Universidade de Aveiro Departamento de Electrónica,
2008 Telecomunicações e Informática (DETI)

Albano Manuel Cardoso Baptista

Nós Remotos reconfiguráveis para Redes Ópticas Passivas hibridas

Reconfigurable Remote Nodes for hybrid Passive Optical Networks

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

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o júri / the jury

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	Doutor Mário José Neves de Lima Professor Auxiliar Convidado da Universidade de Aveiro (Co-Orientador)

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palavras-chave

Comunicações ópticas, redes ópticas passivas de nova geração, anel de dupla fibra, árvore mono fibra, nó remoto, reconfigurabilidade, optimização de redes.

resumo

O presente documento tem por objectivo demonstrar, analisar e optimizar nós remotos passivos para redes ópticas passivas baseadas numa topologia de anel de dupla fibra com multiplexagem no comprimento de onda onde estão penduradas árvores mono fibra baseadas na multiplexagem no tempo. A rede 'Scalable Advanced Ring-based passive Dense Access Network Architecture' (SARDANA) baseada nesta topologia é apresentada e demonstrada.

Na rede SARDANA a interligação entre o anel e as árvores é realizada pelo intermédio de um nó especial denominado de nó remoto. Esse nó remoto é um elemento fundamental para o funcionamento, resiliência e escalabilidade da rede. Neste documento são apresentadas e comparadas diferentes topologias para a implementação desse nó remoto. É também apresentada a reconfigurabilidade remota desses mesmos nós remotos através de módulos de conversão energética e controlo, implementada nos nós remotos.

Um factor importante para a optimização dos nós remotos é a amplificação remota realizada por intermédio de fibras dopadas de érbio pelo que o seu estudo é também apresentado.

Finalmente é demonstrado um protótipo de um nó remotamente reconfigurado e eficiente.

keywords

Optical communications, new generation passive optical networks, double fiber ring, single fiber tree, remote node, reconfigurability, network optimization.

abstract

The objective of this document is to demonstrate, analyze and optimize remote nodes for passive optical networks based on double fiber ring multiplexed in wavelength connected to single fiber trees multiplexed in time. The network 'Scalable Advanced Ring-based passive Dense Access Network Architecture' (SARDANA) based on this topology is presented and demonstrated.

In the SARDANA network the interconnection between the ring and the trees is done by means of a special node, the remote node. This node is a fundamental element to the operation, resiliency and scalability of the network. This document presents and compares different topologies to the implementation of the remote node. Remotely reconfigurability of the remote nodes is also demonstrated by means of optical conversion and control modules.

An important factor to the optimization of the remote nodes is the remote amplification done by means of erbium doped fibers being presented the analysis of the amplifier.

Finally is demonstrated a prototype of a node remotely reconfigured and efficient.

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List of Acronyms

APON	Asynchronous Passive Optical Network
ASE	Amplifier Spontaneous Emission
ATDM	Asynchronous Time Division Multiplexing
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
BPON	Broadband Passive Optical Network
CAPEX	Capital Expenditure
CO	Central Office
CSMA-CD	Carrier Sense Multiple Access – Collision Detection
CWDM	Coarse Wavelength Division Multiplexing
DBA	Distributed Bandwidth Allocation
DCF	Dispersion Compensation Fiber
DS	Downstream Signal
DSF	Dispersion Shifted Fiber
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
EDF	Erbium Doped Fiber
E-PON	Ethernet Passive Optical Network
FTTH	Fiber to the Home
FTTP	Fiber to the Premise
FWM	Four Wave Mixing

GBA	Geographic Bandwidth Allocation
G-PON	Gigabit Passive Optical Network
GVD	Group Velocity Dispersion
IL	Insertion Loss
IM	Intensity Modulation
IP	Internet Protocol
IPTV	Internet Protocol Television
ISP	Internet Service Provider
LAN	Local Area Network
MAC	Media Access Control
MAN	Metropolitan Area Network
MMF	Multi Mode Fiber
NF	Noise Figure
NG-PON	Next Generation Passive Optical Network
NOS	Non Optical Switching
OADM	Optical Add&Drop Multiplexer
OEO	Optic-Eletric-Optic
OLT	Optical Line Terminal
ONT	Optical Network Termination
ONU	Optical Network Unit
OPEX	Operational Expenditure
OPS	Optical Packet Switching
OS	Optical Switching
OSNR	Optical Signal to Noise Ratio
OXC	Optical Cross Connect
PB	Power Budget

PON	Passive Optical Network
QoS	Quality of Service
RB	Rayleigh Backscattering
REC	Reconfigurable
RN	Remote Node
ROADM	Reconfigurable Optical Add&Drop Multiplexer
RSOA	Reflective Semiconductor Optical Amplifier
SARDANA	Scalable Advanced Ring based Passive Dense Access Network Architecture
SMF	Single Mode Fiber
SOA	Semiconductor Optical Amplifier
TD	Tunable Drop
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
US	Upstream Signal
WAN	World Area Network
WDM	Wavelength Division Multiplexer
WDMA	Wavelength Division Multiple Access
XPM	Cross Phase Modulation

List of Symbols

$^4I_{11/2}$	Pump Band
$^4I_{13/2}$	Metastable Band
$^4I_{15/2}$	Ground State Band
B_e	Electrical Filter Bandwidth
Bo	Optical Filter Bandwidth
C	Constant fiber scattering depending on constituents of fiber core
Δv	Resolution Bandwidth of the Optical Spectrum Analyzer
E_0	Ground State Band Energy
E_1	Metastable Band Energy
E_2	Pump Band Energy
Er^{3+}	Erbium Ion
f_{DRS}	Fraction of signal power double Rayleigh Scattered
Fn	Noise Figure
G	Signal Gain
G(z)	Raman Gain
h	Planck Constant
K	Users splitting ratio
L	Erbium Doped Fiber Length
L_{EX}	Coupling excess losses
L_S	Fiber losses, Insertion loss and Equipment filtering
L_T	Total losses
M	Number of wavelenghts

N	Number of Remote Nodes
$\mathbf{N_1}$	Population Density in Ground State Band
$\mathbf{N_2}$	Population Density in Metastable Band
$\mathbf{N_{shot}}$	Shot Noise
$\mathbf{n_{sp}}$	Spontaneous Emission factor
$\mathbf{N_{SP\text{-}SP}}$	Spontaneous-Spontaneous Noise
$\mathbf{N_{S\text{-}SP}}$	Signal to Spontaneous Noise Power
$\mathbf{P_0}$	Initial Power Launched in the fiber
$\mathbf{P_{ASE}}$	Amplified Spontaneous Emission Optical Power
$\mathbf{P_{in}}$	Input Power of Optical Signal
$\mathbf{P_p}$	Input pump power
$\mathbf{P_p^{sat}}$	Saturation pump power
$\mathbf{P_s}$	Upstream signal power
R	Photodetector Responsivity
$\mathbf{r_S}$	Rayleigh Scattering Coefficient
S	Recapture coefficient
U	Number of users
v	Frequency
x	Couling drop factor
y	Couling pass factor
z	Distance
$\boldsymbol{\alpha}$	Attenuation coefficient
$\boldsymbol{\alpha_R}$	Scattering Losses
$\boldsymbol{\alpha_s}$	Scattering coefficient
$\boldsymbol{\Gamma_s}$	Confinement Factor
$\boldsymbol{\lambda}$	Signal wavelength

μ	Inversion Population factor
ρ_{ASE}	Amplified Spontaneous Emission spectral density
σ^2_{RB}	Variance of detected Rayleigh Backscattering
σ^2_{RB-RB}	Variance of the interference of the RB noise with itself
σ^2_{SIG-RB}	Variance of the signal RB interference
σ^2_{T}	Variance of the thermal noise
σ^a_s	Absorption Cross Section
σ^e_s	Emission Cross Section

"Every day you may make progress. Every step may be fruitful. Yet there will stretch out before you an ever-lengthening, ever-ascending, ever-improving path. You know you will never get to the end of the journey. But this, so far from discouraging, only adds to the joy and glory of the climb"

Sir Winston Churchill,
British politician (1874 - 1965)

Chapter 1. Introduction

1.1. Context

Since the ancient times that the principal need of the human kind is to communicate transmitting information from one place to the other. There was a constant motivation to improve the fidelity, increase the data rate and increase the total transmission distance. One of the first related ancestral communications was made by means of fire signals by the Greeks in the 8th century B.C. used to send alarms, demanding help and announcing some special events [Aschoff, 1977]. Until the 19th century A.C. communications provide very low information and were based just on optics and acoustic.

The invention of the telegraph by Samuel Morse in 1838 created a new era of communications, the Electric Era *[Busignied, 1972]*. The Morse code was the most important coding technique used by the telegraph. It was able to communicate 10b/s of electric pulses in a digital scheme through intermediate stations until 1000km *[Jones, 1852]*. Later, in the year of 1876, the telephone was invented by Bell, being the dominant communication system for about hundred years *[Bell, 1876]*. The telephone made possible to communicate analog signals varying continuously the electric current. The development of the telephone leads to the use of coaxial cables instead of the wired pair, increasing the total capacity. The first implemented coaxial cable, in 1940, was a 3 MHz system able to transport until 300 voice channels or a television channel. The amount of information that can be transmitted is directly related to the frequency of the carrier, so, increasing the carrier frequency theoretically increases the available transmission bandwidth. This increase of the frequency leads to the birth of radio, television, radar and microwave using a larger portion of the electromagnetic spectrum. The limitations of the coaxial cables operating at 10 MHz resulted on the implementation of microwaves with carrier frequencies of 1-10 GHz. The first coaxial cable operating with microwaves in 1948 was able to communicate 100 Mb/s at a carrier frequency of 4 GHz. Almost 30 years after, in 1975, an advanced coaxial cable system communicated at 274Mb/s but repeaters were necessary each km, being the communication links relatively expensive *[Agrawal, 2002]*.

In 1960, with the development of a coherent optical source, the laser *[Maiman, 1960]*, and in 1966 a suitable transmission medium, the optical fiber *[Kao, 1966]*, made possible the development of optical communication with higher transmission rate and higher distance reach *[Willner, 2000]*. The first optical fibers, in the sixties, had 1000dB/km of losses, being this value decreased to about 20dB/km in the seventies *[Kapron, 1970]*. The optical communication systems by means of optical fibers had an evolution of five generations *[Kogelnik, 2000]*. In the first generation, in 1980, a communication of 45Mb/s was possible by means of a carrier at 800nm requiring repeaters each 10km *[Sanferrare, 1987]*. The develop of new optical fibers in 1987 providing less than 1dB/km of losses at 1300nm and lower dispersion than previous wavelength carrier made possible the second generation, achieving 1.7Gb/s in a MMF with repeaters each 50km *[Globe, 1980]*. In the third generation, the optical carrier has a wavelength of 1550nm, where the new fibers developed in 1990 had a low loss of 0,2dB/km. For this spectrum the distortion was higher than the previous generation, but it was compensated with DSF and limiting the laser spectrum, achieving communications at 10Gb/s with regenerators spaced by 60-70km *[Nakagawa, 1995]*. In 1992, the implementation of a efficient amplifier, the EDFA and the use of WDM signals made possible the fourth generation, where regenerators spaced by 60-80km made possible to reach distances as high as 35000Km or data rates as high as 10Tb/s in 2001 *[Marra, 2001]*. The current generation, the fifth, is concerned with the extension to more than 1000 WDM channels to the band C, L and S, using Raman amplification and a new generation dry fiber with low attenuation for 1300 to 1650nm *[Thomas, 2000]*.

Early optical communications links were used for trunking telephone lines aggregated in TDM. In 1990, an tremendous demand on communication networks for services such as database, shopping, remote education, telemedicine, video on demand, video conference among others and a rapid proliferation of personal computers with increased storage capacity, processing capabilities and provided with internet, made possible a migration of the services of telecommunications companies worldwide to the optical networks systems *[Driel, 1997],[Hill, 1997],[Holler 1998],[Stone, 1999]*.

1.2. Motivation

There is a growing need for bandwidth driven for the demand from residential and business users. It causes a demand from the scientific community for infrastructure that support large scale data transport and processing *[Ash, 2008]*.

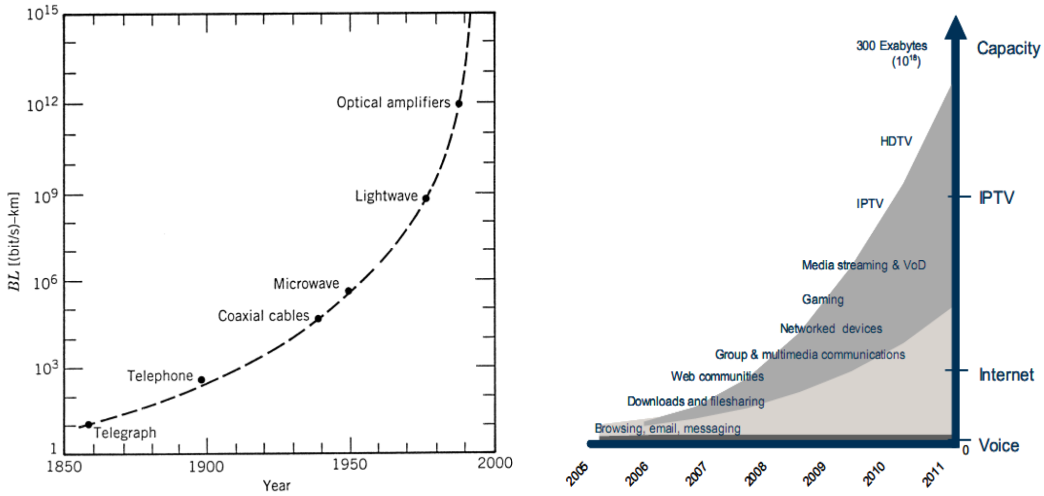


Figure 1.1: Evolution of the Optical Networks capacity in long of the years *[Ash, 2008]*.

The figure 1.1 represents the evolution of the product bandwidth and length of the link in function of the Year. It demonstrates clearly an exponential increase. Telecomm carriers are also quite aware that they need to deal with a continuous and exponential grow of services requiring large bandwidth and that the transportation of data must be provided in a more efficient manner. These bandwidth requirements are mainly driven by IP traffic which now include IP video flavors that have migrated from the initial closed IPTV to a more open internet based model and intensive transaction web 2.0

applications *[Cvijetic, 2007]*. The residential broadband IP rates are increasing from 1-6Mb/s to 25-30Mb/s over copper pairs, or up to 100Mb/s via FTTH. The current and future increase in number of end users requiring these data rates in access area will eventually result in a one or two order of magnitude increase in aggregate bandwidth demand for the ISP.

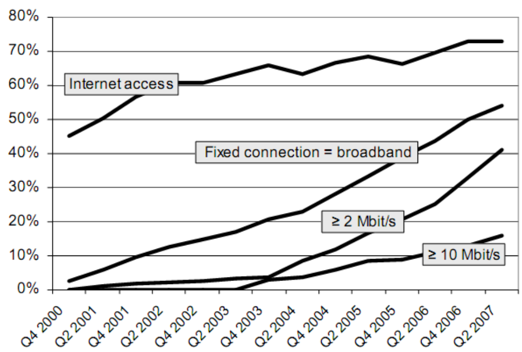


Figure 1.2: Internet and broadband penetration in Sweden per household *[Forzati, 2008]*

Figure 1.2 presents the Internet access and the broadband penetration in Sweden. It demonstrates that in last years the Internet access tends to stabilize although the broadband access as video on demand is increasing considerably together with the high speed data rates connection.

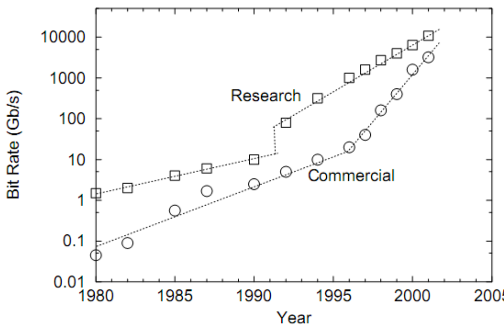


Figure 1.3: Increase in the capacity of lightwave system after 1980 *[Agrawal, 2002]*.

The figure 1.3 shows the comparison between the research data rate per link and the required commercially. It can be seen an approximation of the both lines representing a saturation of the fiber links and the need to improve for higher data rates links and networks. With the constant grow of bandwidth demand it is necessary to develop new optical networks designs able to support the already deployed equipment and providing lower costs, reduced operation efforts, scalability and adaptation to the future services and applications requirements in terms of bandwidth and QoS.

1.3. Structure and Objectives

This document is divided in eight chapters all related to Optical Networks, its different architectures, the optical components, the SARDANA network and practical implementations.

In this first chapter is presented the description of the context of this work and its main proposed objectives together with the chapter division and the studied topics.

Second chapter describes more extensively the optical networks, the evolution along the years, the different architectures and different ways to provide fiber to the user.

The third chapter presents different Next Generation ring based optical networks comparing the architectures. It aims providing the reader with the actual state of art of developed networks based on ring topology as an introduction to a clearly view of the SARDANA network.

The fourth chapter presents the Scalable Advanced Ring Based Passive Dense Access Network Architecture (SARDANA). It presents a brief introduction to the main components of the network as the Central Office (CO), the Optical Network Unit (ONU), the Remote Node (RN) and the fiber structures.

The fifth chapter presents the Remote Node (RN) of the SARDANA network that is the main subject of the whole document. As the RN requires optical pump power to operate is crucial to optimize and reach a high efficient topology. Different topologies are presented and improved in order to increase the efficiency of the network

The sixth chapter presents the main components that required analysis and potentially improvement. The first component is the Erbium Doped Fiber (EDF) responsible for the provision of gain to the data signals requiring an intensive study to optimize length, concentration, pump power and control. The second component is the control module responsible to adjust the optical pump power supplied to the EDF and the amplification/non-amplification selection.

The seventh chapter presents a comparison between the different RNs topologies in terms of required pump power and number of operational RNs for different ring lengths and network's resiliency modes.

The last chapter, the eight, presents the conclusion of the document and work performed and suggests future work in order to improve even more the total efficiency of the network.

1.4. Main Contributions

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

- Understanding the main aspects of the SARDANA network and the main objectives and impairments.

- Understanding the evolution of the Remote Nodes topologies and implementation of different approaches to increase significantly the total efficiency of the network. This aimed reducing the total pump power produced for the Central Office, increase the scalability and provide full resiliency.

- Providing an extensive analysis of the Erbium Doped Fibers amplification by means of analysis of previous documentation, simulating and implementing experimentally tests in order to select the higher efficiency EDFA parameters.

Besides this final work, other documents were done and submitted for the proceedings of some conferences:

- 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", ECOC 2008, Brussels, Belgium, 2008.

- Albano Baptista, Nataša B. Pavlović, Paulo André, David Forin , Giorgio Tosi Beleffi, Jose A. Lázaro, Josep Prat and António Teixeira, “Reconfigurable Remote Node for Hybrid WDM Dual-Fiber-Ring with TDM Single-Fiber-Trees Passive Optical Network”, ICTON 2008, Athens, Greece, 2008.

- Albano Baptista, Nataša B. Pavlović, Paulo André, David Forin, Giorgio Tosi Beleffi, Jose A. Lázaro, Josep Prat and António Teixeira, “Hybrid WDM Dual-Fiber-Ring with TDM Single-Fiber-Trees Passive Optical Network”, CLME 2008, Maputo, Mozambique, 2008.

- Albano Baptista, M. Lima, J. Lázaro, J. Prat, G. Tosi. Beleffi, D. Forin, A. Teixeira, “Remotely Reconfigurable Remote Node for Hybrid Ring-Tree Passive Optical Network”, OFC 2009, San Diego, USA, 2009.

- Albano Baptista, M. Ferreira, A. Quintas, M. Lima, A. Teixeira, “Remote Nodes topologies for hybrid WDM-ring TDM-tree passive optical networks”, Revista do Departamento de Electrónica e Telecomunicações da Universidade de Aveiro, Aveiro, 2008.

Chapter 2. Optical Networks

2.1. Evolution of Optical Networks

The evolution of the optical networks along the years can be divided into three steps, opaque, managed reach and transparent as demonstrated in figure 2.1.

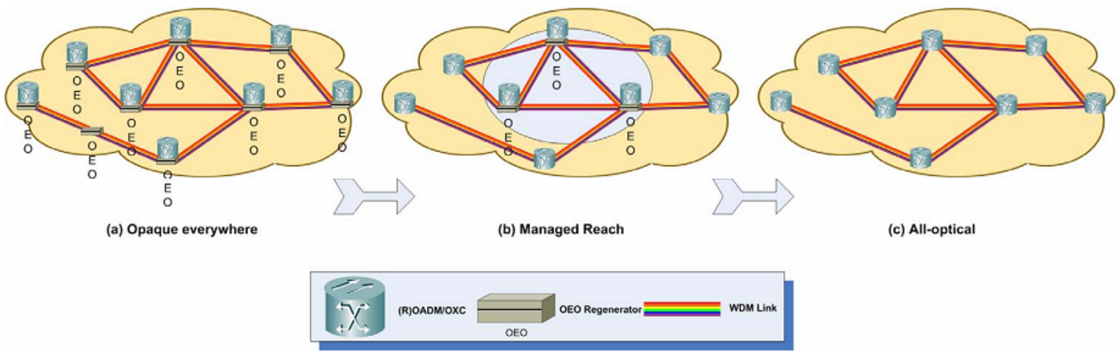


Figure 2.1: Optical Networks Evolution *[Ioannis, 2008]*.

The opaque networks are characterized by the use of Optical Electrical Optical (OEO) conversion enabling the optical signal to reach longer distances. However, the amplification of optical signals by means of OEO requires a high number of regenerators in the network (one per operational wavelength) and the conversion is dependent of the connection bit rate and modulation format, leading to very high costs. In order to reduce these costs, transparent networks were proposed. In these networks, the signal is transported end to end fully optically, without any OEO conversion. The propagation of a signal through a transparent network suffers the impact of a variety of degradation phenomenons that are introduced by different types of signal distortions as GVD, ASE, FWM, XPM, crosstalk, and they get accumulated along the path limiting the system reach and the overall network performance being regeneration necessary in optical domain. All optical regenerators are being developed and are not still commercially available in large scale *[Agrawal, 2002]*. Managed reach approach has been proposed as a compromise between transparent networks and opaque networks as a better approach. In this approach, regeneration is implemented selective at specific network locations keeping the quality of the transmitted signals acceptable from the source until the destination point. The number of regenerators is lower but complex management and monitoring of the signal quality is introduced. Realization of a fully automated and dynamically transparent optical network is difficult to achieve but extremely desirable due to the expected cost and performance benefits *[Wagner, 2000]*.

The improvement of network resources must have in consideration the increasing demand of bandwidth (dedicated and symmetric), subscriber's environment and economical aspects being most critical in the access part of the networks. Improving the reliability performance by duplication of the network resources implementing extra fibers can be too expensive. Future objective of development and implementation of networks will be the migration towards minimizing the CAPEX and OPEX during the access network lifetime *[Chrissan, 2004]*.

2.2. Optical Network Architectures

Single mode fiber can provide almost unlimited transmission bandwidth over extremely long distances being the future end goal to provide optical fiber to each customer premise or home. Fiber to the home (FTTH) can be divided into two main categories according to the fiber distribution as point to point or point to multipoint. In point to point architecture based on fibers, the number of fibers is equal to the number of subscribers being extremely expensive to install and handle. In point to multipoint architecture, many subscribers share one fiber line through a special node, the RN that performs active switching or passive power splitting or wavelength mux/demux functions. *[Makinow, 1997]*.

Point to Point links

The simplest solution to implement fiber connection between the ISP and the user is implementing point to point links. It can have distance reach of less than 1 Km to thousands of Kms. Point to point links are implemented in the transatlantic systems due to the low loss and the large bandwidth *[Agrawal, 2002]*. For fiber links with distances higher from 20-100km it is necessary to compensate the fiber losses depending on the operation wavelength due to the signal being too weak.

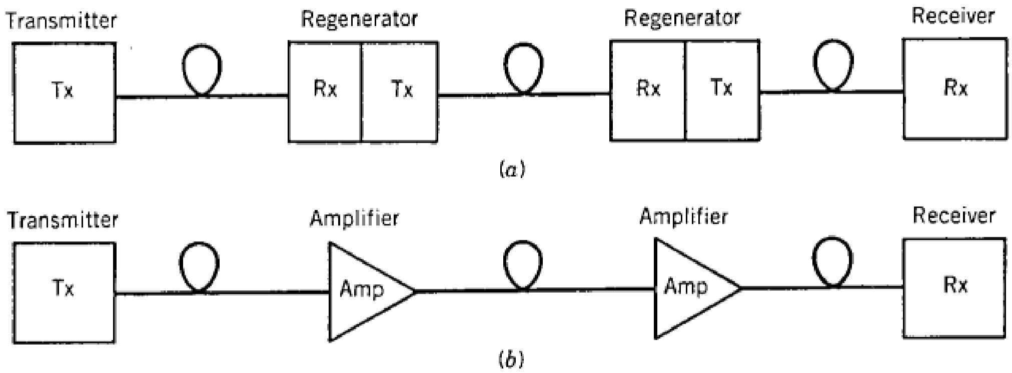


Figure 2.2: Point to point fiber links with periodic loss compensation through (a) regenerators and (b) optical amplifiers *[Agrawal, 2002].*

The figure 2.2 presents the OEO conversion and amplification in point to point links and the regeneration made by optical amplifiers that was introduced in the nineties. The introduction of optical amplifiers such as SOA or EDFA has revolutionized the optical fiber communication system amplifying WDM transmission with almost no complexity. Optical point to point links can now reach more than 3000Km with no regeneration with a bandwidth distance product as high as 100Tb/s*Km *[Agrawal, 2002]*. Despite of the simplicity to provide FTTH due to the almost unlimited bandwidth, it is not considered the best solution due to the required large number of fibers, connectors, splices, the installation costs and maintenance.

Point to Multipoint links

The point to point architecture present some disadvantages: the total resources of the fiber are not fully used and each link requires an independent laser on the transmitter. To face these impairments point to multipoint architectures are preferred. In this architecture the data traffic present in a main fiber is used and shared for several hundreds of users. There are four distinct topologies to implement point to multipoint systems: Hub, Bus, Ring and Star presented in figure 2.3.

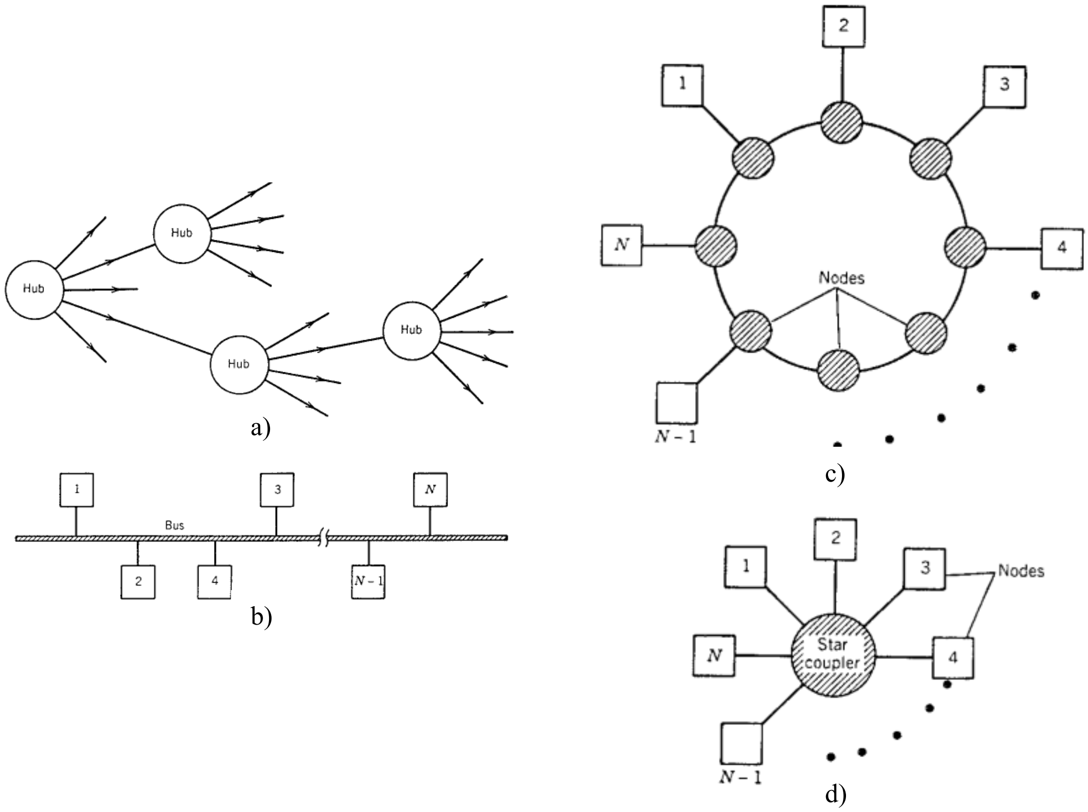


Figure 2.3: (a) Hub topology, (b) bus topology, (c) Ring topology and (c) star topology *[Agrawal, 2002].*

Hub topology

In a Hub topology, the data channel distribution takes place at central locations. Several offices can share a single fiber from the main hub, increasing the total amount of data required by a single hub office. The main problem present on this kind of topology is the reliability in case of malfunction or fiber cut since it can affect a large portion of the network. To reduce this problem extra links can be implemented to prevent against fiber cut, but reducing the total efficiency of the network *[Ghani, 2002]*.

Bus Topology

In a Bus topology, a single fiber carry multichannel optical signal and the distribution is done by using optical taps, splitting a part of the total optical power present in the fiber to each subscriber. It is more difficult to implement than a coaxial bus. One limitation is the increase of the signal loss as the number of users and taps increase, limiting strongly the number of users served by a single optical bus. The implementation of optical amplifiers boosting periodically on the bus, increases the number of subscribers compensating the losses as long as the signal quality remains acceptable. An Ethernet protocol based on a CSMA-CD can provide speeds up to 1Gb/s *[Green, 1996]*.

Ring topology

In a ring topology approach, consecutive nodes are connected by point to point links to form a closed ring. Each of those nodes is able to transmit and receive data using a fiber pair. The nodes listen a predefined bit pattern to recognize its own address and receive the data and transmit by appending the data to an empty token. It is designed to provide backbone services such as interconnection between LANs with lower speed or mainframe computers *[Ross, 1989]*.

Star topology

The last topology is the star where all nodes are connected through point to point links to a central node called a hub. For an active star configuration, all incoming optical signals are converted to electrical domain and then distributed to individual node transmitters. In case of being passive, distribution takes place in the optical domain by means of optical couplers. The power required per each node depends on the number of users that the RN feeds *[Ross, 1989]*.

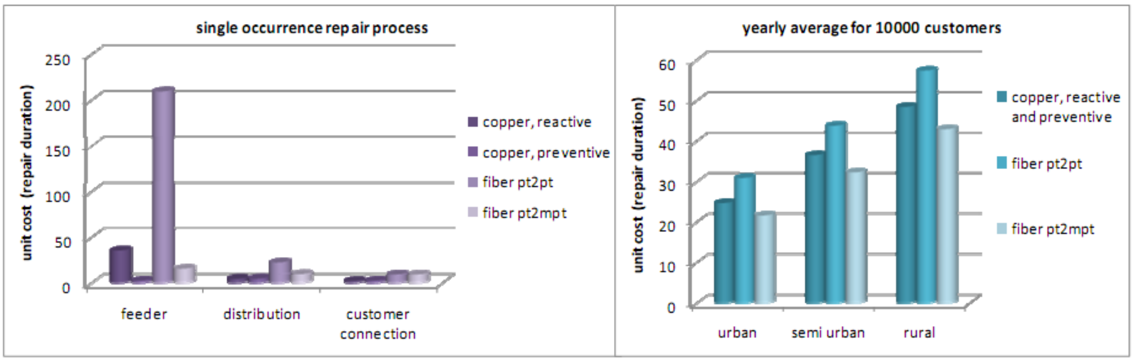


Figure 2.4: Cost for repair for several network scenarios *[Verbrugge, 2008]*.

The figure 2.4 demonstrates the reparation costs for copper and fiber point to point and point to multipoint. It can be seen that point to point fiber links provide higher bandwidth per user however requires higher costs for repairing.

2.3. Multiplexing Optical Signals

The two most important ways to multiplex the channels correspondent to each user in a point to multipoint passive scheme is Time Division Multiplexing (TDM) and Wavelength Division Multiplexing (WDM) *[Agrawal, 2002].* In figure 2.5 are presented four different approaches to provide FTTH as point-to-point links, point to multipoint by means of active optical switching, TDM-PON and WDM-PON.

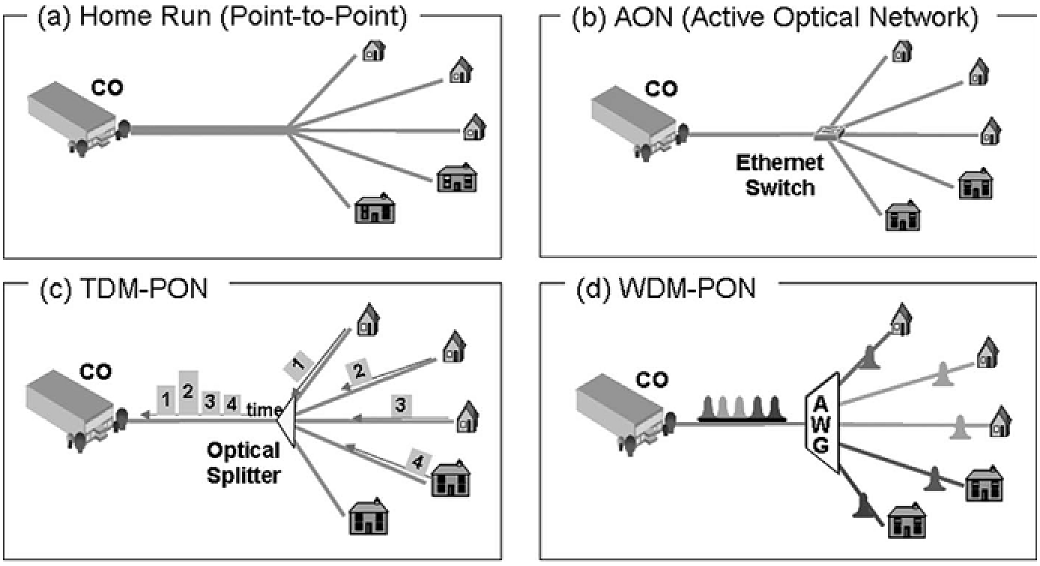


Figure 2.5: Four different approaches of FTTH/P a) Point to point connection, b) Active Optical network with Ethernet switch, c) TDM passive optical network and d) WDM active optical network *[Lee, 2006].*

Time Division Multiplexing and Time Division Multiple Access

TDM is the most popular FTTH approach and has significant deployments in various regions of the world *[Lee, 2006].* It is the selected method for access networks since it allows a single transmitter and receiver shared in the CO and a single transceiver in the OLT, resulting in a cost effective solution. A single wavelength is shared for several ONT that select the specific portion of the broadcast data. Is particularly easy to assign bandwidth to the users due to the fact that the OLTs are able to control the user address and the data packets length. All ONUs are synchronized to a common time reference and have allocated a time slot (capable of carrying several Ethernet frames).

For the Upstream direction the time multiplexing used is TDMA. Dedicated time slots are assigned to each of the multiple subscribers connected to the PON. Each of the subscribers can use the full upstream bandwidth assigned for the duration of its allotted time slot. To connect the multiple subscribers to a single feeder fiber an optical power splitter is used at the RN, combining part of the power to each subscriber. Is required burst mode optical receiver at the OLT that needs to synchronize for each data packet from different users. A useful characteristic using TDMA is Dynamically Bandwidth Allocation (DBA), where not used channel bandwidth for an ONT can be given to other ONTs *[Kramer, 2005].*

A complex algorithm is necessary for management and control of the multiple users over a single fiber to avoid collisions. An incorrect time transmission from a subscriber can shut down the entire network. To avoid collisions of signals in TDMA, access control protocol is used *[FSAN]*. There are two main standards, the G-PON and the E-PON *[Lin, 2002]*. E-PON standard proves a better handle packet data traffic, reduces the cost of the transmission equipment *[IEEE, 2002].* Is questionable that EPON can deliver enough bandwidth and QoS so the G-PON standard was developed providing 2,5Gb/s for DS and 1,25Gb/s for US *[ITU-T, 2003].*

Standardization of TDM is difficult because information and communication technologies are changing at very fast rates. By the time the technology is ready for full scale deployment, it is already outdated. A problem with TDM is that the optical power loss increases as the number of ONU increases due to the increased power splitter ratio. Other problem is the security, as each ONT has access to all the data sent to any of the users. The solution is suitable as long as the bandwidth requirements per subscriber do not become too high.

Wavelength Division Multiplexing and Wavelength Division Multiple Access

In WDM multiple optical 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. This technique allows exploiting the large bandwidth offered by the optical fibers in an efficient way. The resources of the WDM fiber link depends on the density of the channels in the wavelength domain and the length of the link *[Kaiser, 2003]*. The minimum channel spacing is determined by the inter channel cross talk and four wave mixing (FWM). Thousands of

Gb/s channels can be transmitted over the same fiber when spaced bellow 100 GHz. WDM wavelength channels have been standardized by the international telecommunication union ITU on 50GHz spacing between 186 and 196 THz. Each of the channels present on the WDM fiber can carry any transmission format being the network completely transparent *[Agrawal, 2002]*. Figure 2.6 presents a comparation between point to point fiber link, WDM dual fiber link and WDM bidirectional fiber link. Implementing the WDM network with double fiber allows higher number of users connected to it since the spectrum is better used.

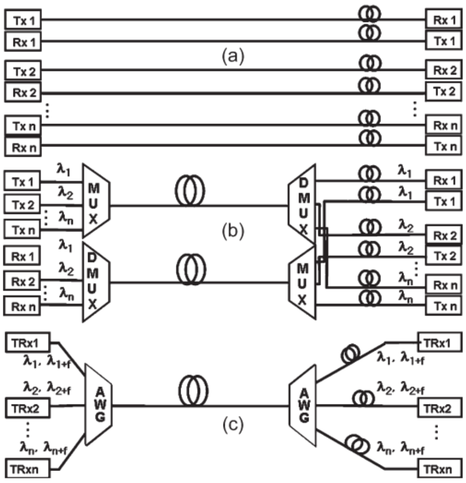


Figure 2.6: Simplification of network that supports point to point connectivity with WDM-PON a) point to point fiber; b) point to point US and DS wavelength in different fibers and c) point to point US and US wavelength *[Lee, 2006]*

WDM networks can be divided into two categories: single and multi hop. In single hop all the nodes are connected to all other nodes, leading to a fully connected network. A N set of transmitters and receivers are attached to either a start coupler or a passive bus. Each transmitter sends its information at a different fixed wavelength. All the transmissions from the various nodes are combined in a passive star coupler or coupled onto a bus and the result is sent out to all receivers. Each receiver sees all wavelength and use tunable filter to select the wavelength addressed to it, being able to support multicast and broadcast. A star passive coupler can be transparent. Different communicating nodes use different information exchange rules without affecting the other nodes in the network *[Chraplyvy, 1990]*. Single hop is a simple solution, but there needs to be carefully dynamic coordination between nodes and need for rapidly tunable lasers or receiver optical filters. In the other hand there is the multi hop topology that is only partially interconnected and is able to avoid single hop drawbacks. Each node has a small number of fixed tuned optical transmitters and receivers. Stations can send information directly only to those nodes that have a receiver tuned to one of the two transmitted wavelengths. Information destined to other nodes will have to be routed through intermediate stations, converting to electric format. It does not require direct paths between each node pair, being necessary multiple hops for a signal to reach the destination. There is a penalty due to the electronic switching maximal speed. Extending broadcast and selecting to the networks cause two problems, more wavelengths are needed as the number of nodes grow and the use of passive star couplers increase the splitting losses. Separate dedicated wavelength is used for the downstream transmission to each user requiring separated laser sources at the CO for each subscriber.

Security issues in WDM networks come only from the physical access to other wavelengths. Due to the demultiplexing in the RN that directs different wavelength to each user the security is highly guaranteed by the architecture of the physical network. It provides virtual dedicated point to point channels to each user without concerns associated with multiple users sharing a channel. While being a simple solution, it remains costly for an access network. An array of receivers or a tunable receiver is required at the ONU and an array of transmitters at the CO.

In the Upstream signals is used WDMA. It is much simpler than TDMA since each subscriber is assigned with a pair of dedicated wavelengths. The user can send data anytime without disturbing or causing collisions with the other users. Each subscriber has a dedicated point to point virtual channel to the OLT sharing a point to multipoint physical architecture so to each user can be provided different data rates and modulations. A WDM multiplexer is used instead of power splitter by means of an AWG or thin film filter. The US as the DS channel spacing can be as narrow as 50 or 100Ghz. With WDM topology there are no QoS issues related to sharing the PON and the IL at the RN is smaller and independent of the splitting ratio. Unused capacity cannot be distributed and WDM networks have an higher CAPEX due to increased number of transmitters in the CO [Agrawal, 2002].

WDM networks has inherent advantages over TDM PON in terms of bandwidth, protocol transparency, security and simplicity in electronics, however the bandwidth for the dedicated wavelength is not fully utilized. The cost of the system is the main concern for the proposed PON networks. The efficiency of the network increases as the number of users increase *[Kaminow, 1997]*.

2.4. Passive Optical Networks

Networks making use of passive couplers (TDM) or passive demultiplexers (WDM) are called Passive Optical Networks (PON). There are not active elements between the CO and the ONU. The main advantages of PONs are the lower cost to implement a structure in the field, reduced OPEX, no need to supply and monitor electric suppliers, higher feasibility and transparency to the modulation format and data rate of the signals *[Lee, 2006]*. The transparency property of the PON enables to upgrade the network without rectifying the deployed network.

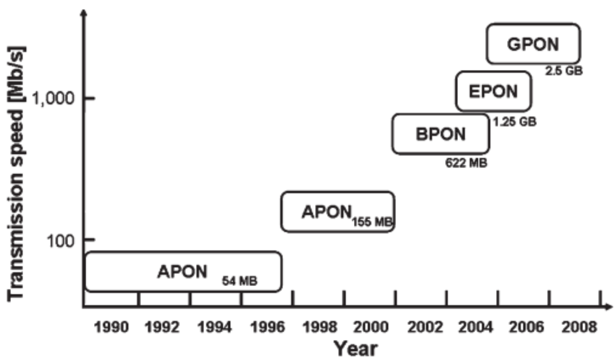


Figure 2.7: History of TDM-PON development *[Lee, 2006]*.

The first deployed PON was TDM based and was referred to as Asynchronous Passive Optical Network (APON) since it was based on ATM protocol. This topology was implemented widely in Germany between 1990 and 1996. It used a shared 54Mb/s fiber and was implemented for compatibility with the existing voice and phone services *[Engineer, 1990]*. The evolution of requested data rate and the emergence of the Internet lead for the new generation of APON able to support until 155MB and further to the Broadband Passive Optical Network (BPON). It was able to supply 155Mb/s in the beginning of the implementation *[Plas, 1995]* being upgraded to 622Mb/s later *[ITU-T, 1998]*. The next approach was developed to optimize the packet based data traffic compared to the A/BPON standard that was optimized for voice traffic. It consists on the

Ethernet Protocol applied in PONs developed by IEEE and referred as the Ethernet PON (EPON). EPON technology provides bidirectional 1,25Gb/s with 1490nm for DS and 1310 nm for US with 1550nm reserved for future demands *[IEEE, 2002].* Having in mind the exponential grow of data traffic demand, and considering that the EPON was not enough to support the needs, the Gigabit PON (G-PON) was developed. The preferred G-PON bit rate was selected to be 2,488Gb/s for DS signals and 1,244Gb/s for US signals *[Kimura, 2003]*. A diagram with the evolution of the TDM based PONs can be seen in the figure 2.7.

Improving Passive Optical Networks

A simple method to upgrade already deployed TDM-PONs is to keep the PON architecture fixed and increase the data rate to be shared for all the users. IEEE is already considering to increase the EPON transmission data rate from 1,25 to 10Gb/s *[Yoon, 2006].* It is still unclear if it is possible to implement a cost effective solution for this data rate due to the high data rate challenges. The second issue related to the improvement of the data rate is that all the ONT must upgrade the equipment at the same time, what can be inconvenient if some of the subscribers have to pay more for a service they do not require.

A different approach to upgrade the networks would be to add extra wavelengths for US and DS and insert WDM filters at both the CO and ONU locations. In order to avoid data-remodulation crosstalk, all the subscribers are required to simultaneous upgrade the ONT equipment what is still an inconvenient for users that do not require higher speed. It can be solved by previous implemented blocking filters into the design of the ONT allowing a wavelength upgrade without affecting the PON users. It allows also a easier upgrade from a TDM-PON into a WDM-PON *[Kramer, 2005].* The main problem of this solution is that the total cost of the network is increased in advance being in some times never used the extra equipment deployed.

Other approach can be seen as reducing the number of subscribers that use the PON as the bandwidth demand increases. This solution is not cost effective since it requires extra feeder fibers installed in the field, extra power splitters and extra OLT in the CO reducing the benefits from a shared network.

The fourth scenario to upgrade a TDM-PON is to convert it into a WDM-PON replacing the power splitter present on the RN by an AWG providing multiplexing/demultiplexing functions and upgrading also the OLT and the ONT. Upgrading to a WDM-PON will provide a virtual point to point link between the CO and the ONU being future bandwidth upgrades easy and case independent situation. Implementing WDM-PONs can also reduce the number of CO between metro and access networks, reducing the total cost of the network *[Lee, 2005]*.

2.5. Conclusions

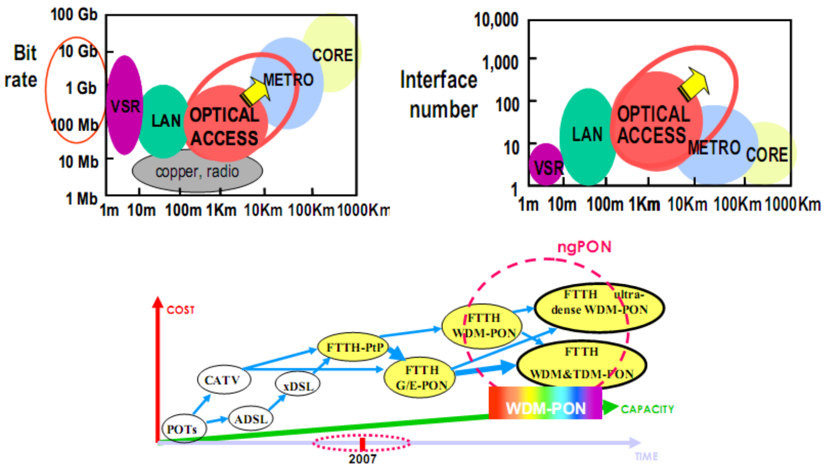
In this chapter is made a short introduction to optical communications networks and the evolution in components that lead to very high speed links. The introduction of all optical regeneration allows very high rate links with reduced costs when compared to links with OEO conversion.

In this chapter is also presented and compared the two main data multiplexing, TDM and WDM and the different network topologies: Hub, Bus, Ring and Star. The evolution of TDM-PON and the migration to WDM-PON is also presented.

Chapter 3. Next Generation Optical Networks

3.1. Introduction

While already standardized TDM optical networks are currently under deployment, recent research is focused on the next generation access networks *[Davey, 2005], [An, 2004]*. Next generation Access Networks are aiming at offering higher user density, extended reach, scalability, flexibility and resiliency while keeping the network simple and economically feasible *[Sananes, 2005]*.



a)

b)

Figure 3.1: a) Network segment definition in terms of Bit rate, interface number and distance served and b) evolution of access technologies *[Prat, 2007]*.

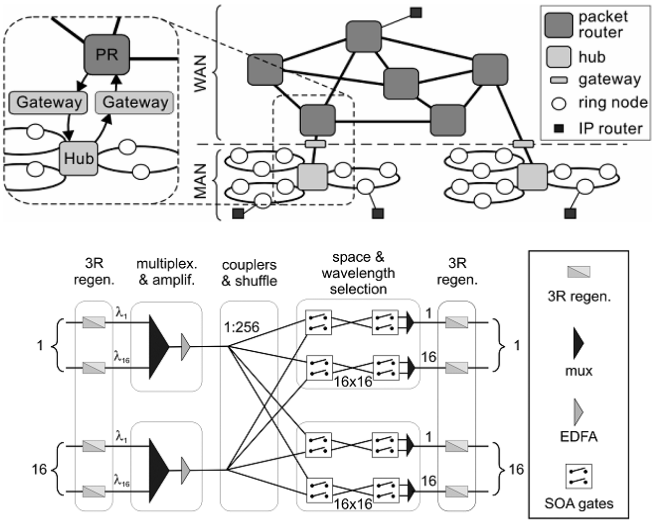
The figure 3.1 presents the evolution of the optical networks towards New Generation optical networks. Research activities are focusing on possible extensions of current GPON and EPON since these systems may suffer bandwidth limitations in the future, and they do not make full use of the optical bandwidth. The high initial CAPEX required in new FTTH deployments compels network designers and operators to assure migration paths that guaranties future full usage of infrastructure investments, avoiding bottlenecks at any demand increase. Thus, the major goal is to reduce the overall access network cost while assuring a remarkable symmetrical bandwidth per user, establishing an optical passive transparent infrastructure over a dense extended-range area, capable of supporting unknown future demands. This is driven the research towards extended practically unlimited bandwidth next generation optical networks. The time scale for the migration of current optical networks systems towards it can be highly variable, perhaps in a 2-8 years timeframe, although driven by the mentioned unpredictable user demands. A wide range of operators and system vendors are aiming their R&D interests towards this field considering this *[Prat, 2007]*.

WDM Technology offers a new dimension for this upgrade. Coarse Wavelength Division Multiplexing (CWDM) has been recently commercially offered, while (Dense Wavelength Division Multiplexing) DWDM is under R&D, although an operator in Easter Asia is offering a simplified version of it [Prat, 2008]. A future implementation of Next Generation Optical Networks can be only foreseen if new cost effective techniques and devices are used. WDM access can be pure WDM-PON or hybrid WDM/TDM-PON, being the later offering a higher level of granularity and scalability, so it constitute one of the main research focus. There are however relevant barriers in the migration towards WDM in FTTH, the increased cost of WDM components in the access field and the availability of technological solutions to guarantee the robust and unlimited usage of the extended PON. There is, for example, the lack of truly passive resilient architectures, the availability of effective colorless devices for single fiber transmission, the lack of tolerance against impairments of extended PONs and the lack of a monitoring system able to detect and locate faults and impairments at any position of the passive FTTH network *[Prat, 2007]*.

3.2. Developed New Generation Optical Networks

In order to understand the current developments in optical communications networks and the different topologies implemented there are present some New Generation optical networks ring based:

Data and Voice integration over DWDM - DAVID



a)

b)

Figure 3.2: a) The DAVID network architecture; b) structure of the broadcast and select switch matrix adopted in DAVID *[Dittmann, 2003];*

The first approach is the project DAVID – Data and Voice integration over DWDM. It aims at proposing a viable approach towards Optical Packet Switching (OPS) by developing networking concepts and technologies for future optical networks, including traffic studies and control aspects. The network covers MAN and WAN, with a distinct operational structure. The topology of the network can be seen in figure 3.2. It consists on multi unidirectional optical rings interconnected by a Hub. The ring is build with one or more fibers operating in WDM and TDM. The WDM rings are interconnected by means of a bufferless hub that controls the resources without limitations between node counts and number of wavelengths. Each WDM channels operate at 10Gb/s and there are 32 of them operating in the ring with a channels spacing of 100Ghz *[Dittmann, 2003]*.

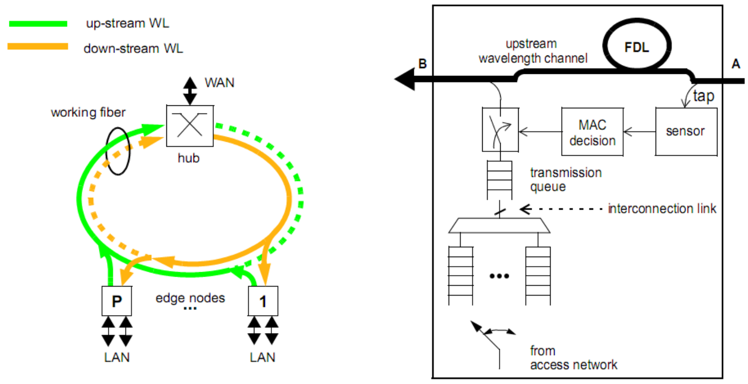


Figure 3.3: a) DBORN architecture; b) functional model of transmitter interface in edge nodes *[Hu, 2003]*.

Other approach is the DBORN-Dual Bus Optical Ring Network. It consists on a WDM MAN with metro clients connected to a ring by means of edge nodes that do not require any active switching elements sharing the wavelengths on the ring as seen in figure 3.3. The ring is implemented with double fibers one being the operational and the other being implemented just for protection in case of fiber failure being the ring resilient. The ring is WDM topology carry independent wavelengths for DS and US. The edge nodes inserted on the ring share one or more of the US and DS wavelengths in an Asynchronous Time Division Multiplexing (ATDM) basis. The edge nodes interfaces are kept as simple as possible by implementing a central hub. The US and DS channels can be modeled as shared unidirectional buses. Simple 1x2 couplers allow Add&Drop functions to the traffic transmission fiber. The network has been demonstrated using cascadable EDFs and 10 transparent nodes spread over more than 200Km providing until 320Gb/s *[Sauze, 2003]*.

FLAMINGO

FLAMINGO – Flexible Multiwavelength Optical Local Access Network Supporting Multimedia Broadband Services is based also in a ring WDM topology with special nodes, the Access Point as demonstrated in figure 3.4. The bandwidth of each WDM wavelength is divided in a TDM topology. One of the WDM channels is reserved and used for control information and as the header of all the payload channels and the others WDM channels carry the payload.

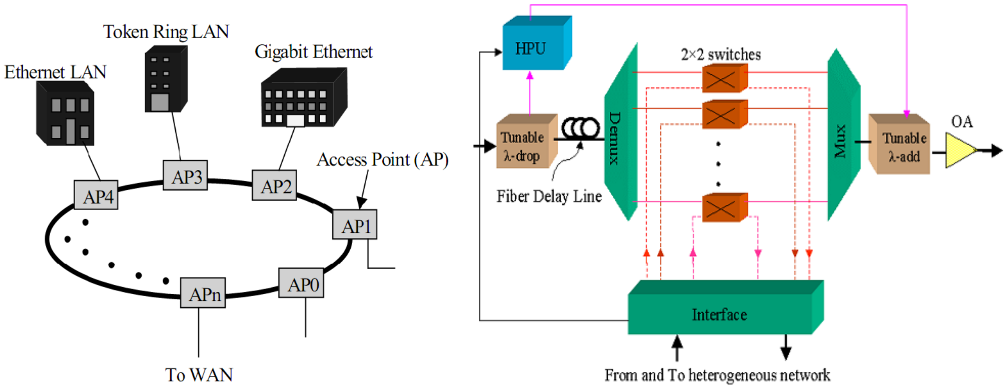


Figure 3.4: a) The FLAMINGO network; b) FLAMINGO Access point *[Dey]*.

Each node is able to transmit and receive in any wavelength. High throughputs at the nodes can be achieved as a result of the high degree of network utilization. The outside plant is completely bit rate and protocol transparent and helps the operators with almost any heterogeneous type of network. The simulated network consists on a 35Km unidirectional ring and 10 nodes, transmitting 4 wavelengths at 2.5Gb/s for a total fiber capacity of 10Gb/s *[Dey]*.

HORNET

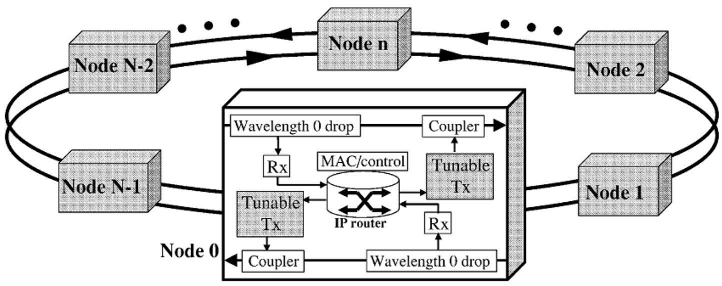


Figure 3.5: HORNET network architecture and node *[Ian, 2003]*.

HORNET is a hybrid optoelectronic ring network topology designed to be cost-effective scale beyond 1Tb/s while efficiently transporting bursty, packet based randomly fluctuating traffic. The ring is implemented with double and bidirectional fibers designed to leverage the currently deployed fiber infrastructure *[White, 2002]*. The network was developed to operate in fiber or node failure. The MAC protocol was designed to efficiently transport variable sized packets, and to provide fair access to the network for all users. The nodes use fast tunable packet transmitters to insert packets onto the ring. The packets are transmitted on the wavelength that is received by the destination node. A special wavelength drop is used to drop one or more assigned wavelength into each node, being completely transparent to the packets not destined to that particular node just requiring enough equipment to process the packets to and from its local users. The network can be scaled until 1,28Tb/s with 64 wavelengths at 10Gb/s each. The optical amplifiers for this network must provide constant gain in dynamic conditions *[Ian, 2003]*.

RingO

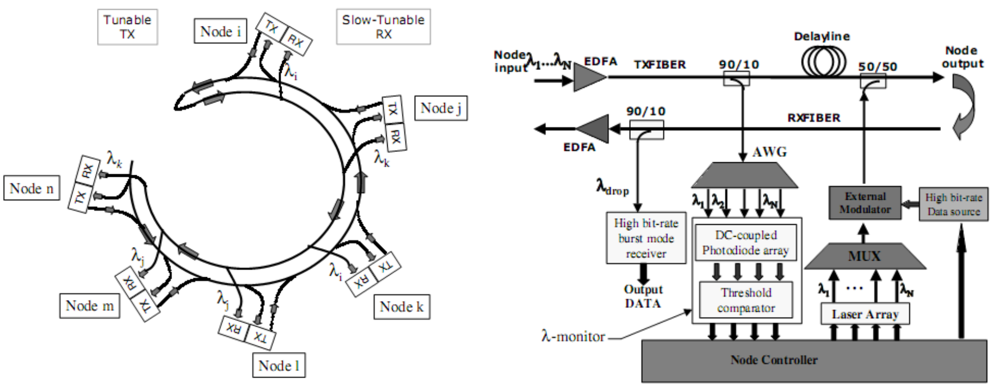


Figure 3.6: a) Scalable architecture of RingO network based on 2 fibers ring; b) Structure of RingO nodes *[Carena]*.

RingO is a WDM ring based optical packet network suitable for a high capacity Metro environment. The first version of the network is based on unidirectional WDM fiber ring with nodes equipped with an interface between the domains optoelectronics. The number of nodes is equal to the number of wavelengths and each of the nodes just operates with the specific wavelength removing it from the ring by a optical drop filter. Each node is implemented with a tunable transmitter to communicate with a specific node in other wavelength. The nods, before transmitting are able to check the busy/free state of the wavelengths to avoid collisions. It does not require any complex optical component such as fast optical switches or wavelength converters and optical buffering is not present. The nodes provide amplification, demultiplexing after amplification, slot monitoring and local packet traffic generation. Transmission and reception of the nodes is done by means of double fiber ring. The network is implemented with 16 nodes with 16 wavelengths working at 10Gb/s each, with a distance of 25km between nodes. The distance of the ring is limited by the amplification ASE accumulation *[Carena]*.

RINGOSTAR

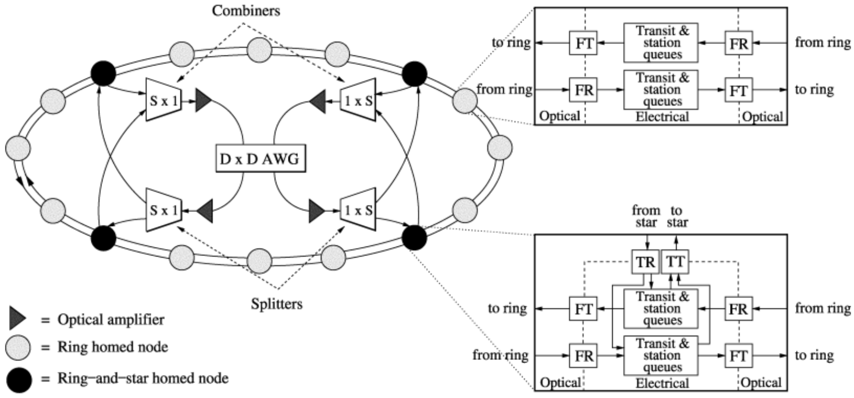


Figure 3.7: RINGOSTAR network and node architecture *[Herzog, 2005]*.

RINGOSTAR is an hybrid ring star architecture. The network uses WDM on the central single hop start exploiting the large spatial wavelength reuse capability of the wavelength routing AWG. Only a subset of ring nodes is directly connected to the star network causing less fiber requirements and node interfaces. The nodes are connected to the central router by means of 1 or 2 fiber pairs. The ring nodes are interconnected with a small number of fibers that can be subdivided into 2 categories: ring and star homed nodes and ring homed nodes. The nodes are connected to a bidirectional dual fiber ring by means of 2 fixed tuned transceivers, 1 per single channel fiber. The ring and star homed nodes are also connected to the central star network using additional tunable transceiver. When necessary an EDFA is implemented to compensate fiber losses, splitting and insertion losses in the star network *[Herzog, 2005]*.

WONDER

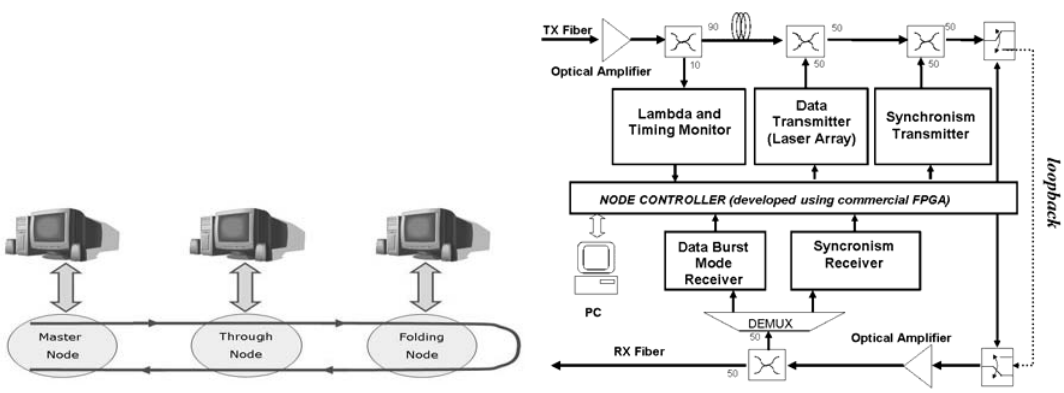


Figure 3.8:WONDER network and node architecture *[Antonio]*.

WONDER architecture is based on a bidirectional optical ring in a WDM technique folded at one node resulting in a folded bus with fault protection capabilities. It limits the optical complexity and uses only commercially available components. The access to WDM chanels adopts the paradigm of tunable transmitters and fixed wavelength receivers. It provides efficient and dynamic packet multiplexing and maximum simplification of the physical layer minimizing the accumulation of physical layer impairments and electronic complexity largely independent from the number of wavelengths. The network, in the transmitting side uses an array of standard DFB lasers, on the optical path only optical amplifiers and passive optical couplers and in the receiver side a standard DWDM demultiplexer and GPON burst mode receivers *[Antonio]*.

3.3. Metro Access Convergence

Large optical networks are typically partitioned into core (inter-city), metro (intra-city) and access networks. It is essential that the core, metro and access networks are able to work interconnected to release the fast provisioning potential of these sub-networks, since a larger part of the anticipated connections will need to traverse both core and metro sub-networks and finally reach the access requiring signal and routing information exchange [Prat, 2008].

While access and metro sub-networks handle local traffic and service-specific features, the core network transports relatively homogeneous connections across long distances leading the core network to be based on different technologies than the others. Simpler optical nodes may be used in access and metro transport [Wang, 2001].

Ring topology is assumed in the metro network to provide resilience while in the access the ring may be combined with the tree topology. The optical node interconnecting the ring and the tree depends on the interface role. Optical Cross-Connect (OXC) and Reconfigurable Optical Add&Drop Multiplexer (ROADM) allow input channel ports being routed to output channel ports by means of optical switches. In access networks a simple OXC architecture can also be used for managing several PONs providing the laser sources and receivers to be shared among thousands of users. PONs can be connected with ROADM in a metro ring to reach a distant router controller in an all-optical connection, but this architecture has a distance limit, not only due to power budget but also due to signaling propagation delays in the DBA. The distant router controller will interoperate with the next hierarchy metro or core network exchanging routing information [Prat, 2008].

3.4. Conclusions

This chapter focused specially on the evolution of the current deployed TDM/WDM optical networks to the Next Generation optical networks revealing the main aspects and requirements of the migration. It presents the state of art of some developed New Generation optical networks based on ring topology. Finally it presents the current convergence of the Metro and Access networks.

From the presented networks while some can provide high number of users, extended reach, high data rate, scalability, flexibility and resiliency, none of them can provide all in a efficient manner, since most of them are not Passive Optical Networks.

These presented optical networks are an introduction to the next chapter where the SARDANA network, an NG-PON metro access network is presented.

Chapter 4. SARDANA network

4.1. Introduction

Scalable Advanced Ring Based Passive Dense Access Network Architecture (SARDANA) is an effort to demonstrate how to exploit the NG-PON in a cost effective and reliable way *[Lazaro, 2008],* it is an FP7 project and provides the main objectives of this document. It consists of a Metro-Access convergence network able to supply at least 100Mb/s to 1024 users spread over more than 100Km [Lazaro, 2007]. There were proposed two different topologies to SARDANA, the first consists on a single fiber ring [Bock, 2006:1] and the second a double ring [Lazaro, 2006]. In figure 4.1 is presented the main structure of the double fiber ring and the respective equipment general scheme.

4.2. SARDANA Topology

This novel PON topology is based on a main ring and secondary trees connected by means of a special node denominated as Remote Node (RN) *[Bock, 2007]*. In order to achieve the highest efficiency from the implemented fibers, in the main ring are present WDM signals that are distributed to each secondary tree serving the users in a TDM topology by means of the RN. When the main ring is implemented with double fiber, one fiber carries the DS signals and other the US signals in order to reduce the total signal degradation imposed in a major part by Rayleigh and Brillouin Backscattering distortions. Two trees are connected to each RN with a splitting ratio of 1:K providing a flexible number of users *[Lazaro, 2006]*.

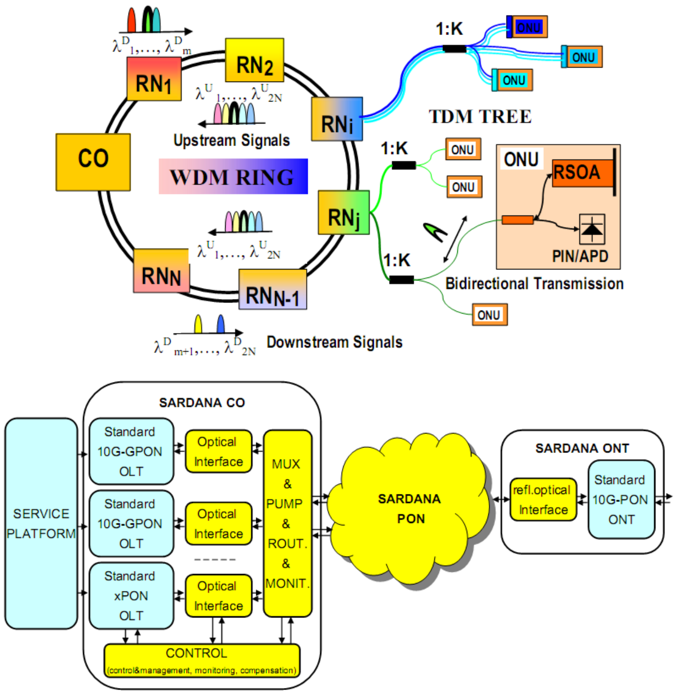


Figure 4.1: a) SARDANA network architecture and b) equipment general scheme *[Prat, 2007]*.

Operating in TDM basis in the trees provide special features to the network: migration from the currently deployed infrastructures overlaying E-PON and G-PON into this novel topology and supplying different services and operators on different wavelengths. With these features the network is flexible and serve users with different transmission requirements *[Bock, 2006:2]*.

Robustness is achieved by the passive ring, monitoring techniques and compensation strategies intelligently supervising and managing the impairments of the PON. Due to the ring, the network is able to provide traffic balance through the shorter path and resiliency in case of fiber, splice, connector or component failure, being the signals redirected to the alternative path

The network scalability is guaranteed by inserting supplementary RN to the ring that is wavelength transparent is a simple task. The network can be scaled to reach a large number of subscribers. DS and US are wavelength multiplexed, so each RN drops 2 DS signals and insert 2 US signals from/to the ring (1 per tree). The number of RNs is a key parameter in terms of network performance because it determines the number of wavelengths of the network and the total network capacity. The optimal and most efficient number of RNs in the ring is independent from the number of users per RN and the number of users is limited by the PB and the link loss between respective CO and ONU. As the PON grows, the link losses also increase becoming a very important parameter and limitation to consider *[Bock, 2007]*. When designing the network a compromise should be made between optimizing power losses and optimizing network performances. Single fiber bidirectional access to the user simplifies the outside plant and cable management, also reducing micro blending risks at user premises *[Polo, 2007]*. The network, allowing the convergence between metro and access simplifies the outside plant and reduces the equipment at the RNs.

4.3. Central Office

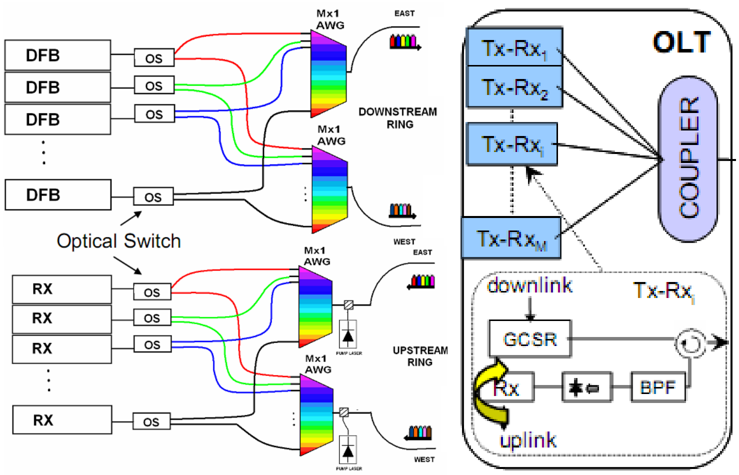


Figure 4.2: Central Office main structure *[Prat, 2007]*.

In order to maintain a completely passive and simple outside plant, all the light generation and control is placed together in the CO. All the complexity is placed in the CO, since its cost is shared among the all users of the PON. The CO uses a stack of tunable lasers for serving the different tree network segments on a TDM basis. Each of the lasers can tune to the appropriate wavelength, use WDM routing and by means of Geographic Bandwidth Allocation (GBA) techniques concentrate resources at the more demanding networks sections *[Prat, 2005]*. The CO can achieve traffic balance and resilience by means of optical switching, selecting the most appropriate path for the DS signals that maximize the PB margins and providing always a path to reach all the RNs even in case of fiber failure. The optical switching can be controlled monitoring the US signals that arrive to the CO to redundant photoreceivers through different sides of the ring, allowing the switching to the path of the higher received signal. A SARDANA CO architecture is shown in figure 4.2 *[Lazaro, 2006]*.

4.4. Optical Network Unit

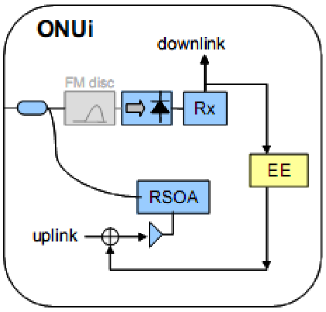


Figure 4.3: Optical Network Unit main structure *[Prat, 2007]*.

Colorless identical ONU avoids colored laser sources at the end user side, decreasing the maintenance and inventory issues. A much more convenient ONU should be based on agnostic wavelength transmission and Reflective Semiconductor Optical Amplifiers (RSOAs) are good candidate due to their reflective and wavelength independent properties. Despite of being the most cost effective candidate for ONU the RSOA also allows the reduction of Rayleigh Backscattering. The RSOA is able to provide amplification and remodulation of the arriving signal, allowing the network to be full duplex *[Lazaro, 2006]*. An ONU based in a RSOA is presented in figure 4.3.

4.5. Remote Node and Remote Amplification

The overlay between the WDM ring and the TDM trees is made by the passive RN. It implements cascadable 2 to 1 fiber optical Add&Drop functions distributing different wavelengths to each of the access trees. The RN with reduced footprint, does not require any environmentally controlled location. The RNs are completely transparent in the ring and compatible with the already deployed fiber structures being no modification required as the network grows. The introduction of a new RN in the ring is a simple task just transmitting 2 more wavelengths from the CO. In order to increase the PB margins each RN is implemented with 2 trees, each with a correspondent wavelength *[Lazaro, 2007]*. The RN Add&Drop signals independent of the direction of the ring provide resilience in case of fiber failure in the main ring. A basic diagram of the main blocks present in the RN is demonstrated in figure 4.4.

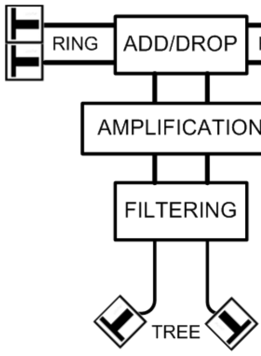


Figure 4.4: Remote Node main structure *[Baptista, 2008:2]*.

To compensate distance, dropping and filtering losses in the outside plant, amplification is convenient *[Lazaro, 2006]*. It allows significant improvement in the scalability of the network, geographical flexibility and average bandwidth per user but decreasing the OSNR *[Bock, 2006:2]*. Amplification is provided by means of EDFs present on the RN remotely pumped from the CO by means of two 1480nm pumping lasers, one for each ring direction, balancing the total power in the ring and providing resiliency in case of fiber failure *[Bock, 2006:1]*. The pump power is provided through the US fiber in order to produce extra Raman gain. The pump power present on the US fiber is previously demultiplexed from the fiber and led to the EDFs for amplification.

4.6. Conclusions

In this chapter the SARDANA network was presented. A brief introduction was made to the main components and structures of the network as the Central Office, the Optical Network Unit and the Remote Node as the different fiber deployments architectures.

Chapter 5. Remote Node Topology

5.1. Introduction

As described in chapter 4.4 the Remote Node (RN) is a very important component in the SARDANA network. It provides three main functions: Add&Drop; amplification; and filtering, of the correspondent WDM channels to each of its trees. This chapter presents and optimizes RN topologies. The different topologies aim to reduce the total amount of pump power produced by the CO, reduce the Insertion Loss (IL) and allow higher scalability and resiliency.

5.2. Remote Node Pump Architectures

The amplification provided by the RN is an important limitation to the total efficiency of the network. It is important to optimize the amplification modules in the RNs, reducing the total amount of pump power required per RN. A second optimization consists on a fairer pump power distribution among the entire network, do not dropping excess pump power to the RNs. Different pump topologies are presented in this chapter: based in couplers, optical switches, tunable power splitters and reconfigurable.

5.2.1. Pump topology 1

The first and easier pump configuration is present in figure 5.1. It consists on simply drop the pump power at 1480nm from the US fiber and directs it to the EDF being the remaining pump power supplied to the other EDF(s). It requires reduced number of optical components to implement but it is not efficient.

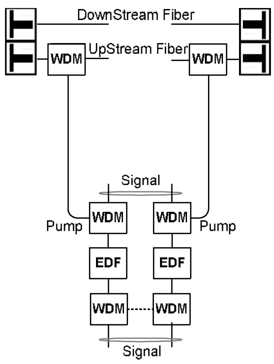


Figure 5.1: Simple Remote node topology to supply pump power to the EDFs *[Baptista, 2008:2].*

Increasing the pump power supplied to the EDF leads to the saturation of the amplification while keep increasing the consumption of that pump power. The efficiency of the network decreases drastically, leading to the impossibility to supply all the RNs with pump power *[Baptista, 2008:2].*

5.2.2. Pump topology 2

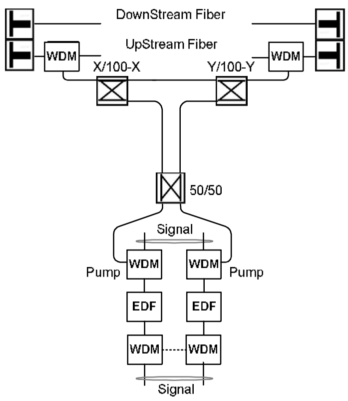


Figure 5.2: Second approach to supply pump power to the EDF*[Baptista, 2008:2].*

A better approach is to provide the EDFs with a fraction of the total pump power available in the network. For that the RN pump topology is proposed in figure 5.2. It consists of three power couplers being two of them inserted in the pump ring path with coupling factors (X / 100-X and Y / 100-Y) and the other a 50/50 for resiliency and power balancing mode. The two power couplers inserted in the pump ring path have different ratios due to the fact that the pump power can arrive from the both sides of the ring.

This topology compared to the previous increases the efficiency. The EDFs are supplied just with a fraction of the total pump power available in the ring. Although with this topology extra IL is introduced due to the two pump power splitters and pump power is wasted *[Baptista, 2008:2]*.

5.2.3. Pump topology 3

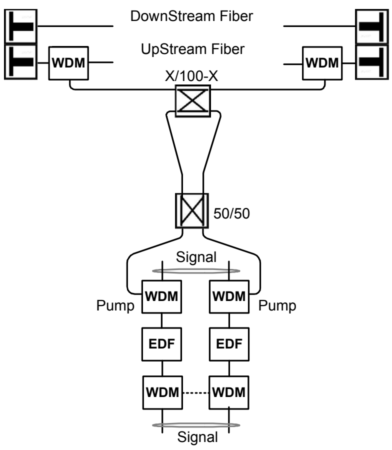


Figure 5.3: Third approach to supply the EDF with pump power based on a single power splitting *[Baptista, 2008:2]*

A third approach consists on a single power coupler with a ratio adjusted to be the most efficient for scalability and resilience purposes. This new configuration is presented in figure 5.3. With this, no pump power is wasted in the pump power coupler and the total IL in the pump ring path is reduced reducing the number of power couplers from two to one leading to a fairer pump distribution and higher network pump efficiency.

A problem arises now: which is the appropriate ratio for the power coupler having in consideration the number of RNs, the number of users per tree, the scalability of the network and the resilient operation. It is impossible to select that value being the most efficient for all the situations individually*[Baptista, 2008:3]*. A pumping configuration proposed that considers all power splitters ratios equal to 90/10 provide resilient and scalable network. A second approach is to provide each RN with a different splitting ratio as 13, 14, 17, 20, 25, 33, 50, and 100. A third approach is to provide each RN with a different splitting ratio as 10, 13, 17, 20, 25, 30, 40, and 50 as it can be seen in figure 5.4.

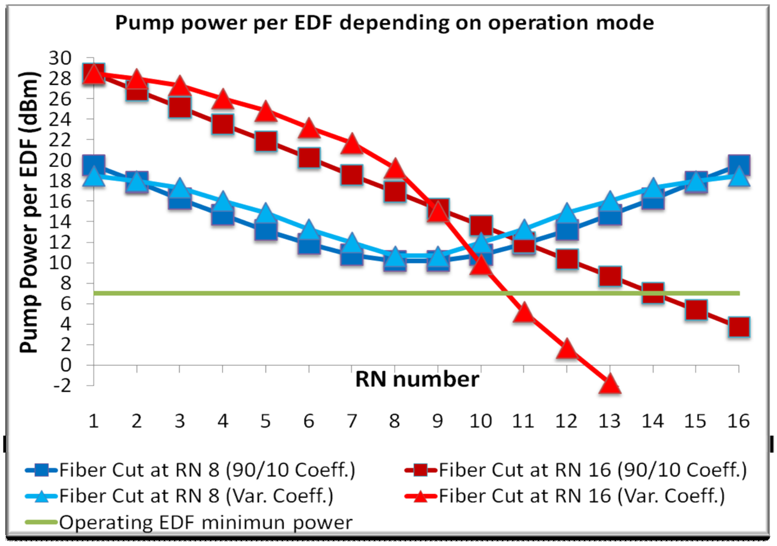


Figure 5.4: Comparison of variable and 90/10 power couplers for different states of the network *[Baptista, 2008:1].*

The first approach is the simplest to implement and the one that provides better resilience and scalability compared to the others but for normal operation mode, it requires higher pump power from the CO than the other approaches. The second approach is the best one for normal operation mode as it requires less pump power demand from the CO. By the other hand it is not resilient, since in case of fiber cut no pump power pass at the central RN to the reminiscent RNs and the scalability is not guaranteed since an introduction of more RNs require all the pump power ratios from all RNs require to be readjusted. The third approach is not scalable as the previous one, is not the best option for the normal operation mode (the intermediate approach) but it provides some resilience in case of fiber cut. The second and third approach require power coupler ratios not available commercially *[Baptista, 2008:1].*

5.2.4 Pump topology 4

The selection of the appropriate power coupler ratio depends on the operational mode: normal or resilient; for this reason, in order to comply with the requirements of both modes one coupler of average value must be chosen.

An alternative propose for the previous configuration is to select between the best option for normal operation and the best option for extreme resilient mode (fiber cut at RN 16) by means of optical switching as presented in figure 5.5.

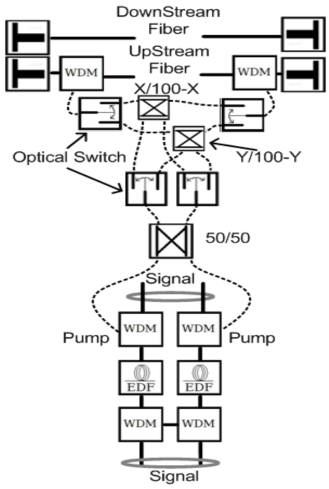


Figure 5.5: Proposed approach to supply EDFs by dual case switching *[Baptista, 2008:1]*.

For the normal operation the ratios would be 13, 14, 17, 20, 25, 33, 50, and 100 and for resilient mode all ratios equal to 90/10 as presented in [Bock, 2007]. The introduction of RNs in the ring until a total number of 16 requires a readjustment of the normal mode power couplers ratios. This readjustment does not allow the network to be fully scalable.

With this topology resiliency is achieved independent of the link failure. Since the resilient mode power couplers are equal to 90/10 to all RNs, increasing the number of RNs does not affect these couplers. Although when operating in resilient mode, excess pump power will be dropped to some RNs being required higher total pump power from the CO reducing the total efficiency of the network.

The implementation of two optical switches introduces extra IL when compared with the previous topologies increasing significantly the total losses in the pump path ring. Higher pump power is required from the CO degrading the efficiency of the network *[Baptista, 2008:3]*.

5.2.5. Pump topology 5

A better approach both in scalability and resilience can be achieved with the introduction of a tunable power splitter instead of the optical switches as presented in figure 5.6. With this approach the RN can adjust the ratio factor to the most appropriate ratio eliminating the extra pump power dropped to the RN and providing complete scalability, resiliency and higher efficiency reducing the total pump power supplied from the CO *[Baptista, 2008:3]*.

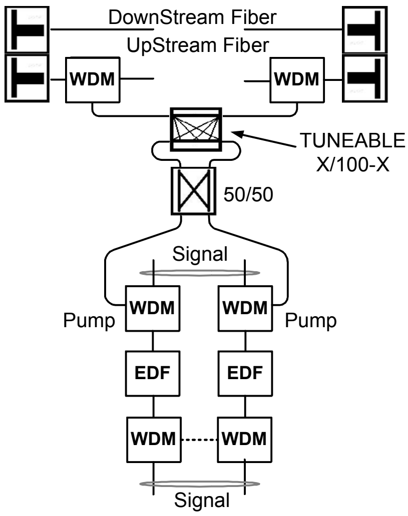


Figure 5.6: Proposed approach to supply EDFs by multi case switching *[Baptista, 2008:1].*

Despite of the apparently simple implementation of this configuration it increases the ring IL in the pump path when compared to the main topology, figure 5.3. Even more, it is difficult to implement a passive optical tunable power splitter controlled precisely and which consume very low optical converted energy.

5.2.6. Pump topology 6

Another approach to make the pump power usage more efficient is the topology that has in consideration the distance from the RNs to the CO. EDFs supplied with signals to be amplified with high power, will not be able to provide gain although it will attenuate and degrade the signals *[Baptista, 2008:2]*. Also, the pump power consumption will increase being required higher pump power for that RN decreasing the efficiency of the network.

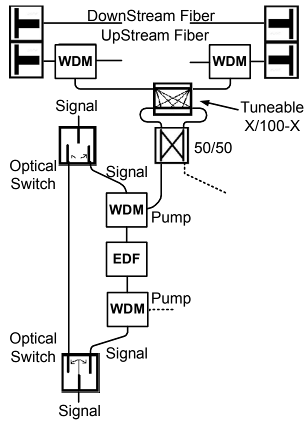


Figure 5.7: Proposed approach to supply EDFs by multi case switching and amplification module selection *[Baptista, 2008:1]*.

With these characteristics, RNs close to the CO where the signals have enough power to reach the ONU do not require providing of gain. A simple solution would be to omit the tunable power coupler and the EDFs in the RN. It allows reducing the components and the cost of the network. Since there are no EDFs, no pump power is required at the RN reducing the total pump power demanded by the CO. Although, it must be considered the scalability and the resilience of the network, where the RN that is the closer to the CO can be the farthest in case of network grow or fiber cut and resiliency. For those cases, amplification must be provided in some situations. The proposed RN in figure 5.7 implements two distinct modules, one of them providing gain to the signal and the other establishing a direct connection without passing the EDF. The selection between those two modules can be achieved by means of an extra stage of optical switching. This approach is the most efficient in terms of pump consumption *[Baptista, 2008:2]*.

5.3. Remote Node Signal Architectures

The signal path topologies are also an important optimization. Reducing the signal losses and reducing the number of EDFs allow dropping lower pump power per RN, increasing the total efficiency.

5.3.1. Signal topology 1

The first and simpler RN signal architecture comprising a single fiber ring is presented in figure 5.8. Each RN provides Add&Drop functions by means of three optical couplers. The first two, introduced in the ring, are designed depending on the number of RNs, to minimize the pass through losses. It is demonstrated in *[Bock, 2007]* that the most efficient solution commercially available able to provide scalability and resiliency is the 90/10 ratio. The third coupler, 50/50, is responsible for traffic balance and resilience operation since it provides the signals to be Add&Drop from both sides of the ring. The 90/10 couplers drop a fraction of the entire spectrum that is then divided 50/50 to each of the trees. Filtering is then required in order to select the appropriate DS and US wavelength to each of the two trees connected to RNs and avoid Amplified Spontaneous Emission (ASE) to interfere with the WDM signals presented in the ring. This filtering is implemented by means of two thin film filters.

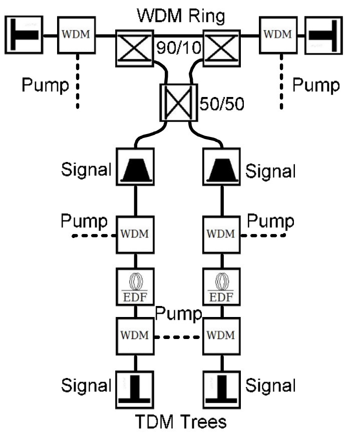


Figure 5.8: Simple Remote Node proposed in *[Baptista, 2008:2]*.

In order to compensate the distance, drop and filtering losses, amplification to the signals is required. Amplification is done by means of EDFs remotely pumped from the CO. Two WDM couplers 1480/1550 are introduced in the RN to previous drop the pump power from the ring and provide it to the EDFs. With this design, the ONU just require some change from the commercially available EPON/GPON ONU. That is the substitution of the 1310nm upstream transmission laser by a laser to transmit on the wavelength assigned to that specific PON segment remaining the rest of the equipment and logical control invariant. Important design parameters to make the network compatible with the

EPON/GPON standards are related to Power Burst (PB) restrictions *[Baptista, 2008:2]*. These topologies based on a single fiber ring are appropriate for non reflective ONU since DS and US signals require different frequencies.

The relationship between the number of RNs (N) and the number of wavelengths (M) is a fixed design parameter which is M/N = 4 *[Bock, 2007]*. The number of RNs is an important parameter in terms of network performance since it determines the number of wavelengths (M) of the network and the total network capacity. Other important factor that limit the network performance is the splitting ratio of the ring couplers, the number of users on each tree and the data rate. The number of users (U) is determined by the number of RNs and the splitting ratio (K) in the network sub segment. Considering an equal power splitting factor for all the RNs, the number of users can be given by (5.1):

$$U = 2 \cdot N \cdot K \qquad (5.1)$$

Increasing the number of RN will require an increase in the network used bandwidth but at the same time increases the power losses in the ring due to the insertion losses of each RN. Minimizing the total power losses in the outside plant can be achieved minimizing the equation (5.2):

$$L_T = (N - 1) \cdot 20 \cdot \log x^{-1} + 10 \cdot \log y^{-1} + N \cdot L_{EX} + 3 \cdot \log_2 K + L_S \qquad (5.2)$$

with L_S representing the fiber losses, insertion losses of optical equipment and wavelength filtering in the outside plant, x and y are the coupling factors of the optical splitter in the ring being the pass through and drop branch respectively (x + y = 1)and L_{EX} represents coupling excess losses at each RN due to manufacturing, aligning and installing process. The number of RNs (N) that minimizes the total losses is (5.3):

$$N = 3 / \ln 2 \cdot (20 \cdot \log x^{-1} + L_{EX})^{-1} \qquad (5.3)$$

It can be seen that the most efficient number of RNs is independent from the total number of users being the number of users just limited by the PB. To increase the number of users in the network it is more efficient to increase the splitting ratio than to insert extra RNs although it reduces the total data rate per user. However it depends on the geographical arrangement of the network.

Considering a constant K for all the RNs, an increasing of the number of users U in the system reduces the PB margin in a constant value. When the coupling factor x tends to 1, the curve of L_T flattens and incrementing the number of RNs does not affect the power losses dramatically *[Bock, 2006:1]*.

The geographical distribution of the users also determines the number of RNs. The best option would be to fix the number of RNs and the bandwidth per user and then calculate the other parameters of the network. However it requires a whole established network in order to minimize the network reconfigurability.

The network capacity depends on the splitting ratio K in the trees. Experimental results demonstrate that, for a K= 16, 32 and 64 the data rate per user is 125, 62.5 and 32.25Mb/s respectively in a GPON at 2.5Gb/s [Bock, 2007].

The main ring couplers ratio (figure 5.8) is also an important parameter to optimize. For the reduction of the ring path attenuation leads to a optimization of x and y according to the equation (5.4):

$$x = (2 \cdot N - 2) / (2 \cdot N - 1) \; ; \; y = 1 / (2 \cdot N - 1) \qquad (5.4)$$

The equation (5.4) demonstrates that the coupling factor stabilizes for N > 3 and that the coupling factors commercially available 90/10 provide a efficient solution for flexible and scalable solution keeping the total losses low *[Bock, 2006:1]*.

The equation (5.5) demonstrates the PB for the network with gain (G) provided by the RN:

$$PB \geq (N - 1) \cdot 20 \cdot \log x^{-1} + 10 \cdot \log y^{-1} + N \cdot L_{EX} + 3 \cdot \log_2 (U / 2N) + L_S - G \qquad (5.5)$$

Remotely optical amplification by means of the remotely pumped EDFs improve the PBs in PONs but for the other hand it produces a reduction of the OSNR that is higher than 26dB for DS and higher than 34dB for US.

Despite the simplicity of the implementation of this RN topology, it requires US and DS signals to have different wavelengths to avoid Rayleigh Backscattering distortions not utilizing the spectrum in a efficient way *[Bock, 2006:1]*.

5.3.2 Signal Topology 2

To avoid the previous impairments of efficient optical spectrum handling and use of non reflective ONU a new topology was proposed in figure 5.9. In this new configuration the main WDM ring is implemented with 2 fibers instead of 1. One of the fibers is used for DS signals and the other for US signals. The US signals follow a similar path to the DS but they pass through different EDFs and different fiber rings.

With this topology requirements related to Rayleigh Backscattering distortions in the ring are relaxed and more efficient utilization of the spectrum can be achieved. Since in the access tree the DS and US signals are present in the fiber with the same wavelength those distortions still remain.

The pump power to the EDFs is present in the US fiber producing extra Raman gain to the signals with lower power, the US signals. With this RN architecture, the transition from double fiber ring to single fiber tree section is provided by means of a 2:2 optical coupler and two isolators as a more cost effective solution than a circulator. Then the TDM trees are implemented with two 1:16 power splitters per tree.

Four EDFs are implemented in the RN, two for US and two for DS for each tree, increasing the total pump consumption compared with the previous architecture where just two EDFs were implemented. After the remote amplification, a second filter avoids addition of ASE noise to other channels which would result in decreasing the OSNR. Finally, for a much more convenient network implementation with identical ONUs, a wavelength agnostic transmission device is implemented. Reflective Semiconductor Optical Amplifiers (RSOAs) are suitable devices due to their capabilities for re-modulation and amplification, as well as their wavelength independence. An ONU has been implemented with a power splitter, an RSOA and a receiver similar to the one user in the CO *[Baptista, 2008:2]*.

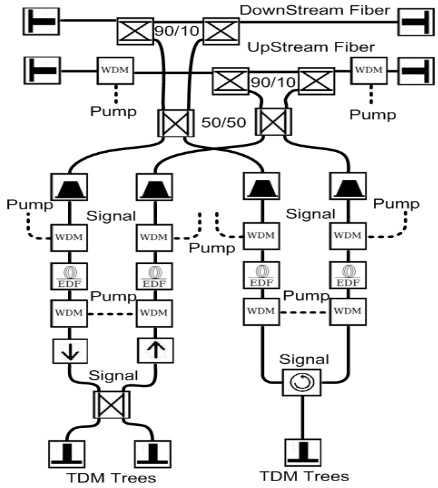


Figure 5.9: Double ring fiber Remote Node simple topology proposed in *[Baptista, 2008:2]*

The figure 5.10 presents the BER sensitivity measurements for a network with the referred RN topology. The four curves represent Back to Back CO-ONU, ONU at RN4, RN8 and RN 12 reaching almost 800 ONUs for 50km. It can be observed a penalty to the most distant ONUs but no floor level was found.

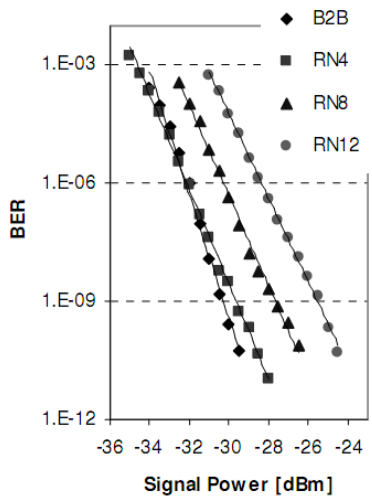


Figure 5.10: Bit error rate measured to the Upstream signal *[Bock, 2007]*.

It has been experimentally demonstrated for 512 ONUs and 50kms ring, 512 ONUs and 100kms ring and 1024 ONUs and 50kms ring with guaranteed downstream bandwidths of 155Mb/s per user *[Lazaro, 2006]*.

5.3.3 Signal Topology 3

With the RN architecture of figure 5.9, the Add&Drop function is still made recurring to couplers 90/10. Usage of those couplers causes the network to be easily scalable and simple to implement, however there are important limitations related to the RN insertion loss in the ring. To solve this limitation a new topology was proposed: the Add&Drop function was made now by means of thin-film filters, which is a very mature technology able to provide very good performances at low cost.

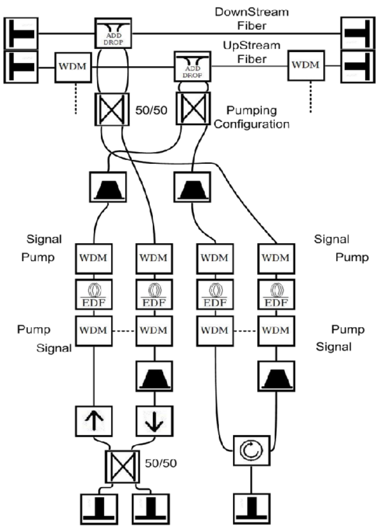


Figure 5.11: Remote Node topology based on OADM thin filters *[Baptista, 2008:2].*

The advantage of this RN configuration is its complete transparency for the WDM channels present in the ring being the RN just dropping the assigned wavelengths and not dropping 10% of the total power as the previous and reducing the drop attenuation from 10,2dB to only 0,8dB and the pass IL from 1,4dB to 0,8dB. Each DS EDF amplifies both the DS signals and other thin-film filter is used forward to limit the ASE noise and select the appropriate wavelength for the corresponding tree. Experimental results had demonstrated that with this RN implementation is possible to achieve 1024 ONUs by means of 16RN spread over a ring with 100Km *[Lazaro, 2007]*.

5.3.4. Signal topology 4

Despite of the topology used for pumping, improvements can be made in terms of signal topology in the RN. The RN topologies proposed previously were implemented with 4 EDFs requiring, therefore, higher pump power and not using one of the properties of the amplifiers based on EDFs that is the multichannel amplification. To solve that limitation several RNs approaches were proposed based on 2 EDFs RNs *[Baptista, 2008:2]*.

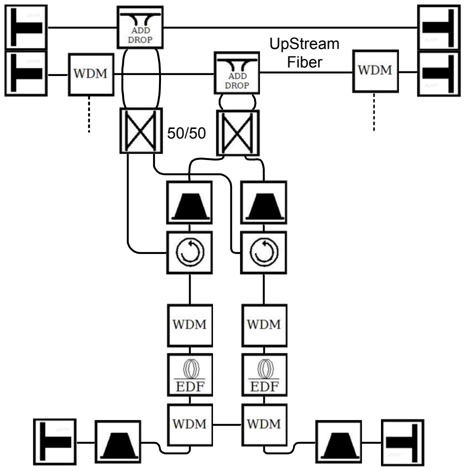


Figure 5.12: RN topology based on 2 EDFs and tunable tree gain *[Baptista, 2008:2].*

The first solution is presented in figure 5.12. This architecture provides independent gain to each tree of the RN. It can be adjusted depending on the distance of the ONUs from the RN and the number of ONUs per tree. By means of optical circulators, each EDF is supplied with the US and the DS signals of each tree, this means, with the same wavelength. Therefore, the Rayleigh Backscattering distortion in the EDF becomes an important limitation for this RN configuration by causing significant signals degradation *[Baptista, 2008:2].*

5.3.5. Signal topology 5

A second proposed architecture with 2 EDFs is presented in figure 5.14. Each EDF is supplied with the DS signal of one tree and the US signal of the other tree, transmitting the two signals at different wavelengths, reducing the Rayleigh Backscattering distortions. This architecture also provides a better stabilization of the transient burst gain. The main disadvantage of this configuration is that the gain of each signal cannot be adjusted independently *[Baptista, 2008:2].*

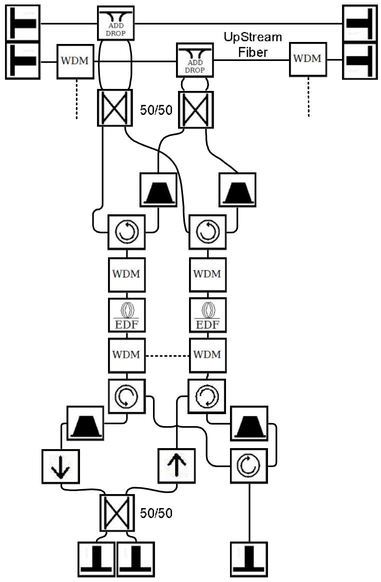


Figure 5.13: RN topology based on 2 EDFs and no tunable independent gain *[Baptista, 2008:2]*.

5.3.6. Signal topology 6

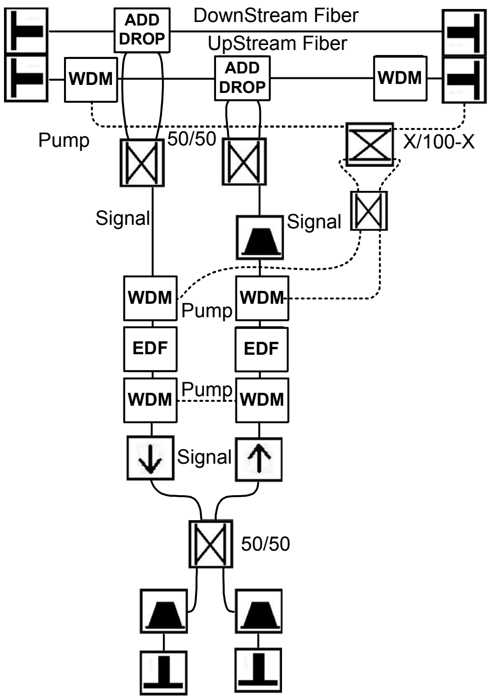


Figure 5.14: RN topology based on 2 EDFs and tunable independent gain to Upstream and Downstream signals *[Baptista, 2008:2]*.

A third alternative to the previous architectures is presented in figure 5.14. An EDF is supplied with the DS signals and the other with the US signals. Since the signals are at different wavelengths, Rayleigh Backscattering distortions is not a limitation. It can also provide independent gain for DS and US signals. This configuration is the adopted as the most appropriated to implement optical switching to select between amplification and non amplification modules since it can operate differently for fiber failure in the US and DS domain *[Baptista, 2008:2]*.

5.4. Remote Node Proposed

Considering the operation points with highest efficiency for different EDFs demonstrated in *[Baptista 2008:3]*, some improvements can be applied to the previous RN topology. Despite the ability of the RN to select between amplification and non amplification modules, for different distances from the CO, different gains are required. Having in mind the previous goal, an improved RN topology is presented in figure 5.15 b).

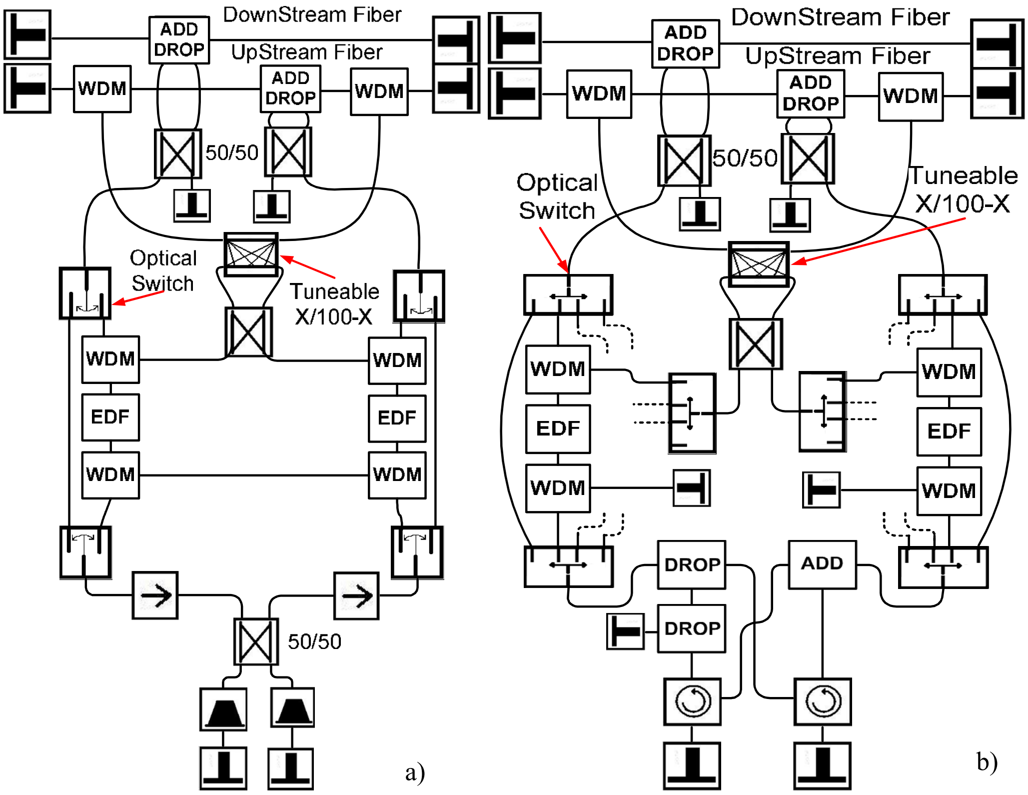


Figure 5.15: a) Proposed Remote node topology based on two EDF, amplification or non amplification modules and tunable pump power splitting *[Baptista, 2008:3]*. b) Upgrade from previous remote node architecture reducing the losses in the trees filtering and providing multiple reconfigurability.

This proposed RN topology is able to select a different EDF optimized to the necessary gain for the operation mode of the network, reducing the total amount of pump power required per RN, increasing the total efficiency of the network. Another improvement presented is related to the usage of circulators instead of power splitters at the tree side of the RN saving extra 3dB thinning the required gain per RN.

5.5. CONCLUSION

This chapter presented the studied topologies of Remote Nodes for the SARDANA network comparing between each other. It starts to present a simplified version of the RN implemented for a single fiber ring requiring an non Reflective ONU since US and DS signals require to be in different frequencies to avoid Rayleigh Backscattering distortions. Although its simplicity, it does not use the optical spectrum in an efficient manner requiring the more sophisticated ONU, so, new topologies were proposed and observed. Alternative topologies are based on double fiber ring. There were studied two different optimizations, the pump and the signal paths.

Pump path topologies started with simple supplying the EDFs present in the RNs with all the pump power available in the ring thus reducing the total network efficiency. To solve this impairment, topologies based on pump power splitting were presented. The RN just drops a fraction of the total pump power available in the ring and supplies it to the EDFs. The main goal here is to optimize the pump power coupling ratios in order to allow the network to operate efficiently in resilient mode and provide scalability. The problem with these topologies is that the optimization of the ratios for normal mode is not efficient for resilient mode. Topologies based on remote reconfigurability solve this problem. The first approach is able to select between 2 distinct power couplers ratios by means of optical switching. One power coupler ratio is optimized for normal mode and the other for resilient mode. Despite of the optimization of this topology, the network is not fully scalable since inserting an extra RN requires modification of the power coupler ratios The second approach is implemented with a tunable power splitter instead of optical switching, allowing an fully scalable and resilient network, dropping just the necessary amount of pump power from the ring. A final optimization consists on reconfigure the RN between two modules: amplification modules and direct link not providing gain. These last pump path topologies consider the distance between the RNs and the CO. It allow a substantially save in terms of pump power for the RNs close the CO, since they do not require gain.

The signal path topologies were also an important optimization demonstrated in this chapter. The first evolution is related to the Add&Drop function, made by means of thin film filters instead of power couplers. With this, the introduction of RNs is almost transparent for the WDM channels present in the ring. A further improvement consists on applying the multi channel amplification characteristics of the EDFs, reducing the number of EDFs from 4 to 2. Three topologies were presented and compared each of them with 2 EDFs. The preferred topology allows adjust independent gain for US and DS signals depending on the operation mode.

Chapter 6. Optical Components analysis

6.1. Erbium Doped Fiber

6.1.1. Theoretical Introduction

A very important component to analyze, understand and optimize is the remotely pumped EDF in the RN. It is crucial for the efficient operation of the network that the EDFs operate at the maximum efficiency point for the requested gain.

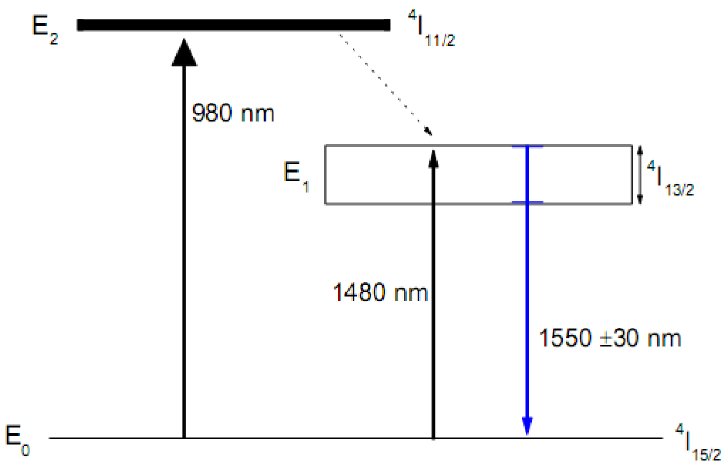


Figure 6.1: Erbium doped fibers energy levels *[André, 2002]*.

The Erbium ions can be used as a system with three energy levels suitable for amplification of C-band (1550nm). In the figure 6.1 the Erbium (Er^{3+}) energy levels are demonstrated *[André, 2002].* The level $^4I_{13/2}$ has a high energy band, that is metastable and presents a high average lifetime of some milliseconds. Ions at this level drop radioactively to the $^4I_{15/2}$ level, emitting photons in the band 1520-1580nm, corresponding to the C band. The population in the $^4I_{13/2}$ level is indirectly pumped with 980nm photons or directly pumped with 1480nm photons. The photons with 980nm are absorbed by the fundamental level and the carriers transit to the $^4I_{11/2}$ level. The non radioactive transition from $^4I_{11/2}$ to $^4I_{13/2}$ occurs within approximately 7μs, increasing the population of the metastable level $^4I_{13/2}$. The EDFs energy transitions can be interpreted as a 3 level system *[Agrawal, 2002].*

The 3 level system requires high pumping powers to achieve inversion of the population. A continuous pump radiation causes transition from the E0 level to the E2 level and at same time from E2 level to the E1 level. If the transitions from the E2 level to the E1 level are fast enough , the population in the E1 level increases compared to the E0 level referenced as inverted population. Spontaneous emission of photons occurs when the population in E0 level is higher than in the E1. When the pump is enough to keep the population in the E1 level higher than E0, the stimulated emission is predominant.

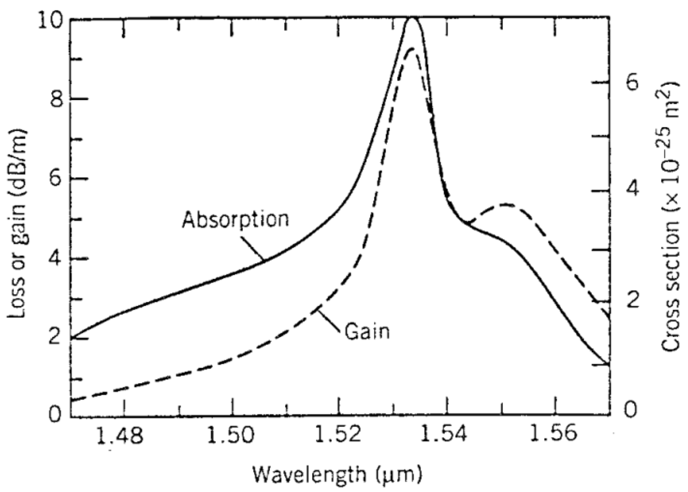


Figure 6.2: Erbium doped fiber absorption and gain dependent on the signal wavelength *[Agrawal, 2002].*

The gain spectrum and absorption is given in figure 6.2. It is the most important feature of an EDFA as it determines the amplification of individual channels when a WDM signal is amplified. The shape of the gain is affected considerably by the amorphous nature of silica and by the presence of other codopants within the fiber core such as Germania and alumina. Mathematically, the total gain of the EDFA is give by the equation *[Agrawal, 2002*]:

$$G = \Gamma_s \exp\left[\int_0^L (\sigma_s^e N_2 - \sigma_s^a N_1)\, dz\right] \tag{6.1}$$

where L is the length of the fiber, N1 and N2 are the population density in the level, E0 and level E1 respectively, Γ_s is the confinement factor, σ^e_s and σ^a_s are the emission and absorption cross sections.

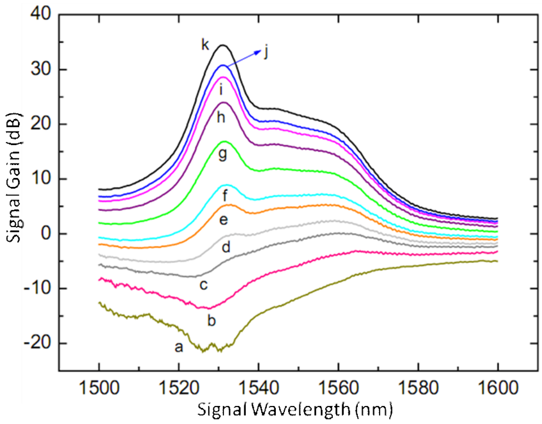


Figure 6.3: Gain Spectrum to low power signals to different pump powers a) 0.4 mW, b) 0.6 mW, c) 1.0 mW, d) 2.0 mW, e) 2.5 mW, f) 3.0 mW, g) 5.0 mW, h) 10.0 mW, i) 20.0 mW, j) 30.0 mW e k) 70.0 mW. *[André, 2002].*

The figure 6.3. presents the signal gain in the EDF for different values of pump power at 980nm and input signal low. For pumping powers higher than the transparency the gain region is higher than 20nm. This characteristic is very important when developing amplifiers since it is able to provide equal gain for signal in 1540 and 1560nm (for this special fiber).

The figure 6.4 shown for the signal gain and signal output power depending on the input signal power for pumping power at 980nm of 15.8, 40.1, 65.8 and 90mW. It demonstrates the saturation effect of the amplifier. For these cases, the efficiency of the amplification decreases for input signal power higher than -20dBm due to the saturation of the amplifier. Lower the input signal power provided to the EDF higher the signal gain until saturation. Further the amplification goes into saturation an exponential increase in the noise figure is achieved. For an efficient amplification, one should not get further into the saturation mode due to the lowering of the gain, higher pump consumption and higher degradation of the signal *[Andre, 2002]*.

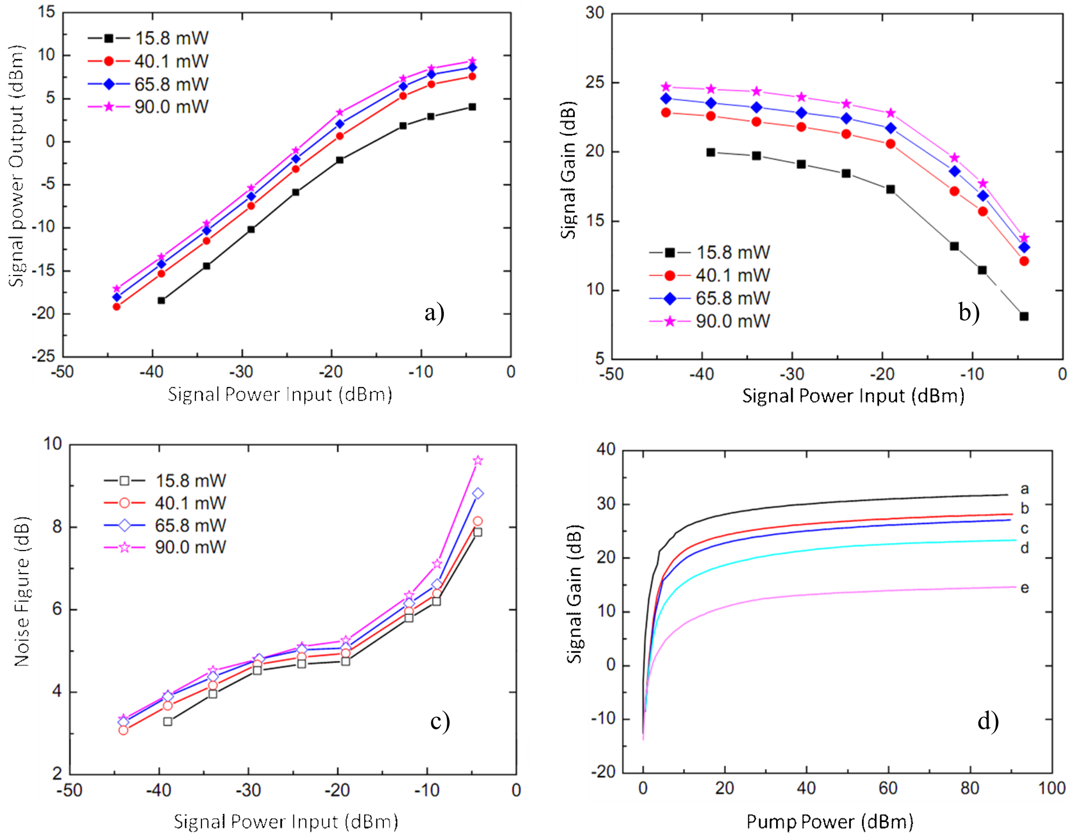


Figure 6.4: a) Output signal power in function of the input signal power to various supplied pump power;b) Gain in function of the input signal power for different supplied pump power;c) Noise figure in function of the input signal power to various supplied pump power;d) Gain in function of the pump power to different values of signal input power(a) –44 dBm, b) –34 dBm,c) –24 dBm, d) –14 dBm e e) –4 dBm.) *[André, 2002]*.

The figure 6.5 shows the small signal gain at 1550nm as function of the pump power and the amplifier length by using typical parameter values. For a given amplifier length L, the amplifier gain initially increases exponentially with the pump power, but the increase becomes much smaller when the pump power exceeds a certain value. For a given pump power, the amplifier gain becomes maximum at an optimum value of L and drops sharply when L exceeds this optimum value. The reason is that the latter portion of the amplifier remains unpumped and absorbs the amplified signal. Since the optimum value of L depends on the pump power P_p, it is necessary to choose both L and P_p appropriately. It is possible to design amplifiers such that high gain is obtained for amplifier length as short as a few meters or even cm for EDFs with peak absorption of 130 dB/m. The output saturation power is smaller than the output pump power expected in the absence of signal *[Agrawal, 2002]*.

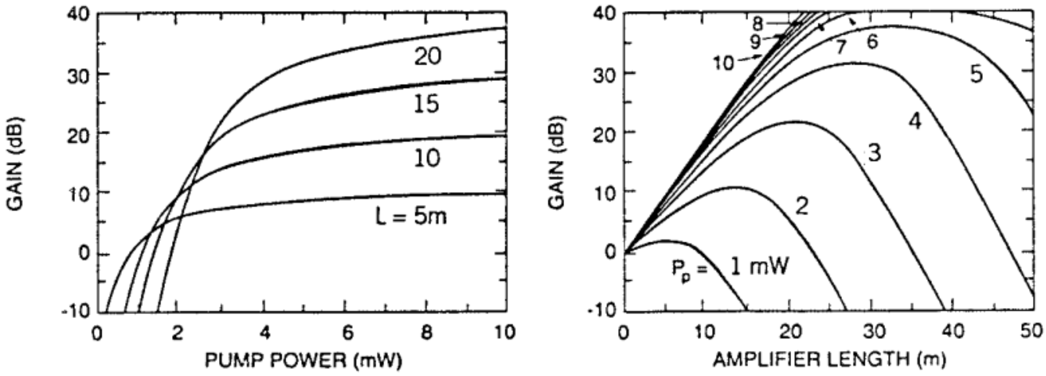


Figure 6.5: Signal gain in function of supplied pump power and EDF length *[Agrawal, 2002]*.

The amplifier noise is the ultimate limiting factor for system applications *[Agrawal, 2002]*. The ASE noise, can be expressed by the following equation:

$$P_{ASE} = \mu \cdot [G_0 - 1] \cdot h \cdot \upsilon \cdot d\upsilon = \rho_{ASE} \cdot d\upsilon \qquad (6.2)$$

where the ρ_{ASE} represents the ASE spectral density, that propagates in the same direction of the signal. The impact of ASE is quantified through the noise figure F_n given by $F_n = 2n_{sp}$. The spontaneous emission factor n_{sp} depends on the relative populations N_1 and N_2 of the ground and excited states as $n_{sp} = N_2 / (N_2\text{-}N_1)$. Since EDFAs operate on the basis of a three level pumping scheme, $N1 \neq 0$ and $n_{sp} > 1$. Thus, the noise figure of EDFAs is expected to be larger than the ideal value of 3dB.

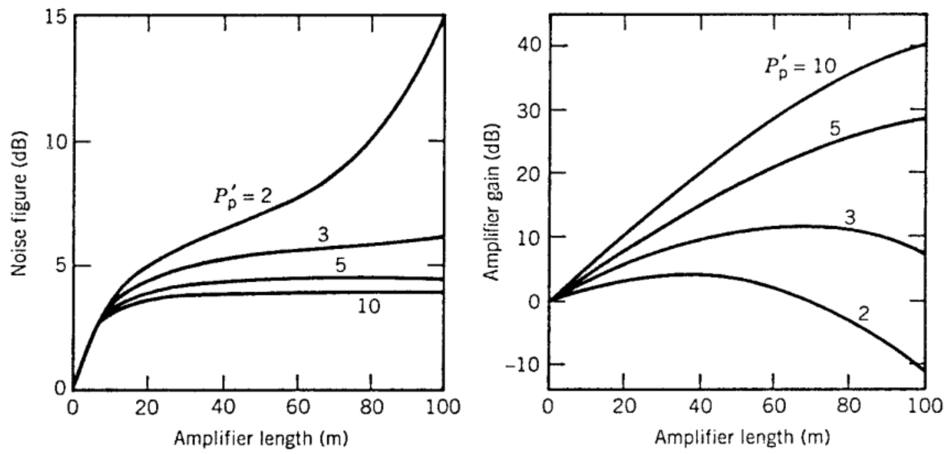


Figure 6.6: Noise figure and amplifier gain in function of supplied pump power and EDF length *[Agrawal, 2002]*.

Figure 6.6 shows the variation of the NF with the amplifier length for several values of P_p/P_p^{sat} and for a 1530nm signal is amplified with an input power of 0dBm. The amplifier gain under the same conditions is present in the same figure. The results show that a noise figure close to 3dB can be obtained for a high gain amplifier pumped such that $P_p \gg P_p^{sat}$. The relatively low noise levels of EDFAs make them an ideal choice for WDM lightwave systems. In spite of low noise, the performance of long haul fiber optic communication systems employing multiple EDFAs is often limited by the amplifier noise *[Agrawal, 2002]*.

The differences of the pumping with 980nm and 1480nm are: Pumping at 980nm allows higher gain for higher pumping powers due to a higher population inversion, the pump power required for transparency is lower for 1480nm due to the higher quantum efficiency, the ASE produced pumping at 980nm is lower due to the higher inversion of population, is easier to tune the laser for 1480nm due to the larger band level *[Andre, 2002]*.

There are three types of amplification schemes: co propagating (signal and pump travelling in same direction), where the NF is lower due to the higher population inversion in the input of the amplifier, the counter propagating (signal and pump travel in opposite directions) allows higher gain due to the higher population inversion in the output of the amplifier and the bi propagation (bi directionally pumping), that allows an intermediate situation. An hybrid bi propagation scheme with 980nm co propagated and 1480nm counter propagated allows an EDF with low noise and high output power *[Andre, 2002]*.

6.1.2. EDF's analysis State of Art in SARDANA network.

EDF measurements and comparisons were demonstrated. It is compared the Gain (G) and the Noise Figure (NF) for a relatively low Erbium concentration EDF the HE980 from OFS with peak absorption at 1530nm of 2,5 to 4,5dB/m.

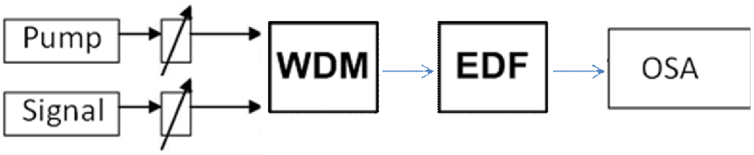


Figure 6.7:Schematic of the experimental analysis of EDF applied in SARDANA *[Bonada, 2007]*.

The system is described in figure 6.7. It consists on the pump source and signal source connected to optical attenuators and multiplexed together by means of an 1480/1550 WDM coupler. The common port of the WDM is then connected to the EDF and then connected to a Optical Spectrum Analyzer.

The measurements were made for 5, 10, 15 and 20m at a signal wavelength of 1543.73nm (42th ITU-T C band channel) with low power, -40dBm and for the pump power varying from -24 to 16 dBm.

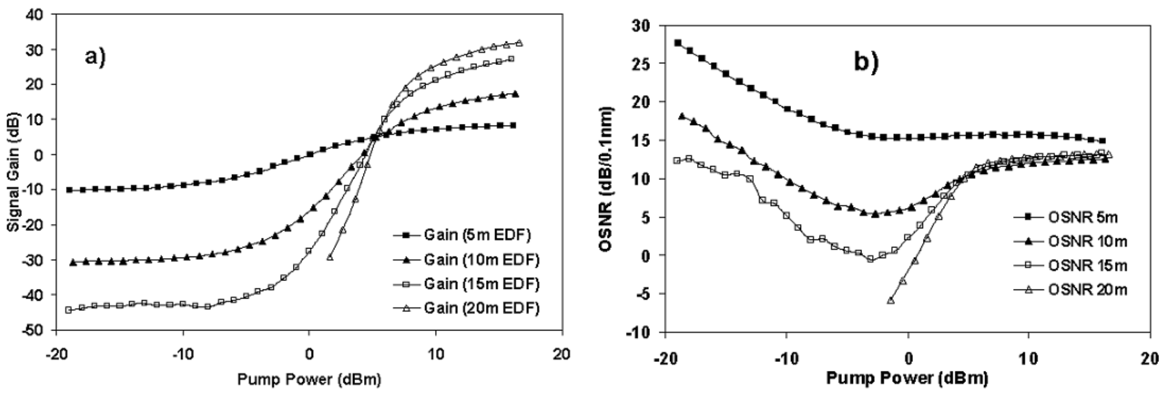


Figure 6.8: a) Signal gain in function of the EDF length and supplied pump power and b) OSNR in function of the EDF length and supplied pump power *[Bonada, 2007]*.

The figure 6.8 demonstrates the gain and OSNR for the different lengths. It can be seen that the transparency of amplification is achieved for approximately 5dBm of pump power and the OSNR is approximately equal to 12 dB/0.1nm for 10, 15 and 20m and 15 dB/0.1nm for 5m for pump power higher than the transparency. The gain is approximately 10dB for 5m of EDF and 30dB for 20m.

The Noise Figure can be defined as the relation between the input SNR and the output SNR of the EDF *[Polo, 2007]*. Considering the main limitation of the signal detection the signal spontaneous noise power ($N_{S\text{-}SP}$), the Noise Figure can be calculated by the forward equation:

$$NF = \frac{P_{ASE}}{h\nu\Delta\nu G} \tag{6.3}$$

where P_{ASE} is the ASE power, $h\nu$ is the energy of photon, $\Delta\nu$ is the resolution bandwidth of the Optical Spectrum Analyzer (0.1nm in the referenced case) and G is the Gain of the EDF.

Considering also the shot noise (N_{shot}) and the spontaneous-spontaneous noise ($N_{SP\text{-}SP}$) powers, the NF is calculated respectively with the equations:

$$NF = \frac{P_{ASE}}{h\nu\Delta\nu G} + \frac{1}{G} \tag{6.4}$$

$$NF = \frac{P_{ASE}}{h\nu\Delta\nu G} + \frac{1}{G} + \frac{P_{ASE}{}^{2}(2B_o - B_e)h\nu}{4(h\nu\Delta\nu)^2 G^2 P_{in}} \tag{6.5}$$

where B_o is the optical bandwidth of the filter after the EDF, B_e the bandwidth of the electrical filter in the receiving circuit and P_{in} is the optical power at the input of the amplifier.

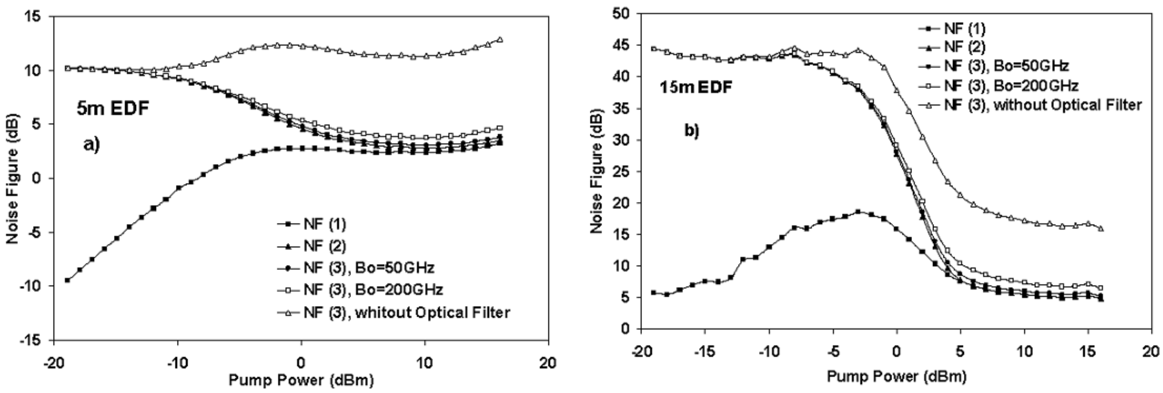


Figure 6.9: Noise figure in function of the supplied pump power and the method used to quantify for a) 5m and b) 15m of EDF length *[Bonada, 2007]*.

From the figure 6.9 it can be seen that considering the three equations for the NF between 5 and 16dBm of pump power the NF achieve values near 3dB for 5m and 5dB for 15m of EDF, although, when no optical filter is used after amplification with equation 3, the NF increased 10dB due to the dependence of the third term in equation with bandwidth of the optical filter B_o. For low pump power supplied to the EDFs it can be seen different behaviors of the NF for the equations.

The highest efficiency is achieved for 10m of EDF, providing 15dB of gain for a signal at -20dBm pumped with 14dBm providing an power conversion efficiency of about 2%.

The figure shows the measured gain curve and pump attenuation for 10m of EDF for pumping power varying from -25 to 16dBm and small signal (-42dBm). The gain saturates for 15dB with an input pump power of 16dBm leading to a pump power consumption of 14dBm. For an input pump power of 11dBm the gain decreases 3dB. A reduction in the supplied pump power also decreases the OSNR after the amplification. For 16dBm of pump power the NF is 5,3dB and reducing the pump power for 11dBm (-3dB of gain) the NF increases to 5,7dB *[Bonada, 2007]*.

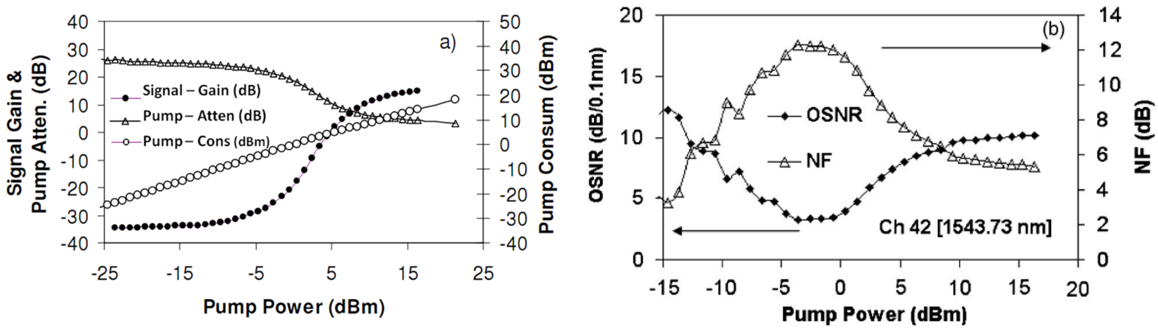
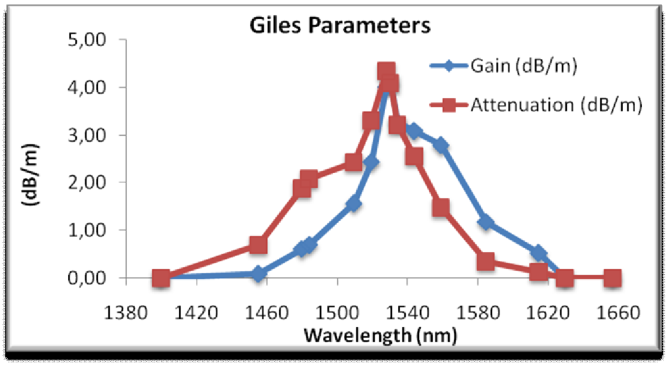


Figure 6.10: a) Signal gain and pump attenuation for 10m EDF in function of the supplied pump power and b) OSNR and Noise figure in function of the supplied pump power *[Lazaro, 2007]*.

6.1.3. Simulation VPI

Analysis of the EDFs characteristics by means of simulation with the VPI. It pretends to study the EDFs for different possible cases and situations possible to be implemented in the real network, and adjust the parameters to the most efficient.

The EDF considered is the HE980 from the OFS. The parameters responsible for a characterization of an EDF by means of optical simulation can be expressed as the Giles Parameters. The figure 6.11 and the table express those parameters for the respective fiber.



Wavelength (nm)	Gain (dB/m)	Attenuation (dB/m)
1400	0,00	0,00
1455	0,09	0,69
1480	0,61	1,88
1484	0,69	2,08
1510	1,56	2,43
1519	2,43	3,30
1528	4,00	4,34
1530	4,08	4,08
1534	3,26	3,21
1544	3,08	2,56
1559	2,78	1,48
1585	1,17	0,35
1614	0,52	0,13
1629	0,00	0,00
1656	0,00	0,00

Figure 6.11: Giles parameters (Gain/Attenuation) for the EDF HE980 *[OFS]*.

These Giles parameters can be inserted in the EDF characteristics in the EDF properties in the VPI. The saturation factor is kept constant and equal to the default value, 2.4e15*1/(m*s).

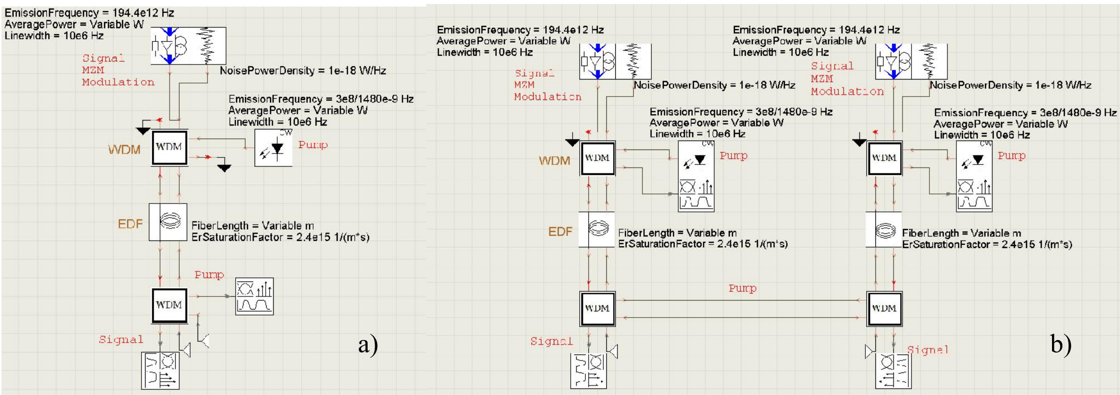


Figure 6.12:a) Schematic for the single direction pumping and b) schematic for bidirectional EDF pumping used in VPI simulation

In order to simulate the EDF in VPI with the same conditions that were demonstrated experimentally in *[Lazaro, 2007],* the schematic is presented in figure 6.12. It consists on an EDF connected at both sides by two WDM couplers 1480/1550nm. These WDM couplers are not default components since they do not implement bi-directionality, so they were implemented providing bi-directionality. The first WDM is supplied with a signal at 194.4THz, the same frequency of the state of art analysis modulated with an MZM, and a NRZ signal at 5Gb/s, and the pump signal at 1480nm. In the second WDM the signal and the pump are separated in order to achieve a better comparison of the real case. The figure implement a second version of simulation that consists of 2 EDFs bi directionally pumped being the reminiscent pump power of and EDF supplied to the other EDF.

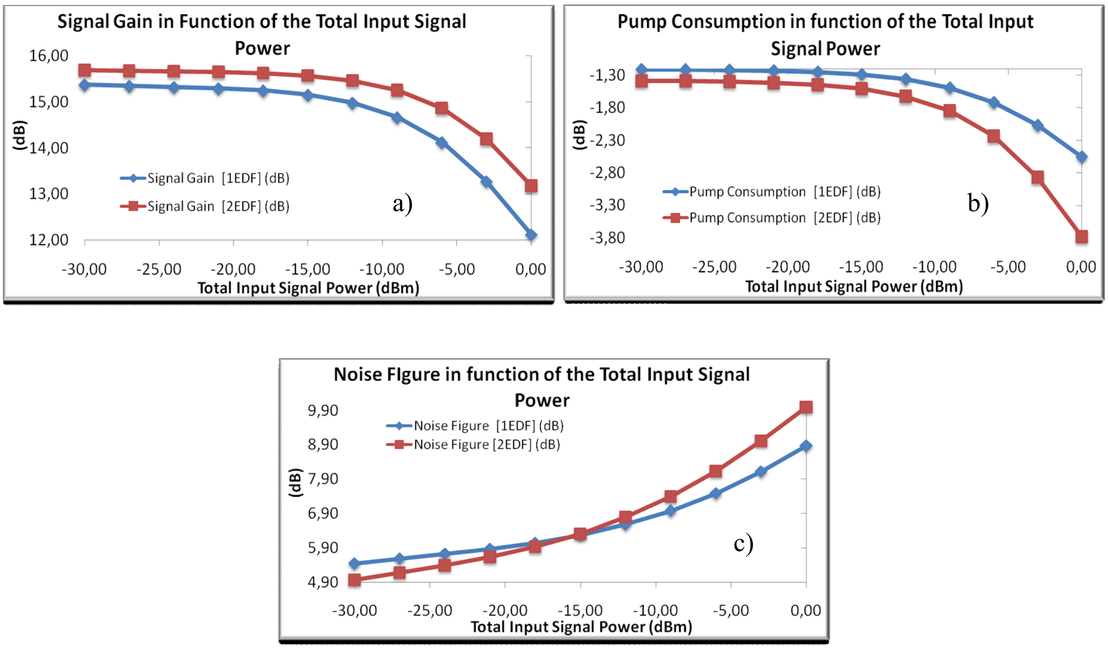


Figure 6.13:a) Signal gain, b) pump consumption and c) Noise Figure in function of the input signal power for the both mono directional and bidirectional schematics.

Figure 6.13 presents the results of a simulation pretending to optimize the EDF's parameters. It consists on adjusting the EDF length for 10m, the pump power to 16dBm and adjusting the signal power from -30dBm to 0dBm analysing the signal gain, pump attenuation and noise figure. It can be seen in figure 6.13a) that, as expected, the gain starts to decrease for signals higher than -15dBm also leading to an increase in the pump attenuation and noise figure, diminishing the signal quality. It demonstrates that, for the specific Giles parameters, the gain efficiency decreases drastically for signals higher than -15dBm. It can be also noticed that higher amplification and better results are achieved for the second schematic where EDFs are bi directionally pumped. In saturation gain mode, for signals with low power, the gain achieved is approximately 16dBm and the pump attenuation is 1.5dB. These values are stricly higher than the presented in *[Lazaro, 2007]* due to the optimal system considered in simulation.

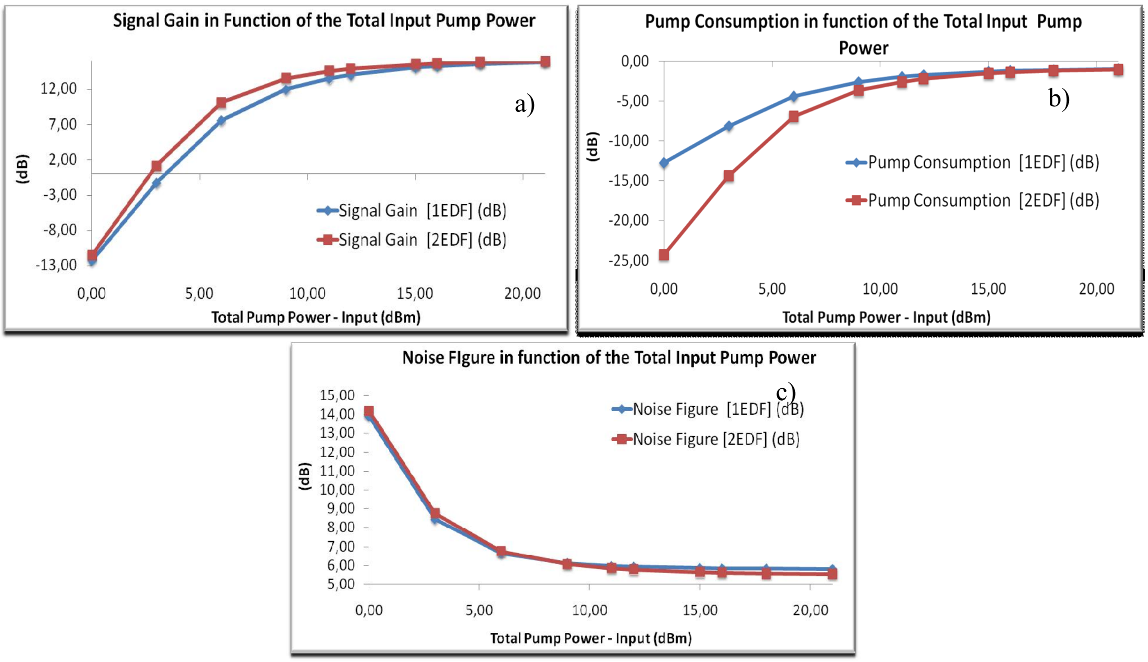


Figure 6.14: a) Signal gain, b) pump consumption and c) Noise Figure in function of the input pump power for the both mono directional and bidirectional schematics.

A second simulation consists on varying the supplied pump power to the EDF from 0 to 20dBm keeping the EDF length at 10m and the input signal power at -30dBm. It can be seen from figure 6.14 that for these Giles parameters, the amplifier saturates for 11dBm of input pump power causing a pump consumption of aproximately -2.5dB, providing a signal gain of approximately 16dB. The Noise figure saturates for of around 6dB.

The graphs demonstrate that the EDF should be just supplied with the minimum pump power responsible for saturate the amplifier. Increasing the pump power for higher values does not increase the gain considerably, decreasing the efficiency of the amplifier. On the other hand, it is desirable option to operate the amplifier in the saturation mode as it does not change significantly the gain for changes of the supplied pump power. Further analysis describe the points of higher efficiency for different gain. It can be seen also that for saturation operation, the bi directionally pumping does not provide significant improvement and increases the pump demand.

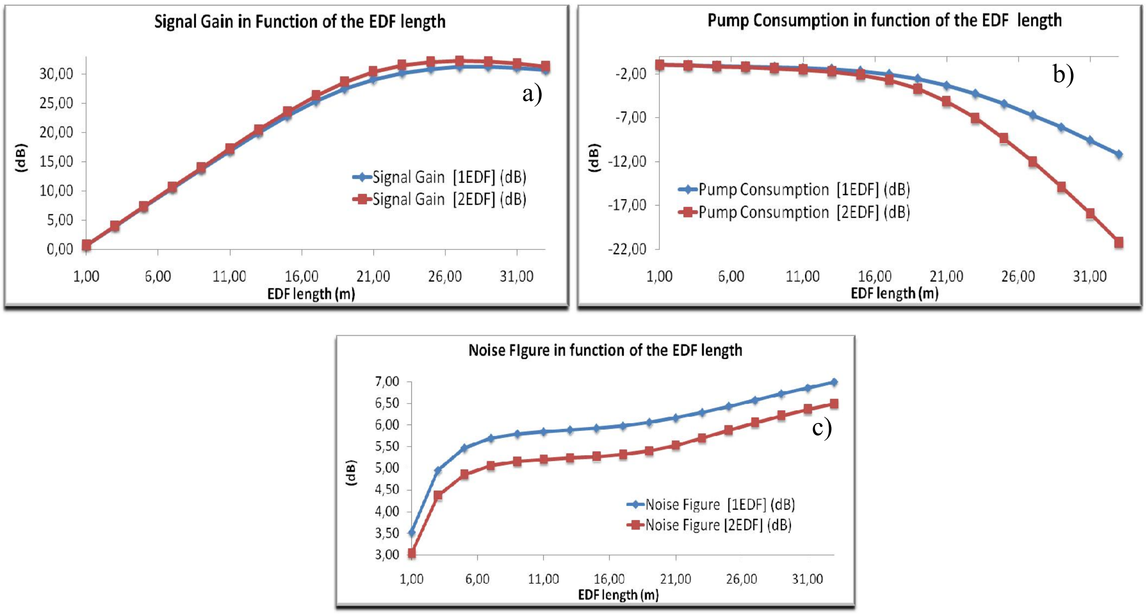


Figure 6.15: a) Signal gain, b) pump consumption and c) Noise Figure in function of the EDF length for the both mono directional and bidirectional schematics.

A third simulation consists on keeping constant the pump power supplied to the EDF at 16dBm and the signal power at -30dBm and varying the length from 1 to 32m as presented in figure 6.15. As the EDF length increases the gain also increases linearly until the 19m where the gain starts to saturate achieving the peak for 25m. The pump consumption is kept mainly constant (about -1dB) until the 19m where it starts to increase. In what regards for the noise figure, it has an initial exponential increase saturating for lengths higher than 7m, starting to increase smoothly after 19m.

This can show that the EDFs length is the most important parameter to optimize in an amplification stage. An extensive analysis will be provided further by means of analysing different lenghts in order to achieve the most efficient amplification.

The forth simulation consists on studying the Rayleigh Backscattering (RB) distortion in an EDF. The schematic of the simulation is presented in figure 6.16. The EDF is supplied with two signals counter propagating in the same wavelength.

The simulation consists in varying the signal’s power from -21dBm to -3dBm keeping the other signal with a constant power of -21dBm. The input pump power is 16dBm and the EDF’s length is 10m. Figure 6.17 shows the results of the simulation in terms of the OSNR and Extinction Ratio.

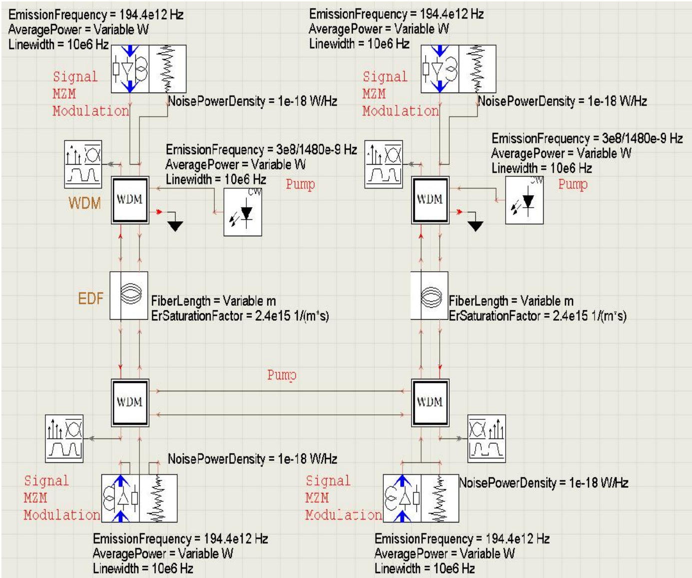


Figure 6.16: Schematic of bidirectional bi pumped EDF to analyse Rayleigh Distortions.

It can be seen that the degradation of the signal, that is mainly limited by the RB power, is linear for the increase of the power difference. It can be easily seen that the best quality signal is achieved for the EDF amplifying both signals in the opposite direction with the same power. In the figure is presented an analysis of the frequency deviation of the signals present on the EDF. Both input signals are kept with constant power of -18dBm and 0dBm, the pump power at 16dBm and the EDFs length at 10m. It can be seen that a simple 2GHz of signal deviation provides an improvement of the signal quality. For signal deviation of 10GHz and further, the signal characteristics are kept constant. An EDF is able to amplify bi directional signals without limitations imposed by RB distortions if they are shift at least 10GHz. Comparing the results of both graphs of figure 6.17, it can be concluded that for these Giles parameters, the EDF provides better efficiency in terms of signal quality for bi directionally amplification for signals with the same input power in the EDF shifted at least 10GHz from each other.

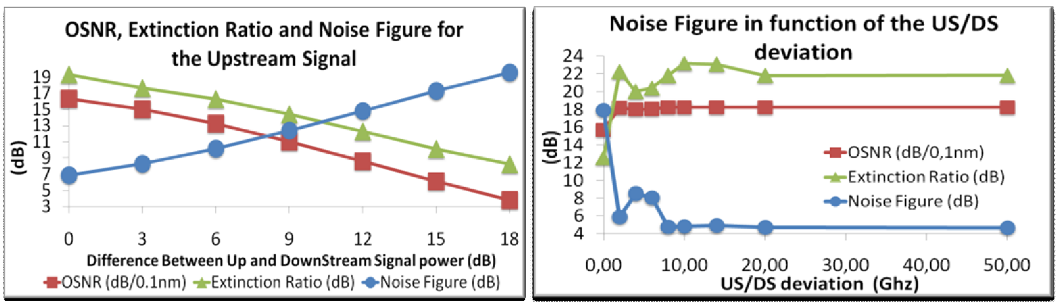
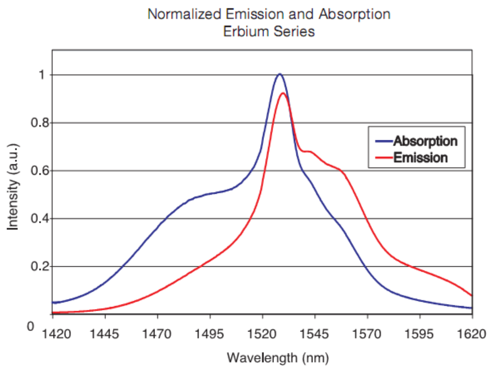


Figure 6.17: OSNR, NF and ER in function of the a) difference between US and DS signal powers and b) US/DS frequency deviation.

6.1.4. Experimental Analysis

As described previously it is very important to optimize the EDF's parameters to achieve the highest efficiency. Experimental analyses were demonstrated for different Erbium concentration EDFs with different lengths [Baptista, 2008:3]. The system was implemented as the one described in the schematic present in figure 6.12 a).



	Peak Absorption (dB/m)
M5-980-125	4,5-5,5
M12-980-125	11-13
ER30-4/125	27-33

Figure 6.18:Giles parameters from the experimental fibers *[Thorlabs]*.

The figure 6.18 and the table show the Giles parameters for the three different fibers used in the experimental. In the laboratory at the moment of this experience there were not the same fibers as used in simulation and analyzed in the state of art. Therefore were used other fibers for the experimental implementation from Thorlabs, the M5-980-125, the M12-980-125 and the ER30-4/125. In the experience is kept constant the signal power at -20dBm and the supplied pump power varied between 6 and 16dBm. In order to match the results of the previous chapters the product Peak Absorption and EDF length is 50 (dB/m x m) and this value is kept constant for the three EDF types. The four products for the fibers are 37.5, 50, 62.5 and 75 (dB/m x m).

The figure 6.19 shows the ratio Gain/Pump (dB/dBm) as an efficiency ratio and the curves of efficiency for 7, 11 and 15 dB of signal gain. It can be seen that for 7dB of gain the higher efficiency is for 37.5 (dB/m x m) for the 5dB/m EDF resulting on 7.5m of fiber. For 11dB and 15dB of gain, the higher efficiency is for the same fiber type but for 10m, resulting on a 50 (dB/m x m) product.

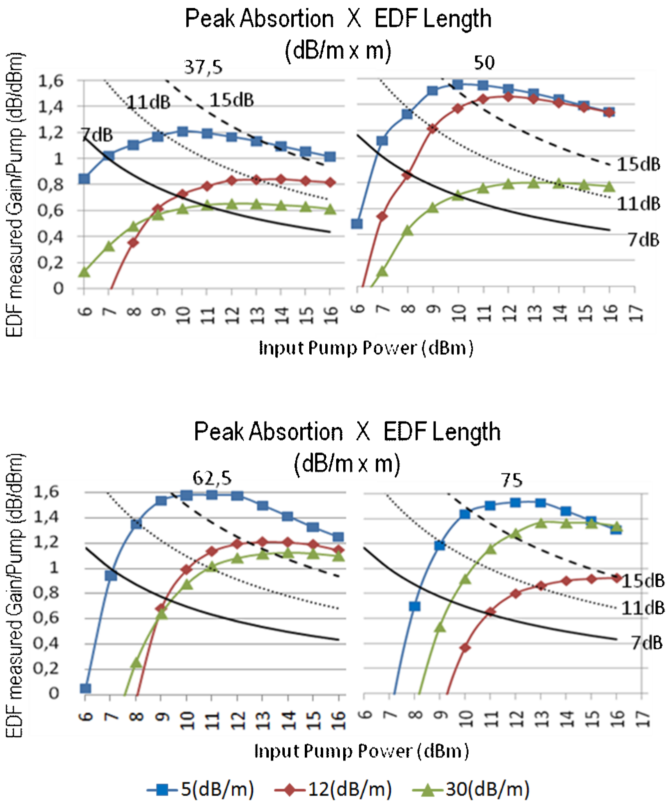


Figure 6.19: Gain/Pump (dB/dBm) in function of the input pump power.

Since 10m of the EDF with 5dB/m is the most efficient for 11 and 15 dB of gain a more extensive analysis is presented in the figure 6.20. For these cases the figure shows the gain and the pump power reminiscent for the EDF with 5dB/m of peak absorption for 7.5, 10, 12.5 and 15 m. For 7, 11 and 15dB of signal gain the EDF with 10m must be supplied with 7, 8 and 10dBm leading to reminiscent pump power of 3, 3 and 7dBm respectively. From these results, it can be seen that the reminiscent pump power from the 7 and 11dB of gain is not enough to supply a second EDF, although the reminiscent pump power from the 15dB gain is able to be redirected to a second EDF. This is an important factor developing the amplifiers configuration since it can lead to an optimal low pump requirement multiple amplifiers.

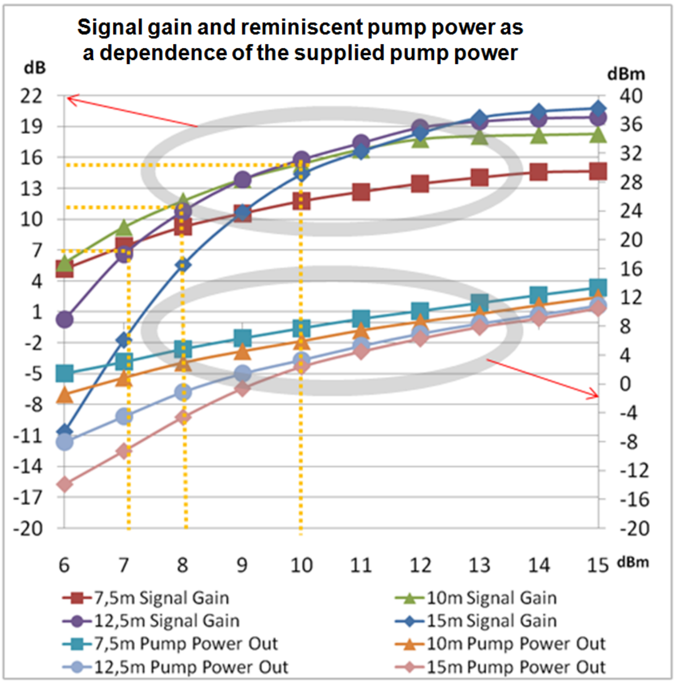


Figure 6.20: Signal Gain and pump reminiscent in function of the input pump power and EDF length.

6.2. Harvesting and Control in RNs

The most important component in the reconfigurability of the network is the power converter, control and harvesting module [Ramanitra, 2006], [Ramanitra, 2007].

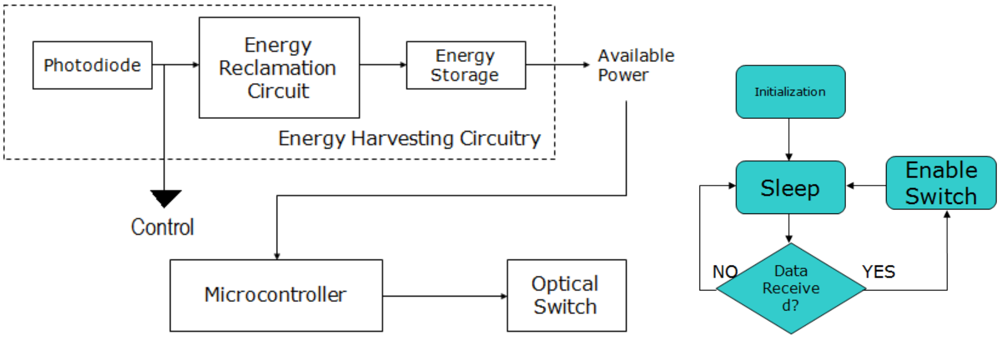


Figure 6.21: Schematic of the harvesting and control module and the micro controller states.

The figure 6.21 represents a block diagram of the equipment in the module and the operational states. An optical signal is supplied to the photodiode in the module. Part of the converted electrical signal is lead to a control unit by means of an RF component and the mainly part of the energy is supplied to an Energy Reclamation Circuit that will be stored (battery or capacitor). On the other hand, the control module is listening tones coded until it recognizes a pre allocated pattern and turn on the microcontroller that is on sleep mode. After the pattern, an operation is communicated and the microcontroller will act over external components, in this case optical switches, with the power stored in the battery/capacitor going back to sleep mode after.

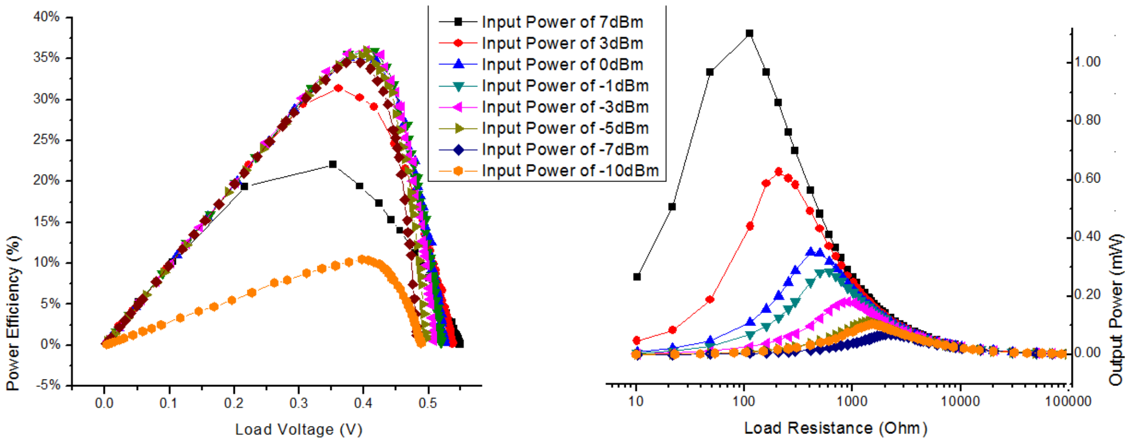


Figure 6.22: Power efficiency in function of the load voltage and the input optical power and the Output power in function of the load resistance and the input signal power.

Figure 6.22 presents the power conversion efficiency optical-electrical in function of the load voltage and the input optical power and the output electrical power as a function of the load resistance and the input optical power. It can be seen that the efficiency is higher for input optical powers between -7 and 0dBm and the output electrical power is higher for higher input optical power, so, the best operation point of this conversion unit is for 0dBm. Experimental tests made on this modules demonstrated the a possibility to control the unit with power as low as -25dBm, although, the minimum power for harvesting is much higher than that, what can be difficult to achieve if multiple modules of those are implemented in a very large network. Different topologies are being considered in order to increase the efficiency of the module and allow harvesting with lower input powers. Some similar equipment had been proposed in [Ramanitra, 2007]. A prototype of our module can be seen in the figure 6.23. In the left side is the input fiber with the optical control signal and energy supplier and in the right side the three optical switches 1 to 4 controlled remotely.

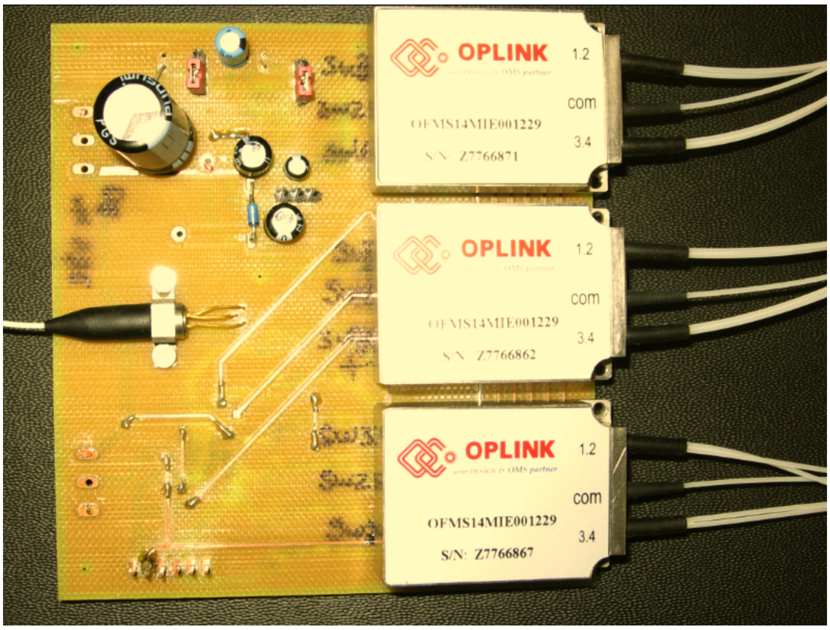


Figure 6.23: Module of harvesting and control developed at Instituto de Telecomunicações, able to control until 3 switches one to four.

6.3. Conclusions

In this chapter an analysis on one of the critical component, the EDF, is presented. It started with a theoretical review, presentation of the state of art made by SARDANA team, some simulation to predict behavior and experimental tests to obtain the higher efficiency operation points. From experimental it was concluded that the EDF that provides better efficiency was the low doped with peak absorption of 5dB/m.

The second component presented was the power converter, harvesting and control module. This module is responsible for the optimization of the network since it controls the optical switches and the tunable power splitters. The control and the energy is supplied by means of an specific WDM signal emitted from the CO keeping the network fully passive. Experimental testes made on this module demonstrated the possibility to control the unit with powers as low as -25dBm. Although, the minimum power for harvesting is much higher than that, what can be difficult to achieve if multiple modules of those are implemented in a very large network.

Chapter 7. Remote Nodes Comparison and Analysis.

7.1. System description and comparison

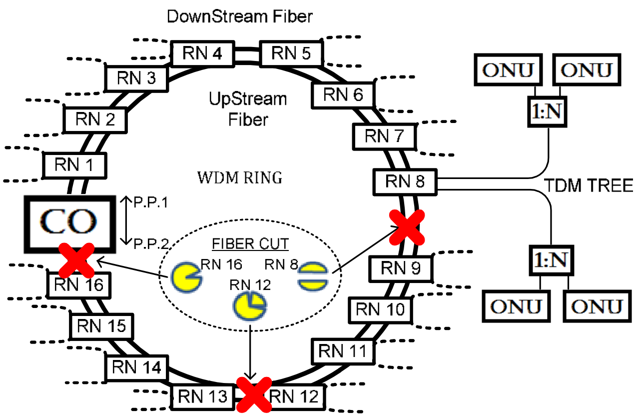


Figure 7.1: System description to analyze the RNs efficiency. Fiber cuts described at RN 8, 12 AND 16 *[Baptista, 2008:3]*.

In order to compare all the referred RN topologies, the SARDANA network was simulated. The figure 7.1 demonstrates the simulated scheme. The ring was implemented with 20, 40 and 60km with 16RNs, each with 2 trees and 32 users per tree 2km distant from the RN, for a total of 1024 users. There are compared the Non Optical Switching (NOS) architecture, the Optical Switching (OS), the Tunable Drop (TD) and the Reconfigurable RN (REC) all present in figure 7.2. The comparison between four RNs is presented in figure 7.3.

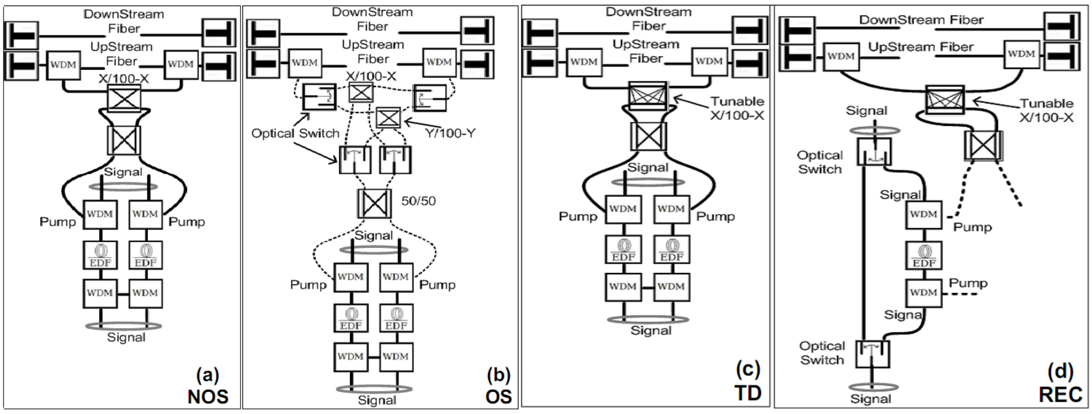


Figure 7.2: a) Non Optical Switching RN topology proposed in *[Lazaro, 2007];* b) Optical Switching RN topology proposed in *[Baptista, 2008:1];* c) Tunable Drop RN topology proposed in *[Baptista, 2008:3]* and d) Reconfigurable RN proposed in *[Baptista, 2008:3].*

In order to compare the different efficiencies of each RN topology, three fiber cuts are simulated. The first cut is for the RN 8, simulating the normal operability of the network. The traffic is balanced for both sides of the ring guaranteeing the signals to travel through the shorter path, reducing the non linear effects and attenuation. The pump power is also supplied equally from both sides of the US ring fiber. Regard the power converter, harvesting and control module is operating in sleep mode, harvesting energy for potentially acts on the network reconfigurability.

For fiber cut at the RN 12 an intermediate resilience mode is simulated. The control modules of some RNs will receive command from the CO to act on the optical switches and tunable power splitters. The network reconfigures and four of the total twelve RNs receive the signals and the pump power through the farthest path, resulting on extra attenuation and signal degradation.

For fiber cut at RN 16 is simulated the extreme mode of operation. The control modules of the RNs will receive also command from the CO to act on the optical switches and tunable power splitters. The network reconfigures and eight of the total twelve RNs receive the signals and the pump power through the farthest path. All the traffic signals and pump power travel through the same side of the ring resulting on the worst case of signal attenuation and degradation.

The comparison between the four RNs topologies and the three operation modes is made calculating the total requirements of the network in terms of pump power and the number of RNs that are not supplied with enough pumping power to operate. It should be noticed that the maximum pump power allowed to be produced by the CO is 44dBm. This value is extremely high, however is used in previous analysis.

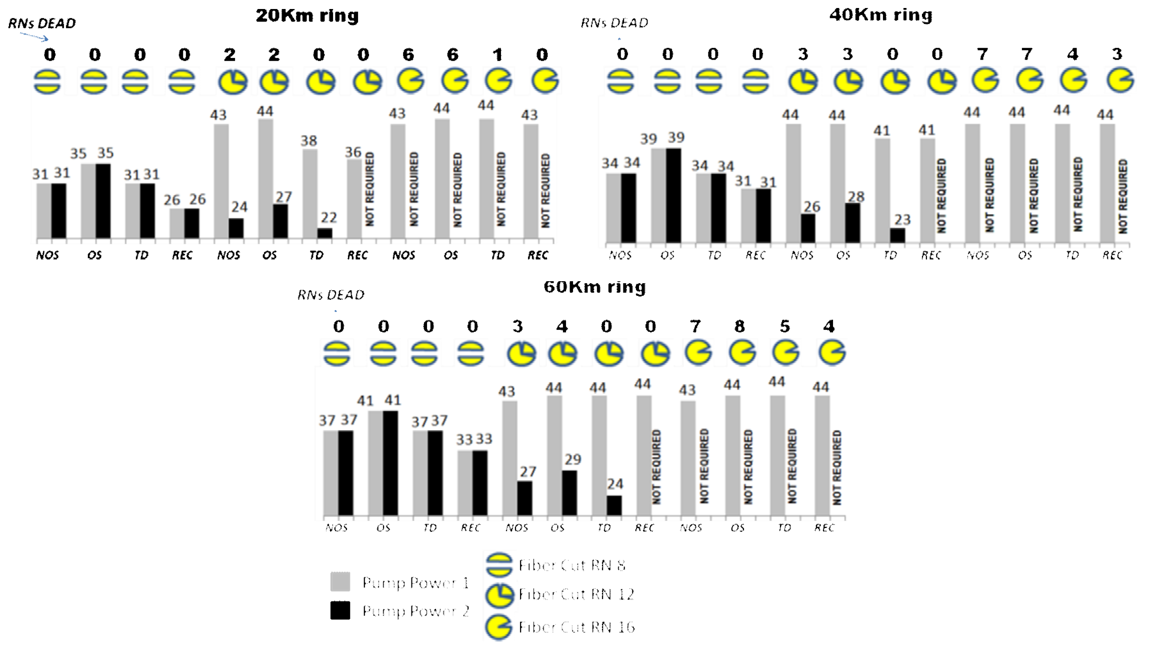


Figure 7.3: Pump power supplied by the CO on both directions and the number of RN with not enough pump power for amplification (dead RN) for the four different configurations of RN. (a) 20km, (b) 40km and (c) 60Km networks *[Baptista, 2008:3]*.

Figure 7.3 demonstrate the results of the comparison between the RNs. For fiber cut at RN 8, the OS topology requires higher pump power than all the others topologies since the IL is higher being therefore not an efficient alternative. Implementing the TD topology the required pump power is the same than for NOS. The REC topology requires the lower pump power, respectively 26, 31 and 33 dBm for 20, 40 and 60Km. All the RNs have enough pump power to operate for fiber cut at RN 8.

For fiber cut at RN 12, the OS topology continues to require higher pump power due to the extra IL and is not able to provide enough pump power for all the RNs, being 2, 3 and 4 RNs out of operation respectively for 20, 40 and 60Km. The NOS topology presents similar results, supplying just 1 more RN with pump power to operate for 60Km comparing to OS topology. TD and REC topologies are able to supply all the RNs with enough pump power however the REC topology requires lower pump power, respectively 36, 41 and 44 dBm for 20, 40 and 60Km of ring's length.

For fiber cut at RN 16 all the topologies require the maximum pump power however substantial difference can be observed in the number of RNs that do not operate. The NOS topology does not supply enough pump power to 6, 7 and 7 RNs to operate respectively for 20, 40 and 60Km. The OS topology follows similar results, however it does not supply with enough pump power one more RN for 60Km. Substantial improvements are observed for TD and REC topologies. The TD topology just does not supply enough pump power for 1, 4 and 5 RNs respectively for 20, 40 and 60. The REC topology is able to operate all the RNs for 20Km, however for 40 and 60Kms there are 3 and 4 RNs respectively without enough pump power to operate.

The REC topology provides higher efficiency for all the four RNs topologies. For fiber cut at RN8 the total pump power required decreases in 5, 3 and 4 dB respectively for 20, 40 and 60Km and for the extreme case, fiber cut at RN16 the number of RNs that do not have enough pump power decreases at 6, 4 and 3 respectively for 20, 40 and 60Km.

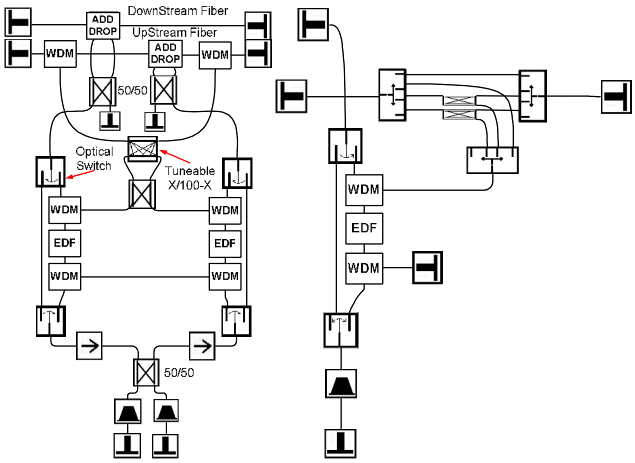


Figure 7.4: RN topology and the respective experimental implementation.

The complete REC topology is present in figure 7.4. Since in the laboratory there was no tunable power splitter, a discrete version was implemented by means of 1 to 4 optical switches, allowing the selection of a non dropping pump power, an all dropping pump power and 2 intermediate levels by means of power couplers. The implemented REC topology pretends to analyze the RN independently for DS and US signals being the RN provided with just one EDF. The implemented RN prototype is seen in figure 7.5.

Figure 7.5: Reconfigurable RN implemented and tested.

Since there was just a 21dBm pump power source in the laboratory and connectors were used instead of splices it was impossible to demonstrate all the RNs and resilience modes.

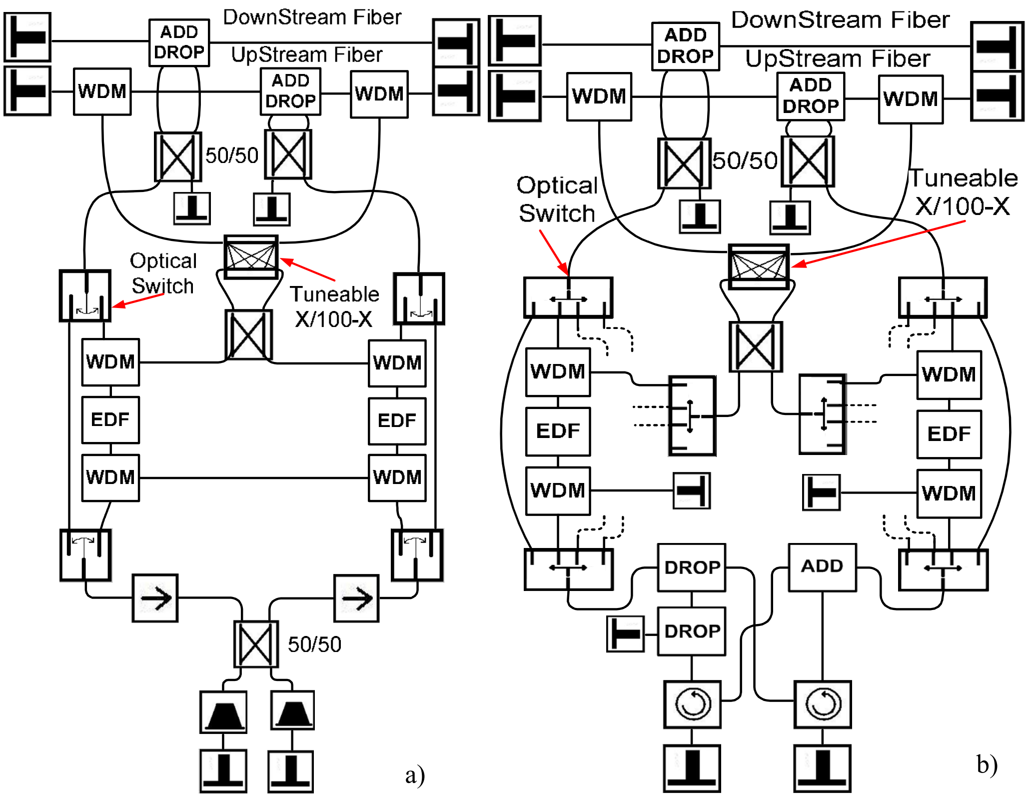


Figure 7.6: a) Proposed Remote node topology based on two EDF, amplification or non amplification modules and tunable pump power splitting *[Baptista, 2008:3]*. b) Upgrade from previous remote node architecture reducing the losses in the trees filtering and providing multiple reconfigurability.

Considering the same schematic of figure 7.1 and described operations for the previous RN comparisons, further RN comparison between the REC RN and the novel structure presented in figure 7.6 b) was demonstrated in figure 7.7. As it can be easily seen, there is a reduction on the required pump power from the CO when the fiber cut is in RN8 of 1, 3 and 3 dB respectively for 20, 40 and 60Km. For fiber cut at RN 16 a reduction of 4dB of pump power is achieved for 20Km and for 40 and 60km there is a reduction of RNs without enough pump power (dead RN) of 3 and 2 respectively.

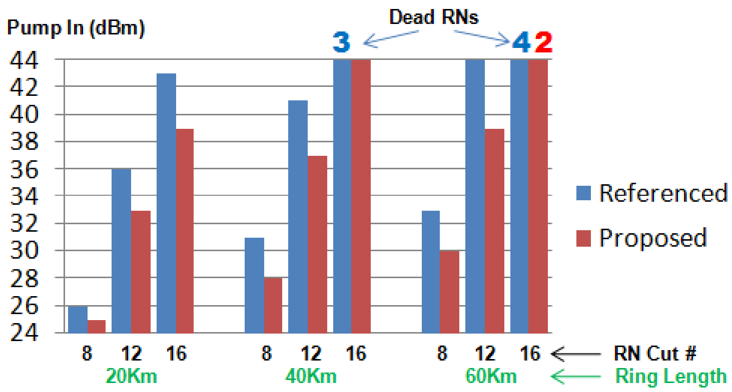


Figure 7.7: Pump Power supplied by the CO and the number of RNs with not enough pump power for amplification for different network operations.

7.2. Conclusions

The introduction of a tunable pump power splitter and optical switching can lead to significant improvements in the usage of the total pump power produced by the CO, reducing 5, 3 and 4dB for 20, 40 and 60km respectively, at normal operation mode (fiber cut at RN 8). In extreme resilience mode (fiber cut at RN 16), for the same pump power supplied by the CO, the number of RNs with no pump power available (dead RN) decreases 6, 4 and 3 unities for 20, 40 and 60km, respectively. Implementation of the reconfigurable RN increases the network scalability, resiliency and robustness, leading to a more efficient NG-PON.

The characterization of different EDF's pump usage efficiency led to the conception of an improved RN design where both pump power and fiber characteristics (length and gain/m) are reconfigurable in order to improve the pump usage and decrease the total power in the fiber for granting full resilience and improved functioning. The network can be totally resilient for 20 and 40km, and reduce in 2 the number of dead RNs for 60km in extreme resiliency. At normal operation mode, the network demands less 1, 3 and 3dB of pump power from the CO respectively for 20, 40 and 60km.

Chapter 8. Conclusions and future work

8.1. Conclusions

This work has been presented in 8 chapters, with themes related to optical networks architectures, new generation optical networks, SARDANA network and its components. The main component studied is the Remote Node which is the limiting factor that limits the networks by the different topologies by the pump power required. Two main components from the RN where then presented and studied the EDF and the optical converter, harvesting and control module.

The SARDANA project architecture provides flexibility, scalability, resiliency, higher user density and bandwidth, robustness and extended reach that are important features for next generation dense FTTH networks also called NG-PONs. It operates in a WDM ring TDM tree topology. Two different main topologies can be applied, one consists on a single fiber ring and the other and more efficient consists on a double fiber ring. To keep simplicity all the light generation and control is placed in the CO and the ONUs are based on reflective devices such as RSOAs.

The RN, as the main theme of this document, is presented in several topologies, some of them referenced as state of art and others as proposed. There are two distinct evolutions in the RNs, the signal and the pump paths.

The pump path optimization aims on reducing the pump losses in each RN and distribute it fairly, just dropping to the RN the enough amount of pump power to its operation.

Pump path topologies started with simple supplying the EDFs present in the RNs with all the pump power available in the ring thus reducing the total network efficiency. To solve this impairment, topologies based on pump power splitting were presented. The RN just drops a fraction of the total pump power available in the ring and supplies it to the EDFs. The main goal here is to optimize the pump power coupling ratios in order to allow the network to operate efficiently in resilient mode and provide scalability. The problem with these topologies is that the optimization of the ratios for normal mode is not efficient for resilient mode.

Topologies based on remote reconfigurability solve this problem. The first approach is able to select between 2 distinct power couplers ratios by means of optical switching. One power coupler ratio is optimized for normal mode and the other for resilient mode. Despite of the optimization of this topology, the network is not fully scalable since inserting an extra RN requires modification of the power coupler ratios.

The second approach is implemented with a tunable power splitter instead of optical switching, allowing a fully scalable and resilient network, dropping just the necessary amount of pump power from the ring. A final optimization consists on reconfigure the RN between two modules: amplification modules and direct link not providing gain. These last pump path topologies consider the distance between the RNs and the CO. It allow a substantially save in terms of pump power for the RNs close the CO, since they do not require gain.

The signal path topologies are also an important optimization. Reducing the signal losses and reducing the number of EDFs allow dropping lower pump power per RN, increasing the total efficiency.

The first evolution is related to the Add&Drop function, made by means of thin film filters instead of power couplers. With this, the introduction of RNs is almost transparent for the WDM channels present in the ring.

A further improvement consists on applying the multi channel amplification characteristics of the EDFs, reducing the number of EDFs from 4 to 2. Three topologies were presented and compared each of them with 2 EDFs. The preferred topology allows adjust independent gain for US and DS signals depending on the operation mode.

An optimized version of the RN is implemented with 2 EDFs, one responsible for the DS signals and the other responsible for the US signals. The RN selects between amplification and non amplification modules allowing the independent reconfigurability of gain for DS and US signals depending on the distance from CO and resiliency mode.

EDFs are important components in the RNs, since they limit the efficiency of the network. An analysis to different EDFs with different parameters has been demonstrated. Low doped erbium concentration (5dB/m of peak absorption) is the most efficient solution. For input signal powers higher than -20dBm, the amplifier saturates leading to a reduction of efficiency. In order to provide 7, 11 and 15dB of gain is required 7, 8 and 10 dBm of pump power, for a reminiscent pump power of 3, 3 and 7 respectively.

The control of the tunable power splitter and the optical switches is done by means of a power converter, harvesting and control module. That module is briefly introduced and presented. Further improvements are required to increase the efficiency of power conversion.

From all the presented RNs, the last proposed is able to provide a completely resilient network for 20 and 40km and reduce 2 RNs with not enough pump power to provide amplification.

8.2. Future work

In the next years the data rate demands will continue to increase and it is necessary to start developing faster and faster access networks. SARDANA is a good vision to the future, although it still can improve to higher reach, users and data rate with a lower CAPEX and OPEX.

It is important for future work to keep analyzing different amplification strategies in order to achieve even higher efficiency in amplification leading to a lower pump requirement. As 44dBm is necessary to keep the network working in the worst case of fiber failure it is convenient to develop new solutions, as:

- The first proposal is to implement each RN with the possibility to provide connection to higher number of users with the same rate. A solution for that is to increase number of wavelengths dropped per RN.

- A second proposal is to study amplification by means of remotely pumped EDFs but installed in the ring, providing gain to all the WDM channels present on the ring. The main disadvantage with this configuration will be the addition of extra noise degrading the signals.

- A third proposal is to implement a mixed implementation of Raman and EDF gain, allowing the signals to travel in the ring with higher power reaching longer distances.

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