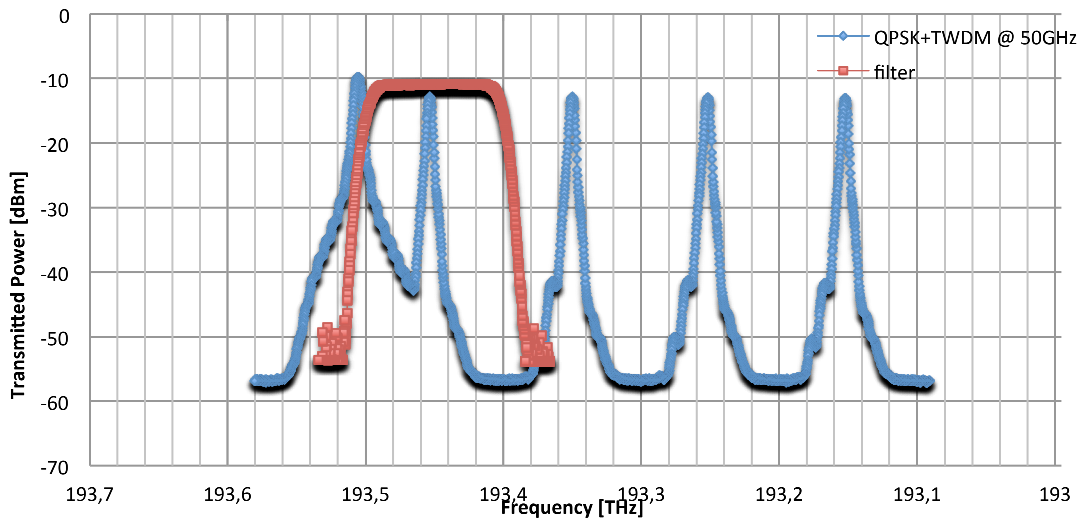



*Figure 4.15 - Optical spectrum for QPSK bit rate 20 Gbps.*

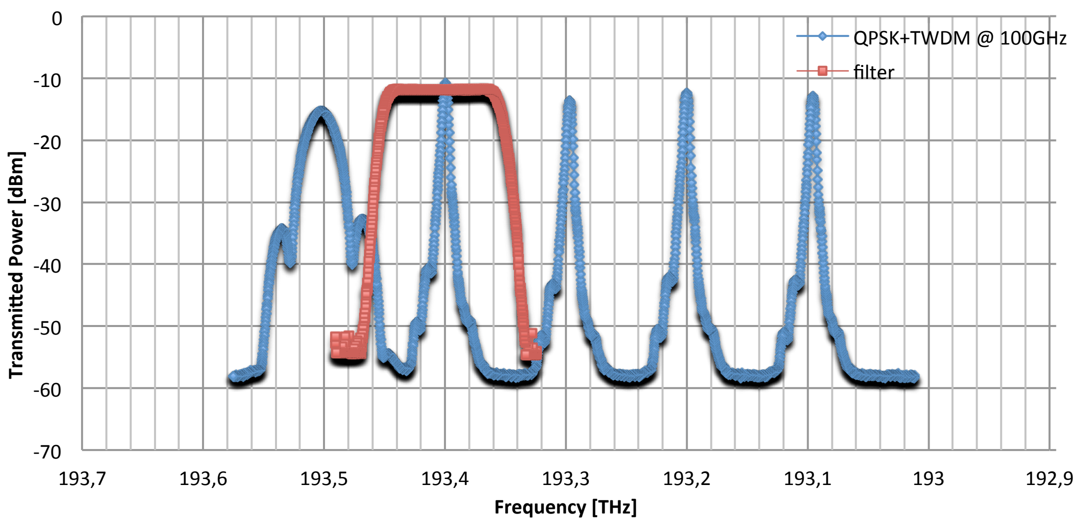



*Figure 4.16 - Optical spectrum for QPSK bit rate 100 Gbps.*

The Figures 4.17-19 present the effect created on the TWDM performance for each bit rate of QPSK modulated signal and for different channel spacing.

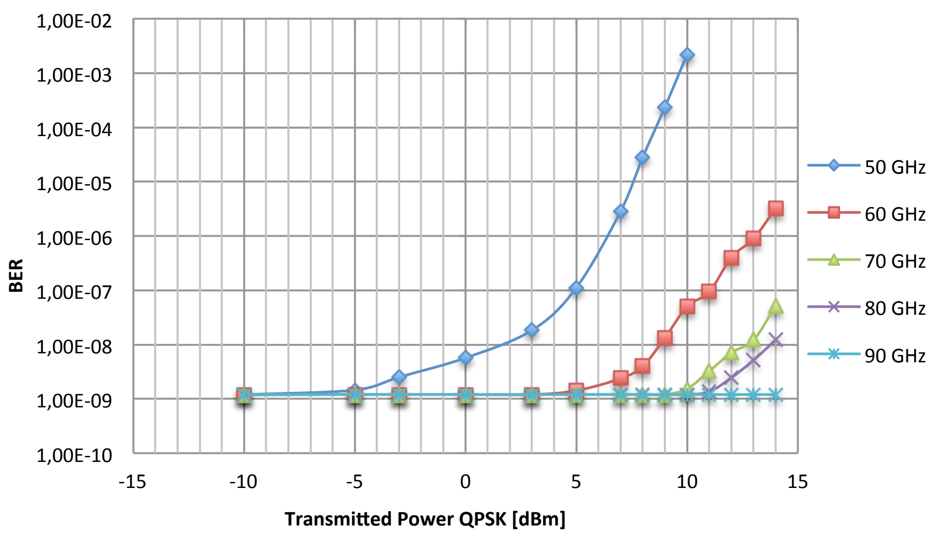



*Figure 4.17 - Effect of QPSK at 20Gbps on TWDM performance.*

Also the laboratory results shows that the coexistence with a signal modulated by QPSK format degrades the performance of TWDM technology, by increasing the signal transmitted power. At 50GHz channel spacing, the BER limit of 1E-3 is trancended with 10 dBm transmitted power. Notice that after 90GHz there is any effect in TWDM performance.

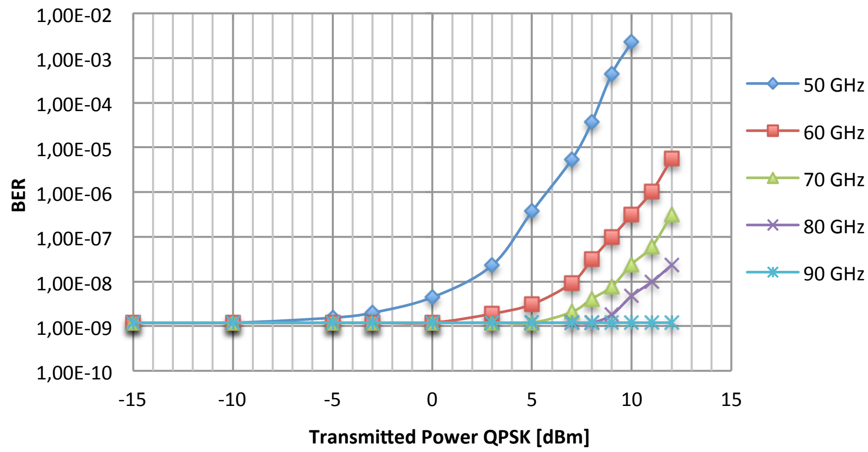



*Figure 4.18 - Effect of QPSK at 40Gbps on TWDM performance.*

QPSK with bit rate 40 GBit/s follows the same lime. At 50GHz channel spacing with 10 dBm of transmitted power the limit of BER is exceed but with more penalty. Again, after 90 GHz, QPSK does not create degradation effect on TWDM.

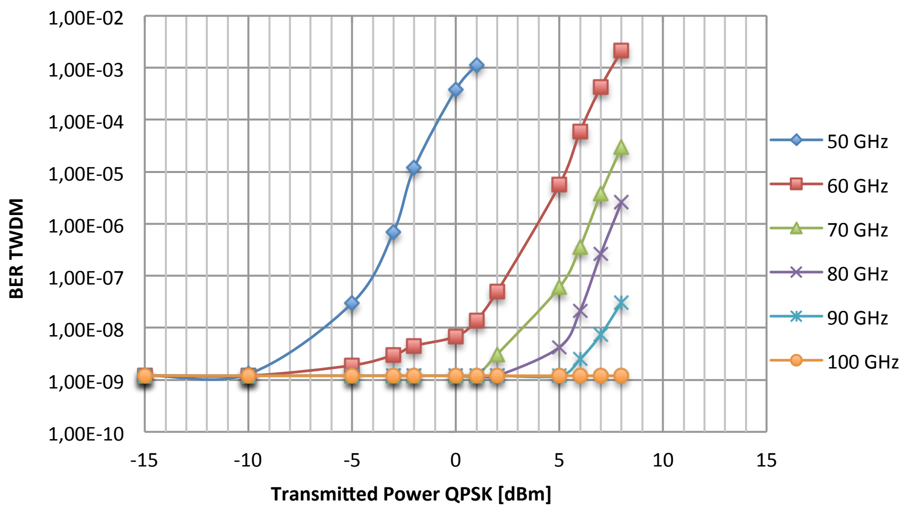



*Figure 4.19 - Effect of QPSK at 100Gbps on TWDM performance.*

About 100GBit/s bit rate, the degradation caused on TWDM performance ir more accentuade. For 50GHz, the BER reaches 1.14E-3 with only 1dBm of transmitted power and its limit is transcended for 60 GHz, too. In this case, TWDM performance stays intact just after 100GHz of channel spacing.

## Conclusions

In a way of comparision and to understand the effects created by a signal modulated with QPSK format on the coexistence scenario was again determined the level of crosstalk between the two coexistent signals. Thus, in the figure 4.20, is presented the calculated crosstalk for the effect of QPSK signal on TWDM performance.

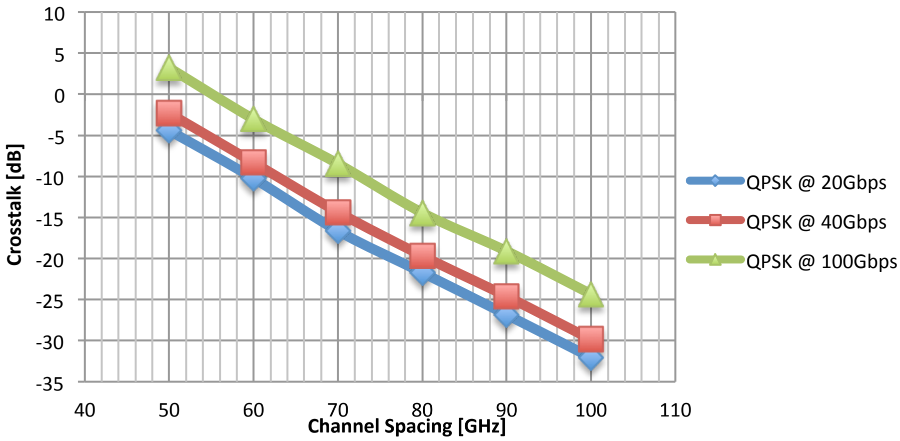



*Figure 4.20 - Linear Crosstalk for the QPSK signal effect.*

Both simulated and experimental results had the same response. This means that, regarding the QPSK transmitted power, bit rate and the channel spacing between the two signals, the conclusions observed are the same as in 3.2.2. Thus, increasing the QPSK transmitted power and bit rate, the performance of TWDM degrades, but increasing the channel spacing between them, it improves. However, as expected and explained in 4.2, are verified better values regarding the experimental setup. In this case, QPSK signal stops degrading TWDM performance after 90 GHz.

Analysing these results against the results obtained in 4.4 with the NRZ signal and observing Figure 4.20, it is verified that the crosstalk effect is lower for this case, causing less degradation on TWDM performance. The NRZ-OOK format encode only 1bit/symbol against 2bits/symbol of QPSK, being less efficient than QPSK format (See 2.8).

## 4.6 Coexistence TWDM and 16QAM signal

### Setup

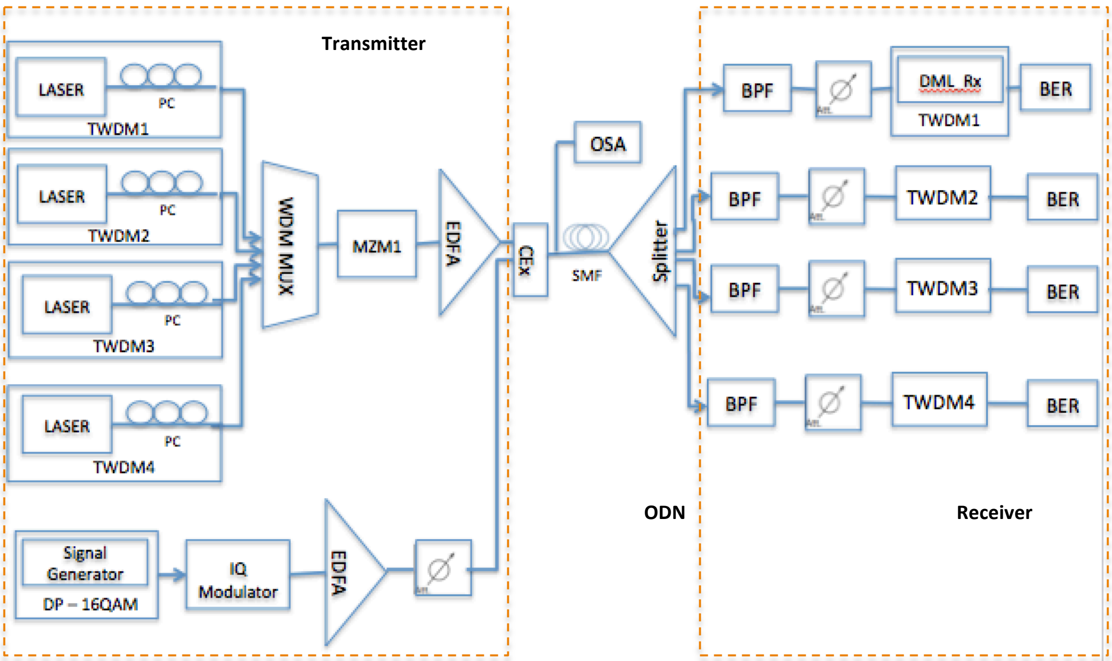


*Figure 4.21 - Experimental coexistence scenario considered between TWDM and 16QAM signal.*

**Results**

The parameters for this coexistence scenario were set up according 4.5, to create a comparison more realistic.

Figures 4.22-23 present the optical spectra of the coexistence scenario for 20 Gbps and 100 Gbps bit rate with 50 GHz and 100 GHz channel spacings, respectively.

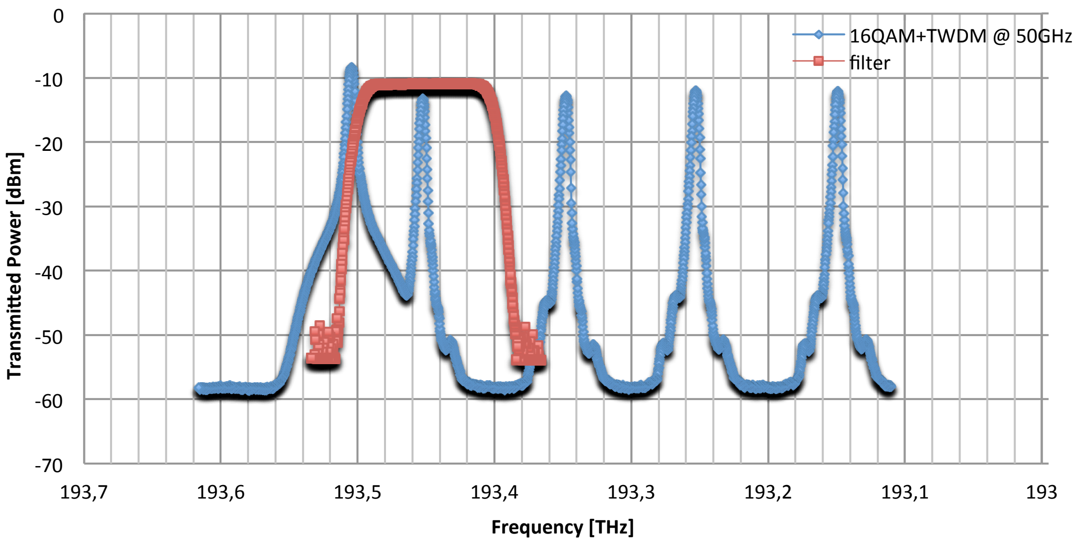



*Figure 4.22 - Optical spectrum for 16QAM bit rate 20 Gbps.*

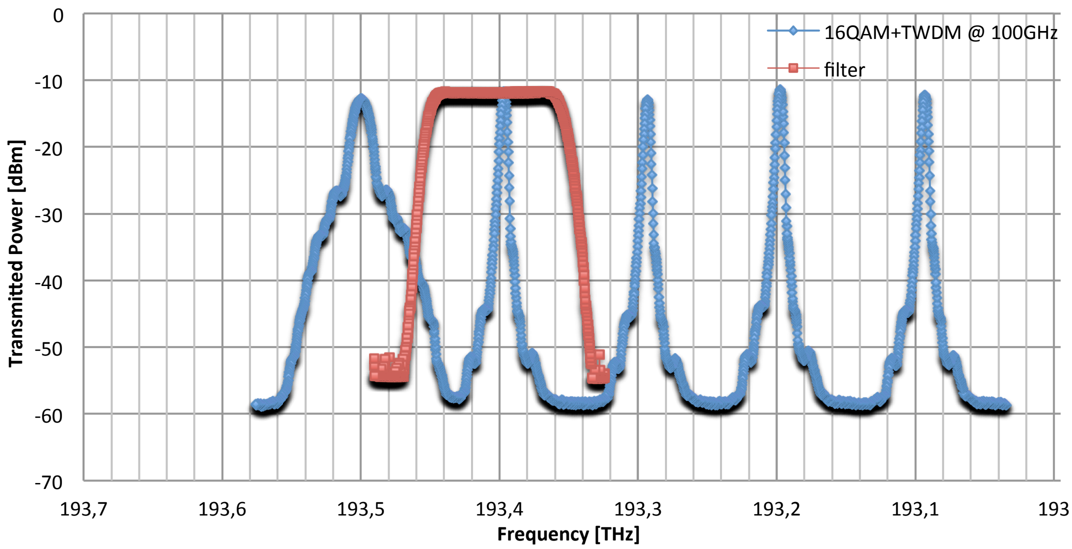



*Figure 4.23 - Optical spectrum for 16QAM bit rate 100 Gbps.*

The Figures 4.24-26 present the effect created on the TWDM performance for each bit rate, introduced in 16QAM-modulated signal, and for different channel spacing.

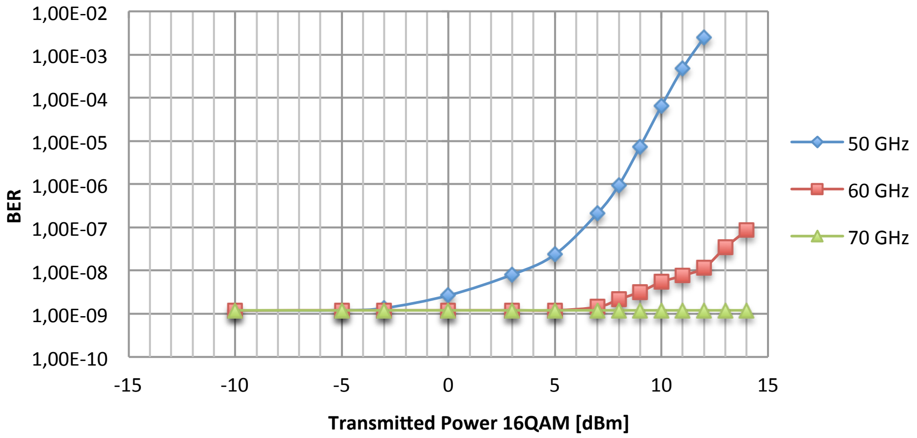



*Figure 4.24 - Effect of 16QAM at 20Gbps on TWDM performance.*

As visualized on the simulated results, also 16QAM signal creates degradation effect on the performance of TWDM technology, by increasing the signal transmitted power. At 50GHz channel spacing, the BER limit of 1E-3 is trancended with 12 dBm transmitted power. Notice that at 70GHz and forward, the coexistence with 16QAM does not create degradation on TWDM.

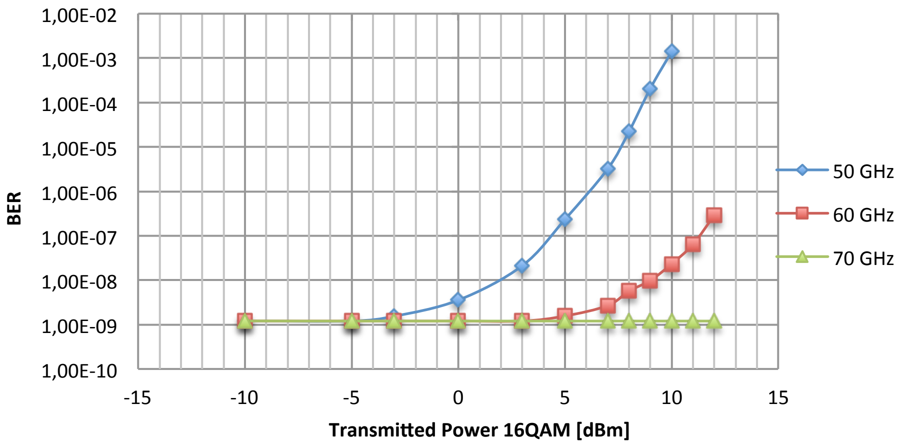



*Figure 4.25 - Effect of 16QAM at 40Gbps on TWDM performance.*

16QAM with bit rate 40 GBit/s follows the same lime but with more penalty. At 50GHz channel spacing the limit of BER is exceed with 10 dBm of transmitted power. Again, after 70 GHz, 16QAM does not create degradation effect on TWDM.

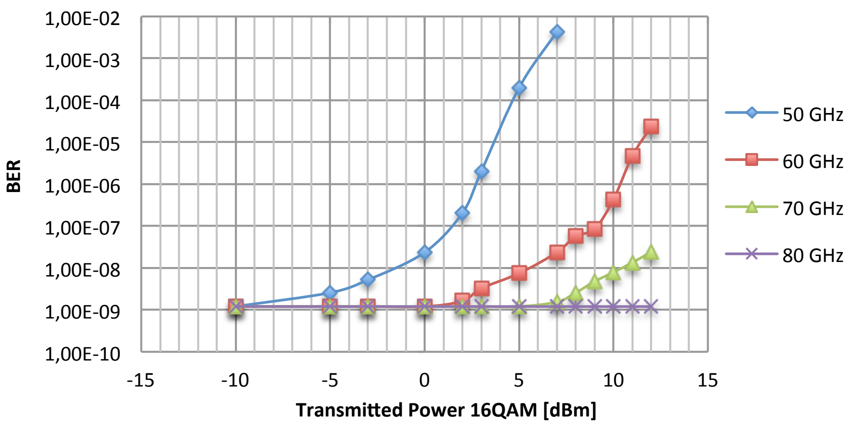



*Figure 4.26 - Effect of 16QAM at 100Gbps on TWDM performance.*

About 100GBit/s bit rate, the degradation caused on TWDM performance ir more accentuade. For 50GHz, the BER reaches the limit with only 7dBm of transmitted power. In this case, TWDM performance stays intact just after 80GHz of channel spacing.

## Conclusions

In a way of comparision was again determined the level of crosstalk between the two coexistent signals. Thus, in the figure 4.27, is presented the calculated crosstalk for the effect of 16QAM signal on TWDM performance.

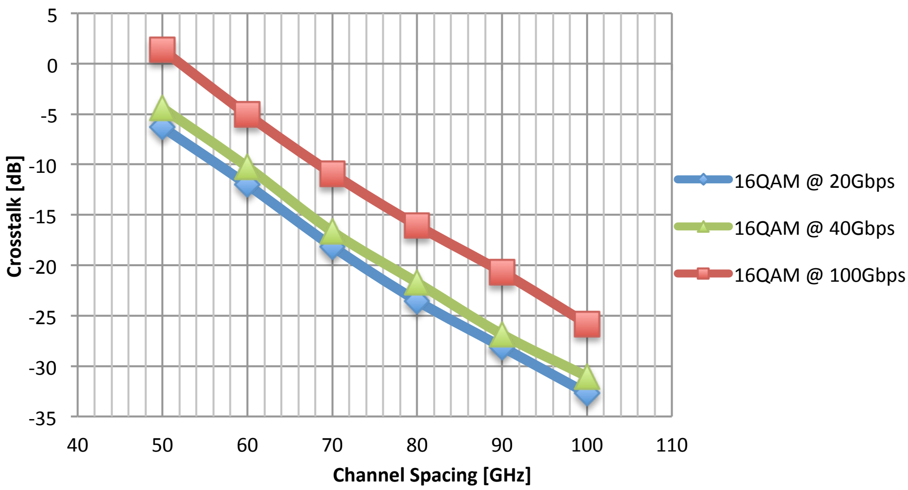



*Figure 4.27 - Linear Crosstalk for the 16QAM signal effect.*

Once again, the laboratory results are in accordance with the simulation results obtained, with some remarkable improvement due to reason already explain in 4.2. Thus, increasing the 16QAM transmitted power and bit rate, the performance of TWDM degrades, but increasing the channel spacing between them, it improves. Also explained by the different level of crosstalk existing in the coexistence scenario.

Another conclusion relapses in the comparison between the previous coexistence scenarios and this one with 16QAM signal. Putting in numbers, for example at 40 Gbps, 70 GHz channel spacing, the values of crosstalk obtained for NRZ, QPSK and 16QAM were -9.35 dB, -14.35 dB and -16.65 dB, respectively. Both simulation and laboratory results shows that this coexistence scenario is the best one in a way that the degradation of TWDM performance is lower and existent for lower channel spacing (See 2.8). The reason was already mentioned in 3.2.3 and it explains the fact that, even existing crosstalk at 80GHz till 100 GHz for 16QAM, it is not significant to cause degradation on TWDM performance.

# 5 CONCLUSIONS AND FUTURE WORK

## 5.1 Conclusions

The PON technology has been evolving rapidly through the years, with significant relevance. The purpose is to respond to the users need of higher bandwidth, created by the appearing of higher number of services and applications. NGPON2 is the next generation access network emerging as a long-term solution to fulfill the necessary requirements to satisfy the future needs. After the selection of TWDM, telecommunication operators have in hands the necessity to study the available optical spectrum options, once mostly of the window with small losses is already occupied. Being one of the most important requirements the compatibility with existing technologies, also it is necessary further studies about coexistence scenarios with the legacy and signals with high data rate formats to meet limitations and system behavior.

In this order of relevance, this work investigation allows to take some conclusions about the influence created by other signals on TWDM performance.

Firstly, GPON, XGPON and TWDM technologies were studied and simulated in VPI Photonics, independently, with the aim to meet each access network limitations and make a comparison about their networks performance. Thus, were withdrawn some conclusions:

- Increasing the transmission bit rate, the sensitivity of the system decreases, which means that its performance degrades. So, it is necessary higher power in the receiver to obtain the same BER;
- Introducing fiber to the scenario, for high bit rates will degrade the performance, due to chromatic dispersion;
- Increasing the transmission bit rate also decreases the maximum reach achieved, for the same transmitted power. So, in order to obtain the same distance in XGPON/TWDM as in GPON, it is necessary to increase the transmitted power. However, for 6 dBm or more, it will be notice the non-linear effects, like the SPM and XPM and the chromatic dispersion will be more accentuated.

Afterward, a coexistence scenario between GPON, XGPON and TWDM, also simulated in VPI Photonics, was presented and study to meet the influence of static Raman induced by GPON within the network. The conclusions are the following:

- Increasing the transmitted power of GPON channel will have a big influence on the performance of the others coexisting signals, through Raman effect:

- In the downstream transmission, exists power transference from GPON to XGPON/TWDM channels, which will cause an increase of their received power. In other words, it improves the received signal leading to a better performance;

- In upstream transmission TWDM channels suffers the same effect. About XGPON channel, the effect will be the opposite. The power transference will happen from it to GPON, causing loss of power in the receiver and degrading its performance.

- Summarizing, Raman effect has influence after 15/20 nm of channel spacing, functioning as an amplifier. It causes power transference from one channel with lower wavelength to the others with higher wavelength.

Lastly, simulated and experimental coexistence scenarios were studied between TWDM and signals with high data rate formats. In this case, channel spacings were chosen very small, from 0.4 to 0.8 nm, to meet the influence of linear crosstalk interference on the performance of TWDM technology. Thereby, were achieve the further conclusions:

- Increasing the transmitted power of the signal, will degrade significantly the performance of TWDM, due to linear crosstalk and nonlinear effects present in the fiber, such as SPM and XPM;

- Increasing the channel spacing between signals creates lower degradation on TWDM performance;

- Increasing the signal bit rate, will increase the degradation of TWDM performance, once the spectrum of the signal gets wider, increasing the crosstalk level;

- Comparing QPSK with 16QAM signal for the same bandwidth, the first one creates less degradation effect due to XPM, which is more significant in signals with higher variation of amplitudes.

## 5.2 Future Work

In order to define the next generation max occupancy of a given network, finding the less aggravating solution, it is interesting to keep studying coexistence between technologies. Thus, it is suggested as future work, the following topics:

- Study the behavior of the system, increasing the number of TWDM channels for 8 and 16 within the coexistence scenarios between legacy and high data rate formats;

- Expand the study of the coexistence between TWDM and signals with different modulation formats to other wavelength range;
- Implement a experimental setup with a coexistence scenario more realistic, which means, within the proposed wavelength spectrum, once the equipment in the laboratory only allow measurements in the C-band;
- Study other advanced modulation formats within the coexistence scenario with TWDM, such as, QDB, PSK, and other variations of QAM as 32-QAM, 64-QAM, etc.

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# Appendix A. LINEAR AND NONLINEAR EFFECTS

## A.1. Introduction

Low loss optical fibers are the new revolutionary mean used to transport huge amount of information from one point to another, at high distances. Combined with optical detectors, optical amplifiers and efficient semiconductor lasers create a remarkable communication system in great use nowadays. However, the light pulses carried on the information may suffer linear and nonlinear effects, causing distortion of the signals and loss of information. Trends reveal the constant need of increase the capacity of an optical channel and obtain higher data rate transmissions. For this purpose, new techniques, as WDM are being implemented, multiplexing independent channels on the same fiber and leading to propagation of higher intensities. In this way, the role of nonlinear effects, such as SPM (Self-Phase Modulation), XPM (Cross-Phase Modulation), FWM (Four Wavelength Mixing), SRS (Stimulated Raman Scattering) and SBS (Stimulated Brillouin Scattering) become even more important [63].

Thus, in this chapter, will be present a summary of some of these effects and their impact on optical communication systems.

## A.2. Linear Effects

The most important linear effects present in the fiber are the attenuation and dispersion. Dispersion effect can be divided in two types: intermodal and intramodal. The first one manifests for MMF (Multimode Fiber), disappearing for SMF (Single Mode Fiber), once the power of the optical signal is combined in one single mode of propagation. Thus, the total dispersion for SMF is the intramodal, also called Chromatic dispersion. These effects create limits to the distance and to bit rate and may degrade significantly the signals.

### A.2.1. Attenuation

Attenuation is imposed when the optical signal is propagate on the fiber. It determines the maximum reach that one signal can be transmitted, since the optical receivers need a minimum quantity of optical power to recover the signal. These losses in the fiber can be compensated with optical amplifiers, but they add noise and costs to the system.

So, the signal propagated on the fiber, with a determined optical power $P_{in}$, suffers an exponential decrease with the distance z, being the optical power at the end calculated by [64]:

$$P_{out} = P_{in} * e^{-\alpha_p z} \quad \text{(A.2.1)}$$

where $\alpha_p$ is the attenuation coefficient in $km^{-1}$, given by:

$$\propto_p = \frac{1}{z} * ln\left(\frac{P_{in}}{P_{out}}\right) \quad \text{(A.2.2)}$$

Nevertheless, is more common to use this parameter in dB/km, given by the following relation:

$$\propto\left(\frac{dB}{Km}\right) = \frac{10}{z} * log\left(\frac{P_{in}}{P_{out}}\right) = 4.343 \ \propto_p \ (km^{-1}) \quad \text{(A.2.3)}$$

The Figure. A.1 [65] presents the attenuation of a SMF and a ZPW (Zero Water Peak) fiber, induced for each wavelength.

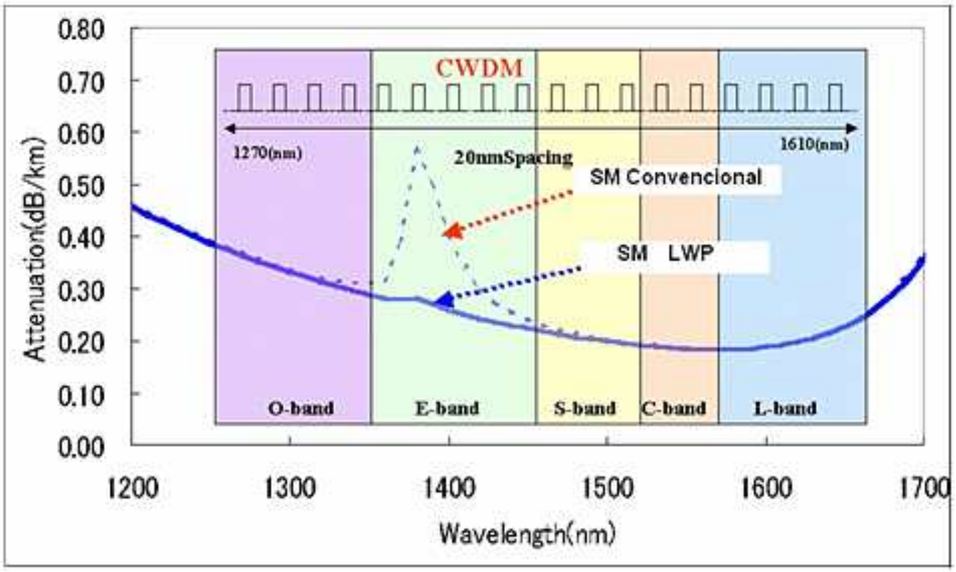


*Figure A.1 – Losses due attenuation vs Wavelength of the fiber.*

The window with minor losses is 1550 nm with around 0.2 dB/km, followed by the 1310 nm window. By this reason, they are the most used in current PON systems.

### A.2.2. Chromatic Dispersion

The spreading of a light pulse as it travels down a fiber is called chromatic dispersion. During the propagation, pulses may overlap being no longer distinguishable by the receiver, due to different velocities achieved by its spectral components. This way, the components will have a delay between each one, causing a temporal pulse broadening. This result is wavelength dependent and it is combined in material dispersion and waveguide dispersion [64].

Material dispersion is directly related with the variation of the refraction index of the material of the fiber core in function of the wavelength. In this order, the spectral components propagates at different spends, resulting the definition GVD – Group Velocity Dispersion.

Regarding the waveguide dispersion, it is associated with the distribution of the power for the core and sheath of the fiber. Since 80% of the optical power is confined on the core, the remaining 20% is propagated on the sheath, travelling much more rapidly then the light confined on the core.

In Figure A.2 is presented the interaction of both material and waveguide dispersion, originating the chromatic dispersion. It is possible to conclude that the two effects have opposite behaviors with the increase of the wavelength. About the chromatic dispersion starts being negative and increases with the increase of the wavelength, reaching ~16ps/nm/km in the third window.

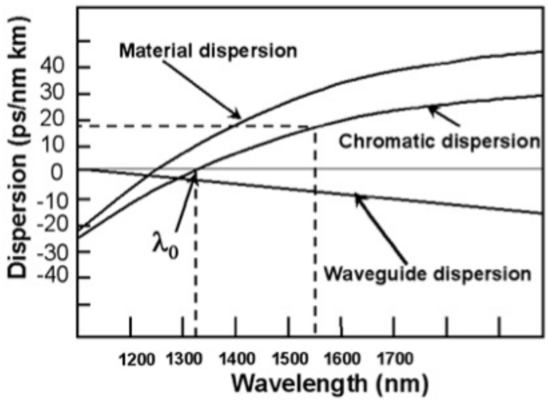


*Figure A.2 – Chromatic dispersion in function of wavelength [64].*

Normally, dispersion parameter in SMF is designed by D and determined theoretically as the sum of the material and waveguide dispersion, calculated separately. The units are ps/(nm.km) [65].

$$D = D_m + D_w = \frac{\lambda_0}{c}\frac{d^2 n}{d{\lambda_0}^2} - \frac{n_1 \Delta}{c\lambda_0}\left(V\frac{d^2(bV)}{dV^2}\right) \quad \text{(A.2.4)}$$

## A.3. Nonlinear Effects

When the pulses are propagated in the optical fiber, they will interact one to the others through nonlinear effects. These effects can be classified into two categories: one originated from the intensity dependence of the refractive index and other from stimulated inelastic scattering. In this research fits the SPM and XPM, produced by the first category and SRS produced by the second.

### A.3.1. SPM (Self-Phase Modulation)

SPM, as the name indicates, means phase modulation of an optical signal by itself, occurring mainly in single-wavelength systems. At high powers, all the materials behave in nonlinear way, increasing the refraction index with the optical intensity.

The magnitude of the optical field can be determined having into account that the phase changes are given by equation A.3.1, showing the referred dependence [64].

$$\emptyset = n\, k_0\, L = (n + n_2|E|^2)k_0 L \quad \text{(A.3.1)}$$

Through equation A.3.1, where L is the optical fiber length and $k_0 = 2\pi/\lambda$, it is possible to conclude that the nonlinear phase shift is achieved by:

$$\emptyset_{SPM} = n_2 k_0 L |E|^2 \quad (A.3.2)$$

By this way, the nonlinear refractive index causes a phase shift, proportional to the impulse amplitude, leading to different phase changes in different parts of the impulse and creating the chirp. This frequency deviation, caused by a Gaussian impulse, is dependent on time and can be observe in Figure A.3 [65].

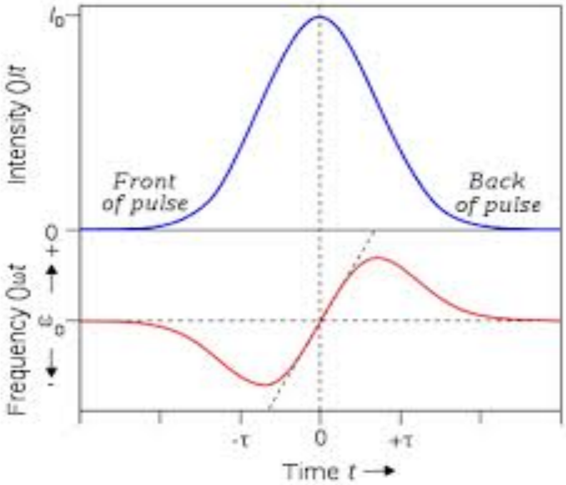


*Figure A.3 – Variation of the frequency deviation, due to SPM effect.*

As notice, the front of the pulse suffers a negative phase shift - negative chirp and the back of the pulse suffers a positive phase shift – positive chirp. As consequence, the spectrum will suffer an extension, due to the new frequencies generated on the spectrum of the incident signal.

### A.3.2. XPM (Cross-Phase Modulation)

Cross-Phase Modulation also induces a nonlinear phase variation, but this one is caused by the presence of other co-propagating signals in the fiber, with different wavelengths. XPM occurs because the refractive index seen by the optical beam inside a nonlinear mean depends on its intensity and the intensity of the other beams propagating at the same time.

The phase variation of two optical signals propagating in the same fiber, with intensities $|E_1|^2$ and $|E_2|^2$, is given by [64]:

$$\emptyset_{SPM+XPM} = n_2 k_0 L (|E_1|^2 + 2|E_2|^2) \quad (A.3.3)$$

It is noteworthy that, for two optical fields with the same intensity, XPM effect contributes two times more to the nonlinear phase variation, than SPM effect. Thus, the chirp and the enlargement of pulses in WDM systems are aggravate by XPM effect, once SPM and XPM are qualitatively similar [65].

### A.3.3. SRS (Stimulated Raman Scattering)

This effect is very relevant in multi-channel systems, since it can behave as an amplifier, transferring optical power from one channel to another.

Figure A.4 presents a diagram with the energy levels that a molecule reach, to understand the process of interaction between the optical source light with the molecular structure of silica [64].

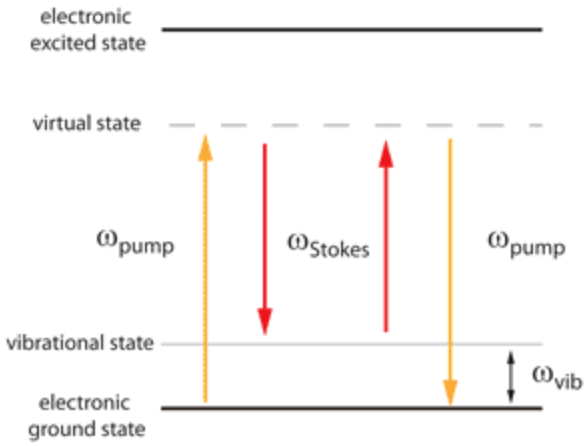


*Figure A.4 – Diagram with the energy levels of SRS process.*

Firstly, a molecule of silica is excited by an incident photon with frequency $\omega_{pump}$, from its fundamental state (ground state) to the virtual state, which is more energetic. After a while, occurs a transition to the vibrational state, releasing a photon with lower energy and lower frequency, $\omega_{stokes}$. This frequency shift is known as Stokes translation.

If the number of incident photons and the available population in the fundamental state gets higher, the SRS process is also more intense. Thus, entering two signals, separated by the Stokes frequency, in a fiber, occurs power transference from the signal with higher frequency (lower wavelength) to the other with lower frequency (higher wavelength) [64].

The interaction between a pump signal and the Stokes radiation, in the co-propagating direction, is given by the coupling of A.3.4 and A.3.5 equations.

$$\frac{dI_s}{d_z} = g_R I_p I_s - \propto_s I_s \quad \text{(A.3.4)}$$

$$\frac{dI_p}{d_z} = -\frac{\omega_p}{\varphi_s} g_R I_p I_s - \alpha_p I_p \quad \text{(A.3.5)}$$

$I_s$ is the intensity of the Stokes beam and $I_p$ the intensity of the pump signal. $\alpha s/\alpha p$ are the losses factors at $\omega_s$ and $\omega_p$ frequencies.

The $g_R$ parameter is the Raman gain coefficient, defining the increase of the Stokes wave. It is known that the Raman gain spectrum extends through a high frequency band and presents two peaks at 13 THz and 15 THz [64].

In WDM networks, the SRS effect can have a significant role, due to its high bandwidth. If sending a considerable number of signals in the system, they can contribute to the SRS effect, where higher wavelengths are amplified against the lower wavelengths that suffer the opposite effect. Continuously, as more signals are sent to the fiber, higher will be the interaction between them. In this order, it is necessary to balance the transmitted power per signal, decreasing it with the increase of the number of signals [64].