Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática
2009

Marco Paulo Flores Ferreira

Nó Reconfiguravel para redes ópticas passivas (PON)

Reconfigurable nodes for passive optical networks (PON)

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

Dedico este trabalho aos meus pais e irmãs por todo o seu incansável e incondicional apoio ao longo de toda a minha vida.

o júri/ the jury

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agradecimentos

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palavras-chave

Comunicações ópticas, redes ópticas passivas de nova geração, amplificadores ópticos remotamente bombeados, reconfigurabilidade, amplificadores de fibra dopada com érbio, algoritmo genético, optimização de redes

resumo

Recentemente , as redes ópticas de nova geração têm sido motivo de acesa discussão nos meios científicos. Com o aumento verificado nos últimos anos do numero de utilizadores e o aparecimento de novos serviços disponibilizados através das redes de acesso, torna-se cada vez mais claro que a fibra óptica é a única solução para disponibilizar a largura de banda necessária.

Neste trabalho é apresentado um novo método passivo capaz de aumentar os níveis de escalabilidade e reconfigurabilidade destas redes. O método consiste no controlo da quantidade de potência de bomba entregue a um amplificador ou conjunto de amplificadores remotos em série, permitindo o controlo independentemente do ganho fornecido por cada amplificador.

Utilizando o método proposto consegue-se evitar o uso de componentes activos, ou mais complexos, para controlo da quantidade de potência de bomba a fornecer aos amplificadores remotos, tornando o processo de amplificação simultaneamente passivo e reconfigurável.

Foi também desenvolvido, no âmbito deste trabalho, uma ferramenta de simulação baseada em algoritmos genéticos, capaz de simular e determinar a melhor solução para diversos cenários, optimizando os diversos parâmetros.

Foi também realizada a caracterização de uma fibra óptica dopada com érbio, onde foi estudado o comportamento do ganho da fibra dopada quando bombeada por um sinal de bomba diferente dos comprimentos de onda nominais, 980nm e 1480nm. Ainda, o caso de bombeamentos com diferentes comprimentos de onda multiplexados foi motivo de estudo.

keywords

Optical comunications, new generation passive optical networks, optical amplifiers remotly pumped, reconfigurability, erbium doped fiber amplifiers, genetic algorithms, networks optimization

abstract

Recently, the new generation optical networks are being the focus of several discussions in the scientific forums. With the observed increase of users in the last years, and the emergence of new services supplied through the access networks, it became even clearer that optical fiber is the best solution to provide the required bandwidth.

In this work it is presented a new passive method capable to improve the scalability and reconfigurability of those networks. The method consist in controlling the amount of pump power to be supplied to one or various remotely pumped optical amplifiers disposed in series, and by this, adjust independently the gain of each.

Using the proposed method, it is possible to dismiss the use of active or/and complex components, to control the remote amplifiers conditions, making all this amplification process passive and reconfigurable.

It was also developed during this work, a simulation tool based in genetic algorithms, capable to simulate and reach the best solution for different network scenarios, optimizing the several parameters.

A laboratory characterization of an erbium doped fiber amplifier it was also performed, where it was studied the gain behaviour of the doped fiber, when it is pumped by a signal which wavelength is different of the nominal wavelengths, 980nm and 1480nm. In this characterization it was also studied the gain behaviour when the amplifier is pumped with multiple multiplexed pump signals.

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List of Acronyms

ASE Amplifier Spontaneous Emission

BPON Broadband Passive Optical Network

CDM Code Division Multiplexing

CM Control Module

CO Central Office

CWDM Course Wavelength Division Multiplexing

DFA Doped Fiber Amplifier

DS Down Stream

DWDM Dense Wavelength Division Multiplexing

EDFA Erbium Doped Fiber Amplifier

EPON Ethernet Passive Optical Network

FBG Fiber Bragg Grating

FTTB Fiber To The Building

FTTC Fiber To The Curb

FTTH Fiber To The Home

FTTN Fiber To The Node

FTTX Fiber To The X

GPON Gigabit Passive Optical Network

IL Insertion Loss

MGA Multiobjective Genetic Algorithm

MEMS Microelectromechanicals

NF Noise Figure

OADM Optical Add Drop Multiplexer

OLT Optical Line Termination

ONT Optical Network Terminal

ONU Optical Network Unit

OXC Optical Cross-Connect

PBS Polarization Beam Splitter

PCM Power Converter Module

PD Photodiode

PON Passive Optical Network

PPC Photovoltaic Power Converter

P2MP Point-To-Multipoint

P2P Point-To-Point

RN Remote Node

ROADM Reconfigurable Optical Add Drop Multiplexer

ROPA Remote Optical Pumped Amplifier

SCM Subcarrier Multiplexing

SNR Signal Noise Ratio

TDM Time Division Multiplexing

TDM-PON Time Division Multiplexing

TF Transfer Function

TPL Tunable Pump Laser

US Up Stream

WDM Wavelength Division Multiplexing

WDM-PON Wavelength Division Multiplexing Passive Optical Network

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1. Introduction

1.1. Motivation

Computer telecommunications were lead for long time by electric technologies. The copper was the medium used during that time for carrying electrical signals encoding the data to be communicated from one computer to another. With the advance of technologies and the call for higher data rates, the copper started to reveal several disadvantages as well as limitations, and in the last two decades, enormous progresses have been made in using alternative mean for communication[1].

Along the telecommunications history some media were proposed/used, from the twisted-pair copper cables, passing through coaxial cable and more recently the fiber-optic cable.

Network designers are often faced with some factors to be improved when they project a new network. Network capacity, reliability, cost, scalability and simplicity are some of the key benchmarks on which a network is evaluated[2]. After the 80's with the proliferation of the personal computers and the World Wide Web, the Internet has experienced tremendous growth[3]. On that time, telecommunications industry began setting more emphasis in fiber optics. Comparing with the copper, optical fiber provides very low-loss transmission that allows data transfers between long distances, but clearly it most significant benefit is the high bandwidth[2].

In the latest years, data traffic has exceeded voice traffic and follows an explosive path as a result of abundant data services, offered over the access networks. Voice, data (IP, Ethernet), music and video (broadcasting and interactive, streaming, and real time) are some services that now are provided by the new networks topologies. The continuous development and aggressive environment in the computer market that almost each three months has a new, smaller, more versatile, more capable and at lower cost device also contributes for the growing of users and the increase of bandwidth demands. Also, most of this new services demand quality of service, reliability, availability and real-time [4].

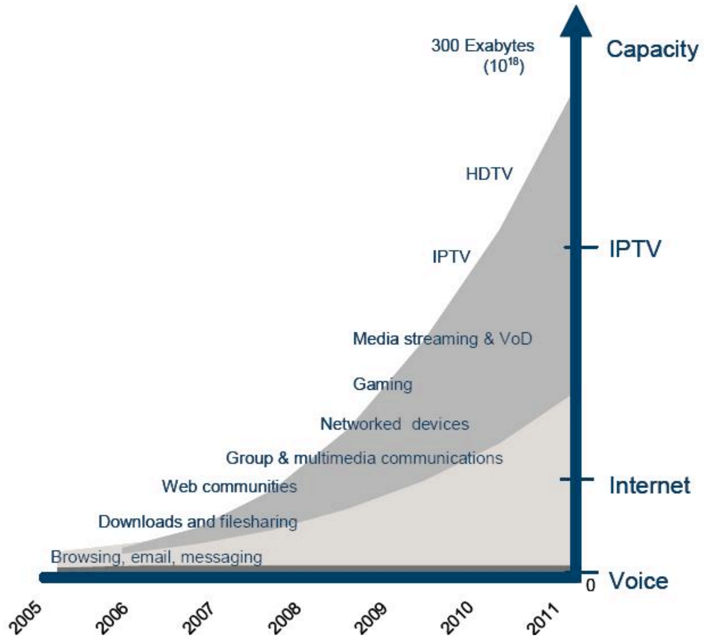


Figure 1-1Evolution of products bandwidth in terms of years[5]

The evolution of products bandwidth in function of years is represented in Figure 1.1. It demonstrates clearly an exponential increase, and it shows also the expected continuation of that growth.

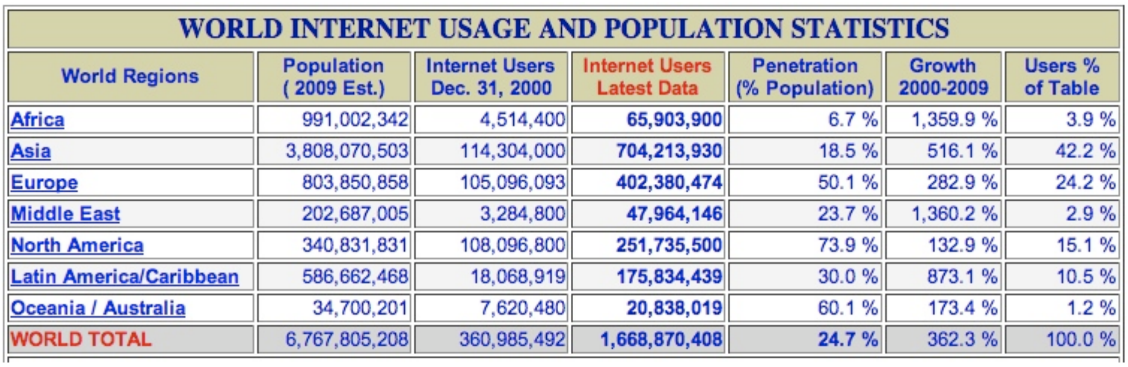
All of these reasons provide a reasonable basis to think of a new generation of networks with the ability to respond to all this needs. Tendency, since the 80's till now, a lot of technological advancements were needed to be made since that simply increase the network capacity by building more of the same is unlikely to be a cost-effective option.

One of the earliest technological advances was the ability to carry multiple channels of light on a single fiber optic cable. This evolution is the basis of the more recent networks and it is known as Wavelength Division Multiplexing (WDM). Basically, in WDM system, each lightstream is carried at a different optical frequency and multiplexed onto a single fiber, optimizing the optical infrastructure by sharing the fiber capacity. Earliest WDM systems supported less than ten wavelengths on a single fiber. Since 2000, this number has rapidly grown to over one hundred and sixty wavelengths per fiber, providing a tremendous growth in network capacity[6]. Implementation of WDM in previously existent optical networks allowed an immediate increase in its available capacity, and a gradual increase is possible increasing the number of multiplexed channels.

In the mid 90’s, the maximum capacity of a wavelength was roughly 2.5Gb/s. With the time this limit grew, from 10Gb/s to 40Gb/s and still growing with much discussion regarding evolution to 100Gb/s or even higher[5]. This combined with the greater number of wavelengths per fiber has expanded the capacity of optical networks by several orders of magnitude in the last 25 years. However, with this capacity growth mixed with the increase of the networks size, another problem arises. All this information has to be electronically processed at numerous points in the network and it required a lot of electronic terminating and switching equipments, which presented challenges in cost, power consumption, heat dissipation, physical space and maintenance.

The optical-bypass technology has reduced the blockage imposed by the problem approached in previous paragraph. This technology eliminates much of the required electronic processing and allows a signal to remain in the optical domain for all, or much, of its path from source to destination. This technology was achieved by the evolution in a lot of different areas such optical amplification, optical switching, transmission formats, and techniques to counteract optical impairments[2].

An important step to become economically viable to bring the optical fiber till the access networks and the end users premises, was the appearance of optical amplifiers. Prior the existence of this technology, optical signals had to be regenerated at roughly 40km intervals using costly electronic equipments. In each signal regeneration had to be an optical ➔ electrical ➔ optical conversion, which beyond the limitations talked for the switching equipments also inserted a bottleneck limitation by the used electrical components. With the emergence of erbium doped fiber amplifiers, that are used to amplify signals in C+L fiber window, it was allowed to amplify optical signals without such conversion, allowing by this appear all optical long distance systems with ranges of the order of 500Km before needing to be fully regenerated[7].



WORLD INTERNET USAGE AND POPULATION STATISTICS

World Regions	Population (2009 Est.)	Internet Users Dec. 31, 2000	Internet Users Latest Data	Penetration (% Population)	Growth 2000-2009	Users % of Table
Africa	991,002,342	4,514,400	**65,903,900**	6.7 %	1,359.9 %	3.9 %
Asia	3,808,070,503	114,304,000	**704,213,930**	18.5 %	516.1 %	42.2 %
Europe	803,850,858	105,096,093	**402,380,474**	50.1 %	282.9 %	24.2 %
Middle East	202,687,005	3,284,800	**47,964,146**	23.7 %	1,360.2 %	2.9 %
North America	340,831,831	108,096,800	**251,735,500**	73.9 %	132.9 %	15.1 %
Latin America/Caribbean	586,662,468	18,068,919	**175,834,439**	30.0 %	873.1 %	10.5 %
Oceania / Australia	34,700,201	7,620,480	**20,838,019**	60.1 %	173.4 %	1.2 %
WORLD TOTAL	6,767,805,208	360,985,492	**1,668,870,408**	**24.7 %**	362.3 %	100.0 %

Figure 1.2 World Internet usage and population statistics[8]

In Figure 1.2 it is possible to see the increase of the number of Internet users since the year 2000, and is estimated that it has increased 362% worldwide, and in some regions the growth was higher than 1000%. These raise of users, plus the new services supplied by the optical network talked before, support the idea that the new generations networks should have high levels of network capacity, scalability and simplicity to support any improvement in the network. This was the motivation for this work, and as result it is presented a new passive and remote method to control signal gain conditions, which increase the network scalability and reconfigurability levels keeping it management simplicity.

1.2. Structure

This document is divided in six chapters, all related with optical telecommunications. Inside it is possible to read about several subjects about the physical layer of optical networks, reference is made about the novel SARDANA network, and is also proposed a new method to improve the scalability and reconfigurability of the new generation all-optical long reach networks.

In the first chapter is presented the motivations for this work and its main proposed objectives. It is also in this chapter the description of this work structure.

Second chapter does an introduction to the optical networks. It describes the three layers of the optical networks (core, metro and access), giving more emphasis to access networks. Here it is possible to read about data distribution, network topologies and multiplexing techniques. In this chapter is also introduced the concept of all optical networks.

Chapter three presents the Scalable Advanced Ring Based Passive Dense Access Network Architecture (SARDANA). It is explained the functioning of this network, and are studied the behaviours of the used components to implement the remote nodes (RN) proposed for this. From all studied components, should be enhanced the laboratory characterization of the erbium doped fiber amplifier (EDFA), since the results are important to fundament the proposed method. In the end of this chapter there is a critical analysis of the proposed topologies for SARDANA and the proposed method is based in the revealed topologies limitations.

The fourth chapter presents the concept of the new method. A description of the method is done and its principle of operation is explained. The results of a practical implementation are also presented in order to prove in practice the method functioning.

In the fifth chapter a developed simulation tool is presented, which is used to reach an optimal solution for a system based in the proposed method. It is based on Multiobjective Genetic Algorithms (MGA) so a brief explanation of this type of algorithms is also done here. Using the developed simulation tool an eight RN system was simulated. The results for these simulations are presented here, and several method optimization parameters are studied.

In the last chapter, the sixth, it is presented the conclusion of the document and the performed work. There are also some suggestions for future work in order to improve the proposed method and the simulation tool.

1.3. Main Contributions

In the author's opinion, the main contributions of this work may be summarized as follows:

- The development of a new passive method capable to provide higher levels of reconfigurability and scalability to new generation long reach optical networks.
- A practical study of erbium doped fiber amplifiers behaviour when pumped with pump signals which wavelengths are different from the usually used 980nm and 1480nm; and when pumped with several pump signals, with different wavelengths, multiplexed.
- The developments of a simulation tool capable to simulate the proposed method for different network scenarios, and to perform the optimization of several parameters in order to minimize the network pump budgets.
- The study of several optimizations influence in the function of the proposed method.

In the segment of the presented work, it was developed and submitted a patent request to protect the method, and the summary of the protected invention is presented following.

"**Remote and passive method to control the pump power in remote amplification systems** -The presented invention describes a remote and passive method to control the pump power that is supplied to an optical remote amplifier or a set of optical remote amplifiers, in order to vary independently the gain of each amplifier.

With this method, it is possible to dismiss the use of active or complex components, to control the amount of pump power that is supplied to remote amplifiers, making the process of amplification simultaneously passive and reconfigurable."

2. Optical Networks

2.1. Telecommunications Network Architecture

Optical telecommunication, such as any other emerging technology started very expensive. So, in order to be economically profitable, implementation costs had to be shared by the highest amount of users as possible. Therefore, optical fiber started to be implemented in transport networks, which connected cities separated by long distances and transported huge amounts of data. But, with the gradual increase of data traffic, and the reduction of optical network implementation costs, the fiber started to come closer to the end user. This gradual deployment, divided the network in multiple geographic tiers, and depending on the authors, they can be called in different ways [9][10][11].

Networks may cover a small geographical area or spread over an entire continent, it can transmit Terabits of information per second or only few Gigabits, so it is useful to classify them into distinct groups. Three are the usual: core network, metro network and access network. Figure 2.1 shows an overview of typical public fiber network architecture.

These layers are distinguished according to network served users, transmitted data rates and geographical extension. Being so, core networks were the first to be implemented interconnecting countries or even spanning entire continents, transmitting huge quantities of data traffic that comes from thousands of millions of users. In the other end of the network, there are the access networks that only spans few kilometres and serve only few tens of hundreds of costumers.

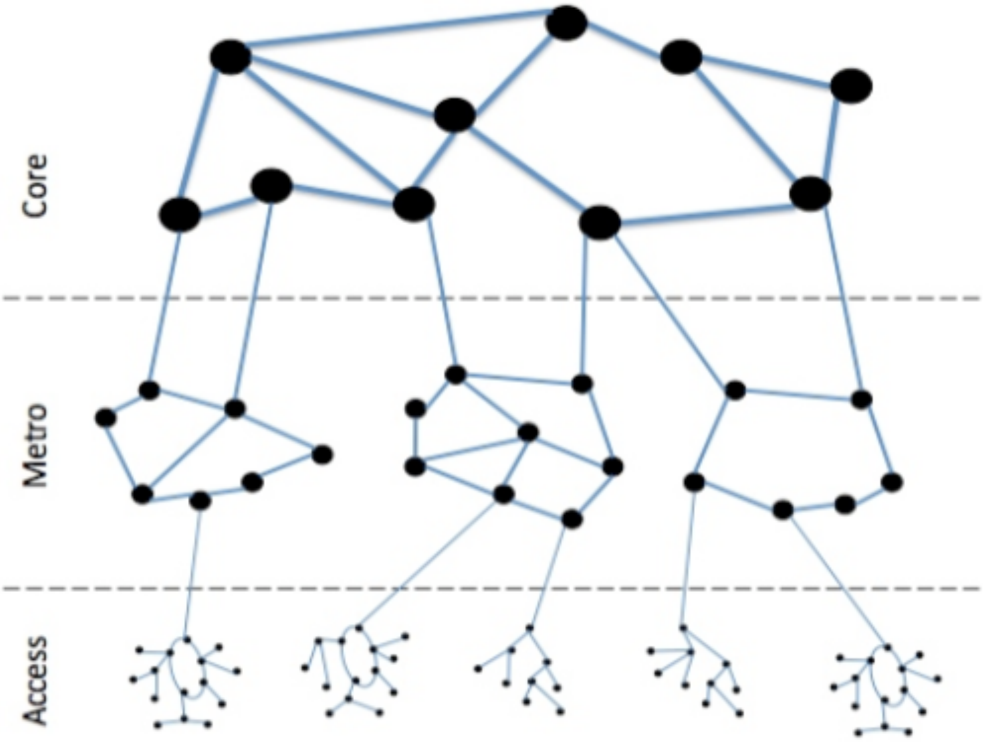


Figure 2-1 Typical public fiber network architecture[2]

As said previously, optical networks implementation goes from the core to the access networks. Figure 2-2, shows the cost of infrastructure per network node along the years. As can be seen, the different layers implementation is directly related with the reduction of infrastructures cost. Another reason that is not explicit in figure is the huge increase of users in last years, which allowed the dilution of installation cost.

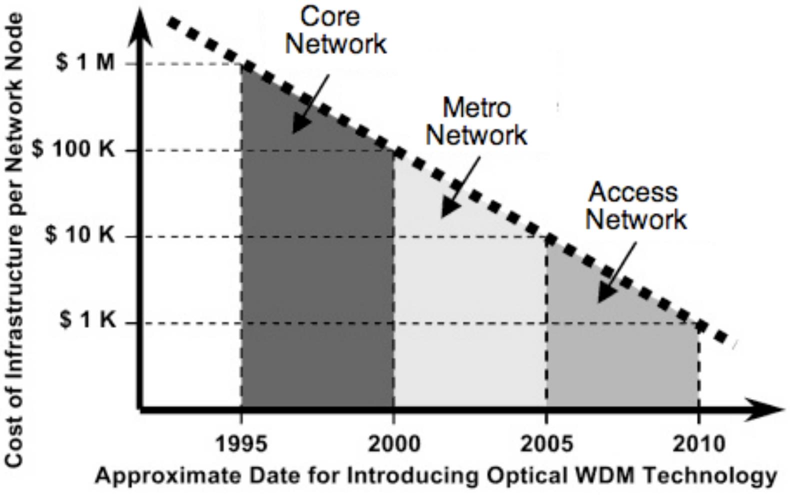


Figure 2-2 WDM technology prices evolution along the years and its application in the different network layers[2]

2.1.1. Core Network

Nowadays, with the exception of some unusual markets or geographic conditions where terrestrial microwave may still be deployed, optical networking is the only relevant technology used in the core networks.

Core networks cover large areas such as a country or a whole continent and the bulk of the traffic is carried through it. Nodes in this part of the network have to deal with enormous amounts of traffic, in orders of Terabits per second, so, protection is of huge importance, since a failure would result in a flood of customer complains.

Traffic here is highly aggregated and thus represents thousands or millions of users, so core network nodes are likely to have traffic destined for virtually all other core nodes. In core networks, only some nodes are connected directly through point-to-point links. The creation of a virtual circuit between two arbitrary nodes requires switching at one or more intermediate nodes. It is unlike that a single user uses the total capacity of a single virtual circuit in the core network, and thus adding new users in this part of network will generally not change the core significantly. For this reason, reconfiguration is likely to be less of an issue in core networks.

Initially, the switching of channels at each node was being done electronically. However, this makes the networks limited by the electro-speed bottleneck and makes the network installation and maintenance very expensive as we cannot alter neither the bit rate nor the modulation format without changing the hardware at each node.

During the 90's, with the appearance of WDM technology, it became possible to transmit multiple WDM channels over each point-to-point (P2P) link. An all-optical WDM network is desired, and with the appearance of the optical cross-connects (OXC) and the optical add-drop multiplexer (OADM) this concept could start to be better used. In such network, a WDM signal passes through intermediate nodes without being converted to the electrical domain[11]. This also allows the coexistence of a variety of protocols, dismissing electric conversions.

Figure 2.3 shows an example of a core network covering a large part of the United States of America.

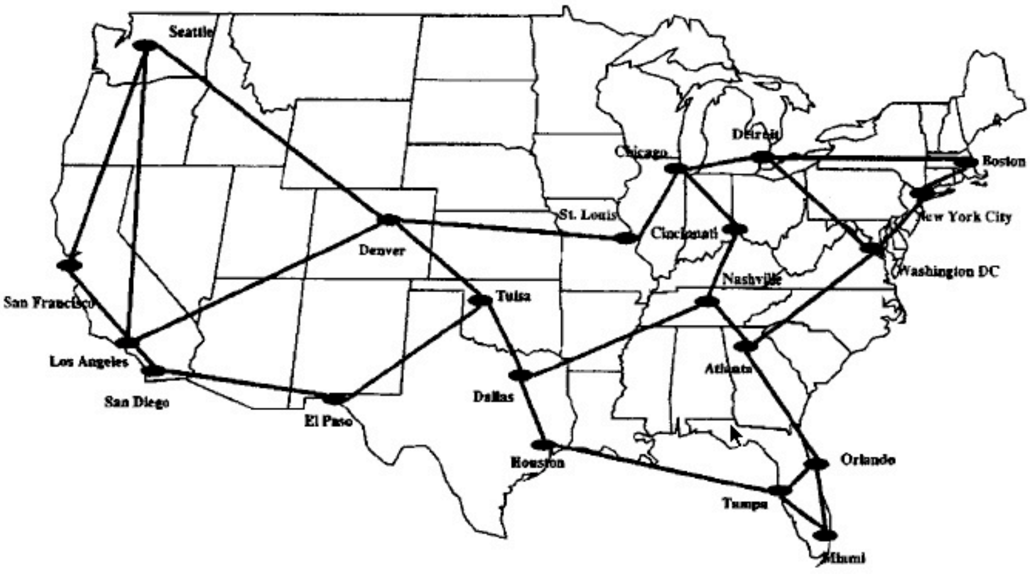


Figure 2-3 WAN implemented in the United States of America[11]

2.1.2. Metropolitan Network

In the present, the largest incremental amount of fiber deployed is not in the core, but in the metro and access network. Digital TV, and new Internet services are continuously spanned to a large population of users, and in most cases, this content has to be cached at a metro level. Fiber was the solution for this greatest traffic growth.

Metro networks typically spans a metropolitan region, covering distances of a few tens to a few hundreds kilometres and typically they are attached to one or two core network nodes. The topology of choice for metro network is a ring, and this ring usually employs up to four fibers to provide protection against network failures. Metro are the ones responsible to provide the traffic adaptation from the core to the access networks, and a single metro network may serve various local networks.

Several metro networks can be interconnected with a ring to form a regional network. The main difference between the rings used for regional and metropolitan networks stems from the scaling and cost considerations. In metro rings, traffic flows at a modest bit rate compared with a regional network and usually it just uses two fibers, one for carrying the data and the other for protection issues.

As core networks, the advent of WDM deployed in the 1550nm range has added versatility to metro optics by providing multiple lightpaths per fiber and greatly increasing the capacity of the pre-existent fiber. This influenced the implementation of optical components in this network layer, in function of the electrical components that were used till then.

2.1.3. Access Network

In last years we had observed a rapid growth in consumers broadband in the whole world. Until few years, cooper wires and cable TV cable were the only means of transporting information from a provider central office (CO) localized in metro layer to the costumer. Mostly because of the already referred traffic increase, these transport media are being “shorted” or even eliminated by the use of fiber optics.

Access networks enables end-users (business and residential costumers) to get connected to the rest of the network infrastructure. The transmission distances in access are relatively short (<20Km), so fiber losses as well as the dispersive and non-linear effects occurring inside the fibers are not of much concern.

This brings us to the context of the fiber to the X (FTTX). FTTX is a generic term for any broadband network architecture that uses optical fiber to replace all, or part, of the usual cooper local loop used for the last mile telecommunications. The X letter could be changed depending on the end point where the fiber is deployed. Some examples are represented in Figure 2-4, where the fiber to the node (FTTN), fiber to the curb (FTTC), fiber to the building (FTTB) and fiber to the home (FTTH) are represented. FTTN, it is a much more cost effective solution, since it allows each single fiber serve a larger population and dilute installation costs. Closer to the end user, less profitable is for the network provider implement fiber, be the extreme case the FTTH where highest is the cost per user.

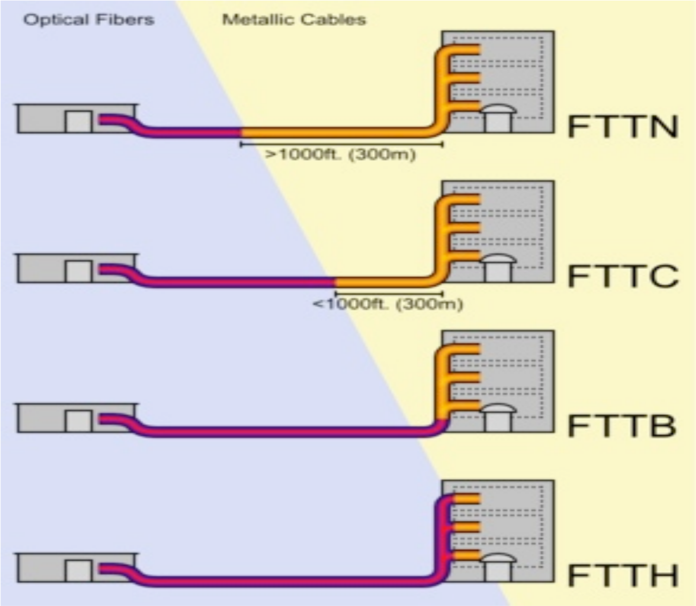


Figure 2-4 Representation of different LAN architectures[12]

In order to balance the cost and performance of a network, the compromise solution was to try to implement an all-optical network, without any electronic dependence. These networks are know as passive optical networks (PON), and offer very high capacities and reconfiguration with low maintenance costs. These networks will be deeply studied further, but firstly will be presented some network distribution schemes and topologies.

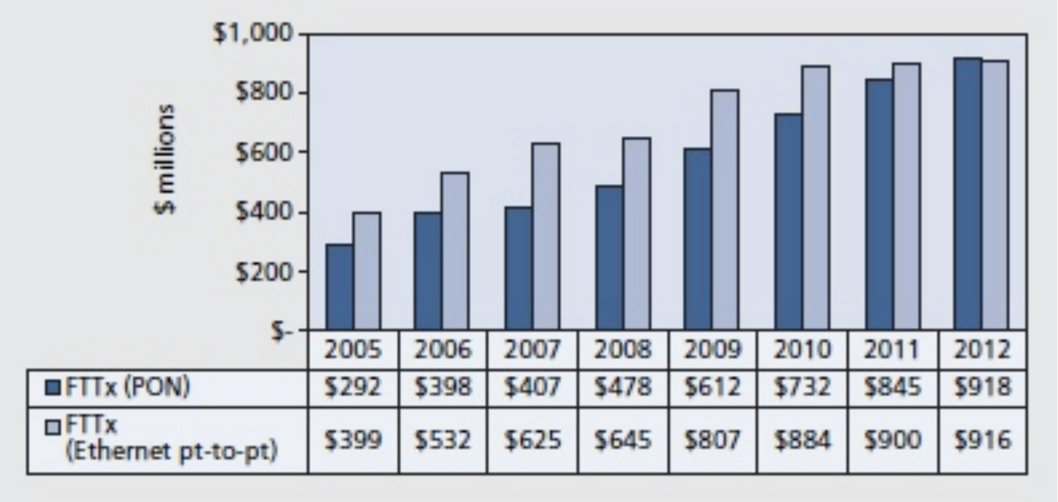
2.1.3.1. Access Network Distribution and Topologies

Point-to-Point and Point-to-Multipoint

According to the fiber distribution, FTTX can be divided in two main categories: point-to-point (P2P) and point-to-multipoint (P2MP), which is also commonly referred to as a PON[13].

In P2P architectures, a single fiber runs all the way from the CO to the end user. In P2MP architecture, a single fiber runs from the CO to the network and usually ends at a splitter cabinet. From the splitter cabinet short runs of fiber connect each of the end users, where the signal is spanned normally in equal parts.

The P2P architecture is the simplest way to implement and manage FTTX architectures. However, it is not the most efficient due the required large number of fibers, connectors, splices, installation cost and maintenance. More, the total resources of the fiber normally are not fully used and each link requires an independent laser on the CO. In a way to solve all these disadvantages, the P2MP architectures are usually preferred. In these architectures, more fiber capacity is used since it is shared by several hundreds of users at same time; being also shared by all these users the deploying and operation costs.



	2005	2006	2007	2008	2009	2010	2011	2012
■ FTTx (PON)	$292	$398	$407	$478	$612	$732	$845	$918
□ FTTx (Ethernet pt-to-pt)	$399	$532	$625	$645	$807	$884	$900	$916

Figure 2-5 Capital equipment expenditures for PON and P2P[13]

Both architectures are nowadays deployed, with P2P currently outpacing the P2MP installations. Figure 2.5 shows the evolution of the capital equipment expenditure, for each architecture, since 2005, and the expectations for coming years. As can be seen, the capital expenditures in P2MP architectures are growing faster than for Ethernet P2P architectures, and it is expected that by 2012 they catch up the P2P. After then, it is predicted that the capital spent in P2P will probably decline; and mostly because the WDM technology maturation, investments in P2MP architectures will continue to grow and will probably dominate[13].

There are four distinct commonly used topologies to implement a network: bus, tree, ring and star topologies. A brief explanation of each of these topologies will follow now.

Bus Topology

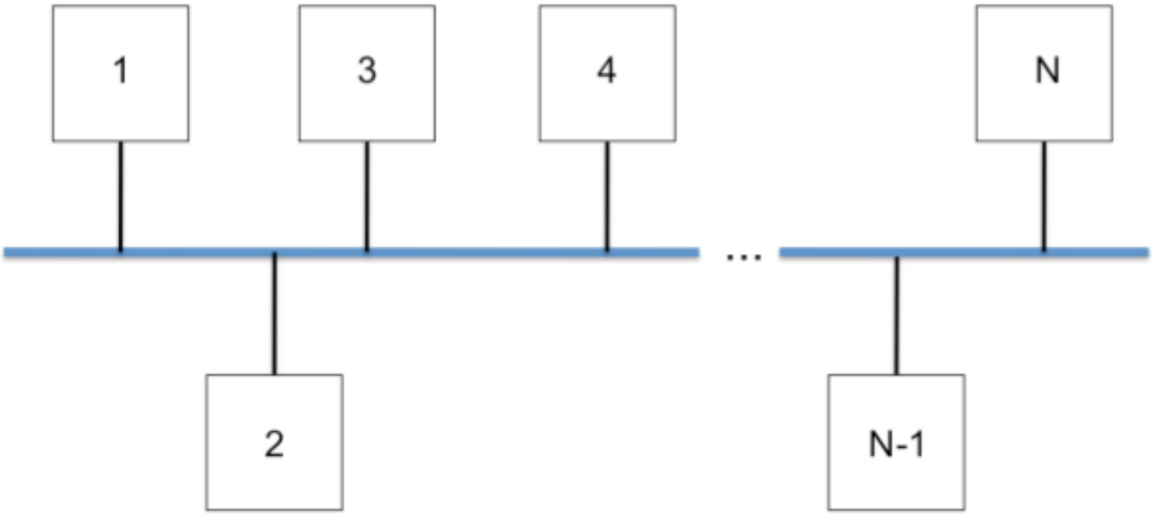


Figure 2-6 Schematic illustration of the bus topology employed for LAN

In a bus topology, a single fiber carries multichannel optical signals, and the distribution is done by using optical taps. Contrarily to non-optical bus networks, such standard Ethernet, optical bus networks are more difficult to implement[14]. The impediment is that there is no low-perturbation optical-tap for efficiently coupling optical signals into and out of the main optical fiber line. Access to the optical data bus is usually preformed using an active or a passive coupling element. An active coupler converts the optical signal on the data bus to its electrical baseband before any data processing (such as injecting additional data into the signal stream or merely passing on the received data); a passive coupler employs no electronic elements (it tap off a portion of the optical power from the bus for each node).

This is a very simple and flexible way to connect multiple users, and has the advantage of does not need too much fiber to be implemented. It has the disadvantage of increasing the signal loss as the number of users and taps increase, limiting strongly the number of users served by a single optical bus[15]. Other weakness of this topology is the lack of protection in case of fiber cut. In networks like this, information is transmitted by broadband, what means that every user will have access to all the transmissions. This could be a disadvantage, related with the security of the network. This is typically the chosen topology for cable television networks.

Star Topology

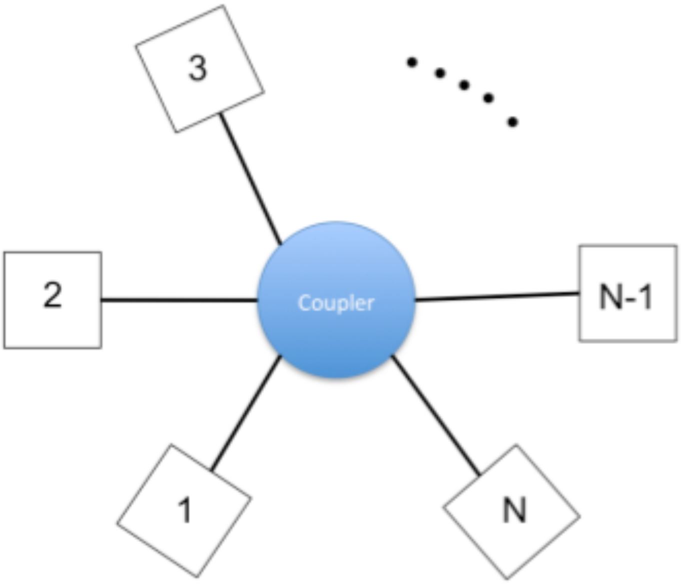


Figure 2-7 Schematic illustration of the star topology employed for LAN

In the case of star topology, all nodes are joined at a single point called the central node or hub. A passive power splitter is used at the hub to divide the incoming optical signal among all the outgoing lines to the attached stations. It has the capacity of interconnect a huge number of elements but it is important to have in mind that the power reaching each node depends of the number of users, and decreases as their number increases. Alternatively it could be used an active hub to control all routing of messages in the network from the central node, or a heavy switching burden[14].

If it is used a passive power splitter the information is broadcasted to all the RN in the network, so this requires extra attention with security issues. Using the active components, this problem does not exist, since the central node creates virtual P2P connections between the attached stations. Another problem is related to reliability. A failure in a central component can result in an inoperability of the entire network.

Ring Topology

In a ring topology, consecutive nodes are connected by P2P links that are arranged to form a single closed path. Data is transmitted from node to node around the ring, and in each node there is an active or a passive component that has the ability to recognize if the data is addressed to it or not, and accept it if it is, or forwards to its next neighbour if not. When active components are used, the information is passed around the ring in form of tokens (a group of information bits plus overhead bits), and each node monitors the bit stream, after converting the optical signal to electrical. Data transmission is done using the empty tokens[15]. Passive ring topology is very popular in WDM networks. Each node has an optical add drop multiplexer (OADM) that can drop one or more wavelengths that are addressed to it, and at same time easily add data to the ring. In this kind of networks, RNs share the fiber capacity and because of this, they are more popular in metro network layers, since bandwidth allocation is dependent of the number of nodes and available wavelengths.

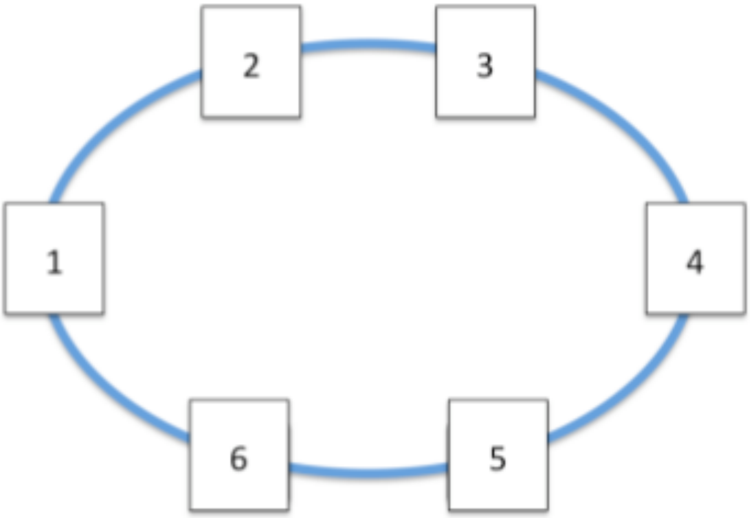


Figure 2-8 Schematic illustration of the ring topology employed for LAN

The biggest advantage of this topology is protection. This solution provides resilience to the network; if it occurs a fiber cut, the signal can be sent in the inverse direction, keeping the ring operational[16].

Hybrid Topology

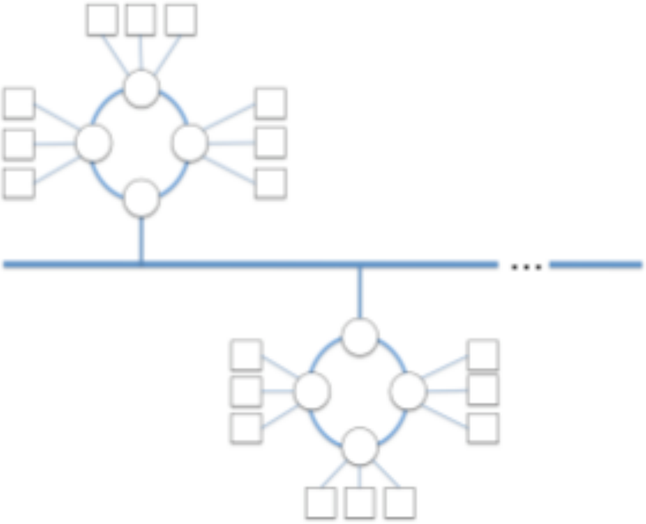


Figure 2-9 Schematic illustration of the hybrid topology

A hybrid topology, that combines two or more of the previously presented topologies, is most common to be present in a real solution. A possibility could be a bus-ring-star topology, which is represented in the Figure 2-9. Here, one of the remote nodes of a ring network is connected to a bus, which is consequently connected to other remote nodes by a star topology network. These allow having the advantages of the multiple topologies[16].

2.1.3.2. Multiplexing Optical Signals

The high bandwidth provided by the fiber, are unlike to be used in its totality by a single user. This is even more noted in access networks where multiple users should share fiber capacities at the same time to make the network financially rentable. To utilize the system capacity fully, it is necessary to transmit many channels simultaneously through multiplexing.

Various multiplexing techniques have being used in optical telecommunications, such as multiplexing in time or frequency domain, code multiplexing, subcarriers, etc. However, it should be highlighted the time division multiplexed (TDM) and the frequency, or as it is usually known, wavelength division multiplexing (WDM)[15].

Time Division Multiplexing (TDM)

The TDM is a type of multiplexing where various signals are multiplexed in the time domain, and transmitted in one single channel. The time domain is divided in time slots and blocks of information from different signals are multiplexed on time, and in that way share the same channel. In Figure 2-10 is represented a system where three channels are multiplexed using TDM.

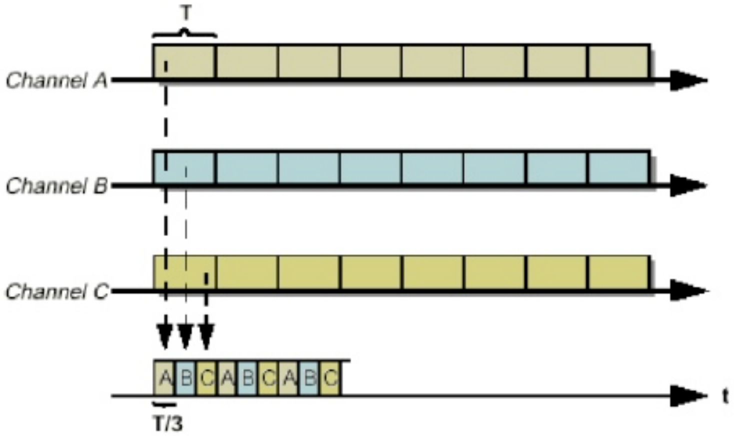


Figure 2-10 Three channels system multiplexed using TDM[17]

In the example, for each user is assigned a single channel. This is represented in the figure in the list diagram. There, each user transmits information within a specific assigned time slot at a prearranged data rate. When some users do not have data to sent or be received by the CO, the assigned time slots will be empty, wasting bandwidth. A more efficient process would be to dynamically assign the time slots, where time slots of an idle or low-utilization user are assigned to a more active customer. The problem is that this method requires a much more complex synchronization and management scheme.

In TDM systems, a single transmitter and receiver in the optical line termination (OLT) and a single transceiver in the optical network unit (ONU) are sufficient to proceed the communications between the CO and multiple users associated to OLT, as can be seen in Figure 2-11, so it is a cost effective solution, making it the most popular FTTH approach [18].

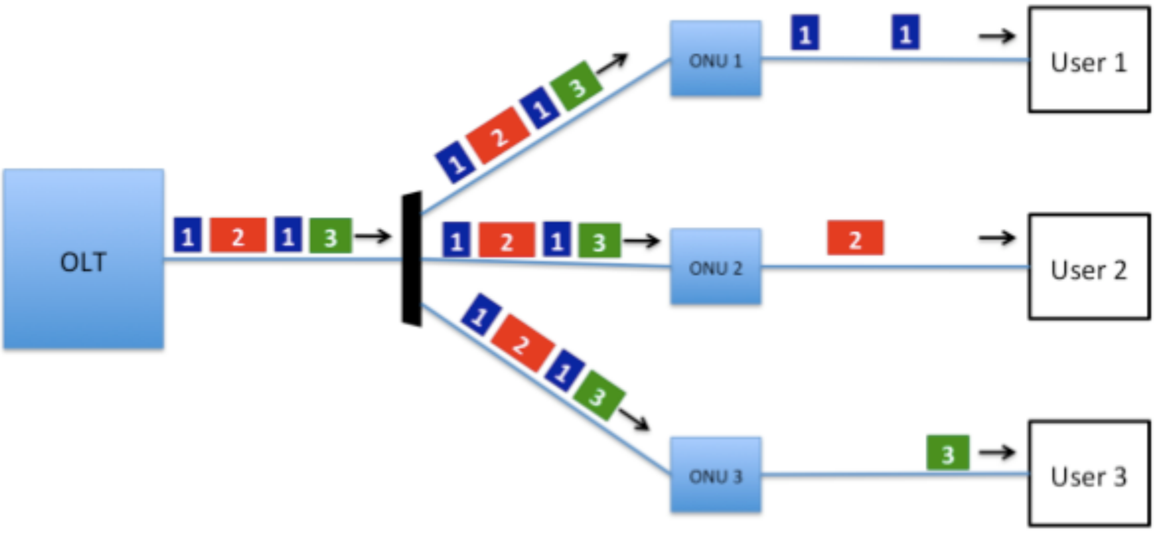


Figure 2-11 Example of downstream connection in a network working in TDM

In this method a single wavelength is shared for several optical network terminals (ONT) that select the specific portion of the broadcast data. Is particularly easy to assign bandwidth in the downstream to the user due to the fact that the OLTs are able to control the user address and the data packets length. The downstream signal is then broadcasted to all users, and each discards or accepts the incoming information packets, depending on the packet header address. Here some considerations must be taken about security, so encryption may be used to maintain privacy.

Sending traffic in upstream is more complicated, because users share the same wavelength and collisions between the transmissions of different users could occur. To avoid that, the system should use a TDM assignment protocol.

Traditional TDM is a well-understood technique and has been used in many electronic network architectures throughout more than 50-year history of digital telecommunications[19]. Still, in the context of high-speed optical networks, TDM is under pressure from the so-called "electro-optical" bottleneck[20]. In a line operating in TDM, the fastest available electronic transmitting, receiving and processing technology limits the maximum line rate. So, TDM faces severe problems to fully exploit the enormous bandwidth of optical fiber.

Wavelength Domain Multiplexing (WDM)

In Wavelength Division Multiplexing (WDM), multiple carriers at different wavelengths are multiplexed together onto the same fiber and demultiplexed at the RN into separated channels by means of optical techniques and sent to the correspondent receiver, as can be seen in Figure 2-12.

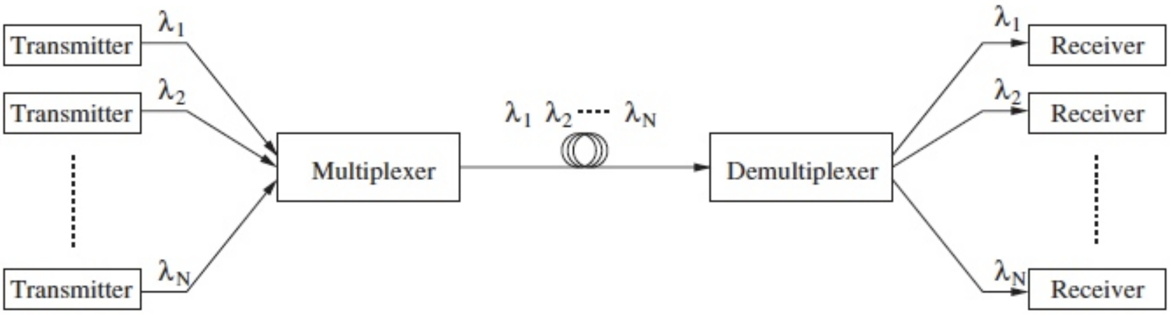


Figure 2-12 Example of a network using WDM multiplexing[20]

As seen in the Figure 2-12, each transmitter sends on a separate wavelength λ_N. All the wavelengths are multiplexed and sent in a single fiber to the receivers. At the receiving side, a wavelength demultiplexer separates the wavelengths and forwards each to its respective receiver.

WDM has some key system features as capacity upgrade, transparency, bidirectional transmission and wavelength routing[21].

Capacity upgrade. The classical application of WDM has been to upgrade the capacity of existing P2P fiber optic transmission links. If each wavelength supports an independent network channel of a few gigabits per second, WDM can increase the capacity of a fiber system with each additional wavelength channel. This is a feature that can allow future upgrades to basic PON implementation.

Transparency. An important aspect of WDM is that each optical channel can carry any transmission format. By using different wavelengths, fast or slow asynchronous and synchronous digital data and analog information can be sent simultaneously, and independently, over the same fiber without the need for a common signal structure. This is an important feature for triple-play (simultaneous voice, data, and video transmission) PON implementations.

Bidirectional transmission. In a WDM system, independent wavelength channels can be sent in either direction through the same fibber. This is interesting since it can reduce the use of infrastructures by a factor of two.

Wavelength routing. Instead of using electronic means to switch optical signals at a node, a wavelength-routing network can provide a pure optical end-to-end connection between users. This is done by means of a lightpaths that are routed and switched at intermediate nodes in the network. This feature will be better explained further.

A major point when implementing a WDM system is that the wavelength channels in WDM must be spaced properly to avoid linear and non-linear interference between adjacent channels. One fiber characteristic that should also be in mind when implementing a WDM system is the attenuation of light in a silicon fiber as function of the wavelength. The attenuation vs. signal wavelength profile can be seen in Figure 2-13:

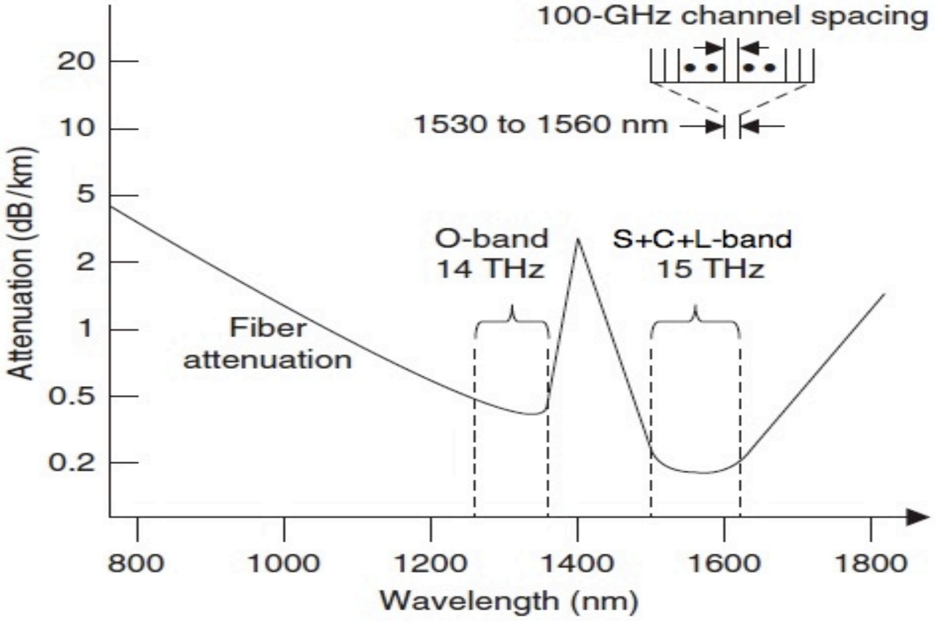


Figure 2-13 Fiber attenuation Vs. signal wavelength[21]

The curve shows that the two low-loss regions of a standard G.652 single mode fiber extend over the range from about 1279 to 1350nm (O-Band) and from 1480 to 1625nm (S+C+L-Band). Depending on the application and on the wavelength region being used, the spacing between channels could be wider or narrower, 100 to 200Ghz (0.8 to 1.6 nm). The narrower the spacing, the stricter wavelength control required in the optical source. On the other hand, the wider wavelength separation, the less costly becomes the WDM implementations since wavelength control requirements are relaxed significantly[21].

There are two major alternatives for WDM networks: Dense WDM (DWDM) and Coarse WDM (CWDM). The first one is mostly used for high capacity systems and long haul transmissions, while the second is for shorter transmissions and metro/access networks[23]. CWDM allows the wavelengths to be spaced farther apart, which allows for economical solutions in sparse applications as compared to DWDM that uses very close spaced wavelength (around 0.8nm). Figure 2-14 helps to see the difference between both of them.

Figure 2-14 Representation of a 16 channels CWDM and DWDM systems

Other Multiplexing Techniques

Besides TDM and WDM, there are others multiplexing schemes such as code division multiplexing (CDM) or the subcarrier multiplexing (SCM), among others.

In CDM, the optical channels are modulated with different multiplexing codes, taking advantage of various correlation techniques. With this method, it is possible to multiplex multiple signals with different transmitting rates in a single optical signal, so it can be regarded as an asynchronous way of sharing the time or the frequency, depending on the approach. It can be normally used in association with a WDM or TDM system, allowing the deployed network to multiply the number of users that can be supplied[24]. These systems suffer from signal-noise ratio (SNR) limitations and technological complexity that limit the number of users to a fraction of the theoretically possible[25].

SCM is a multiplexing method in frequency domain. This can be done by combining multiple microwave carriers at different frequencies and modulating the optical transmitter with the combined signal. At the receiver, the signal is detected like any other signal and the rest of the processing, to separate the subcarriers and extract the data from each subcarrier, is done electronically. SCM is widely used by cable operators for transmitting multiple analog video signals using a single optical transmitter. This reduces the cost network since each user does not require an optical transmitter/laser. The main issue in the design of the SCM is the trade-off between power efficiency and signal fidelity[10].

Whichever the technique used, the aim is always to improve the shared capacity of the fiber. So, the best approach could be to combine different multiplexing techniques in different dimensions, such as time, frequency, electrical or optical domain. Hybrid multiplexing has been investigated in several works in access, with the aim of reaching high resource sharing levels[25].

2.1.3.3. Distribution in Optical Networks

Network signals' power budgets, security issues, etc can be influenced by the way that signals are distributed in a network. Following, two techniques will be discussed.

In a TDM based network, the data is normally broadcasted to all nodes, and each node only observes the information that is in the assigned time slots. All this process is made in the electronic domain. With the use of WDM, considering some special components, it is possible to do this selection all in the optical domain.

Broadcast and Select Networks

The main idea here is that one node sends a signal in a specific wavelength and data is equally split and sent to the other network nodes. To understand better, lets see the example of Figure 2-15, where a star topology is presented:

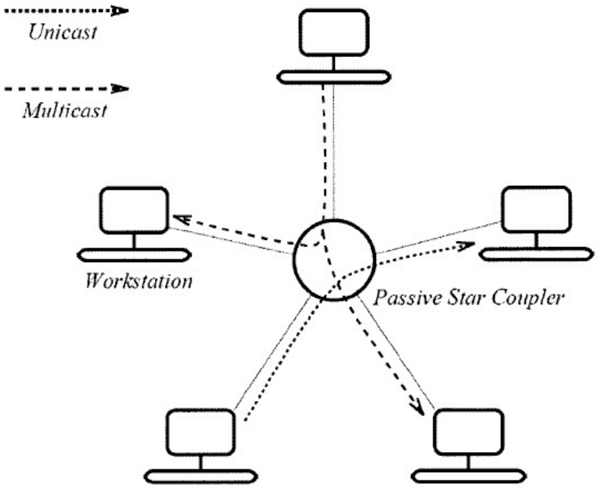


Figure 2-15 Schematic of a star topology broadcast and select architecture, where is also represented unicast and multicast service[9]

In this example, nodes send their data to the star on one available wavelength, using a laser that produces an optical information stream. The star optically combines the streams from multiple sources and the power of each stream is equally splitted and forwarded to all the nodes. At node's receiver, only the assigned information is received, using for example an optical filter, if it is a WDM based network. This kind of distribution is the one used in TDM based networks. But in these cases, instead of an optical filter, there is a transceiver, and the data selection is done in electrical domain, being bandwidth limited by the maximum processing capacity of those components.

In the picture, it is made the differentiation between unicast service and multicast service. For example in a WDM network, when a source transmits on a particular wavelength, more than one receiver can be tuned to that wavelength. When that happens, that is called multicast. Otherwise, if for one transmitted wavelength exist only one receiver tuned to that wavelength, that is called unicast.

The flexibility of these networks depends mostly of the nature of receivers and transmitters. If all the transmitters are tunable and the receivers are fixed, only unicast connections are allowed. In the other case (tunable receivers and fixed transmitters), we may have unicast and multicast connections. Here, it is not important the collision avoidances, since each transmitter has a different wavelength. In the case that both transmitters and receivers are tunable, much more complex network protocols are required, once most transmitters and receivers have to be controlled to coordinate the data in the network.

Wavelength Routing Networks

WDM technology made the people realizes that optical networks are capable of providing more functions than just P2P transmission. Major advantages can be achieved by incorporating some of the switching and routing functions that were preformed by electronics into the optical part of the network[10]. The electronics at a node must handle not only all the data intended to that node but also all the data that is being passed through that node to other nodes in the network.

The idea would be the networks to provide lightpaths to its users. A lightpath is an optical communication channel between two nodes in the network, and it may span more than one fiber link. At intermediate nodes in the network, the lightpaths are routed and switched from one link to another link. In some cases, lightpaths may be converted from one wavelength to another along their route. So, different lightpaths can use the same wavelengths since they don’t share any common link. This allows the same wavelength to be reused spatially in different parts of the network.

One example of a wavelength routing network can be seen in the Figure 2-16. In the picture, lightpaths are established between nodes A and C on wavelength channel λ_1, between B and F on wavelength channel λ_2, and between D and E on wavelength channel λ_1. We can note the reuse of λ_1 and the overlapping of two different lightpaths with different wavelengths. Between the nodes A and G we can observe that one wavelength conversion was made.

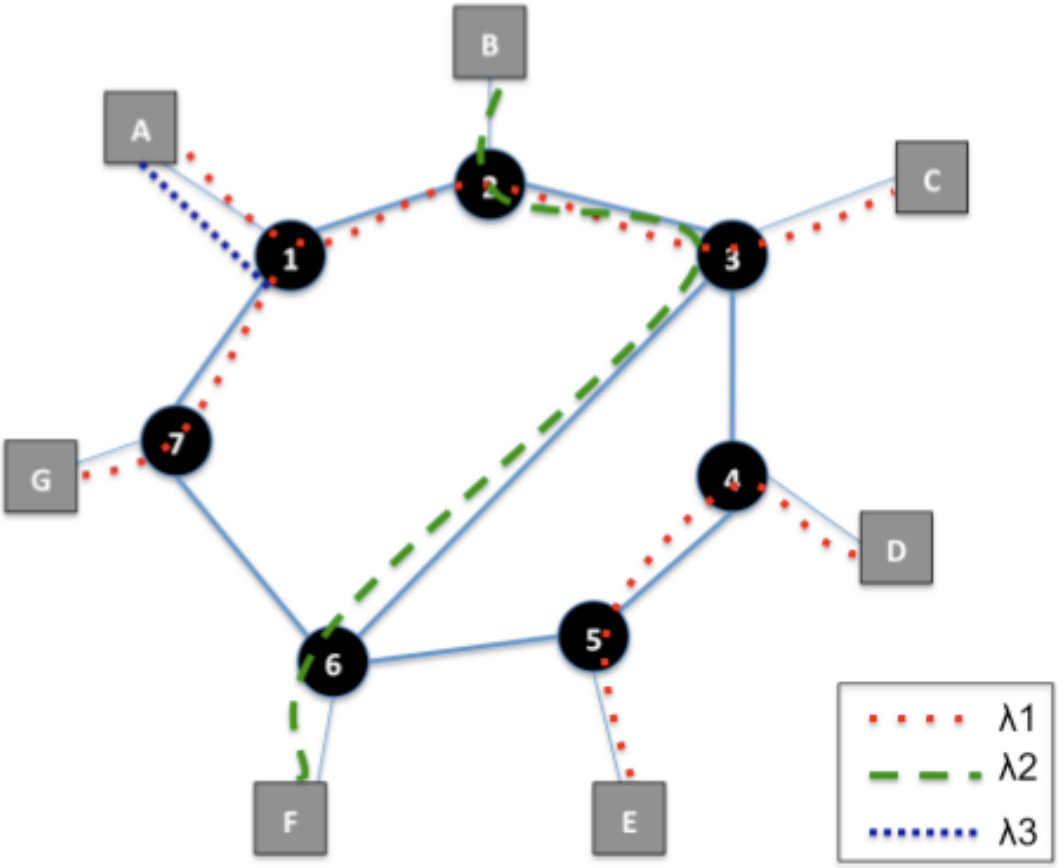


Figure 2-16 Scheme of a wavelength routing network

2.2. Passive Optical Networks (PON)

A passive optical network (PON) is a special type of optical network, that provides the possibility to bring optical fiber cabling and signals, if not till the end user, at least until next it in an economical efficient way. This network has the particularity of not having any or almost any active components between the central office and the costumer's premises. Instead, only passive optical components are placed in the network transmission path to guide the traffic signals contained within specific optical wavelengths. With this change, it is obtained a significant cost save in maintenance by eliminating the need to power and manage active components in the outside cable plant.

There should exist two fundamental components in each extremity of the network: an optical line terminal (OLT), situated at the CO and either an optical network terminal (ONT) or an optical network unit (ONU) at the far end of network. The difference between ONT and ONU is that the ONT is used when the fiber extends into the costumer premise, and the ONU is used when the fiber line terminates in some type of telecommunications cabinet located near a cluster of businesses or homes. In this last case, the connection between the ONU and the end users can be made by means of medias as twisted-pairs wires, coaxial cable or even through fiber.

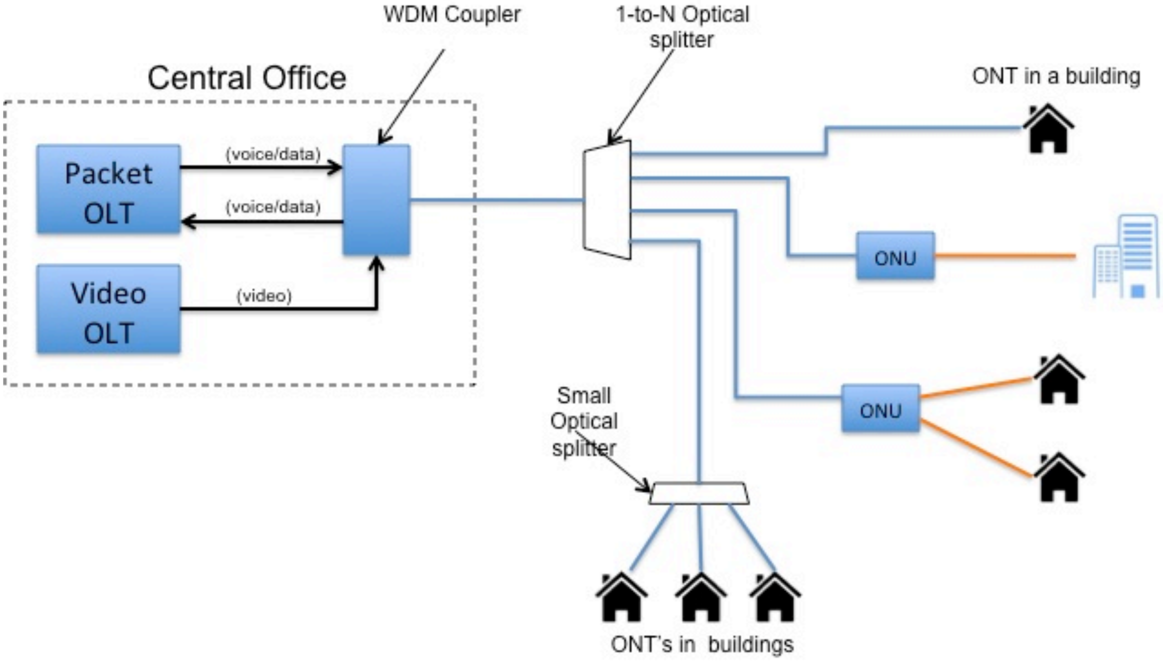


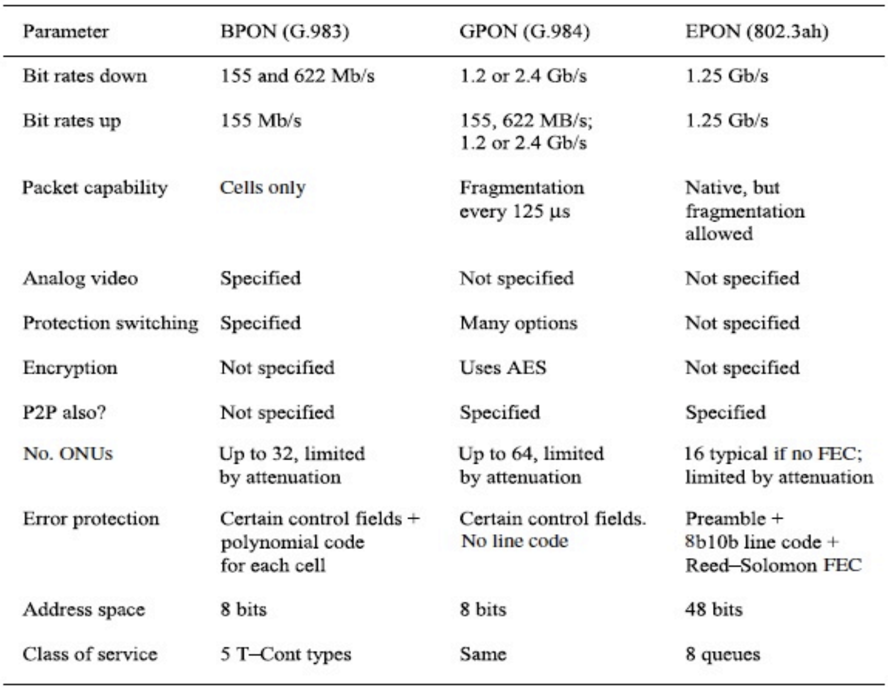
Figure 2-17 Typical passive optical network configuration [11]

The typical configuration of a PON is demonstrated in Figure 2-17. Multiple services are multiplexed in the CO and sent by a single fiber to some component that passively split the optical signal by several network fiber branches. In the figure is represented an optical splitter, but depending on the multiplexing technique used (TDM, WDM, hybrid) it could be a RN, or an OADM, etc. Then signals are directed to the ONTs that are implemented directly in the end user house and in this case we have a FTTH implementation, or to some ONU near building, having in this case a different FTTX implementation. In the figure we can see a FTTC where fiber goes till near a building, and then the signal has to be transported by other different media, such as coaxial cable or copper.

The potential of PONs to deliver high bandwidths to users in access network and their advantages over other current access technologies have been widely recognized. They are compromised of only use passive elements (fibers, splitters, splices, etc.) therefore are less costly. In addition to being capable of very high bandwidths, a PON can operate at distances significantly higher than the distances supported by high-speed DSL variants[26]. Furthermore, PONs reduce installation and maintenance cost, while also allowing easy upgrades to higher speeds, since upgrades need only be done centrally at the network operator's CO where the relevant active equipment is housed.

After more than twenty years of active research, PON-based broadband optical access systems are finally seeing wide-scale deployments in Asia and North America. In Europe, carriers and service providers are also actively looking into PONs as the next-generation broadband access solutions[27].

All PON systems have essentially the same theoretical capacity at optical level. The limits of upstream and downstream bandwidth are set by the electrical overlay, the protocol used to allocate the capacity and manage the connection. There are several alternative PON implementation schemes, where can be highlighted the broadband PON (BPON), Ethernet PON (EPON) and gigabit PON (GPON). The structure of each is basically the same being the key difference between them the transmission protocols used, but in all the cases the eventual goal is to provide broadband access to each user and to deliver audio, video, and internet traffic on demand, while keeping the cost low. The characteristics of each are summarized in Figure 2-18.



Parameter	BPON (G.983)	GPON (G.984)	EPON (802.3ah)
Bit rates down	155 and 622 Mb/s	1.2 or 2.4 Gb/s	1.25 Gb/s
Bit rates up	155 Mb/s	155, 622 MB/s; 1.2 or 2.4 Gb/s	1.25 Gb/s
Packet capability	Cells only	Fragmentation every 125 µs	Native, but fragmentation allowed
Analog video	Specified	Not specified	Not specified
Protection switching	Specified	Many options	Not specified
Encryption	Not specified	Uses AES	Not specified
P2P also?	Not specified	Specified	Specified
No. ONUs	Up to 32, limited by attenuation	Up to 64, limited by attenuation	16 typical if no FEC; limited by attenuation
Error protection	Certain control fields + polynomial code for each cell	Certain control fields. No line code	Preamble + 8b10b line code + Reed–Solomon FEC
Address space	8 bits	8 bits	48 bits
Class of service	5 T–Cont types	Same	8 queues

Figure 2-18 Differences between BPON, GPON and EPON[28]

2.2.1.1. TDM-PON and WDM-PON

In a time division multiplexing PON (TDM-PON) or in a wavelength division multiplexing PON (WDM-PON), the fiber plant from the OLT at a CO to the ONU at costumer sites is completely passive.

The difference between them is the way the signal is delivered to the different ONUs in the system. A TDM-PON uses a passive power splitter as remote terminal and the same signal from the OLT is multiplexed in time domain and broadcasted to different ONUs by the power splitter. Then, ONUs recognizes their own data through the address labels embedded in the signal. Most of the commercial PONs (including BPON, GPON, and EPON) falls into this category[27]. One the other hand, WDM-PON uses a passive WDM coupler as the remote terminal. Signals for different ONUs are carried in different wavelengths and routed by the WDM coupler to the proper ONU. Since each ONU only receive its own wavelength, WDM-PON has better privacy and better scalability. Although they already have dropped in recent years, the only problem is that WDM devices are significantly more expensive, which makes WDM-PONs economically less attractive. The architecture of both TDM-PON and WDM-PON are shown in Figure 2-19.

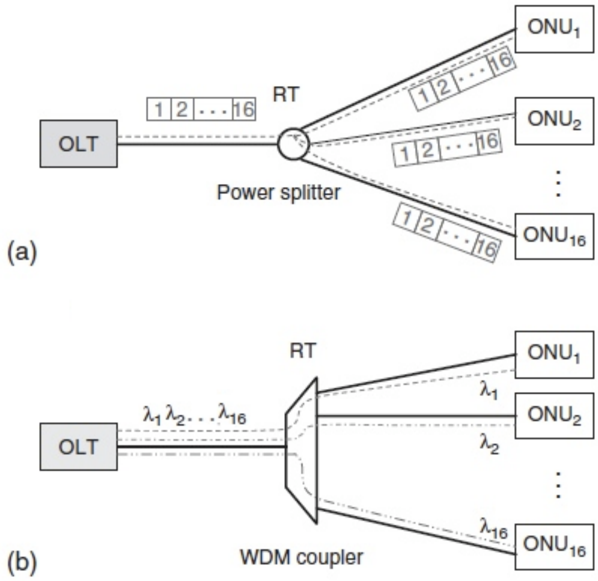


Figure 2-19 Architecture of (a) TDM-PON and (b) WDM-PON[27]

2.2.1.2. Hybrid WDM/TDM PON

TDM and WDM have advantages and disadvantages in a complementary way. The advantages of the former are disadvantages of the latter and vice versa[4].

The available bandwidth and the network resources are better used in TDM-PON than in WDM-PON, hence TDM-PON is more efficient. Conversely, TDM-PON requires a complex time arbitration mechanism to avoid time slot collisions, and WDM-PON does not require such arbitration. Since TDM-PON is based in a fixed number of well-synchronized time slots, TDM-PON is not easily scalable. Conversely, the number of wavelength available in the grid is the only limitation of WDM-PON. Other drawback of TDM-PON comparatively with WDM-PON is the security. Due to TDM-PON broadband nature, bad actors can “listen” to time slot that belong to other ONUs. In WDM-PON that does not happen, however that does not mean that this is a 100% secure method.

To combine the advantages of both methods the best idea is to make a hierarchical WDM/TDM-PON[4].

Some solutions based in hybrid WDM/TDM-PONs have been developed in the last years[29][30][31]. A scheme of this network design is represented in Figure 2-20. This network is based in two stages, one first WDM stage where the multiple wavelengths are sent out through one fiber from the OLT to some component, that then demultiplex the signal. Then in each wavelength we have TDM, being the data delivery by time slots at each network terminal (NT).

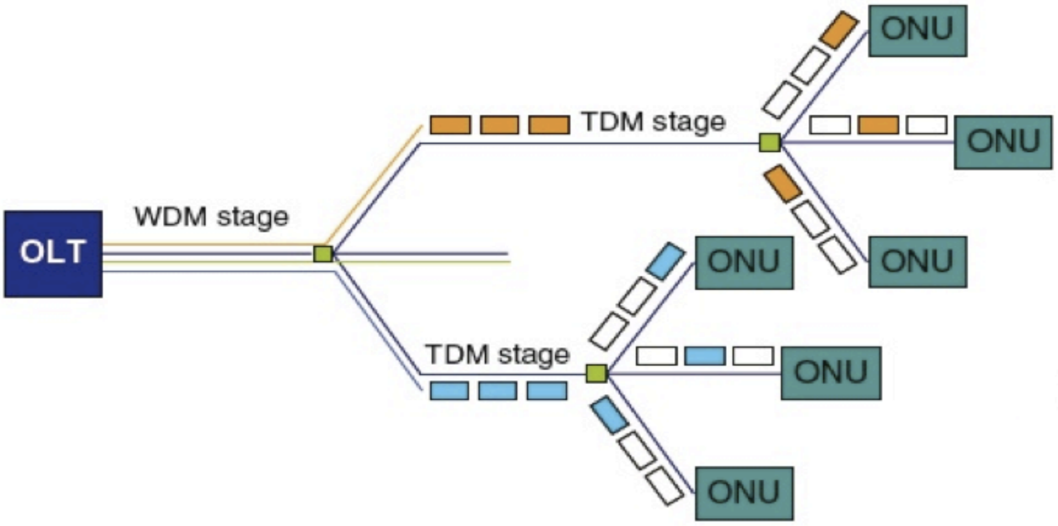


Figure 2-20 Schematic of a hybrid WDM/TDM-PON[25]

2.3. Conclusion

In this chapter the main focus were in some characteristics of optical telecommunication networks. We talked about the different network layers and the intention was to show that each layer has different priorities.

From the different discussed architectures, the access networks are the ones where more evolutions can be made, being the reason for that the associated implementation costs, that was too high in a near past. But, with the maturation of some key technologies, such as WDM components, it starts to be economically efficient to implement these networks, bringing finally the fiber to the end user premises, and consequently the theoretical unlimited bandwidth provided by it.

Many studies continue to be made in this area, and it is the purpose of this work to contribute on the optimization of a new network that has been developed in the scope of the

European project Scalable Advanced Ring-based Passive Dense Access Network Architecture (SARDANA). This project goal is developing a PON network based in a ring topology providing a FTTH service. The key performances that this project aims to improve are the scalability and the robustness, since they constitute pillars of such a cost-sensitive segment.

In next chapter, a brief explanation about the SARDANA network will be made, and will be presented the proposals to optimize the network operation.

3. SARDANA

3.1. Introduction

Scalable Advanced Ring-based passive Dense Access Network Architecture (SARDANA) is an European project that aims at extending the limits of passive FTTH networks in terms of scalability, resilience and minimum infrastructure requirements [32].

This project has as key performances to improve the network scalability and robustness. The proposed network is a PON where cascadable RN are implemented in a new hybrid architecture and where WDM/TDM multiplexing techniques are used in overlay. Another goal of this project is to use the pre-existent PON networks, and with the minimum civil work investments implement the developed concept.

The resulting network is desired to be able to serve more that 1000 users with symmetrical several hundred Mbit/s, spread along distances up to 100 km, at 10Gbits/s, in a flexible way, also supporting multi-operator service.

Robustness is achieved by means of the development of new monitoring and electronic compensation strategies over the PON, but these are not the main subjects of this work. Robustness is also improved by using the passive central-ring protection.

3.2. Technical Approach

The SARDANA network transparently combines the WDM and TDM dimensions to reach the extra large user-density. Network is composed by two distinct parts, a first one that is based on a WDM ring where large amounts of up stream and downstream information are transported and a second part based in TDM trees, transmitting several wavelengths from corresponding operators, sharing a common infrastructure. A scheme of the network architecture is represented in Figure 3-1. As can be seen, RNs connects the WDM ring and the TDM trees. They are desired to be completely passive, and they implement cascadable 2-to-1 fiber optical Add/Drop which goal is to distribute different wavelengths to each of the access trees. Then, each tree equally splits data using an optical splitter with a splitting ratio of 1:N providing a flexible number of users [33].

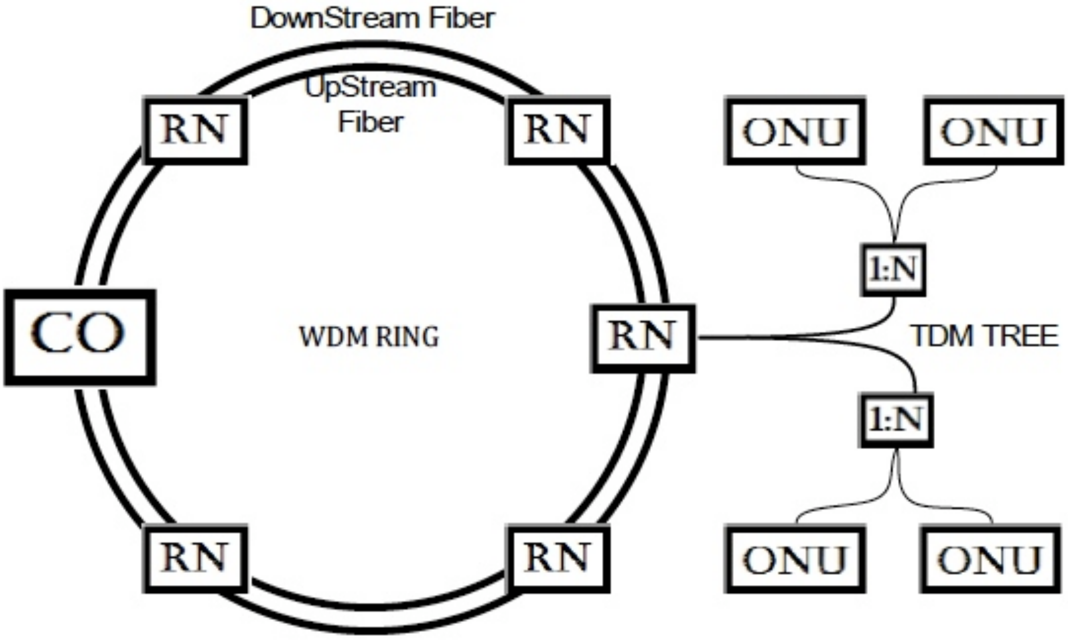


Figure 3-1 Sardana network topology [32]

The main ring is implemented with double fiber, one fiber carries the downstream (DS) signal and the other the upstream (US) signal in order to reduce signal degradation imposed in a major part by Rayleigh and Brillouin Backscattering distortion[34]. The fact that the network trees operate in TDM basis, provide to the network the ability of migration from the currently deployed infrastructures, overlaying EPON and GPON, into this novel topology and supply different services and operators on different wavelengths. With this feature the network is flexible and serves users with different transmission requirements. The network is also able to provide traffic balance through the shorter path and resiliency in case of fiber, splice, connector or any component failure, due to its ring topology.

Scalability is also guaranteed; inserting supplementary RNs on the ring is wavelength transparent, so it is a simple task. However, the number of RN has an important role in the network performance. It determines the number of necessary wavelengths for the functioning of the network and the total network capacity. The optimal and most efficient number of RN in the ring is independent from the number of users per RN, being the number of users limited by the power budget (PB) and the link losses between respective CO and ONU. The link losses increase is directly related with the network growth, so it is an important parameter and limitation to consider[35].

In order to compensate add/drop losses, fiber attenuation, filtering and insertion loss (IL), the RN provides remote amplification by means of Erbium Doped Fiber Amplifier (EDFA) remotely pumped by pumping lasers located at the CO[36].

3.2.1. Remote Node

Remote nodes are a key component on this network architecture. They are the responsible to add/drop signals to/from the WDM ring, and then drive it to the destination users tree. It is desired that they have the less IL as possible, allow high level of scalability, and provide gain to the signals. In a basic way, a RN has three main distinct blocks. A basic diagram of the main blocks present in the RN is demonstrated in Figure 3-2.

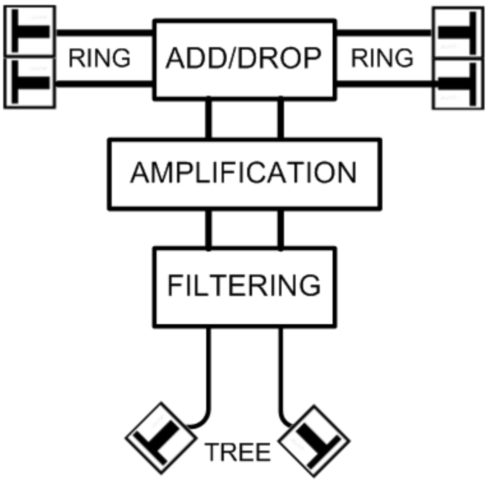


Figure 3-2 Diagram of main blocks present in proposed SARDANA network RN [35]

The first block is the one responsible to make the interconnection between the WDM ring and the TDM trees. It should add and drop the signals but also the remote pump needed to supply the EDFA. The second main block is the amplification. Signals suffer losses along their way, so most of the times they need to be amplified in order to reach the CO or the ONU with the desired signal power. The third and last one is the filtering block. As said previously, each RN connects two TDM trees to the WDM ring. For each tree branch is assigned a WDM channel, and this block is the responsible to direct each of the dropped channels to the respective branch.

In [36][37] are presented some RN architectures for signal and pump add/drop, with the objective to optimize the total amount of pump power emitted by the CO, reduce the IL and allow to the network higher scalability and resiliency levels. In Figure 3-3, it is presented the scheme of a proposed RN topology where multiple reconfigurations are provided, and at the same time a good IL ratio is achieved.

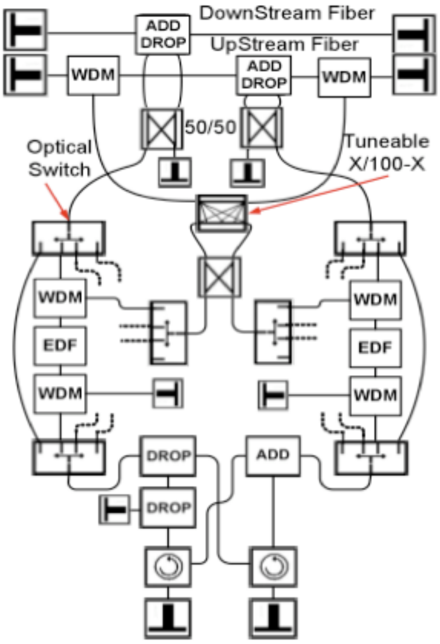


Figure 3-3 Proposed RN topology that provides multiples reconfigurability [38]

In the signal add/drop process, an optical add/drop OADM is the responsible to add or extract from the WDM ring the RN corresponding wavelength channels. In the presented RN topology, it is used an optical switch to provide multiple reconfiguration to the RN. At each switch exit it could exist a different EDFA that provides distinct gain or no EDFA if there is no need of signal amplification. After being amplified, signals are then routed to the correspondent tree branch, by using optical filters that extract only the addressed wavelength channel. The inverse operation is taken if the signal goes from the TDM tree to the CO.

The gain in an EDFA depends among other factors, on the pump power that is coupled with the signal that has to be amplified. In a remote optical pumped amplifier (ROPA) system, the strategy used to vary the amplifier gain is to vary the pump power supplied to the amplifier. Thus being, a strategy to control the EDFA gain is to control the pump power extracted by the RN from the WDM ring. In the topology of Figure 3-3, to do this variation, it is proposed the use of a tunable coupler; varying the coupling ratio, it will extract more or less pump power, depending if we increase or decrease respectively the coupling ratio (X parameter in the figure).

However, some features of the proposed topologies are still not optimized. As an example, there are used active components to provide reconfigurability to the RN, such as the tunable coupler or the optical switches. Within this work it is our intention to study some solutions to solve these problems, and further some proposals will be presented. But first it would be interesting to understand the operation of some of the RN components.

3.3. Used Components

Optical components are the basis of optical communication systems, and their status determines the progress of optical communications. On the other hand, the demands of communication development promote the evolution of optical components technology [38]. So, in order to be financially profitable to implement optical fiber in metro/access networks, some components had to be optimized or even invented. WDM technology is one example, and was one of the responsible for the final push to implement such networks.

Summarily, optical components can be classified in two distinct groups:

- Active components
- Passive components

The key difference is the need (or not) of any type of energy to operate, respectively. Normally, active components are reconfigurable, therefore needing electrical energy. Some techniques are proposed to solve this electrical need [39], and they will be talked further.

Passive components obviously play an important role in PONs. The key passive components for PON applications include wavelength-selective couplers, optical power splitters, optical connectors, and optical splices.

All have its limitations and it is important to know them before implementing new network architectures. To understand how each component influences the RN topology, it is interesting to understand how they work and in which way they have influence. Some characteristics are common to all components, and those are IL and attenuation. With some exceptions, low values in these two parameters lead to a better component.

Looking to the proposed RN topology in Figure 3-3, some specific components were used to implement it. A brief description of them will be made now, in a way to understand the possible advantages and disadvantages that each of them bring to the RN. These optical components will be addressed:

- Optical Add/Drop Multiplexer
- Optical Coupler/Splitter
- Isolator
- Circulator
- EDFA
- Switch

3.3.1. Optical Add/Drop Multiplexer

The Optical Add/Drop Multiplexer (OADM) has emerged as one of the key building blocks for network at the metro, regional and access level[40]. They add and drop wavelengths from intermediate point along a transmission link or ring, providing a simple and effective way to access a general mesh network along links or within ring subnets. They can be static or reconfigurable, and in the latter case it is usual to be called reconfigurable OADM (ROADM).

The three fundamental OADM designs are parallel, serial, and band drop architectures, and are presented in Figure 3-4.

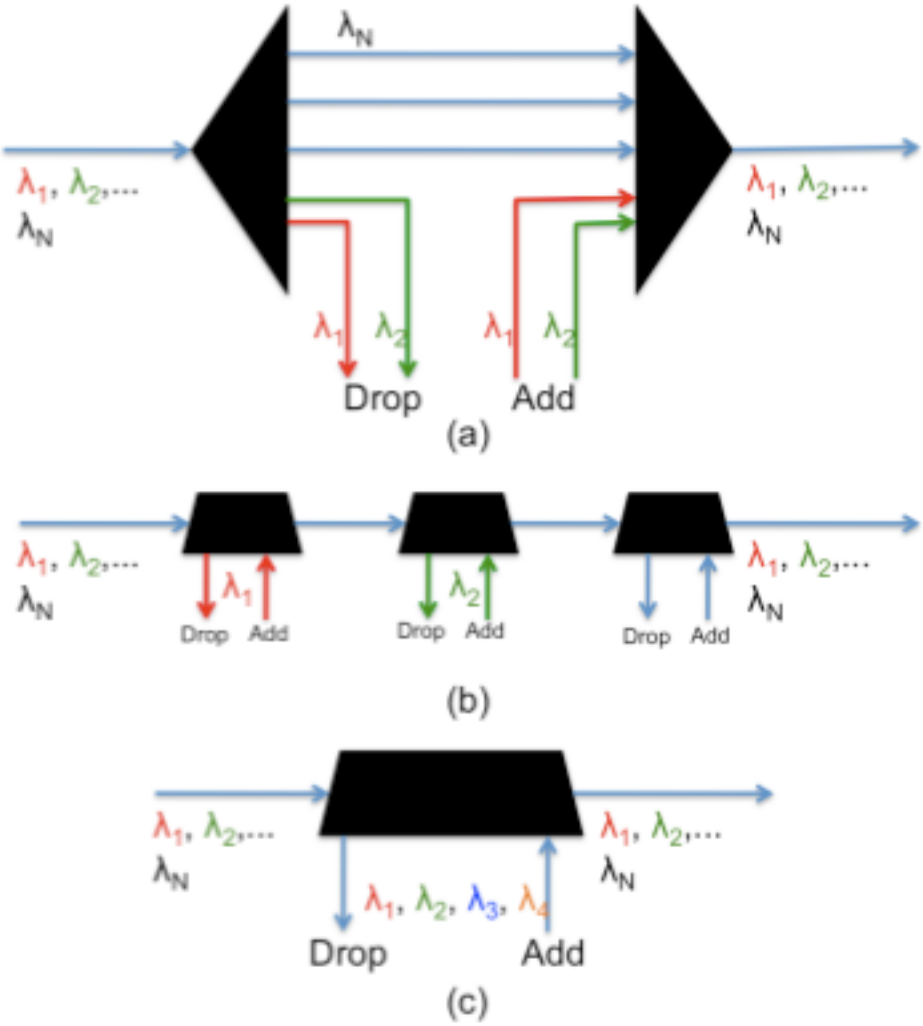


Figure 3-4 Schematic of a (a) parallel, (b) serial and (c) band drop OADM architecture [10]

In the parallel architecture, all incoming channels are demultiplexed. Some of the demultiplexed channels can be dropped locally and others are passed through. So there are no constraints on which channels can be dropped and added. As a consequence this architecture imposes minimal constraints on planning lightpaths in the network. In addition, the loss through the

OADM is fixed, independent of how many channels are dropped and added. However, this is not a good solution when only few channels have to be dropped or added. It is not cost effective since regardless how many channels are dropped, all of them have to be demultiplexed and then multiplexed all together again.

In the serial architecture, a single channel is dropped and added from an incoming set of wavelengths. This architecture in many ways complements the parallel one referred above. This is highly modular since the price depends on the number of added/dropped channels. Therefore, the cost is low if only few channels are dropped and gets higher if we want to drop more channels. That is so, because to add/drop more channels we only have to cascade more devices. Another problem of extracting more wavelengths is the increase of IL in the system, being that increase directly proportional to the number of added/dropped wavelengths.

In the band drop architecture, a fixed group of channels is dropped and added from the aggregate set of channels. Then, the dropped channels typically go through a further level of demultiplexing where they are separated. A typical implementation could drop, for example, four adjacent channels out of 32 channels using a band filter. This architecture tries to make a compromise between the parallel architecture and the serial one. Within the dropped channels group, add or drop additional channels do not affect the other lightpaths in the network, as the pass-through loss for all the other channels that are not in this group is fixed. The problem of this architecture is that it complicates wavelength planning in the network and puts several constraints on wavelength assignment because the same sets of wavelengths are dropped at each location.

Resuming, the architectures discussed above are the ones that are feasible based on today technology, and commercial implementations of all of these exist nowadays[10]. Serial and band drop architectures have a low loss entry, but they have poor flexibility in dealing with traffic changes in the network. The parallel configuration, appealing to the use of controllable couplers makes it a more flexible architecture comparing with the other two[41].

3.3.2. Optical Coupler/Splitter

The optical couplers could be used for a variety of functions, including splitting a light signal into two or more streams, combining two or more light streams, or transferring a selective range of optical power from one fiber to another.

(a) splitter (b) combiner (c) coupler

Figure 3-5 Schematic of a optical (a) splitter, (b) combiner and (c) coupler [41]

The most important parameter in the couplers is the coupling ratio. That represents the percentage division of optical power between the output ports. Being P1 and P2 the output powers, we have[42]:

$$\text{Coupling ratio} = \frac{P_2}{P_1 + P_2} \times 100\%$$

There are also three important characteristics in the couplers:

1. Splitting Loss: it is the power level at the coupler's output vs. power level at its input, measured in dB. For an ideal 2 x 2 coupler this value is 3dB.

2. *Insertion Loss:* it's the power loss which results from imperfections of the coupler's manufacturing process.

3. *Directivity:* Some amount of input power leaked from one input port to another input port.

Couplers can be designed to be either wavelength selective or wavelength independent. The difference among them is the fact that in wavelength selective couplers the coupling ratio depends on the wavelength. This is used to combine signals at different wavelengths into a single fiber without losses. Normally they are known as WDM couplers, and they can also be used to separate two different wavelength signals coming on a common fiber. WDM couplers are very useful to combine 980 nm or 1480 nm pump signals with a 1550 nm signal to be amplified in a doped fiber amplifier.

There are commercial solutions of tunable couplers, where the coupler ratio can be mechanically altered[43]. In the proposed topology present in Figure 3-3, it is used a tunable coupler that allows improving significantly the network reconfiguration. However, these are active components and in a PON this could be a problem.

A splitter does the same as a coupler, but the difference between them is the fact that splitters are made to have only one input.

3.3.3. Isolator

Couplers and most of passive optical devices normally work the same way if their inputs and outputs are reversed. However, in many systems there is the need for a passive non-reciprocal device.

An isolator is one device which function is to allow the transmission of light in only one direction, blocking all transmission in the opposite direction. Along an optical fiber transmission line, all end faces of the network components are continuously generating return beams. Isolators are used in strategic places to eliminate this return beams, being used mostly at the output of optical amplifiers and lasers to prevent unwanted feedback into them, which would otherwise degrade their performance or even though damage them.

The key parameters in this component are the IL, and its isolation, which is the imposed loss in the reverse direction, and which should be as larger as possible.

3.3.4. Circulator

A circulator is similar to an isolator, but it has multiple ports, typically three or four. A 3-port circulator is presented in Figure 3-6.

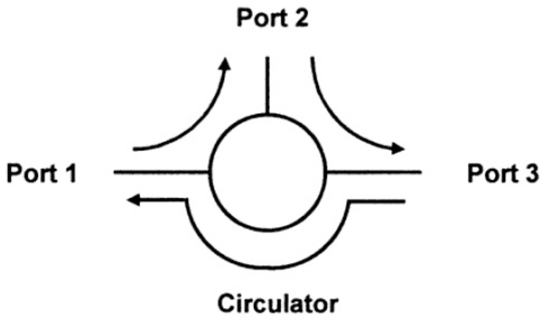


Figure 3-6 Schematic of a three-port circulator [44]

In a three port circulator, as the one in Figure 3-6, an input signal on port 1 is sent out on port 2, an input signal in port 2 is sent out to port 3, and a input signal at port 3 is sent out on port 1.

Circulators are a really important component in optical communications, mainly in WDM systems, since they allow the implementation of important components such as optical filters and OADM. Using a circulator and N Fiber Bragg Grating (FBG) it is possible to implement an OADM capable to drop N channels. Figure 3-7 shows an example of an OADM that is capable to drop 1 channel. To extract more than one channel, we only haves to place FBGs in series, those are capable to reflect the wanted channels.

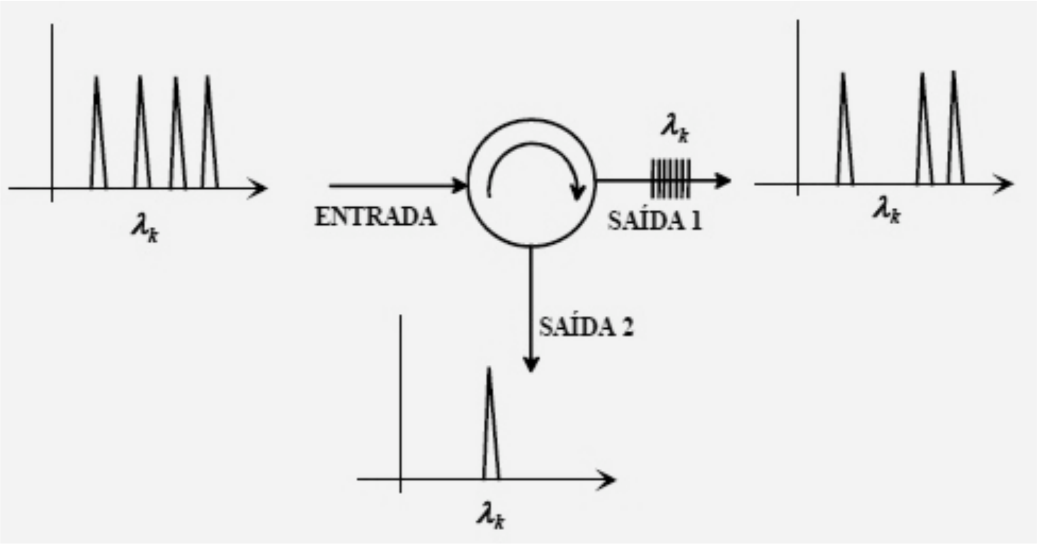


Figure 3-7 Schematic of an optical filter using a circulator and a FBG[45]

3.3.5. Optical Switch

Also know as photonic switch, the optical switch is a device that establishes and releases an optical path of lightwave transmission, commanded by a prescribed control[46]. Contrarily to the previously traditional switches used to connect optical fiber lines, which converted the photons from the input side to electrons internally, in order to do the switching, and then converted it back to photons on the output side, the optical switches does all this routing only in the optical domain. By this, it is possible to direct the input signals whatever is the specific data rates and protocol used.

There are several switching technologies; such as optical microelectromechanical (MEMS) based switches, thermal optical switches, electro-optical switches, opto-optical switches, or acousto-optical switches[47]. Depending on the used technology, an optical switch may operate by mechanical means, such as physically shifting an optical fiber to drive one or more alternative fibers, by electro-optic effects, magneto-optic effects, or other methods. Switches using mechanical operation are used mostly for applications that do not require a fast operation time, such as routing around a fault or direct signals by a different way. The others, such as the electro-optic or magneto-optic effects, may be used to perform logic operations[12].

As for other components, IL is an important performance parameter regarding optical switches operation. Other parameters that are important, depending the application, are the switching speed, crosstalk, polarization-dependent loss, wavelength dependency, size, scalability, and power consumption.

To applications such as the RN proposed previously, the most practical technology is probably the optical MEMS switches. It makes use of tiny mirrors that reflect the input signal to an output port. This technology has low IL and crosstalk between the gates. Although these switches are not so fast, in such application the switching time is not a key issue[47].

3.3.6. Erbium Doped Fiber

Optical networks, inevitably suffer from signal attenuation due to variety of factors including absorption, bending and components IL. Therefore to compensate these signal losses, some amplification has to be done to the signal in its way between the transmitter and the receiver, in order to reduce errors and permit light to be transmitted to a longer distance. Before the advent of optical amplifiers, losses were recovered using regenerators. These regenerators converted the optical to electrical signal, do amplification in electrical domain and convert the electrical signal back to optical, to continue the transmission in the optical communication network.

In order to avoid these optical-electrical-optical conversions, amplify light signals of multiple wavelengths simultaneously, and provide amplification whichever the used signal bit rates and modulation, optical amplifiers had started to be used in optical telecommunications.

Doped fiber amplifiers (DFA) are a class of fiber amplifiers that make use of rare-earth elements as a gain medium, by doping the fiber core during the manufacturing. Although they were studied as early as 1964, their use became practical only 25 years later[15]. There are many different rare-earth elements, such as erbium, holmium, neodymium, samarium, thulium, and ytterbium, and the amplifier properties are determined by the used element.

Erbium doped fiber amplifier (EDFA) is one type of DFA. As most of the optical amplifiers, in the EDFA the optical gain is realized when the erbium doped fiber is pumped to achieve population inversion. EDFA have attracted most attention because they operate in the wavelength region near 1550 nm (C+L band). EDFA has emerged has the major enabler in the development of the worldwide fiber-optic networks[7]. Their deployment in WDM systems after 1995 revolutionized the field of fiber-optic communications and led to lightwave systems with capacities exceeding 1 Tb/s[15].

3.3.6.1. Theoretical Introduction

As in all DFA, in EDFA the key phenomenon behind signal amplification is stimulated emission of radiation by atoms in presence of an electro-magnetic field, being the field in optical amplifiers an optical signal.

According to the principles of quantum mechanism, any physical system is found in one of the discrete number of energy levels. Lets consider an atom and two of its energy levels, E_1 and E_2, with $E_2>E_1$. An electromagnetic field whose frequency, f_c, satisfies the condition $hf_c=E_2-E_1$ induces transitions of atoms between the energy level E_1 and E_2, where h is the Planck's constant (6.63×10^{-34} Js). Lets attempt Figure 3-8.

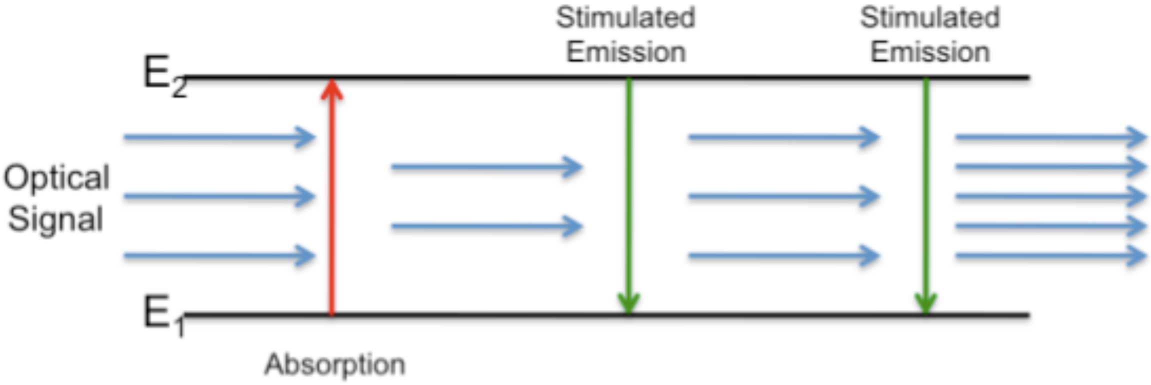


Figure 3-8 Representation of different atoms transitions in a physical system

Two kinds of transitions can occur, as can be seen in Figure 3-0. From level E_1 to level E_2, the absorption of photons from the incident electromagnetic field; and from the level E_2 to E_1. In this latter situation, occurs te emission of photons of energy hf_c, the same energy as that of the incident photons. This emission process is known as stimulated emission. Being so, if the stimulated emission was to dominate over absorption, we will have a net increase in the number of photons of energy hf_c and consequently an amplification of the signal. Otherwise, the signal will be attenuated.

Lets call to the population (number of atoms) in the energy levels E_1 and E_2, respectively N_1 and N_2. Another condition for amplification to occur is that N_2 must be higher than N_1 ($N_2>N_1$). This condition is known as population inversion. The reason for this term is that, at thermal equilibrium, lower energy levels are more highly populated. Therefore, at thermal equilibrium, we have only absorption of the input signal.

In order to have amplification, the population must be inverted, and this can be achieved by supplying additional energy in a suitable form, to pump the electrons to the higher energy levels. In DFA, this energy is in optical form and it is usually known as pump.

Some studies indicate that the erbium atom can be appropriately described as a 3 levels system for optical amplification at 1550nm [7][15]. In Figure 3-9, the Erbium (Er^{3+}) three energy levels are demonstrated.

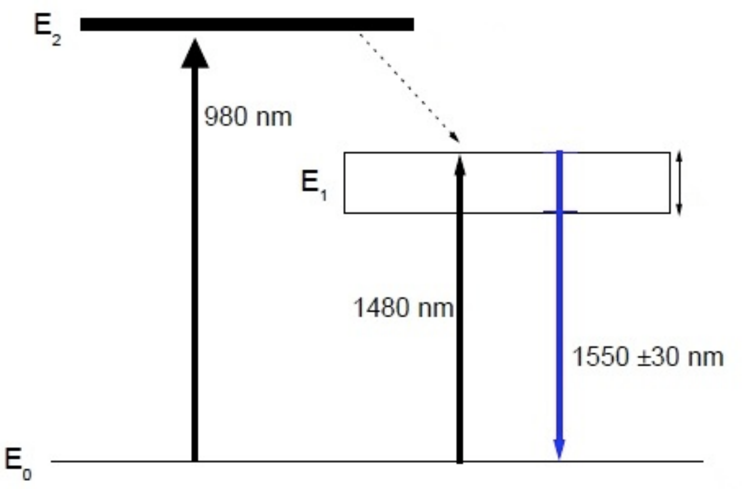


Figure 3-9 Schematic of Erbium three energy levels [48]

Level E_1 has a high-energy band, which is metastable and presents a high average lifetime of some milliseconds. The electrons in level E_1 transit to level E_0 emitting photons witch wavelength is between 1520 and 1580 nm.

To have the population inversion in level E_1, the electrons should be excited to that level. Basically, that population pumping could be done directly by photons witch wavelength is 1480mn or indirectly by photons with 980 nm of wavelength. In the indirect case, the fundamental level absorbs photons at 980 nm, the carrier's transit to E_2 level, and rapidly (around 7μs) a non-radioactive transition occurs from the level E_2 to level E_1, increasing the population in the metastable level E_1. In the other case, the use of a 1480nm signal allows to directly pump photons to level E_1[15].

The three level system requires high pumping powers to achieve inversion of the population, and consequently gain. A continuous pump radiation causes transition from the E_0 level to the E_2 level and at same time from E_2 level to the E_1 level. If the transitions from the E_2 level to the E_1 level are fast enough, the population in the E_1 level increases compared to the E_0 level referenced as inverted population. Amplifier spontaneous emission (ASE) of photons occurs when the population in E_0 level is higher than in the E_1; ASE is the principal source of noise in DFA. When the pump is enough to keep the population in the E_1 level higher than E_0, the stimulated emission is predominant[41].

The basic EDFA scheme is represented in the Figure 3-10. The pump and the signal to be amplified are coupled by an optical coupler, and injected in the doped fiber. A big part of pump signal is absorbed along the doped fiber, occurring the population inversion and the amplification of the signal. At the end of the doped fiber, a WDM coupler removes the excess pump. The isolators in the figure reduce the re-alimentation from signals that come from the far end of the EDFA, and to reduce the injection of noise from spontaneous emission. In the scheme of Figure 3-10, the pump is injected in the same direction of signal, and is known as co-directional. This allows lower noise figure (NF) due to the higher population inversion in the input of the amplifier. In a way to improve the gain of the amplifier, the pump can be injected in the contrary direction of the signal (counter directional), which imposes higher population inversion in the output of the amplifier. But in this case, there is a higher level of NF. It is also possible to have a dual scheme, where the pump is injected in both directions (bi directionally pumping), and that allows an intermediate situation. The problem is that it is required two pump lasers.

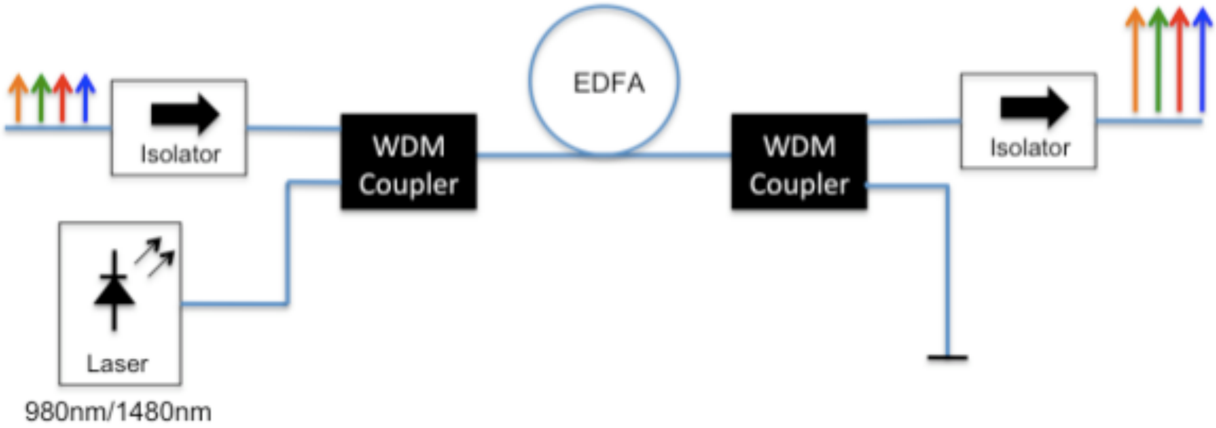


Figure 3-10 Schematic of an Erbium Doped Fiber Amplifier implementation

The gain (G) of an EDFA is function of fiber length (L), population density in level E_0 and E_1 (N_0 and N_1 respectively), confinement factor (Γ_s), and emission and absorption cross-sections (σ^e_s and σ^a_s respectively) and can be calculated using the follow equation:

In an EDFA, the amplification can be influenced by several factors, such as the wavelength of the signal to be amplified, signal power, pump wavelength, pump power, EDF erbium

$$G = \Gamma_s \exp\left[\int_0^L (\sigma_s^e N_2 - \sigma_s^a N_1)\, dz\right]$$

concentration, EDF length and pumping scheme. In order to understand how amplification is influenced by these factors, some of them were verified in the lab. It is important to emphasise that to understand EDFA behaviour is of crucial importance when architecting an RN architecture, since most of reconfiguration is reached because we can vary in a controlled way the EDFA conditions.

3.3.6.2. EDFA Characterization

An EDFA was characterized in the laboratory, in order to observe the behaviour of an EDFA for different factors. With the exception of the results for the variation Gain Vs. Input Signal Wavelength, in which we used the results provided in [48], for all other characterizations we used a relatively low Erbium concentration EDF, the HE980 from OFS, with peak absorption at 1530nm of 2.5 to 4.5dB/m and 10 meters of length.

Gain Vs. Input Signal Wavelength

EDFA gain as a function of input signal wavelength is an important factor since it is the greatest responsible for nowadays EDFA being the most deployed fiber amplifier, as its amplification window coincides with the third transmission window (1530~1570nm C-band) of silica-based optical fiber. This aspect is so important as it determines the amplification of individual channels when a WDM signal is amplified. The gain shape is affected considerably by the amorphous nature of silica and by the presence of other co-dopants within the fiber core such as Germania and Alumina[48].

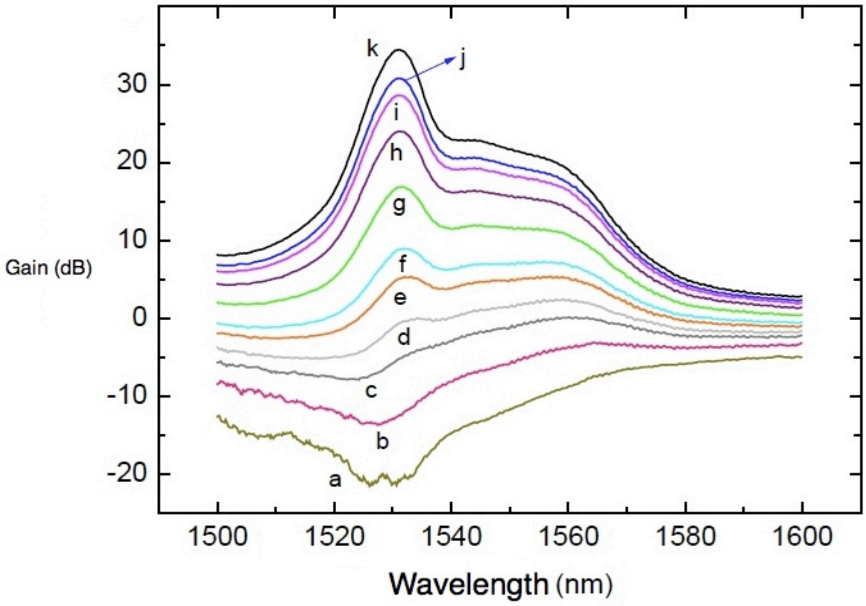


Figure 3-11 Gain spectrum for small signals for various pump power values: (a) 0.4mW (b) 0.6mW(c) 1mW (d) 2mW (e) 2.5mW (f) 3mW (g) 5mW (h) 10mW (i) 20mW (j) 30mW (k)

In Figure 3-11 is presented the considered spectrum, for a small input signal for various pump powers at 980nm. For the EDFA, for pump powers higher than 2mW, the transparency is exceeded, that means we start having gain, and for superior pump powers the gain bandwidth is higher than 20nm. This characteristic is very important when developing amplifiers, since it is able to provide almost equal gain for signals in that range (for the EDFA used in the example the range would be from 1540 to 1560nm).

Gain Vs. Input Signal Optical Power

Figure 3-12 shows the gain variation as a function of input signal optical power for different pump optical powers. For this characterization it was used a pump at 1480nm.

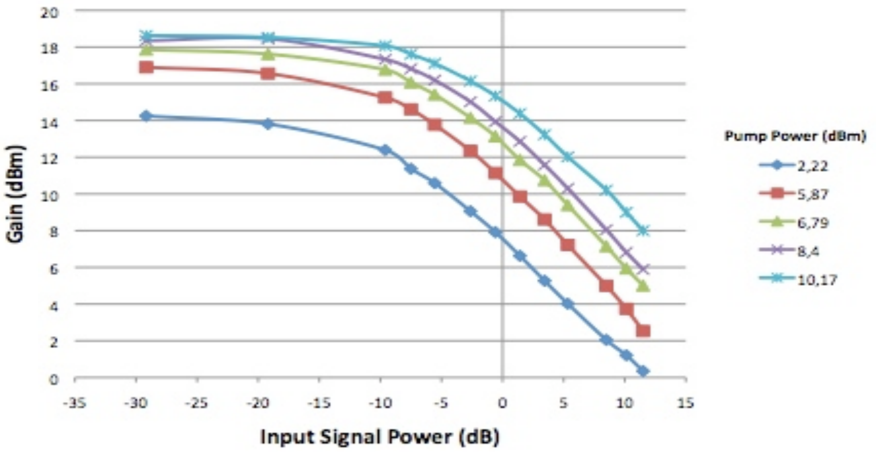


Figure 3-12 EDFA Gain vs. Input Signal Power

Observing the results, we can conclude that the maximum gain provided by the EDFA depends on the input signal power. The bigger the input signal power, the less is the gain that EDFA can provide to the signal. Is also possible to see that for small input signals, the maximum EDFA gain is constant (around -20 dBm of input signal power).

Output Signal Optical Power Vs. Input Signal Optical Power

Figure 3-13 presents the output signal power as a function of input signal power for different pump powers. In both plots, it is possible to observe the gain saturation effect of the amplifier. For these cases, the efficiency of the amplification decreases for input signals higher than -20dBm due to the saturation of the amplifier.

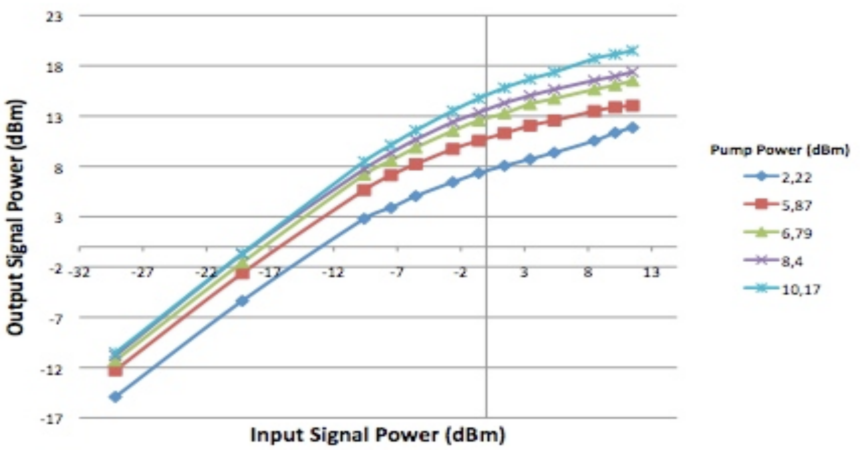


Figure 3-13 EDFA Output Signal Optical Power vs. Input Signal Optical Power for different pump powers

Gain Vs. Pump Optical Power

Probably the most important characteristic of an EDFA is its gain behavior as a function of the pump power. Figure 3-14 shows that dependence for various input optical powers, with 1450.12nm of wavelength. As previously, we can see that gain reaches the saturation as we increase the pump power, and that for the same pump power the gain is higher for lower input signal values.

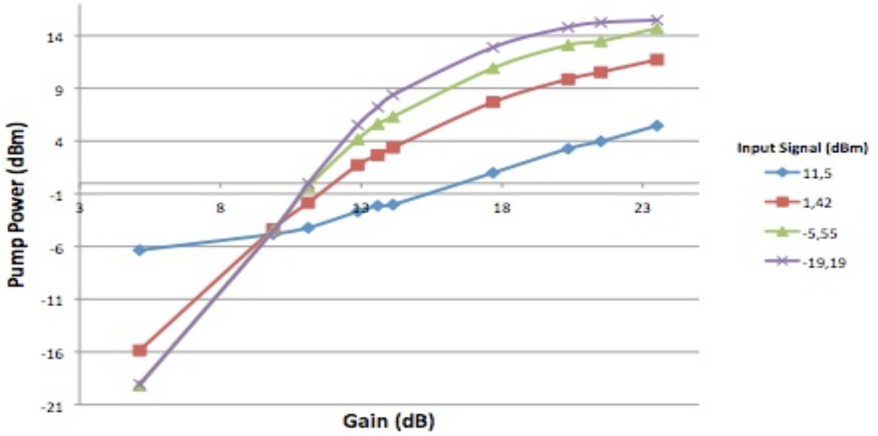


Figure 3-14 EDFA Gain Vs, Pump Optical Power for different input signal powers

So, to have an efficient amplification, the input signal power should not get into the saturation mode due to the lowering of the gain and higher pump consumption. However, if it operates at saturation, EDFA would achieve optimum noise performance since that reduces the rate of spontaneous emission, thereby reducing ASE. Other advantage of operating in the gain saturation region is that small fluctuations in the input signal are reduced in the output-amplified signal[12].

Gain Vs. Pump Wavelength

A factor that would have influence in the method that will be proposed further, is the relation between the gain and the pump wavelength. Seeing Figure 3-9, we notice that the level E_1 has a wide band, and it is possible to take advantage of that. So, in laboratory it was measured the gain for different pump wavelength in the region of 1480nm. In Figure 3-15, we can see the association between these two parameters, for different pump powers, coupled with a 1550.12nm input signal with -25,6dBm of optical power.

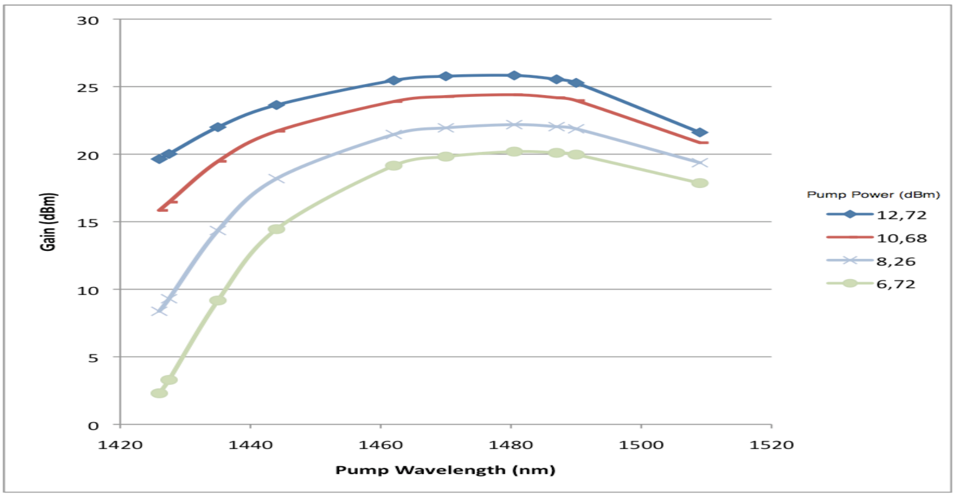


Figure 3-15 EDFA Gain vs. Pump Wavelength for different pump powers

For the range 1460 till 1500 nm, the signal gain is almost the same. This is a important characteristic because that means we can use all this band to supply pump to EDFA, having in this way a much more adaptable and elastic system. In Figure 3-16 it is possible to see in more detail the gain variation for the 1470~1490nm band.

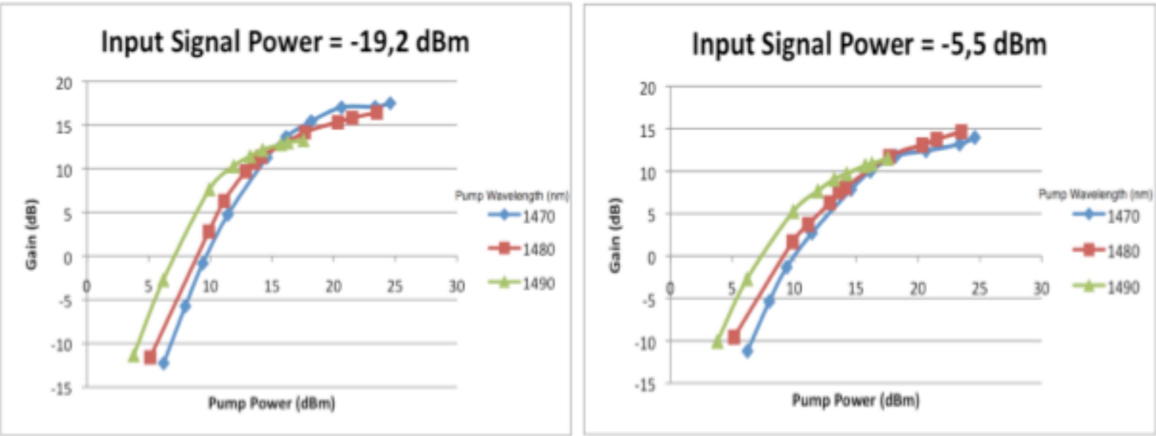


Figure 3-16 EDFA Gain Vs Pump Wavelength for 1470, 1480 and 1490nm pump

Multiple Wavelength Pumps Multiplexed

Another important characteristic for the further proposed method is to see the behaviour of the EDFA if it is pumped with different wavelength multiplexed pumps. In the laboratory it was made a study, to observe how the gain varies if we use one, two or three pumps multiplexed with the signal to be amplified. For that it was used a continuous signal at 1555,75nm with -25,56dBm of power. Figure 3-17 shows the results:

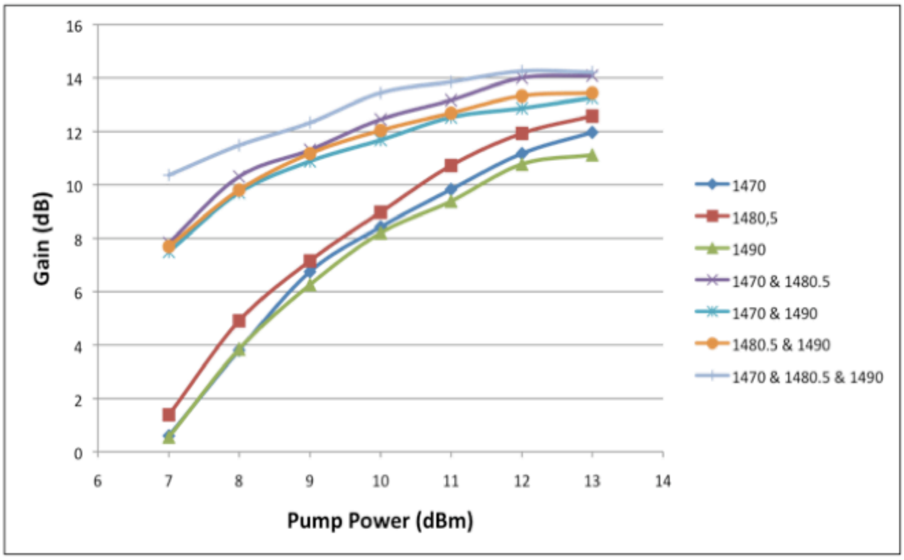


Figure 3-17 EDFA Gain vs. Pump Power for different multiplexed wavelength pumps

The strategy used was to see for the same pump power how the gain changes. So, in the multiplexed pumps, each of the multiplexed pumps has the same pump power as the other one, being the pump power assigned in the x label the individual pump power and not the sum of pumps multiplexed signal power.

Analyzing the results, we can see that we have approximately the same gain if we use only one pump or two pumps multiplexed with half of the pump power each.

3.4. Proposed RN Architecture Limitations

Although the good characteristics of previous presented RN topology, it still have some limitations that should be solved. Being a proposal to be implemented in a PON, it is not difficult to understand that the existence of active components, such as the tunable coupler and the switches, could be a problem. More, to control switches, an extra channel should be used to carry some communication protocol. Other problem could be the maximum light power that components can handle before "burn".

3.4.1. Active Components

As was told previously in the chapter 3.1, a PON should not use any active component. But actually, in this type of networks they could be present, since it is possible to feed them without requiring external electrical power, as his proposed here [39][49]. The active components can be updated using a remote powering technology via fiber optics. The key element of these systems is a pigtailed Power Converter Module (PCM) that converts optical power carried by the fiber into electrical power. The PCM consist in a photovoltaic cell that converts optical energy to electrical energy.

This elegant solution to supply active components could be a good solution, if there is not the problem of the efficiency of these components. In the example presented in [39], there were tested a photodiode (PD) and a photovoltaic power converter (PPC). In the PPC, the produced open-circuit voltage rises linearly with an increasing input optical power. It can produce an almost constant value around 4.8V at 25dBm and a low voltage value of about 0.56V for only 0dBm. Short-circuit current rise exponentially with an injected optical power increase. The PCMs voltage and current behaviour, when injected optical power at λ=1543 nm can be seen in Figure 3-18. The pink line represent the PD and the blue one the PPC.

These results show the efficiency problems of this solution. Other issue is the required extra light power to feed the PCM. An extra-dedicated wavelength channel is required to supply the module and the correspondent light budget increase.

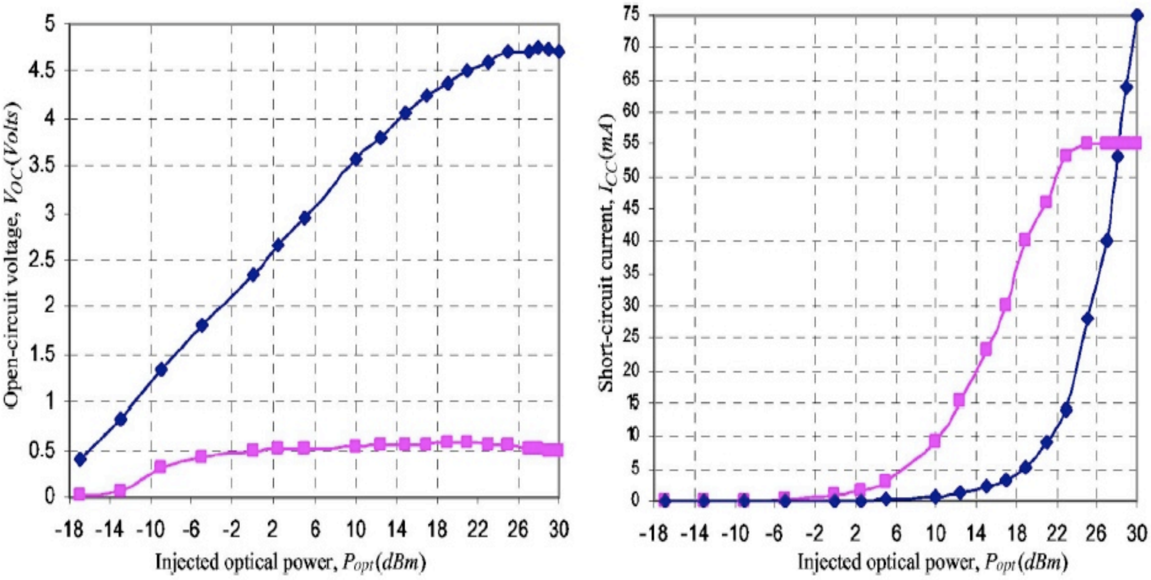


Figure 3-18 PCM voltage current behaviour, when injected optical power at λ=1543 nm[39]

3.4.2. Communication Protocol

Other problem of the proposed RN architecture is the necessity of a control signal for reconfiguration. All reconfigurable components, such the switches and the tunable coupler, require some control unit that controls their reconfiguration. To control such control module (CM) is required an extra wavelength channel, with the aim to do the communication between the CM and the CO. The CM is listening coded tones until it recognizes a pre allocated pattern and turn on the microcontroller that is on sleep mode. After that, an operation is communicated and the microcontroller will act over the reconfigurable components[41].

So, this and the referred extra wavelength channel to supply the PCM are two channels that could be used for data communication. A better solution would be to use the wavelength channel dedicated to power supply the PCM, to also carry the control information, where part of the converted signal is lead to a control unit by mean of an RF component. Still, although these drawbacks, this allows a more flexible network able to adapt more easily to the changes and with more and better responses to different situations.

3.4.3. Network Power Budgets

When we see an optical component datasheet, one common specification is the maximum power handling[50][51]. So, this should be an important factor to have in consideration.

The pump power required in order to all RNs operate efficiently, in some cases it can reach high values, in the order of 44dBm [52]. For some of those cases, solutions in the market do not exist, so the idea exists but it cannot be implemented.

3.5. Conclusion

In this chapter it was made the allusion to the architecture of a new FTTH network, in the case the SARDANA network. This was thought in order to improve the scalability, reconfiguration and resilience in passive FTTH networks.

Related with this network, it was presented the architecture of a RN as well as a brief analysis of the used components to implement such network. Further experimental EDFA characterization was presented in this chapter: EDFA behaviour when pumped with signals of different wavelength, of 1480nm, and for the case when the EDF is pumped with multiple multiplexed pumps at the same time.

In the last part of the chapter, a survey was made of features that could be improved in the presented topology. It became clear that the use of active components went against the main concept of the PON networks.

In chapter 4 will be presented a new method to control in a passive way the pump power extracted to pump the EDFA. The method aims to simultaneously avoid the use of active components in the RN, and optimize the gain of EDFA depending on the momentary network conditions.

4. Proposed Method

4.1. Introduction

The previous chapters are introductory to optical telecommunication networks, with emphasis on access networks. These networks must be cost-effective; therefore one way is to keep the structure totally passive.

The doped fiber amplifier (DFA) are optical amplifiers that are based in a rare earth doped fiber (such as Ytterbium (Yb), Erbium (Er), Neodymium (Nd), Thulium (Tm), etc.), that when traversed by a optical signal with a specific wavelength, normally called pump signal, interacts with the doped fiber ions taking them to higher energy levels, then after provide gain to optical signals in another optical band. These amplifiers can be remotely pumped from a centralized location, such as a CO, and, in this case, they are known as remote optical pumped amplifiers (ROPA). In DFA, the amount of gain provided to the signal depends, among other factors, of the pump wavelength and power that is supplied to the DFA.

The network conditions can change due to several factors. A fiber cut occurred, components degradation, new RNs added to the networks, even there was an increase of distance between the CO and some ONU; making necessary to readjust the gain conditions in several network RNs. A method to optimize on time the pump power delivered to the DFA is of huge utility, and if this is a passive method, in this context, even better.

Some proposals for optimizing the pump power to be given to the DFA have been presented[37][36][53]. It is proposed the use of fixed couplers to extract a constant amount of pump power for each RN. However, this strategy in many cases proves to be ineffective since pump power could be wasted, or not be enough, to provide gain at each RN. Another factor against this strategy is that, unless these fixed couplers are physically changed, the network does not provide reconfigurability. To solve these problems it was proposed the use of tunable couplers, however those are active components, requiring an active system (or remotely active) to control it.

In this work a remote configuration and passive method to act over conditions of one or several remote pumped DFA disposed in series will be presented. Applying this method to the RN referred in chapter 3, it will be possible to avoid the active optical components, tunable couplers and switches, and the respective control and optical supplying channels. Also, optimization of pump power extracted in each RN, rationalizes the signal power that optical components have to handle. With the presented method, it is also possible to adjust independently the amplification in each ROPA.

4.2. Method Description

The method that is proposed here is a passive and efficient way to enable pump reconfiguration in ROPAs. It consists of a matrix of one or more power and wavelength tunable pump lasers (TPL) and a three port WDM filter, which has a known transfer function (TF). The filter should be placed near the DFA, and it is the responsible for the pump extraction. Then, the extracted pump is coupled with the signal which has to be amplified, and the multiplexed signals crossed through the DFA. The complete system is represented in the Figure 4-1.

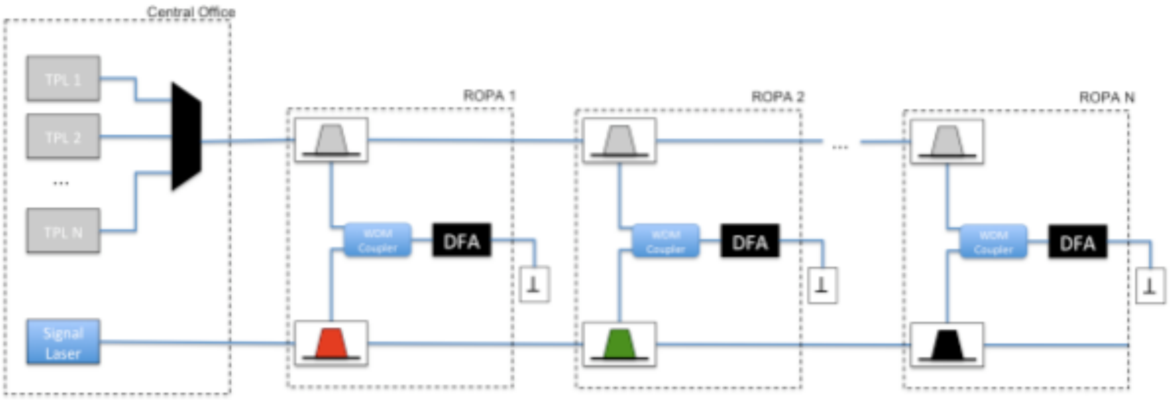


Figure 4-1 Schematic of implementation of proposed method

There is no active component near the amplifier, being the unique active components used in the method the TPLs that could be in a centralized place, such as the CO. With this method the optical components required to implement reconfigurability to the network are reduced, since it dismiss the use of switches and tunable couplers. This represents a reduction of IL, and consequently, reducing the gain requirements of the signal. Removing these components also represents a RN cost reduction, due to the fact that these components are usually more expensive than a filter.

In the proposed method, each ROPA should have a specific three port filter, which TF is personalized. Thus it is possible to independently adjust the operating characteristics of each amplifier (the gain for example). This adjustment is then achieved by varying the emission power and wavelength of the pump lasers.

4.3. Principle of Operation

In a WDM filter, we have three ports: one where the signal is applied, and two where it exits, from these one with the transmitted signal and the other with the reflected. The schematic of a three port filter and respectively typical TF are represented in Figure 4-2 and Figure 4-3 respectively.

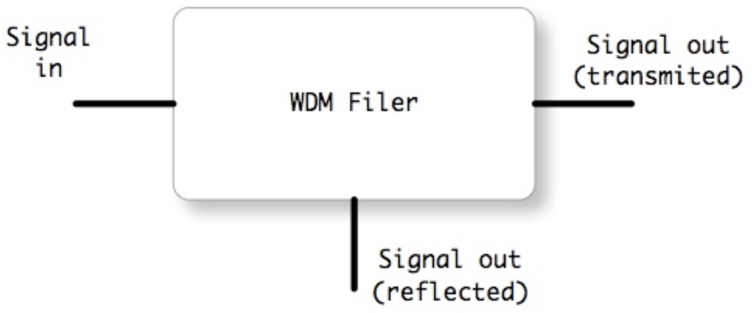


Figure 4-2 Schematic of a three-port filter

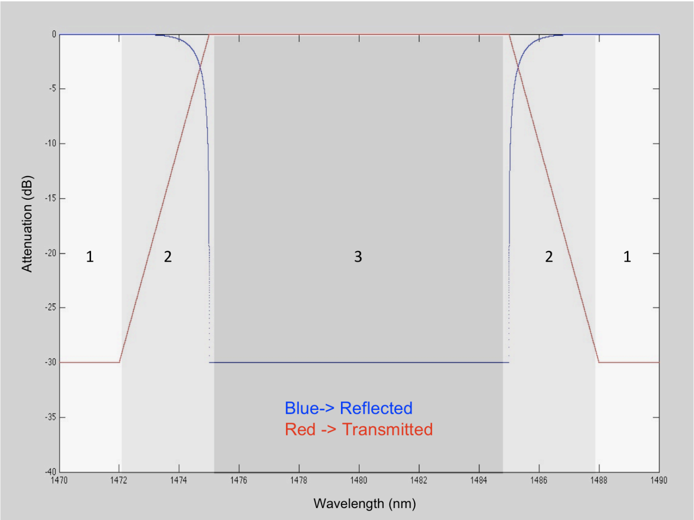


Figure 4-3 Typical transfer function of a filter, where are represented at blue the transmitted signal and black the reflected one

The TF can be divided into three distinct zones. The first where all the signal is transmitted and almost none is reflected (1); the second is where the reflected signal increases while the transmitted is reduced and vice versa (2); and the last one where all the signal is reflected and almost none is transmitted (3). As what concerns the part represented with number 2 will be referred hereafter as the cut zone.

The proposed method takes advantage of the filters cut zone slope. If the pump wavelengths are along the filter cut zone, the reflected pump signal power can be adjusted and used to pump the amplifier. In the example of Figure 4-3, it is possible to vary the pump that is extracted to the filter from 0 to less than -30dB.

It is important to note that the TF presented above is merely illustrative. An infinite number of filtering TF shapes are possible, and this should be taken into account when designing the network. If, for each ROPA, is used a different filter TF, it is possible to achieve higher reconfigurability by combining all them together. By changing the characteristics of the filters TFs, such as: the slope of the cut zone; the bandwidth covered by the cut zone; the attenuation levels; or even use more than two cut zones could increase the levels of reconfigurability of the network (Figure 4-4).

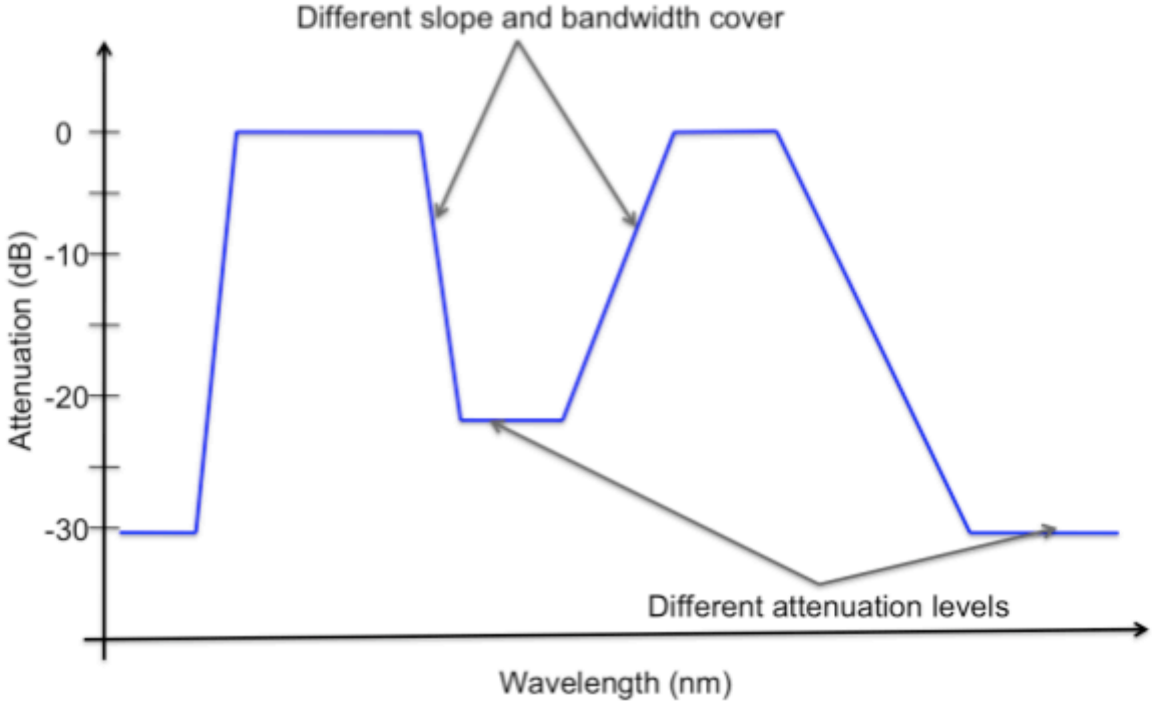


Figure 4-4 Schematic of a possible filter transfer function of the transmitted signal for enhanced reconfigurability possibilities

Another strategy is to use multi-pump signals. The latter can be a good solution in case of a larger network, as it simplifies the dependence between the filters TFs in each ROPA. In the best case, each ROPA would be assigned a pump laser with fixed wavelength. For this situation, it would be enough to adjust the respective pump laser emission power to optimize the amplifier conditions; however this is not the most efficient solution in terms of pump count.

To better understand the operation of the method lets observe the following example of a network with three RNs as in Figure 4-5, where each RN has a ROPA (in the case an EDFA) site to enable extended network reach. In this example only down stream is considered. At the CO, two TPL are multiplexed and sent along the feeder fiber, together with three DS data signals. At RN1, signal λ_1 is extracted and amplified by means of EDFA1 to compensate the losses caused by attenuation and components ILs. The other two signals, λ_2 and λ_3 continue and are extracted respectively in RN2 and RN3. Since these signals have to travel a greater fiber distance, they will suffer higher losses, so they need a larger amount of gain.

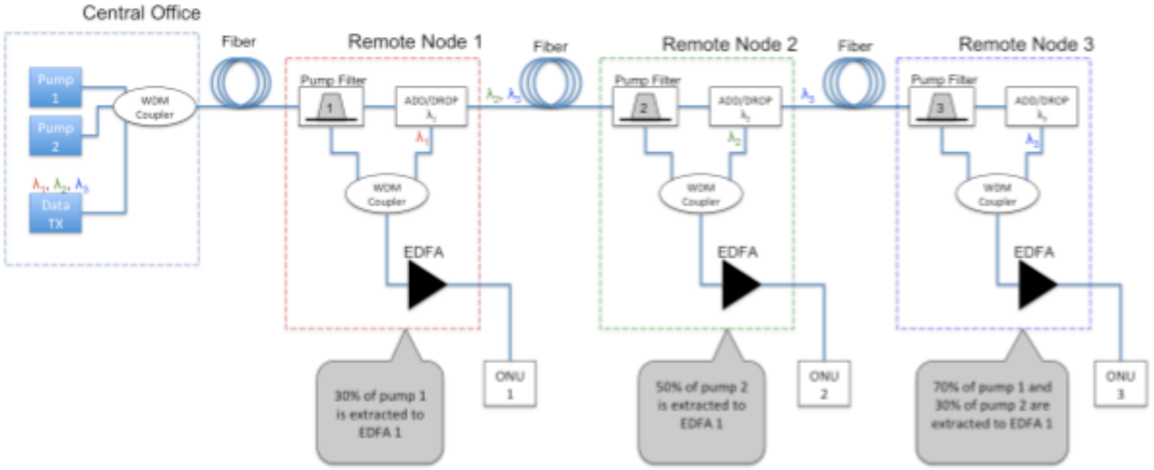


Figure 4-5 Schematic of a three remote nodes network where the proposed method is applied, and with a possible solution

Each RN had a specific filter assigned, for which the TF was optimized to provide multiple combinations between the TFs of the three RNs. To meet the minimum signal gain requirements, it is only necessary to adjust the emission wavelength and power of the two pump lasers in the CO. A possible solution is represented in the Figure 4-5.

Suppose now that this example network is deployed with some kind of optical layer protection (e.g., duplication of feeder fiber). If a cut occurs between the RN1 and the RN2, then, signals λ_2 and λ_3 have to propagate over a longer protection fiber. In this scenario, it is necessary to provide higher gain to those signals, therefore is necessary to supply more pump power to EDFA of RN2 and RN3. Since there exist various combinations between the TFs of the three RN, to solve this problem, it is only necessary to adjust the pumps parameters, such the emission power and wavelength, to one of the available solutions that satisfies the gain requirements.

4.4. Practical Implementation

In the laboratory were tested some assemblies in order to verify some features of the proposed method. It was quite difficult to implement the proposed method in practice due to the lack of a key component that is the wavelength TPL. Therefore were used two pumps with fixed wavelengths, where only the emission power was variable. The two pumps emission wavelengths were centered at the available filters pass TF. To multiplex the pumps signals, polarization multiplexing was used, a polarization beam splitter (PBS) was used to avoid 3dB loss of coupling the two pumps. In all assemblies, gain is measured in an amplified signal of 1450,12nm with -12dBm of peak power before amplification. Follow the performed assemblies and obtained results.

Assembly 1:

In this assembly the simpler situation was implemented, where for each filter is assigned a dedicated pump laser. Two add/drop filters where used, centered in different wavelengths (1471nm and 1491nm), and two pump lasers with 1470nm and 1490nm wavelengths multiplexed by a PBS. At the drop port of each filter is associated a 10m EDFA. The assembly scheme and filters and pumps dispositions are represented in Figure 4-6 and Figure 4-7.

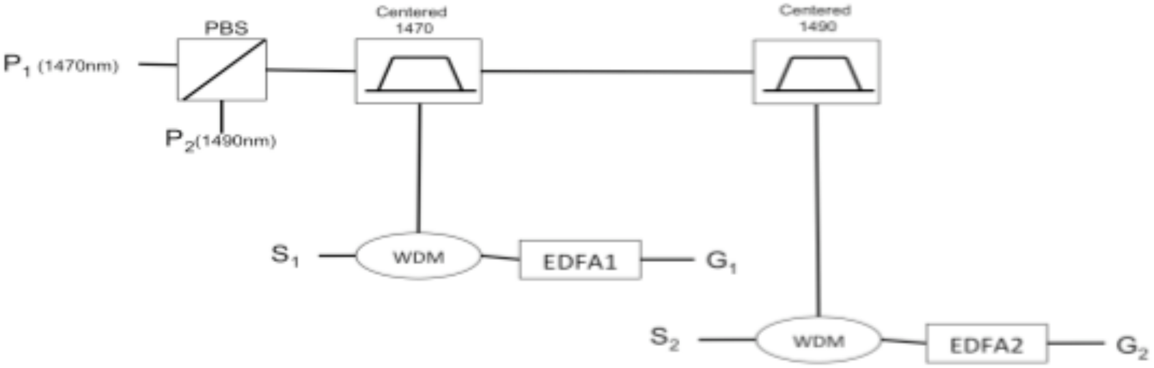


Figure 4-6 Schematic of assembly 1

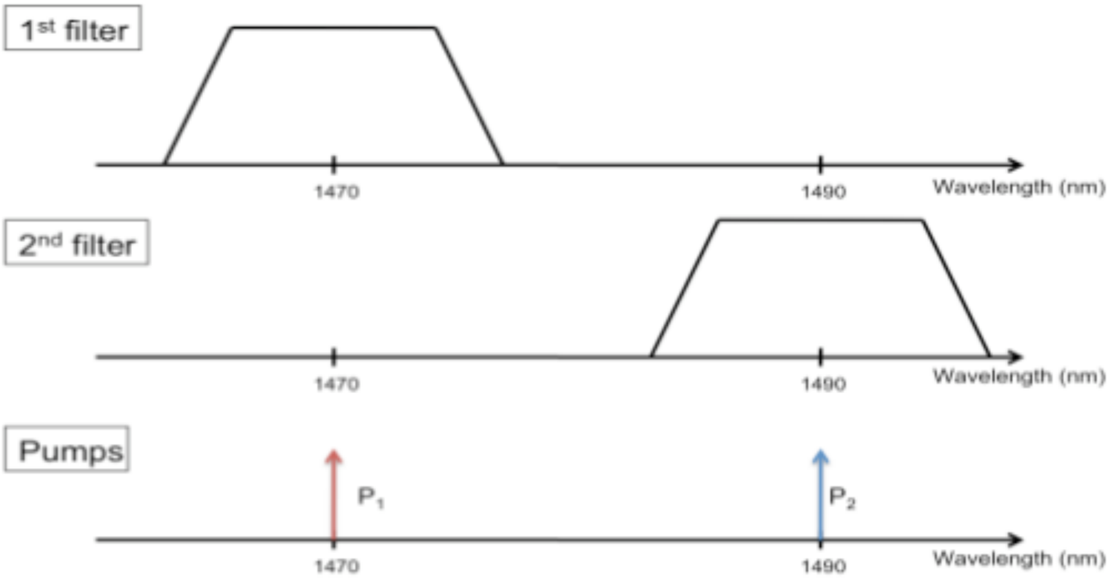


Figure 4-7 Assembly 1 filters and pumps dispositions

The intention of this scheme was to demonstrate the possibility to independently vary the gain (G1 and G2) in each EDFA, changing only the power output of pump lasers P_1 and P_2.

As it can be seen from the results, shown in Figure 4-8, the gain of EDFA1 and EDFA2 only depend on pump P1 and P2 respectively. Since the two EDFA are identical, for the same pump power, the same gain was expected. However that was not what happened, as shown by the results. The reason is simple, the P2 suffers greater attenuation due to filter 1 IL, and indeed the pump power that is pumped into EDFA2 is lower than the pump in EDFA1, for the same conditions.

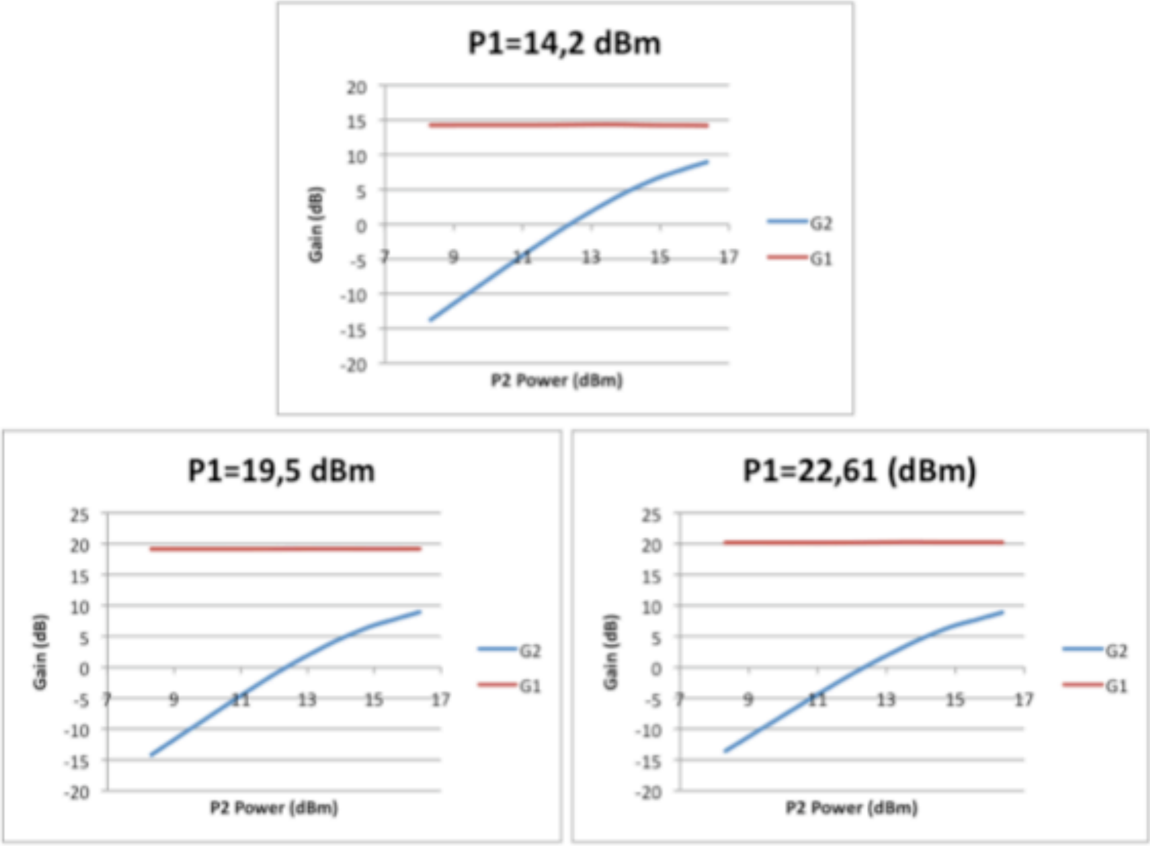


Figure 4-8 Results of the assembly 1

Assembly 2:

In the second assembly, the intention was to verify how the gain changed by moving the pump signal along the filter cut zone. But as previously stated, it was not available in the laboratory any wavelength tunable pump laser. Therefore, the solution was to move the filter. Since there was not any available tunable filter, it was used a tunable coupler to simulate the filter cut zone.

In this assembly, it was intended that the gain of the second amplifier could be varied without influencing the gain of the first. The schematic of assembly 1 can be seen in Figure 4-9.

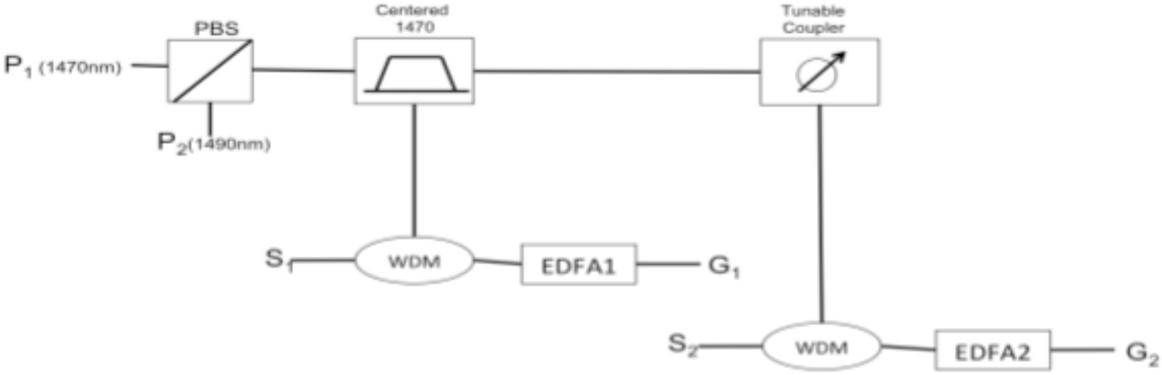


Figure 4-9 Schematic of assembly 2

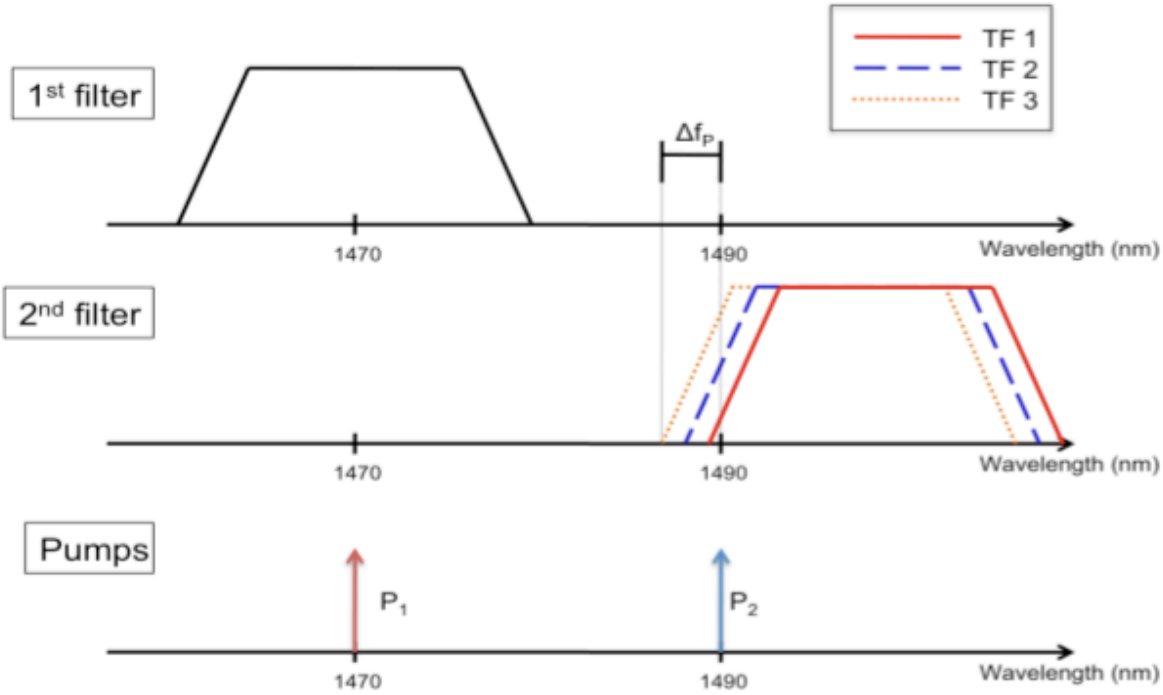


Figure 4-10 Assembly 2 filters and pumps dispositions

In Figure 4-10 a schematic of what was performed is presented. Δf_P is the range that pump wavelength can be moved, keeping the laser centered in the filter cut zone. The different TFs represent possible positions that filter 2 could have in relation to the 1490 pump laser. In the TF 1 example, the filter will extract almost no pump. The TF 3 represents the opposite situation; in that case almost all pump power is extracted.

For the tunable coupler used, increasing of the coupling ratio simulates moving the filter towards the illustrative TF 1 line in Figure 4-10, i.e. the pump power extracted is reduced. Reducing the coupling ratio represents the filter moving towards TF 3 line, increasing the pump power extracted. The obtained results are represented in Figure 4-11.

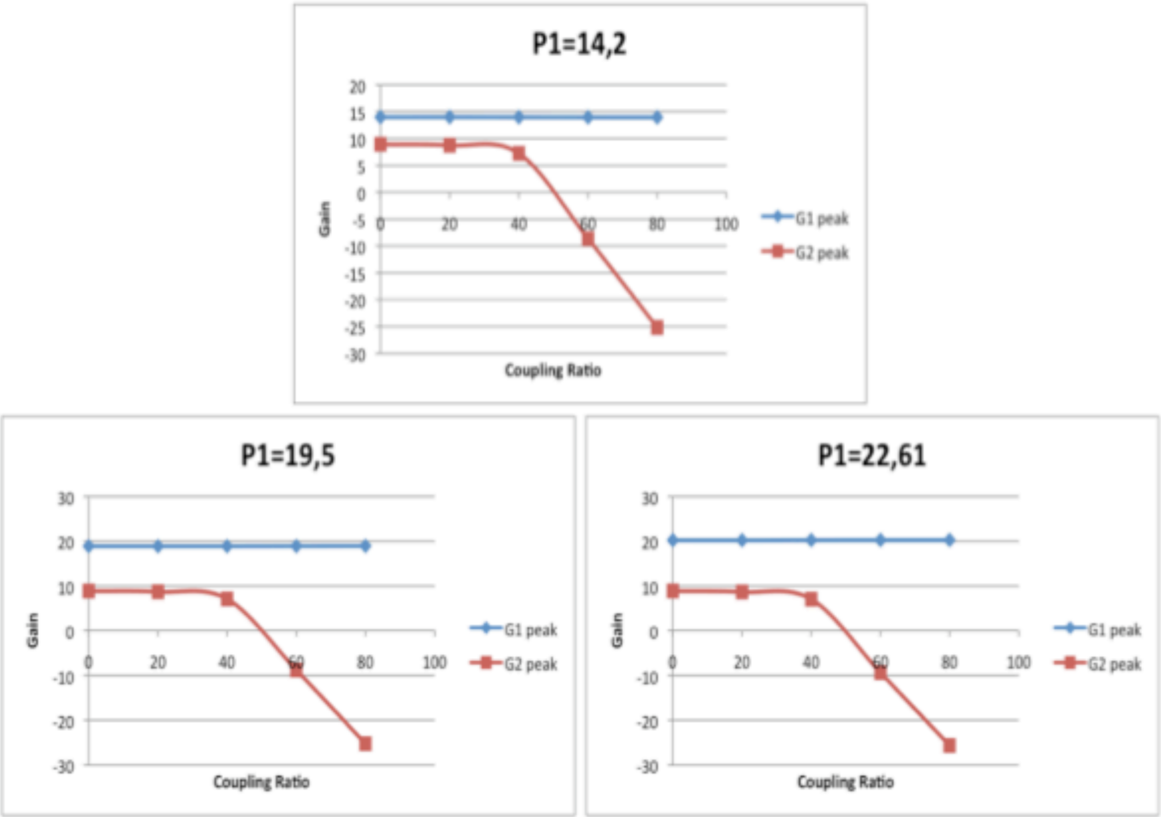


Figure 4-11 Results of the assembly 2

As expected, the results showed that varying the pump power extracted by the filter 2 does not affect the gain in EDFA1. It is also possible to see that the gain in the EDFA2 is not dependent on the P1 power.

Assembly 3:

In the proposed method, if the pump is centered in the filter cut zone, part of the pump power is reflected and the remaining is transmitted. In this case, the performance of the following amplifiers is affected by the changes in the dropped power for the first amplifier.

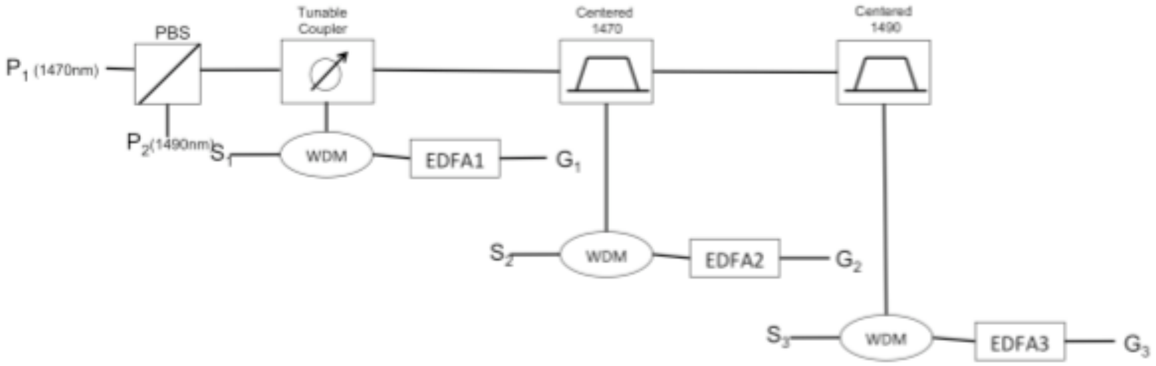


Figure 4-12 Schematic of assembly 3

In Figure 4-12 is presented the referred assembly. The system is pumped with two different wavelength pumps (1470 and 1490nm). The first filter, which is, again, simulated by a tunable coupler, has a TF whose cutting zones are centered with both pumps. The other two filters are centered in one of each pump. The filters relative position to the pumps is presented in Figure 4-13.

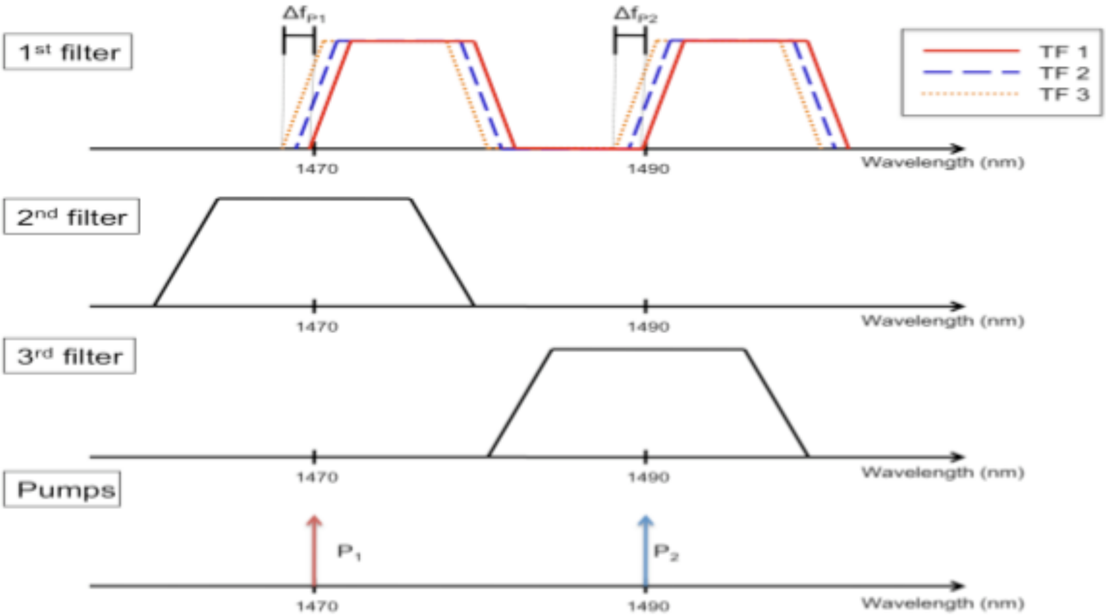


Figure 4-13 Assembly 3 filters and pumps dispositions

The tunable coupler simulates a filter with two band-passes, and two of their cut zones are centered in P1 and P2 wavelength. Δf_{P1} and Δf_{P2} represent the amplitudes that the pumps can move by keeping the pumps still centered in the filters cutting zones. The other two filters are centered in P1 and P2 emission wavelengths, respectively. Thus, all the transmitted pump power by the filter 1 is pumping the EDFA2 or the EDFA3.

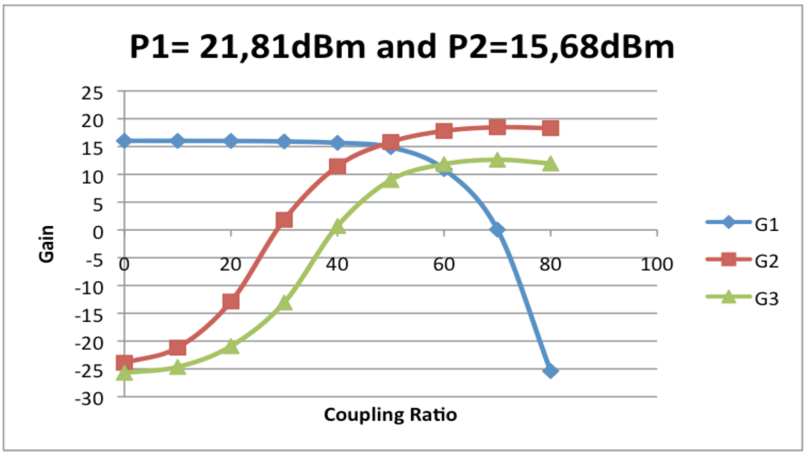


Figure 4-14 Results of the assembly 3

As it can be seen in Figure 4-14, increasing the coupling ratio, that is the same as moving the filter to the TF 1 situation in the Figure 3-14, the amount of extracted pump is reduced, and the non-extracted pump follows to the other filters. Consequently, the gain in EDFA1 is reduced and the gains of the other two filters are improved. The gain curves of the other two amplifiers are parallels, because the amount of each pump P_1 and P_2 extracted in the first filter, in percentage terms, are the same.

5. Simulation

5.1. Introduction

For the proposed method to work best, optimized filters TFs must be used, and, for each scenario, the respective pump wavelength and emission power should also be accounted for. Obtaining the optimized solution is extremely difficult when performed analytically, so, in order to facilitate this task, it was developed a simulation tool, capable to optimizes several parameters, such as filters TFs, the pumps power and wavelengths, with the aim of reducing the network power budgets keeping it working efficient.

For the algorithm to be able to reach the optimum results, it makes use of Multiobjective Genetic Algorithm (MGA). It was entirely implemented using the program Matlab® and it is based on the Matlab Genetic Algorithm and Direct Search Toolbox™.

MGAs are search algorithms based on the mechanics of natural selection and natural genetics. They combine survival of the fittest among string structures with a structured yet randomized information change to form a search algorithm with some innovative flair of human search. In every generation, a new set of artificial creatures (string) is created using bits and pieces of the fittest of the old; and occasionally a new part is tried for good measure. These random searches efficiently exploit historical information, trying by that search new points with expected improved performance[54].

5.2. Developed Simulation Tool

The MGA finds the best set of parameters that minimizes the associated error of multiple functions at same time. To get an idea of how many functions are minimized, lets see the example of an eight RNs network. In this case, are minimized eight functions, each per RN, plus one extra function, the *calc_error_pump()*, that forces the algorithm to minimize the pump power budget for each pump signal source used.

The parameters that are optimized by the algorithm are the filters TFs form and disposition, and the pumps wavelength and emission power. Briefly, for a given set of initial parameters, the simulation tool calculates the amplified signal power that reaches the ONUs, for each RN. Then, this value is compared with the desired pump budget at the ONU and the differences between these two values are the errors that are optimized by the algorithm. The MGA generates several populations of parameters in each iteration, and for each generation, the parameters are evaluated, and the respective error calculated. The next iteration will generate a new set of populations, in function of previous results. This process repeats till some stop criterion occurs (such number of iterations, time, etc). The flux diagram of this process is represented in Figure 5-1.

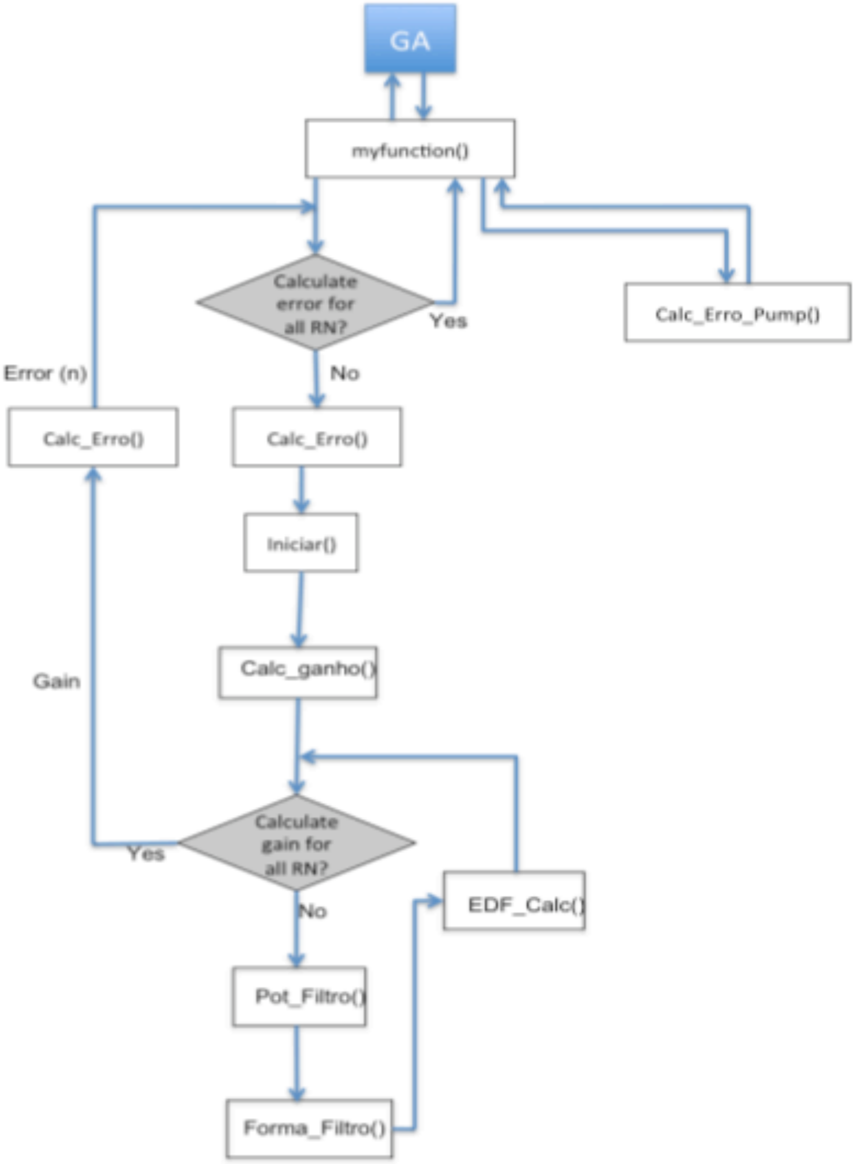


Figure 5-1 Developed flux diagram

Next the operation of each functions that composes the developed simulation tool will be explained:

- *calc_erro[parameters]*

This is the main function of the algorithm. It receives the parameters from MGA, and returns the error that is associated to them. *Parameters* is a vector which size is equal to the number of variables to be optimized; in the specific case of a eight RN system and two pump lasers sources it should be optimized two pump signal powers, two pump signal wavelengths, and thirty two filters TFs points (8RN x 4 points). In this case there are optimized thirty-six parameters.

For each RN is associated a *calc_erro()* function, and the MGA tries to minimize the error of each. The returned error is the difference between the desired signal power in the receiver and the signal that reaches it after amplification. However, it was determined that if the signal after amplification was higher than the desired, the associated error for that case is zero. While this may result in an excessive use of pump power, this problem is reduced because the algorithm is optimizing at same time the function *Calc_Erro_Pump()*, that is responsible to minimize the system pump signal budgets.

It is in function *calc_erro()* that each parameter is assigned to respective variable. It is also here that function *iniciar()* is called, initializing all the variables of the algorithm.

- *calc_erro_pump[parameters]*

This function is minimized at same time as the others *calc_erro*() functions. It creates a vector with the pump signal powers of the system, and determines the norm of that vector. The magnitude of this vector is the error related to this function, and a smaller vector represents lower values of system pump signal budgets.

- *calc_ganho[pump_wl1, pump_power1, ... ,pump_wlN, pump_powerN]*

This function has, as input, the pump signal powers and wavelengths; returning a vector which size is equal to the number of RN. In each position of that vector is the gain of each RN.

Here, in function *calc_ganho()*, all the losses, such attenuation and ILs, are applied to the pump signal. Another particularity in this function is that the excess pump is reused, being added to the transmitted pump power. To determine which is the excess pump power, this function make use of the *edf_calc()* function.

- *pot_filtro[pump_wl, pump_power, f1, f2, f3, f4]*

The algorithm can only optimize filters with trapezoidal TF. Such filters TFs are represented in Figure 5-2. As can be seen, there are four important points, and those are the ones that are optimized by the algorithm. The MGA, for each RN generates a filter TF, and this function applies the condition that f1<f2<f3<f4.

In function of the filter TF defined by these four points, function *pot_filtro()* returns the pump power that is extracted and reflected by the filter.

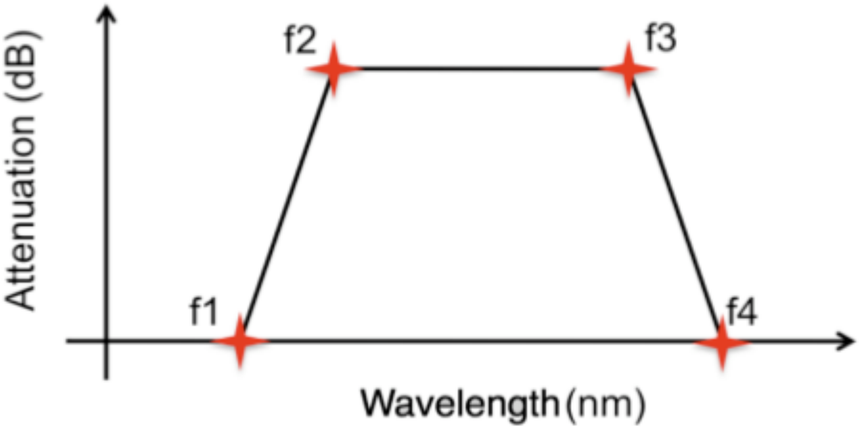


Figure 5-2 Schematic of a filter transfer function

- *edf_calc[pump_power]*

This function is related with two files, the *pumpVSgain.dat* and *pumpVSexcess.dat*. Both files have two columns with same size, where the first column is the pump power, and the second one is, respectively, the gain and the excess pump associated to that pump power. The values for these files should be taken from preliminary characterizations of the amplifiers to be used. Then, the function performs a polynomial of third order curve fitting for each data file, followed by a polynomial evaluation for that pump power.

The algorithm optimizes the gain in each EDF of the system, controlling the pump power that is given for the amplifier. Using the polynomial evaluations, for a given pump power as input, the function returns a vector with two variables, being the first the gain associated to that pump power, and the second the respective excess pump.

- *iniciar[f11, f12, f13, f14, … , fN1, fN2, fN3,fN4]*

In this function are initialized part of the algorithm variables. Variables such as the desired signal power in the receiver, pump signal attenuation, drop loss, add loss, pass loss, mean distance between RNs, signals budgets at the receiver if there is any remote amplification and filters rejection ratio. All system filters TFs points are also defined in this function.

With the previously presented functions, the developed algorithm is able to simulate and optimize reconfigurable optical pumped amplifiers (ROPA), giving as result several parameters that minimize the pump power needed, so that, in all RNs, the extracted channels after amplification have, at least, a given minimum power. Summarizing, the parameters optimized by the algorithm are:

- Pump Power;
- Pump Wavelength;
- Trapezoidal Filters Transfer Function;
- Filters Disposition;
- Filter Slope of cut area.

Most systems are different, and some parameters are singular for each situation. Some parameters have to be taken into account when simulating a particular case, and those should be provided to the algorithm. The parameters that should be provided in advance to the algorithm are:

- Minimum power that signal should have at the receiver;
- Pump drop insertion loss;
- Pump add insertion loss;
- Pump pass insertion loss;
- Pump link loss per kilometre;
- Mean distance between RN;
- Signal that reaches the receiver if it is not amplified (signal from CO less several losses);
- Filter rejection ration;
- EDF characterization;
    - Pump Input Power Vs Gain;
    - Pump Input Power Vs Pump Output Power.

Some steps can be taken to improve the MGA performance. MGAs are capable to perform virtually infinite combinations of parameters until it find one that meets the ideal solution. However, if there is an initial idea of the possible range of parameters values that fit the function, it is possible to maximize the probability of finding a good solution in a faster way. The initial population range, defines the lower and the upper bounds of the first generation parameters. A good choice for the initial population range, i.e., a population range that allows an exhaustive search from the algorithm is very important, because the next generations are framed upon the best fitted members of the previous generations[55].

Parameters bounds are other important factor of the MGAs. It is a set of lower and upper bounds of the pumps power and wavelengths, and filters TF points. This is useful to define the maximum or minimum of each parameter. This is very useful to limit the searching universe for each parameter. To better understand the importance let see one example where the limit bound of pump wavelengths are important. If it is used an EDFA such the one characterized previously in Chapter 3.3.6.2, we only reach gain for pump wavelengths between 1460~1490nm. If the algorithm searches solutions outside this range, resources are wasted. Delimiting the bound with these two values, it is guaranteed that solutions will be in this interval. If other type of DFA is used, other limits could be settled.

Another important consideration in the GA is the population size. It specifies how many individuals there should be in each generation. A small number will make the GA search the solution space more thoroughly, thereby reducing the chance that the algorithm returns a local minimum and not a global minimum. A large population size can solve this problem, however, it also causes the algorithm to run slower. Other MGA optimization could be readed in the Matlab® users manual[56].

5.3. Simulated System

To study the proposed method behaviour, the developed simulation tool was used. It was simulated an eight RNs network, where remotely pumped EDFAs are used to compensate signal losses. For each RN is assigned a signal channel that would require more or less amplification if the RN is further or closer to the CO. It is desired that at each receiver the signal has at least -20dBm. The distance between each RN is considered to be equal , and it was decided to be eight kilometres, since this is one of the scenarios that are proposed for SARDANA. For this network scenario, the assumed network losses and the signal power budgets in the receivers of each RN, without any amplification, are shown in Figure 5-3 and Figure 5-4. All results presented below are based in a HE890 DFA characterization using the VPI transmission maker®.

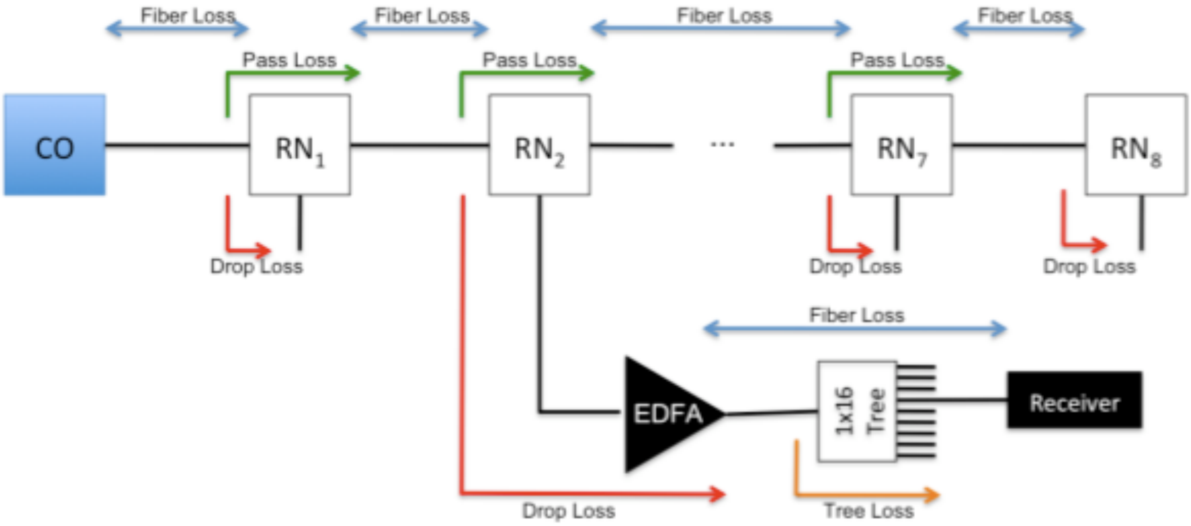


Figure 5-3 Considered network scenario, including the parameters related to component losses

Table (a)	Loss (dB)
Signal Fiber Attenuation (per Km)	0,2
Pump Fiber Attenuation (per Km)	0,25
Signal Drop	3,9
Pump Drop	3,8
Signal Pass	0,6
Pump Pass	2,5
Pump Add	4
Tree (1x16)	17,5

Table (b)	Signal Power (dBm)
Transmitter CO	-11
Receiver RN_1	-12,07
Receiver RN_2	-14,33
Receiver RN_3	-16,6
Receiver RN_4	-18,86
Receiver RN_5	-21,13
Receiver RN_6	-23,4
Receiver RN_7	-25,66
Receiver RN_8	-27,93

Figure 5-4 (a) Used loss parameters for the simulated network and (b) signal power budget in receivers for each network RN

Observing the Figure 5-4(b), it is clear that it will be necessary to provide gain to the signals assigned to the RNs after the RN_4, in order to achieve the required -20dBm of signal power. Plus, as saw in Figure 3-14, for pump powers lower than a given value, the EDF instead of gain it inflicts attenuation to the signal, so, even for RNs where the signals theoretically do not need to suffer gain, a minimum pump power is required to compensate these losses in the EDF.

The simulation tool will optimize the pump signal power and wavelength, filters TFs and filters disposition. Figure 5.5 shows how would be the gain as a function of pump wavelength for each RN in a system where all filters TFs are not correlated. In this case, it is only possible to change one EDFA gain at each time, unless there is more than one pump signal. In the case that exist one pump for each RN, it is only necessary to vary the emission pump power assigned to the RN which gain is desired to optimize. These would be the simplest case to control.

The further the RN from the CO, the greater is the amount of pump signal required. The third graphic of Figure 5-5 shows that to have gain in the last RN EDFA, it is required, for this example, at least 40dBm of pump signal. This is the minimum pump power required to provide to the simulated network in order to have gain in the last RN. This value is important, in terms of comparison, for the remaining studies that will be presented following, since this is the minimum pump signal value in order to have gain in the last RN.

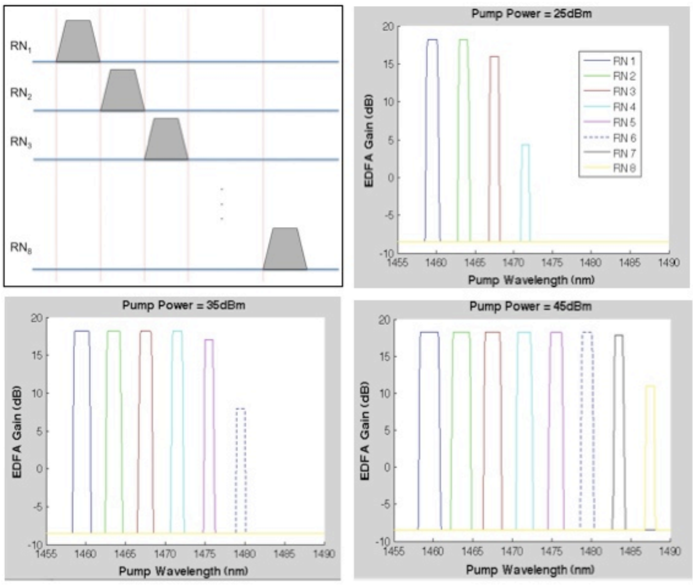


Figure 5-5 Gain in function of pump wavelength for each RN in a system where all filters TF are not correlated

To understand how the filters disposition optimization is imperative, it is important to know how the network gain in each RN DFA would be if all the filters where similar. For a fair comparison, it should be simulated the case where all RN DFA, in the best case would have at least some gain. In Figure 5-6, are presented the results for a network where the filters are all similar, supplied with a 45dBm pump signal. Comparing this with the previous results, where a 45dBm pump signal could provide 10dB of gain to the last RN; in this case, it only reaches the fifth. This means that to have gain in the last RN it would be necessary a higher pump signal power. However, in this case, it is assured that if some RN has gain, all RNs that came before also have it; although their amplifiers are likely to be operating in saturation regime.

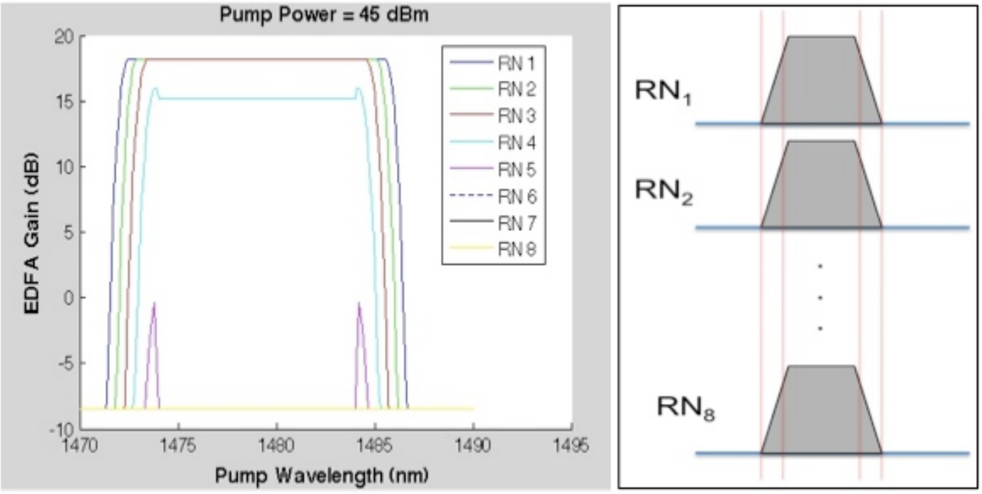


Figure 5-6 Simulation results for a network which filters are similar

A way to minimize pump signal budgets, and at same time optimize the gain of several DFA with a single pump wavelength, is by optimizing the filters disposition and TFs. In Figure 5-7 and Figure 5-8 are presented the results of two exemplificative simulations that will be study. Organizing the filters disposition, as shown in Figure 5-7 where all filters are shifted to the left of the previous one by 1 nm, it is possible to note that, with the 45dBm of pump, it is possible to provide gain even to the eight RN. It is also possible to provide gain to more than one RN at the same time with a single pump wavelength. Optimizing the filters TF, as shown in Figure 5-8, provides the possibility of multiple combinations between the filters of all RNs. Combining these optimizations with multi-pumping, results in a more flexible system, with the pump budgets better distributed by each pump signal source.

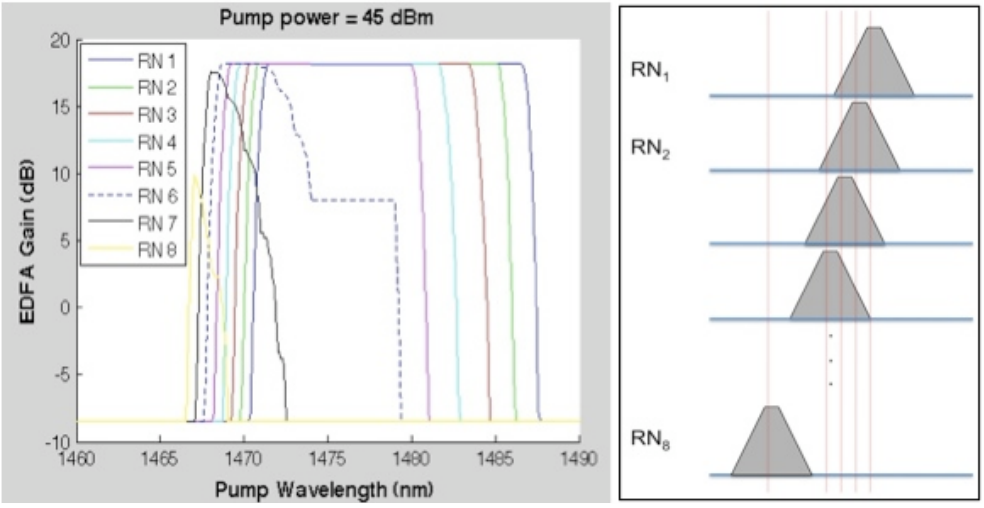


Figure 5-7 Simulation of filters disposition optimization

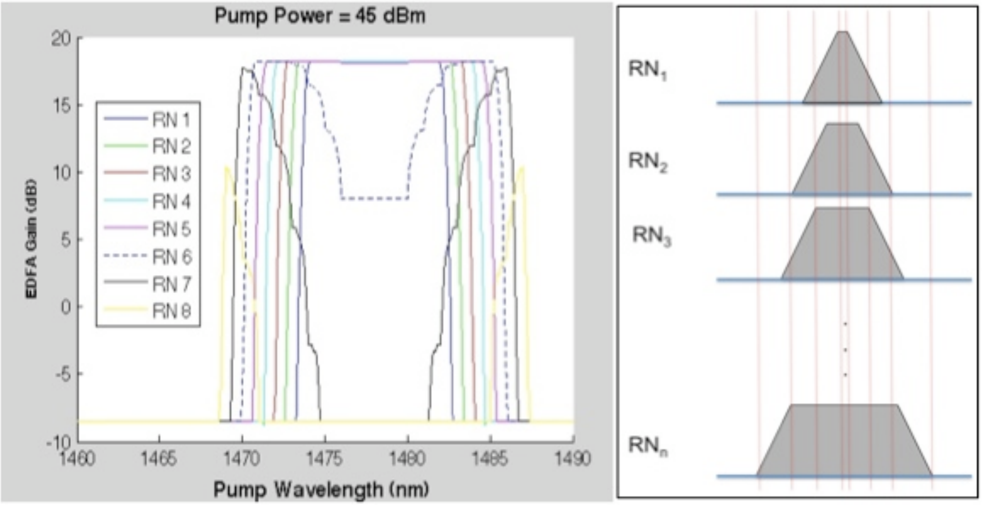
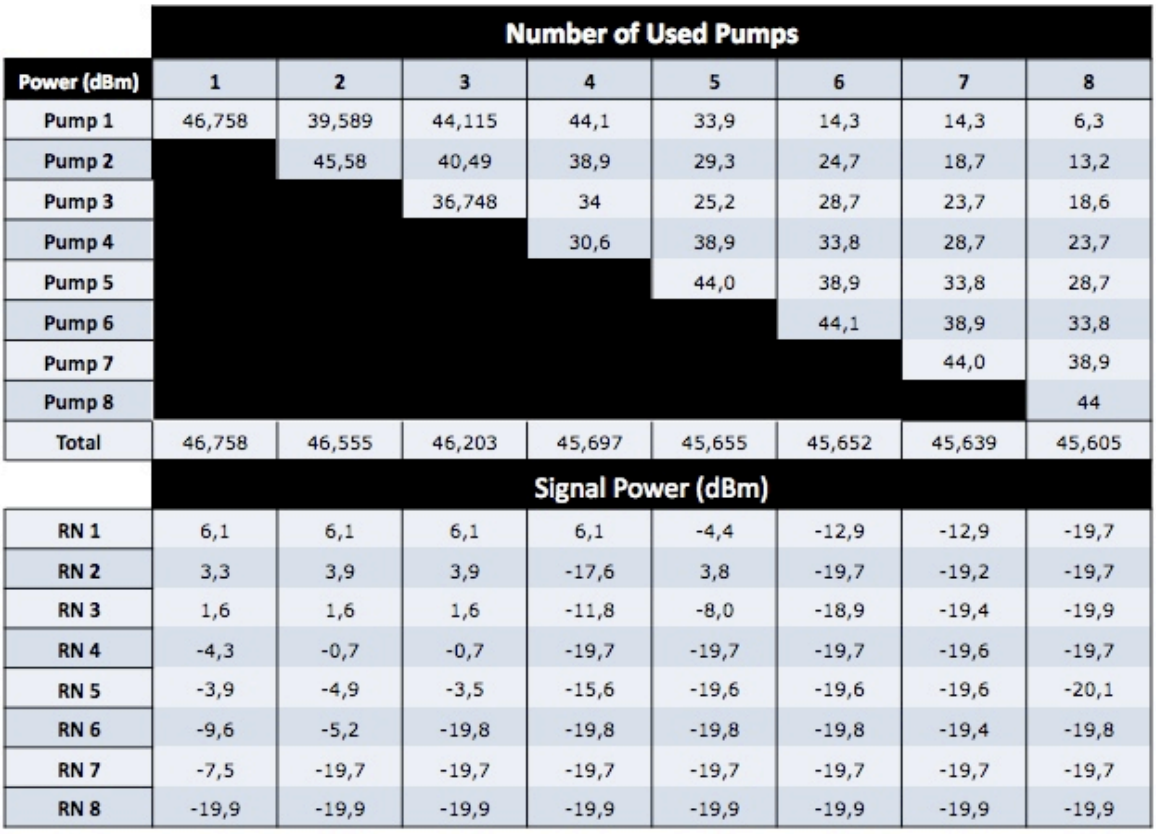


Figure 5-8 Simulation of filters transfer function optimization

It was used the simulation tool to simulate at the same time, all the previously talked optimizations, for the proposed network topology of Figure 5-3. The goal was to have in each receiver a signal with at least -20dBm of power, with the minimum pump power budget as possible.



	Number of Used Pumps							
Power (dBm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Pump 1	46,758	39,589	44,115	44,1	33,9	14,3	14,3	6,3
Pump 2		45,58	40,49	38,9	29,3	24,7	18,7	13,2
Pump 3			36,748	34	25,2	28,7	23,7	18,6
Pump 4				30,6	38,9	33,8	28,7	23,7
Pump 5					44,0	38,9	33,8	28,7
Pump 6						44,1	38,9	33,8
Pump 7							44,0	38,9
Pump 8								44
Total	46,758	46,555	46,203	45,697	45,655	45,652	45,639	45,605
	Signal Power (dBm)							
RN 1	6,1	6,1	6,1	6,1	-4,4	-12,9	-12,9	-19,7
RN 2	3,3	3,9	3,9	-17,6	3,8	-19,7	-19,2	-19,7
RN 3	1,6	1,6	1,6	-11,8	-8,0	-18,9	-19,4	-19,9
RN 4	-4,3	-0,7	-0,7	-19,7	-19,7	-19,7	-19,6	-19,7
RN 5	-3,9	-4,9	-3,5	-15,6	-19,6	-19,6	-19,6	-20,1
RN 6	-9,6	-5,2	-19,8	-19,8	-19,8	-19,8	-19,4	-19,8
RN 7	-7,5	-19,7	-19,7	-19,7	-19,7	-19,7	-19,7	-19,7
RN 8	-19,9	-19,9	-19,9	-19,9	-19,9	-19,9	-19,9	-19,9

Figure 5-9 Result of the simulation of a system, using different numbers of pump wavelengths

Figure 5-9 shows the results where are used 1 to 8 pump wavelengths. Analysing the results, we can conclude that using a higher number of pump wavelengths it is possible to reach the desired signal power in each RN, avoiding to have DFA operating in saturation. Other characteristic is the reduction of the total pump budgets. The difference between using one or eight pumps is more than 1 dB, which for the case, represent a reduction of more than 11 Watts of pump power. There is a big slope in the total pump value, between using three or four pumps. That can be explained by the fact that when are used four or more pumps, each pump only has to be shared in maximum by only two RNs. In Annex A is presented the filters forms for each of the solutions.

5.4. Method Validation

As there was not available material to verify on practice any optimized solution, it was used the program VPItransmissionMaker® to simulate one optimization reached by the developed simulation tool. It was simulated a four RNs system, with the same characteristics as the network used before. The filters TFs and disposition are represented in Figure 5-10.

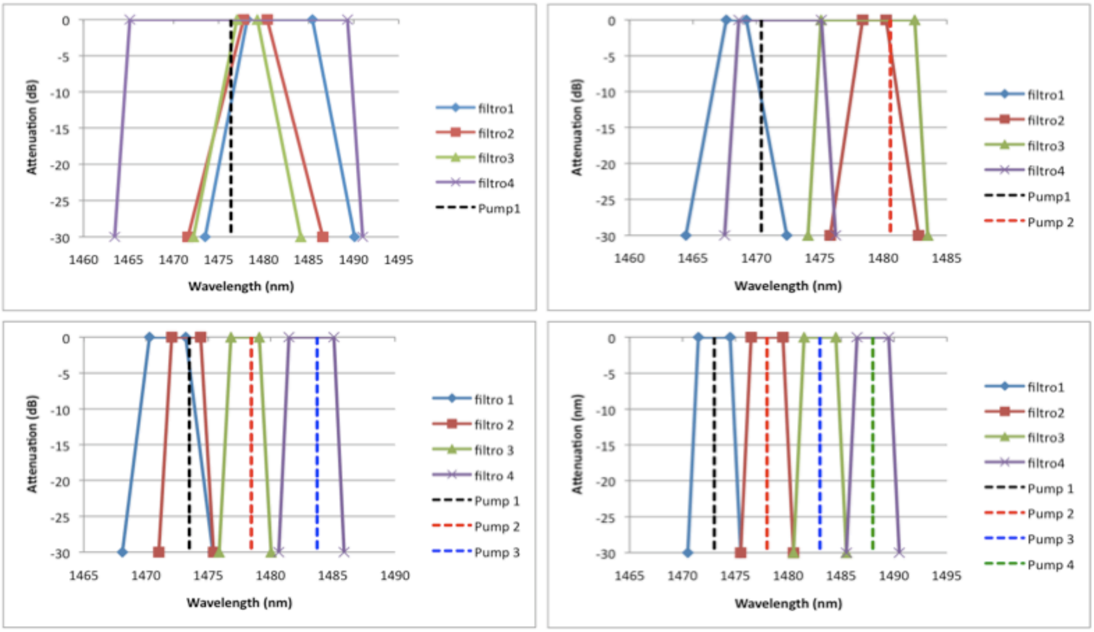


Figure 5-10 Optimized filters TFs and disposition for a four RNs system

In Figure 5-10 it is possible to observe how the simulation tool do the optimization of filters TF and disposition, and the pumps wavelength. When is used only one pump wavelength, it is possible to see that the pump is centred in the cut zone of all the RNs, except the last one. But, if the number of pump wavelengths is equal to the number of RNs, each pump wavelength is centered with each RN filter. In the other cases, the available pumps are shared by the RNs. The filters TFs, the pump wavelengths, and the pump powers for this optimization, are presented in Annex B.

All the four cases (one, two, three and four pump wavelengths), where simulated with VPItransmissionMaker®, and the comparison between the signal value at each receiver calculated by the simulation tool and the VPI simulations is presented in Figure 5-11. The schematic of the simulation is presented in figure 5-12.

	1 Pump		2 Pumps		3 Pumps		4 Pumps	
	Simulation Tool	VPI	Simulation Tool	VPI	Simulation Tool	VPI	Simulation Tool	VPI
RN1	-12,942	-12,213	-16,269	-18,11	-15,999	-25,822	-19,21	-21,77
RN2	-11,224	-15,21	-16,435	-18,655	-19,354	-18,094	-19,354	-21,182
RN3	-16,527	-19,5	-19,996	-23,408	-19,996	-22,73	-19,996	-21,323
RN4	-19,02	-23,252	-19,974	-22,168	-19,492	-20,529	-19,492	-21,339

Figure 5-11 Signal power at each receiver by the optimization tool and by the VPITransmissionMaker®

The results, although not ideal, are good. The differences are easily explained by some reasons. The most important one is that the algorithm assumes that the gain is always the optimum, whichever the pump wavelength, and in practice this is not real. Other possible reason is some error in the polynomial evaluation in the function *edf_calc()*.

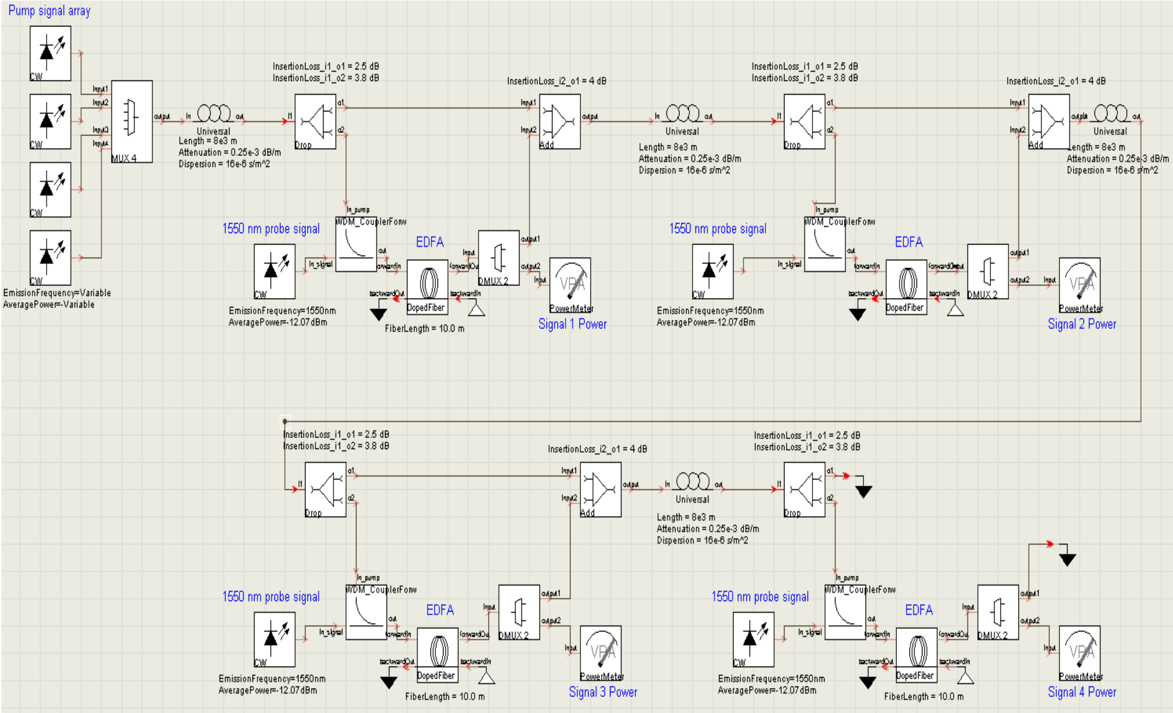


Figure 5-12 Schematic of the four RN system simulated with VPItransmissionMaker®

5.5. Conclusion

In this chapter it was presented a simulation tool of the proposed method, capable to optimize pump budgets for different scenarios. For that, the tool makes use of genetic algorithms, provided by the program Matlab®.

Using the developed tool, it were studied some optimizations for the proposed method, like the influence of the filters TF and disposition, and the number of used pump wavelengths. It stayed clear that these optimizations are fundamental for the method good behaviour. Optimizing the filters TF and disposition, it is possible to minimize the pump signal budgets, and arrange multiple optimization solutions. The use of multiple pump wavelengths, despite the cost associated to implement and maintain this kind of systems, result in a reduction of the required pump, and this is more evident if it is used a number of pump wavelengths higher that half of the number of RNs. Using multiple pump wavelengths, also allow to have a more accurate system, avoiding the necessity to have amplifiers working in saturation.

A validation of the simulation tool was preformed, using for that the program VPItransmissionMaker®. It was simulated one of the optimizations, reached by the simulation tool and the results were good. However, some improvements are required, and those are suggested for future work.

6. Conclusions and Future Work

6.1. Conclusions

The intention of this work was to achieve a solution to improve the reconfigurability and scalability of the new generation long reach optical networks. Thus, it was presented a new passive method to remotely control the pump signal supplied to the remotely optical pumped amplifiers implemented in those future optical networks.

It was also developed a simulation tool in Matlab®, capable to simulate the implementation of the proposed method in different scenarios. Using this tool, some studies about method optimization were performed. The results of these studies proved that the filters TFs shapes and disposition are very important to the method optimization. With these studies it was also concluded that the use of a higher number of pump signals results in more accurate systems.

It was performed a characterization in the laboratory of an EDFA. The presented method implies the tuning of the pumping source in a wide band. Typically, the doped amplifiers are pumped with a specific wavelength pump signal, for which the gain efficiency is higher. So, in this characterization it was study the gain behaviour when an EDFA is pumped with pump wavelengths different of the usually used. It was conclude that for a wide band between 1460-1490nm the gain was fairly the same, and the method take advantage of this property. It was also studied the gain characteristics for multi-pumping, with pumps inside the range talked before. It was concluded that the gain provided in this case it was almost the same as the gain provided by only one pump, which power is equal to the sum of the powers of the multiplexed pumps.

6.2. Future Work

The implementation of the method in practice requires the study of two fundamental components: tunable pump laser and optical filters. Future studies should be made about these two components, mostly in the filters ones because it is important to know how they can be optimized.

With the algorithm as it is now, it is possible to perform a fairly complete study and optimization for several situations. However, a lot of changes could be made to have even better results. Firstly, this algorithm is only capable to simulate and optimize trapezoidal filters. It would be interesting to simulate other types of filters forms besides the trapezoidal ones.

The method only simulates the gain effect in the signal, and does not take in account other linear and nonlinear effects, such as Raman. In case of Raman, since for DFA amplification is required relatively high levels of pump signal, Raman effects would add extra in line gain to the signal, consequently reducing the minimum pump signal budgets required for the system operate efficiently.

As seen previously in chapter 3.3.6 the EDFA gain for pump wavelengths around 1460-1490nm is almost constant, and the proposed method takes advantage of that. The developed algorithm assumes that the gain is equal whichever the pump signal wavelength. However, this is not completely true. So, if the algorithm to determine the signal gain, also has to take into consideration the pump wavelength and not only the pump power it would be a great improvement, being the results even more realistic.

Another change that could be made is the possibility of the model to directly calculate the signal losses, and not only the pump signal losses, dismissing by this the necessity of parallel calculations.

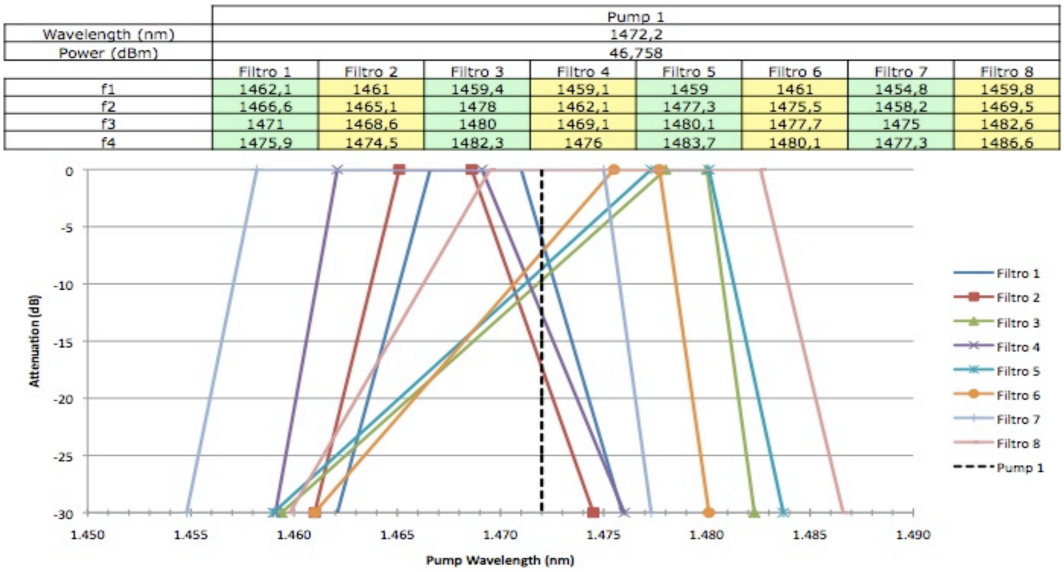
A good feature, which should be implemented, would be a more friendly user interface. As it is now, all the variables have to be inserted manually in the algorithm code, so it is still required to know very well how the code is structured in order to perform alterations and perform different scenarios.

Annexes

Annex A

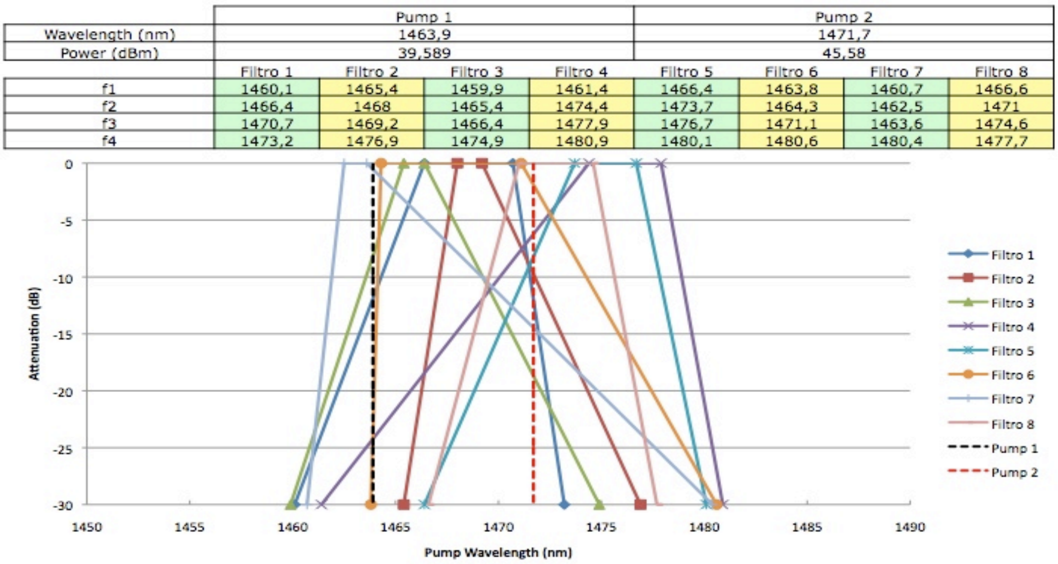
In this annex are presented the results of the simulation tool optimization for the eight RNs network talked in chapter 5-3. Here are schematized the filters disposition and TFs, and the respective pump wavelengths. In this optimization, it was simulated and optimized the cases where are used one to eight pumps. This annex allows to have a better idea how the simulation tool performs the optimizations.

1 Pump



	Pump 1							
Wavelength (nm)	1472,2							
Power (dBm)	46,758							
	Filtro 1	Filtro 2	Filtro 3	Filtro 4	Filtro 5	Filtro 6	Filtro 7	Filtro 8
f1	1462,1	1461	1459,4	1459,1	1459	1461	1454,8	1459,8
f2	1466,6	1465,1	1478	1462,1	1477,3	1475,5	1458,2	1469,5
f3	1471	1468,6	1480	1469,1	1480,1	1477,7	1475	1482,6
f4	1475,9	1474,5	1482,3	1476	1483,7	1480,1	1477,3	1486,6

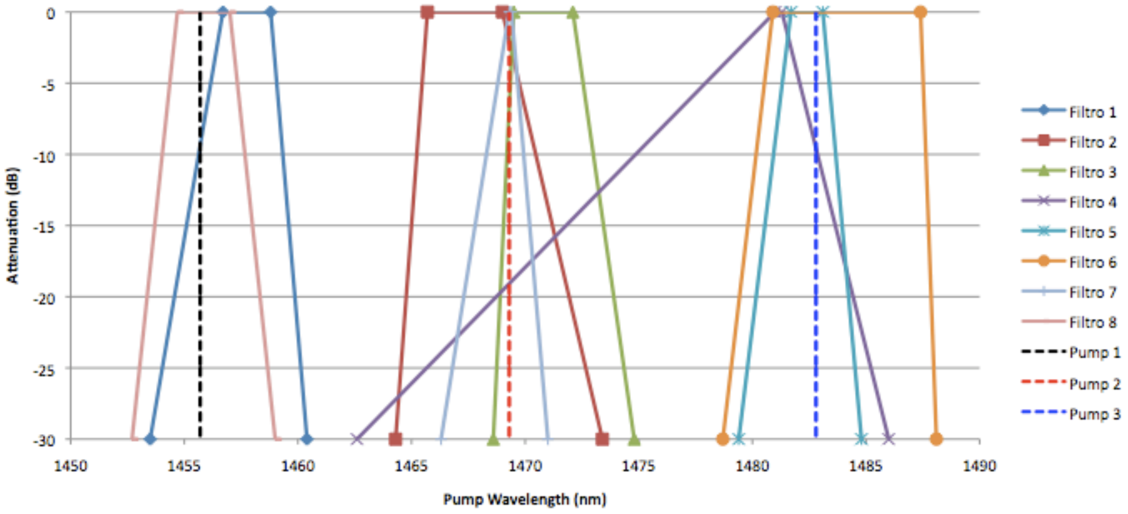
2 Pumps



	Pump 1				Pump 2			
Wavelength (nm)	1463,9				1471,7			
Power (dBm)	39,589				45,58			
	Filtro 1	Filtro 2	Filtro 3	Filtro 4	Filtro 5	Filtro 6	Filtro 7	Filtro 8
f1	1460,1	1465,4	1459,9	1461,4	1466,4	1463,8	1460,7	1466,6
f2	1466,4	1468	1465,4	1474,4	1473,7	1464,3	1462,5	1471
f3	1470,7	1469,2	1466,4	1477,9	1476,7	1471,1	1463,6	1474,6
f4	1473,2	1476,9	1474,9	1480,9	1480,1	1480,6	1480,4	1477,7

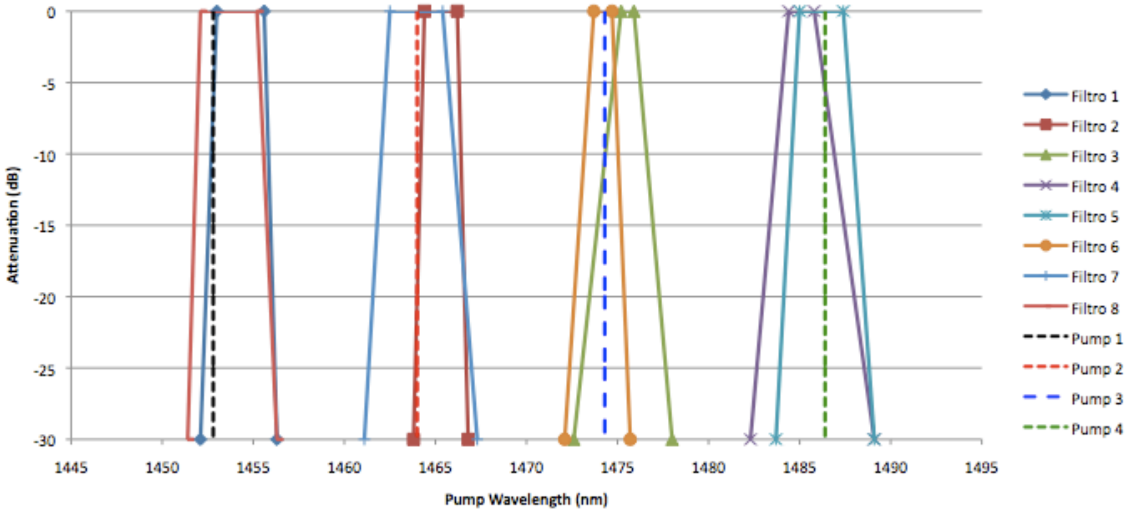
3 Pumps

	Pump 1			Pump 2			Pump 3	
Wavelength (nm)	1455,7			1469,3			1482,8	
Power (dBm)	44,12			40,49			36,75	
	Filtro 1	Filtro 2	Filtro 3	Filtro 4	Filtro 5	Filtro 6	Filtro 7	Filtro 8
f1	1453,5	1464,3	1468,6	1462,6	1479,4	1478,7	1466,3	1452,7
f2	1456,7	1465,7	1469,5	1481	1481,7	1480,9	1469,3	1454,7
f3	1458,8	1469	1472,1	1481,3	1483,1	1487,4	1469,4	1457
f4	1460,4	1473,4	1474,8	1486	1484,8	1488,1	1471	1459



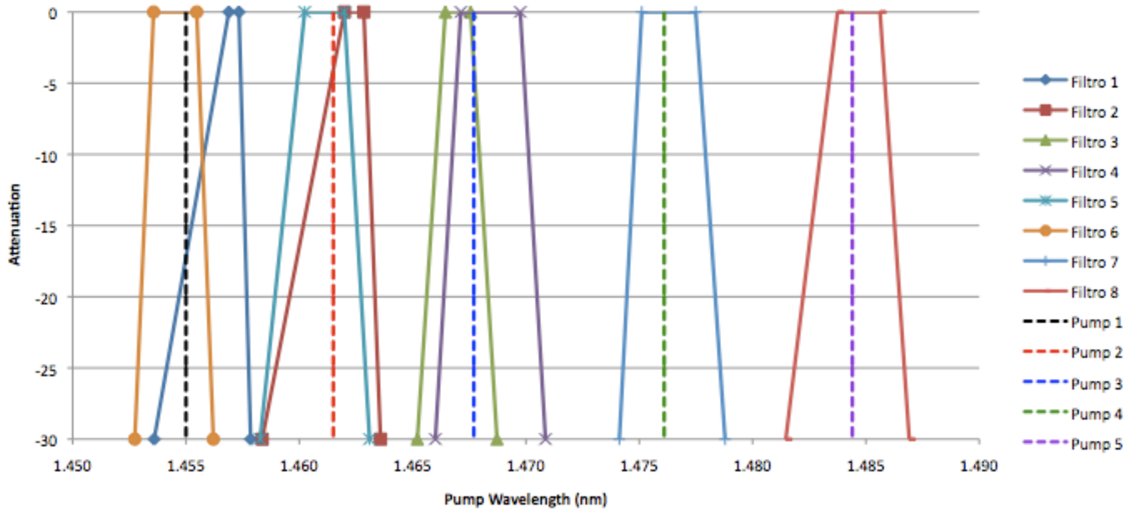
4 Pumps

	Pump 1		Pump 2		Pump 3		Pump 4	
Wavelength (nm)	1452,8		1464		1474,3		1486,4	
Power (dBm)	44,1		38,9		34		30,6	
	Filtro 1	Filtro 2	Filtro 3	Filtro 4	Filtro 5	Filtro 6	Filtro 7	Filtro 8
f1	1452,1	1463,8	1472,6	1482,3	1483,7	1472,1	1461,1	1451,4
f2	1453	1464,4	1475,2	1484,4	1485	1473,7	1462,5	1452,1
f3	1455,6	1466,2	1475,9	1485,8	1487,4	1474,7	1465,4	1455,2
f4	1456,3	1466,8	1478	1489,1	1489,1	1475,7	1467,3	1456,3



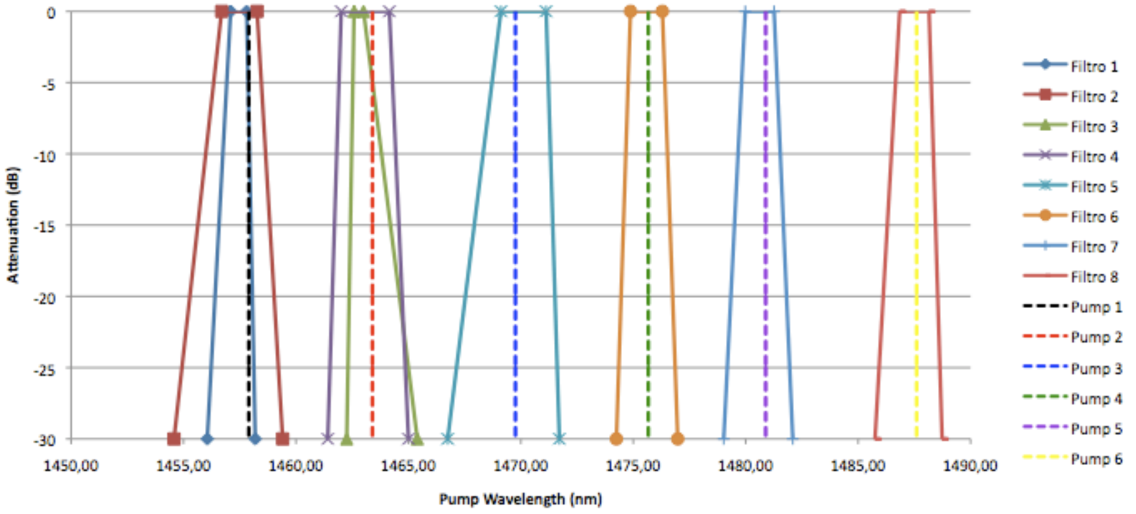
5 Pumps

	Pump 1		Pump 2		Pump 3		Pump 4	Pump 5
Wavelength (nm)	1455,0		1461,5		1467,7		1476,1	1484,4
Power (dBm)	33,9		29,3		25,2		38,9	44,0
	Filtro 1	Filtro 2	Filtro 3	Filtro 4	Filtro 5	Filtro 6	Filtro 7	Filtro 8
f1	1453,6	1458,4	1465,2	1466,0	1458,3	1452,7	1474,1	1481,5
f2	1456,9	1462,0	1466,4	1467,1	1460,2	1453,6	1475,1	1483,8
f3	1457,3	1462,8	1467,6	1469,7	1462,0	1455,5	1477,5	1485,6
f4	1457,9	1463,6	1468,7	1470,9	1463,1	1456,2	1478,8	1486,9



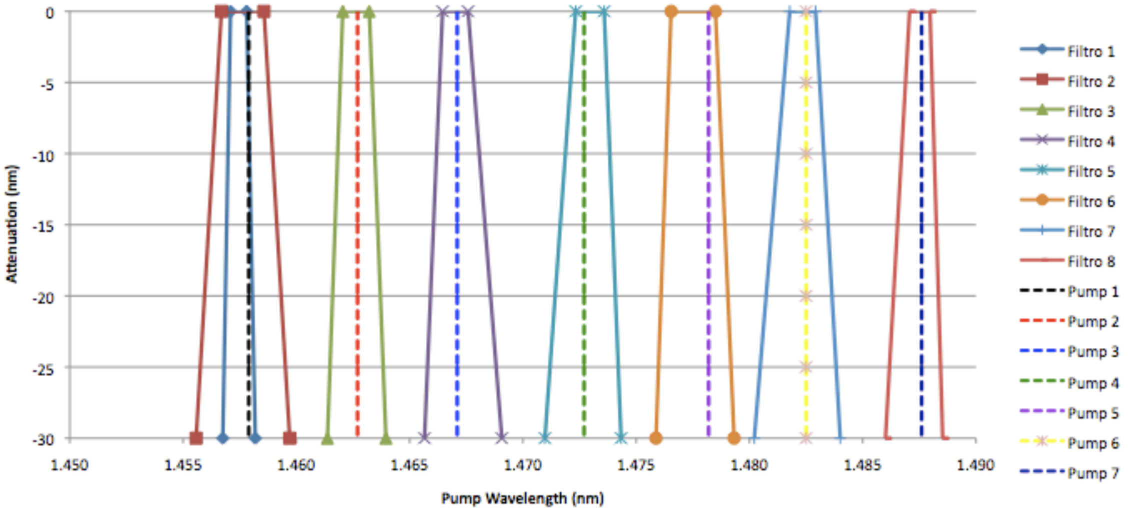
6 Pumps

	Pump 1		Pump 2		Pump 3	Pump 4	Pump 5	Pump 6
Wavelength (nm)	1457,9		1463,4		1469,76	1475,67	1480,89	1487,60
Power (dBm)	14,3		24,7		28,74	33,79	38,85	44,08
	Filtro 1	Filtro 2	Filtro 3	Filtro 4	Filtro 5	Filtro 6	Filtro 7	Filtro 8
f1	1456,05	1454,58	1462,26	1461,41	1466,75	1474,25	1479,02	1485,75
f2	1457,10	1456,69	1462,59	1462,01	1469,12	1474,88	1479,98	1486,85
f3	1457,80	1458,27	1463,00	1464,15	1471,12	1476,29	1481,26	1488,15
f4	1458,19	1459,41	1465,40	1465,00	1471,71	1476,98	1482,09	1488,73



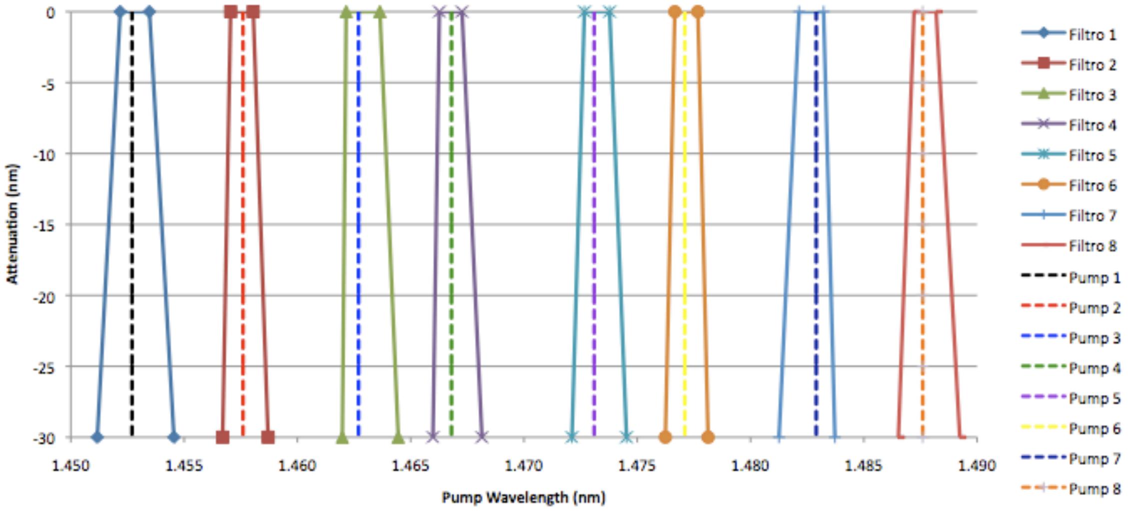
7 Pumps

	Pump 1		Pump 2	Pump 3	Pump 4	Pump 5	Pump 6	Pump 7
Wavelength (nm)	1457,9		1462,7	1467,1	1472,7	1478,2	1482,5	1487,6
Power (dBm)	14,3		18,66	23,70	28,74	33,84	38,89	44,05
	Filtro 1	Filtro 2	Filtro 3	Filtro 4	Filtro 5	Filtro 6	Filtro 7	Filtro 8
f1	1456,8	1455,6	1461,4	1465,7	1471,0	1475,9	1480,2	1486,0
f2	1457,1	1456,7	1462,0	1466,5	1472,3	1476,5	1481,8	1487,1
f3	1457,8	1458,6	1463,2	1467,6	1473,6	1478,5	1482,9	1488,0
f4	1458,2	1459,7	1464,0	1469,1	1474,3	1479,3	1484,0	1488,5



8 Pumps

	Pump 1	Pump 2	Pump 3	Pump 4	Pump 5	Pump 6	Pump 7	Pump 8
Wavelength (nm)	1452,7	1457,6	1462,7	1466,8	1473,1	1477,1	1482,9	1487,6
Power (dBm)	6,3	13,2	18,6	23,7	28,7	33,8	38,9	44
	Filtro 1	Filtro 2	Filtro 3	Filtro 4	Filtro 5	Filtro 6	Filtro 7	Filtro 8
f1	1451,2	1456,7	1462,0	1466,0	1472,1	1476,2	1481,3	1486,5
f2	1452,2	1457,1	1462,2	1466,3	1472,7	1476,7	1482,1	1487,2
f3	1453,5	1458,0	1463,6	1467,3	1473,8	1477,7	1483,2	1488,2
f4	1454,6	1458,7	1464,5	1468,1	1474,5	1478,1	1483,7	1489,2



Annex B

In this annex it is possible to observe the optimization results for the four RNs network simulated in chapter 5-4. These are complementary to the figure 5-11. These were the values that were used in VPI TransmissionMaker® in order to do the method validation.

1 Pump

	Pump 1			
Wavelength (nm)	1476,368			
Power (dBm)	22.569			
	Filter 1	Filter 2	Filter 3	Filter 4
f1	1473,502	1471,593	1472,207	1463,458
f2	1478,180	1477,769	1477,030	1465,144
f3	1485,420	1480,395	1479,294	1489,314
f4	1490,098	1486,570	1484,117	1490,999

2 Pumps

	Pump 1		**Pump 2**	
Wavelength (nm)	1470,389		1480,558	
Power (dBm)	20,592		16,321	
	Filter 1	Filter 2	Filter 3	Filter 4
f1	1464,444	1475,816	1474,069	1467,491
f2	1467,625	1478,369	1475,098	1468,614
f3	1469,217	1480,224	1482,472	1475,120
f4	1472,397	1482,777	1483,501	1476,243

3 Pumps

	Pump 1		Pump 2	Pump 3
Wavelength (nm)	1473,478		1478,453	1483,742
Power (dBm)	11,254		14,930	20,737
	Filter 1	Filter 2	Filter 3	Filter 4
f1	1468,102	1471,026	1475,872	1480,661
f2	1470,278	1472,064	1476,822	1481,476
f3	1473,188	1474,385	1479,093	1485,094
f4	1475,364	1475,423	1480,043	1485,909

4 Pumps

	Pump 1	Pump 2	Pump 3	Pump 4
Wavelength (nm)	1473	1478	1483	1488
Power (dBm)	4,715	9,902	15,292	20,488
	Filter 1	Filter 2	Filter 3	Filter 4
f1	1470,5	1475,5	1480,5	1485,5
f2	1471,5	1476,5	1481,5	1486,5
f3	1474,5	1479,5	1484,5	1489,5
f4	1475,5	1480,5	1485,5	1490,5

Bibliography

[1]. **Subir Bandyopadhyay, Ralf Klasing.** *Dissemination of information in optical networks: from technology to algorithms.* s.l. : Springer, 2007.

[2]. **Simmons, Jane.** *Optical Network Design and Planning.* s.l. : Springer, 2008.

[3]. **Kee Chaing Chua, Mohan Gurusamy, Yong Liu, Minh Hoang Phung.** *Quality of service in optical burst switched networks.* s.l. : Springer, 2006.

[4]. **Kartalopoulos, Stamatios V.** *Next Generation Intelligent Optical Networks: From Access to Backbone.* s.l. : Springer, 2007.

[5]. *Market Trends in Optical Networks - the Service and technology Impact.* **Ash, John.** s.l. : ICTON, 2008.

[6]. **Wang, Peng-Jun.** *Multichannel Optical Networks.* s.l. : Kluwer Academic Publishers, 2000.

[7]. **P. C.Becker, N. A. Olsson, J. R. Simpson.** *EDFA- Fundamentals and Technology.* s.l. : Academic Press, 1999.

[8]. **Group, Miniwatts Marketing.** *Internet World Stats.* [Online] opyright © 2001 - 2009, Miniwatts Marketing Group. www.internetworldstats.com.

[9]. **Mukherjee, Biswanath.** *Optical WDM Networks.* s.l. : Birkhäuser, 2006.

[10]. **Ramaswami, Rajiv.** *Optical Networks, A Practical Perspective 2nd Edition.* s.l. : Morgan Kaufhann, 2002.

[11]. **Agrawal, Govind P.** *Lightwave Technology, Telecomunication Systems.* s.l. : John Wiley & Sons, Inc., 2005.

[12]. *Wikipedia.* [Online] http://en.wikipedia.org/wiki/Fiber_to_the_x.

[13]. *FTTx: Current Status and the Future.* **Hutcheson, L.** Industry Analyst Forum.

[14]. **Keiser, Gerard.** *Optical Fiber Communications- Third edition.* s.l. : McGrawn-Hill, 2000.

[15]. **Agrawal, G.P.** *Fiber Optics Communication Systems.* 3rd. s.l. : John Wiley & Sons Inc., 2002.

[16]. **Powers, John.** *An Introdution to Fiber Optic Systems - 2nd Edition.*

[17]. **2008/2009, Alunos da disciplina Comunicações Ópticas de.** *COMUNICAÇÕES ÓPTICAS E APLICAÇÕES* . s.l. : António Teixeira e Mário Lima, 2009.

[18]. **Chang-Hee Lee, Wayne V Sorin, Byoung Yoon Kim.** Fiber to the Home Using a PON Infrastructure. *JLT.* 2006, Vol. 24, 12.

[19]. *Optical Networking Update.* **Green, P. E.** 1996, IEEE Journal on Selected Areas in Communications 14.

[20]. **Maier, Martin.** *Optical Switching Network.* s.l. : Cambridge, 2008.

[21]. **Keiser, Gerd.** *FTTX concepts and applications.* s.l. : John Wiley and Sons, 2006.

[22]. *2.5 Gb/s 16-Channel Bidirectional WDM Transmission System Using Bidirectional Erbium-Doped Fiber Amplifier Based on Spectrally Interleaved Synchronized Etalon Filters.* **Chung, C. H. Kim and Y. C.** IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 11, NO. 6.

[23]. *An Arrayed Waveguide Grating (AWG) for DWDM/CWDM application based on BCB polymer.* **Adam, I.** 2008, International Conference on Electronic Design.

[24]. *Coarse WDM:CDM:TDM Concept for Optical Packet Transmission in Metropolitan and Access Networks Supporting 400 Channels at 2.5 Gb:s Peak Rate.* **Pfeiffer, T.** 2000 , JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 18, NO. 12, .

[25]. **Prat, Josep.** *Next-Generation FTTH Passive Optical Network.* s.l. : Springer, 2008.

[26]. **Heliotis, Ioannis P. Chochliouros & George A.** *Optical Access Networks and Advanced Photonics.* s.l. : Information Science Reference, 2009.

[27]. **Lam, Cedric F.** *Passive Optical Network Principles and Practice.* s.l. : Elsevier, 2007.

[28]. **Jr., Paul E. Green.** *Fiber to the Home, the New Empowerment.* s.l. : Wiley, 2005.

[29]. **J. Segarra, V. Sales, J. Prat:.** An All-Optical Access-Metro Interface for Hybrid WDM/TDM PON Based on OBS. *J Lightw. Technol.* 2007, Vol. 25.

[30]. **Bock, C.** Hybrid WDM/TDM PON Using the AWG FSR and Featuring Centralized Light Generation and Dynamic Bandwidth Allocation. *Lightw. Technol.* 2005, Vol. 23.

[31]. **An, Fu-Tai.** SUCCESS: A Next-Generation Hybrid WDM/TDM Optical Access Network Architecture. *J. Lightw. Technol.* 2004, Vol. 22.

[32]. **Prat, Josep.** SARDANA Factsheet. *Sardana Web Site.* [Online] http://www.scribd.com/word/full/8773767?access_key=key-173somqvwwr471t2gqzm.

[33]. *Remotely Amplified SARDANA- Single-fibre-tree Advanced Ring-basedDense Access Network Architecture.* **Prat, JA Lázaro and V Polo and C Bock and M Omella and J.** 2006. ECOC 2006.

[34]. *High-density Optical Burst Switched Access Network combining WDM and TDM over a Passive Optical Infrastructure.* **Prat, Carlos Bock and Josep.** 2006. OFC 2006.

[35]. **Bock, C.** 2007, Vol. 25, no.6.

[36]. *Hybrid WDM Dual-Fiber-Ring with TDM Single-Fiber-Trees Passive Optical Network.* **Baptista, Albano.** 2008. CLME 2008.

[37]. *Reconfigurable Remote Node for Hybrid WDM Dual-Fiber-Ring with TDM Single-Fiber-Trees Passive Optical Network .* **Baptista, A.** 2008. ICTON.

[38]. *Tunable optical splitter technology.* **Shilin Xiao, Qingji Zeng, Jianxin Wang, Huandong Zhao, Hao Chi, Yun Wang, Fengqing Liu, Xu Zhu.** 2002.

[39]. *Optical access network using a self-latching variable splitter remotely powered through an optical fiber link .* **Hary Ramanitra, Philippe Chanclou, Jackie Etrillard.** 2007. JOE 2007.

[40]. *Multiwavelength Optical Networks: Architectures, Design and Control.* **Thomas E. Stern, Georgios Ellinas, Krishna Bala.** s.l. : Cambridge University Press, 2008.

[41]. **Baptista, Albano.** *Reconfigurable Remote Nodes for hybrid Passive Optical Networks - Tese de Mestrado .* s.l. : Universidade de Aveiro, 2008.

[42]. *Optical communications essentials.* **Keiser, Gerd.** s.l. : McGraw-Hill Professional, 2003.

[43]. **Corporation, Newport.** *www.newport.com.* [Online] http://www.newport.com/Variable-Ratio-Couplers/139699/1033/catalog.aspx.

[44]. *Polarized light in fiber optics.* **Collett, Edward.** s.l. : SPIE Press, 2003.

[45]. **Rocha, Professor Ferreira da.** *Slides das aulas práticas da disciplina de Redes Ópticas.* 2009.

[46]. **Yen, Chai.** *Applied photonics.* s.l. : Accademic Press, INC., 1994.

[47]. *OPTICAL SWITCHING TECHNOLOGY COMPARISON: OPTICAL MEMS VS. OTHER TECHNOLOGIES.* **Xiaohua Ma, Geng-Sheng.** s.l. : IEEE Optical Communications, 2003.

[48]. **André, Paulo.** *Componentes optoelectónicos para redes fotaicas de alto débito.* s.l. : Tese de doutoramento Universidade de Aveiro, 2002.

[49]. *Scalable and Multi-service Passive Optical Access Infrastructure Using Variable Optical Splitters.* **H Ramanitra, P Chanclou, Z Belfqih, M Moignard, H Le Bras, D Schumacher.** s.l. : OFC 2006, 2006.

[50]. **JDSU.** JDSU Products Web Site. *JDSU Web Site.* [Online] http://www.jdsu.com/products/optical-communications/products.html.

[51]. Comptron Web Site. [Online] http://www.compotron.co.uk/.

[52]. *Improved remote node configuration for passive ring-tree architectures.* **Baptista, A.** 2008. ECOC 2008.

[53]. *Power budget improvement for passive outside plant long reach high density access network using high bit rate RSOA-ONUs.* **Lazaro, J. A.** s.l. : ECOC 2007, 2007.

[54]. **Goldberg, David E.** *Genetic Algorithms- in Search, Optimization & Machine Learning.* s.l. : Addiso-Wesley, 1989.

[55]. **B. Neto, A. Teixeira, N. Wada, P. André.** Efficiente use of hybrid Genetic Algorithms in the gain optimization of distributed Raman amplifiers. *Optic Express.* 2007.

[56]. *Matlab users manual.*

[57]. *MEMS and MOEMS: technology and applications.* **Rai-Choudhury, P.** s.l. : SPIE Press, 2000.

[58]. **Niloy K. Dutta, Masahiko Fujiwara.** *WDM technologies: optical networks : volume III.* s.l. : Academic Press, 2004.

[59]. **Murata, Hiroshi.** *Handbook of optical fibers and cables.* s.l. : CRC Press, 1996.

[60]. *IP over WDM.* **Liu, Kevin H.** s.l. : John Wiley and Sons, 2002.

[61]. **Kartalopoulos, Stamatios V.** *Security of Information and Communication Networks.* s.l. : Wiley-IEEE, 2009.

[62]. *Optical access network using a self-latching variable splitter remotely powered through an optical fiber link.* **Hary Ramanitra, Philippe Chanclou, Jackie Etrillard.** 2007. JOE 2007.

[63]. *Optical switching.* **El-Bawab, Tarek S.** s.l. : Springer, 2006.

[64]. *The essential guide to telecommunications.* **Dodd, Annabel Z.** s.l. : Prentice Hall PTR, 2002.

[65]. **Dixit, Sudhir.** *IP over WDM: building the next-generation optical Internet.* s.l. : John Wiley and Sons, 2003.

[66]. **Alwayn, Vivek.** *Optical network design and implementation.* s.l. : Cisco Press, 2004.

[67]. **Albano Baptista, Nataša B. Pavlović, Paulo André, David Forin, Giorgio Tosi Beleffi, Jose A. Lázaro , Josep Prat , and António Teixeira.** Improved remote node configuration for passive ring-tree architectures . 2008.