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Departamento de Electrónica,
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André Bastos Araújo da Mota

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Tese de 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 Luís Jesus Teixeira, Professor Auxiliar do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro, e do Dr. Paulo Monteiro, Professor Auxiliar do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro

Dedico este trabalho aos meus pais, irmão e namorada.

o júri

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André Bastos

palavras-chave Rede Óptica, SSMF, NZDSF, Compensação da Dispersão, Switches Ópticos.

resumo

O presente trabalho tem como objectivo o estudo de uma rede óptica que ligará o Instituto de Telecomunicações com a Nokia Siemens Networks. Vários testes com diferentes taxas de transmissão foram realizados para estudar o comportamento desta rede na presença de efeitos lineares e não lineares e daí validar a sua operacionalidade.

Para implementar cada nó reconfigurável, uma placa genérica foi implementada com o intuito de poder operar remotamente as reconfigurações da rede. Para facilitar a configuração da placa, foi criado interface simples para operar os switches ópticos.

Foi também realizada uma aplicação que, com o conhecimento de todas as combinações da rede, permite definir completamente as definições e cada nó tendo em consideração um objectivo de dispersão total.

keywords Optical Network, SSMF, NZDSF, Dispersion Compensation, Optical Switches.

abstract

The objective of this work was to study and define the needed assets to implement a reconfigurable optical link that connects IT-Aveiro to NSN-Amadora. For validating the potential of the link, several were the simulations made having in mind determining the viability of the link for current trend bit rates and configurations.

To operate the reconfiguration of the nodes a sample board was designed and mounted with the objective of testing the concept. An interface was developed to ease the use of the board and provide a local interface at each node if local operation is required.

Also, and now from the point of view of the general reconfiguration of the link, a program where all combinations of the network can be tested, was designed and an algorithm to provide all nodes configuration having a targeted dispersion and usage of a certain fiber type.

Table of Contents

List of Acronyms

DCF	Dispersion Compensation Fiber
GVD	Group Velocity Dispersion
PMD	Polarization Mode Dispersion
SPM	Self Phase Modulation
XPM	Cross Phase Modulation
FWM	Four Wave Mixing
SSMF	Standard Single Mode Fiber
NZDSF	Nonzero Dispersion Shifted Fiber
DWDM	Dense Wavelength Division Multiplexing
RI	Refractive Index
RFTS	Remote Fiber Testing System
DPDT	Double Pole Double Throw
PCB	Printed Circuit Board
BER	Bit Error Rate
LED	Light Emitting Diode
NRZ	Non Return to Zero
EDFA	Erbium Doped Fiber Amplifier
WDM	Wavelength Division Multiplexing
OTN	Optical Transport Networks
OE	Optoelectronic
PDL	Polarization Dependent Loss
MEMS	Micro Electrical Mechanical Systems
ESBG	Electrically Switchable Bragg Gratings
OSI	Open System Interconnection
ISO	International Standards Organization
ADC	Analog/Digital Converters
OPS	Optical Packet Switching
OBS	Optical Burst Switching
OSM	Optical Signal Monitors

OTDM	Optical Time Division Multiplexing
ADC	Analog/Digital Converters
SOA	Semiconductor Optical Amplifier
OADM	Optical Add/Drop Multiplexer
OXC	Optical Cross Connects

Chapter 1

Introduction

1.1 Motivation and Objectives

The actual core optical communication networks are based on long haul connections and high bit rates. In order to reveal all the effects and effectively prove that a system is functional, these systems have to be tested in testbeds, where tests can be made where all the factors that vary can be controlled (e.g. temperature, vibrations caused by vehicles, etc.). There are several optical testbeds in many countries however in Portugal there are still some problems.

So, Institute of Telecommunications with the partnership of Nokia Siemens Networks considered to implement an Optical Network for Advanced Tests (ROTA) flexible and bidirectional located between Aveiro and Lisbon, more precisely between Institute of Telecommunications (IT) and Nokia Siemens Neworks (NSN) located in Alfragide, supported by the “dark” fibers of the FCCN (Fundação para a Computação Científica e Nacional) network, where these fibers are implemented along the railway that binds Aveiro to Lisbon, as can be seen in Figure 1.1.

Fig.1.1: Route of the Optical Network implemented between Aveiro and Lisbon.

To achieve such flexibility this network has to be configurable in several nodes along the route and will comport two kinds of fibers, the ITU-T G.652 commonly known as Standard SMF and the ITU-T G.655 also known as NZDSF (Non Zero

Dispersion Shifted Fiber) and these fibers can be selected along the route. Four nodes will be implemented, two terminals located in Aveiro and Gare do Oriente (Lisbon) and two intermediate nodes, one in Coimbra B and the other one in Entroncamento. Each node will have optical amplification equipment compatible with C band (1530 – 1560nm), dispersion compensators as well as several optical switches operating on the C+L bands (1530 – 1610nm). To control this optical network will be necessary 12 switches 1x4, 14 switches 1x2 and 4 switches Dual 2x2 Add/Drop.

The nodes above described will be controlled by a communication channel on the terminal stations, this channel should be used to control all the switches, such switches will allow the selection of the transport fiber, the inclusion of chromatic compensation dispersion modules and the accomplishment of “loop-backs” or the inclusion of other optical elements during the route.

FCCN Corporation holds a dorsal network located between Braga and Gare do Oriente, that takes one cable of 24 ITU-T G.652 fibers as well as 24 ITU-T G.655 fibers. Among these fibers will be selected only 2 ITU-T G.G52 fibers and 2 ITU-T G.655 fibers to implement the object optical link.

Along this route there are several racks and its main objective is to split this principal network into others local networks. These racks are located at Braga, Campanhã, Aveiro, Coimbra B, Vermoil, Entroncamento, Setil and Gare do Oriente rail stations.

The link will encompass the racks at Aveiro, Coimbra B, Entroncamento e Gare do Oriente rail stations, the remaining (Vermoil and Setil rail station) will just work as a shunt or bypass.

The distances between the patching bastidores are, Aveiro – Coimbra B: 58.1Km, Coimbra B – Vermoil: 58.5Km, Vermoil – Entroncamento: 57.7Km, Entroncamento – Setil: 53.3Km, Setil – Gare do Oriente: 52.4Km.

In Aveiro there is an access to the local network through the rack and in this there are two cables, each one constituted by 24 ITU-T G.652 fibers and another 24 ITU-T G.655 going in direction to the University of Aveiro passing by one box that will follow these fibers into Institute of Telecommunications.

Gare do Oriente is connected to Lisbon local network trough a similar cable as the one described above, that is implemented in the following way: the rack on Gare do Oriente is connected to the one located in Entrecampos and, after this the cable goes to FCCN Lisbon where the local network is split to several paths, such as University Nova de Lisboa, University of Lisbon, Nokia Siemens Networks and Universidade Técnica in pares of ITU-T G.652 fibers.

This presents the introduction to the work that is now going to be presented, where an operational network dark fiber is going to be used to build the first scientific test bed of Portugal.

1.2 State Of The Art

This section is divided in two parts, one describes different optical testbeds which are implemented in several countries in order to evaluate what is the implemented technology in each testbed and with what purposes they were built.

The other part of this section presents the ITU-T G.652 and ITU-T G.655 fibers in order to assess which are their properties and, therefore, limitations. In this part was not study the last development in optical fibers in order to chose which fibers bring the best results to the optical network, because as was said in section 1.1 the cable that was used to establish the optical network has just two kinds of fibers that are the ITU-T G.652 and ITU-T G.655. So, it is not possible to say that will be done a state of the art test bed. It was also studied the dispersion compensation fiber (DCF) and its applications.

1.2.1 Optical Testbeds

There are several optical testbeds which were implemented in different countries with different characteristics and purposes. Some of these implemented testbeds were studied in order to assess the state of the art in optical testbeds, and those were: DARPA Quantum Network testbed, GÉANT2 network, Fastweb testbed and finally Acreo National testbed. These four optical testbeds are described below.

1.2.1.1 DARPA Quantum Network Tetsbed

BBN has designed and built the world's first Quantum Network testbed, delivering end-to-end network security via high-speed Quantum Key Distribution (QKD), and testing that Network against sophisticated eavesdropping attacks [1]. BBN has fielded this ultrahigh-security network into commercial fiber across the metro Boston area. BBN's QKD network comprises 10 nodes. It is both extremely secure and 100% compatible with today's Internet technology [1]. Four of the 10 nodes are running 24x7 over Boston metro telecom fiber between BBN, BU and Harvard and protecting Internet traffic; four other nodes are free space; and two are based on polarization entanglement through fiber [1].

1.2.1.2 GÉANT2 Network

The GÉANT2 network provides the high-performance, state-of-the-art network infrastructure that is fundamental to the European Union's vision of a European Research Area (ERA) [2]. The network is the core activity of a coherent set of initiatives that seek to develop all aspects of European research and education networking [2]. The project which the network is being built and developed, also includes an integrated research programme, the development of support services for network users, initiatives to monitor and address disparities in the level of development of research and education networking around Europe, and a comprehensive study into the future of European research and education networking [2].

GÉANT2 connects 30 European National Research and Education Networks (NRENs), DANTE and TERENA across 34 countries [2]. NRENs connect research and educational institutions within their respective countries, providing GÉANT2 connectivity to more than 30 million research and education end users in over 3,500 institutions across Europe [2]. The GÉANT2 network is shown in Figure 1.2.

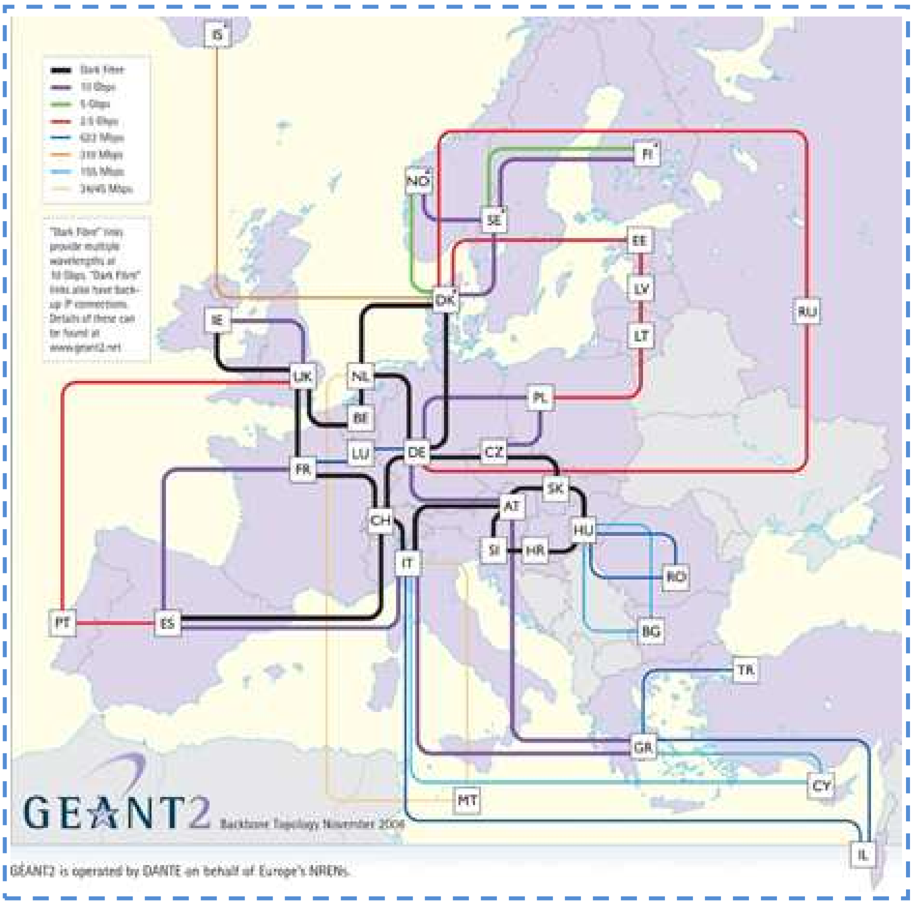

Figure 1.2: GÉANT2 network [2].

The project’s overall objectives are :

- To plan, build and operate a multi-gigabit pan-European backbone research network interconnecting Europe's NRENs, over which a suite of advanced services will be offered to meet the increasingly demanding requirements of Europe’s research and education community [2];

- To conduct joint research into the development of networking technologies and services, with the primary aim of developing ideas from concept to production service to directly serve the users of GÉANT2 and its connected NRENs [2];

- To support effectively and directly projects and users who have advanced networking requirements [2];
- To pursue initiatives targeted at closing the 'digital divide', through both in-depth analysis of the picture of research networking in developing areas and the provision of direct support [2];
- To examine the future of research networking, exploring the case for the sustaining of research and education networking beyond the conclusion of the project [2].

The technologies required by GÉANT2 are well ahead of the market, and hence the network offers suppliers an attractive opportunity to be involved at the leading edge of networking [2]. Furthermore, in terms of scale and reach, GÉANT2 is one of the largest users of very high capacity links in Europe, and hence a major player in the market [2].

The network has been built using leased IP infrastructure, for which public invitations to tender are published in the Official Journal of the European Commission [2]. Equipment (routers and switches) is usually purchased outright, and upgraded as service and technology advances demand [2]. Points of presence (PoPs) are generally leased co-location spaces, providing ease of interconnection with NRENs [2].

1.2.1.3 Fastweb Testbed

Since January 2004 the high-tech, fiber-to-the-home carrier/provider Fastweb has sponsored OptCom and its PhotonLab experimental facility by providing on-premise access to 8 installed dark fiber rings for a total of 240 km [3].

The fibers are ITU-T G.652 standard single-mode and belong to operational cables running through all parts of Torino [3]. They make up an excellent testbed for realistic field trials for optical communications systems and networks in the challenging metro environment [3].

OptCom is planning to use the testbed for tests during the development of the WONDER prototype, for research on new modulation formats and within the CISCO URP project [3].

The availability of this testbed is virtually unique in Italy and possibly Europe, given the extension and the specific layout, encompassing transit through POPs, miniPOPs, residential areas, industrial areas, bridges, railroad tracks and busy avenues with heavy traffic [3].

As a first accomplishment, the testbed will be thoroughly characterized as for the physical propagation properties of its fiber rings [3].

1.2.1.4 Acreo National Testbed

The network of the Acreo National testbed covers two metropolitan areas, Stockholm and Hudiksvall, which are connected through the high-capacity transmission link [4].

Acreo’s services, initially IP-TV, Video-On-Demand, IP telephony and Internet, are offered to the users in Hudiksvall on a test basis through the trunk link from Stockholm [4].

In Hudiksvall metro and access architectures will be verified, and a wide range of access technologies evaluated, e.g. by end-users using advanced applications [4]. Access technologies varies from FTTH to WLAN and xDSL, typical applications are voice, video and data, including HDTV [4]. Presently 230 contracted end-users from seven different access areas are connected to the Hudiksvall testbed [4].

Acreo testbed is linking Stockholm to Hudiksvall and the trunk link is about 400 km long and carries several channels at 2.5 Gb/s connecting the two metro networks via 16x16 channel optical crossconnects [4]. Both DWDM and CWDM system technologies are implemented in the link. The trunk link also carries one 40 Gbps channel with the purpose to field-test high-speed transmission for future cost-effective implementation [4].

The metropolitan transport network in Stockholm consists of a DWDM ring with ten 2.5 Gb/s channels [4]. The nodes of the ring connect to a number of broadband access networks with more than 20 000 end-users [4]. The users in Stockholm will be offered high-speed peer-to-peer connectivity, as well as IP-TV and Video-On-Demand [4].

The Stockholm network will be used to test Generalized MPLS (GMPLS), the method for multilayer control of the networks [4]. ITU-T is developing an architecture for Automatic Switched Networks (ASON) and the corresponding GMPLS protocols are currently standardized by IETF [4].

The testbed is built according to the open network concept, i.e. all end-users of the network have an opportunity to selectively choose from all services available in the network. The network will also be available for all service providers to deliver their services to all end-users [4]. These two requirements lead to the concept of open network, which in other words can also be called operator neutral network [4].

1.2.2 Optical Fibers

In ROTA Project will be used two kinds of optical fibers to perform the optical network, the ITU-T G.652 and ITU-T G.655. These two fibers are single-mode fibers that are the most important and the ones that give the best results when it is wanted to do long haul networks.

Single-mode fibers have the benefit of not having reflections from the core-cladding boundary but rather the electromagnetic wave is tightly held to travel down the axis of the fiber [5]. The longer the wavelength of light in use, the larger diameter of fiber that can be used and still have light traveling in a single-mode. The core on single-mode fibers has a diameter between 4 µm and 10 µm but is typically 8 µm [5].

It is important to refer that the region in which light travels in a single-mode fiber is often called the “mode field” and the respective mode field diameter is quoted instead of the core diameter, because a significant proportion (more than 20%) of the light travels in the cladding. So the “apparent diameter” of the core is somewhat wider than the core itself [5].

Single-mode fiber usually has significantly lower attenuation than the multimode, but this has nothing to do with fiber geometry or manufacture. Single-mode fibers have a significantly smaller difference in refractive index between core and cladding. This means that less dopant is needed to modify the refractive index as dopant is a major source of attenuation [5].

A fiber is single-moded or multi-moded at a particular wavelength, so there is a characteristic called the “cutoff wavelength” that separates these two types of fibers. Cutoff wavelength is the shortest wavelength at which the fiber remains single-moded, at shorter wavelengths than the cutoff the fiber is multimode [5].

A very important characteristic of a given fiber is the “Numerical Aperture”. When light is introduced to the end of a fiber there is a critical angle of acceptance. For example, if a ray enters the fiber at a greater angle it will leave the core and eventually the fiber itself. Considering in three dimensions, a cone is formed around the end of the fiber within which all rays are contained that can be called cone of acceptance [5]. The sine of the largest angle contained within the cone of acceptance is called the “Numerical Aperture” [5]. The Numerical Aperture is also intended as a measure of the light capturing ability of the fiber. However, it is used for many other purposes. For example it may be used as a measure of the amount of loss that might be expected in a bend of a particular radius [5].

1.2.2.1 ITU-T G.652 Fiber

The ITU-T G.652 fiber, also known as Standard SMF (SSMF), is the most used fiber. This fiber has a simple step-index structure and it is optimized to operate on 1310 nm band, because it is where this fiber has the minimum dispersion of the signal.

The nominal mode field diameter at 1310 nm shall lie within the range of 8.6 µm to 9.5 µm [6]. For a given nominal mode field diameter, the mode field deviation from nominal should not exceed the limits of ± 0.6 µm [6]. The recommended nominal value of the cladding diameter is 125 µm. The cladding deviation should not exceed the limits of ± 1 µm [6].

At 1310 nm wavelength the ITU-T G.652 fiber has a dispersion null, but it also can operate at 1550 nm band, although it is not optimized for this region. At 1550 nm this fiber has high values of chromatic dispersion in the order of 17 ps/(nm.km) [6], as can be seen in Figure 1.3.

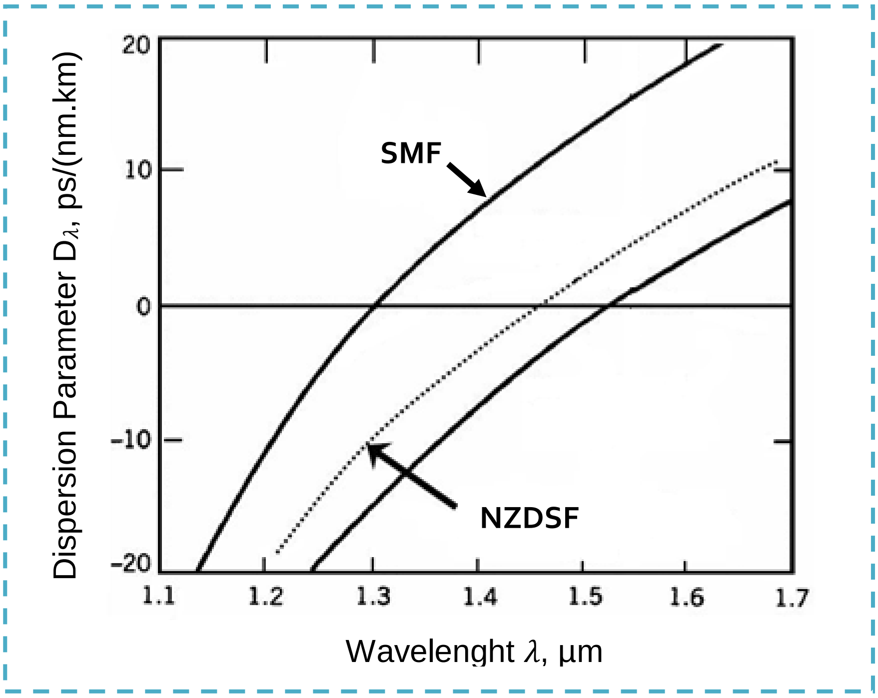

Figure 1.3: Dispersion slope relatively to ITU-T G.652 and ITU-T G.655 fibers.

The attenuation value of the ITU-T G.652 fiber at 1550 nm band is typically 0.2 dB/km. The maximum value of attenuation at 1310 nm band is 0.4 dB/km [6]. The PMD (Polarization Mode Dispersion) parameter is less than 0.1 ps/km [6].

The supported distances without having dispersion compensation relatively to different bit rates for the ITU-T G.652 and ITU-T G.655 fibers at 1550 nm band are presented in Table 1.1.

Fiber	2.5 Gbits/seg	10 Gbits/seg	40 Gbits/seg
ITU-T G.652	1000 Km	60 Km	3 Km
ITU-T G.655	6000 Km	400 Km	25 Km

Table 1.1: Maximum lengths of ITU-T G.652 and ITU-T G.655 fibers for some bit rates without having dispersion compensation at 1550 nm band [7].

1.2.2.2 ITU-T G.655 Fiber

The ITU-T G.655 fiber also known as Nonzero Dispersion Shifted Fiber (NZDSF) is the most recent development in optical fibers field. This fiber is optimized for WDM (Wavelength Division Multiplexing) systems, as well as for the use in long haul networks [7]. The ITU-T G.655 fiber can attenuate the non-linear effects shifting the wavelength of null dispersion outside the 1550 nm band. The practical result of this operation combines on a little but finite amount of chromatic dispersion at the 1550 nm band and this minimize the non-linear effects such as FWM (Four Wave Mixing), SPM (Self Phase Modulation) and XPM (Cross Phase Modulation) which mostly occur in DWDM (Dense Wavelength Division Multiplexing) systems [7].

The nominal mode field diameter at 1550 nm shall lie within the range of 8 µm to 11 µm [8]. For a given nominal mode field diameter, the mode field deviation from nominal should not exceed the limits of ± 0.7 µm [8]. The recommended nominal value of the cladding diameter is 125 µm. The cladding deviation should not exceed the limits of ± 1 µm [8].

Relatively to the chromatic dispersion ITU-T G.655 fiber has 4.5 ps/(nm.km) and 0.2 dB/km for the attenuation, these values are taken at 1550 nm band [8]. At 1310 nm band this fiber as a maximum value for the attenuation of 0.35 dB/km. In ITU-T G.655 fiber the PMD parameter is less than 0.1 ps/km [8].

In Table 1.2 are the characteristics of the ITU-T G.652 and ITU-T G.655 fibers relatively to the attenuation, chromatic dispersion and polarization mode dispersion at 1550 nm band.

	ITU-T G.652	ITU-T G.655
Chromatic Dispersion (ps/(nm.km))	17	4.5
Attenuation (dB/km)	0.2	0.2
PMD (ps/km)	< 0.1	< 0.1

Table 1.2: Values of Chromatic Dispersion, Attenuation and PMD for ITU-T G.652 and ITU-T G.655 fibers at 1550 nm band [6], [8].

1.2.2.3 Dispersion Compensation Fiber

Dispersion is a phenomenon that occurs in all types of optical fiber. After attenuation, dispersion is the next limiting factor that determines how much and how far information can be transmitted on a given fiber [9].

The dispersion compensation should be used in applications with high bit rates, because when a signal needs to be transmitted over long distances the dispersion severely impairs it. There are several methods to implement dispersion compensation in an optical link, from those one can highlight two: the first one with the introduction of a compensation dispersion fiber and the second one with the use of a Fiber Bragg Grating (FBG). A series of FBG's or one very long FBG can hold some centimeters to meters. The advantages and disadvantages of each dispersion compensation technology are presented in Table 1.3.

Technology	Advantages	Disadvantages
DCF	✓ Simple construction, highly reliable; ✓ Provides continuous compensation over a wide range of optical wavelengths (i.e. Does not require precise laser).	✓ Usually DCF has a small core size which may make it prone to certain types of nonlinearities.
FBG	✓ Potentially lower insertion loss.	✓ Less prone to nonlinear effects.

Table 1.3: Advantages and disadvantages of DCF and FBG technologies [9].

In project ROTA the first method was used to implement, therefore is the one which will be looked deeper into.

Dispersion compensating fibers (DCF) made possible to increase the transmission length and bit rate without electronic regeneration [10]. DCF's with both positive and negative slope have been demonstrated and are commercially available [10]. Broadband dispersion compensation always leaves residual dispersion that will have to be compensated after the link [10]. A dispersion compensation fiber (DCF) has a dispersion characteristic that is opposed to the transmission fiber. The dispersion compensation is reached when there is a span of DCF along the transmission path. The total dispersion inserted in the DCF loop has to be equal and opposite relatively to the accumulated dispersion on the transmission fiber [5].

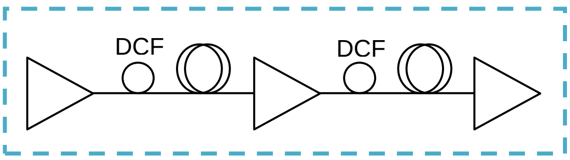

Figure 1.4: Compensation of dispersion at the beginning of the transmission fiber (Pre-Compensation).

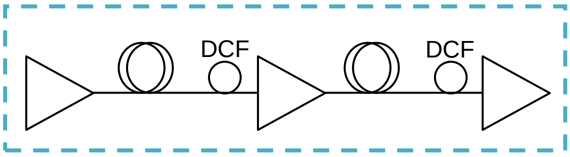

Figure 1.5: Compensation of dispersion at the end of the transmission fiber (Post-Compensation).

The DCF can be inserted at the beginning (pre-compensation), as can be seen in Figure 1.4, or in the end (post-compensation), as it is represented in Figure 1.5, of some installed fiber between two amplifiers. In chapter 4 will be study which method to compensate the chromatic dispersion (pre or post-compensation) brings the best results into the optical network.

1.3 Structure

This document is divided in seven chapters that describe various subjects related to the optical network such as its optical components, the implemented boards, experimental tests and an application which simulates the optical network.

In this first chapter is presented the description of the context in which this work appears and its main proposed objectives together with the chapter division and the studied topics. It was also presented state of the art of the implemented optical networks in other countries and the optical fibers that will be used in this optical network.

In the second chapter is studied the single mode fiber and its linear and non linear properties in order to understand the limitations that the optical fiber can bring into the optical network.

In the third chapter are presented some key performance indicators of optical switches components in order to enable the understanding and comparison between the different optical switches technologies that are also presented. It is presented a characterization of the optical switches 1x2, mini 1x4 and dual 2x2 Add/Drop and its purposes.

In the fourth chapter it is studied which compensation (pre or post-compensation) brings the best results into the optical network. It is also studied the response of the system for different bit rates with the pre-compensation setup. It was done an experimental implementation for 40 Gbit/s bit rate with 40 km of SSMF. For this experimental implementation three configurations were tried: Back to back, pre-compensation and post-compensation.

In the fifth chapter was implemented a prototype board that has the same functions to the ones that will be introduced in each node along the optical network. Associated to this board was implemented a program in order to control the optical switches positions.

In the sixth chapter was made the application “Closest Dispersion” with the main objective to simulate the optical network. This application gives a dispersion value and its associated path which is the closest dispersion relatively to the introduced one when compared to all the possible routes, with the different fiber combinations, which can be used in the optical network. Attached to each dispersion value given by the application there is a file which contains the positions of each optical switch for all the nodes along the optical network. At the end of this chapter it is presented a solution to control all the optical switches which are implemented along the optical network with the electrical and optical devices needed and the necessary protocol to transmit all the information.

Finally, the seventh chapter summarizes the final conclusions of the performed work together with the contributions and some suggestions for future work.

Chapter 2

Optical Fiber

2.1 Introduction

The optical communications systems have been suffering a significant development since 1960 with the laser discovery. In that time occurred a lot of preliminary experiences of information transmission with luminous beam rays propagated along the atmosphere but the atmosphere medium variability was a limiting factor so it was necessary to find another way to guide the light signals.

Today, the way to guide the light signals is the optical fiber which is constituted by fine cylindrical glass structure denominated by core. This structure is surrounded by a concentrical glass layer that is the cladding but with a refractive index (RI) slightly small. Nowadays, the optical fibers are the focus element on the optical communications systems, because silica fibers can transmit light with losses as small as 0.2 dB/km. Even then, optical power reduces to only 1% after 100 km [11]. Although the fiber application is not just used for the transport channel, they are used in integrated optical devices like amplifiers, Bragg gratings, couplers, polarizers and switches.

The fast development of the optical communications is allied to the advantages of the optical fibers use when compared with others ways of information transport.

Of all the fiber advantages is important to mention the high bandwidth, low losses, low weight and volume and the most important, the immunity to all the electromagnetic interferences.

In this chapter will be boarded exhaustively the optical fiber characteristics more specifically the mono-mode fiber, because in this project ROTA was just used this type of fiber, as well as nowadays in a lot of applications.

As was said before an optical fiber is an optical waveguide which has a core and a cladding where both are made of transparent materials (glass or plastic). In the step index fiber the core RI (η_1) is slightly higher when compared to the cladding RI (η_2) because of the large difference between the core-cladding. In the gradual index fibers the RI inside the core has a gradual decrease [12].

2.2 Linear Properties

The most important optical fibers properties are the attenuation, chromatic or intramodal dispersion and birefringence. These three properties depend from wavelength and they impose a limit to the distance and to the maximum bit rate rhythm [12].

The optical fiber attenuation comes from different contributions such as Rayleigh scattering, silica absorption and impurities presence. The used transmission windows correspond to the spectral regions where the attenuation local minimums of Silica are presented. Those windows correspond to the following wavelengths: 800 nm (first transmission window), 1310 nm (second transmission window) and 1550 nm (third transmission window). These denominations of the transmission windows are also associated to their chronologic utilization beginning [12].

In an optical fiber the total dispersion is the result from material dispersion and waveguide dispersion, therefore part from the radiation tends to propagate along the cladding where the RI is less than the core RI.

The other property of the optical fibers is the birefringence. The monomode fibers can support two states of orthogonal polarization that varies randomly along the propagation. As a consequence, the introduced signal will have a propagation delay between these two polarization states, usually known as polarization mode dispersion (PMD) [12].

2.2.1 Dispersion in Single-Mode Fiber

The main advantage of single-mode fibers is that intermodal dispersion does not exist, because the energy of the injected pulse is transported just by a single mode. The frequency dependence of the group velocity leads to pulse broadening simply because different spectral components of the pulse disperse during propagation and do not arrive simultaneously at the fiber output, this phenomenon is referred as group-velocity dispersion (GVD), intramodal dispersion, or chromatic dispersion [11]. Chromatic dispersion has two contributions that are the major source of dispersion which are the material dispersion and waveguide dispersion.

The chromatic dispersion origins from the interaction of the electromagnetic wave with the electrons of a dielectric and appears by the dependence relatively to frequency of the RI $n(\omega)$ that is related with the propagation constant $\beta(\omega)$ which is expressed in the following equation [13].

$$n(\omega) = \frac{c.\beta(\omega)}{\omega} \tag{2.1}$$

Generally this relation is not known in an explicit way. However, the propagation constant (β) can be expanded in a Taylor series where the parameter corresponding to the group velocity dispersion is very often characterized by the parameter D that is expressed in ps nm^{-1} km^{-1}. The parameter D describes the temporal delay between two pulses separated by 1 nm in spectral domain after 1 km of propagation. The parameter D is related to β_2 (superior order term responsible for the dispersion) with the following equation [12]:

$$D = \frac{2.\pi.c}{\lambda^2}.\beta_2 \tag{2.2}$$

The spectral region where D is positive is known as anomalous dispersion region and the region where D is negative is known as normal dispersion region which is where the impulse components corresponding to the higher frequencies travel more slowly than the components with lower frequencies. In the anomalous region dispersion happens the opposite behavior [12].

The total dispersion is given by the sum of the material dispersion (2.4) and the waveguide dispersion (2.6). The material dispersion has a positive slope in order to the wavelength while the waveguide dispersion for a step index fiber has a negative slope and value in order to the wavelength. The sum of this two components gives a shift on the wavelength where occurs the fiber dispersion zero λ_{ZD}, for an approximately value of 1310 nm [12].

2.2.1.1 Material Dispersion

Material dispersion (D_m) results from a variation in propagation delay with wavelength, and is affected by fiber materials and dimensions. Some wavelengths have higher group velocities, so travel faster than others. One cause of this velocity difference is that the index refraction of the fiber core is different for different wavelengths, this phenomenon is called material dispersion and it is the dominant source of chromatic dispersion in single-mode fibers. Since every pulse consists of a range of wavelengths it will spread out to some degree during its travel.

As all optical signals consist of a range of wavelengths although this range could be only a fraction of a nanometer wide but there is always a range involved. Typically optical pulses used in communications systems range from about 0.2 nm to 5 nm wide for systems using single-mode fibers (with lasers) [14].

If the signal has a $\Delta\lambda$ spectral width, the signal temporal width after the propagation along a fiber with length *L* will be [12]:

$$\Delta_{\tau m} = -\frac{L}{c}.\left(\lambda^2.\frac{d^2 n_{n(\lambda)}}{d\lambda^2}\right)\left(\frac{\Delta\lambda}{\lambda}\right) \quad (2.3)$$

The material dispersion parameter D_m will be [12]:

$$D_m = \frac{\Delta\tau}{L.\Delta\lambda} = \frac{1}{\lambda.c}.\left(\lambda^2.\frac{d^2 n_{n(\lambda)}}{d\lambda^2}\right) \quad (2.4)$$

For the pure silica case the value of the material dispersion is null at 1270 nm wavelength band. In the doped silica case, that constitutes the fiber core, there is a shift for bigger wavelengths of the position where the zero of dispersion occurs, λ_{ZD} [12].

2.2.1.2 Waveguide Dispersion

Waveguide dispersion (D_W) will be influenced by the shape, design, and chemical composition of the fiber core, therefore it will have a very significant effect on the group velocity. This is because the electric and magnetic fields that constitute the pulse of light extend outside of the core into the cladding (20%) [14]. The amount which the fields overlap between core and cladding depends strongly on the wavelength and travels at a faster velocity because of the cladding RI which is lower than the core RI.

The RI experienced by the wave is an average of the refractive index of core and cladding depending on the relative proportion of the wave that travels there. So, since a greater proportion of the wave at shorter wavelengths is confined within the core, the shorter wavelengths "see" a higher RI than do longer wavelengths [5]. Therefore shorter wavelengths tend to travel more slowly than longer ones. That is why signals are dispersed (because every signal consists of a range of wavelengths) [14]. These two forms of dispersion have opposite signs, so they tend to counteract one another like it is shown in Figure 2.1 [12].

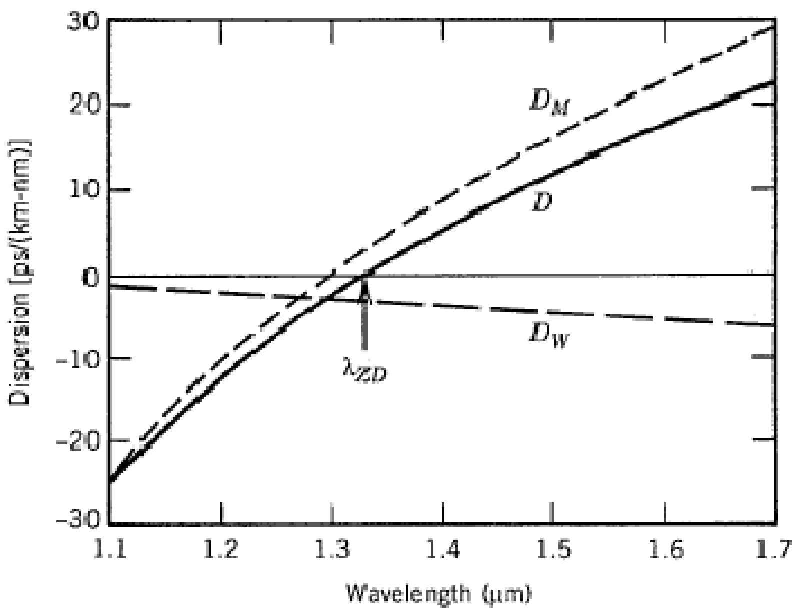

Figure 2.1: Dispersion in order to wavelength for a conventional single-mode fiber [11]

It is important to refer that waveguide dispersion occurs even when does not exist the material dispersion and only results by the difference between the two RI (core and cladding).

If the signal has a $\Delta\lambda$ spectral width, the signal temporal width after the propagation along a fiber with length *L* will be [12]:

$$\Delta_{\tau w} = -\frac{L}{2}.(n_n - n_b).\left(V.\frac{d^2(b.V)}{dV^2}\right)\left(\frac{\Delta\lambda}{\lambda}\right) \tag{2.5}$$

The waveguide dispersion parameter D_W is given by [12]:

$$D_w = -\frac{(n_n - n_b)}{2.\lambda}.\left(V.\frac{d^2(b.V)}{dV^2}\right) \tag{2.6}$$

It is possible to change the profile of the cladding RI in order to decrease the waveguide dispersion that origins the λ_D shift for bigger wavelengths, as in the dispersion shifted fibers case, where the zero dispersion occurs for 1550 nm wavelength.

2.2.1.3 Polarization Mode Dispersion

In single-mode fibers there are not just one mode but two modes (travelling on physically the same path). This is due to the fact that light can exist in two orthogonal polarizations. So there is the possibility to send two signals without interference from one another on single-mode fiber if their polarizations are orthogonal [5]. In normal single-mode fiber a signal consists of both polarizations. However, polarization states are not maintained in standard single-mode fiber. During its journey light couples from one polarization to another randomly.

Ideally, the core of an optical fiber is perfectly circular and therefore has the same index of refraction for both polarization states. However, mechanical and thermal stresses introduced during manufacturing result in asymmetries in the fiber core geometry. This asymmetry introduces small RI differences for the two polarization states, a property called birefringence [14] which is a potential source of pulse broadening.

Birefringence creates differing optical axes that generally correspond to the fast and slow axes. Birefringence causes one polarization mode to travel faster than the other, resulting in a difference in the propagation time called the differential group delay (DGD) where DGD is the unit that is used to describe PMD [14].

If the input pulse excites both polarization components, it becomes broader as the two disperse along the fiber because of their different group velocities. So this phenomenon is called the PMD and has been studied extensively because it limits the performance of modern lightwave systems [11].

PMD effects resemble to the chromatic dispersion effects, but with some key differences: Chromatic dispersion is a rather stable, linear effect, making compensation relatively easy, but PMD is a linear effect that is time-varying in fiber links, making compensation difficult. PMD is very stable in components, unlike chromatic dispersion the effects of PMD are dependent in the launched polarization state. In high-bit-rates systems, PMD may introduce errors as pulses spread into one another and this will decrease the signal to noise ratio.

2.2.2 Attenuation

The attenuation quantifies the optical signal loss along its propagation in the optical fiber. The power variation of certain signal along the propagation can be described by the following equation [12]:

$$\frac{dP}{dZ} = -\alpha P \tag{2.7}$$

Where the attenuation coefficient is α and the optical power is *P*. If P_{in} is the injected power in a fiber with length *L*, the output power P_{out} is given by [15]:

$$P_{out} = P_{in}.e^{-\alpha L} \tag{2.8}$$

It is normal to express α in units of dB/km by using the follow relation [15]:

$$\alpha\,(dB/km) = -\frac{10}{L} log10\left(\frac{P_{out}}{P_{in}}\right) \approx 4.343\alpha \qquad (2.9)$$

As was said in section 2.2.1.2, the optical signal spread predominantly in the core but also extends to the cladding of the optic fiber. So, its losses are given by a weighed mean of all the existents losses in each fiber layers [16]. The optical fiber attenuation depends from the wavelength of the transmitted signal, being originated by several factors as the material absorption, Rayleigh scattering and waveguide imperfections [11], [12].

Figure 2.2 shows a typical curve for the attenuation in order to the wavelength of a high quality silica glass. The minimum values for the attenuation are at 1300 nm and 1550 nm band reaching in this last band 0.2 dB/km for the mono-mode fiber [13]. The losses are considerably high for low wavelengths and exceed the 5 dB/km in the spectrum visible region [11].

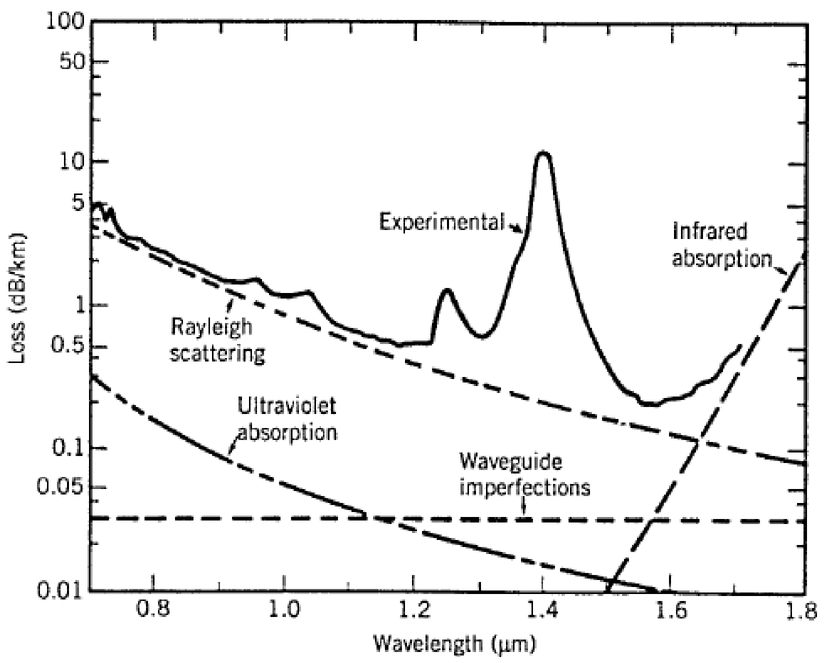

Figure 2.2: Optical fiber attenuation in order to the wavelength [11].

2.3 Nonlinear Properties

The nonlinear effects refer to phenomena that occur due to the nonlinear response of the medium beside high intensity optical signals. The non linear effects can be divided in a generic mode in two categories: *i)* stimulated scattering, like Brillouin and Raman due to the interaction between the optical signals and the acoustic vibrations of the medium and *ii)* modulation of the silica refractive index in consequence of the variations of the optical signal intensity [12].

The nonlinearities limit the performance of the optical communications systems, but they can also be explored in advantageous applications, for example, to compensate the linear effects consequences, like chromatic dispersion and attenuation [17] [18].

2.3.1 Nonlinear Phase Modulation

All materials behave nonlinearly at high intensities and their RI increases with intensity. As it is shown in equation (2.10) the RI can be divided in two parcels: one is linear with the electric field and the other one is non linear which changes with electric field intensity and that will originate phenomena like self-phase modulation (SPM) and cross-phase modulation (XPM) [12].

$$n_{eff} = n + n_2 . |E|^2 \tag{2.10}$$

Where n_{eff} is the effective refractive index, n is the linear refractive index, n_2 the nonlinear refractive index and $|E|$ is the amplitude of the electric field.

The RI change caused by a particular amount of intensity change is much greater than the RI change caused by the same amount of intensity change at lower total light level. This is called the "*Nonlinear Kerr Effect*" [5].

At very high powers, Kerr nonlinearities can be used to balance the effects of chromatic dispersion in the fiber. For medium power levels (below the level to form solitons) Kerr effect has been used to construct devices that compress and re-form pulses. But at high power levels the result of Kerr effect are SPM and XPM [5].

2.3.1.1 Self-Phase Modulation

As a result of Kerr effects, the RI of the glass experienced by a pulse of light varies depending on the point within the pulse that the RI is experienced. This changes the phase of the lightwaves that make up the pulse. Changes in phase amount to changes in frequency. Therefore the frequency spectrum of the pulse is broadened. In many situations the pulse can also be spread out and distorted [5].

During the signal propagation the electric field gets a non linear phase shift given by:

$$\Phi_{NL}(z,t) = \gamma . P(z,t). z \tag{2.11}$$

Where *P(z,t)* is the impulse optical power, and γ is the nonlinear coefficient that is defined in the following equation [12], where w_0 is the carrier central frequency and A_{eff} is the effective mode area:

$$\gamma = \frac{\omega_0 . n_2}{c . A_{eff}} \tag{2.12}$$

This shift combines in one variation of the instantaneous frequency along the impulse. It is possible to say that impulses peak accumulate non linear phases shifts much more quickly than the impulses tails [12]. This combines in a wavelength expansion of the spectrum ascendant zone of the impulse and a compression in the descendant region. So, the impulse propagation on the normal dispersion region of the fiber originates a spread of the impulses in the temporal domain and causes an impulse compression on the anomalous dispersion region [12].

In general, spectral broadening of the pulse induced by SPM increases the signal bandwidth considerably and limits the performance of lightwave systems.

2.3.1.2 Cross-Phase Modulation

The intensity dependence of the refractive index can lead to other linear phenomenon known as “Cross-Phase Modulation” (XPM) which occurs when there are multiple optical channels transmitting simultaneously in the same fiber [11] with signals at different wavelengths and the Kerr effect caused by one signal can result in phase modulation of the other signals [5]. It is important to refer that the nonlinear phase shift for a specific channel depends not only on the power of that channel but also on the power of the other channels and vary from bit to bit depending on the bit pattern of the other channels [11].

The non linear phase of each signal is proportional to the intensity of the other signal and it is given by [12]:

$$\Phi_{NL,i}(z,t) = \gamma.\left[P_i(z,t) + 2.P_{3-i}(z,t)\right].z \tag{2.13}$$

In contrast to other nonlinear effects, XPM effect involves no power transfer between signals. The result of the XPM impact can be asymmetric spectral broadening and distortion of the pulse shape. The total phase shift depends on the powers in all channels and would vary from bit to bit depending on the bit pattern of the neighboring channels. It is difficult to estimate the XPM impact on the performance of multichannel lightwave systems. The reason is that the preceding discussion has implicitly assumed that XPM acts in isolation without dispersive effects and is valid only for CW optical beams [7]. In practice, pulses in different channels travel at different speeds. The XPM-induced phase shift can occur only when two pulses overlap in time. For widely separated channels they overlap for such a short time that XPM effects are virtually negligible. On the other hand, pulses in neighboring channels will overlap long enough for XPM effects to accumulate [7].

2.3.2 Four-Wave Mixing

When a high-power optical signal is launched into a fiber, the linearity of the optical response is lost. One such nonlinear effect, which is due to the third-order electric susceptibility is called the optical Kerr effect. Four-wave mixing (FWM) is a type of optical Kerr effect, and occurs when light of two or more different wavelengths is launched into a fiber. Generally speaking FWM occurs when light of three different wavelengths is launched into a fiber, giving rise to a new wave (know as an idler), the wavelength of which does not coincide with any of the others [19]. FWM is a kind of optical parametric oscillation. In the transmission of dense wavelength-division multiplexed (DWDM) signals, FWM is to be avoided because its distortions are resistant to dispersion compensation. Therefore, FWM will ultimately limit the channel density and the capacity of DWDM systems [20]. But for certain applications, FWM provides an effective technological basis for fiber-optical devices. FWM also provides the basic technology for measuring the nonlinearity and chromatic dispersion of optical fibers [19].

Figure 2.3 represents a schematic diagram that shows FWM in the frequency domain with two channel pump wave and Figure 2.4 represents a system with one channel pump wave (degenerated FWM).

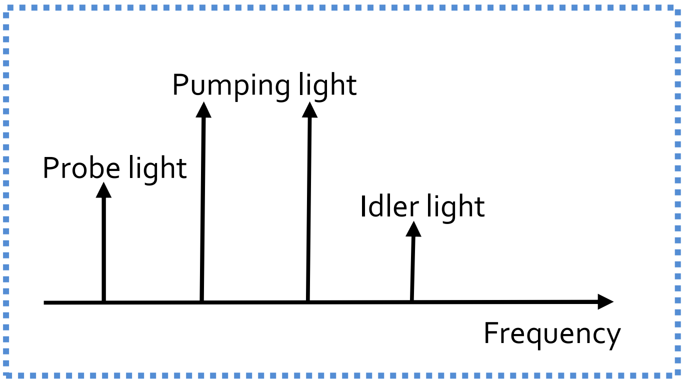

Figure 2.3: *FWM* with two channel pump wave.

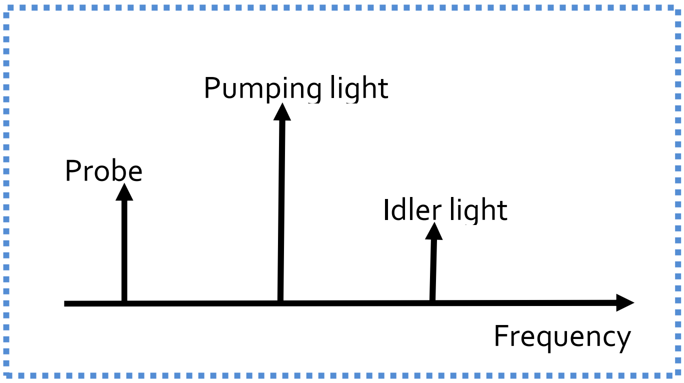

Figure 2.4: *FWM* with one channel pump wave.

As can be seen, the light that was there before launching, sandwiching the two pumping waves in the frequency domain, is called the probe light (or signal light). The idler frequency f_{idler} may then be determined by the following equation [19]:

$$f_{idler} = f_{p1} + f_{p2} - f_{probe} \tag{2.14}$$

Where f_{p1} and f_{p2} are the pumping light frequencies and f_{probe} is the frequency of the probe light.

This condition is called the frequency phase-matching condition. When the frequencies of the two pumping waves are identical, the more specific term "*degenerated four-wave mixing*" (*DFWM*) is used, and the equation for this case may be written as the equation (2.14) where f_p is the frequency of the degenerated pumping wave [19].

$$f_{idler} = 2f_p - f_{probe} \tag{2.15}$$

When there is the interaction between three signals each one with different frequencies (ω_i, ω_j, ω_k) will be produced nine new signals. In a generic way, the interaction of *N* signals will give a total of *M* new products of *FWM* and *M* is obtained by [12]:

$$M = \frac{1}{2}.(N^3 - N^2) \tag{2.16}$$

In DWDM systems where the channels are equally spaced it will appear FWM products with new frequencies as well as products with the same frequencies of the existent channels and those new products will decrease the channels performance. Figure 2.5 summarizes all FWM terms falling on each frequency in an equal spaced four-channel system [21] where the four signals are respectively in positions 1, 2, 3 and 4.

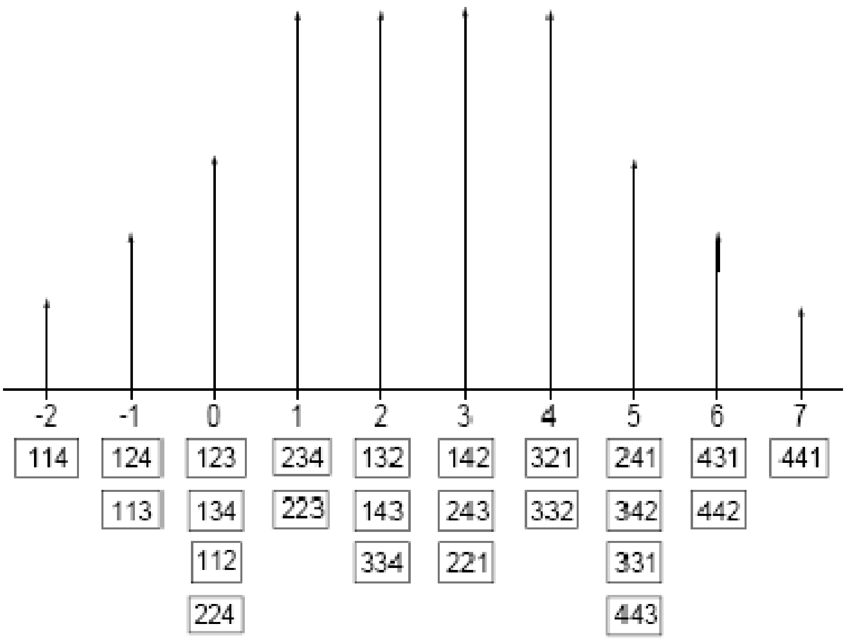

Figure 2.5: FWM products by 4 signals located in positions 1, 2, 3 and 4 [21].

2.5 Conclusions

In this chapter were shown and studied the linear and non linear effects which are presented in optical fibers. The study of the effects that can occur in an optical fiber is important especially when it is necessary to understand some behaviours and limitations of the optical network.

Some of the major impairments, e.g. chromatic dispersion associated to the optical fiber, will be discussed together with the impact in the optical network in chapter 4.

Chapter 3

Optical Switches

3.1 Introduction

The last decade has having an enormous increase of voice and data traffic, with Internet and its associated services being the primary cause of this increase. To meet this traffic expansion, optical transport networks (OTN) are gradually evolving [22] in order to provide more transport capacity, rapid provisioning, intelligent management and higher survivability features. From the deployment of the first point to point Wavelength Division Multiplexing (WDM) transmission system in the 90s with 2 or 4 channel, current optical networks are utilizing intelligent network equipment like Optical Add/Drop Multiplexers (OADM), Optical Cross Connects (OXC) capable of handling tens of fibers with tens of channel per fiber and speed more than 10 Gbit/s per channel. In the next phase of the evolution, it is envisaged that optical layer will also provide the means for economic use of network resources by exploiting the advances of optical packet switching (such as higher throughput, rich routing functionalities, excellent flexibility and finer granularity), which matches the bursty nature of current and future IP services. However, for the all-optical packet switch to be competitive with the upcoming terabit high-speed IP routers, it should operate beyond 10 Gb/sec per wavelength to actually take advantage of the optical transparency of the payload data. At 40 Gbit/s and up, regeneration will be necessary after the signal travels through various components in a number of switching nodes. All-optical regeneration solutions will have to be pursued if OE (Optoelectronic) conversion is to be avoided throughout the network.

Core component of the different optical network elements are optical switches, which are combined together for the construction of complex switching systems, such as OXCs and OADMs. Optical switches have attracted significant attention due to:

- The transparency to higher layer protocol formats they allow. Since, there is no optoelectronic conversion, thus no electronic processing of the incoming signal, there is no need to know the timing of the incoming data/bits. However, as the need for more bandwidth continues to increase, it has become clear that current optical networks will become increasingly constrained by the need to convert optical signals into electronic form to allow the signal to be switched. For speeds beyond 10 Gbit/s per wavelength optical regeneration is needed;

- Cost reduction due to the absence of OE conversion or if this is not completely feasible to the minimisation of OE conversion;

- Lower power consumption and footprint compare to their electronic counterparts.

Different technologies like MEMS, Thermal Optic, Electro Optic, Opto Mechanical, etc can be used for the realization of an optical switch. Each technology has its own advantages and disadvantages and not all technologies can be used for the same network applications [23].

The key performance indicators for evaluating different optical switches, independent from the technology are:

- Switching time/speed. It refers to the time needed to change the state of the switch, and therefore it is associated with the maximum supported throughput as well as the reconfiguration rate of the devices;

- Signal Quality. In general, optical switches are deployed to work in a specific band and for a specific bit rate. Outside of this band and/or for higher values of the bit rate, the quality of the switching with respect to cross-talk, loss, dispersion and PMD may be significantly reduced. This is called performance variation due to parameter sensitivity. The most significant parameters are:

    → Insertion loss: It refers to the signal power that is lost due to the switch. Ideally, the insertion loss should be the same for all the sets of input-output connections;

    → Crosstalk: Crosstalk is generated when signals following one path through the switch leak power to another path through the switch;

    → Polarization-dependent loss (PDL): If the loss of the switch is not equal for both states of polarization of the optical signal, the switch is said to have polarization-dependent loss. It is desirable that optical switches have low PDL.

- Reliability. Due to the vast amount of traffic every link carries, any fault in the network can disrupt the service of millions of end users. Existing telecommunication networks offer high reliability (99.999% uptime) and thus redundancy of switch paths inside a fabric, redundancy of switch fabrics and of switches as a whole may be needed to provide sufficient reliability;

- Size. It refers to their size, which should be comparable to that of their electronic counterparts;
- Power. Power consumption is also a critical issue and should be comparable to their electronic counterparts;
- Temperature.

The optical switches serve in many different domains the optical networking efficiency. The main applications of optical switches are [24]:

- Fast Provisioning: Optical cross connects uses optical switches as a mean to setup/tear down or reconfigure light-paths/channels. Such functionality allows the replacement of fiber patch panel with intelligent network elements, which transform Optical Transport Networks (OTN) into intelligent Automatic Switch Optical Networks [25].

- Packet Switching. Although OTN follows the approach of connection oriented technologies, advances into optical packet switching technology allow the switching of data at 10Gbit/s line rate. Such rates require switching times in the order of ns.

- Protection Switching. In case of a link failure, traffic should be switched from the primary link/fiber to a backup link/fiber in time less than 50msec. Taking into consideration the fact that it takes some time to detect the fault and notify the adjustment nodes, optical switches components should be capable to switch the traffic in less than 50 ms time.

An optical switch may operate by mechanical means, such as physically shifting an optical fiber to drive one or more alternative output fibers or by other effects occurring in some material under some conditions (eg. Acouto-optic, Electro-optic, Magneto-optic, etc). From these technologies, several types of switches have been developed and studied. Switches have been mainly grouped in two classes, when considering the base building technology: Free space and Guided wave.

The first class, free space, encompasses devices that perform switching by working on optical free space collimated beams. From this technology are examples: MEMS (Micro Electrical Mechanical Systems), liquid crystals, electroholography based devices or ESBG (Electrically Switchable Bragg Gratings). In the other group, guided wave, switching is performed recurring to effects occurring in the waveguides, from these are example: thermo-optic, electrooptic, acousto-optic, gel/oil-based, semiconductor optical amplifier (SOA) and ferro-magnetic devices [26], [27]. These two classes are schematically presented in Figure 3.1.

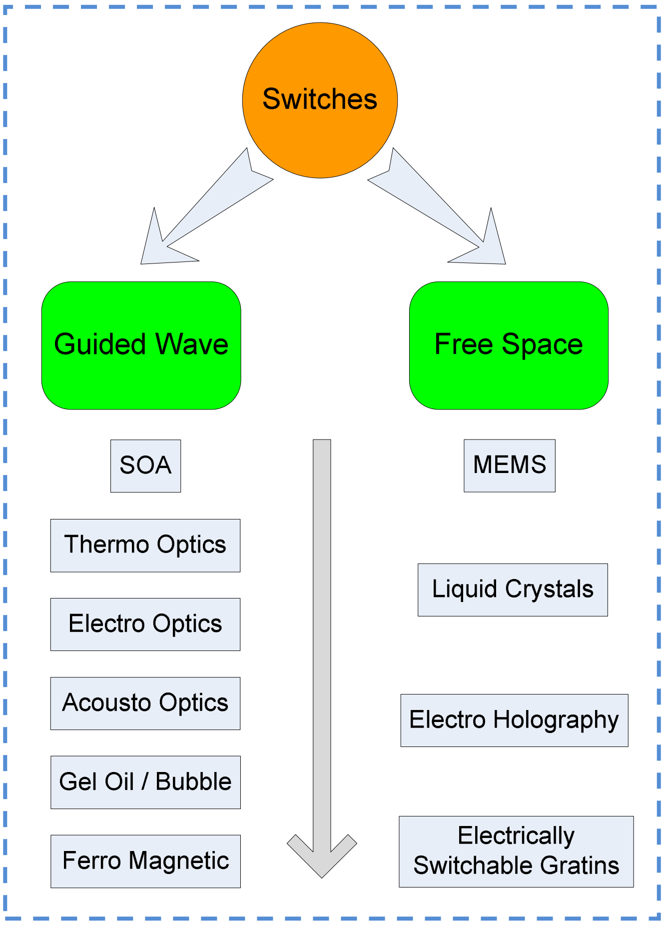

Figure 3.1: Optical switching technologies: guided wave based switches and free space based switches.

Typically, comparing free-space to guided wave usually, the latter results in increased losses, but on the other hand, in higher switching speeds. Therefore, when choosing a switching technology, a compromise should be reached between these two parameters, loss and speed.

Slow optical switches, such as those using moving fibers, may be used for alternate routing of an optical transmission path, such as routing around a fault, called restoration and protection. Fast optical switches, such as those using electro-optic or magneto-optic effects, may be used to perform logic operations and bit length switching as optical time division multiplexing / demultiplexing (OTDM).

When evaluating the performance of different optical switches, several are the parameter switch should be considered, eg.: switching time, reliability, energy usage, port configurations and scalability, optical insertion loss, cross-talk, extinction ratio, temperature resistance, polarization-dependent loss characteristics and cost. The requirements on these parameters are different and depend on the final applications. Typical usage of switches in networks are, eg.: optical cross connect, protection switches, OADM, Optical Signal Monitors (OSM) and network provisioning are some of the applications where switches are the core.

In these scenarios, switching time, for example, is one of the crucial parameters to be considered. Switches for inline provisioning, existing inside wavelength crossconnects, are used to reconfigure or accommodate new lightpaths allowing rapid management of connections across a network; for these applications switching time on the order of miliseconds to seconds are needed. On the same line is protection switching, where the traffic stream must be switched into a secondary fiber if the primary one fails. For SDH/SONET compatibility several tens of ms are required (up to 50 ms). An opposite example is optical packet or burst switching (OPS/OBS) where switching time requirements are set to few picoseconds, in order to be significantly shorter than the packet duration [28].

Insertion loss is another crucial requirement that must be carefully considered. Device losses add to fiber losses and only an efficient scheme and packaging can help lowering of the total network losses. This reflects directly in network costs related to extra amplification needed as well as the need or not for regeneration.

The losses should be kept low especially in the switching fabrics, since in topologies where many will cascade, signal to noise ratio (SNR) will decay.

Installed equipments have to be reliable, therefore, are expected to behave without visible performance degradation for some decades. This has direct implications in choosing technologies for difficult accessibility places. One general example is any equipment with moving parts is expected to have some degradation dependent on the usage (eg. MEMS in very active reconfigurable nodes).

Energy consumption of the switching fabric is also a very important parameter, especially due to the fact that the density of devices is growing and therefore advanced power dissipation schemes need to be used in order not to disrupt the function of the switch or accelerate the aging.

Many technologies have been developed along the years. Each has its own limitations and benefits, and based on these, they are more or less adapted to each of the function. A summary of actual technologies and applications is presented in Table 3.1.

Technology	Advantages	Disadvantages	Applications
Moving fiber (Opto-Mechanical)	Low loss and cross-talk	Low switching and stabilizing time, poor scability	Protection, OADMs
MEMS	Small size	Low reliability due to moving parts	Large OXC
Bubble	Easy to integrate	Long switching time (down to 10 ms), limited reliability high power consumption	Protection and Restoration, OADMs, medium OXC
Thermo Optic	Easy to integrate	Long switching times, high loss and cross talk, high power consumption	Protection and Restoration, OADM, medium OXC.
Liquid Crystal	Good reliability	Temperature dependent, slow switching time (ms)	Protection and Restoration, small OXC and OADMs
Electro Optic	Fast switching	Medium loss and high cross talk, polarization dependent poor scalability	Protection and Restoration, OADMs, Packet or Burst switching
Acousto Optic	Flexible switching	Medium loss and complexity	Protection and Restoration, small OXC and OADMs
Electro Holography	Highly flexible and possible built in wavelength demultiplexing	Medium loss and high power	Protection and Restoration, small OXC and OADMs
SOA	Fast switching, Gain	Noise addition, actually moderately expensive	OADM, Packet or Burst switching

Table 3.1: Summary of the main characteristics of some of the available technologies. [28], [29].

In this project were used the opto-mechanical switches in each node along the optical link. This technology was the first commercially available for optical switching, namely for the basic functions of protection and restoration. In opto-mechanical switches, the switching function is performed by some mechanical means. These means include prisms, mirrors, and directional couplers. Mechanical switches exhibit low insertion losses, low polarization dependent loss, low crosstalk, and low fabrication cost. Their switching speeds are in the order milliseconds, which may not be acceptable for some types of applications, but in this optical network the switching speeds are not a relevant issue, because all the switches will be configured when the optical network is “off”. Another disadvantage of the opto-mechanical switches is the lack of scalability. The opto-mechanical switches characteristics are presented in Table 3.2. [27]

Scalability	Switching speed	Reliability	Losses	Port-to-Port repeatability	Cost	Power consumption
2D Medium (32^2) **3D High (512^2)**	Tens of ms	Moderate	Few dB	High for small switches Moderate for big switches	Medium	Medium

Table 3.2: Characteristics summary of the Opto-mechanical switches.

The used switches were the opto-mechanical, because they are the only ones that can be latch type. The switches have to be latch type, because latching operation ensures that the switch remains in position following power loss, so it is just necessary that the current applied to the coil has to be a pulse with minimum duration of 20 ms to change the switch’s position. So, the latch type brings less power consumption to change the switches positions.

The only switches available on the market with the latch specifications are from Oplink and belong to the OFMS series, which will be better described in the following section.

3.2 Switches Specifications

3.2.1 Switch OFMS 1x2

3.2.1.1 Switch Design and Features

As the most important product in optical switching and routing product family, Oplink's OFMS 1x2 optomechanical switch features low insertion loss, high isolation, fast switching speed and compact size. This simple and elegant 1x2 optomechanical switch design uses a simple wedge mounted on an electrical relay. In this structure, port 1 and port 2 are aligned without the wedge. When the electrical relay inserts the wedge into the optical path, optical refraction directs the light to port 3 in a few milliseconds. The OFMS 1x2 switch configuration it is presented in Figure 3.2.

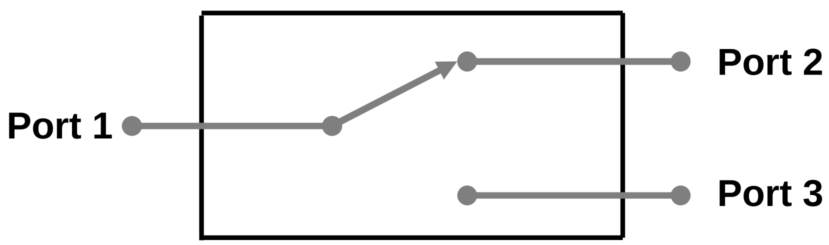

Figure 3.2: Configuration for OFMS 1x2 switch.

Oplink's refractive optical design is about 20 times less sensitive to mechanical and thermal drift than mirror approach. This latitude allows simple mechanical design with high stability and reliability across the entire wavelength and temperature range (-20 to 75 degrees C).

Designed as a latching device, Oplink's 1x2 switch holds its position without power. The switch is also equipped with two status sensors that allow electrical readout of the actual switch position. Using a proprietary process technology, the switch achieves zero sticking.

Oplink's dual fiber collimator design minimizes the 1x2 switch size. Thus, it can be easily integrated into high-density optical systems to save precious shelf space.

Oplink's switch is optically passive; therefore transparent to both signal format and bandwidth.

With epoxy-free optical path, Oplink’s 1x2 switch is ideal for high power applications. Unlike some approaches using moving fiber, where high power laser beam can damage the bonding in between fibers, the optical wedge directs the beam to either port 2 or 3 with minimum loss during transition. The uncoupled light stays close to the fiber core so that the power is dissipated gradually in the cladding layer.

The switch 1x2 is very useful in the nodes, because is this switch which will allow to select the fibers that will travel each path.

3.2.1.2 Electrical Control

Electromagnetic relay is used in Oplink fiber-optic switch design. The relay consists of two multi-turn coils, wound on an iron core, to form an electromagnet. When the coil is energized, by passing current through it, the core becomes temporarily magnetized and then the magnetized core attracted the iron armature. The armature is pivoted which causes it to operate the optical switching and one or more sets of contacts. The contacts are to provide an electrical readout of the switch position. Latching operation ensures that the switch remains in position following power loss. The current applied to the coil is a pulse with minimum duration of 20 ms recommended. The coil resistance is 101.2±10% Ω and the maximum recommended cycle rate is 10 Hz. The electrical pin assignment is shown in Table 3.1 and Figure 3.2. Pin 3-4-5 and 10-9-8 are a pair of contacts which are dual ON-ON DPDT (double pole, double throw) switches operating together. Failure to connect the contacts will disable the position sensing function, but will not affect the switch operation.

Optical Path	**Electrical Drive**				**Status Sensor**			
	Pin 1	Pin 6	Pin 7	Pin 12	Pin 4-3	Pin 4-5	Pin 9-8	Pin 9-10
1-2	+V	GND	-	-	Open	Closed	Closed	Open
1-3	-	-	GND	+V	Closed	Open	Open	Closed

Table 3.3: Electrical pin layout of the 1x2 switch.

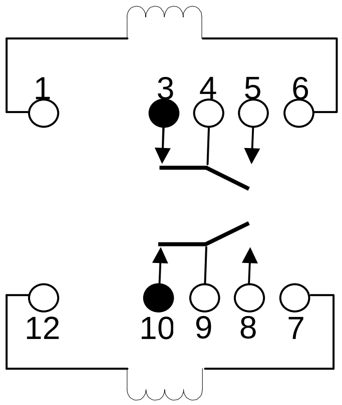

Figure 3.3: Switch electrical pin layout.

CTL0	**0**	**1**	**0**	**(1,1) is forbidden. There shall be no time that CTL0 and CTL1 are both at level of High**
CTL1	0	0	1	
Status	Previous Status	0	1	-
Optical	Previous path due to latching	1-2	1-3	-

Table 3.4: Truth table for the control pins of 1x2 switch.

3.2.1.3 Specifications

Parameter	Value
Operating Wavelength Range	1260 – 1310 nm and/or 1510 - 1610 nm
Insertion Loss [1,2]	< 0.5 dB
Wavelength Dependent Loss	< 0.15 dB
Temperature Dependent Loss	< 0.2 dB
Polarization Dependent Loss	< 0.1 dB
Return Loss [2]	> 55 dB
Channel Cross Talk	> 60 dB
Repeatability	±0.02 dB
Switching Time	< 10 ms
Operating Current	75 – 115 mA
Operating Voltage	3.5 – 4.5 VDC
Durability	10^7 cycles
Operating Power Handling	500 mW
Operating Temperature	0 -70 ºC
Storage Temperature	-40 – 85 ºC
Fiber Type	Corning SMF-28
Package Dimensions	44.0 (L) x 15.5 (W) x 9.0 (H) mm

Table 3.5: Parameters values for the Switch OFMS 1x2.

NOTE:

1. Insertion loss is specified at 23ºC over all wavelength range and all SOP.
2. Excluding connectors.

3.2.2 Switch OFMS mini 1x4

3.2.2.1 Switch Design and Features

The OFMS series Mini 1×4 optical fiber switch is free space micro optic based optomechanical switch. The switches are designed for use in optical channel monitoring, Remote Fiber Testing Systems (RFTSs), and network switching for fault protection applications.

→ **Key Features**

- Wide operating wavelength range;
- Fast switch speed;
- Highly stable & reliable;
- Low insertion loss;
- Low PDL;
- Mini size;
- Built-in position monitor.

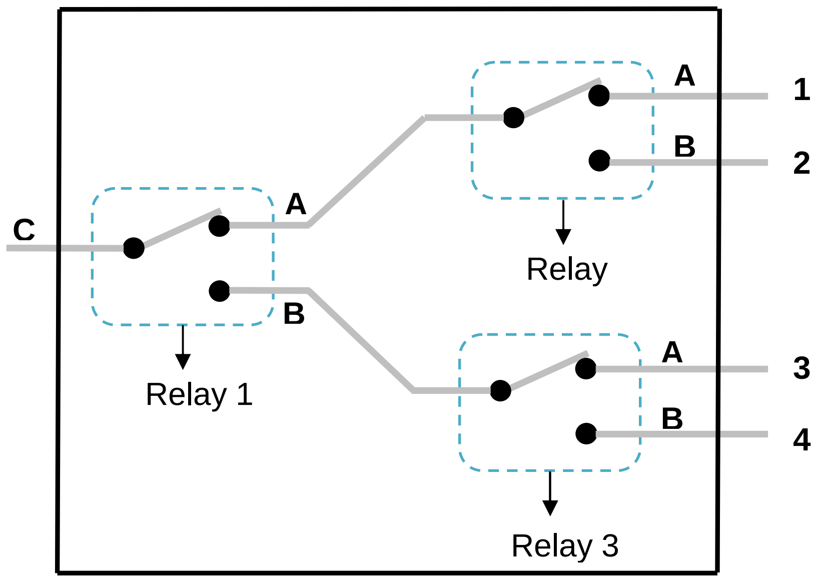

Figure 3.4: Functional diagram of mini 1x4 switch.

Light can be directed in the 1×4 switch from port C to any of the ports 1~4 or from any of the ports 1~4 to port C. As shown in the Figure 3.3, in order to direct light between port C and ports 1~4, the three electrical relays shall be set correctly.

The following table shows how each relay shall be set for each optical path. For example, if it is wanted to switch to port 1, Relay 1 and 2 shall be both set to A side. In this example, it does not matter which side Relay 3 is at.

Optic Path	Relay 1	Relay 2	Relay 3
C ↔ 1	Set to A	Set to A	Not Care
C ↔ 2	Set to A	Set to B	Not Care
C ↔ 3	Set to B	Not Care	Set to A
C ↔ 4	Set to B	Not Care	Set to B

Table 3.6: Relays position for the different paths of the mini 1x4 switch.

When a relay is at “Not care” state, set or reset this relay does not affect the optical thru path, however actuation of “Not care” relay is still not recommended.

Relay status is the term used to describe the relay position, i.e., the relay is at A side or B side. Status of relay can be read from the status sensors. User can always read status of each relay first and then determine how to set each relay.

The 1×4 switch has no OFF state, which means there is always one optical thru path between port C and port 1-4.

The switch 1x4 is very useful, because it is this switch that will allow to compensate the chromatic dispersion of each fiber or even do a signal bypass.

3.2.2.2 Electrical Control

The three relays have same pin out. The following table lists electrical pin assignment for the relays.

Optic Path	Electrical Drive				Status Sensor			
	Pin 1	Pin 6	Pin 7	Pin 12	Pin 4-3	Pin 4-5	Pin 9-8	Pin 9-10
1-2	+V	GND	-	-	Open	Closed	Closed	Open
1-3	-	-	GND	+V	Closed	Open	Open	Closed

Table 3.7: Electrical pin layout of mini 1x4 switch.

If a relay is at B side and a ≥20ms 5V DC electrical pulse is applied to pin 1 and pin 6 at the polarity shown, the relay is then set and optical path move to A side. If a relay is at B side, and a pulse is applied to pin 12 and pin 7 at the polarity shown, the relay has no reaction. If a relay is at A side and a ≥ 20ms 5V DC electrical pulse is applied to pin 12 and pin 5 at the polarity shown, relay is then set and optical path move to B side. If a relay is at A side, and pulse is applied to pin 1 and pin 5 at the polarity shown, the relay has no reaction.

Pin 3-4-5 and 10-9-8 are a pair of metal contacts which are dual ON-ON DPDT (double pole, double throw) switches operating together. Their Open/Close status provides the readout of switch's position. This function let the user know which side the switch is at without monitoring the optical signals. Failure to connect the contacts will not affect switch optical functions.

Parameter	**Specifications**			**Unit**	**Notes**
	Min	**Typ**	**Max**		
Relay Type	Latching, two coil			-	-
Switching time		3	10	ms	-
Switching driving voltage	4.5	5	5.5	V DC	-
Coils resistance	101.2 ± 10%			Ω	-
Switch driving current	40	-	60	mA	1
Driving pulse width	20	-	-		-

Table 3.8: Relay specifications of mini 1x4 switch.

NOTE:

1. The driving current is derived from the driving voltage and the coils resistance.

CTL0	**0**	**1**	**0**	**(1,1) is forbidden. There shall be no time that CTL0 and CTL1 are both at level of High**
CTL1	0	0	1	
Status	Previous Status	0	1	**-**
Optical	Previous path due to latching	A side	B side	-

Table 3.9: Truth table for the control pins of mini 1x4 switch.

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3.2.2.3 Specifications

Parameter	Value
Operating Wavelength Range	1260 – 1360 nm or 1525 - 1610 nm
Insertion Loss [1,2]	< 0.5 dB
Polarization Dependent Loss	< 0.1 dB
Wavelength and Temperature Dependent Loss	< 0.5 dB
Return Loss [2]	> 50 dB
Channel Cross Talk	> 55 dB
Repeatability	±0.05 dB
Switching Time	< 20 ms
Operating Power Handling	300 mW
Operating Temperature	0 -70 ºC
Storage Temperature	-40 – 85 ºC
Fiber Type	SMF-28
Package Dimensions	43.0 (L) x 30.0 (W) x 11.0 (H) mm

Table 3.10: Parameters values of Switch OFMS Mini 1x4.

NOTE:

1. Insertion loss is specified at 23ºC over 1310 nm and/or 1550 nm wavelength range and all SOP.

2. Excluding connectors.

3.2.3 Switch OFMS 2x2 Add/Drop

3.2.3.1 Switch Design and Features

The OFMS 2x2 Add/Drop is designed for use in re-configurable optical add/drop multiplexers, optical cross-connect systems, and network switching for fault protection and restoration applications. The switch can be directly mounted on PCB and has contacts to provide an electrical readout of the switch state (Cross or Bar). As the other switches the latching type ensures the switch remains in current state when electrical power is off.

In order to do the loop-backs in each node it is necessary to implement this switch 2x2 Add/Drop.

→ **Key Features**

- Compact size;
- Seam-seal package;
- Highly stable & reliable;
- Latching type.

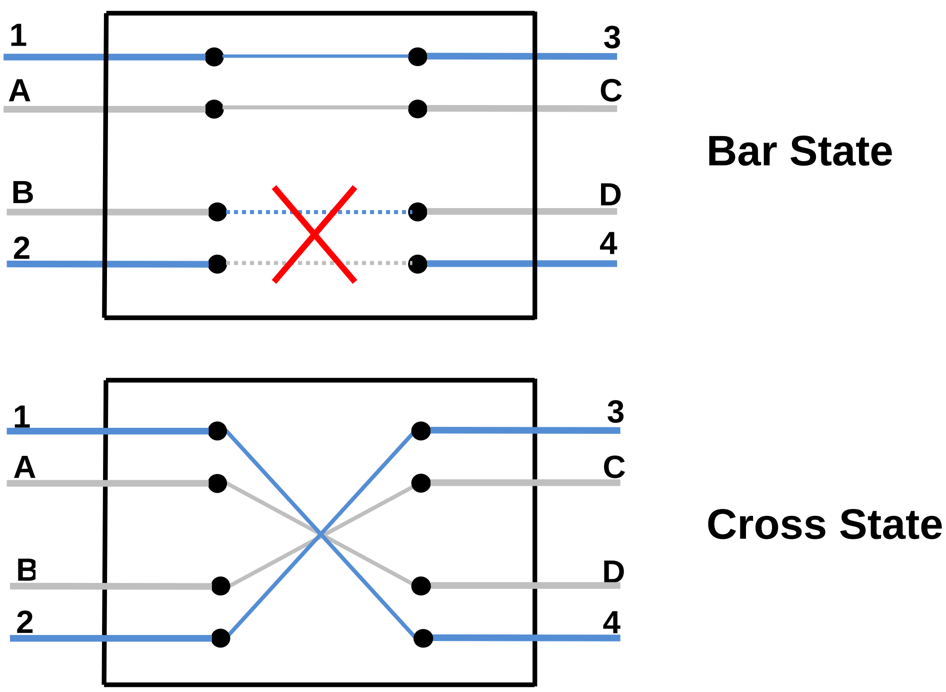

Figure 3.5: Functional diagram of 2x2 Add/Drop switch.

3.2.3.2 Electrical Control

The three relays have same pin out. The following table lists electrical pin assignment for the relays.

Optic Path	**Electrical Drive**				**Status Sensor**			
	Pin 1	Pin 6	Pin 7	Pin 12	Pin 4-3	Pin 4-5	Pin 9-8	Pin 9-10
Cross state	+V	GND	-	-	Open	Closed	Closed	Open
Bar state	-	-	GND	+V	Closed	Open	Open	Closed

Table 3.11: Electrical pin layout of 2x2 Add/Drop switch.

Pin 1 and 6 are two terminals of the first coil. Pin 12 and 7 is the second coil. The coil resistance is 101.2 ±10% Ohm. The drive voltage for the coil is 4.5~5.5V.

As in the other switches, pin 3-4-5 and 10-9-8 are a pair of contacts which are dual ON-ON DPDT (double pole, double throw) switches operating together. The contacts are to provide an electrical readout of the switch position. Failure to connect the contacts will disable the position sensing function, but will not affect the switch operation.

CTL0	**0**	**1**	**0**	**(1,1) is forbidden. There shall be no time that CTL0 and CTL1 are both at level of High**
CTL1	0	0	1	
Status	Previous Status	0	1	**-**
Optical	Previous path due to latching	Cross	Bar	-

Table 3.12: Truth table for the control pins of 2x2 Add/Drop switch.

3.2.3.4 Specifications

Parameters	Values
Operating Wavelength Range	1260 – 1310 nm and/or 1510 - 1610 nm
Insertion Loss [1,2]	< 1.1 dB
Wavelength Dependent Loss	< 0.2 dB
Polarization Dependent Loss	< 0.1 dB
Return Loss [2]	> 50 dB
Channel Cross Talk	> 50 dB
Repeatability	±0.02 dB
Switching Time	< 10 ms
Operating Current [3]	40 – 60 mA
Operating Voltage [3]	4.5 – 5.5 VDC
Coil Resistance	101.2 ± 10% Ω
Durability	10^7 cycles
Cycle Rate	10 Hz
Operating Power Handling	500 mW
Operating Temperature	0 - 70 ºC
Storage Temperature	-40 - 85 ºC
Fiber Type	SMF-28
Package Dimensions	54.0 (L) x 15.5 (W) x 9.0 (H) mm

Table 2.13: Parameters values for the Switch OFMS 2x2 Add/Drop.

NOTE:

1. Insertion loss is specified at 23ºC over all wavelength range and all SOP. Add 0.4dB (max.) to insertion loss over operating temperature range.
2. Excluding connectors.
3. Current is derived from driving voltage and coil resistance. Pulse of > 20ms duration is recommended for latching type.
4. The mechanical tolerance is ± 0.2mm.

3.3 Conclusions

In this chapter was firstly presented some key performance indicators of optical switches components in order to enable the understanding and comparing between the different optical switches technologies that were also presented.

The chosen switch technology was the Opto-mechanical from OPLINK, since these offer latch type characteristic in order to reduce the power needed to change the switches positions.

The chosen switches to perform each implemented node along the optical network were the OFMS 1x2, mini 1x4 and the 2x2 Add/Drop, because with these switches it is possible to chose which fiber will travel each path (Switch OFMS 1x2), chose between SSMF or NZDSF dispersion compensation or even the signal bypass (Switch OFMS mini 1x4) and the possibility of loop-backs in each node (Switch OFMS 2x2 Add/Drop).

Chapter 4

Simulation and Results

4.1 Introduction

In order to study the response to the implemented system for different bit rates (2.5, 10, 40 Gbit/s) were developed different scenarios that correspond to different routes that can be traced in the optical network, such as Aveiro → Coimbra → Aveiro, Aveiro → Entroncamento → Aveiro, and at last Aveiro → Lisboa → Aveiro.

It is necessary to refer that all the simulations that will be presented and explained were done for the scenario Aveiro → Lisbon → Aveiro for two situations, the first one is when the optical network is travelled by ITU-T G.652 optical fiber (SSMF) and the other one when the optical network is travelled by the ITU-T G.655 optical fiber (NZDSF).

Since that this system is strongly influenced by the chromatic dispersion, will be verified which compensations (pre or post compensation) bring the best results. The scenario Aveiro $\rightarrow$ Lisboa $\rightarrow$ Aveiro was chosen because it can bring the highest amount chromatic dispersion.

In one attempt to improve the Bit Error Rates (BER) when the optical network has a 40 Gbit/s bit rate, were made some tests with the inclusion of filter at the end of the optical network and putting the system with total dispersion compensation.

4.2 Optical components characteristics

4.2.1 Laser

Lasers are the most commonly used light sources in optical communications. These devices can generate high power outputs with a narrow-linewidth radiation and provide a better coupling of the light to the fiber when compared to LED's (Light Emitting Diode). Finally, lasers have a higher bandwidth.

Characteristics:

- Sample Rate: 640 GHz;
- Bit Rate: Bit Rate Default (2.5, 10 ou 40 Gbit/s);
- Laser Emission Frequency: 193.1 THz;
- Laser Average Power: 1 mW;
- Laser Linewidth: 10 MHz;
- Rise Time: 0.25/Bit Rate Default;
- PRBS Type: PRBS;
- Mark Probability: 0.5;
- Modulator MZ Extinction Ratio: 15 dB;
- Laser Noise Threshold: -100 dB;

4.2.2 Optical Fiber

For these simulations were used two kinds of optical fibers, the ITU-T G.652 (Standard SMF) and ITU-T G.655 (NZDSF). These two fibers are single-mode fibers that are the most important and the ones that give us the best results when we want to do long haul networks.

Single-mode fibers have the benefit of not having reflections from the core-cladding boundary but rather the electromagnetic wave is tightly held to travel down the axis of the fiber. The longer the wavelength of light in use, the larger the fiber diameter which can be used and still have light travel in a single-mode.

The compensation of the dispersion is achieved when it is put a loop of DCF on the transmission path. The total of the dispersion on this loop has to be equal and opposite value to the accumulated dispersion on the transmission fiber. Each fiber has its own characteristics that are described below.

ITU-T G.652 Characteristics:

- Attenuation: 0.2 dB/Km;
- Reference Frequency: 193.1 THz;
- Dispersion: 17 ps/nm.km;
- Dispersion Slope: 0.08x10^{3} s/m^{3};
- Core Area: 80.0x10^{-12} m^{2} MHz;
- Zero Dispersion Wavelength: 1310 nm.

ITU-T G.655 Characteristics:

- Attenuation: 0.2 dB/Km;
- Reference Frequency: 193.1 THz;
- Dispersion: 4.2 ps/nm.km;
- Dispersion Slope: 0.09x10^{3} s/m^{3};
- Core Area: 80.0x10^{-12} m^{2} MHz;

DCF Characteristics:

- Attenuation: 0.4 dB/Km;
- Reference Frequency: 193.1 THz;
- Dispersion: -98 ps/nm.km;
- Dispersion Slope: -0.2×10^{3} s/m^{3};
- Core Area: 15.3×10^{-12} m^{2} MHz;

4.2.3 Amplifiers

With the demand for longer transmission lengths, optical amplifiers have become an essential component in long-haul fiber optical systems.

An optical amplifier performs gain without the need to first convert to electrical domain. An optical amplifier may be thought of as a laser without an optical cavity, or one in which feedback from the cavity is suppressed. The bandwidth of these amplifiers it is between 3 THz to 25 THz and there are three types of configurations as what regards placement of the amplifiers in the link, Booster, Line and Pre-Amplifier like is shown in Figure 4.1.

Pre-Amplifier:

- Located before the receiver;
- Low signal $\Rightarrow$ low noise:
    - Typically pumped from the output to avoid losses in the coupler of an already small signal;
    - High pumping and not use in saturation.

Booster Amplifier:

- Located before the transmitter;
- Targets compensate the loss of the modulation devices and the lack of the power in the lasers:
    - 100 mW.

Line Amplifier:

- Should provide high gain, high output power and low noise;
  - Should be similar to the cascade of an pre-amplifier and a booster amplifier;

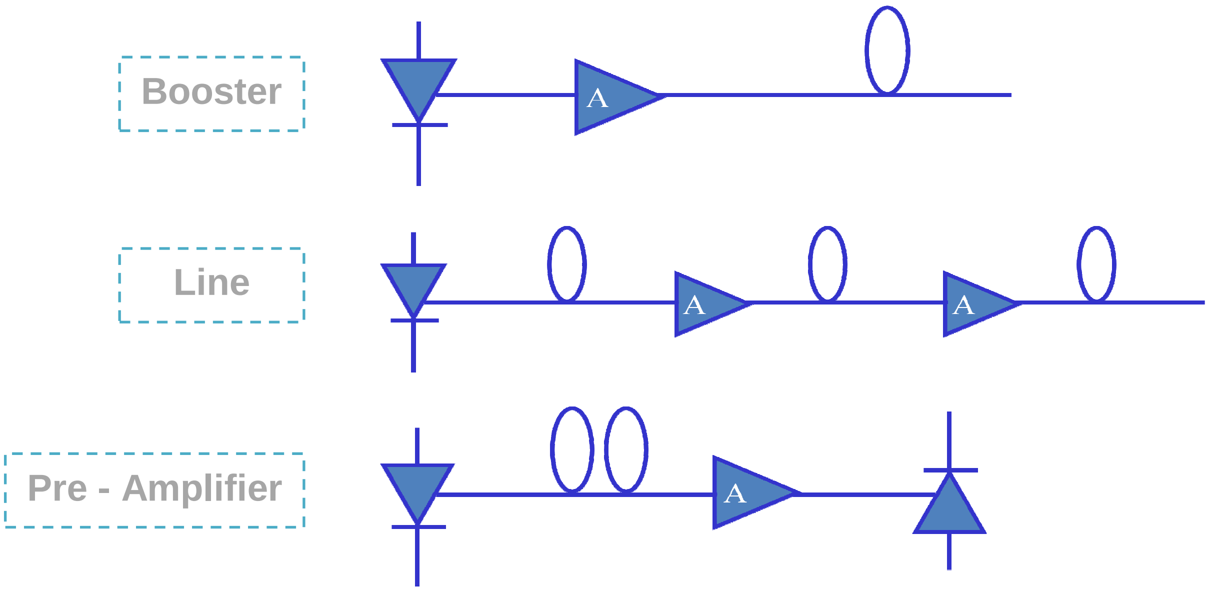

Figure 4.1: The three types of amplifiers placement in a link.

In VPI the amplifier model can act as a gain-controlled, power-controlled or saturable amplifier. The chosen mode was the power-controlled because with this mode it is possible to have at the output of the amplifier the same power signal that is on the beginning of the transmission fiber. In this mode the pump power is variable and the parameter output power specifies the total power that is controlled by enhanced parameters which is the Sampled Signals, Parameterized Signals, Noise Bins, and Distortions. On Figure 3.1.2 it is presented the system-level amplifier in the Power-Controlled mode.

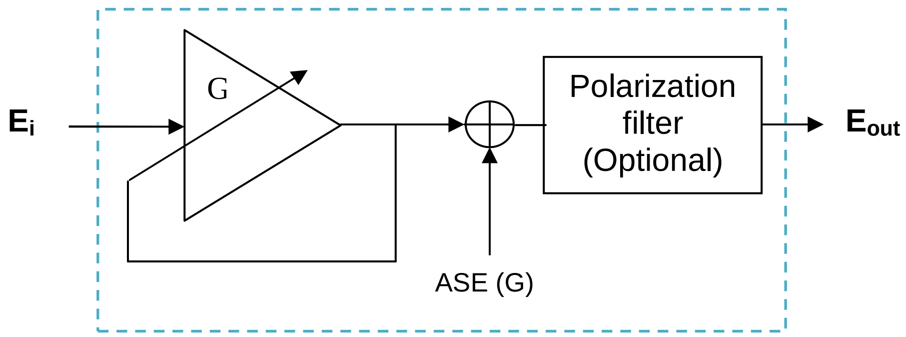

Figure 4.2: System-level amplifier in the Power Controlled mode.

At low input powers, the amplifier's gain will be limited and the output power (average over one block) will be limited, as in a real device, by setting a maximum amplifier gain G_{max} by the parameter Gain Max. This limiting is achieved by downscaling output power, P(f):

$$P(f) = \frac{\mathrm{Pout(f)}}{\mathrm{k}} \tag{4.1}$$

Where k is the ratio of the Gain Max to the unscaled gain, where the unscaled gains value is averaged over the signal wavelength range by relating the total input and the total output powers. This power limiting is useful in providing realistic simulations. If the output power is set to an unrealistic high value, the output will always equal the power limited by the maximum gain.

Amplifier Characteristics:

- Amplifier Type: Power Controlled;
- Output Power: 1 mW;
- Gain Max: 100 dB;
- Noise Figure*: 4.0 or 8.0 dB;
- Noise Bandwidth: 4 THz;
- Noise Center Frequency: 194.0 THz;

*Additionally, the amplifier corrupts the output signal E_{out} by amplified spontaneous emission (ASE) noise. The resulting NF (noise figure) is defined by the quotient of the SNR at the input divided by the SNR at the output measured by an ideal, shot-noise limited photodiode [30]:

$$NF = 10 \log \frac{\mathrm{SNR\_in}}{\mathrm{SNR\_out}} \tag{4.2}$$

The minimum value NF_{min} can be below of 3 dB, such as in low-gain amplifiers. For high-gain amplifiers (G»1) the NF is above 3 dB, commonly referred to as the quantum limit.

4.2.4 Filters

Optical filters are key components of optical communications systems. They are widely used for example WDM signal demultiplexing, noise and distortion suppression and fiber dispersion compensating. In dependence on the specific application the filter design includes development of the filter with prescribe magnitude and phase response. The module that was used on the simulations supports the simulation of optical filters using a wide range of standards models and procedures: causal physically realizable filters (Butterworth, Chebyshev, Bessel and Elliptic) or idealized filters (Rectangular, Trapezoid, Gaussian and Integrator), as well as the design of minimum-phase and complementary power filters with a given amplitude response.

The used model on the simulations was the Trapezoid filter which provides an ideal approximation of a real filter but with some transition band. It passes the signal unaltered in the frequency range defined by the bandwidth parameter and reduces the power by stop band attenuation dB at stop band. Transition between the pass band and stop band is described by linearly increasing attenuation from zero to stop band attenuation. The minimum phase parameter specifies whether the phase response should be modified to ensure that the filter is causal and minimum-phase.

Filter Characteristics:

- Filter Type: Band Pass;
- Transfer Function: Trapezoid;
- Bandwidth: 4 x Bit Rate Default Hz;
- Center Frequency: 193.1 THz;
- Stop Bandwidth: 8 x Bit Rate Default Hz;
- Stop Band Attenuation: 40 dB;
- Minimum Phase: Off;
- Noise Threshold: -100 dB;
- Active Filter Bandwidth: 1.0 THz;
- Active Filter Bandwidth Center Frequency: 193.1 THz;

4.2.5 PIN Photodiode

A photodiode allows the conversion of the received optical power into electric current. The PIN photodiode has two regions of semiconductor material, one of type N and other of type P, separated by a lightly doped intrinsic region. As this, when inversely polarized, the depletion region is increased and the junction's capacity is reduced which enables them to provide higher bandwidth. The presence of the intrinsic region also increases the sensibility to light and provides a region of elevated electric field.

When a photon reaches the depletion region, it originates an electron-hole pair. Due to the presence of the electric field, the electron and the hole will be accelerated in opposite directions producing an electric current.

The relationship between the photodiode's current I_p and the incident optical power P_0 is given by:

$$R = \frac{I_p}{P_0} = \frac{\eta q}{h\nu} = \frac{\eta q \lambda}{hc} \tag{4.3}$$

$\eta \rightarrow$ Quantum efficiency;

$q \rightarrow$ Electron's charge;

$\lambda \rightarrow$ Wavelength;

$h \rightarrow$ Planck's constant;

$c \rightarrow$ Speed of light in vacuum.

The thermal noise is introduced by the resistive components of the receiver. Shot noise is a consequence of the random characteristic of the process of photon detection. At last, the noise due to the dark current is generated when the photodiode is not illuminated, due to current leaks and to the thermal excitation of carriers.

PIN Characteristics:

- Responsivity: 1.0 A/W;
- Dark Current: 0.0 A;
- Thermal Noise: 10.0 x 10^{-12} A/$Hz^{1/2}$;
- Shot Noise: ON;
- Stop Bandwidth: 8 x Bit Rate Default Hz;
- Stop Band Attenuation: 40 dB;
- Minimum Phase: Off;
- Noise Threshold: -100 dB;
- Active Filter Bandwidth: 1.0 THz;
- Active Filter Bandwidth Center Frequency: 193.1 THz;

4.3 Pre and Post-Compensation

In order to verify which compensation offers the best results were considered two scenarios, one referring to the pre-compensation and the other one to the post-compensation.

In each scenario (pre and the post-compensation) the optical network will be travelled just by SSMF (ITU-T G.652) and then by NZDSF (ITU-T G.655).

It is necessary to refer that the dispersion compensation can not be done totally. In the implemented system it is just possible to compensate the following dispersions, 340, 680, 1020, 1360, 1700 or 2040 ps/nm. For example, if the path has 58.1 km of SMF fiber will be just possible to compensate 40 km or 60 km.

To take some conclusions about this subject it was important to compensate the same amount of dispersion for the pre-compensation setup and for the post-compensation setup for each used fiber.

In order to understand how the dispersion and the loop backs are made in the optical network, Figure 4.3 represents the PCB's that will be implemented in the terminal nodes that are located in Aveiro and Lisbon and Figure 4.4 represents the PCB's that will be implemented on the intermediate nodes that are located in Coimbra and Entroncamento.

The selected route to do these tests was Aveiro$\rightarrow$ Lisboa $\rightarrow$ Aveiro, since that this scenario is the one that has the longest length that is possible to make on the implemented optical network, so it is here that exists the largest amount of dispersion and attenuation introduced to the signal.

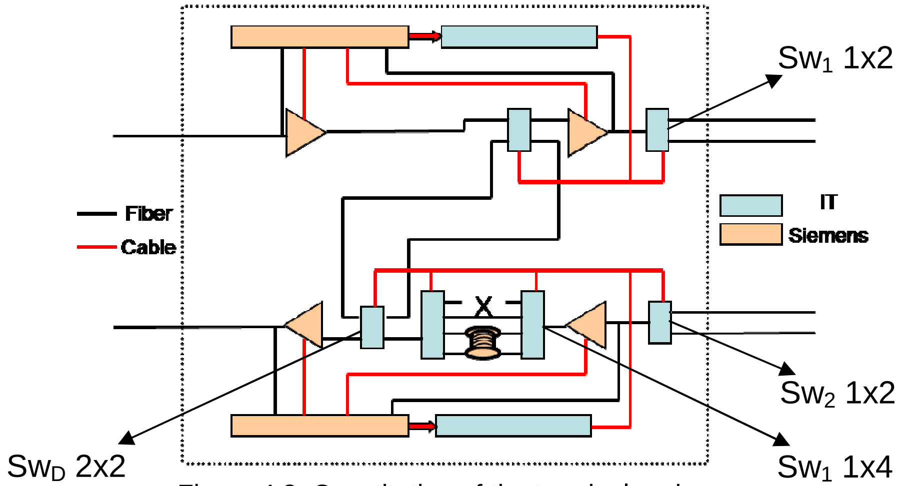

Figure 4.3: Constitution of the terminal nodes.

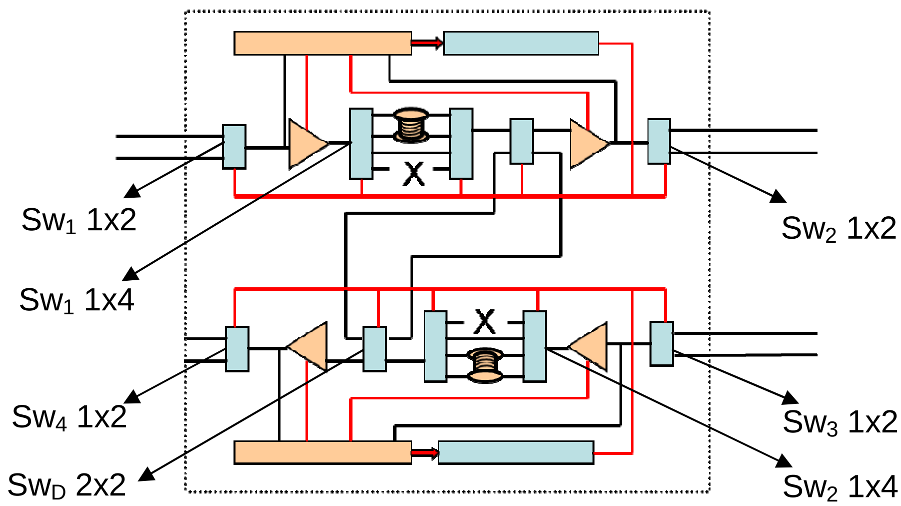

Figure 4.4: Constitution of the intermediate nodes.

Observing Figures 4.3 and 4.4 is possible to understand how can be selected the compensation when the path is travelled by NZDSF or SMF and basically this is done due to the switches 1x4 were its operation was explained in Chapter 3. The switches 1x2 give the possibility to choose which fiber will do the next path. The loop backs that can be done along the network are just possible with the switches 2x2, for example if the chosen route is Aveiro → Lisboa → Aveiro the loop back will be done in the terminal node located in Lisbon where the switch 2x2 has to be correctly configured.

In Figure 4.5 it is represented the scenario Aveiro → Lisboa → Aveiro when the chosen compensation is the pre-compensation that is made on the nodes along the route before each travelled path by the optic fiber. Since it is not possible, due to the boards, to compensate the Aveiro – Coimbra path in Aveiro’s node, this compensation will be made in Coimbra’s node together with the compensation of Coimbra – Entroncamento path.

Basically on Figure 4.5 there is an externally modulated laser (TX) at a 10 Gbit/s bit rate with a NRZ (Non Return to Zero) signal with PRBS bit stream. The emission frequency of the laser is at 193.1 THz and with an optical power of 0 dBm (1 mW). This signal will pass through the entire optical network and in each node the signal will have dispersion compensation and an optical amplification. In the end of the network exists a power attenuator (Swept Attenuator) with the main objective to put the BER’s between 10^0 and 10^{-18}. This block is very useful for producing BER versus Received Optical Power plots as can be seen on Figure 4.5. So, this block has a lowest attenuation that will produce the best BER and in each step this block will increment 1 dB to the attenuation in order to reach the 10^0 BER. As it is known the lowest signal power brings the biggest BER into the system.

The RxBER block is an optical receiver with BER estimation. So, as has been said on section 4.2, this block estimates Bit Error Rate for intensity modulated direct detection optical transmission systems.

As the name says, the power meter block calculates the power of an optical signal. This block and the RxBER block will be connected to an analyzer of numerical data in order to be possible to have BER vs Received Power graphics.

At the TX output is connected another power attenuator followed by the power meter RxBER, numerical analyzer in order to have the Back to Back configuration. Basically this configuration allows comparing the results obtained when the signal passes through the entire network with the best results that the system can have (Back to back configuration).

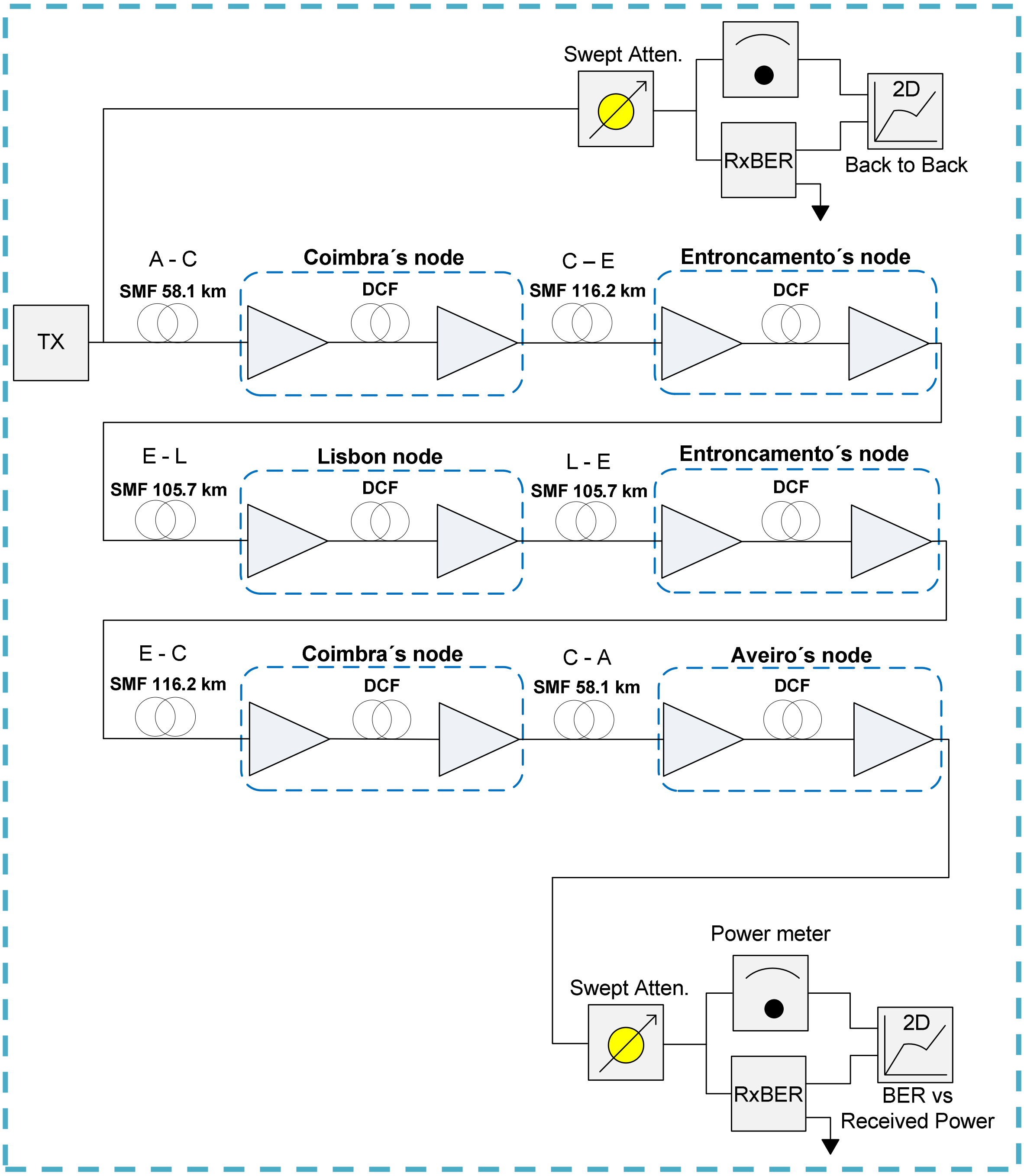

Figure 4.5: Pre-compensation setup with SMF fiber.

In Figure 4.6 it is represented the scenario Aveiro $\rightarrow$ Lisbon $\rightarrow$ Aveiro when the chosen dispersion compensation is the pre-compensation but just when the network is travelled by NZDSF.

In this figure the A – C means the path between Aveiro and Coimbra, C - E the path between Coimbra and Entroncamento, E – L the path between Entroncamento and Lisbon, for the other cases is the same thing when the signal direction is Lisbon to Aveiro.

It is important to mention that the rules described above for the compensation of dispersion are applied in this scenario too.

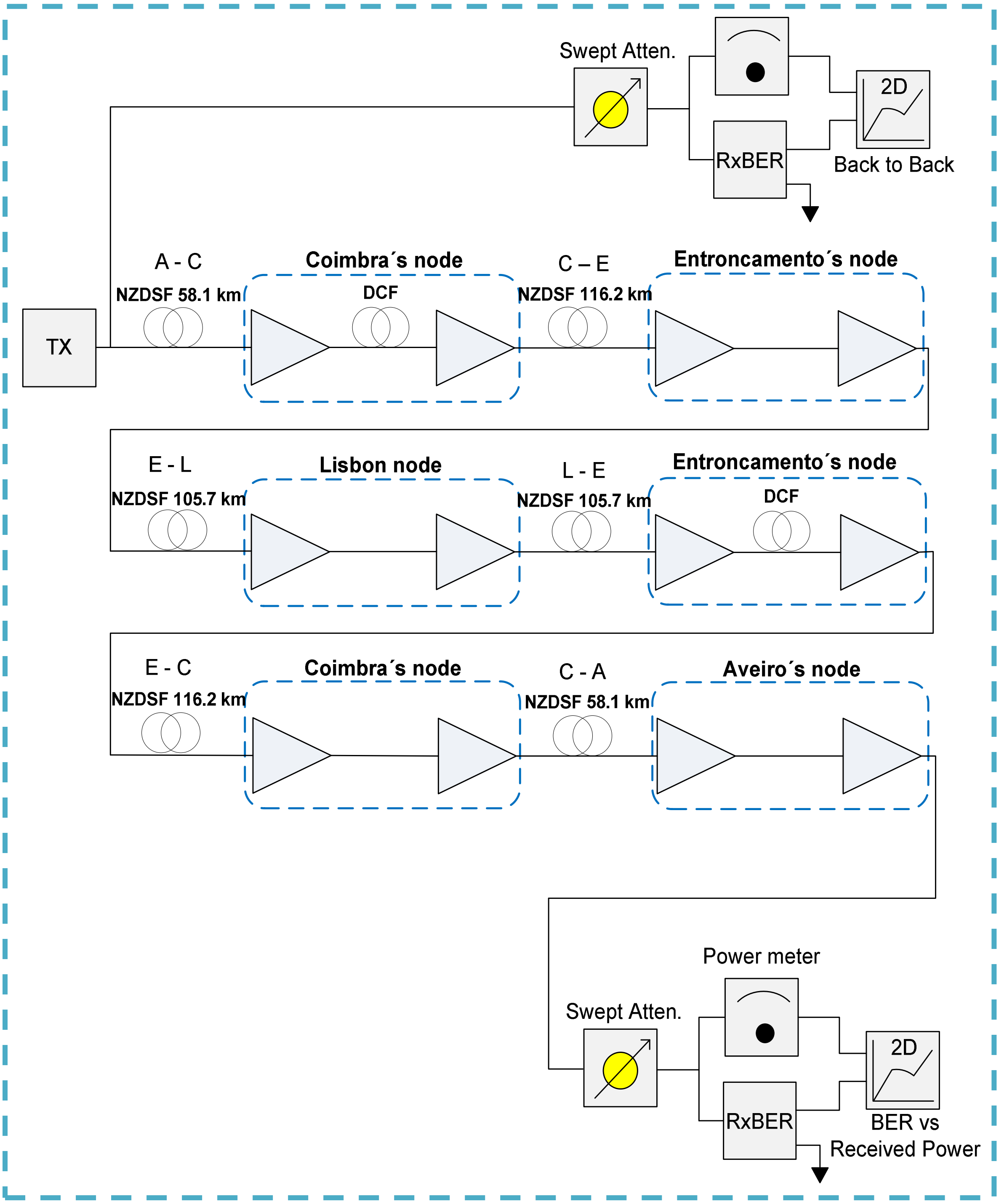

Figure 4.6: Pre-compensation setup with NZDSF fiber.

The results obtained on VPI for the setup with the SMF (Figure 4.5) and for the setup with NZDSF (Figure 4.6) are presented in Figure 4.7. In this figure are included the results for the Back to back configuration and the results obtained at the end of the network for each fiber.

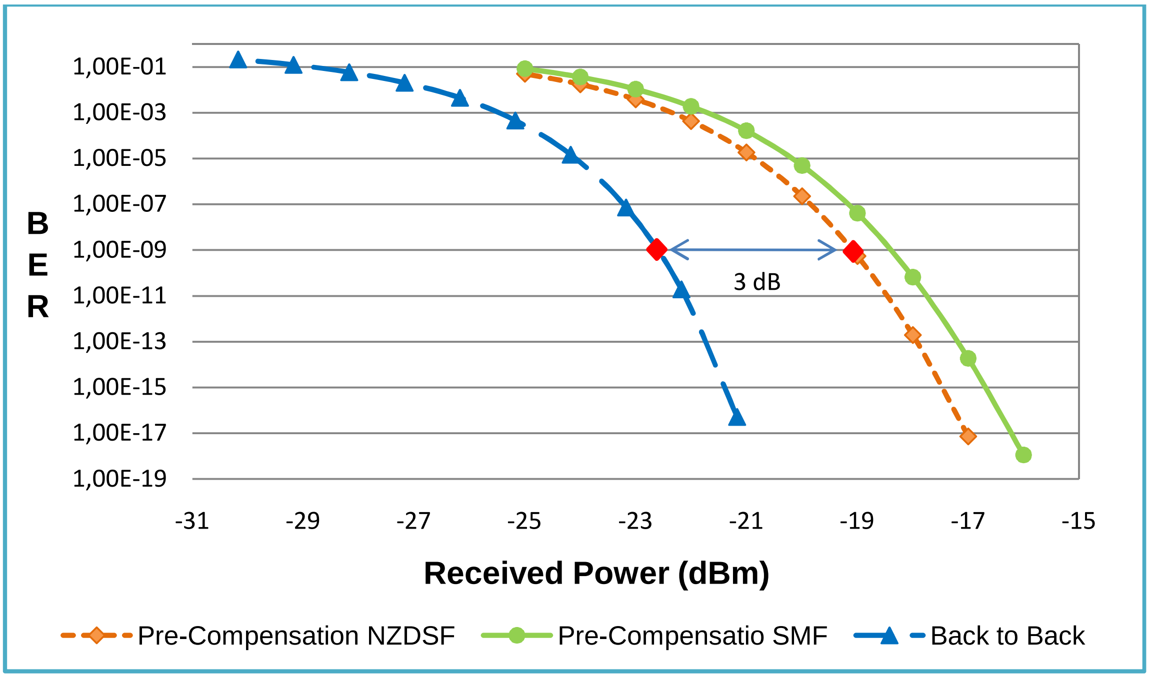

Figure 4.7: BER vs Received Power of Pre-Compensation setup with SMF, NZDSF and back to back configuration at 10 Gbit/s bit rate.

As can be observed by Figure 4.7 there is a power penalty when the transmission has no errors (BER < 10^{-9}) between the Back to back configuration and the pre-compensation NZDSF setup of 3 dB's. The main reason for this difference is that in the NZDSF setup without having the compensation, it has 2343 ps/nm of dispersion and introducing the dispersion compensation modules will be compensated 2380 ps/nm, so at the end the full system will have -37ps/nm of dispersion.

For the pre-compensation SMF setup exists 4 dB's (BER = 10^{-9}) of power penalty relatively to the Back to back configuration. The main reason for this difference is like as the case related above, the SMF setup without having compensation has an amount of dispersion of 9486 ps/nm and the compensation of dispersion modules will compensate 9520 ps/nm, so at the end of the system the amount of dispersion will be of -34 ps/nm.

The difference of the optical power received vs BER between the back to back configuration and in the end of the optical network, it is also from the non filtering of the signal at the end of the optical network which is very important, because all the amplification thatis performed along the route adds some noise to the signal and this noise will decrease the signal to noise ratio (SNR). Even that all gain is important to return the original amplitude into the signal.

The post-compensation setups were made on VPI by the same way that were made the pre-compensation setups, but now as the name says the compensation of dispersion is made after each travelled path. On the NZDSF post-compensation setup the compensation of dispersion modules were introduced in Lisbon node when the signal direction is Aveiro – Lisbon and in Aveiro's node when the signal has the opposite direction.

The results obtained on VPI for the SMF post-compensation setup and for the NZDSF post-compensation setup are presented in Figure 4.8. In this figure are included the results for the Back to back configuration and the results obtained at the end of the network for each fiber.

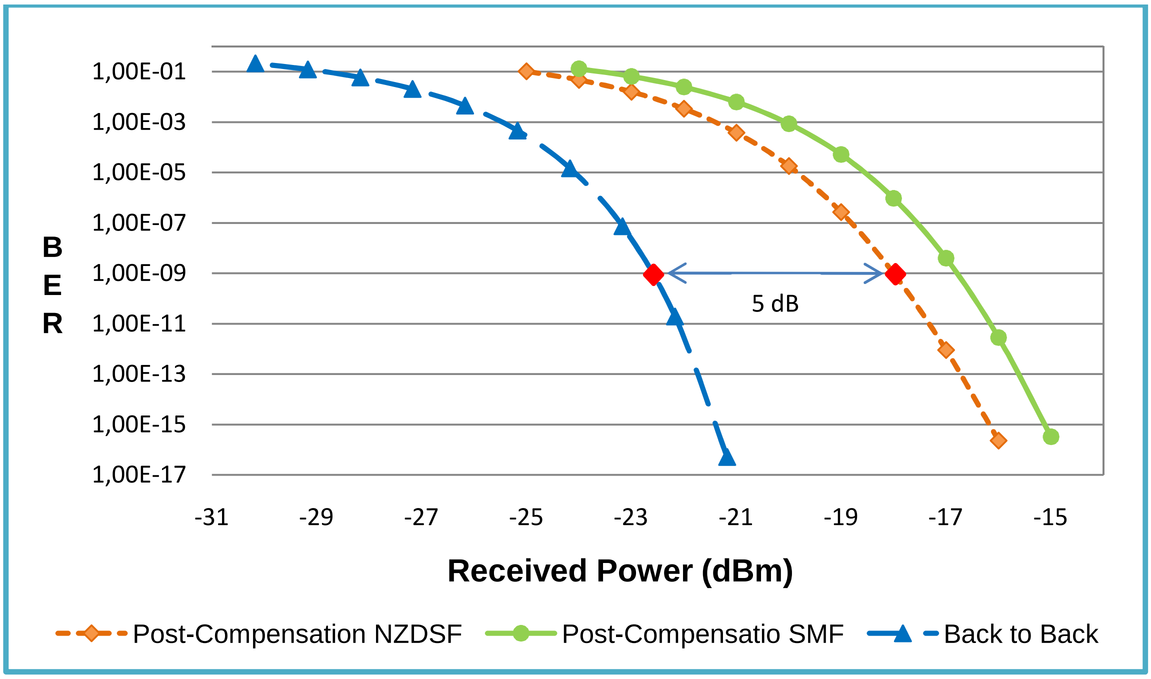

Figure 4.8: BER vs Received Power of Post-Compensation setup with SMF, NZDSF and back to back configuration at 10 Gbit/s bit rate.

Examining Figure 4.8 there is power penalty of 5 dB's when comparing the Back to back configuration with the NZDSF post-compensation setup and a power penalty of 6 dB's when comparing the Back to back configuration with the SMF post-compensation setup. These values were taken when BER = 10^{-9}, because this is the threshold value in order to have transmission without having errors.

As it was said in the beginning of this chapter the compensation of dispersion was the same either in the pre-compensation setup as in the post-compensation setup, so it is attributed the same explanation for the power penalty as the one taken above for the pre-compensation setup. It is also important to refer that all the amplification made in the pre-compensation setup was also made in the post-compensation setup, so the explanation of the introduced noise by the amplifiers and consequently the decrease of the SNR that was done above fixes here too.

The difference of the power penalty between the setup with SSMF and NZDSF can be explained by the fact that when the setup of pre or post-compensation is travelled by NZDSF, though this brings a small but higher amount of dispersion when comparing to the SMF, there are fewer modules of dispersion compensation fiber along the optical network. So, there will be fewer losses and linear and non linear effects introduced into the signal.

In Figure 4.9 it is compared the post-compensation setup with the pre-compensation setup for SMF and NZDSF.

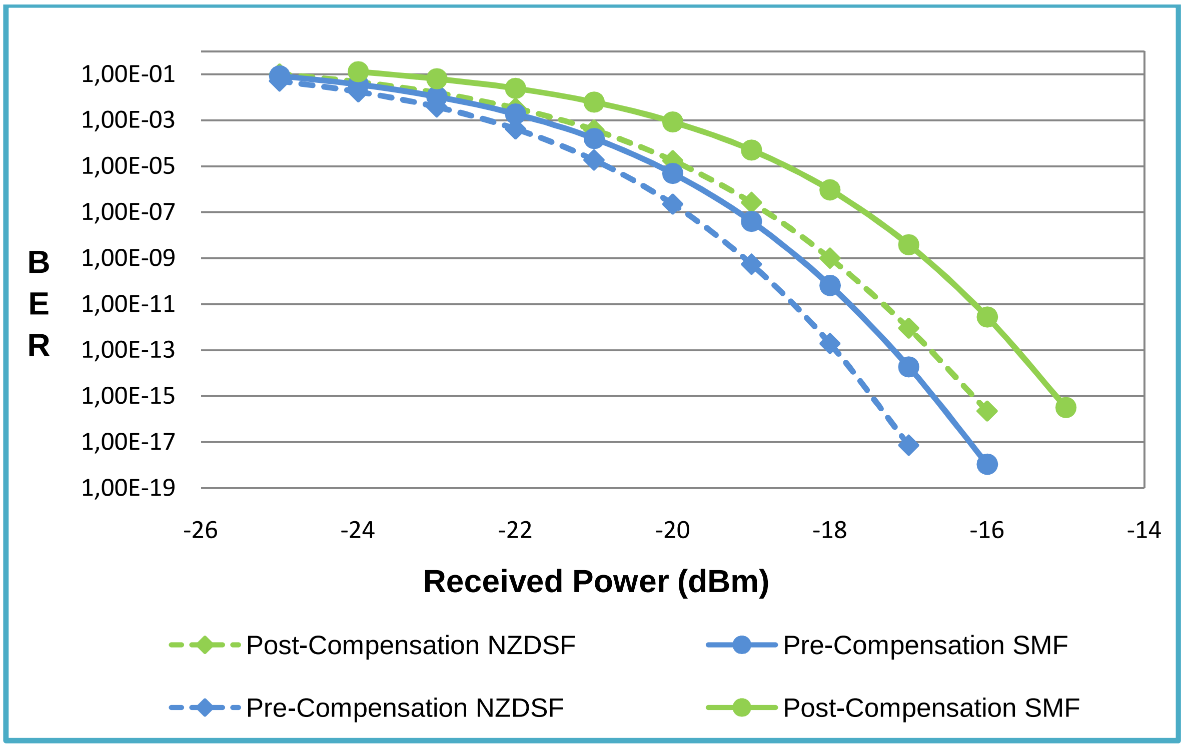

Figure 4.9: BER vs Received Power of Post-Compensation setup with SMF and NZDSF at 10 Gbit/s bit rate.

As can be observed by Figure 4.9 there is a power penalty between the post compensation setup and the pre-compensation setup of 3 dB’s for each fiber. With the help this figure it is possible to conclude that the pre-compensation brings better results into the optical network than the post-compensation setup.

4.3.1 Conclusions

The conclusion is that performing pre-compensation is better than post-compensation. The base for this conclusion are the simulation results (2 dB’s of power penalty when pre-compensation setup is compared with the post-compensation setup for both fibers). Another aspect that is possible to conclude is that the lower BER gives greater differences of power penalty between Back to back configuration and pre and post-compensation setups.

4.4 Simulation for different bit rates

As was mentioned in section 4.2, in the implemented optical network between Aveiro and Lisbon it is possible to cross different routes due to the nodes that are located in each train station.

The chosen route to test the system response for different bit rates (2.5, 10, 40 Gbit/s) was Aveiro → Lisbon → Aveiro, according to what was said before this is the route which presents the most problems since it is the longest one, so it will have the biggest amount of dispersion and signal attenuation. Signal attenuation is compensated by the two optical amplifiers in each node, however they will introduce some noise to signal that will decrease the signal transmission quality.

All the tests for the different bit rates in this route will be performed with SMF and NZDSF, it is also important to refer that the dispersion compensation implemented was the pre-compensating setup either to SMF and for NZDSF in the same way as the one done in section 4.3.

The same tests, as the described below, but for the others possible routes were done in the optical link and are presented Appendix A.

4.4.1 Bit Rate = 2.5 Gbit/s

In Figure 4.10 it is represented for 2.5 Gbit/s bit rate the route Aveiro → Lisbon → Aveiro with the Back to back configuration and when travelling in NZDSF and SSMF.

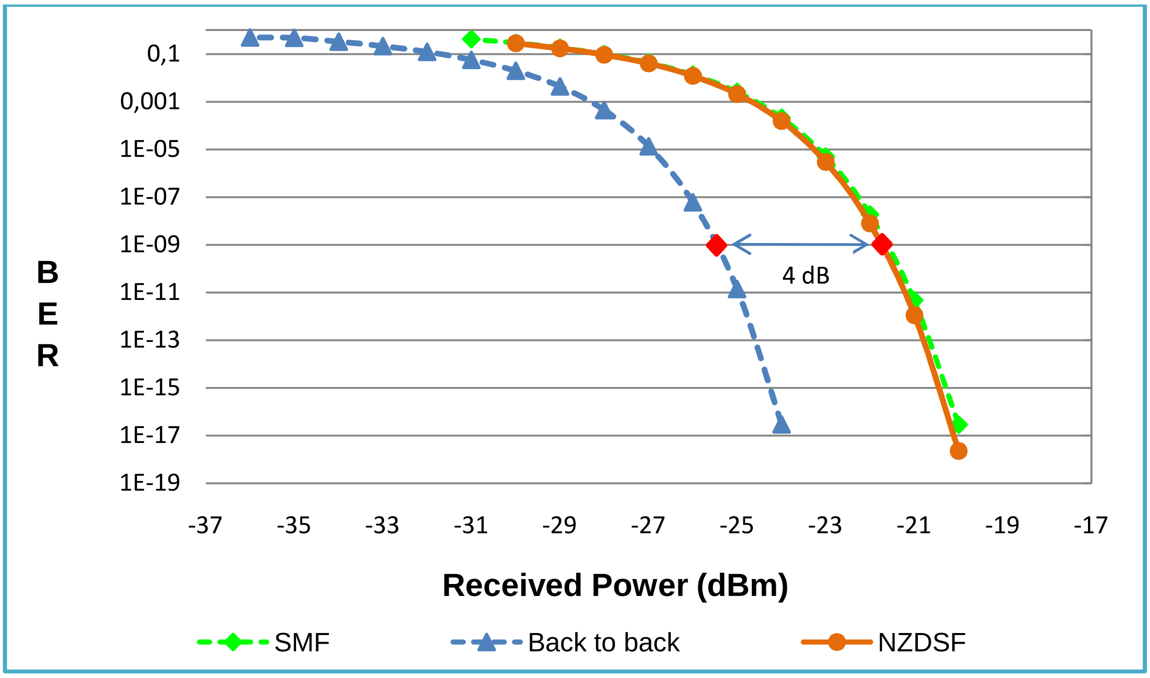

Figure 4.10: BER vs Received Power of Aveiro → Lisbon → Aveiro with SMF, NZDSF fiber and back to back configuration for 2.5Gbit/s bit rate.

As can be observed by Figure 4.10 there is a power penalty when the transmission has no errors (BER < 10^{-9}) between the Back to back configuration and when the route is travelled by NZDSF and even when is travelled by SMF of 4 dB's. The main reason for this difference is that in the NZDSF setup without having the compensation it has 2343 ps/nm of dispersion and introducing the dispersion compensation modules will be compensated 2380 ps/nm, so in the end the full system will have -37ps/nm of dispersion.

For the SMF setup an explanation for that power penalty is that the SMF setup without having compensation has an amount of dispersion of 9486 ps/nm and the compensation of dispersion modules will compensate 9520 ps/nm, so at the end of the system the amount of dispersion will be of -34 ps/nm.

4.4.2 Bit Rate = 10 Gbit/s

In Figure 4.11 it is represented for 10 Gbit/s bit rate the same route that was mentioned before with the Back to back configuration, when it is travelled by the NZDSF and when it is travelled by the SMF.

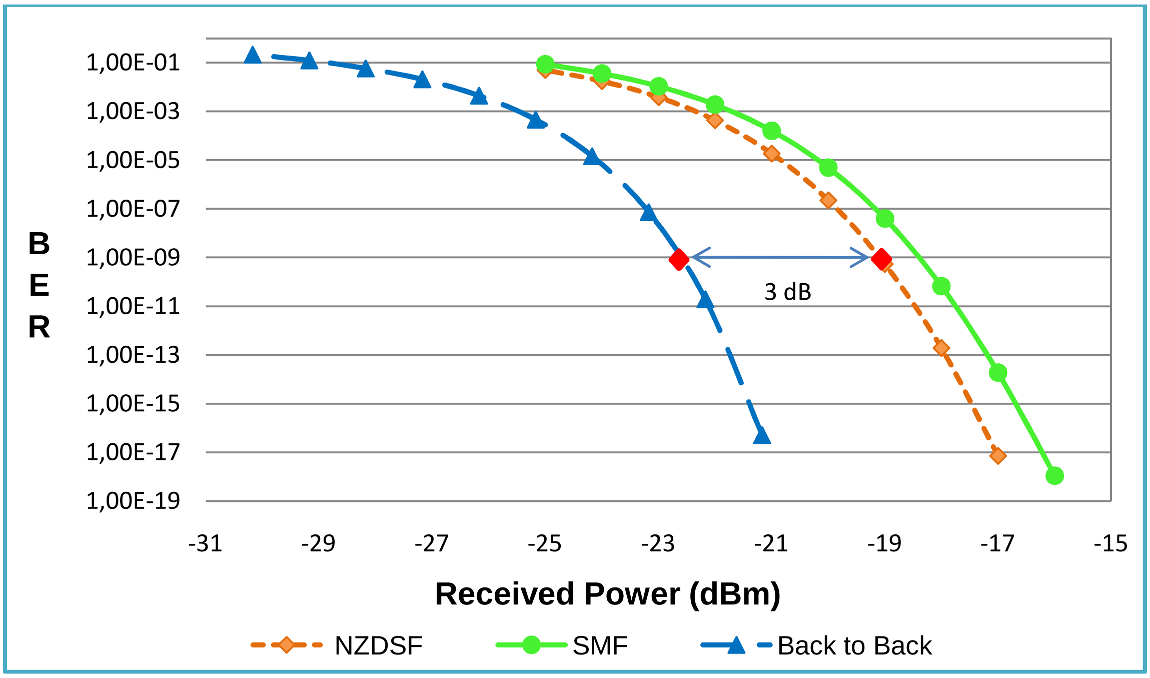

Figure 4.11: BER vs Received Power of Aveiro → Lisbon → Aveiro with SMF, NZDSF fiber and Back to back configuration for 10Gbit/s bit rate.

As can be observed by Figure 4.11 there is a power penalty when the transmission has no errors between the Back to back configuration and when the route is travelled by NZDSF of 3 dB's. The main reason for this difference is the same which was described in section 4.4.1 for the NZDSF setup.

For the SMF setup there is 4 dB's of power penalty relatively to the Back to back configuration. The explanation that was done in section 4.4.1 for the SMF setup applies here too.

The difference of the optical power received vs BER between the Back to back configuration and NZDSF or SMF setups lies in the fact that all the amplification that made along the route will introduce some noise to the signal and consequently this noise will decrease the SNR.

4.4.3 Bit Rate = 40 Gbit/s

In Figure 4.12 it is represented for 40 Gbit/s bit rate the same route that was mentioned before with the back to back configuration, when it is travelled by the NZDSF and when it is travelled by the SMF.

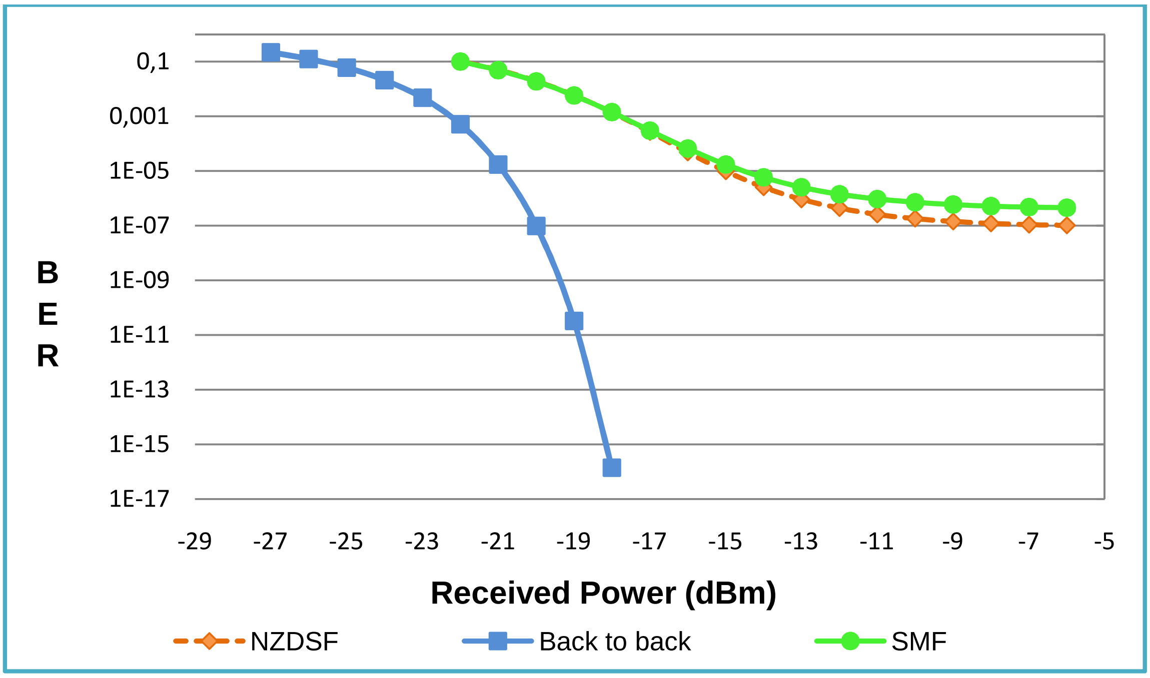

Figure 4.12: BER vs Received Power of Aveiro → Lisbon → Aveiro with SMF, NZDSF fiber and back to back configuration for 40Gbit/s bit rate.

Observing Figure 4.12 it is not possible to transmit any signal because the limit to have signal transmission without having errors is not reached. Even that this BER could be reached it would not be possible to say that the transmission will occur without having errors, because for 40 Gbit/s bit rate the system should have BER < 10^{-12} in order to be possible to have a good signal transmission. So, the NZDSF setup tends to the 10^{-7} BER with the increase of the received power. The behavior for the SMF setup is similar to the NZDSF setup butin this case, with the increase of the received power the system tends to 10^{-6} BER which is little worst than the NZDSF setup.

One of the possible things that contribute to the inability of the system to reach the 10^{-9} BER is the fact that the accumulated dispersion at the end of the network is not completely compensated and in 40 Gbit/s transmissions it is mandatory that the system has to be completely compensated. The other reason, just like was said before is the contribution of the noise introduced in the signal by the amplifiers. So, in order to be possible to transmit along this route with a 40 Gbit/s bit rate a new scenario was implemented on VPI when the signal travelled through SMF and NZDSF. The only difference from the scenarios that were presented before (Figure 4.5 and 4.6) is that now at the end of the system there is a section of SMF fiber that will introduce a complete dispersion compensation into the route. As was said before at the end of the system using SMF there is an amount of dispersion of -34 ps/nm, so the introduced SMF fiber at the end of the system will have a positive dispersion which will turn into zero the accumulated dispersion. The length of this introduced fiber has to be 2 km, as the dispersion is of 17 ps/(nm km), so at the end of this fiber the dispersion will be 34 ps/nm. The same happens for the NZDSF setup, but know the length of the introduced SMF fiber has to be 2.18 km. Another component that will be introduced into the end of the optical network is a filter before the power attenuator that has the function to decrease some noise that was introduced by all the amplifiers that are implemented in all the nodes along the route.

In Figure 4.13 it is represented for 40 Gbit/s bit rate the route Aveiro → Lisbon → Aveiro with the Back to back configuration, when it is travelled by the NZDSF and when it is travelled by the SMF, but now with all the transformation that were made into the system.

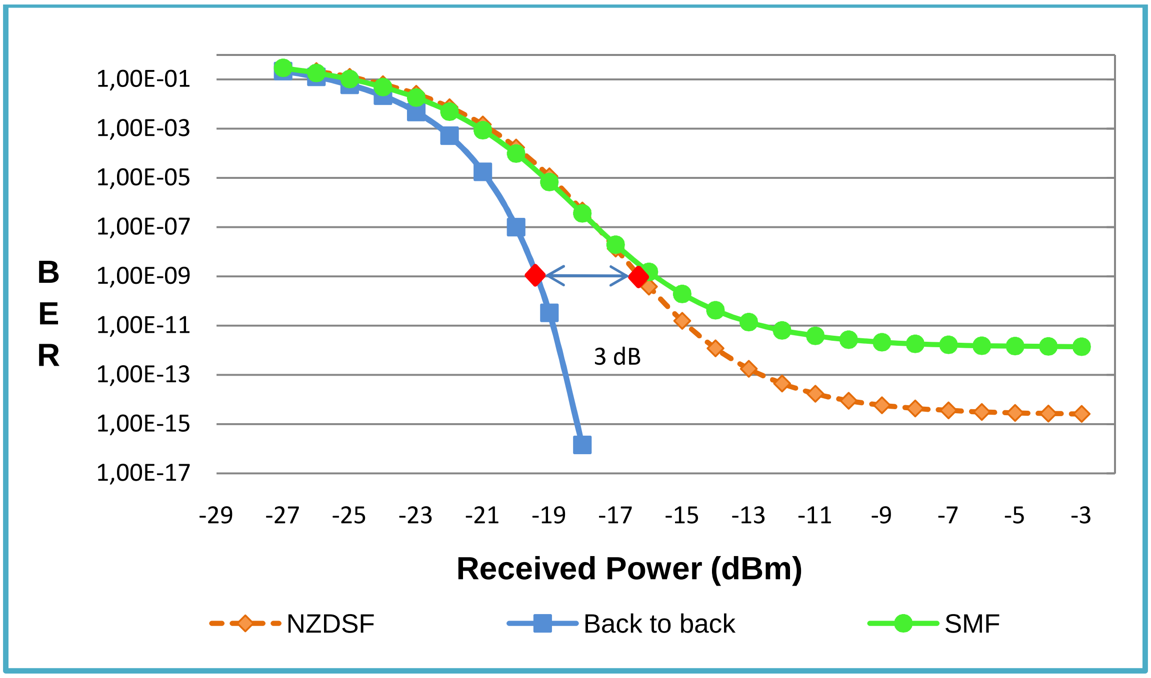

Figure 4.13: BER vs Received Power of Aveiro → Lisbon → Aveiro with SMF, NZDSF fiber and Back to back configuration for 40Gbit/s bit rate with filter and total dispersion compensation at the end of the optical network.

As can be observed by Figure 4.13 there is a power penalty when the transmission has no errors between the Back to back configuration and when the route is travelled by NZDSF of 3 dB's.

For the SMF setup there is 4 dB's of power penalty relatively to the back to back configuration. Now with implementation of SMF and the filter at the end of the system it is possible to have a better signal transmission. With these implementations the system when is travelled with NZDSF tend to a BER of 10^{-15} and 10^{-12} when using SMF.

4.4.4 Conclusions

After the analysis of the different bit rates it is possible to conclude that for a 2.5 Gbit/s there is 4 dB’s of power penalty between the Back to back configuration when compared to the NZDSF setup or even to the SMF setup when the transmission has no errors (BER < 10^{-09}).

For a 10 Gbit/s bit rate there is a power penalty between the Back to back configuration and the NZDSF setup of 3 dB´s and 4 dB’s for the SMF setup at the 10^{-09} BER.

For the 40 Gbit/s bit rate it is not possible to have transmission without errors (BER < 10^{-9}) either for NZDSF setup and either for SMF setup because they do not even reached a 10^{-9} BER in the best scenario.

In Aveiro $\rightarrow$ Lisbon $\rightarrow$ Aveiro route is reliable to transmit at 2.5 Gbit/s for received powers higher than -22 dBm and for 10 Gbit/s the received power should be greater than -20 dBm for the NZDSF setup and -19 dBm for the SMF setup. But in this route it is not reliable to transmit at 40 Gbit/s bit rate when there is not a filter and complete dispersion compensation at the end of the system.

4.5 Experimental Results

4.5.1 Introduction

With the objective to study the behavior of the optical network in the laboratory for 40 Gbit/s bit rate, some experiences were made.

As in the simulations, two setups were implemented, one with the pre-compensation of dispersion and the other with post-compensation of dispersion, but now these two setups were just travelled by SSMF.

As can be seen in Figure 4.14, which represents the post-compensation setup there is a laser with an emission wavelength at 1548 nm and with an optical power of 13 dBm. This laser will be modulated by a Mach-Zender Modulator at a 40 Gbit/s bit rate with a NRZ (Non Return to Zero) sequence with PRBS bit stream.

After this the signal will pass by an Erbium Doped Fiber Amplifier (EDFA) followed by the 40 km SSMF. After passing the SSMF the signal will be amplified once again by another EDFA and then will have the pre-compensation of dispersion.

For the Back to back configuration (without SMF and DCF) another device was implemented which is a band-pass filter in order to decrease the amplifier noise in the signal. This filter was not implemented in the normal setup because it has 7 dB's of power losses and this difference at the received power is very significantly in the system.

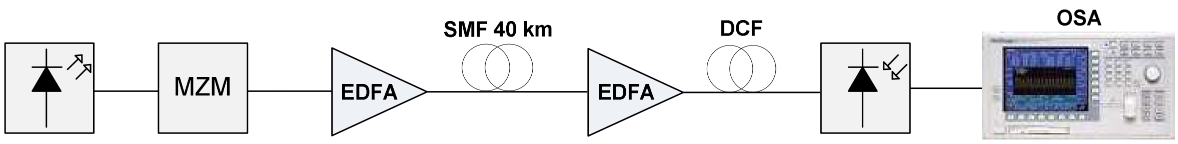

Figure 4.14: Laboratorial post-compensation setup for 40 Gbit/s bit rate.

4.5.2 Results

The obtained results are presented in Appendix (B). Due to laboratory problems the obtained results did not allow concluding, as it is possible to see in each Figure. However, was possible to understand that high bit rates are highly sensitive to any kind of effect that can be felt in the lab (polarization, biasing, etc).

4.6 Conclusions

In this chapter were presented the main properties of important optical devices used in the simulations such as optical source, optical fiber, optical amplifier, optical filter and a photodiode.

In this chapter was studied which compensation brings the best results for the optical network and was possible to conclude that the pre-compensation is the best way to achieve better results.

It was also studied the optical network response for different bit rates in the Aveiro → Lisbon → Aveiro route with the pre-compensation setup when compared with the Back to back configuration. In order to achieve better results for 40 Gbit/s bit rate was implemented total dispersion compensation and an optical filter at the end of the optical network.

Chapter 5

Implemented Hardware

5.1 Introduction

It is important to mention that all the boards that will be implemented in each node along the optical network will be done by the WITHUS Company, but in order to do some experimental tests a prototype board was made to control two optical switches 1x2 and another two optical switches mini 1x4. Basically this board has just an MCP23S17 (SPI interface) device which will activate each optical switch and its required position. Since the operating voltage of switches mini 1x4 is between 4.5 and 5.5 volts and the MCP23S17 can operate with this voltage, the chosen VCC was of 5 volts. For the optical switches 1x2, as was said in chapter 3 the operating voltage is between 3.5 and 4.5 volts, so with just one resistance at each relay terminal it is possible to pass from 5 volts to a voltage between the mentioned interval.

5.2 Control Device

To control the switches positions was chosen the MCP23S17 (Figure 5.1) which is a 16-Bit I/O expander with serial interface, where according to the description this device provides 16-bit, general purpose parallel I/O expansion for SPI applications. This device was chosen, because these 16-bit are enough to control all the switches that will be implemented in the prototype board.

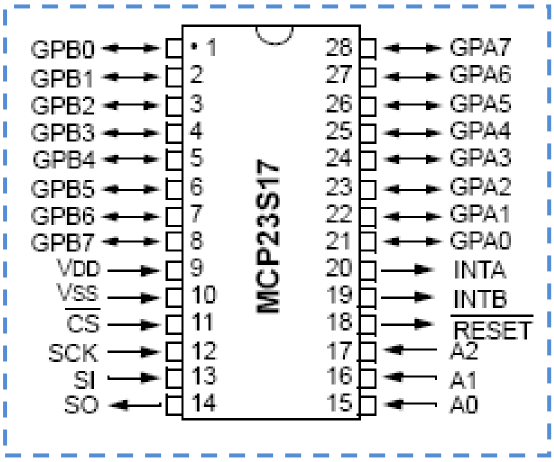

Figure 5.1: Pin diagram of MCP23S17.

The MCP23S17 consists of multiple 8-bit configuration registers for input, output and polarity selection. The system master can enable the I/Os as either inputs or outputs by writing the I/O configuration bits (IODIRA/B). The data for each input or output is kept in the corresponding input or output register. The polarity of the

Input Port register can be inverted with the Polarity Inversion register. As was mentioned on chapter 3 all the switches have some pins which are status sensor in order to be possible to know the configuration of each switch. So, if the I/O configuration bits are as outputs these pins will activate or change the switches positions, but if they are at input state they will receive from the switches some voltage which correspond to the switches position.

The 16-bit I/O port functionally consists of two 8-bit ports (PORTA and PORTB). The MCP23S17 can be configured to operate in the 8-bit or 16-bit. As each switch 1x2 has one relay, so each switch 1x2 needs 2 bits to control the two positions that are possible to configure in it. Each switch mini 1x4 has three relays, so each one needs 6 bits to control the four possible positions. So, to control all the switches are need 10 bits (2 + 2 + 6). It is just need to control one switch mini 1x4 because the two switches min 1x4 are in parallel configuration as can be seen in Figure 4.4 (chapter 4), for example if it is wanted the first position of the switch mini 1x4 the next switch mini 1x4 will be configured in the same position.

Features:

- 16-bit remote bidirectional I/O port
  - I/O pins default to input;
- High-speed SPI interface
  - 10 MHz (max.);
- Three hardware address pins to allow up to eight devices on the bus;
- Configurable interrupt output pins
  - Configurable as active-high, active-low or open-drain;
- INTA and INTB can be configured to operate independently or together;
- Configurable interrupt source
  - Interrupt-on-change from configured register defaults or pin changes;
- Polarity Inversion register to configure the polarity of the input port data;

- External Reset input;
- Low standby current: 1 μA (max.);
- Operating voltage:
  - 1.8V to 5.5V @ -40℃ to +85℃;
  - 2.7V to 5.5V @ -40℃ to +85℃;
  - 4.5V to 5.5V @ -40℃ to +125℃.

5.3 Schematics and Software

Before the presentation of the electrical scheme and the PCB (Printed Circuit Board) it is important to know how the switches can be controlled and all the implemented electronic to control the optical switch 1x2 and the optical switch mini 1x4, which are presented in Figure 5.2 and Figure 5.3, respectively.

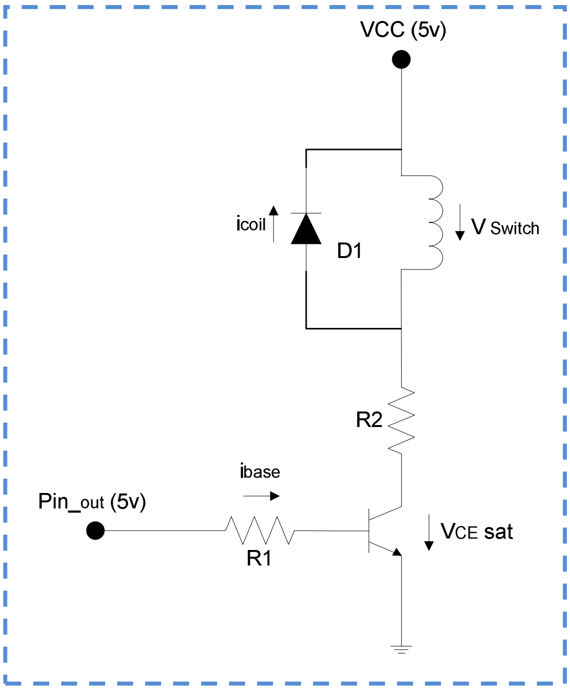

Figure 5.2: Electric circuit to control the optical switch 1x2.

As was mentioned in chapter 3 the switch 1x2 has as specifications the operating voltage (V_{Switch}) between 3.5 and 4.5 volts and the operating current (i_{coil}) between 75 and 115 mA. So, in order to calculate the R_2 resistance will be attributed a voltage of 4 volts that will pass through the coil (V_{Switch}). Therefore, the value of R_2 has to be between the following interval:

$$R_{2_{max}} = \frac{Vcc - V_{Switch} - V_{CE\,sat}}{i_{coil_{min}}}; \qquad (5.1)$$

$$R_{2_{max}} = \frac{5 - 4 - 0.2}{0.075} = 10.6\Omega$$

$$R_{2_{min}} = \frac{Vcc - V_{Switch} - V_{CE\,sat}}{i_{coil_{max}}}; \qquad (5.2)$$

$$R_{2_{max}} = \frac{5 - 4 - 0.2}{0.115} = 7\Omega$$

For each value of R_2 it is important to prove if for each operating current the operating voltage of the switch (V_{Switch}) is confined to the values described above.

$$Vcc - (V_{CE\,sat} + R_2 * i_{coil}) = V_{Switch;} \qquad (5.3)$$

For R_2 = 10.6 Ω and i_{coil} = 75 and 115 mA the voltage V_{Switch} will be 4.005 volts and 3.581 volts, respectively.

For R_2 = 7 Ω and i_{coil} = 75 and 115 mA the voltage V_{Switch} will be 4.275 volts and 3.995 volts, respectively. Can be concluded that for each value of R_2 the operating voltage of switch 1x2 will be within the mentioned range. So, the value for R_2 attributed was 10 Ω.

By the equation 5.4 the maximum power in this resistance will be 132.25 mW, where R = 10 Ω and a maximum current that will pass through the resistance of 115 mA.

$$P_{max} = V * i^2 = R * i^2; \quad (5.4)$$

To control the optical switch mini 1x4 it is not necessary to have R_2, because the interval of the operating voltage for this switch includes the Vcc value and the coil will push the necessary current to come into operation. So, the electrical circuit to control this switch is presented in Figure 5.3.

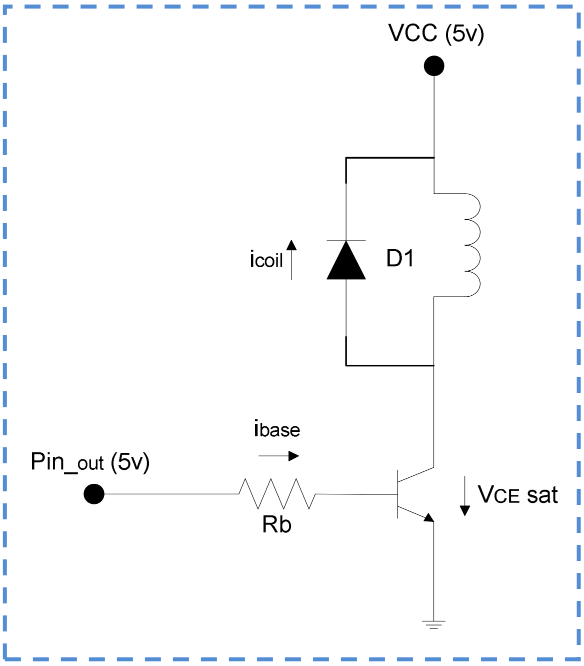

Figure 5.3: Electric circuit to control the optical switch mini 1x4.

The main purpose of resistance R_b is to limit the transistor's base polarization current. When the Pin_{out} is activated R_b will have at one terminal 5 volts and in the other 0.7 volts. The current that pass through R_b ensures that the transistor is in the saturation mode, so a good value for the i_{base} current will be 5 mA. By the equation 5.5 the value for resistance R_b will be:

$$R_1 = \frac{SPI_{out} - 0.7}{i_{base}}; \quad (5.5)$$

$$R_1 = \frac{5 - 0.7}{0.005} = 860\Omega$$

In both electrical circuits, the main function of diode D_1 is just to protect the transistor against current with different direction when the relay is shut down.

The implemented circuit is presented in Figure 5.4, the complete electrical scheme of the board and the PCB layout (bottom and top) are presented in Appendix.

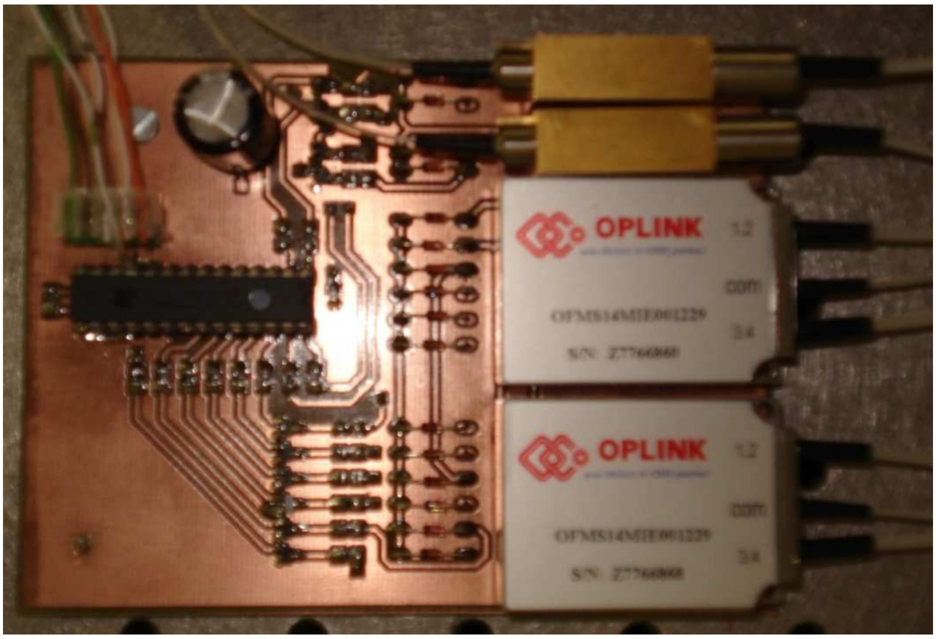

Figure 5.4: Photo of the implemented circuit.

Associated to the board a program was made in order to control the optical switches positions. For each switch and respectively its position there is a button that when is clicked a character will be send by the serial port (Com port) to a microcontroller which will translate the received information and after that will send the right bits to the MCP23S17. Then this device will activate the right output ports to control the specified switches and its positions.

It is important to refer that the program has a particular characteristic, as was said before, the switches are latch type, so when a button is clicked in order to change the switch position will be applied to the corresponded switch an electrical signal of 20 ms duration.

In Figure 5.1 is presented the interface to control all the switches which constitute the implemented board.

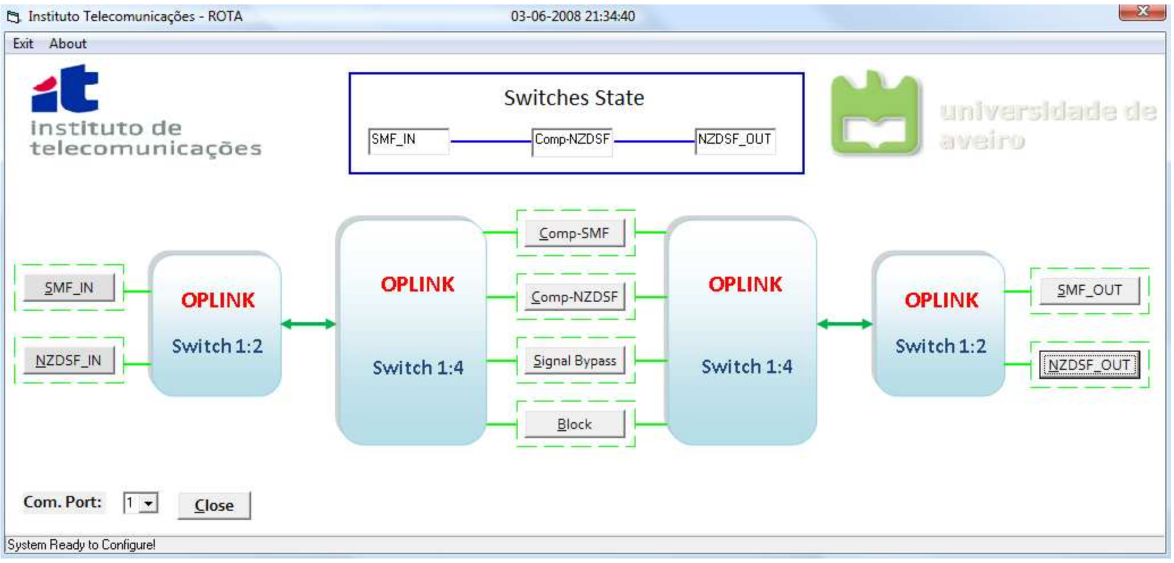

Figure 5.5: Interface to control the implemented board.

5.4 Conclusions

In this chapter was implemented a prototype board that has the same functions of the ones that will be introduced in each node along the optical network. The program implemented to control this board was tested.

In the end was possible to conclude that either the board as the program were successfully implemented and tested.

Chapter 6

Application “Closest Dispersion”

6.1 Introduction

Along the optical network it is possible to cross different routs each one with different dispersions and allied to each route there is a specific attenuation. The main objective of this application is to write a dispersion value and then the application will calculate for a determinate route, with the different fiber combinations that are possible to make in this route, which one brings the closest value relatively to the introduced one.

In this application the user can chose in which route he wants to see the fiber combinations that brings the closer dispersion value relatively to the introduced one, or can even chose an option that will see for all the possible routes, and in each route all the possible fiber combinations, which one brings the closest dispersion value.

An important characteristic of this application is that when the program returns a value, and attached to this value is created a file that contains all the switches configurations that will be done in each node along the optical network in order to reach this value.

6.2 Application Functioning

The application has an initial menu which contains all the different routes that are possible to trace along the optical network when the origin is at Aveiro or Lisbon, as can be seen in Figure 6.1

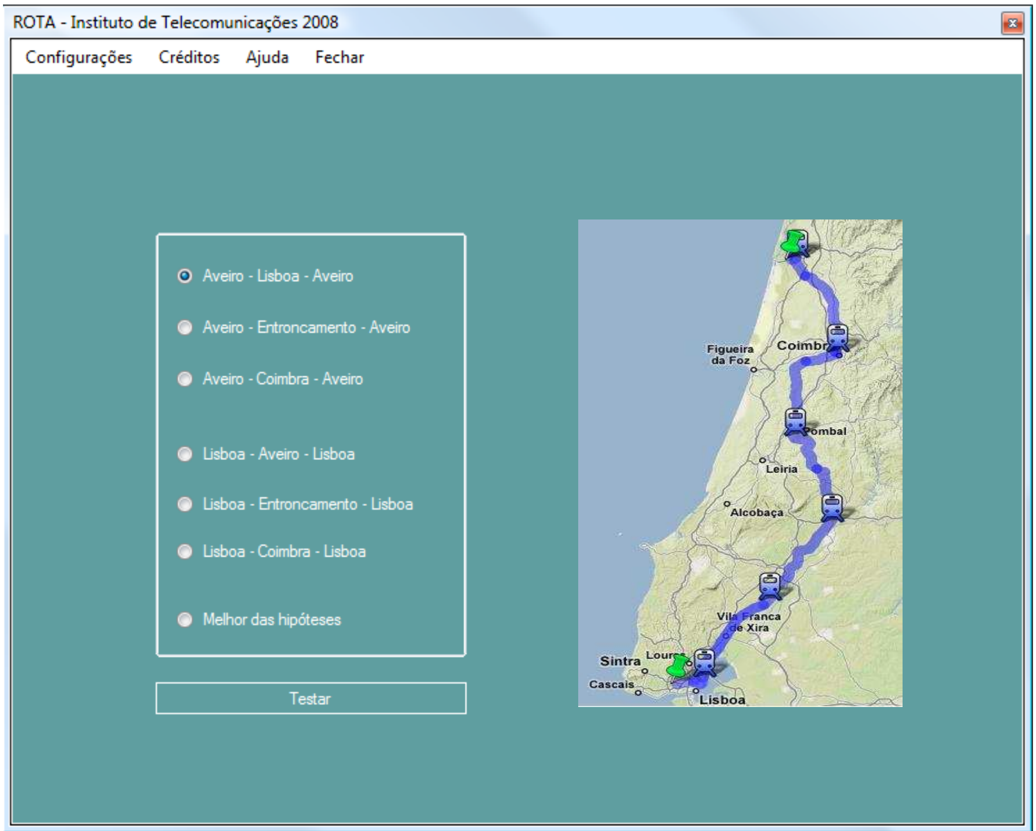

Figure 6.1: Application initial menu.

This menu has also an option called “Melhor das hipóteses” which gives the user’s possibility to select where he wants to be the origin of the optical network. When the origin is selected the application will return the best dispersion value when all the routes are compared. So, basically if the user selects the origin to be Lisbon and write a dispersion value, the application will run all the routes that are possible to trace with origin in Lisbon and for each route it will select the closest value relatively to the introduced one. In the end the application will compare the selected values and will return the value that is closer to the written one. If the application does not find a dispersion value equal to the introduced, for each route the application will select two values, one will be the value that is closer to the introduced but with an higher dispersion. The other one is the value that is closer to the introduced but with a smaller dispersion, as can be seen in Figure 6.2.

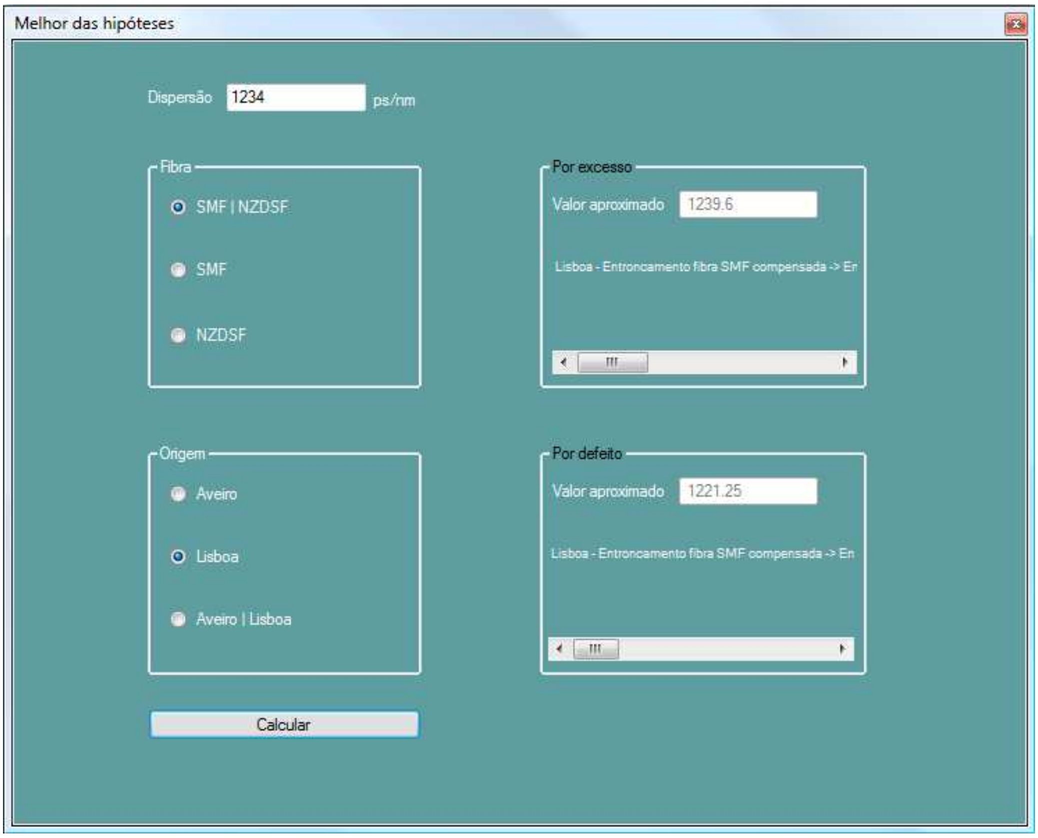

Figure 6.2: Application menu for the option “Melhor das hipóteses” and the returned closest values relatively to the introduced by the user.

As can be observed by the shown figures, when the chosen value by the application is presented, below it is described the route and the fiber configurations which drives into the referred value.

In order to understand the implemented algorithm will be done an example when the route is Aveiro → Entroncamento → Aveiro.

Basically for each route (Aveiro → Lisbon → Aveiro, Aveiro → Coimbra → Aveiro, etc…) the application has an algorithm which will create a matrix with a number of columns equal to the number of sections that constitute the route, and a number of lines equal to the number of fiber combinations that are possible to trace along the route. For example if the chosen route is Aveiro → Coimbra → Entroncamento → Coimbra → Aveiro (Aveiro → Entroncamento → Aveiro), the application will create a matrix with 4 columns and 256 lines (4^4).

The number 256 comes from the following calculation, in the described route if the travelled path is Aveiro → Coimbra there are four ways to make it, the first one is when the path is travelled by SMF, the second one is when the path is travelled by NZDSF, the third one is when the path is travelled by SMF and at Coimbra’s node it is done the respective compensation and the fourth one is when the path is travelled by the NZDSF and at Coimbra’s node the respective compensation is made. As can be seen for each path there are four different dispersions that correspond to the way which the path is travelled and it is or it is not compensated. For the route Aveiro → Entroncamento → Aveiro there are four paths each one with four different ways to travel it, as can be seen in Table 6.1. So, all the possible ways to travel the designated route are $4^4 = 256$ and the dispersion value for each way is given by the sum of all the columns, as it is presented in Figure 6.3.

Aveiro → Coimbra	Coimbra → Entron.	Entron. → Coimbra	Coimbra → Aveiro
1 – SSMF	1 – SSMF	1 – SSMF	1 – SSMF
1 – SSMF	1 – SSMF	1 – SSMF	2 – NZDSF
1 – SSMF	1 – SSMF	1 – SSMF	3 – SSMF Comp.
1 – SSMF	1 – SSMF	1 – SSMF	4 – NZDSF Comp.
1 – SSMF	1 – SSMF	2 – NZDSF	1 – SSMF
. . .	. . .	. . .	. . .
4 – NZDSF Comp.	4 – NZDSF Comp.	4 – NZDSF Comp.	4 – NZDSF Comp.

Table 6.1: Matrix of all the possible ways for Aveiro → Entroncamento → Aveiro route and the chromatic dispersion for each number.

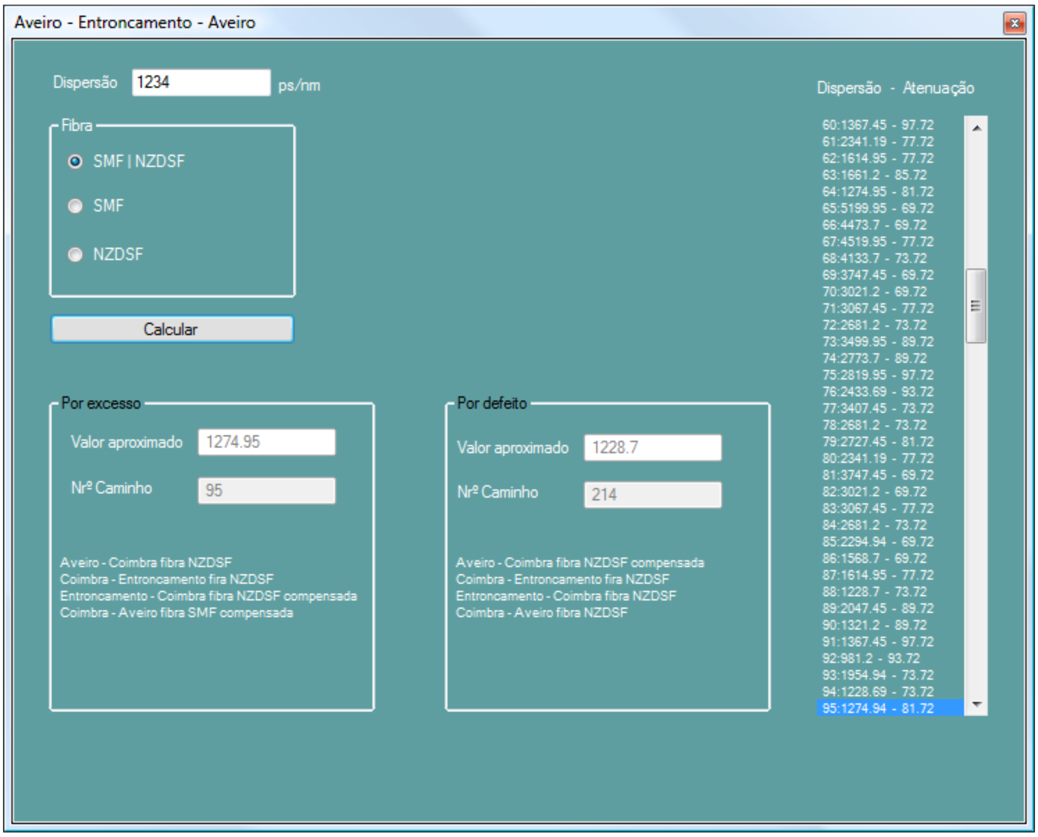

Figure 6.3: Application interface that contains the two returned values and all the combinations that are possible to make along Aveiro – Entroncamento – Aveiro route.

As can be seen in Figure 6.3, it is possible to trace Aveiro → Entroncamento → Aveiro route when this is travelled just with SSMF or NZDSF. For these cases in the created matrix that is presented in Table 6.1 will just be selected the lines (ways) which contain the numbers 1 and 3 for SSMF case and 2 and 4 for the NZDSF case.

In all these generated 256 ways, some of them will have the same dispersion, but linked to each dispersion there is an attenuation value. The algorithm will verify for the same dispersion values which one has the lower attenuation value. It is important to refer that the same path travelled by the same fiber can have different attenuations, because if at the end of the path there is dispersion compensation, this compensation will introduce some attenuation into the signal.

The dispersion compensation values which are taken in account in each node can be changed and exported to a file, as can be seen in Figure 6.4.

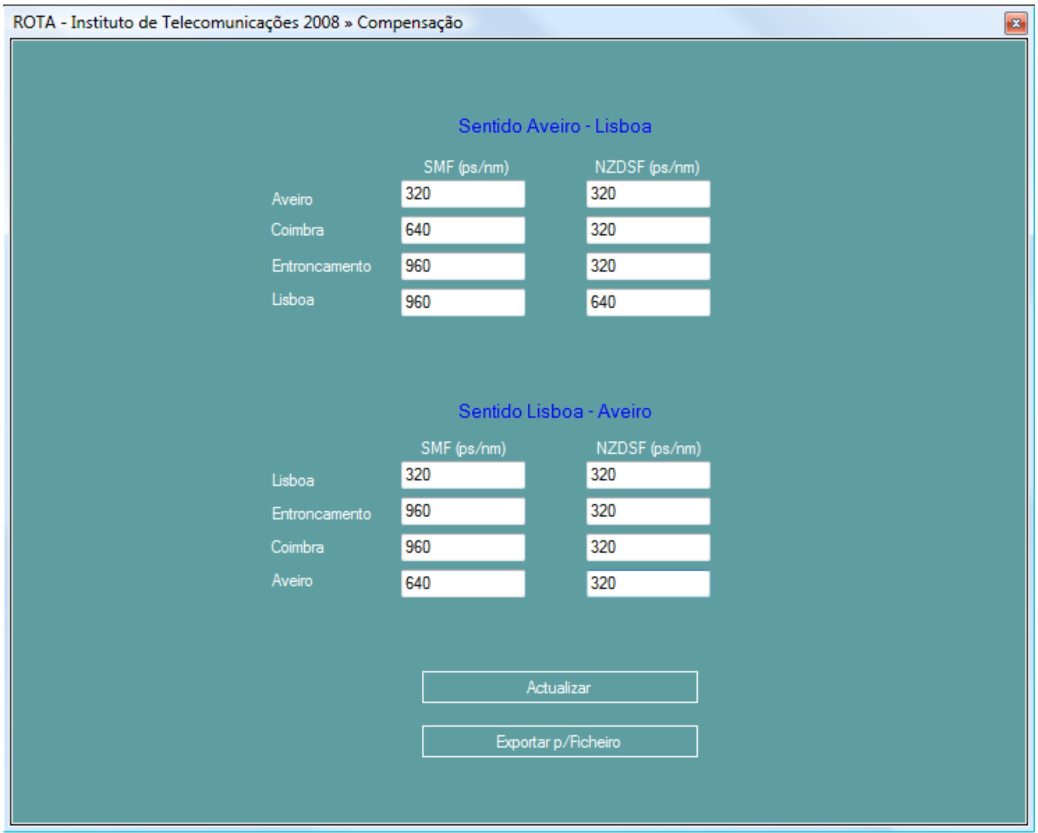

Figure 6.4: Application menu where the dispersion compensation values can be changed.

If the user just click in the button “Actualizar” the application will use the changed values until it is restarted, so when the application is turned on again it will use the default values. If the user click in the button “Exportar p/ Ficheiro” the application will save the changed values into a file and whenever the application is turned on it will has as default values the ones that are saved in the file. There is the possibility to use the values that were as default before exporting the changed values into a file and to this the user has just to delete the file with the new values. The same action can be done for attenuation values where the user has the possible to change the attenuation constant.

As was mentioned in section 6.1, when the application gives the chosen dispersion values and its described route the application saves into a file the switches configuration for all the nodes that are presented along the route. In this file the first line saves the switches configuration in each node when the taken direction is Aveiro → Lisbon and the second line saves the switches configuration in each node when the direction is Lisbon → Aveiro, as can be seen in table 6.2 and 6.3, respectively. It is important to have a better look into Figure 4.3 and 4.4 (Chapter 4, section 4.3) in order to understand the next two tables.

	Aveiro → Lisbon direction (1st line)															
	Aveiro		**Coimbra**					**Entroncamento**					**Lisbon**			
Sw	Sw_D 2X2	Sw_1 1X2	Sw_1 1X2	Sw_1 1X4	Sw_1 1X4	SW_D 2X2	Sw_2 1X2	Sw_1 1X2	Sw_1 1X4	Sw_1 1X4	Sw_D 2X2	Sw_2 1X2	Sw_3 1X2	Sw_1 1X4	Sw_1 1X4	Sw_D 2X2
Bits	0	1	1	1	0	0	1	1	1	0	1	x	x	x	x	x

Table 6.2: Corresponding switch position in each node when the direction is Aveiro → Lisbon for the route which appears in Figure 6.3 (1274.95 ps/nm).

	Lisbon → Aveiro direction (2nd line)															
	Lisbon		**Entroncamento**					**Coimbra**					**Aveiro**			
Sw	Sw_D 2X2	Sw_1 1X2	Sw_3 1X2	Sw_2 1X4	Sw_2 1X4	Sw_D 2X2	Sw_4 1X2	Sw_3 1X2	Sw_2 1X4	Sw_2 1X4	Sw_D 2X2	Sw_4 1X2	Sw_3 1X2	Sw_1 1X4	Sw_1 1X4	Sw_D 2X2
Bits	x	X	x	x	x	1	1	1	0	1	0	0	0	0	0	0

Table 6.3: Corresponding switch position in each node when the direction is Lisbon → Aveiro for the route which appears in Figure 6.3 (1274.95 ps/nm).

If in the switch 2x2 the corresponding bit is “0” the switch will do the forward of the signal, but if the bit is “1” the switch will introduce a loop back into the optical network, obviously in the node where the switch is located.

For the switch 1x2, if the bit is “0” the next path will be travelled by SSMF, but if the bit is “1” the next path will be travelled by NZDSF.

For the switch 1x4 is presented in table 6.4 the description of each position and the corresponding bits. As was mentioned in chapter 5 it is just necessary to control one switch 1x4 because the other one it is parallel connected. For each switch 1x4 there are four possible positions, so to control these positions it is necessary two bits.

When the bit is “x” means that it is not important the switch position (do not care).

Bits		Position	Description
0	0	1	SSMF compensation
0	1	2	NZDSF compensation
1	0	3	Signal Bypass
1	1	4	Block

Table 6.4: Corresponding bits of each switch position and its description.

The configurations of each switch that are presented in Table 6.2 and 6.3 are according to the example that is presented in Figure 6.3 when it is chosen the dispersion 1274.95 ps/nm which is given by the application when it is wanted the 1234 ps/nm dispersion in Aveiro → Entroncamento → Aveiro route.. For this dispersion value Aveiro → Coimbra path is travelled by NZDSF, Coimbra → Entroncamento is travelled by NZDSF, Entroncamento → Coimbra is travelled by NZDSF having compensation in Coimbra’s node and Coimbra → Aveiro path is travelled by SMF having compensation in Aveiro’s node.

The information with the switches positions can be sent for all the nodes through the following protocol. The protocol layer is based in Micro LAN, DB2 or LIN communication. The 1-Wire protocol, also called Micro LAN, requires small amount of hardware and consists of a sophisticated communication protocol to ensure the security of data [31]. Data transmission and reception is done according to the encoded RZ asynchronous signal. PWM modulation occurs at 115 kbaud Rate. Broadcast and unicast messages are allowed in the bus. The MAC address defined for the slave devices is addressable and the technology used is Plug & Play. [31]

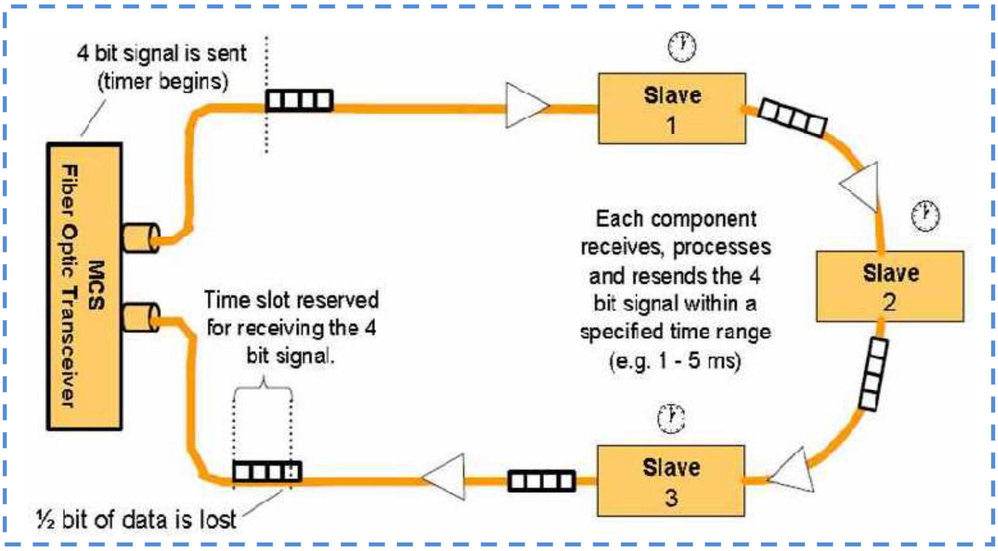

Figure 6.5: Illustration of the protocol functionalities and interaction with the nodes in the network. [31]

The firmware, which manages data transfer to and from Slave devices, is related to the International Standards Organization (ISO) reference model of Open System Interconnection (OSI), which specifies a layered protocol having up to seven layers. According to this model [31]:

- Electrical and timing requirements and the characteristics of the 1–Wire bus are related to the Physical layer;
- Software functions, like TouchReset, TouchByte, or TouchBit, are related to the Link layer;
- Multi-drop access system functions, like First, Next or Access, which support selection of individual network nodes, are relative to the Network layer;

- Software which transfers memory data, other than ROM contents, to and from the individual network nodes is related to the Transport layer;
- A Session layer may or may not be needed;
- The Presentation layer provides a file structure which allows memory data to be organized into independent files and randomly accessed;
- The Application layer comprises the final application designed by the customer.

The boards which will be implemented in each node in order to send the information with the switches positions are coupled analog/digital converters (ADC). The analog signals acquired by sensors, like temperature and optical signal power, are converted to digital signals so they can be sent to a processing unit. The processing unit is a microcontroller from ATMEL. A PWM module is used to adjust the feedback system of the laser power. It also has on/off actuators incorporated. The communications gateway lets other devices, like computer systems, to communicate with the main node, commonly designated as master, through SPI, I2C or RS232 protocols. The optical communications module has a PIN photodiode with sensitivity of -20 dBm, a laser with maximum emitted power of 4 dBm, a bandwidth of 800 kbps and operates at 5 VDC [31].

6.3 Conclusions

In this chapter was made an application with the main objective to simulate the optical network. This application gives a dispersion value and its associated path which is the closest dispersion relatively to the introduced one when compared to all the possible routes, with the different fibers combinations, which can be done in the optical network. Attached to each dispersion value given by the application there is a file which contains the positions of each optical switch for all the nodes along the optical network. It was even presented a solution to control all the optical switches with the extra electrical and optical devices needed and the necessary protocol to transmit all the information which will change the switches positions.

Chapter 7

Conclusions and Future Work

7.1 General Conclusions

This work was presented in six chapters which have focused into optical test beds. Several optical testbeds that were implemented in other countries and each testbed with different specifications and characteristics were presented to assess the objectives and panoramas in other test bed environments.

The linear and non linear characteristics of optical fibers were studied in order to assess the ones that could limit our objective.

In the Aveiro → Lisbon → Aveiro path several scenarios were simulated in order to evaluate which compensation brings the best results. With the simulation results was possible to observe that the pre-compensation is the configuration that offers the best results. 2.5 and 10 Gbit/s are well behaved, however, 40 Gbit/s are somehow limited even when there is a total dispersion compensation and a filter at the end of the optical network.

Although the boards that will be introduced in each node along the optical network will be done by the WITHUS Company, a board was projected and implemented which will control two optical switches 1x2 and another two optical switches mini 1x4 in order to simulate the ones that will be implemented in each node. In order to control this board an interface was developed with the main purpose to change each switch position with the click in a specific button. The board and the associated program functionalities were verified.

Along the optical network it is possible to cross different 4368 routes each one with different dispersion and attenuation. So, an application was made with the main purpose to target a dispersion value given by the user and the application will calculate for all the possible routes. With all different fiber combinations, the result is the one closest dispersion value relatively to the targeted one. This application allows the user to choose which route he wants, or can even choose an option that will seek among all possible routes which brings the closest dispersion. An important characteristic of this program is that when the program returns a value, attached to this value there is a file that contains all the switches configurations that will have to be done in each node along the optical network in order to reach this dispersion value. It was presented a solution to control all the optical switches in each node with the extra electrical and optical devices needed in all the nodes and the necessary protocol to transmit all the information in order to change the switches positions.

7.2 Contributions

The performed work described on this document contributed to explore the reliability of the optical network implemented between Aveiro and Lisbon. The board specifications allow to understand how the compensation of dispersion and the loop back can be introduced in the optical network.

The preliminary simulations allow to understand all the limitations of the optical network and which compensation brings the best results.

The configuration program simulates the optical network which gives to the user the routes that bring the lower chromatic dispersion relatively to the introduced by the user, where these routes can be tested in the future.

Besides this final work, one document was done and submitted for the proceeding of the Portuguese-Mozambican congress of Engineering:

- A. Bastos, P. André, A. Teixeira, P. Monteiro, “Rede óptica de testes avançados: conceito e especificação”, Maputo, Mozambique, September 2008.

7.3 Future Work

As future work for the optical network several things have to be implemented and tested:

- The first thing which is from vital importance to the optical network is the implementation of each node and the respective boards in order to be possible to do all the network configurations and transmissions.

- After the nodes and boards implementation it will be necessary to test the communication path and when this is working start some trial experiments as the ones that were presented before.

- Define a generic platform for general test beds with different topologies.

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Appendix

A - Simulation for different bit rates

In this section are presented the tests when the route is travelled by SMF or NZDSF at different bit rates (2.5, 10, 40 Gbit/s) and for different routes which can be done in the optical network. The compensation of dispersion was done by the same way that is described in chapter 4 (pre-compensation).

In Figure A.1, A.2 and A.3 it is presented the route Aveiro → Coimbra → Aveiro for 2.5, 10, 40 Gbit/s bit rate, respectively.

In Figure A.4, A.5 and A.6 it is presented the route Aveiro → Entroncamento → Aveiro for 2.5, 10, 40 Gbit/s bit rate, respectively.

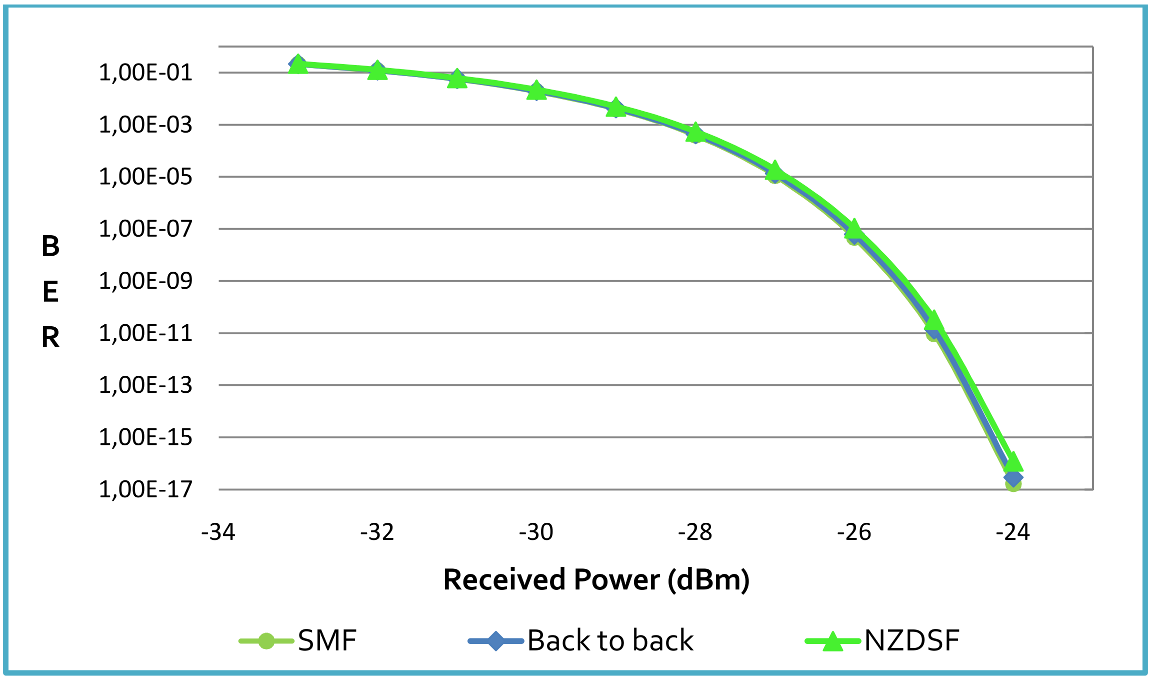

Figure A.1: BER vs Received Power of Aveiro → Coimbra → Aveiro with SMF, NZDSF and Back to back configuration for 2.5 Gbit/s bit rate.

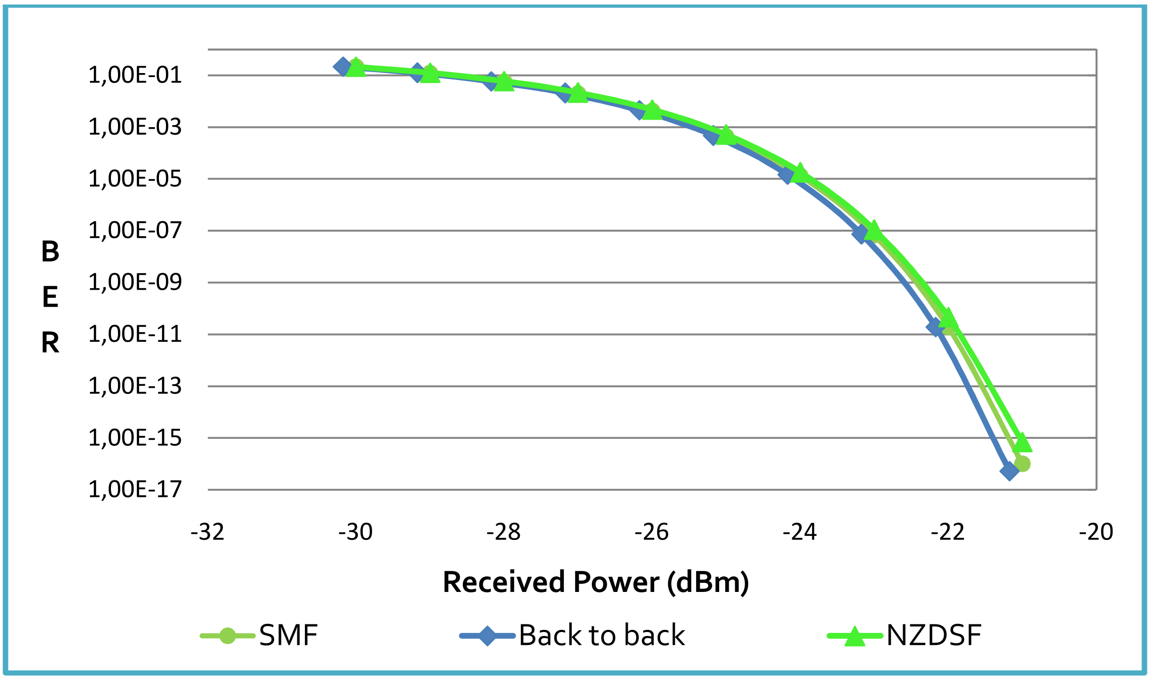

Figure A.2: BER vs Received Power of Aveiro → Coimbra → Aveiro with SMF, NZDSF and Back to back configuration for 10 Gbit/s bit rate.

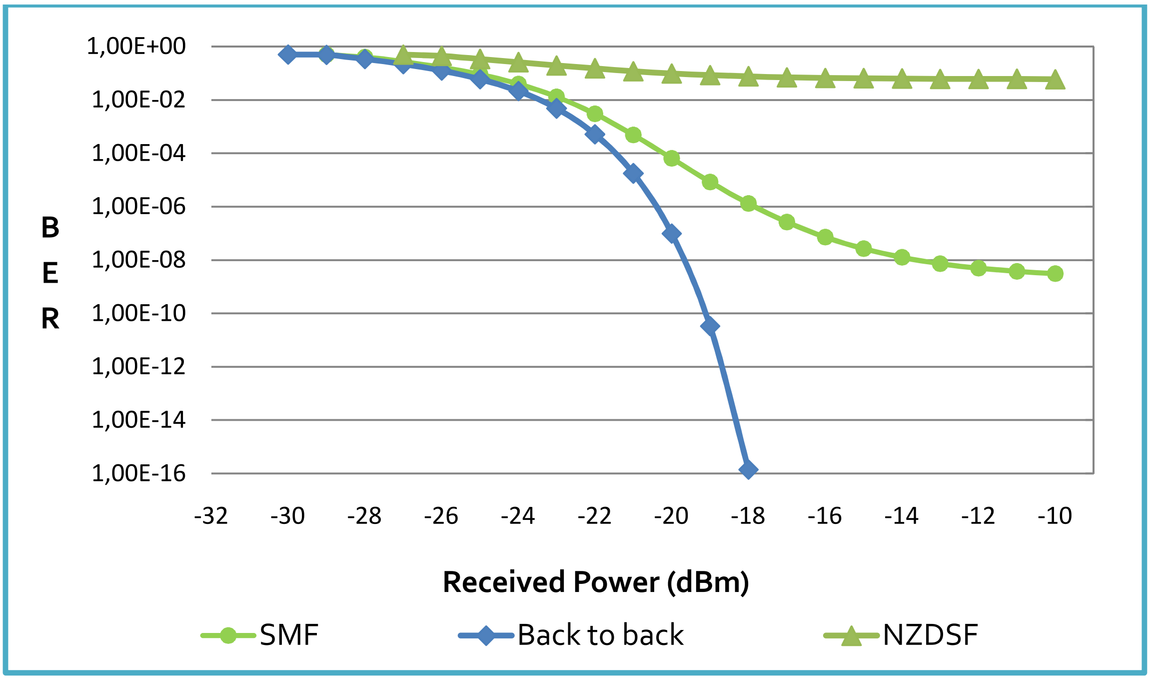

Figure A.3: BER vs Received Power of Aveiro → Coimbra → Aveiro with SMF, NZDSF and Back to back configuration for 40 Gbit/s bit rate.

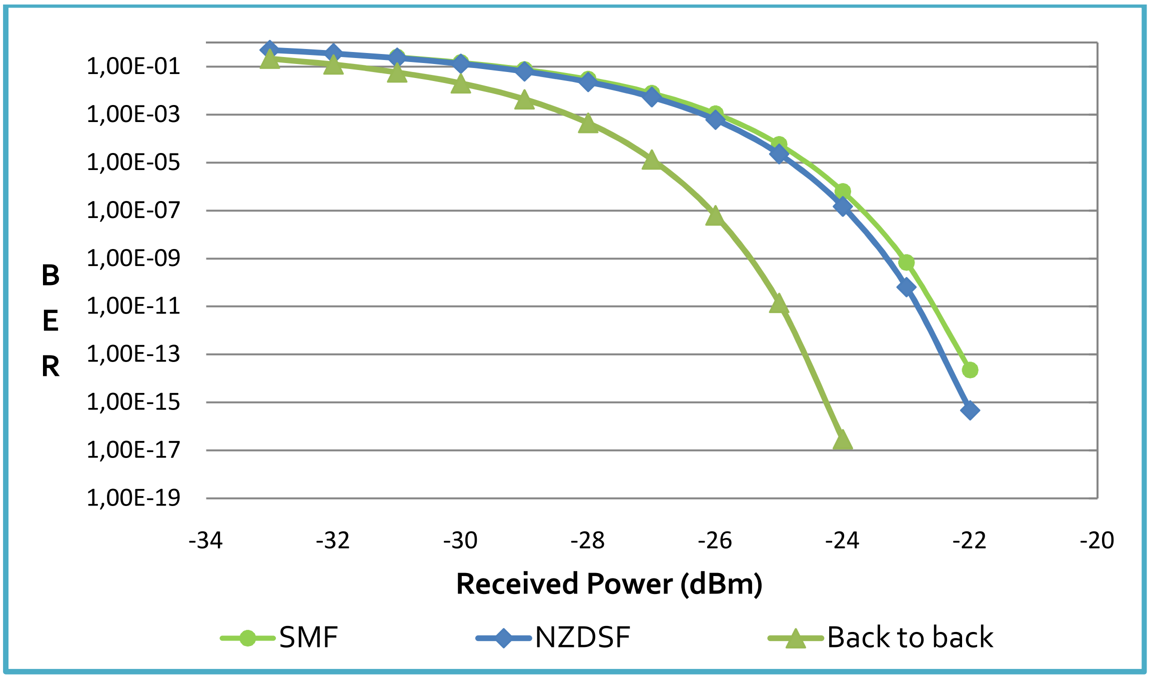

Figure A.4: BER vs Received Power of Aveiro → Entroncamento → Aveiro with SMF, NZDSF and Back to back configuration for 2.5Gbit/s bit rate.

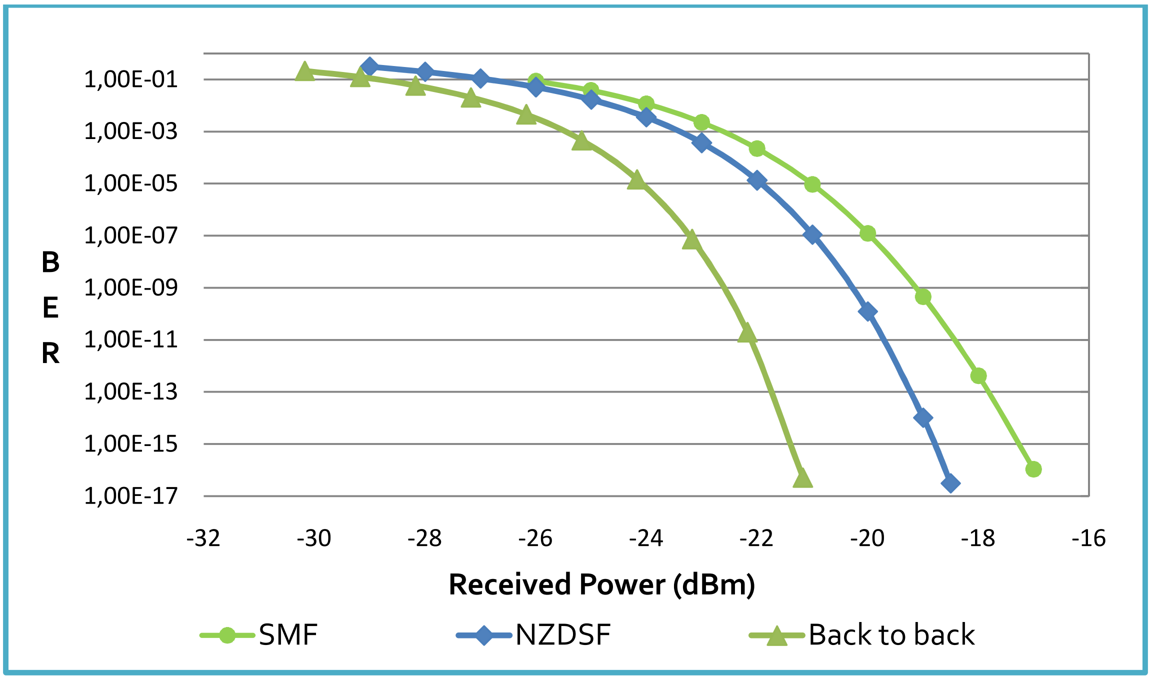

Figure A.5: BER vs Received Power of Aveiro → Entroncamento → Aveiro with SMF, NZDSF and Back to back configuration for 10 Gbit/s bit rate.

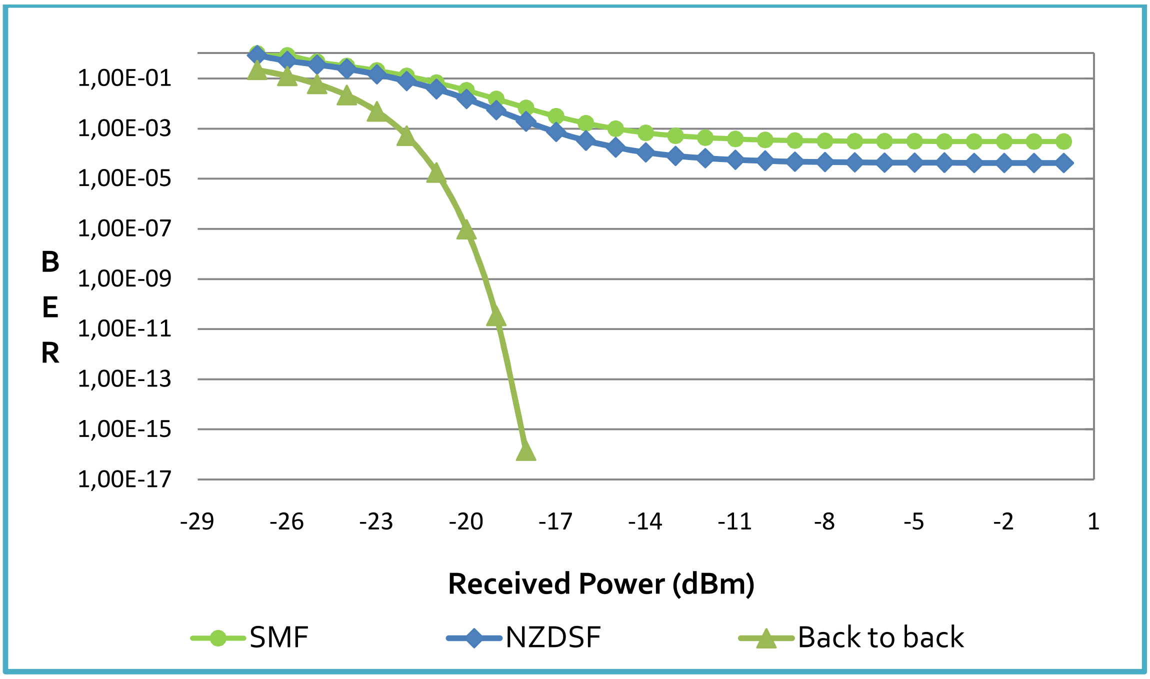

Figure A.6: BER vs Received Power of Aveiro → Entroncamento → Aveiro with SMF, NZDSF and Back to back configuration for 40 Gbit/s bit rate.

B - Experimental Results

In Figure B.1 it is presented the eye diagram of the Back to back configuration for a 40 Gbit/s bit rate.

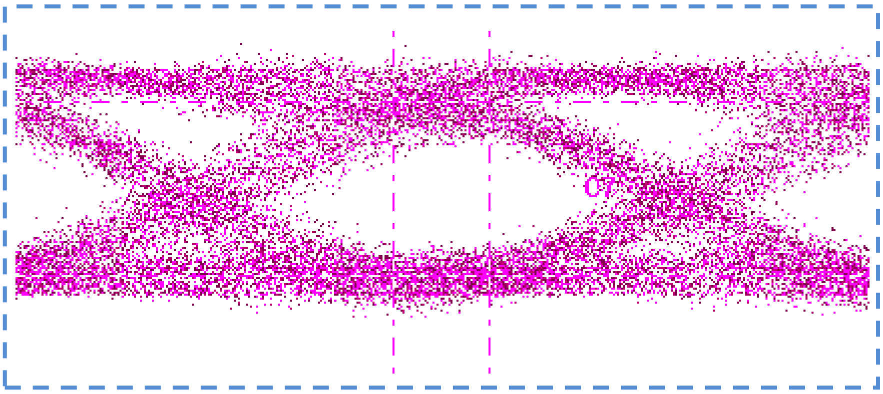

Figure B.1: Eye diagram of the back to back configuration for 40Gbit/s bit rate.

Normally to have a good transmission at 40 Gbit/s the Q factor has to be approximately 6 that correspond to a 10^{-09} BER. The obtained Q value was near of 6 (5.43), but the Back to back configuration it is the setup which brings the best results, so the next configurations will have a worst Q value.

In Figure B.2 it is presented the eye diagram of the post-compensation setup for a 40 Gbit/s bit rate and the obtained quality factor (Q) was 4.46. In Figure B.3 it is represented the eye diagram of the pre-compensation setup for the same bit rate and the obtained Q factor was 3.37.

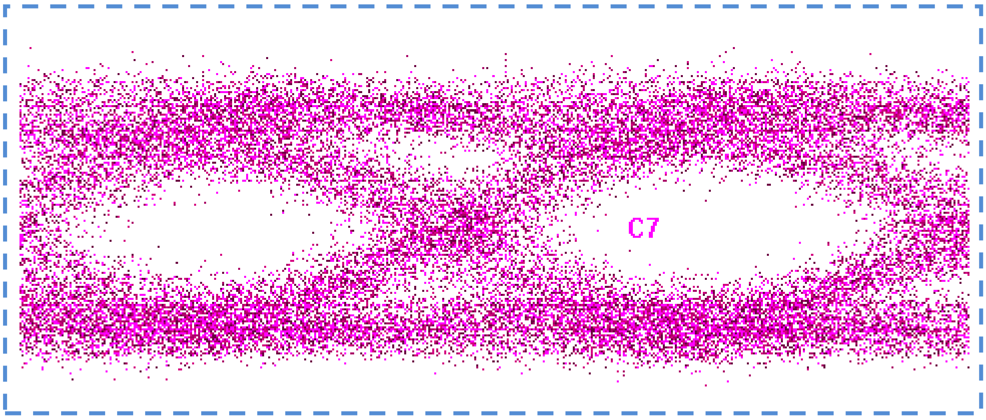

Figure B.2: Eye diagram of the post-compensation setup for 40Gbit/s bit rate.

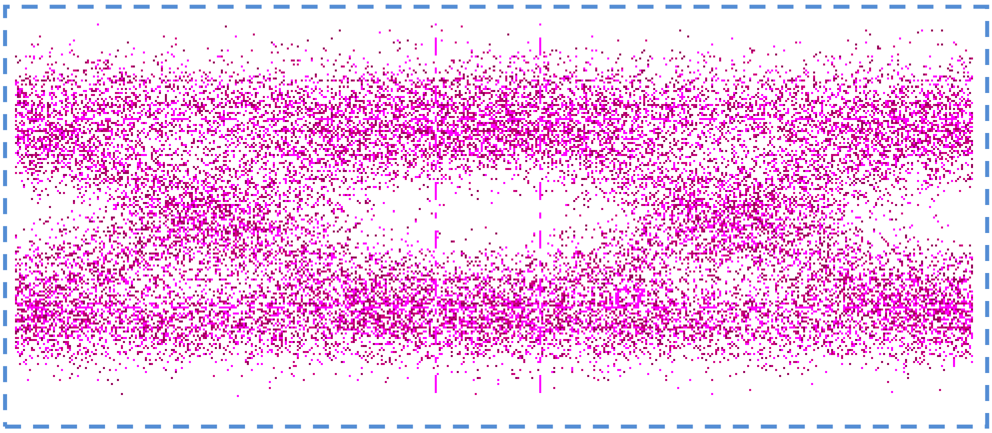

Figure B.3: Eye diagram of the pre-compensation setup for 40Gbit/s bit rate.

C - PCB and Electrical Schematic

In Figure C.1 and Figure C.2 are presented the PCB layout top and bottom, respectively. In Figure C.3 is presented the complete electrical schematic of the prototype board.

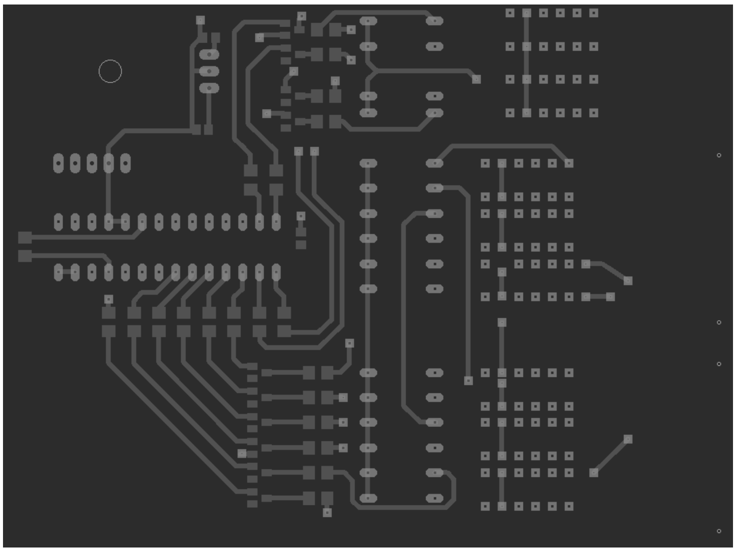

Figure C.1: PCB layout of the prototype board (Top view).

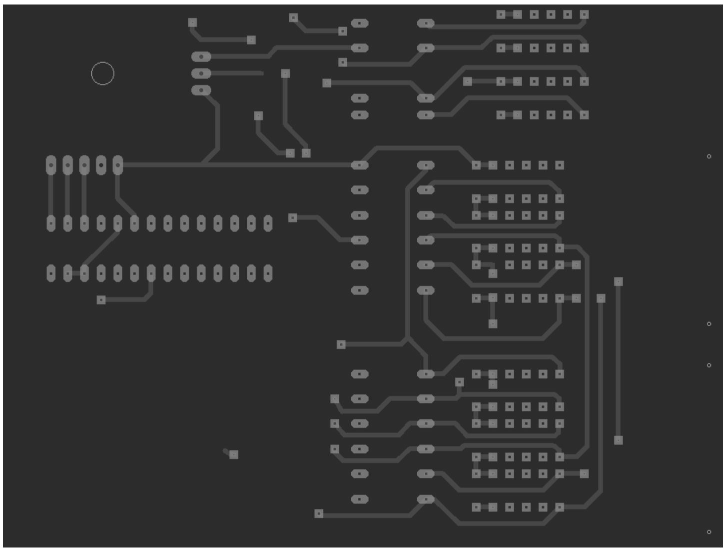

Figure C.2: PCB layout of the prototype board (Bottom view).

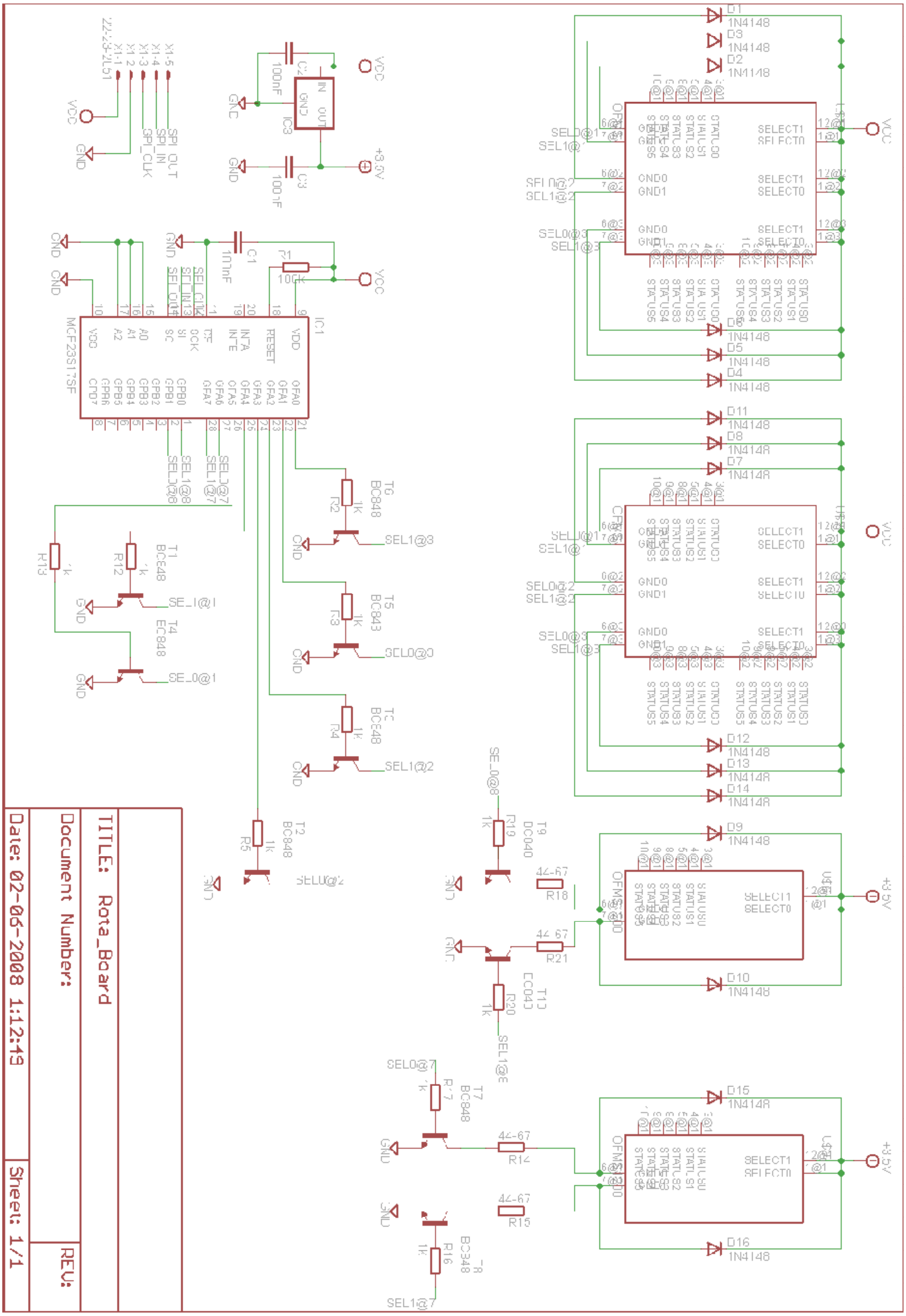

Figure C.3: Complete electrical schematic of the prototype board.