Planning Tool of Point to Point Optical Communication Links

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Resumo

A utilização de fibra óptica em sistemas de telecomunicação de longas distâncias tem tido um grande crescimento nos últimos anos e tem tendência a aumentar dadas as inúmeras vantagens que estes sistemas apresentam. A utilização de ferramentas computacionais no dimensionamento e planeamento deste tipo de sistemas é essencial, permitindo testar o desempenho da ligação.

Neste trabalho, foi implementado uma ferramenta computacional para auxiliar o planeamento de sistemas em fibra óptica ponto a ponto. Esta ferramenta foi desenvolvida em MATLAB®/Simulink, uma vez que este *software* tem uma interface gráfica que facilita a construção de sistemas através de módulos predefinidos. Recorrendo à interface gráfica o utilizador poder dimensionar uma ligação em fibra óptica e simular o seu desempenho a alto nível. A ferramenta obtida tem a capacidade de testar sistemas com diferentes complexidades como por exemplo a utilização de *Wavelength-Division Multiplexing* (WDM) ou a optar entre receptores ópticos do tipo p-i-n Photodiode (PIN) ou Avalanche Photodiode (APD).

Para validação do *software* desenvolvido, foram efectuadas comparações dos resultados obtidos com resultados publicados por outros autores.

Finalmente, foi simulado o desempenho de uma hipotética ligação baseada na rede da Fundação para a Computação Científica Nacional (FCCN).

Os resultados obtidos mostraram que a ferramenta computacional fornece uma simulação viável de acordo com a análise teórica do sistema e também que é possível planear e testar um sistema de telecomunicações de fibra óptica utilizando esta ferramenta.

Palavras chave: Simulink, fibra óptica, simulador de sistemas *de telecomunicação, WDM*.

Abstract

The use of fibre optics in long haul telecommunication systems has a been growing in the last years and tends to increase given the numerous advantages that these systems present. The use of computational tools in the design and planning of such systems is essential, allowing to test the performance of the connection.

In this work, a computational tool was implemented to assist or plan fibre optic systems. This tool was developed in MATLAB®/Simulink, since this software has a graphical interface that facilitates the construction of systems through predefined modules. Using the graphical interface, the user can size a fibre optic connection and simulate its performance at a macro level. The obtained planning tool has an ability to test systems with different intricacies such as the Wavelength-Division Multiplexing (WDM) or to choose the type of optical receivers between p-i-n Photodiode (PIN) or Photodiode (APD.

For validation of the developed software, comparisons of results that were obtained with results published by other authors were made.

Finally, it was simulated the performance of a hypothetical connection based in a network of the Fundação para a Computação Científica Nacional (FCCN).

The results showed that the computational tool provides viable simulation according to the theoretical analysis of the system and also that it is possible to plan and test a fibre optic telecommunication system using this tool.

Keywords: Simulink, fibre optic, simulator of telecommunication systems, WDM.

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List of Abbreviations

APD	Avalanche Photodiode
ASE	Amplified Spontaneous Emission
BER	Bit Error Rate
DFA	Doped Fibre Amplifier
DTU	Danmarks Tekniske Universitet
EDFA	Erbium-Doped Fibre Amplifier
FWM	Four-Wave Mixing
FCCN	Fundação para a Computação Científica Nacional
FCT	Fundação para a Ciência e Tecnologia
ISCTE-IUL	Instituto Superior de Ciências do Trabalho e da Empresa - Instituto Universitário de Lisboa
IST	Instituto Superior Técnico
ITU-T	International Telecommunications Union Telecommunication Standardization Sector
MPN	Mode-partition Noise
NDSF	Nondispersion-shifted Fibre
NZDSF	Non-zero Dispersion-shifted Fibre
OSNR	Optical Signal to Noise Ratio
PIN	p-i-n Photodiode
PON	Passive Optical Network
SBS	Stimulated Brillouin Scattering
SDH	Synchronous Digital Hierarchy
SMF	Single-Mode Optical Fibre
SNR	Signal to Noise Ratio
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
STM	Synchronous Transport Module
WDM	Wavelength-Division Multiplexing
XPM	Cross-Phase Modulation

Chapter 1

1. Introduction

In this project, a computational tool was implemented to assist the planning of point-to-point fibre optic systems. This topic was chosen in order to fulfil the increasing need to find an open source software to simulate fibre optics systems, using a high-level approach. The introduction of this project is divided into five subsections: the first one explains the motivation behind this project. The second one explains the context behind this project. The third subsection explains the objectives and the dissertation structure. The last subsection is the state of the art, which is a presentation of each technology and their current development.

1.1 Motivation

In the last 50 years, the technology of fibre optical communications has been developing very fast along with the digital processing technology. This type of advancements revolutionised the telecommunications industry with a massive increase in demand for communications bandwidth, due to increased use of the internet and other consumer services. Figure 1.1 shows an increasing number of Internet users in the World from 2005 to 2016.

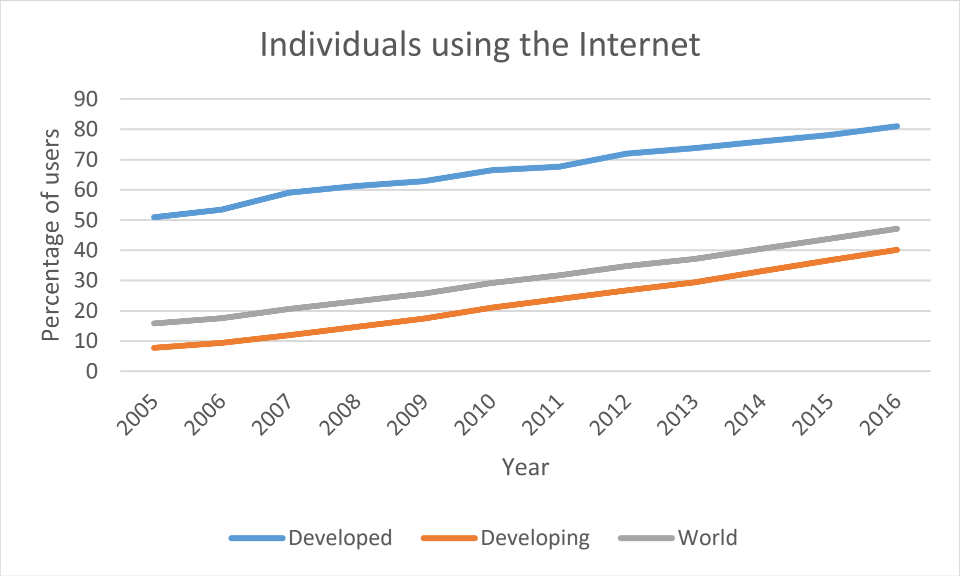

Figure 1.1 Percentage of internet users from 2005 to 2016 [1] The value for 2016 was estimated.

The simulation of fibre optic telecommunication systems is an important process within an optical fibre network design. The construction of fibre optic telecommunication systems can be very expensive, so before every installation, all the components must be tested together in a simulation, to assure that the connection is reliable.

The main users of fibre optic telecommunication systems simulators are companies and students of Telecommunications. Of both, companies are the most important clients of designing companies since they are more willing to pay than students that use student licenses given by the University. The design of most fibre optic telecommunication systems simulators makes a different approach from the “Macro” level. The signal is simulated to the single photon, making the simulation very detailed but very complex, asking the user for many parameters and using many blocks to make the signal of the system. Nowadays, there are many companies in the market that provide simulations fibre optic telecommunication systems, for example *VPIphotonics* and *OptSim*. This project intends to provide a reliable tool to simulate fibre optic telecommunication systems with an easily accessible platform without the need to buy independent commercial software.

1.2 Context

The fibre optic telecommunication systems are systems in which optical fibre communications are designed. These systems need to be well studied since there are many factors that produce noise or attenuation which make the fibre optic telecommunication systems unreliable. In order to test the fibre optic telecommunication systems, simulators capable of testing the design of the system were developed to detect problems and to make the planning of fibre optic telecommunication systems more reliable and accessible.

The approach presented in this project observes the fibre optic telecommunication systems in a “Macro” level, which means dividing the fibre optic telecommunication systems into three main blocks: optical transmitter, communication channel and an optical receiver (Figure 1.2). This approach does not simulate the optical signal to each photon like most other simulators do, instead it sees each component as a “Black Box” and work as intended. With this approach the objective is to simplify the construction of the fibre optic telecommunication systems for the user, making it a more user-friendly simulator. In addition, it does not consider every single noise and attenuation present in the communication testing only the main ones.

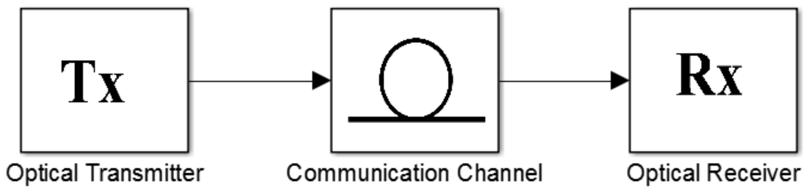

Figure 1.2 The main blocks that form an optic system.

The fibre optic telecommunication systems are divided into many components. The optical transmitter emits a modulated light signal that needs to get to the optical receiver, passing through the communication channel to establish an optical communication. However, there are many factors that attenuate the power of the source need to be computed to achieve an optimal performance. Most of the impairments come from the communication channel, but the objective of it is to achieve the bit error rate (BER) desired by the user to satisfy his connection requirements. Afterwards, all the steps needed to make a suitable fibre optics communication network were in place, and today there are fibre optical cables all around the word in Figure 1.3.

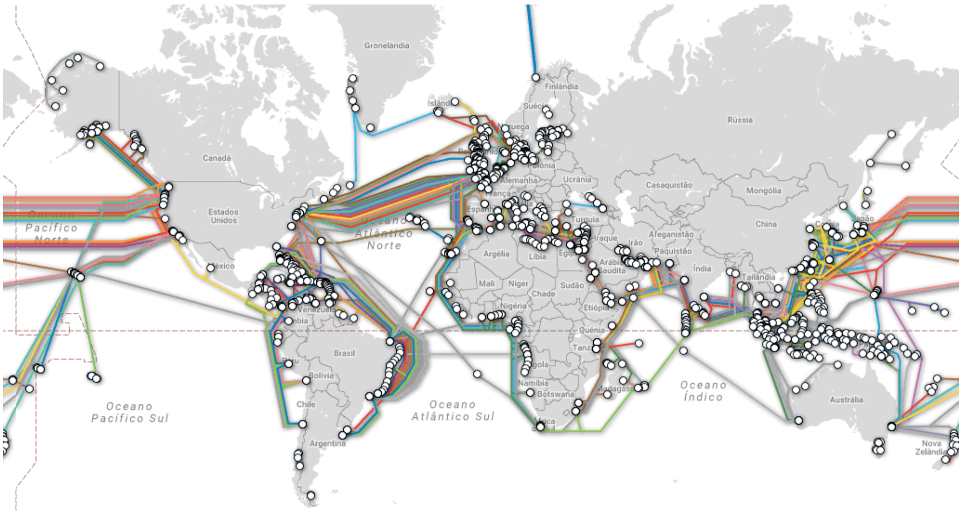

Figure 1.3 World map with undersea cable transmission systems until October 2016 [2]

1.3 Objectives and dissertation structure

The aim of this project is to implement a simulator of fibre optic telecommunications systems at a macro level, the implementation was made using MATLAB® and Simulink. The simulator provides a simple construction tool in a Simulink library were the components of a fibre optic telecommunications systems can be added. The different parameters of the components can be altered by the user interface window that opens by pressing the blocks. The simulator will provide the necessary components to construct a fibre optic telecommunications system. By constructing this library in Simulink there is always the possibility of growth, which means that the program was constructed with the intent of allowing students to add more complexity to the simulator by adding other blocks or functionalities. The dissertation document is structured as follows:

- In Chapter 2, a theoretical analysis of fibre optic telecommunications systems including the appllication of each component and phenonmena that occur in the system.
- In Chapter 3, the simulator that was implemented with an explanation on the construction of the system and each block with a comparision of values with other simulators. This comparison will be followed by the construction and analysis of a real life project of a fibre optic telecommunications system with the simulator.
- In Chapter 4, the final conclusions are presented.

1.4 State of the art

In this section is divided into two subsections, that explained in which point the technology has been developed. Since, this project contains two types technology, fibre optics and fibre optic simulator, an explanation on their development is evaluated separately.

1.4.1 Fibre optics

Since the beginning of time, humans tried to communicate from longer distances and with as much information as possible. Nevertheless, this would only become possible in the 19th century, with the development of the electrical telegraph. However, this electrical telegraph had a limited capacity of sending only 15 words per minute, which was a very primitive system compared to the one used nowadays [3].

The fibre optic telecommunication systems did not always use silica fibres, this discovery and some other discoveries led to the technology used nowadays. One of the first findings regarding optical-fibre communications happened in 1880 with the Photophone, invented by Alexander Graham Bell and Charles Sumner Tainter. Although this device worked, it had a short range and it did not work without clear air conditions [4]. The Photophone did not use fibre until 1961 when Charles C. Eaglesfield proposed the use of a hollow optical pipeline made of reflective pipes. Five years later, a paper was published by Charles Kao and George Hockham demonstrating that the use of fibreglass could dramatically decrease if the glass was pure enough, so they proposed that the loss could be reduced below 20 dB/km, which would be practical for communications [5]. Later in 1970, Corning Glass Works achieved the first low-loss optical fibre suitable for optical fibre communications, reaching less than 20 dB/km [6].

There has been a growth in the required data to establish a telecommunication. This requirement has always enticed the necessity for faster and more reliable means of communications. The development of fibre optic communications can be stated to have started in the 19th century, with the development of the electrical telegraph. However, this electrical telegraph had a limited capacity of sending only 15 words per minute, which was a very primitive system compared to the one used nowadays.

The technology of telecommunications grew exponentially since the electrical telegraph, from inventions such as the telephone, the radio and the television until today with the use of computers and the internet. Since the creation of computers and the internet in the 1960s, the bit rate in which information is transmitted has become increasingly faster.

Figure 1.1 shows that the number of users with internet access continuous to rise. Most of these new connections will already be made from optical fibre cables, and many of the old copper wiring ones were or will be replaced by fibre optical cables. Figure 1.4 shows an increasing growth in the number of optical fibre cables used in different countries.

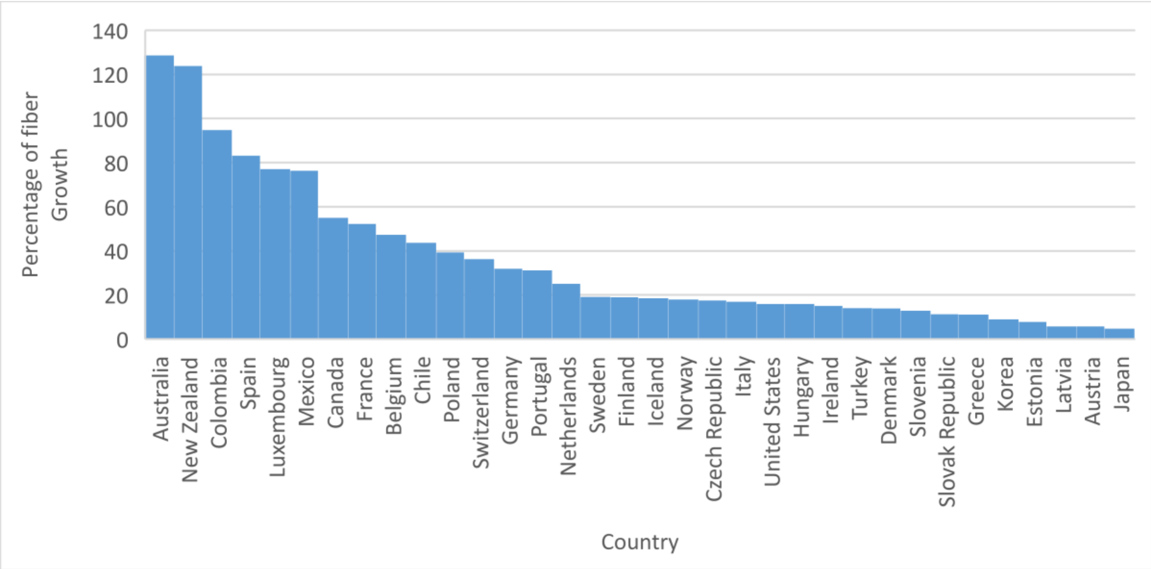

Figure 1.4 Growth in fibre optical cables per country [7]

In many countries, the growth of fibre cables is rising. However, it seems to be less significant in other countries. For instances in Japan the growth is just 4.82%, but the percentage of coverage is already 74.1%. This means that there is less growth because the coverage is almost total. On the other hand, in Australia, the growth was 128.57%, but the percentage of coverage is only 13.4% [8]. The difference in between these countries is obvious, the growth will directly relate with the total coverage, but the final conclusion is the same, many countries are investing in this technology. Even if it does not seem that most countries are investing in this technology by its growth, the reason behind it is because they have already invested already a lot in this technology and is already implemented.

With the appearance of fibre optic telecommunications, many parameters had to be introduced and adapted in order to study the phenomena that occur in this kind of telecommunications. An example of this is the optical signal to noise ratio (OSNR) which was previously analysed as the signal to noise ratio (SNR). The OSNR represents the ratio between the power of the signal and the noise power in that signal. This is one of the most important concepts in fibre optic telecommunications because is used to evaluate the amount of noise in relation to the signal that is received. One of the other parameters essential for this type of communications is the bit error rate. The BER is the ratio of the received bits that have been altered due to noise, distortion and interference. Thus, to improve the BER of the communication channel, the fibre needs to have the smallest distortion as possible. However, even when using silica fibres, where the losses are as small as 0.2 dB/km, the optical power after 100 km would be only 1% [9]. Thus, the choice of the components that make the communication channel need to be studied in order to achieve a good connection and the most cost efficient option.

1.4.2 Simulators

The use of fibre optical telecommunications systems simulators is needed to test the viability of the projected communication, through the selection of the components, the technology, the frequencies and many other options given by the simulator. Through the simulation of the system, the user is able to know if his solution is viable and maybe if it is the most cost efficient one. If the simulator provides the information about the most cost efficient solution, which many of them do, the user can make changes to save money on the project, or on the maintenance of the system.

The MATLAB® software has the capacity to run numerical models programmed by the user, which opens many possibilities for further research in many areas. This software will be used for the simulation of the fibre optic telecommunication systems, and together with Simulink, a block diagram environment for multi-domain simulation already integrated within MATLAB® [10]. The simulator presented in this "paper" was created on MATLAB® Simulink since it is a free tool for students. Also, this software is commonly used in Universities worldwide to test fibre optic telecommunication systems.

However, there are many programs that already provide fibre optic telecommunications systems simulation, each one of them provides many options and different capacities. Some of them are companies such as VPIphotonics and Synopsys, these companies provide many solutions for optical systems. However, these programs are closed platforms that require licenses and cannot be modified by the user. There also other studies with proposals for a fibre optical telecommunication systems simulators made by different Universities such as Robochameleon made by Danmarks Tekniske Universitet (DTU) [11] and also a Master's dissertation from Instituto Superior de Ciências do Trabalho e da Empresa - Instituto Universitário de Lisboa (ISCTE-IUL) [12].

VPIphotonics

The company VPIphotonics provides many simulators that help with optical component and systems that design tests for photonic networks and products. This software also provides a cost-efficient solution by providing equipment choices and the respective bill of materials. From the many products that they provide the one that has most similarities with this project is Link Engineering which is divided into two different programs VPIlinkConfigurator and VPIlinkDesigner. The VPIlinkConfigurator is a graphical interface that provides a performance assessment of the optical network, and as the VPIlinkDesigner provides the cost-effective, easy-to-use tool which enables fast and optimum network design. Figure 1.5 is an example of the graphical interface in Link Engineering software from VPIphotonics.

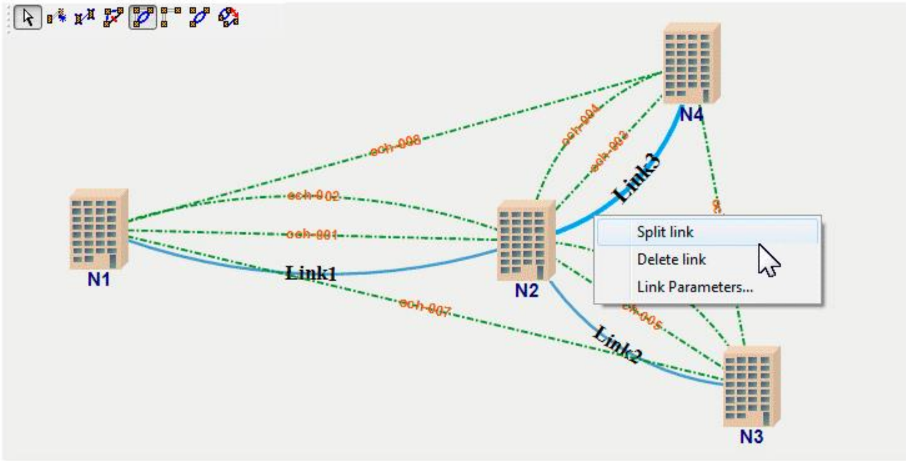

Figure 1.5 Fibre optic planning tool with four stations using Link Engineering [13]

These simulators are very detailed but require a license to use the software and the user cannot add new blocks made by him. The amount of possibilities and options that the user has can be very complex but it can also be confusing for a new user to use the VPIlinkConfigurator that is more complex than the VPIlinkDesigner. This software includes a MATLAB® interface, which provides a comprehensive set of additional functionalities for the user, including the ability to integrate and model equipment models and parts of communication links specified in MATLAB®.

Synopsys

The company Synopsys has a simulator OptSim used to design and simulate optical communication systems. It uses easy-to-use graphical interface for the user to combine with lab-like measurement instruments. This software was released in 1998, and engineers use it in academic and industrial organisations. Figure 1.6 presents an example of an OptSim design and as can be observed it simulates at the signal propagation level.

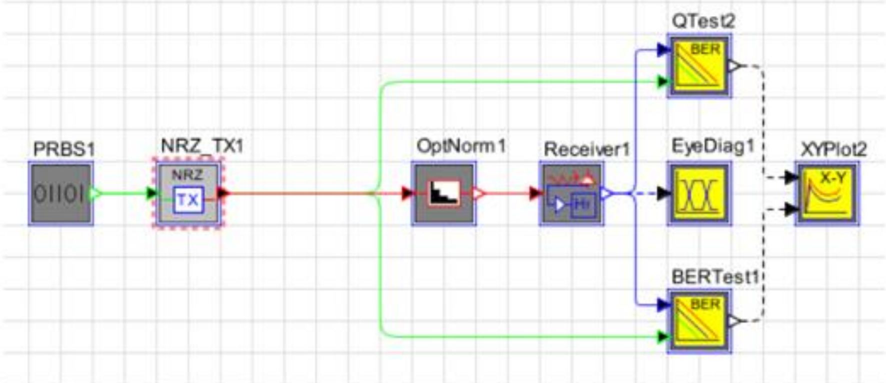

Figure 1.6 Application to detect receiver's sensitivity with OptSim [14]

The main features of this program support multiple parameters for a scans-based optimisation. It has a design tool with multiple engines running in a time and frequency domain. Also, has a MATLAB® interface in order to facilitate the development of custom user models with m-file language and the Simulink modelling environment. This means that the software is able to run models added by the user and the user also has the possibility to work in parallel with the SPICE engine.

Fibre optics telecommunications simulators from other Universities

The projects developed by other Universities such as DTU and ISCTE-IUL showed different approaches to a fibre optic telecommunication system. *Robochameleon* the project was developed in MATLAB® which consists of a framework to build a fibre optic telecommnunication system which can be accessed by the MATLAB®'s terminal, providing a coherent simulation because it simulates according to the signal level [11]. However, since this project was not built with Simulink, that is a graphical interface for MATLAB®, it does not have the capacity to connect different models. Thus, the construction of the fibre optic telecommunication system using *Robochameleon* is not very intuitive. In order to work with this program, there is a necessity to read the user manual to understand how the construction of the fibre optic telecommunication system is possible. However, the results are very precise with a full graphical analysis of each component.

The dissertation from ISCTE-IUL developed a planning tool for fibre optic communication system developed in Java. This simulator also uses Google Maps in order to choose the route of the connection Figure 1.7. However, the insertion of data to execute mathematical operations is managed in *Structured Query Language* (SQL) and *PHP: Hypertext Preprocessor* (PHP). This project provides a graphical interface in which is possible to select points on Google Maps using a Google Maps Script and plan a realistic fibre optic telecommunications system simulation.

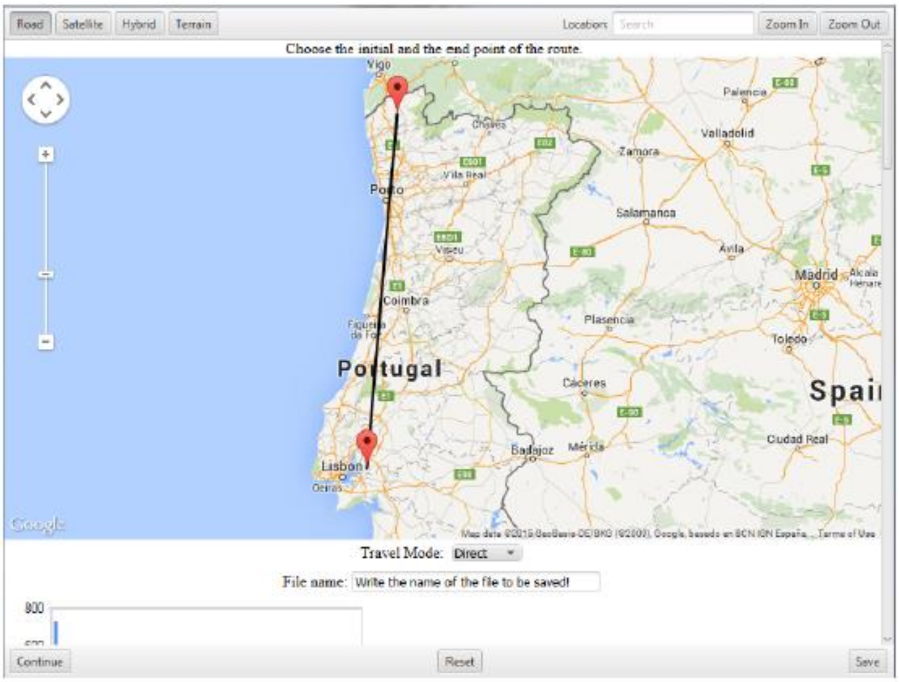

Figure 1.7 Optical link planning using a Google maps application in simulator from ISCTE-IUL [15]

Chapter 2

2. Theoretical Overview

The development of the simulator cannot be made without a theoretical analysis of the system. This analysis includes the components used in the simulator and the techniques and phenomena that occur in the system. The construction of the simulator will implement equations and parameters discussed in this section and a theoretical analysis of the simulator results that can be compared with the theoretical overview, in order to determine the authenticity of the results provided by the simulator.

2.1 Fibre Optic Communications

An explanation of fibre optic communications is the information transmitted from a light source of a transmitter through an optical fibre that is connected to a receiver. However, in real life conditions, many fibre optic communications need amplifiers, filters, connectors and other equipment to achieve a fibre optic communication. The equipment used for a fibre optic communication can bring attenuation and distortion to the system, so when planning a fibre optical telecommunications system all this attenuations and distortion need to be taken into account.

Some of the parameters that are necessary to determine many equations in the fibre optic telecommunications systems are constants such as the speed of light in vacuum. Table 2.1 represents all the parameters that are predefined as constants in any system and are used in the determination of some equations in this project. The parameters in Table 2.1 are: the speed of light in vacuum $c\ [m/s]$, the elementary charge $q[C]$, the Planck's constant $h[\,J \cdot s\,]$, the Boltzmann constant $k_b\ [J/K]$ and the room temperature $T[K]$.

Table 2.1 Values of the constants used in fibre optic telecommunications systems

$c\ [m/s]$	$q\ [C]$	$h\ [J.s]$	$k_b\ [J/K]$	$T[K]$
299792458	$1{,}601 * 10^{-19}$	$6.626 * 10^{-34}$	$1{,}381 * 10^{-23}$	290

The need for amplifiers and other similar equipment is because most fibre optic communications are made for long-distance communications, since fibre optics is the fastest and more reliable way to transmit information over long distances. Although this type of equipment inserts distortion and attenuation to the transition, in many cases is necessary and can be verified by achieving a better OSNR. In the next sections, all the equipment available in the simulator is explained, as well as the correspondent attenuation that they bring to the optical signal transmitted in the simulation. The equipment taken into account were: transmitters, optical fibre, amplifiers, filters and receivers. Note that the connectors and splices were considered to be a part of the optical fibre.

This technology came to replace the copper cables that were used for long-haul communications. The advantage of using fibre optical cables instead of copper cables is the possibility to communicate with a higher bandwidth. Although the cost for a fibre optic communication is higher than copper cables, the use of fibre optical cables has future-proof capabilities since the market of telecommunications is requiring higher speed and fidelity. The higher speeds of transmitted information come from the increase in bandwidth, and the increased fidelity comes from the fact that fibre optic communications need less signal boosting per meters, so the insertion of noise from regenerators or amplifiers is diminished, and consequently the signal has a higher fidelity. One of the basic concepts of fibre optic communications that need to be taken into account is the relation between the signals wavelength and the signal frequency. The relation between these two parameters is demonstrated in Equation *(2.1*), where the parameters are wavelength λ, frequency v and c is the speed of light in vacuum.

$$\lambda = \frac{c}{v} \tag{2.1}$$

2.2 Optical Transmitter

The light source in a fibre optic communication is generated in a transmitter that converts an electric signal into a light signal. The optical transmitter contains a light source that transmits the light signal through the fibre. The transmitter can modulate the signal internally or externally. The use of internal modulation has some disadvantages related to the signal transmission. Since in fibre optic communications the emitted power only reproduces an electrical current if the variations of current are reasonably slow. The necessity for slow variations is due to the emission of photons that can replicate the exact variations in the electrical current. Thus, this happens only if the bandwidth of the laser is similar or higher than the transmitted bit-rate. Ultimately, the necessity of slow variations in the current will limit the use of higher bitrates with internal modulation, with bit-rate higher than $10[Gbit/s]$ [16]. With external modulation, the chirp parameter C inserted by the transmitter is zero, the chirp parameter is related to the frequency chirp imposed on signal. The signal can be chirped meaning that the carrier frequency is changing with time, broadening the signal and leading to power penalties of the received power due to pulse broadening.

The bit-rate for a signal Synchronous Transport Module (STM) level-N is given by the Equation *(2.2)* [17]. STM is the recommended Synchronous Digital Hierarchy (SDH) for fibre optic networks by the International Telecommunication Union (ITU-T).

$$\mathrm{B}_{STM-N} = \mathrm{N}\times 155.52\times 10^{\,6}\mathrm{bit/s} \tag{2.2}$$

Another problem when using internal modulation is the fact that the lowest level of current has to be higher than the threshold current. The threshold current is the needed current that the laser needs to operate. The solution to this problem is to use levels of current above the threshold current, which will generate that the current for the logic level "0" higher than zero. Thus, by having a current higher than zero results in a new parameter to quantify how far is the half power from the minimum power, being the logic level "0" equal to zero. ITU-T defined this parameter in the recommendation G.957, designated by extinction ratio R_{ext}.

The extinction ratio influences the receiver sensitivity because the power emitted during 0 bits due to spontaneous emission can be a significant fraction, detailed moreover in Section 2.4.1. The mean power of the logic level "0" and "1" being respectively P_0 and P_1. The extinction ratio is given by the Equation *(2.3)* [9]. Note that for simplification normally r_{ext} is represented as $r = 1/r_{ext}$, and by the ITU-T Rec. G.957 the minimum value for the extinction ration is $R_{ext} = 8.2[dB]$or r_{ext}=6.6.

$$r_{ext} = \frac{p_{1_{[W]}}}{p_{0_{[W]}}} \tag{2.3}$$

The emitted power of the light source is one of the influential parameter. This parameter can be limited by nonlinear effects and other parameters. However, the maximum power can be limited also by cost efficiency, since the more power the system emits the more expensive will be to maintain it. However, if not enough power is used to compensate for all the attenuations of the system, the receiver might not receive a detectable signal. This parameter can be measured and is the receiver sensitivity, this issue will be discussed further in Section 2.4. Another influential parameter of the optical transmitter is the root mean square width of the source spectrum σ_λ $[m]$. In a normal distribution, the full width at half maximum or Δv is given by the Equation *(2.4)* [16].

$$\sigma_\lambda = \frac{\Delta\lambda}{2\sqrt{2 \cdot \ln(2)}} \tag{2.4}$$

The linewidth $\Delta\lambda$ in $[m]$, can be determined with the Equation *(2.5)*, where the nominal wavelength is represented by λ_0, speed of light in vacuum c and linewidth of the laser Δv in $[Hz]$.

$$\Delta\lambda = \frac{\Delta v \cdot c}{{\lambda_0}^2} \tag{2.5}$$

However, if the linewidth of the transmitter is small, normally smaller than $\Delta\lambda\ << 1\ [nm]$, then the root mean square width of the source spectrum will not depend on the linewidth of the transmitter laser. The maximum linewidth will be determined with the signal's bit rate, thus, in order to determine the linewidth used in Equation *(2.4)* the maximum linewidth calculated with Equation (*2.6*) is used instead, where the parameter B is the bit-rate of the system.

$$\Delta\lambda_M = \frac{B}{{\lambda_0}^2} c \tag{2.6}$$

The transmitter also sets the number of channels using wavelength-division multiplexing technique, where WDM multiple signals can be carried through a single fibre using different wavelengths. With more than one channel there will be crosstalk produced in the filters that are analysed in Section 2.6. The frequency for each channel is determined by the Equation *(2.7)*, the parameters in this equation are the frequency of n[th] channel v_n, the frequency of the first channel v_1 and channel spacing Δv_{ch}.

$$v_n = v_1 + (n-1)\Delta v_{ch} \tag{2.7}$$

The channel spacing is the gap between two neighbouring frequency, the space between two signals can lead to crosstalk if the space is not big enough, moreover in Section 2.6.1. There are also power penalties that the system will have to take into account directly related with the optical transmitter. This power penalties are related with the mode-partition noise and relative intensity noise, moreover Section 2.7

2.3 Optical Fibre

The optical fibre is the communication channel of a fibre optical telecommunications system, the optical fibre is made, in most cases, of two layers of a transparent material that can be either plastic or glass. The reason for it, they have the lowest attenuation per kilometre with the capability to transmit optical signals. The two layer are set within another to form an inner core and an outer cladding that can be observed in Figure 2.1. The transmission can be achieved within the fibre by transmitting light through the inner core and reflecting it through the fibre. This phenomenon is achieved by transmitting the optical signal throughout the fibre and propagating it due to the inner core having a refractive index n_1 that is higher than the refractive index of the cladding n_2 represented in Figure 2.1. The Snell's law, Equation *(2.8)*, is the principle behind the refraction within the fibre, where $\emptyset_1$ and $\emptyset_2$ are the angle of incidence and refraction, respectively. With this principle, it is possible to predict the total internal reflection in the core of the fibre. The total internal reflection is the phenomenon that provides the propagation of the light through the fibre.

$$n_1 \sin(\emptyset_1) = n_2 \sin(\emptyset_2) \tag{2.8}$$

Normally optical fibres are exclusively made of glass, mainly silica (SiO_2). However, normally the silica fibres are not pure silica, since pure silica fibres are usually not suitable for most fibre optical telecommunications systems, so some dopants are added such as GeO_2 and P_2O_5. Even with low attenuation per kilometre, the optical fibre is the main source of attenuation in a fibre optic communication discussed in Section 2.3.3. Also, presents performance limitations of a fibre optical telecommunications system with fibre dispersion by broadening optical pulses inside the fibre discussed in Section 2.3.4. For means of simplification, the simulator also has the attenuation generated by the connectors and splices, which are devices used to connect the fibres with connectors and the fibre with the other devices with splices. This attenuation will be inserted with fibre losses in Section 2.3.3.

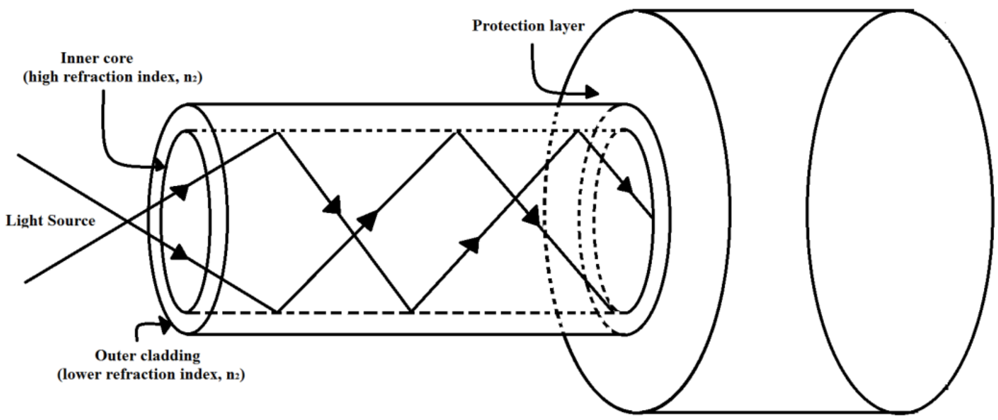

Figure 2.1 Optical fibre structure, adapted from [16]

There are many types of fibres currently in use, their functions can go from submarine cables as shown in Figure 1.3, aerial suspended on poles and long-haul applications. Following the ITU-T recommendations, which is the global standardisation organisation for telecommunication systems. In this project only two types of optical fibres were used. The nondispersion-shifted fibre (NDSF) also known as the standard single-mode optical fibre (SMF) and the non-zero dispersion-shifted fibre (NZDSF), also referred as ITU-T G.652 and ITU-T G.655 respectively. These types of fibres were designed to overcome different problems within fibre optical telecommunications system and are explained in the following sections. Although, these two types of fibres were the only ones introduced this means that they were the only ones with already inserted standard values, following an example for each fibre. However, the users can always customise each block to replicate another type of fibre.

There are also some other important parameters of the fibre that are related to nonlinear effects that will be analysed in Section 2.3.5. The parameters that will directly influence the nonlinear effects are the effective core area of the fibre $A_{eff} = \pi w^2$. Where the w is the field radius also referred as spot size. The effective core area determines how tightly the light is constrained within the core. It will affect directly the nonlinear effects in the transmission, by restraining the power in the system for a smaller effective core area.

2.3.1 Nondispersion-shifted fibre (ITU-T G.652)

The standard *ITU*-T G.652 is the most used optical fibre in a telecommunications system. This type of fibre optimised to work with wavelengths in the $1310\ [nm]$ band, which comes from having its zero-dispersion wavelength at $1310\ [nm]$ [18]. The zero-dispersion wavelength is where the material dispersion and waveguide dispersion cancel each other. Although this type of fibre is optimized to work in with wavelengths in the $1310\ [nm]$ band, it can also operate in the wavelengths in the $1550\ [nm]$ band. A typical attenuation parameter for this type of fibre is $0.2dB/km$ and a chromatic dispersion at $17ps/nm/km$ at $1550\ nm$.

In this project, there is a possibility to introduce the attenuation of the fibre if the user wants to use a specific value. However, if no value is introduced the simulator will use the values of a standard Corning SMF-28 fibre that is a ITU-T G.652 taken from its datasheet [19].

2.3.2 Non-zero dispersion-shifted fibre (ITU-T G.655)

The limiting factor for a fibre link in long-haul systems is the fibre dispersion. The limiting factor is not the power since the use of amplifiers to keep the power of the signal throughout the system. However, the amplifier noise often forces the need to increase the channel power in order to keep a high OSNR. Ultimately this increases the accumulation of the nonlinear effects of the fibre ends up limiting the length of the system. So, the need to develop a type of fibre such as NZDSF that mitigates these nonlinear characteristics was necessary. This type of fibre surpasses these effects by having a bigger effective core area A_{eff}, that is demonstrated in Section 2.3.5, which will diminish the restrictions from the nonlinear effects. Also, the zero-dispersion wavelength is outside of the $1550\ [nm]$ band. The ITU-T G.655 achieves a small chromatic dispersion at $1550\ [nm]$, usually at $4.5ps/nm/km$ and the attenuation parameter usually at $0.2dB/km$.

The fibre ITU-T G.655 is divided into two families which the values for the chromatic dispersion drop before or after $1550\ [nm]$, which are called NZD+ and NZD- respectively. In this project, there is also a possibility to introduce the attenuation of the fibre NZDSF if the user wants to use a specific value. However, if no value is introduced the simulator will use the values of a standard Corning LEAF fibre that is a ITU-T G.652 taken from its datasheet [20]. With the information taken from the datasheet, Figure 2.2 was reconstructed and inserted in the simulator for a standard ITU-T G.652 fibre.

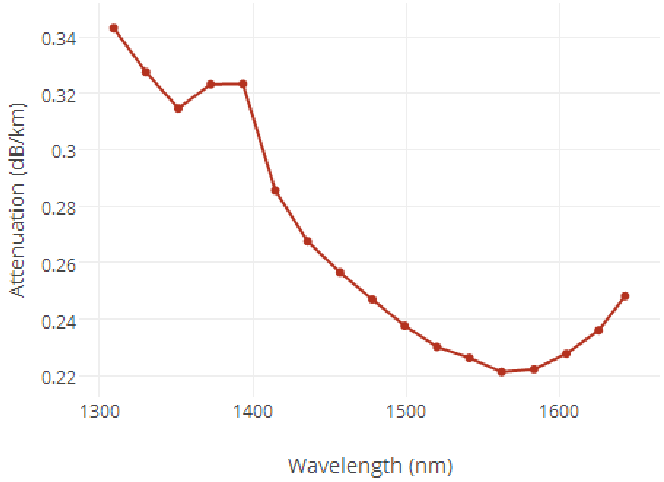

Figure 2.2 Variation of the attenuation of the through the wavelength of Corning LEAF fibre [20]

2.3.3 Fibre Losses

The fibre losses reduce the power of the signal reaching the receiver, this attenuation $A_T[dB]$ can be measured with the attenuation coefficient $\alpha\ [dB/km]$ that takes into account the material absorption and other sources of power attenuation in the fibre. This parameter can also be represented in Neper per kilometre $\alpha_n\ [Np/km]$, and it can be converted with the Equation (2.9) [16] .

$$\alpha_{[dB/km]} = 4.343 \alpha_{n_{[Np/km]}} \qquad (2.9)$$

The attenuation coefficient changes with the signal wavelength, as showed in the Figure 2.2 [20]. Another power reduction parameter is the attenuation from splices and connectors of the fibre, A_S and A_C respectively, this splices and connectors are necessary to form the fibre link. With Equation (2.10) [15], the fibre losses or attenuation of the fibre can be calculated, where L_{Total} stands for the total length of the fibre in $[km]$, N_S to the number of splices in the link and N_C the number of connectors.

$$A_T = \alpha \cdot L_{Total} + N_S \cdot A_S + N_C \cdot A_C \qquad (2.10)$$

2.3.4 Fibre Dispersion

The fibre dispersion also known as chromatic dispersion causes pulse broadening. Thus, the spectral components of the pulse travel at slightly different group velocities. By the pulses travelling at different velocities will result in intersymbol interference between the receiving pulses increasing the bit errors at the receiver, represented in Figure 2.3.

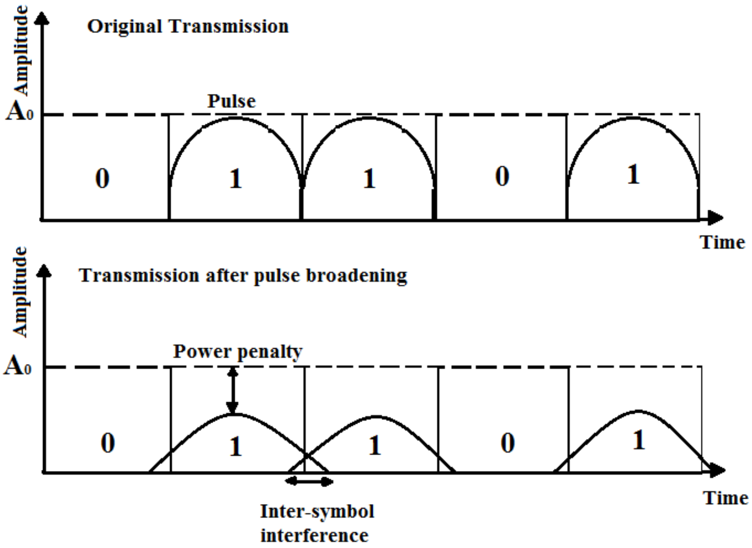

Figure 2.3 Representation of pulse broadening in the fibre link, adapted from [12]

The fibre dispersion is divided into two types of dispersion material dispersion and waveguide dispersion. Material dispersion results from the variation of the inner core refractive index with the wavelength. Waveguide dispersion results from some of the optical power, inserted in a SMF, escaping from the inner core and keep propagating in the cladding. This optical power travels at faster speeds than the inner core resulting in pulse broadening. The both types of dispersion are considered in the Equation (2.11) [16] referring to the fibre chromatic dispersion.

$$D_\lambda = D_r + S_r \cdot (\lambda - \lambda_0) \tag{2.11}$$

In Equation (2.11) the parameters are the central wavelength λ_0, the wavelength of the signal λ, the dispersion slope since S_r and the dispersion parameter D_r. The dispersion parameter D_r $[ps/(km \cdot nm)]$ can be calculated with the Equation (2.12) [9], where the speed of light in vacuum is represented by c and β_2 represents group velocity dispersion parameter.

$$D_r = -\frac{2\pi \cdot c \cdot \beta_2}{\lambda^2} \tag{2.12}$$

The parameter S_r is the differential-dispersion parameter or dispersion slope since $S_r = dD/d\lambda$ resulting in the Equation (2.13) [9], with β_3 representing the third-order dispersion parameter.

$$S_r = \left(\frac{2\pi \cdot c}{\lambda^2}\right)^2 \cdot \beta_3 + \left(\frac{4\pi \cdot c}{\lambda^3}\right) \cdot \beta_2 \tag{2.13}$$

2.3.5 Nonlinear Effects

The assumption that is made by despising the nonlinear effects is that within the optical fibre the optical signals will not interact with each other. Also, it is assumed that these properties do not directly affect directly the optical signal power transmitted to the fibre. Although in NZDSF fibres there were improvements in order to have the smallest the nonlinear coefficient as possible, these effects cannot be despised when planning a fibre optic telecommunication system. Also, if the systems contain optical amplifiers, nonlinear effects may accumulate over long distances, due to the nonlinear effects dependence on the fibre length. However, most nonlinear effects occur early in the fibre since in longer ranges the signal will be attenuated. The nonlinear effects are divided into two types stimulated light scattering and nonlinear phase modulation.

2.3.5.1 Stimulated Light Scattering

The stimulated light scattering is divided into two types stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS), these effects are explained in the following sections.

Stimulated Brillouin scattering

The acoustic vibration in the optical fibre will interact with the light signal, transmitted in the fibre, causing a nonlinear effect called stimulated Brillouin scattering. This effect causes the down-conversion of the light signal, causing the appearance of phonons from the released energy. Phonons are the collective excitation of atoms that form the fibre, this phenomenon will cause an acoustical pressure wave, referred to as electrostriction, which travels through the fibre at the speed of sound following the same direction of the light signal. The propagation of the electrostriction will periodically change the refractive index of the fibre since it depends on the density of the fibre, with the biggest influence being the variation in the core diameter. This nonlinear effect will affect the maximum threshold power that can be determined by the Equation *(2.14)* [9].

$$P_{th} \approx \frac{21 \cdot A_{eff}}{g_B \cdot L_{eff}} \tag{2.14}$$

With the Equation *(2.14),* it can be observed that this constraint due to SBS will be affected by the fibre dimensions with the effective core area A_{eff}, the SBS gain $g_B \approx 5 \times 10^{-11} [m/W]$ for silica fibres and the effective interaction length L_{eff} that can be calculated with the Equation *(2.15)* [9].

$$L_{eff} = \frac{1 - \exp(-\alpha L)}{\alpha} \tag{2.15}$$

Stimulated Raman scattering

The photons of a light signal transmit simultaneously through the fibre if a light signal has a lower energy and frequency can be stimulated by another light signal with higher frequency and energy. This phenomenon can result in the nonlinear scattering of light photons, this effect is called stimulated scattering effect. This effect causes the downshifting of the frequency, causing the appearance of phonons from the released energy, phonons as it was referred in the previous section are the collective excitation of atoms that form the fibre, this phenomenon will shift the frequency of an amount equal to the molecular vibration frequency also called Stokes shift. The effect of SRS in a fibre optic telecommunications system is the reduction of maximum threshold power inserted in the fibre. The maximum threshold power limited by the SRS can be determined with the Equation *(2.16*) [9], where the SRS gain $g_R \approx 6\times10^{-13}[m/W]$ at $1550\ [nm]$.

$$P_{th} \approx \frac{16 \cdot A_{eff}}{g_R \cdot L_{eff}} \tag{2.16}$$

2.3.5.2 Nonlinear phase modulation

The nonlinear phase modulation is divided into three types: four-wave mixing (FWM), self-phase modulation (SPM) and cross-phase modulation (XPM). These effects are explained in the following sections.

Self-phase modulation

By applying a light source to a material an electric field is created, and it will cause variations in the refraction index of that material, this phenomenon is called Kerr electro-optic effect. These variations in the refraction index of the fibre will result in variations in the phase of the light, this effect is called self-phase modulation. The Kerr effect varies with the square of the electric field. Thus, reducing the transmission power, the electric field will be reduced as well. First and foremost, the nonlinear parameter must be determined resorting to the Equation *(2.17*) [9], where $n_2\ [m^2/W]$ is the numerical value related to dopants inside the core of silica fibres.

$$\gamma = \frac{2\pi n_2^2}{\lambda \cdot A_{eff}} \tag{2.17}$$

The important part to observe in Equation *(2.17*) is that the nonlinear parameter directly related with A_{eff}. Once again proving that NZDSF fibres have a bigger A_{eff} will decrease the nonlinear effects. Also, it fluctuates with the wavelength of the signal λ.The Phase shift produced by SPM is given by the Equation *(2.18*) [9].

$$\phi_{NL} = \gamma \cdot P_{in} \cdot L_{eff} \tag{2.18}$$

In order to reduce the impact of SPM from the phase shift must be $\phi_{NL} \ll 1$. Thus, the value maximum accepted value for the phase shift was considered $\phi_{NL} = 0.1$. Solving the Equation *(2.18*) in order of P_{in} the maximum power that can be inserted in the fibre can be determined with the Equation *(2.19*), where N_A is the number of amplifiers, since the phase shift will accumulate over multiple amplifiers.

$$P_{in} < \frac{0.1}{\gamma \cdot L_{eff} \cdot N_A} \tag{2.19}$$

Cross-phase modulation

The crosstalk generated in WDM technique also creates a variation of the transmitted power in the fibre. Thus, the crosstalk power insertion with a WDM system will induce limitations of the insertion power in the fibre. Since the nonlinear shift it not only depends on a specified channel but also on the power of other channels. This variation in the phase shift can be determined by the Equation *(2.20*) [9] for the jth channel.

$$\phi_j^{NL} = \gamma \cdot L_{eff} \cdot \left(P_j + 2 \sum_{m \neq j} P_m \right) \tag{2.20}$$

In order to get the maximum value for P_j, as in SPM, the value for the phase shift must be $\phi_{NL} = 0.1$. Thus, by solving the Equation *(2.20*) in order of P_j the Equation *(2.21)* is obtained.

$$P_j < \frac{0.1}{\gamma \cdot L_{eff} \cdot N_A} - 2 \sum_{m \neq j} P_m \tag{2.21}$$

Four-wave mixing

In a link with WDM, channels with different wavelengths can mix forming a new wave with a different frequency. This effect is known as four-wave mixing, in order to prevent this effect from occurring the signal power is limited. This effect is one of the major significant degrading effects in WDM in a fibre optic telecommunications system. However, the limitation factor needs some parameters that imply the use of the real simulation of the signal. Thus, due to the complexity of implementing this nonlinear effect, this effect was not implemented in the program.

2.4 Optical Receiver

The optical receiver is the opposite end of the optical transmitter line, the function of an optical receiver is to detect the optical signal and converting it into an electrical signal, by interpreting the information received from the optical signal. The detection of the optical signal is possible due to a photodetector inserted within the optical receiver. The photodetector is converting the detected light that shines upon him, into an electrical signal. The two main types of photodiodes used are an avalanche photodiode and a *p-i-n* photodiode.

The difference between the APD and PIN receiver is that the APD receiver has an amplification of the signal M_{APD} within the receiver. However, in PIN receiver normally the same parameter is usually $M_{pin} = 1$, which means that there is no amplification of the signal. This will result in the APD receiver having an extra noise factor F_A in comparison with the PIN receiver, but APD receivers supporting less power at the end of the photodetector since the signal is amplified after the optical to electrical signal conversion. Although this can be proved to result in a better communication, for this reason both solutions are presented to the user in the simulation.

The ability to detect the optical signal received from the optical receiver can be measured, this parameter is called receiver sensitivity. The receiver sensitivity is a very important parameter since if the optical power that reaches the optical receiver is lower than the receiver sensitivity. The optical receiver will not detect it, moreover in the following sections. Another parameter that of the receiver that should be taken into account in a fibre optic telecommunication system is the overload power of the receiver. This parameter differs from each receiver and is normally presented in the datasheet of the receivers, if the received power surpasses this parameter the receiver can get permanent damage.

2.4.1 Receiver Sensitivity

The sensitivity of a receiver is the minimum input signal of the receiver. In order to determine the receiver sensitivity, the BER required by the receiver must be determined. The BER is defined as the probability of bit errors per time unit, the number of bit errors is the number of bits received that have been altered due to distortion, interference and noise. The receiver sensitivity in order to operate at a specified probability of BER requires a minimum average received power $\overline{P_i}$. Since, the bit misinterpretation corresponding to "1" or "0" in a bit stream can be both included by defining the error probability as the Equation (2.22) [9].

$$BER = p(1)P\left(\frac{0}{1}\right) + p(0)P\left(\frac{1}{0}\right) \tag{2.22}$$

The bits with the logical level "1" and "0" have the same probability to occur so $p(1) = p(0) = 0.5$ and the BER probability can be determined with Equation (2.23) [9] that depends only on the Q parameter. The parameter Q is the ration between a signal current mean difference and a total noise current drift pattern.

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{2.23}$$

Noting that in the Equation (2.23) $erfc$ stands for the complementary error function that is given by the Equation *(2.24)*.

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-y^2} dy \tag{2.24}$$

Solving the equation in order to the parameter Q the Equation (2.23), since there is a requirement to have specific BER in order to maintain reliable simulation, the Equation *(2.25)* is obtained.

$$Q = \sqrt{2} \cdot erfc^{-1}(2 \cdot BER) \tag{2.25}$$

With the parameter Q the required minimum average received power $\overline{p_i}$ can be obtain for a given value of Q since both equations are correlated with the Equation *(2.26)* [9], where σ_S is the shot-noise, σ_T is the thermal noise, M is the gain of the receiver and R the responsivity of the receiver.

$$Q = \frac{2 \cdot M \cdot R \cdot \overline{p_i}}{\sqrt{{\sigma_S}^2 + {\sigma_T}^2} + \sigma_T} \tag{2.26}$$

The thermal noise and the shot noise cause fluctuations in the current. The shot noise is generated by the fact that the electrical current in the receiver is a stream of electrons that is generated at random times. The thermal noise occurs due to the fluctuations of current generated by a random thermal motion of electrons in a resistor. This noise is equal for the APD and PIN receivers. On the contrary, the shot-noise only affects ADP receivers since the PIN receivers normally do not have a gain. The shot-noise can be determined with the Equation *(2.27)* [9].

$$\sigma_S = \sqrt{(2 \cdot \overline{p_\iota}) \cdot 2 \cdot R \cdot q \cdot F_A \cdot \Delta f \cdot M^2} \tag{2.27}$$

With the Equation *(2.26)* and *(2.27)* resolving in order of $\overline{p_\iota}$ then Equation *(2.28)* [9] is obtained. This formula is the receiver sensitivity for whether PIN receivers and APD receivers.

$$\overline{p_\iota} = \frac{Q}{R}\left(q \cdot F_A \cdot Q \cdot \Delta f + \frac{\sigma_T}{M}\right) \tag{2.28}$$

In order to solve Equation *(2.28)*, there is a need to determine some parameters such the responsivity of the receiver R. The responsivity of the receiver is the ratio between the output current of the photodetector and the optical power received, this parameter is sometimes characterized as the performance of the receiver. This parameter can be determines with the Equation *(2.29)* [9], this equation can be determined knowing the elementary charge $q[C]$, the quantum efficiency of the receiver η that can take values from $[0,1]$, the Planck's constant $h[J \cdot s]$ and the frequency of the optical signal $v\ [Hz]$, that can be determined with the Equation *(2.1)*.

$$R = \frac{q \cdot \eta}{h \cdot v} \tag{2.29}$$

Another parameter needed to determine the Equation *(2.28)*, is the excess noise factor F_A that can be calculated with the Equation *(2.30)* [9], where k_A is the ionization-coefficient ratio and M is the gain of the receiver, these parameters depend on the type of receiver if it is an APD or a PIN receiver.

$$F_A = k_A \cdot M + (1 - k_A) \cdot \left(2 - \frac{1}{M}\right) \tag{2.30}$$

Normally in PIN receivers $M_{pin} = 1$ and $k_{A_{pin}} = 0$ resulting in the $F_{A_{pin}} = 1$. On the other hand, the ionization-coefficient ratio for APD receiver is higher being in the range $0 < k_A < 1$ and the gain of the receiver for APD is also higher enhancing the signal that should improve the SNR. The gain of the APD receiver M_{APD} is given by the Equation *(2.31)* [9] and should be at least $M_{APD} > 10$.

$$M_{APD} = \frac{1}{\sqrt{k_A}} \cdot \sqrt{\frac{\sigma_T}{Q \cdot q \cdot \Delta f} + k_A - 1} \tag{2.31}$$

In order to determine if the PIN receiver or the APD receiver is better for the optical communication in study, the simulator will evaluate which receiver has the biggest sensitivity $\overline{P_\iota}$. The best receiver will be the one that has the lowest $\overline{P_\iota}$ because the minimum average received power for specified value will require less value for the same performance. Also, a lower $\overline{P_\iota}$ will provide a lower optical signal to noise ratio, moreover Section 2.8.

The thermal noise or Johnson-Nyquist noise σ_T , in the Equation *(2.32)* [9], is the noise generated by the thermal motion of electrons inside conductors. The formula used to determine this noise can be determined by considering the room temperature $T = 290\,K$; the Boltzmann constant k_B $[J/K]$; the resistor $R_L = 1k\Omega$ and the amplifier noise figure f_n is in linear and not in [*dB]*.

$$\sigma_T = \sqrt{\frac{4k_BT}{R_L} f_n \Delta f} \tag{2.32}$$

The last parameter that was not presented so far to solve Equation *(2.32)*, is the effective noise bandwidth of the receiver Δf. This parameter depends on the receiver design. However, in this simulator the standard value of this parameter was determined in Equation *(2.33)*.

$$\Delta f = 0.7 \cdot B \tag{2.33}$$

The amplifier noise figure f_n in case the connection has several amplifiers can be determined with the Equation *(2.34)* [9], this equation follows the *Friis* formula, where f_{n_i} is the linear noise figure of the amplifier i, and g_{i-1} is the linear gain of the amplifier $i-1$.

$$f_n = f_{n_1} + \frac{f_{n_2} - 1}{g_1} + \frac{f_{n_3} - 1}{g_1 \cdot g_2} + \frac{f_{n_4} - 1}{g_1 \cdot g_2 \cdot g_3} + \cdots + \frac{f_{n_i} - 1}{g_1 \cdot g_2 \cdot g_3 \cdot \ldots \cdot g_{i-1}} \tag{2.34}$$

2.4.2 Receiver Sensitivity with Preamplification

In a fibre optical telecommunication system, the amplifier can be inserted anywhere between the optical transmitter and the optical receiver. One technique when using amplification in the fibre is positioning the optical amplifier before the optical receiver is preamplification, demonstrated in Figure 2.4. This technic can have significant improvements in the system by improving the optical signal to noise ratio. This issue is further discussed in Section 2.8. The use of preamplification improves the sensitivity of the optical receiver, this improvement comes from the amplification of the signal before reaching the receiver. However, the thermal noise becomes negligible comparing it to the noise induced by the preamplifier.

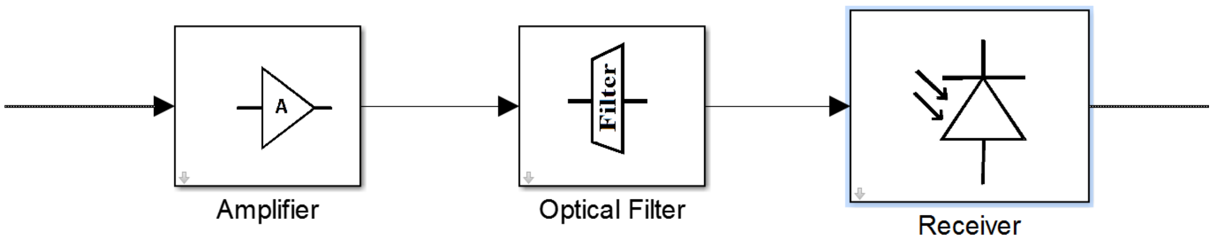

Figure 2.4 Demonstration of Preamplification technic

With this technique, the use of an optical filter is imperative in order to reduce some of the amplifier noise. Since, a phenomenon called amplified spontaneous emission (ASE) occurs in the amplifier, further discussion of this issue in Section 2.5, an optical filter is used between them, in order to minimise the noise induced by the optical amplifier, as it can be observed in Figure 2.4. The sensitivity of the receiver maintains the same definition from Section 2.4.1. However, the equation to determine it is changed due to the predominant noise factor with preamplification ceases to be the thermal noise and becomes the noise induced by the preamplifier. This change can be observed with the Equation*(2.35*) [9] that is used to determine the receiver sensitivity using this technique.

$$\overline{p_i} = h \cdot v \cdot F_n \cdot \Delta f \cdot Q \left(F_A \cdot Q \cdot + \frac{\sqrt{\frac{\Delta v_{opt}}{\Delta f}}}{M} \right) \tag{2.35}$$

In order to determine the Equation *(2.35*), the only parameter that has not been presented yet is the bandwidth of the optical filter Δv_{opt}, if a filter is not used than Δv_{opt} will be the bandwidth of the amplifier.

2.4.3 Sensitivity Degradation

The sensitivity of the receiver in Section 2.4.1 only takes into account the receiver noise, if the optical signal received is an ideal stream such as optical pulse with a constant energy for 1 bits and no energy for 0 bits. For a realistic optical signal, the noise added at optical amplifiers per example and degradation through the fibre link results in the minimum average optical power required $\overline{p_i}$ increasing.

Degradation of the sensitivity due to the extinction ratio

In most transmitters, some power is still emitted by 0 bits, this means that they still emit some power in their off state. In the case of semiconductor lasers, the ratio between the off-state power P_0 and the on-state power P_1 is called extinction ratio R_{ext}. The R_{ext} can influence the receiver sensitivity, because of its relation with the power emitted during 0 bits, as it was referred in Section 2.2. This phenomenon degrades the receiver sensitivity, by analysing the definition proposed by ITU-T Rec. G.957 it is possible to determined that the optimal extinction ratio is $r_{ext} = \infty$. This optimal extinction ratio will generate the lowest sensitivity degradation. This is also possible to be verified by combining the definition of the mean receiver sensitivity, given by Equation *(2.36)* [9] and Equation *(2.3)*.

$$\overline{p_i} = \frac{(p_0 + p_1)}{2} \tag{2.36}$$

On the other hand, as it was discussed in Section 2.4 it is also given by Equation *(2.26)* resulting in the Equation *(2.38)* when combining the Equations *(2.37)* and *(2.36)*.

$$Q_{ex} = \frac{(1-r)}{(1+r)} \frac{2 \cdot M \cdot R \cdot \overline{p_\iota}}{\sqrt{{\sigma_S}^2 + {\sigma_T}^2} + \sigma_T} \tag{2.38}$$

It can be observed that the sensitivity generated with extinction ratio Equation *(2.28)* will be different than in the Equation *(2.38)* if $r > 0$. Resolving the Equation *(2.38)* in order of $\overline{p_\iota}$ the Equation *(2.39)*is obtained.

$$\overline{p_\iota}_{ex} = \frac{(1+r)}{(1-r)} \left(q \cdot F_A \cdot Q \cdot \Delta f + \frac{\sigma_T}{M} \right) \tag{2.39}$$

The power penalty induced by the extinction ratio is given by the ratio between $\overline{p_\iota}_{ex}$ and $\overline{p_\iota}$ represented in the Equation *(2.40)*.

$$\delta_{ex} = 10 \cdot log_{10} \left(\frac{\overline{p_\iota}_{ex}}{\overline{p_\iota}} \right) \tag{2.40}$$

However, since the formulas are similar, the only difference is the extinction ratio that can also be simplified using the Equation *(2.41)*. So, analysing the equation is possible to confirm that the optimal extinction ratio is $r_{ext} = \infty$, resulting in $\delta_{ex} = 0[dB]$ having no degradation to the sensitivity whatsoever.

$$\delta_{ex} = 10 \cdot log_{10} \left(\frac{(1+r)}{(1-r)} \right) \tag{2.41}$$

Degradation of the sensitivity due to the Timing Jitter

One of the assumptions of Section 2.4.1 is that the sample of the signal is at the peak of the voltage pulse. However, the sample is determined by the clock-recovery circuit since the input for this circuit comes from a noisy nature it results in a fluctuation. This phenomenon is called timing jitter and it ultimately causes a degradation in the receiver sensitivity. The degradation caused by the timing jitter to the receiver sensitivity can be determined by the Equation *(2.42)* [9].

$$\delta_j = 10 \cdot log_{10} \left(\frac{1 - b/2}{(1 - b/2)^2 - Q^2 b^2/2} \right) \tag{2.42}$$

In the Equation *(2.42)* the parameter Q can be determined with the Equation *(2.26)* and the constant b can be determined with the Equation *(2.43)* [9].

$$b = \left(\frac{4\pi^2}{3} - 8 \right) \cdot \left(B \cdot \tau_j \right)^2 \tag{2.43}$$

The parameters in the Equation *(2.43)* are B that stands for the bit-rate of the system and τ_j is the root-mean-square value of the timing jitter.

Degradation of the sensitivity due to the Intensity Noise

The light emitted by a transmitter has power fluctuations, these fluctuations are referred as intensity noise. These fluctuations cause a variation in the signal power and in order to take into account this phenomenon in the system, a degradation of the sensitivity s taken into account. This degradation can be determined by the Equation *(2.44)* [9].

$$\delta_I = -10 \cdot log_{10}(1 - {r_I}^2 Q^2) \tag{2.44}$$

The parameters from the Equation *(2.44)* are the parameter Q from the Equation *(2.26)* and the parameter for the intensity noise r_I. This particular parameter can be determined with the Equation *(2.45)* [9].

$${r_I}^2 = 2 \cdot RIN \cdot \Delta f \tag{2.45}$$

The parameters in the Equation *(2.45)* are RIN that stands for the relative intensity noise, and varies between optical transmitters and Δf that stands for the receiver bandwidth.

2.5 Optical Amplifier

The Optical Amplifier is a device that is commonly used in fibre optic communications in order to amplify the optical signal without converting it to an electrical signal. The optical amplifier is used due to the losses in the fibre, this attenuation of the signal results in a signal power that cannot be detected by the receiver without some amplification of the signal. The placement of an optical amplifier is crucial in the system in order to boost the signal. It is regularly placed before a device with large losses or in order to boost the signal before the optical receiver. Despite the insertion of noise, it can ultimately improve the optical signal to noise ratio.

The amplification of the optical signal is obtained through the emission of photons from dopant ions from a beam of light into a doped fibre within the optical amplifier, a representation in Figure 2.5. This type of amplifier is called doped fibre amplifier (DFA) and the most used type of DFA is an erbium-doped waveguide amplifier (EDFA). The only other competitor to an EDFA is a Raman amplifier. The Raman amplifier is more expensive and has less gain than an EDFA. Still, the EDFA continues to be the preferred amplifier type in the marked.

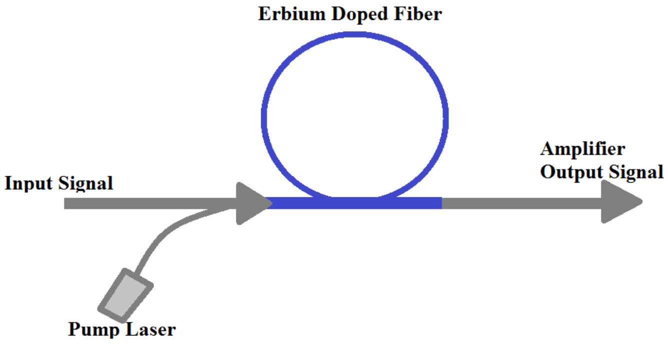

Figure 2.5 The composition of a standard EDFA, adapted from [16]

In a fibre optic communication an amplifier can be an optical amplifier or electrical amplifier, the most common are optical amplifiers and were the ones implemented in this simulator. The use of an electrical amplifier would be in order to amplify the signal after the receiver, which means that after the conversion of the signal from optical to electrical.

2.5.1 Amplifier Noise

The use of optical amplifier also brings noise to the system. Most of this noise comes from ASE. This phenomenon degrades the OSNR by inducing fluctuations in the amplitude of the signal while adding timing jitter generated through fluctuations in the frequency. The amplifier noise generated by ASE P_{ASE} can be determined with the Equation *(2.46)* [16].

$$p_{ASE} = 2 \cdot f_n \cdot (g - 1) \cdot h \cdot v_0 \cdot B_0 \tag{2.46}$$

The parameters from Equation *(2.46)* are: amplifier noise figure f_n , amplifier gain g, Plack's constant h, central frequency v_0, and the bandwidth of the amplifier B_0. The central frequency can be determined with central wavelength and with Equation *(2.1)*. Note that the noise from the system until reaching the amplifier is amplified. Then the amplifier noise will be added to the noise that is already in the system, thus, the amplifier noise presented in this section takes in to account only the noise added by the amplifier in question.

2.5.2 Amplifier Gain

The amplifier gain G [dB] is the amplification to the signal given by the optical amplifier. The expression reverting to this gain is the Equation *(2.47)*, the power received by the amplifier $P_{in_{amplifier}}$[dBm] will have an amplification G [dB]. Thus, the emitted power from the amplifier $P_{out_{amplifier}}$[dBm] can be calculated with the Equation *(2.47)*.

$$P_{out_{amplifier}} = P_{in_{amplifier}} + G \tag{2.47}$$

2.5.3 Amplifier Gain Saturation

The amplification of the optical signal showed some limitations. Firstly, the amplifier gain in Section 2.5.2 does not take into account that the gain is reduced if the power received by the amplifier is comparable to the power saturation of the amplifier $P_{sat_{amplifier}}$. Secondly, the optical amplifier cannot be amplified the signal over the saturation power, this limitation will cause a phenomenon called Gain Saturation. The amplifier gain will diminish as the signal power received $P_{in_{amplifier}}$ by the amplifier converges to the saturation power. The gain saturation can be observed in Figure 2.6 for a gain G_0 at 30 [dB].

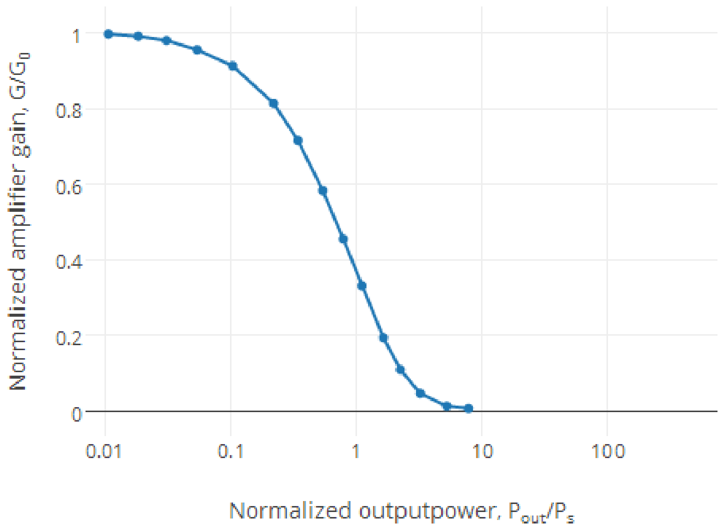

Figure 2.6 Saturated amplifier gain G as a function of the output power (normalised to the saturation power) for gain G_0 at 30 [dB].

If the signal power received is equal or even more than the saturation power, the gain of the optical amplifier will be zero. This saturation of the amplifier's gain can be determined by the Equation *(2.48)* [9], in which $p_{out_{amplifier}}$ is the power emitted by the amplifier in Wats, g_0 stands for the amplifier gain and g is for the true amplifier gain or saturated gain.

$$g = g_0 exp\left(-\frac{g-1}{g}\frac{p_{out_{amplifier}}}{p_{sat_{amplifier}}}\right) \tag{2.48}$$

Note that in the Equation *(2.48)* the parameters are in lower case since they are not in decibels. Usually, the gain of the amplifier is presented in $[\mathrm{dB}]$, in order to convert it from $[\mathrm{W}]$ to $[\mathrm{dB}]$ the Equation *(2.49)* is used.

$$G = 10 \cdot \log_{10}(g) \tag{2.49}$$

2.6 Optical Filter

The use of many channels is possible with WDM and with an optical transmitter with the capabilities to emit more than one channel. The optical filter is used to separate and analyse each channel in specified frequency, since every channel has a different wavelength, rejecting other frequencies. The relation between wavelength λ and frequency v is given by the Equation *(2.1)*, where c is the speed of light in vacuum. The optical filter is also used to filter the signal in order to provide less noise, per example by using the preamplification technic, further discussed in Section 2.4.2. The optical filter is able to filter some of the noise caused by the preamplification if the bandwidth of the optical filter Δv_{opt} is lower than the bandwidth of the receiver. The main objective of using an optical filter in this situation is providing less noise reaching a better ONSR at the entrance of the optical receiver. The optical receiver parameters that this simulator takes into account is the bandwidth of the filter and the sum of the filter's transmissivity. The sum of the transmissivity of the filter is the amount of power that is detected by a specific channel from the neighbouring channels.

2.6.1 Crosstalk

When separating the channels, the optical filter can detect some of the power emitted by the adjacent channels if the channel spacing is not big enough. With this phenomenon, the optical filter will add to the signal noise that is referred to as *out-of-band* crosstalk. Note that crosstalk only happens if the transmitted signal is using WDM, more than one channel since the crosstalk is a phenomenon where channels interfere with the detection or transmission of other channels.

Out-of-band

Optical filters often leak a fraction of the signal power from adjacent channels that interfere with the detection process. This type of crosstalk is called *out-of-band* or *heterowavelength* and it can be observed in Figure 2.7. In Figure 2.7 it can be observed that the filter bandwidth ends up detecting some of the adjacent channels power, if the difference between the channel's frequency is not big enough, this can be augmented by applying a bigger channel spacing. By detecting adjacent channels power it ultimately adds a boost to the signal power with more power than the channel originally had. This type of crosstalk can ultimately be avoided if the channels spacing is big enough.

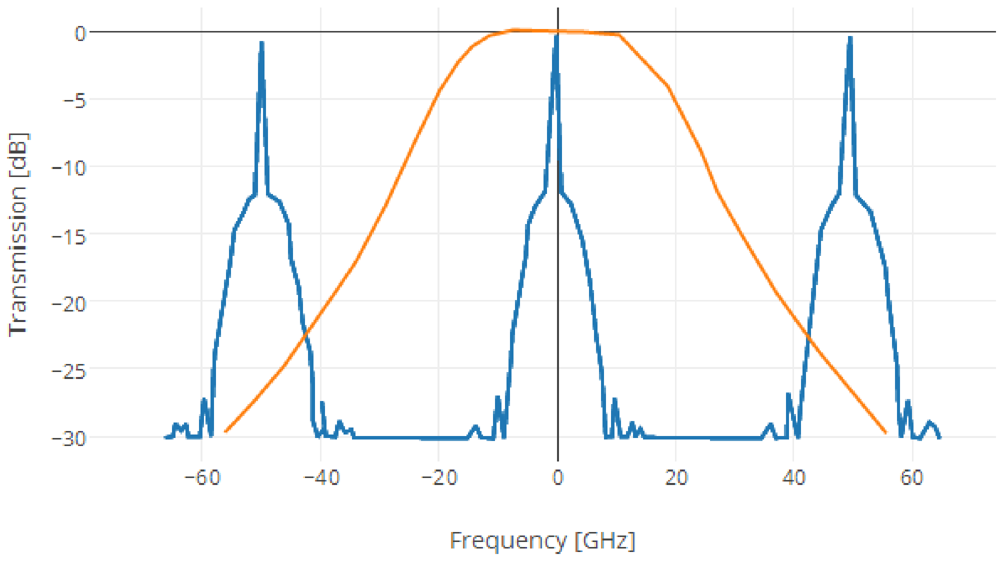

Figure 2.7 Transmissivity of an optical filter with a 40-GHz bandwidth shown detecting other channels on the spectra of three 10-Gb/s channels separated by 50 GHz

So, in order to remove this additional power generated by crosstalk a power penalty needs to be taken into account. This power penalty can be calculated with the Equation (*2.50*) [21], where R_n is the responsivity of the n^th channel, P_n is the power of the n^th channel, T_{mn} is the transmissivity between n^th and m^th channels.

$$\delta_{X_o} = 10 \cdot \log_{10}\left(1 + \frac{\sum_{n \neq m}^{N} R_n P_n T_{mn}}{R_n P_m}\right) \tag{2.50}$$

If the peak power is assumed to be the same for all channels and the responsivity is nearly the same for all channels $R_n \approx R_m$ the Equation (*2.50*) can be approximated by the Equation *(2.51)*, where X is the parameter for the measure of the *out-of-band* crosstalk.

$$\delta_{X_o} \approx 10 \cdot \log_{10}(1 + X) \tag{2.51}$$

The parameter X can be determined through the Equation (*2.52*). This parameter is the fraction of the total power leaked into the detected power for a specific channel in a filter, which means that it is the total out-of-band crosstalk measured by the system.

$$X = \sum_{n \neq m}^{N} T_{mn} \tag{2.52}$$

The transmissivity T_{mn} is the only parameter needed to calculate an approximate value to the power penalty generated by the out-of-band crosstalk that can be determined combining Equations *(2.51)* and (*2.50*). However typical values of X such as 0.01 produce less than $0.1[dB]$ penalty.

In-band

In WDM components the filtering of the different wavelength for the different channels can be incomplete because of partially overlapping transmission peaks. The penalty caused by the *in-band* can be calculated with the Equation *(2.53)*.

$$\delta_{X_i} = -10 \cdot log_{10}(1 - Q^2 {r_X}^2) \tag{2.53}$$

The Equation *(2.53)* can be determined by parameter Q from Equation *(2.26)* and parameter r_X that can be determined with the Equation *(2.54)*.

$${r_X}^2 = X_2(N - 1) \tag{2.54}$$

Note that in the Equation *(2.54)* the parameter X_2 is defined as the Equation *(2.55)* where P_n is the constant or all sources of in-band crosstalk and P_0 is the input peak power.

$$X_2 = \frac{P_n}{P_0} \tag{2.55}$$

In practice $P_n \ll P_0$ because the devices in the fibre such as the waveguide-grading router are built to reduce this kind of crosstalk.

2.7 Power Penalty

In a fibre optical telecommunications system, there are many phenomena that degrade the signal that reaches the receiver. In this section were included the power penalties that this simulator takes into account. The power penalties that were included are the ones that have the biggest effect fibre optical telecommunications system simulation. Note that the power penalty due to chromatic dispersion is divided into two types dispersive pulse broadening and frequency chirping. Thus, the power penalty due to chromatic dispersion is the sum of both power penalties.

2.7.1 Penalty due to Dispersive Pulse Broadening

To avoid the intermodal dispersion and the associated modal noise the use of single-mode fibres for fibre optic communications is recommended since it nearly avoids this problem, but the group-velocity dispersion limits the bit-rate distance product, by broadening optical pulses exceeding its allocated value. The dispersion induced pulse broadening can also be calculated by a power penalty decreasing the receiver sensitivity, that can be calculated with the Equation *(2.56)* [9].

$$\delta_d = -5 \cdot \log_{10}(1 - (4 \cdot B \cdot L_{Total} \cdot D \cdot \sigma_\lambda)^2) \tag{2.56}$$

The penalty introduced by dispersive pulse broadening can be determined with the dispersion of the fibre D, the total length of the fibre L_{Total}, the bit-rate B and the root mean square width of the source spectrum σ_λ in [m] from Equation (*2.4*).

2.7.2 Penalty due to the Frequency Chirping

A chirped optical pulse is an optical pulse with time-dependent phase shift, this means that the frequency increases and decreases with time, thus its spectrum is considerably broadened resulting in degradation of the system performance. The worst-case scenario for the penalty introduced by frequency chirping can be determined with the Equation *(2.57)* [9], in which the value of the chirp parameter C needs to be given to the simulator.

$$\delta_c = 5 \cdot \log\left[\left(1 + 8 \cdot C \cdot B^2 \cdot L_{Total} \frac{D \cdot {\lambda_0}^2}{2\pi \cdot c}\right)^2 + \left(8 \cdot B^2 \cdot L_{Total} \frac{D \cdot {\lambda_0}^2}{2\pi \cdot c}\right)^2\right] \tag{2.57}$$

The parameters of the Equation *(2.57)* apart from the chirp parameter are the speed of light in vacuum c, the dispersion of the fiber D, the wave-length λ_0, the bit-rate B and the total length of the fibre L_{Total}.

2.7.3 Penalty due to the Reflection Feedback

In a fibre optical telecommunications system, some light is reflected back where the refractive-index discontinues, this discontinuation only happens in the splices, connectors and fibre ends. The reflected light provokes an optical feedback degrading the performance light wave systems. The power penalty caused by the optical feedback can be determined with the Equation *(2.58)* [9].

$$\delta_{ref} = -10 \cdot log_{10}(1 - Q^2 {r_{eff}}^2) \tag{2.58}$$

The Equation *(2.58)* can be determined by the parameters Q from Equation *(2.26)* and effective intensity noise r_{eff} . The effective intensity noise can be determined with the Equation *(2.59)* [9] knowing the relative intensity noise (RIN) and the receiver bandwidth Δf .

$${r_{eff}}^2 = 2 \cdot RIN \cdot \Delta f \tag{2.59}$$

2.7.4 Penalty due to the Mode-Partition Noise

A semiconductor laser exhibits mode-partition noise (MPN) because of anticorrelation between pairs of longitudinal modes, this anticorrelation makes the longitudinal modes fluctuate provoking large intensity fluctuations in the individual modes. The existence of fibre dispersion is what makes MPN unsynchronized different modes since they are transmitted at different speeds. Thus, the receiver current exhibits additional fluctuations. The power penalty caused by MPN can be determined for a required BER with the Equation *(2.60)* [9].

$$\delta_{mpn} = -5 \cdot log_{10}(1 - Q^2 {r_{mpn}}^2) \tag{2.60}$$

The Equation *(2.60)* can be determined parameters Q from Equation *(2.26)* and the relative noise level of the receiver power r_{mpn} that can be determined with Equation *(2.61)* [9].

$$r_{mpn} = \left(\frac{k}{\sqrt{2}}\right)\{1 - exp[-(\pi \cdot B \cdot L_{Total} \cdot D \cdot \sigma_\lambda)^2]\} \quad (2.61)$$

The relative noise level of the receiver power can be determined with the bit-rate B, the dispersion D, the total length of the fibre L_{Total} , the root mean square width of the source spectrum σ_λ with Equation *(2.4)* and the mode-partition coefficient k that ranges from [0;1].

2.8 Optical Signal to Noise Ratio

When planning a fibre optic telecommunication system, improving the received signal is always the main concern. This improvement is important since it may help choose which components should be in the system or which transmitted power or which gain. In order to evaluate the quality of the received signal a parameter was designed, the OSNR. This parameter measures the ratio between the received signal and its noise. Usually, this is the best way to analyse the performance of the fibre optic telecommunication system. The OSNR can be determined in each component of the system, thus evaluating its performance. The basic evaluation of the OSNR is in the Equation *(2.62)* [16], in which p_{out} is the signal power and p_n is the noise power.

$$osnr = \frac{p_{out}}{p_n} \quad (2.62)$$

The Equation *(2.62)* shows how the $osnr$ is obtained in linear units and it is typically presented in $[dB]$, so Equation *(2.62)* can be used to convert it into $[dB]$. However, there can be another representation of Equation *(2.62)*, in order to obtain the result already in $[dB]$, Equation *(2.63)*.

$$OSNR = P_{out} - P_n \quad (2.63)$$

The OSNR is only valid if the signal to noise ratio is being determined for an optical signal. The signal is converted to an electrical signal in the receiver, so within the receiver is not possible to determine the OSNR. In a fibre optic telecommunication system, after the signal is converted to an electrical signal, the parameter that can evaluate its quality is the SNR. Also, in order to have some backup power, this means that the power reaching the receiver has to be higher than the necessary for the system to run. This power can be allocated if some degradation of components is developed over time that will cause new power penalties that the system did not consider. This allocation of power is known as system margin M_s that takes into account the needed power in order to achieve a reliable communication and the received power leaving usually a margin of $6\ [dB]$.

2.8.1 OSNR in the Transmitter

The simulator does not determine the transmitter OSNR, instead, it requires it to determine the noise inserted on the system by the transmitter. The transmitter noise can be determined by Equation *(2.64)*.

Please note that the OSNR of the transmitter is at the exit of this component since the signal is already converted into an optical signal.

$$P_{n_{transmitter}} = P_{out_{transmitted}} - OSNR_{transmitter} \tag{2.64}$$

Equation *(2.64)* can be determined if the transmitted power of the transmitter, $P_{out_{transmitted}}$, and the optical signal to noise ration of the transmitter, $OSNR_{transmitter}$, are provided. The noise of the transmitter will propagate throughout the system with the noise added by other components.

2.8.2 OSNR in the Optical Amplifier

The optical amplifier, mentioned in Section 2.5.1 also brings some noise into the system, the most dominant being the noise generated by ASE. The noise power p_n at the amplifier can be determined using Equation *(2.65)* [16]. The parameter p_{n_s} is the noise that is propagated in the system until that point, including all the noise introduced by the previous amplifiers and by the optical transmitter.

$$p_n = p_{ASE} + p_{n_s} \tag{2.65}$$

The noise from the system p_{n_s} will be attenuated by the fibre. However, in the amplifier the noise of the system will be amplified. Since the signal power is being amplified, the noise that is already in the system will be amplified too. Thus, the noise system that is inserted in Equation *(2.65)* is determined by Equation *(2.66)*.

$$P_{n_s} = P_{n_{received}} + G \tag{2.66}$$

Also, as it was mentioned in Section 2.5.2, the optical signal after the amplifier is given by the Equation *(2.47)*, so in the optical signal after the amplifier can also be represented by Equation *(2.67)* [16], where $p_{in_{amplifier}}$ is the power received by the amplifier and g is the gain of the amplifier.

$$p_{out} = g \cdot p_{in_{amplifier}} \tag{2.67}$$

By combining Equation *(2.62)*, Equation *(2.65)* and Equation *(2.67)*, the OSNR at the end of the optical amplifier can be determined by Equation *(2.68)*:

$$osnr_a = \frac{g \cdot p_{in_{amplifier}}}{p_{ASE} + p_{n_s}} \tag{2.68}$$

2.8.3 OSNR at the Optical Receiver

The OSNR can be determined at the entrance of the optical receiver, before is converted into an electrical signal. The noise power that reaches the optical receiver is the sum of all the noise of the system. This parameter does not differ between APD or PIN receivers, since the gain and noise insertion from these receivers only affect the electrical signal. So, the noise power p_n at the entrance of the optical receiver can be determined by Equation *(2.69)* [16], where p_{n_s} is the sum of all the noise of the system until the signal reaches the receiver.

$$p_n = p_{n_s} \tag{2.69}$$

The p_{out} is the received power by the optical receiver $p_{out} = p_{in_{receiver}}$. By combining Equation *(2.62)*, Equation *(2.69)* and the received power, the OSNR at the end of the optical amplifier can be determined with Equation *(2.70)*(*2.68*) .

$$osnr_r = \frac{p_{in_{receiver}}}{p_{n_s}} \tag{2.70}$$

The OSNR Equation *(2.70)* is normally presented in $[\mathrm{dB}]$, so if Equation *(2.63)* is taken into account, the OSNR at the end of the amplifier can be determined directly in $[\mathrm{dB}]$ with Equation *(2.71)*.

$$OSNR_r = P_{in_{receiver}} - P_{n_s} \tag{2.71}$$

2.8.4 BER at the Optical Receiver

After the OSNR at the entrance of the receiver the BER can be determined. The required BER and the BER determined at the entrance of the receiver are not the same thing. The BER at the receiver is the total bit error rate of the system. On the other hand, the BER that is required by the receiver is used to determine the sensitivity of the receiver. The BER required by the receiver is determined by the user, so if the user requires a minor BER the sensitivity will be higher. Further discussion on this issue in Section 2.4.1.

Firstly, in order to determine the BER at the entrance of the receiver, the parameter Q must be calculated using Equation (*2.72*). The parameters in this equation have already been explained in the previous sections. The parameter $osnr_r$ is the optical signal to noise ratio at the receiver.

$$Q = \frac{osnr_r \cdot \sqrt{\frac{\Delta v_{opt}}{\Delta f}}}{\sqrt{2 \cdot osnr_r + 1} + 1} \tag{2.72}$$

If the parameter Q is obtained, the BER at the entrance of the receiver can be determined using Equation (2.23), since the relation between the BER and parameter Q does not change from Section 2.4.1.

2.8.5 SNR at the Optical Receiver

The OSNR can only be calculated until the entrance of the receiver, because after that the signal is converted from an optical signal to an electrical signal. The SNR is the signal to noise ratio of the electrical signal that reaches the receiver, in a way the SNR of the system. The two types of receivers will have a different SNR from each other, because the APD receiver has a gain added to the signal, but an added noise power from that gain. However, this added noise power can ultimately improve the SNR of the receiver.

In Section 2.4, the concept of APD and PIN receivers is explained. The formulas used to determine the sensitivity of the receiver do not differ, but the values used for the gain and noise are different for each receiver, because usually the PIN receiver does not have a gain $M_{pin} = 1$. Nonetheless, there is the possibility that a PIN receiver can have a gain, so the equation to determine the SNR Equation *(2.73)* is the same for both. The only parameters that are different are the gain M and the excess noise factor, F_A.

$$snr_r = \frac{(MRp_{in})^2}{p_{n_s} + 2qM^2F_A(Rp_{in} + I_d)\Delta f + 4\left(\frac{k_BT}{R_L}\right)f_n\Delta f} \tag{2.73}$$

The parameters from Equation *(2.73)* are the elementary charge $q\ [C]$, the gain M, the excess noise factor F_A, the received power p_{in}, the dark current I_d, the noise figure f_n, the responsivity R, k_B the room temperature $T = 290\,K$, the Boltzmann constant $k_B\ [J/K]$, the resistor $R_L = 1k\Omega$ and the bandwidth of the receiver Δf. The parameter p_{n_s} is the noise power that is propagated in the system, so the SNR of the receiver takes into account the noise power of the system and the noise of the receiver as well. Thus, the SNR of the receiver is in fact the signal to noise ratio of the system.

2.8.6 System Margin

The system margin is the allocated power in order to prevent the system failure in case of the appearance of some power penalties that may develop due to degradation of components or other events. Usually, the system margin needs to be at least $6dB$ [16], this means that the difference between the received power and the required power to maintain the system, minus the power penalties generated in the transmission should leave a margin of at least $6dB$. The equation used to determine the systems margin is Equation *(2.74)*, where $P_{in_{receiver}}$ is the received power at the receiver, δ_d is the power penalty due to pulse broadening, δ_c is the power penalty due to chromatic dispersion, δ_{mpn} is the power penalty due to MPN, δ_{ref} is the power penalty due to reflection feedback, δ_{X_i} and δ_{X_o} are the both power penalties due to crosstalk.

$$M_s = P_{in_{receiver}} - \overline{P}_{\iota_{real}} - \delta_d - \delta_c - \delta_{mpn} - \delta_{ref} - \delta_{X_i} - \delta_{X_o} \tag{2.74}$$

The last parameter in Equation *(2.74)* that was not referred before is $\overline{P}_{\iota_{real}}$ this parameter is the real receiver sensitivity, which means that the receiver sensitivity mentioned before in Section 2.4.3 can be degraded. Thus, in order to determine the real receiver sensitivity, Equation *(2.75)* must be used. As it was discussed in Section 2.4, the average receiver sensitivity differs between PIN and APD or even if it has preamplification or not. However, in Equation *(2.75)* the formula does not change in any way, only $\overline{P}_{\iota}$ is used accordingly.

$$\overline{P}_{\iota_{real}} = \overline{P}_{\iota} - \delta_{ex} - \delta_I - \delta_j \tag{2.75}$$

Chapter 3

3. Simulator implementation

The implemented simulator is a Simulink library, and even though the installation of the simulator is straightforward, an explanation of its installation was provided in this section. This section also provides an explanation on how to use the simulator and on how to change and use each component to facilitate their comprehension. The last parts of this subsection are used to verify the accuracy of the results that were obtained using the simulator. These tests were a result comparison between the simulator that was implemented and another simulator. Finally, a real-life project was implemented to test the capacities of the simulator, and a theoretical analysis of the results was done in order to verify the accuracy of the results. The simulator can be accessed in the following url: https://drive.google.com/open?id=0B94fXxJbjhdtNmE4aEY0ZmJOeXc

3.1 How to use the Software

The simulator built on this project was made using MATLAB®/Simulink, the project was developed as a library for Simulink where the user can make a fibre optic telecommunication system using a graphical environment simply by adding models. The Simulink libraries need to have the specified version in order to work, this means that if the project was made with MATLAB® version R2015b a user with version R2013b cannot get access to the library. However, the project was saved in five versions in order to facilitate the access to the project: R2015a, R2015b, R2013a, R2013b and R2016b. After opening MATLAB® in the directory where the project is saved the user opens Simulink and starts a new project. A new project can be open by pressing the Blank Model option. Then by pressing the Simulink Library Browser button, the library should appear with the name "FOTS Simulator", as showed in Figure 3.1. Note that in order to use this simulator there is no required installation other than MATLAB® with the Simulink tool, this comes from the fact that the function "*slblocks.m*" adds the program to the library.

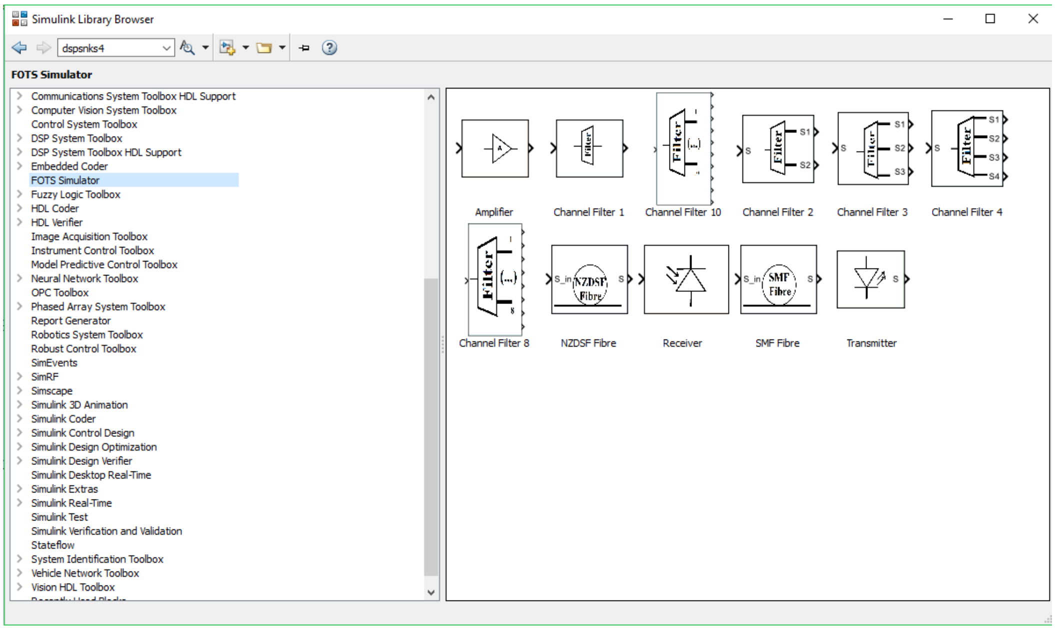

Figure 3.1 Simulink Library Browser with FOTS Simulator installed.

The library can also be accessed by opening the project directly, the models can also be changed if the project is opened. However, in order to change the models, the library needs to be unlocked by simply pressing the unlock button on the bottom left corner, represented by a lock. If the blocks are already inserted in a new model and changes are made to them the library link will be broken. However, after the new model is saved if the changes are submitted the library will be changed.

The parameters for each component of the fibre can be changed, in a new model, by simply pressing the component block. By opening the window of the component block, the options for each component and a simple explanation for each parameter of the component can be observed. The information that follows is an explanation of how to use each component.

The data that the simulator returns is divided into three types: a text file, an excel document and the Simulink outputs. These types of data are created by the receiver block, so they are explained with more detail in Section 0

3.1.1 How to use the Optical Transmitter

The optical transmitter is the starting block for every fibre optic telecommunication systems simulation, this block is the only one that can be connected directly to any block on the library. The parameter can be changed by simply pressing on the transmitter block, representation in Figure 3.2. Also, the figure allows identifying that every parameter already has a standard value. In the regards that the user does not know the value of a specific parameter, it is recommended that the standard values remain the same.

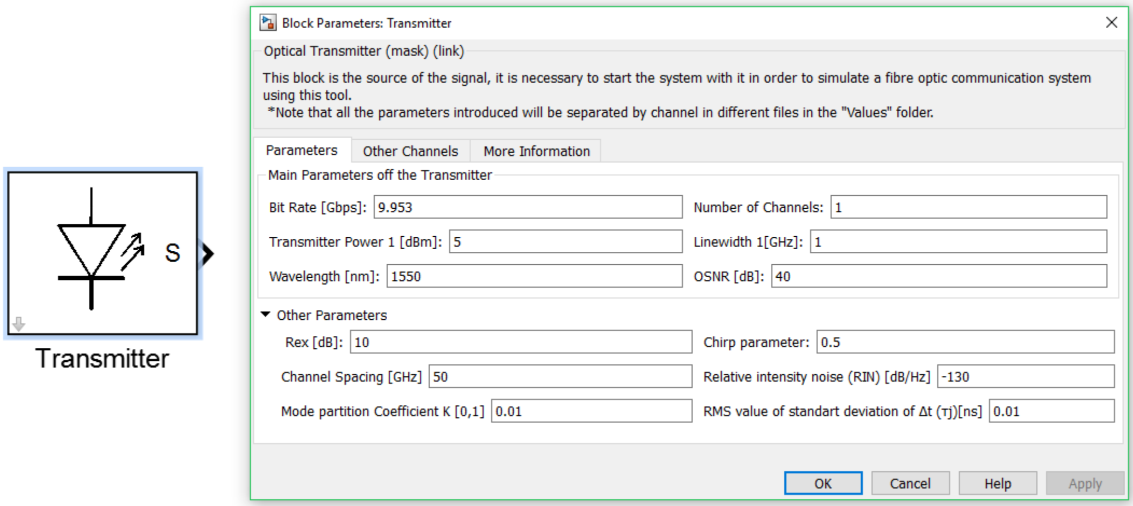

Figure 3.2 Transmitter block and window where its parameters can be edited

The main parameters of the transmitter are: the bit-rate, the signal power, the linewidth, the wavelength and the central wavelength. In order to add more than one channel, the number of channels must be inserted. Note that if the number of channels surpasses 10 channels, all the channels will have the same linewidth and the same starting signal power. However, if the number of channels is between the interval]1, 10], the values for each signal power and respectively linewidth can be inserted in the "Other Channels" tab. This constraint was implemented because the Simulink software requires a block for each new parameter. Since infinite block cannot be added and would make the insertion of values complicated, a decision was made to limit the number of custom channels that can be created with different powers and linewidth. In addition, the value for the channel spacing must be changed in this tab. The parameters tab has a collapsible panel that appears by pressing the "Other Parameters", as it can be observed in Figure 3.2. These parameters are associated with the power penalties and sensitivity degradation, the last tab "More information" provides information about each parameter. Table 3.1 contains the standard parameters of the transmitter block.

Table 3.1 Default parameters of an optical transmitter

$B\ [Gbps]$	$Pe\ [dBm]$	$\Delta v\ [GHz]$	$\lambda\ [nm]$	$OSNR\ [dB]$	$\Delta v_{ch}[GHz]$	$Rex\ [dB]$	C	$RIN\ [dB/Hz]$	K	$t_j\ [ns]$
9,953	5	1	1550	40	50	10	0.5	-130	0.01	0.01

3.1.2 How to use the Optical Fibre

The optical fibre block can be inserted between the transmitter and the receiver, the use of this block is the basic principle in each fibre optic telecommunications systems work. However, the user can connect the transmitter directly to the receiver in order to test the losses of the system without the fibre. There are two types of fibres built in this library as it was referred in Section 2.3. However, any type of fibre should be possible to build with these blocks by simply modifying the parameters. The only difference between the block using a SMF and NZDSF is that the standard parameter is specified following an example of each type of fibre. The parameter of the fibre can be edited in the pop-up window opened when pressing the block as the example Figure 3.3.

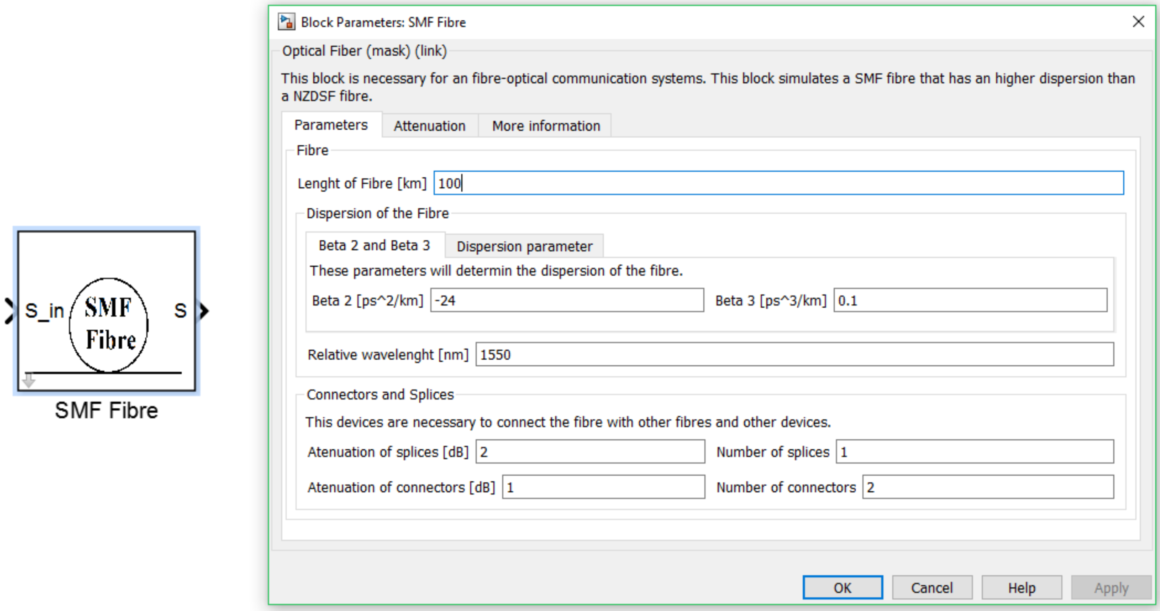

Figure 3.3 SMF fibre block and window where its parameters can be edited

The main parameters of the optical fibre can be edited in the main window, the fibre dispersion can be presented in two ways, but if in the dispersion parameter tab is inserted a different value than 0 the program will take it into account. There is also the attenuation of splices and connectors that are asked in this block for means of simplification. The attenuation of the fibre can be inserted in three different ways, the first one is by not adding any information about the fibre attenuation and the program will assume that the values stay the same as the example G.655 or G.652, either if using a NZDSF fibre or SMF fibre. The second way is to assume that the attenuation of the fibre does not change with the frequency and it is given a constant value. The last one is giving specific values for specific intervals defined by the user as can be observed in Figure 3.4.

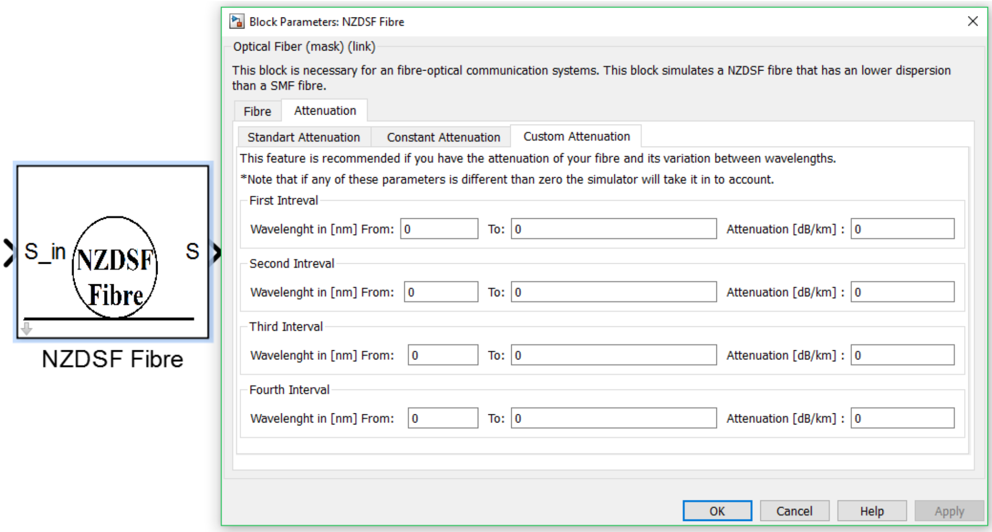

Figure 3.4 NZDSF fibre block and window where its parameters can be edited

Although, there are only two types of fibres introduced in the program, they can always be changed. This means that these types of fibres were the only ones that the standard values were already implemented following an example for each fibre. However, the user can always customise each block to replicate another type of fibre. The nonlinear effects throughout the fibre are verified in this block, these effects take into account the sum of the power of every channel transmitted in the fibre. The limitations of the nonlinear effects will only limit the threshold power or incident power in the fibre. Thus, if any nonlinear effect surpasses the threshold power or incident power limitations this block will print a warning message in the MATLAB® terminal and in a pop-up message (Figure 3.5).

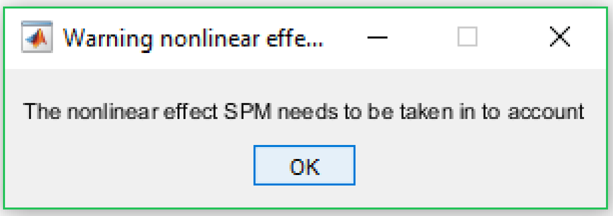

Figure 3.5 Nonlinear effects warning from the fibre block

The standard values of the parameters for each type of fibre block are represented in Table 3.2. Every attenuation parameter of each fibre is set as zero, this can be observed in Figure 3.4. Thus, these parameters were not represented in Table 3.2.

Table 3.2 Default values for the fibre blocks

Fibre	$Length\ [km]$	$\beta_2\ [ps^2/km]$	$\beta_3\ [ps^3/km]$	$\lambda_r\ [nm]$	N_S	$A_S\ [dB]$	N_C	$A_C\ [dB]$	Dis
SMF	100	-24	0,1	1550	1	2	2	1	0
NZDSF	100	$-2{,}8$	0,08	1550	1	2	2	1	0

3.1.3 How to use the Optical Amplifier

The amplifier is used to amplify the signal's power, moreover Section 2.5. This block can be inserted any position between the optical transmitter and optical receiver, one example of its use is shown in Figure 2.4. The amplifier parameters can be changed by pressing the amplifier block, which will open a new window where the parameters can be inserted and with some information about each parameter, an example of this is presented in Figure 3.6. An explanation for each parameter can be found in Section 2.5, the information found in that section is more detailed the information presented in the program.

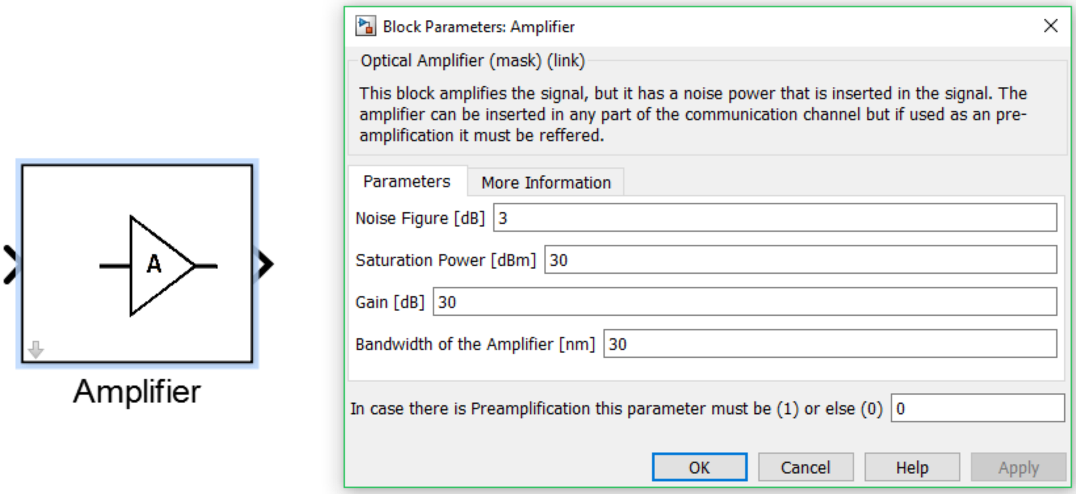

Figure 3.6 Amplifier block and window where its parameters can be edited

The use of the technique preamplification presented in Section 2.4.2 will change the formula used to calculate the average receiver sensitivity. So, in order for the program to calculate the value correctly the last parameter on the pop-up window must be inserted "1". If the parameter is "0" the simulator will assume that there is no preamplification in the system. Table 3.3 contains the standard values that are implemented in the amplifier block, these values can be altered by submitting new values and a simple explanation of each one is presented in the block window.

Table 3.3 Standard values for the Amplifier block

$F_n\ [dB]$	$P_s\ [dBm]$	$G\ [dB]$	$B_0\ [nm]$	Pre
3	30	30	0,3	0

The values on Table 3.3 were already explained in Section 2.5, however, the parameter Pre is just a needed variable in order for the program to understand if the amplifier is applying the preamplification technique. The values of Pre consist of 0 or 1 if the amplifier is being applied was a preamplifier so this value should be 1 otherwise the value should be 0.

3.1.4 How to use the Optical Filter

The optical filter only works using WDM, besides the block Channel Filter 1, because it could be used to support a preamplification fibre, as it is demonstrated in Figure 2.4. There are many types of blocks with optical filters, the difference between them is that they filter specific channels that the user want to analyse further. The number of channels is limited to 2000 channels, this limit comes from the fact that in Simulink it is not possible to create a [N,N] without giving a maximum value of N. Thus, in order to assure that the user can simulate any type of system the maximum number of channels was set at a high value. The number the user inserts in the filter will print the graphic and in the text file for that channel. This option is to avoid the user of having to read the matrix built in excel.

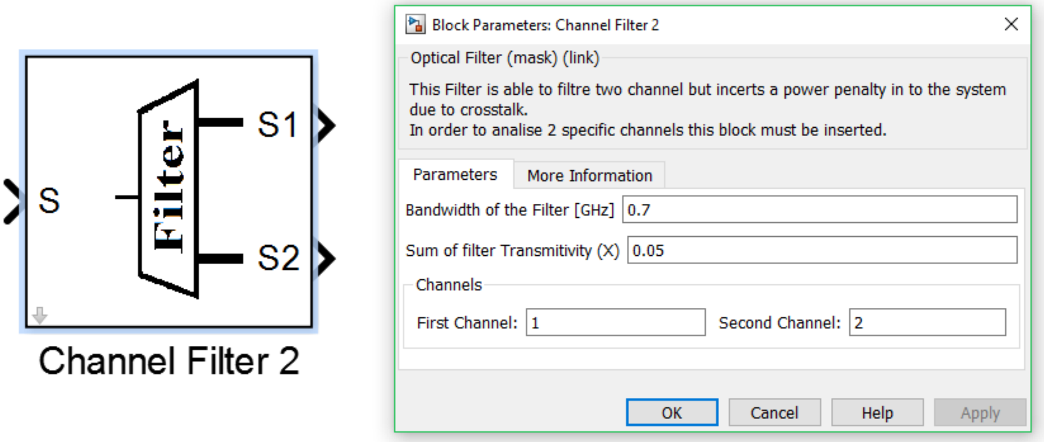

Figure 3.7 Optical filter block for two channels and window where its parameters can be edited

The parameter that is inserted into the optical filter block is just the specific channels that the user wants to filter, the number of channels that the filter is able to filter will depend on the type of filter. The other parameters that can be inserted on the filter block are the sum of the filter transmitivity and the filter bandwidth. These parameters have all a more detailed explanation in Section 2.6. This component if used is supposed to be used right before the optical receiver and there is only one use in the optical signal simulation, every other block can be connected to it. The standard values inserted in the optical filter block are represented in Table 3.4.

Table 3.4 Standard values of an optical filter block for two channels

X	$1^{st}\ Channel$	$2^{nd}\ Channel$	$B_{filter}[GHz]$
0,05	1	2	7

3.1.5 How to use the Optical Receiver

The optical receiver is the block that will receive the optical signal and convert it into an electrical signal. This block is supposed to be the last block of the system in this simulator, so any other block can connect to it. There are two types of receivers implemented in the simulator, PIN receiver and APD receiver instead of providing both types of blocks there is only one. The parameters of the receiver block can be modified in the block window, represented in Figure 3.8.

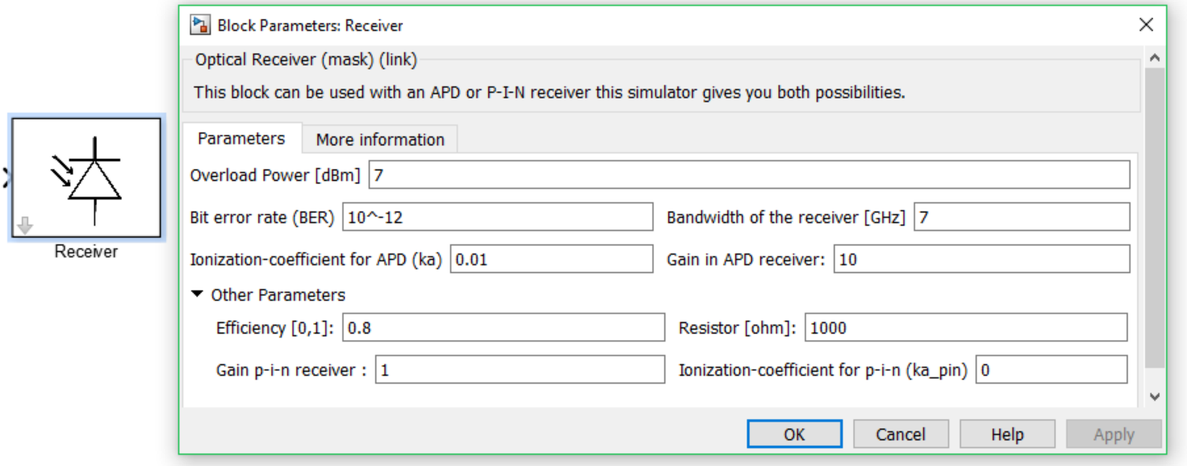

Figure 3.8 Receiver fibre block and window where its parameters can be edited

The decision of having both types of receivers was made in order to provide the user with a comparison between both receivers by observing the difference between the SNR achieved and the system margin. The comparison between them can be observed in many ways since the information provided by the simulator has three types of sources. The information can be taken for the excel file created by the program called "Data.xlsx", this file contains the main matrix of the program, this matrix contains all the main parameters that needed to be shared for each block. The size of this matrix can go from [1 34] to [2000 200], the reason behind it is [1 34] is or the smallest systems possible with only one channel and with a transmitter and receiver. The 34 is the number of parameters that are needed to run the systems simulation, this number will rise with the number of components since each time an amplifier is added two new parameters are added to the matrix. This will depend on the number of channels since the maximum is 2000 but also on the number of amplifier blocks that can be added, the maximum number of amplifiers is (200-34)/2 = 83. The decision for limiting the maximum size can seem arbitrary but this comes from the fact that when using Simulink, a matrix can have a variable size. However, the maximum size must be defined, which means that a maximum number of parameters must be stated. Thus, the limitation of the matrix was set to very high values usually the number of channels can go up to 300 and the number of amplifiers should not be higher than 20. Even with this limitation the program can be adapted to receive more parameters but each block and subblock have to be changed manually in the *Explore* option of Simulink option.

There is always another way to analyse the system by opening the "ChanelX.txt" file that corresponds to the X^{th} channel. This file can be found in the folder "*Values*" and there is one file for each channel so the user can open a specific channel and observe a simple overview of the signal propagation through the channel. The objective of this source of data is to analyse a channel independently from other channels, Figure 3.9 show an example. This example is from a standard fibre optic telecommunications system consisting of two fibres one amplifier and obviously one transmitter and one receiver.

```
Channel1.txt - Notepad
File  Edit  Format  View  Help
Transmitter:
        Channel 1:
                Transmitted power:5.000 [dBm]           Bit rate:9.953 [Gbit|s]         Wavelength:1550 [nm]
                Extinction Ratio: 10 [dB]               Linewidth:1.0 [nm]              Chirp Parameter:0.50

                OSNR:40.00 [dB]
-----------------------------------------------------------------------------------------------------------------------
SMF Fibre:      Lenght:100.000 [km]
                Attenuation of Connectors:1.000 [dB]                    Attenuation of Splices:2.000 [dB]
                Number of Connectors:2.000                              Number of Splices:1.000
                Attenuation per km:0.180 [dB/km]                        Dispersion:18.817*10^-6 [ps|km|nm]

                Power at the end of the Fibre:-17.00 [dBm]
-----------------------------------------------------------------------------------------------------------------------
Amplifier:              Gain 29.92 [dB] Noise Figure: 3.00

                Power after Amplification: 12.917 [dBm] Noise Power (Pase): -17.267 [dBm]
                OSNR:29.753 [dB]
-----------------------------------------------------------------------------------------------------------------------
SMF Fibre:      Lenght:100.000 [km]
                Attenuation of Connectors:1.000 [dB]                    Attenuation of Splices:2.000 [dB]
                Number of Connectors:2.000                              Number of Splices:1.000
                Attenuation per km:0.180 [dB/km]                        Dispersion:18.817*10^-6 [ps|km|nm]

                Power at the end of the Fibre:-9.08 [dBm]
-----------------------------------------------------------------------------------------------------------------------
Receiver:               Bandwitdh: 6.97 [GHz]
        Received Power: -9.083
        PIN Receiver:   ka:0.010                        M:  1
        APD Receiver:   ka:0.000                        M:  2

        OSNR:29.753 [dB]

        PIN Receiver:
                Sensitivity:-26.318 [dBm]                       SNR_pin: 21 [dB]
                Systems Margin: 10 [dB]
        APD Receiver:
```

Figure 3.9: Example of a source of data printed in a text file

Figure 3.9 can be analysed and easily obtain all the important data throughout the fibre such as the OSNR of each parameter that adds noise, the attenuation of the fibre, the distortion, etc. Note that these parameters can only be an easy way to observe the parameters that were inserted by the user and correct mistakes if necessary. One of the last important details of the data provided by this file is the gain of the amplifier since the amplifier can be saturated and the user does not notice it, so if the user inserts a gain it does not mean that the amplifier will amplify the signal with that gain, moreover Section 2.5.3.

The last kind of data source provided by the simulator are outputs of Simulink this consists of a graphical analysis of the OSNR throughout the fibre either from the first channel if a channel is not specified or from a specified channel using the filter block. The receiver will also provide a graphical analysis of the signal OSNR by wavelength if more than one channel is provided so the user can observe that each wavelength provides an optimal OSNR for the system, Figure 3.11 shows an example of such graphs. There is also a graphical analysis of the systems margin by each wavelength with equal intent to the previous one. The output sources also consist of important information being printed in the MATLAB® message box from the parameter values presented in Figure 3.10. There can also be warnings if the threshold power surpasses the limitations on which the nonlinear effects will have to be taken into account, or simple warnings such as non-compatible values and so forward.

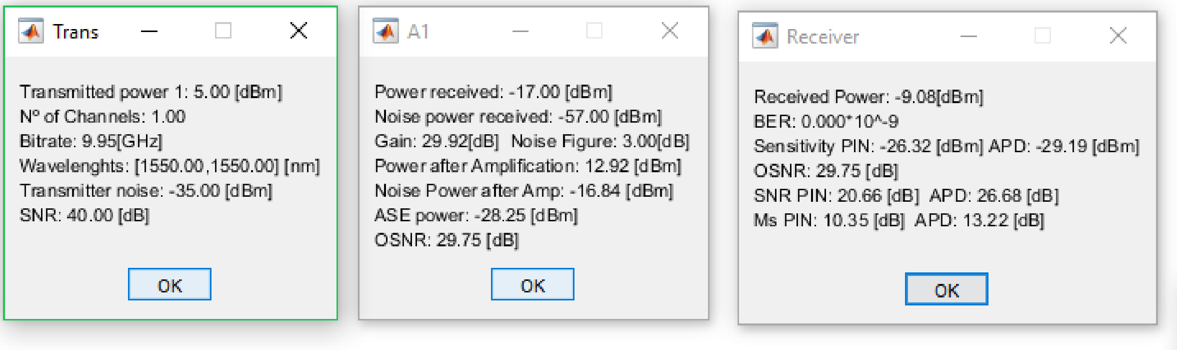

Figure 3.10 Message box return from the simulator

The receiver block also returns three graphical analysis of the system. The first one is represented in Figure 3.11. This figure includes two types of graphics: the OSNR throughout the fibre and the power throughout the fibre.

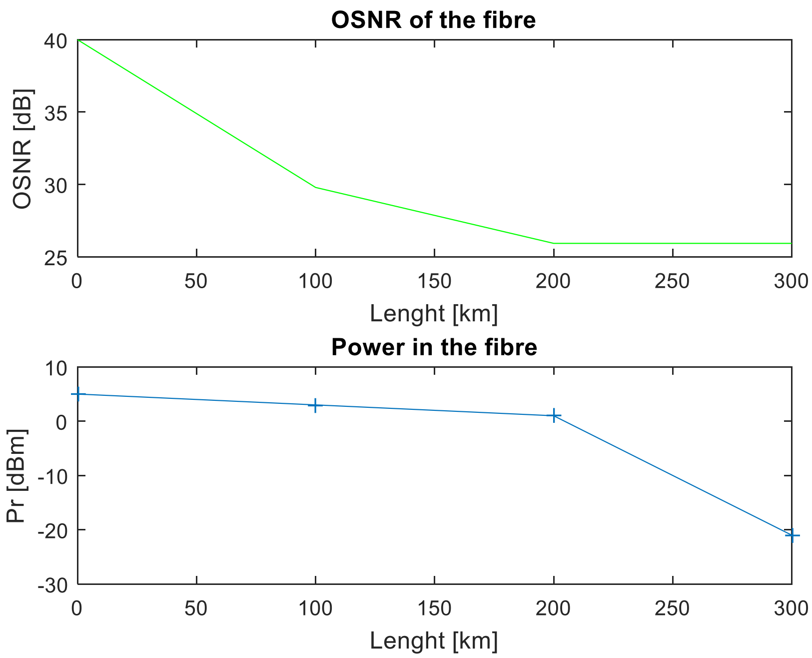

Figure 3.11 Graphical analysis of the OSNR and power throughout the fibre

The second type of graphical analysis that is presented in this simulator can only be represented if more than one channel is used. The reason behind it is that Figure 3.12 is a comparison between the OSNR of each channel, where the graphic shows a similar variation with the different attenuations parameters of the fibre through wavelength.

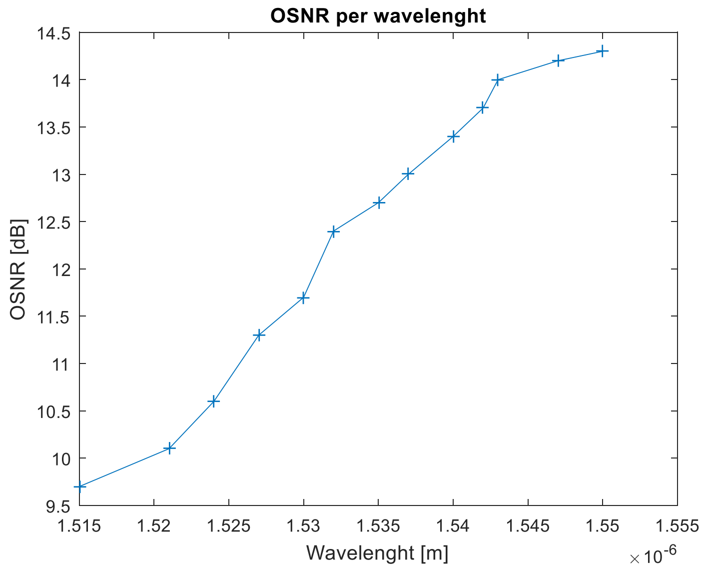

Figure 3.12 OSNR per wavelength

The last type of graphical analysis is Figure 3.13, which contains a graphical analysis of the systems margin for every channel. The graphical representation shows the minimum required systems margin represented in red. By analysing Figure 3.13, it can be taken into consideration that the wavelengths from $1520\ [nm]$ to $1540\ [nm]$ are the only ones that comply with the minimum systems margin, for this example.

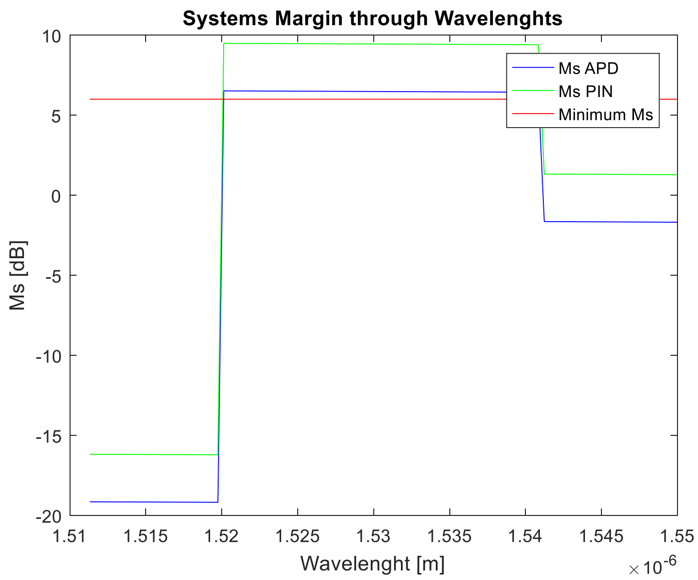

Figure 3.13 Systems Margin for PIN and APD receivers

The receiver block also displays a warning error if the power penalty due to chromatic dispersion surpasses the maximum value of $2\ [dB]$ [21]. Figure 3.14 represents the warning message that is displayed. A similar warning is presented if the overload power of the receiver is surpassed.

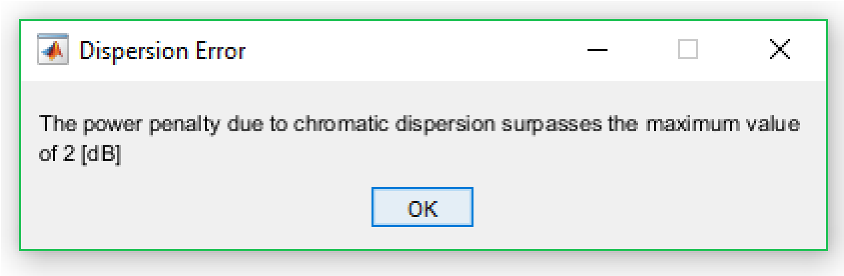

Figure 3.14 Warning message for the maximum value of the power penalty due to chromatic dispersion

The values standard values for the receiver block are represented in Table 3.5. The parameters ka and M are the only ones that will be different for both receivers.

Table 3.5 Standard values for the receiver block

P_{OV} $[dBm]$	BER	APD		PIN		R [Ω]	η	B [GHz]
		ka	M	ka	M			
7	10^{-12}	$0{,}01$	10	0	1	1000	$0{,}8$	7

3.2 Comparison with another simulator results

The simulator must be tested thoroughly in order to determine if the results that the simulator returns are true and viable in a fibre optic telecommunications system. The fastest way to check is running the program and observing if the results that return for a specific system are viable for a real fibre optic telecommunications system. However, this only helps to detect absurd values. The only way to really test the program is to compare it with other simulators. The simulator that the results were compared to was the ISCTE simulator. The simulations were compared with the simulations that were tested in the dissertation [12], the results are expected to be slightly different since both simulators have different parameters that are taken into account and some parameters were not known.

3.2.1 Case Study

The case study is presented in chapter 5 of the dissertation, which consists of a connection between Lisbon and Porto with a distance of about 280 kilometres. The system involved two amplifiers and four fibres with a length of 80 kilometres. The last section was shorter since the distance is only 280, so the last one was assumed to have 40 kilometres. The representation of the systems built using the simulator is represented in Figure 3.15.

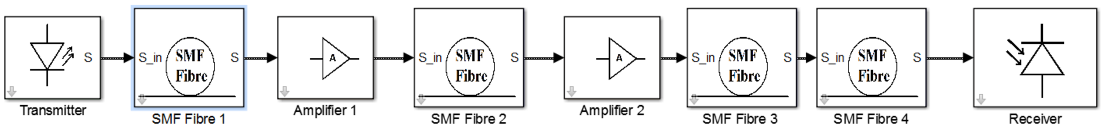

Figure 3.15 The system that was built using the simulator

The input values were presented in snapshots of the simulator. However, there are some parameters that this program takes into account that were not presented. This problem was resolved by keeping the default values of the components or in some cases adapting the values in order to achieve a similar representation with the project presented. The parameters inserted in the transmitter block are represented in Figure 3.16.

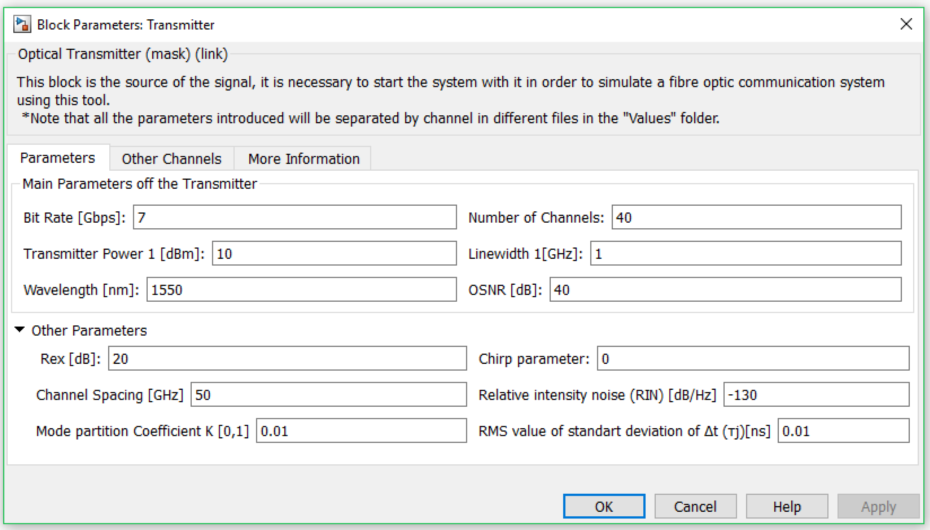

Figure 3.16 The transmitter block parameter for the case study comparison

The last four parameters and the linewidth were not presented in the dissertation, so the parameter values stayed the same as the standard value. However, the chirp parameter was set to zero because it is referred to the project that the system is using external modulation. Thus, as it was discussed in Section 2.2 the use of external modulation is commonly used in order to remove the chirping of the frequency to improve the system performance.

The optical fibre blocks are basically the same although the last one has smaller dimensions as it was mentioned before. The parameters can be observed in Figure 3.17. The only parameter of the fibre that cannot be observed in the figure is the attenuation of the fibre, which was not presented in the project presentation. However, it is said that the system uses SMF-28 fibre so typical values were inserted in order to achieve the same attenuation.

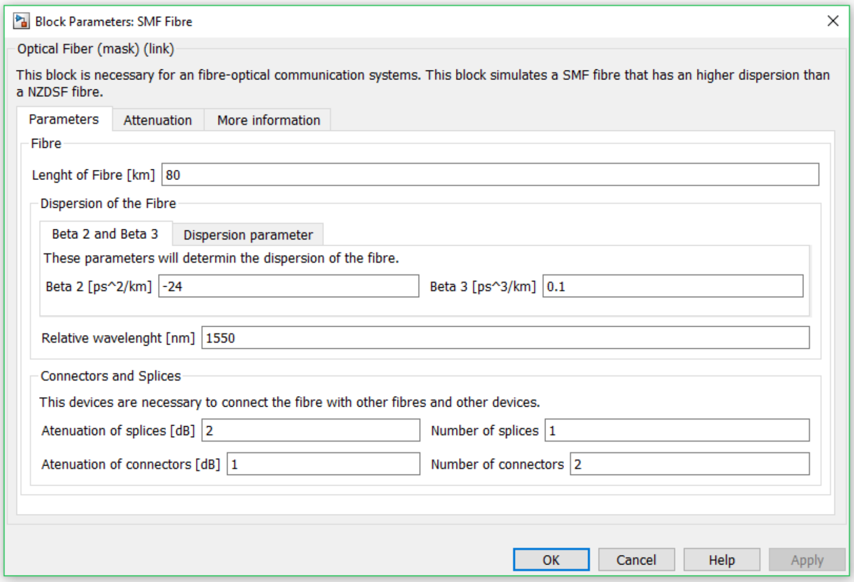

Figure 3.17 The fibre block parameter for the case study comparison

Note that one of the major differences between both projects is that in this project, DCF fibres were not implemented. These fibres are used to compensate dispersion in the fibre. Since in the other project there are more 13.6 kilometres of DCF it is normal that the attenuation in each fibre is greater than the one that will be obtained by this simulator. The loss of the fibre, in this project, is adapted in order to achieve the same attenuation values of that project. This decision was made based on the fact that the attenuation in the fibre is a parameter that does not need much testing. The optical fibre can be seen as a black box that achieves a specific attenuation at the end of the fibre, as this simulator is already describing.

The amplifier parameters are all presented in the dissertation. However, the noise figure of the amplifier is not. Therefore, in order to determine the noise figure of the amplifiers the simulation was tested with several typical values that the noise figure can have. The parameter value that was compared to determine the noise figure was the ASE noise power since the other parameters were presented in the project, obtaining a value of $F_n = 6\ dB$. The parameters inserted in the amplifier block are presented in Figure 3.18. The gain of the amplifiers is equal to the losses in the fibre and both amplifiers have exactly the same parameters.

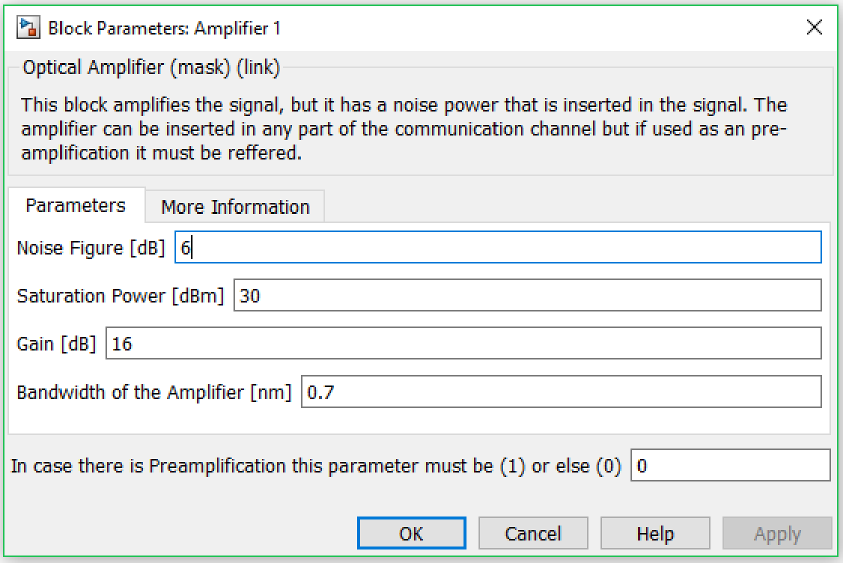

Figure 3.18 The amplifier block parameter for the case study comparison

The last block used was the receiver block, the only information that was given about this block was the required BER and that a PIN receiver is used. Since in this program the receiver block takes into account a PIN receiver and an APD receiver at the same time, there is no necessity to change anything. The parameters inserted in the receiver block are presented in Figure 3.19.

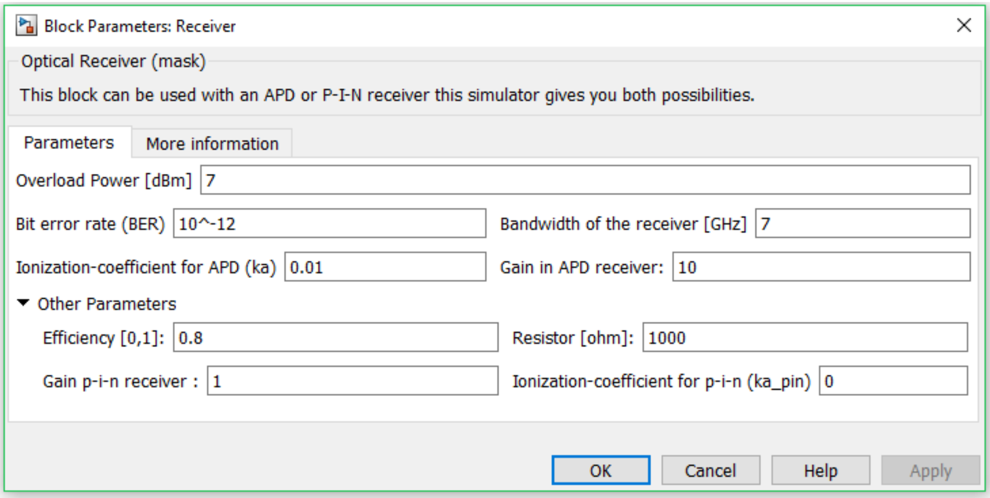

Figure 3.19 The receiver block parameter for the case study comparison

The results present in the simulator are compared and discussed in order to understand their differences. These parameters are presented in Table 3.6, where number 1 represents the other simulator and number 2 represents this simulator. The first parameter is the ASE noise power obtained in each amplifier. This noise power is the same in both amplifiers because they have the same parameters. These parameters are really similar and it is normal since the noise power inserted in order to run this simulation was based on a comparison between the ASE noise power of both simulators. The second parameter is the sensitivity of the PIN receiver. In order to determine this parameter, the formula for sensitivity with preamplification was used, by reading the case study in the other dissertation the formula that was used is intended for a preamplification case. The values obtained for the receiver sensitivity have a difference of about 3 $[dBm]$ an explanation for this difference could be the fact that this simulator takes into account the sensitivity degradation caused by some phenomena in the systems. However, this degradation does not reach above $1\ [dB]$ so there is a need to find another explanation. Another explanation could be the fact that the receiver bandwidth and the amplifier bandwidth is not given in the project, the values that were assumed in this simulation were different from the ones that were used. The third parameter is the received power in the receiver the difference between both simulations is small and easily explained. The fibre was not provided and also the use of DSF fibres that added 13.6 kilometres of length were the contributing factors for this difference.

Table 3.6 Comparison between values of both simulators

Simulator	$P_{ASE}\ [dBm]$	$\overline{P_i}\ [dBm]$	$P_r\ [dBm]$	$M_s\ [dBm]$	$\delta_{ex}\ [dB]$	$\delta_X [dB]$	$\delta_{cd}\ [dB]$
1	-36	-35.5	-16.1	15	0,4	0	0
2	-37,12	-39,12	-15,91	17,22	0,0869	0	0,5

The fourth parameter is the systems margin, the difference between the simulators is easily discovered since it is roughly the same difference of the receiver sensitivity. Considering that the receiver sensitivity is one of the parameters that is used to determine the systems margin, the difference of about $2\ [dBm]$ makes sense since it is the difference between the sensitivities. The fifth parameter is the power penalty due to the extinction ratio, this parameter is different for both simulators. However, an explanation for this matter was not discovered. The formulas used for both simulators are equal since one uses r_{ext} and the other $r = 1/r_{ext}$. After some testing and calculating using both equations it was concluded that in both equations the result $\delta_{ex}\ [dB] = 0{,}0869$ is obtained. The sixth parameter is the power penalty due to crosstalk this parameter is the sum of both crosstalk power penalties taken into account in this simulator. The value for the power penalty is approximately $0\ [dB]$ in both simulators as expected. The last parameter is the power penalty due to chromatic dispersion, which is the sum of the power penalty due to pulse broadening and frequency chirping. The explanation for the difference between them is simple since the use of DCF in the other simulator aims to cancel the dispersion in the fibre. Thus, the power penalty obtained in that simulator is normal to be zero. However, in this simulator the dispersion in the fibre is still taken into account.

The last observation between both results can be observed by comparing the graphical analyses returned by both simulators. In Figure 3.20, the result obtained using the ISCTE simulator, including the values that were obtained and also the graphical analysis of the power throughout the fibre

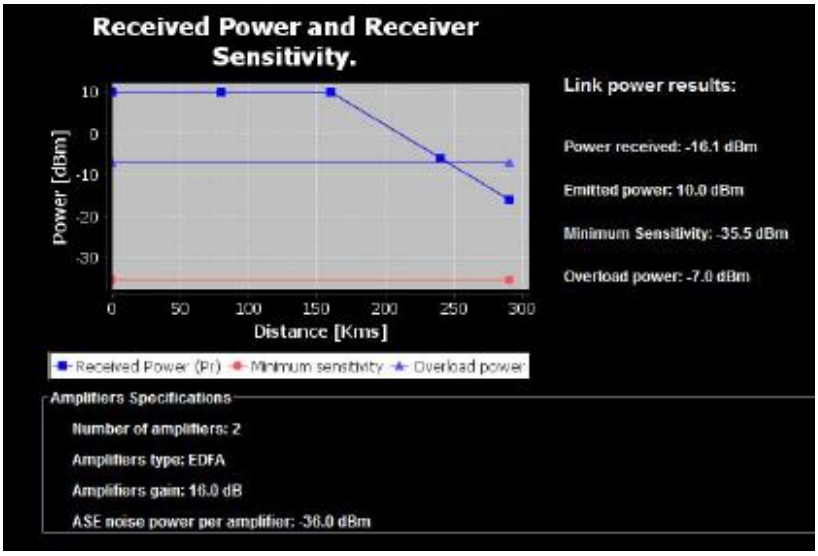

Figure 3.20 The graphical analysis of the cases study presented by the ISCTE simulator [12]

Figure 3.20 can be compared with Figure 3.21, both show a similar decline in the system's power. Even though the systems have different received powers, they are simulating the same system. The comparison between both figures is only between the graphic from Figure 3.20 and the last graph of Figure 3.21. The first graphic is the OSNR throughout the fibre and it cannot be compared since the ISCTE simulator does not provide one.

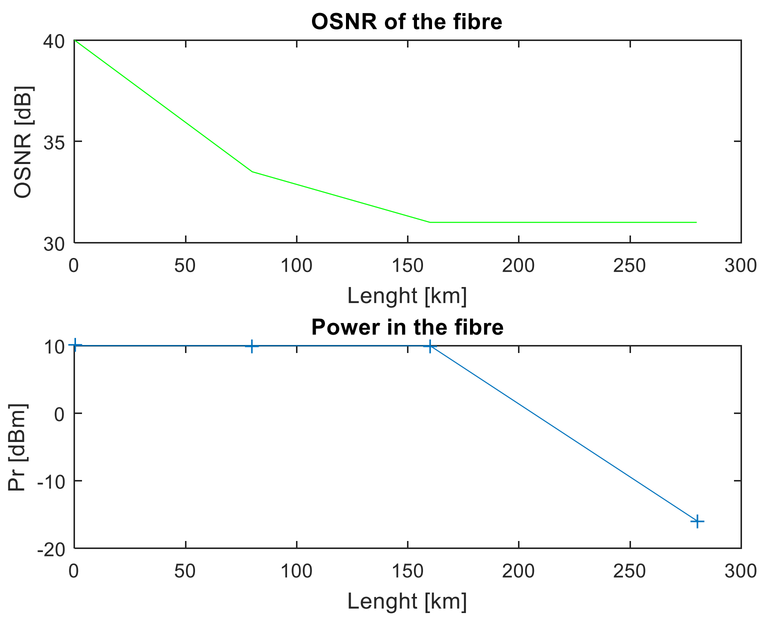

Figure 3.21 The output of the case study received by the simulator built in this project

3.3 Testing the simulator in a real-life project

3.3.1 Presenting the Project

The objective of the simulator is to run real life projects and run the exact system in a computerised environment. So, in order to test the capacity of this simulator a real-life project should be tested. The project that was chosen was the fibre optic telecommunications system that was made by Fundação para a Computação Cientifíca Nacional (FCCN) is a part of the Fundação para a Ciência e a Tecnologia (FCT). The main mission of this foundation is to plan and manage the infrastructure of digital research covering Portugal. Their services are available in education and research institutions, Instituto Superior Técnico (IST) has the available data from this project.

The project consists of a fibre optic telecommunications system connecting all major universities from Braga to Lisbon, a demonstration of the project is represented in Figure 3.22. However, for means of simplification and since this program simulates only a point to point connect, the local networks and connection to the universities were not taken into account only the connection from station Braga until station Oriente in Lisbon.

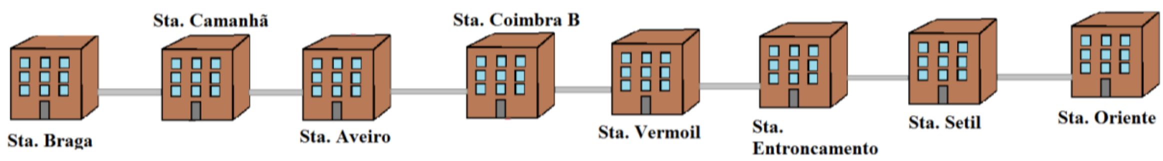

Figure 3.22 The FCCN network from the provided data

The information provided for each connection consists of the length of the fibre, the attenuation per kilometre for some wavelength, the dispersion of the fibre and the insertion losses of the fibre which can be observed in Table 3.7. Note that in this table the values of the fibre were obtained to multiple experiments and this information was provided by IST. The values for the attenuation and dispersion from Table 3.7 are only for the wavelength $1550\ [nm]$. The stations between Braga and Oriente were considered to be amplifiers that amplify the signal with a gain equal to the attenuation of the fibre.

Table 3.7 Values obtained from the project

Sections	Length [km]	Insertion losses [dB]	Dispersion [ps/km/nm]	Attenuation [dB/km]
Sta. Braga to Sta. Campanhã	56,9	11,5	15,33	0,217
Sta. Campanhã to Sta. Aveiro	67,3	14	16,34	0,221
Sta. Aveiro to Sta. Coimbra	58,1	12	16,55	0,245
Sta. Coimbra to Sta. Vermoil	58,5	11,5	16,75	0,265
Sta. Vermoil to Sta. Entroncamento	57,7	11,4	16,23	0,265
Sta. Entroncamento to Sta. Setil	53,3	11	16,23	0,258
Sta. Setil to Sta. Oriente	52,4	11	16,38	0,203

The data from Table 3.7 has the only parameters that are already defined by the network. The rest of the parameters of the fibre optic telecommunications system were not provided. Thus, the decisions on what parameters to use were adapted to the project, such as the gain of the amplifiers since they are usually equal to the attenuation of the fibre. Another information that was given about the project is that the type of fibre used in the system was a SMF fibre, the rest of the decisions are presented in the next section. The connection as a length of approximately 400 kilometres and Figure 3.23 has a representation of the network in a map.

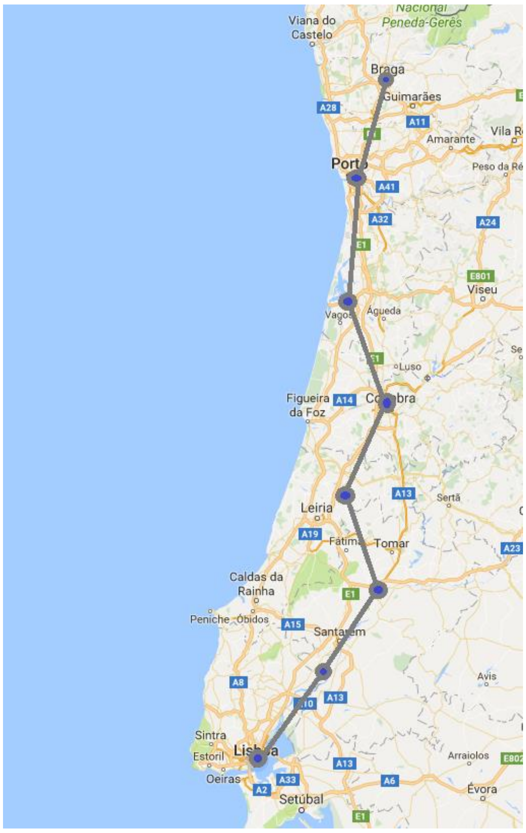

Figure 3.23 Map of the project

3.3.2 Project Simulation

The first thing to introduce in order to build this system is to open a new window, add a transmitter block and edit the parameters for the transmitter. The project was divided into two implementations: in the first one a transmitter with internal modulation was used and in the second one an external modulation was used. The representation of the system in the simulator is presented in Figure 3.24.

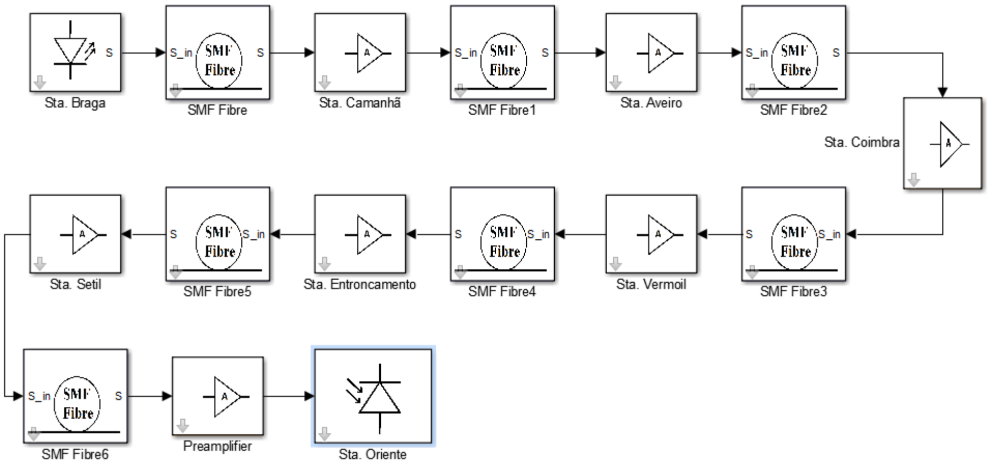

Figure 3.24 Representation of the FCCN project in the simulator

The considerations for this system were every amplifier gain is equal to the loss of the fibre before it, there is a use of preamplification on the last amplifier before the receiver and the parameters of the transmitter are presented in Table 3.8. The only parameter that is missing in that table is the number of channels that is 32 channels.

Table 3.8 Transmitter parameters for FCCN project simulation

$B\ [Gbps]$	$Pe\ [dBm]$	$\Delta v\ [GHz]$	$\lambda\ [nm]$	$OSNR\ [dB]$	$\Delta v_{ch}[GHz]$	$Rex\ [dB]$	C	$RIN\ [dB/Hz]$	K	$t_j\ [ns]$
2,5	0	1	1550	40	50	10	0,5	−130	0,01	0,01

The first implementation of the project used an internal modulation, which means that the chirp parameter needed to be taken into account. The chirp parameter was set as 0.5, a standard value for this parameter. For the external modulation, the only difference in the parameters was that the chirp parameter was set as 0. Figure 3.25 shows the values that were inserted in each parameter. Since the number of channels surpasses 10 channels, the transmitted power and the linewidth of the 32 channels is the same as the one that was implemented for the first channel.

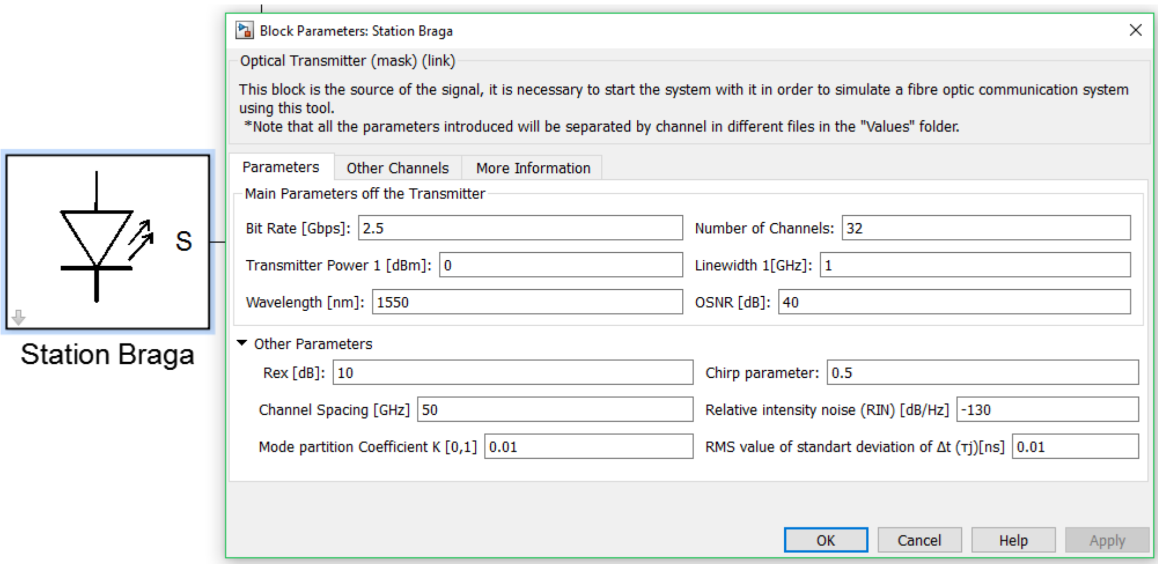

Figure 3.25 Transmitter block parameters for the FCCN simulation project.

The wavelength for the first channel is $1550\ [nm]$, and since the channel spacing is set as $\Delta v_{ch} = 50\ [GHz]$, the wavelength of each channel is compressed in the interval $[1537{,}68\ ;\ 1550{,}00]\ [nm]$. The $OSNR$ at the exit of the transmitter was set as $40\ [dB]$ because it is the standard value for the $OSNR$ of the transmitter. The bit-rate was set as $2.5\ [Gbps]$ and the rest of the values kept the standard values (Figure 3.25). The system was also tested with a bit-rate was set as $10\ [Gbps]$. However, the dispersion penalty in the system surpassed the maximum value that is set for this parameter and the bit-rate was changed to 2.5 $[Gbps]$ in order to meet the requirements for the maximum power penalty due to dispersion.

The fibre links that connect each station were SMF-28 fibres. Their parameters were different according to the information provided for each connection (Table 3.7). The insertion loss of each fibre was taken into account as the loss from the splices and connectors. The values from Table 3.7 were inserted in the fibre block represented in Figure 3.26.

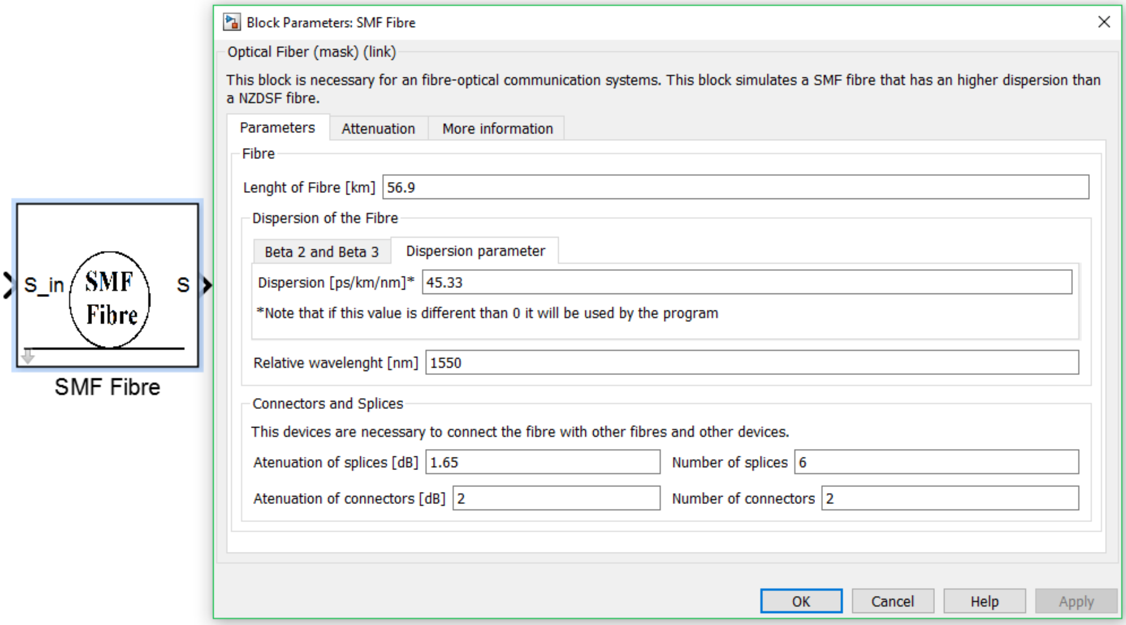

Figure 3.26 SMF fibre block parameters for the FCCN simulation project

The attenuation of each fibre had to be inserted with the custom attenuation option, since the attenuation changes between some intervals of wavelength. Figure 3.27 shows a representation of the insertion of the custom attenuation in the first fibre, in the attenuation tab.

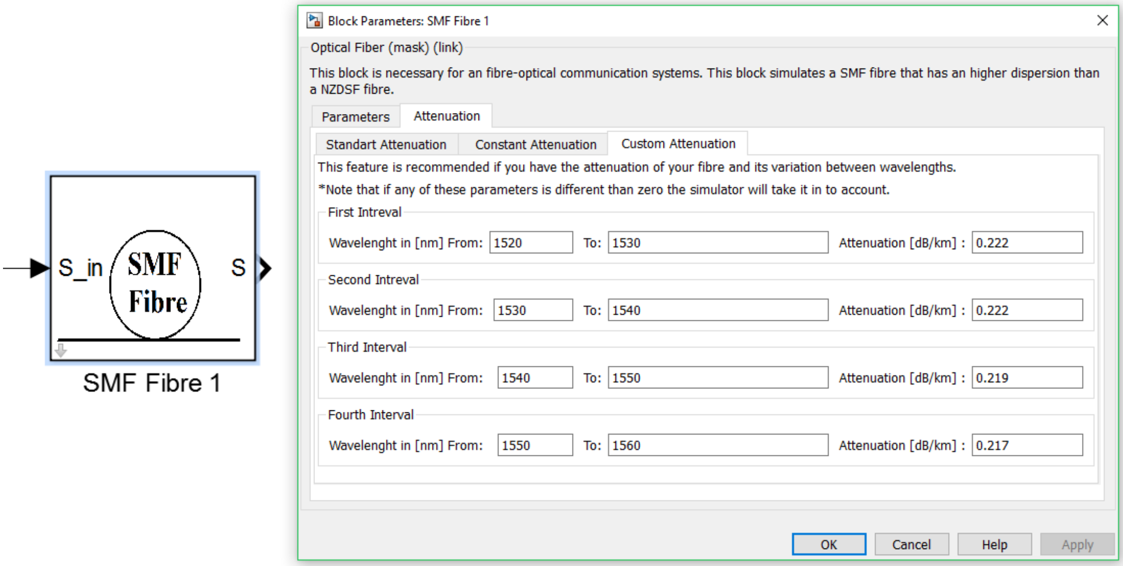

Figure 3.27 SMF fibre block custom attenuation demonstration for the FCCN simulation project

The block that inserted afterwards was the amplifiers for each station of the connection. The amplifier's gain was set to have a gain equal to the losses from the fibre. Thus, the gain changes from amplifier to amplifier, but the other parameters stay the same. Figure 3.28 is a representation of the parameters inserted in the first amplifier. The noise figure was set as $6\ [dB]$, the saturation power as $30\ [dBm]$ and the amplifier bandwidth at $3\ [nm]$.

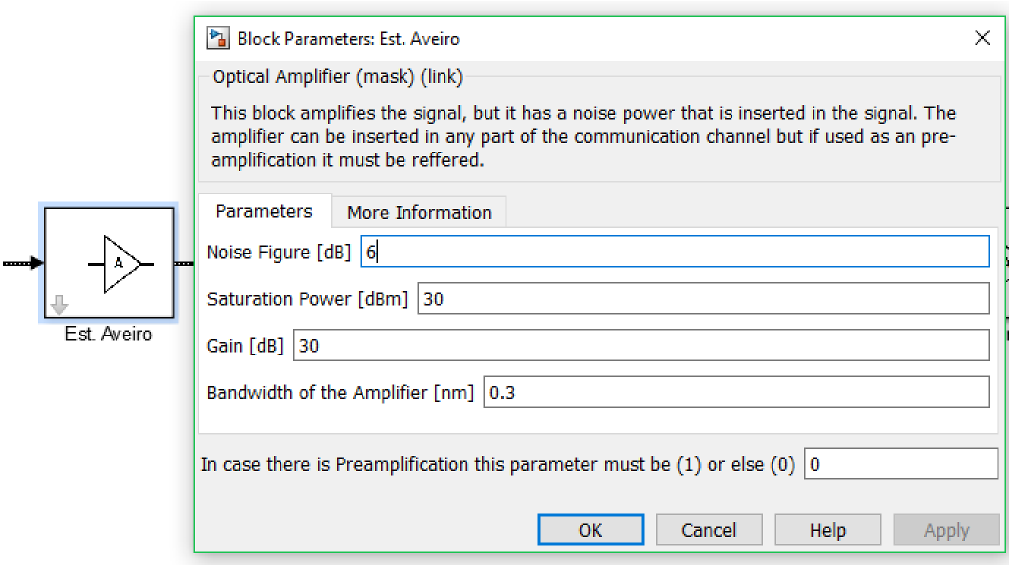

Figure 3.28 Amplifier block parameters for the FCCN simulation project

The last amplifier before the receiver is a preamplifier, so the last value of the amplifier block was set as “1”. The last block inserted in the system was the receiver. The values from this block were not changed from the standard values as it can be observed in Figure 3.29.

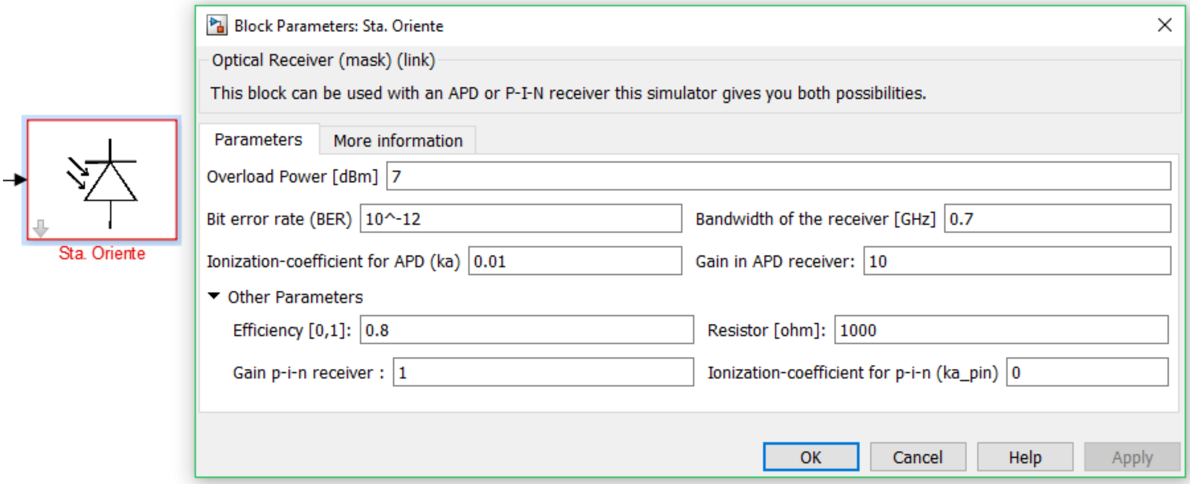

Figure 3.29 Receiver block parameters for the FCCN simulation project

3.3.2.1 Project with Internal Modulation

The first test of the FCCN project simulation used an internal modulation. As it was mentioned before, the difference of using internal and external modulation with this simulator is that the chirp parameter was set as 0.5. The values obtained for the transmitter are represented in Figure 3.30, these values do not add any other information about the transmitter, beside the transmitter noise. The value for the transmitter noise is determined if the values of the OSNR and transmitted power are known.

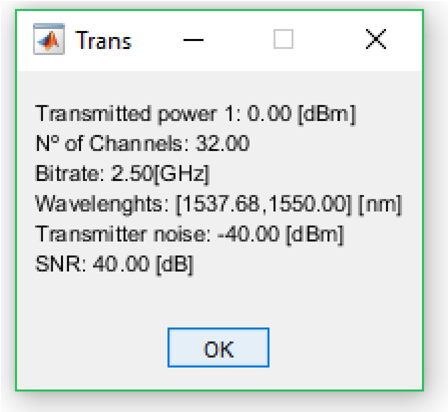

Figure 3.30 Transmitter message box in FCCN system

The values obtained in each amplifier and provided by the respective message box are represented in Table 3.9. The parameters mentioned are: the received power P_r, the received noise P_{n_r}, the gain G, the transmitted power P_t, the transmitted noise P_{n_t}, the ASE noise power or the noise of the amplifier P_{ASE} and the $OSNR$ at the end of the amplifier.

Table 3.9 Amplifier values provided by the amplifier message box in FCCN system

$Amplifiers$	P_r $[dBm]$	P_{n_r} $[dBm]$	G $[dB]$	P_t $[dBm]$	P_{n_t} $[dBm]$	P_{ASE} $[dBm]$	$OSNR$ $[dB]$
1	$-23{,}96$	$-63{,}96$	25	1,04	$-19{,}15$	$-36{,}18$	20,19
2	$-27{,}97$	$-48{,}16$	30	2,03	$-12{,}72$	$-31{,}17$	14,75
3	$-24{,}32$	$-39{,}07$	28	3,68	$-9{,}90$	$-33{,}17$	13,59
4	$-27{,}38$	$-40{,}97$	30	2,62	$-12{,}72$	$-31{,}17$	11,89
5	$-24{,}13$	$-36{,}02$	28	3,87	$-7{,}40$	$-33{,}17$	11,28
6	$-20{,}83$	$-32{,}10$	22	1,17	$-9{,}84$	$-39{,}14$	11,02
7	$-23{,}96$	$-63{,}96$	25	1,04	$-19{,}15$	$-36{,}18$	20,19

The values of the transmitted power of the amplifier are the only values that are consistent. This comes from the fact that the amplifier gain changes in order to keep the transmitted power of the amplifiers similar to the transmitted power of the transmitter, 0 $[dBm]$. The objective of doing this is the same as keeping the amplifier's gain equal to the attenuation in the fibre. This power is not exactly equal to the loss of the receiver, this happened because after the simulation, it was discovered that if the power was kept at 0 $[dBm]$, the system's margin would be lower than 6 $[dB]$. The correct approach would be to add a preamplifier, but the difference was approximately 3 $[dB]$. Thus, it did not make sense to add an amplifier with a such lower gain and using a preamplifier would change the formula for the sensitivity, and ultimately the system would end up having a system margin approximately to 30 $[dB]$, which would be too much backup power. The final solution that was implemented was to add some power to the amplifiers that result in the power at the end of the amplifiers being slightly over 0 $[dBm]$.

The received power and received attenuation differ from each amplifier, since these values are attenuated in the fibres and each fibre has different length and attenuation. However, the values of the noise power received seem to be increasing, because the noise was accumulated throughout the systems. Even though the noise power is attenuated in the fibre, the noise is amplified in the amplifier, equal to the losses in the fibre and also ads the noise power of the new amplifier. The $OSNR$ keeps decreasing due to reasons presented before. The transmitted power is kept similar throughout the fibre and the noise power keeps increasing. However, it can be observed in Figure 3.31 and the values in Table 3.9 that the $OSNR$ keeps decreasing at slower pace, even though the noise figure for each amplifier is still $6\ [dB]$. The reason for this phenomenon is the fact that the noise power in the fourth amplifier is already at a value, in which the added noise power afterwards is not that different from the existing noise in the system. Also, Figure 3.31 shows a graphic of the power in the fibre. The last two power values are the same, since between the preamplifier and the receiver there is no source of power loss.

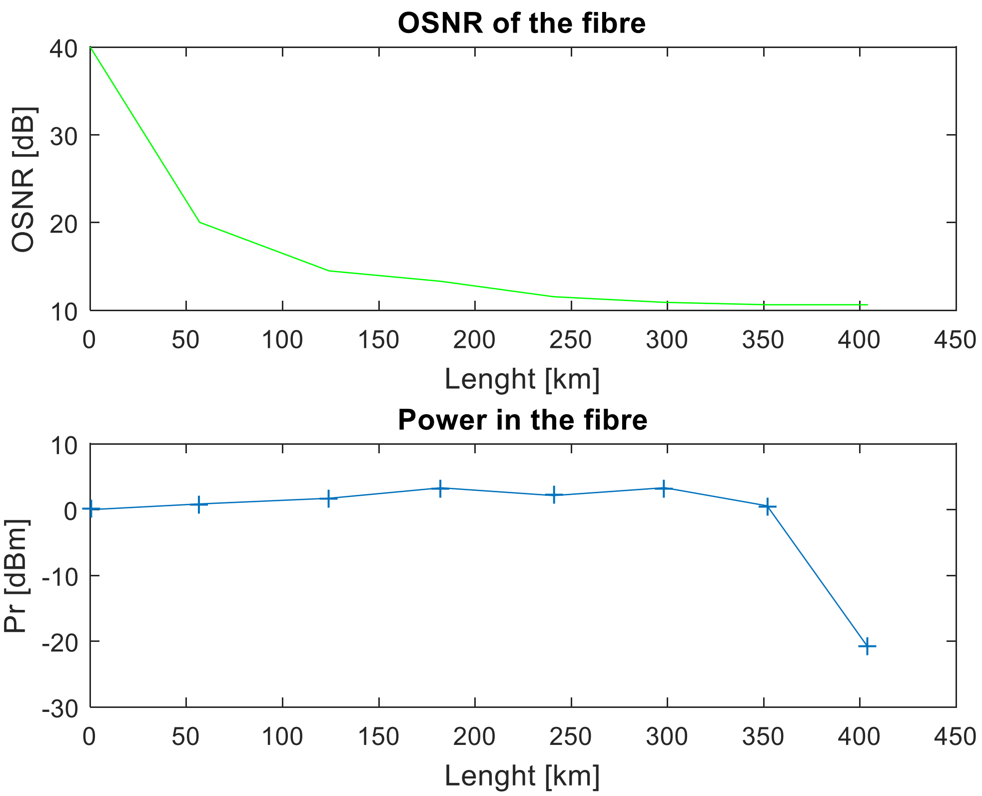

Figure 3.31 Graphical analysis provided by the simulator of the OSNR and power thought out the fibre

The loss of power in the last section of the fibre is due to the fact that no preamplifier was used. Thus, the last attenuation caused by the last section was not amplified until the signal reaches the receiver. The final results from the simulation are obtained by the receiver (Figure 3.32). There are two types of values that are obtained, because the receiver block works as a PIN receiver and as an APD receiver at the same time.

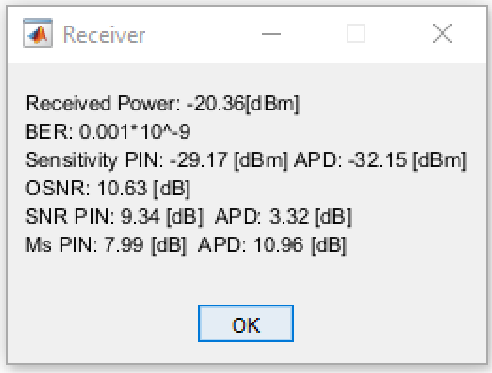

Figure 3.32 Receiver message box in FCCN system with internal modulation

Through comparing the receiver sensitivity for each type of receiver, it can be concluded that for this case the APD receiver has the bigger system margin. This conclusion is possible since a greater sensitivity will result in a bigger system margin, and this assumption can be observed in Figure 3.32. The value for the $OSNR$ is the same for both types of receivers, since is the signal to noise ratio of the optical signal before reaching the receiver. The SNR at the receiver will be lower, because it takes into account the inserted noise from the receiver and all the other noise that reaches the receiver.

The non-linear effects taken into account did not report any detection. Thus, it is not necessary to change the system power in order to comply with the non-effects requirements. The OSNR changes per wavelength, this phenomenon can be observed in Figure 3.33. The changes in the OSNR presented in the graphic of Figure 3.33 have an abrupt variation, this phenomenon happens in this project because the information of the attenuation in the fibre changes abruptly and not gradually, these values can be observed in Figure 3.28. The received power also does not surpass the overload power. The received power is lower than 7 $[dBm]$ and the warning message if this value was surpassed was not showed. In addition, the maximum value for the power penalty due to chromatic dispersion was not surpassed since the value for this power penalty was around $0{,}11$ $[dB]$ and the maximum value is 2 $[dB]$.

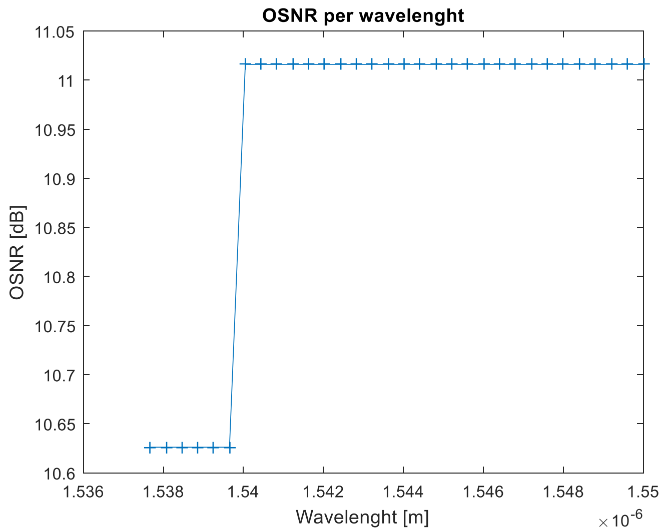

Figure 3.33 Graphical analyses of the OSNR per wavelength in the FCCN system

The last observation that can be made about this system is about the graphical analysis of the system's margin, presented in Figure 3.34. The information presented in Figure 3.32 about the system's margin, contains only the system's margin for the first channel. However, there is a need to verify if all the channels comply with the minimum system's margin required.

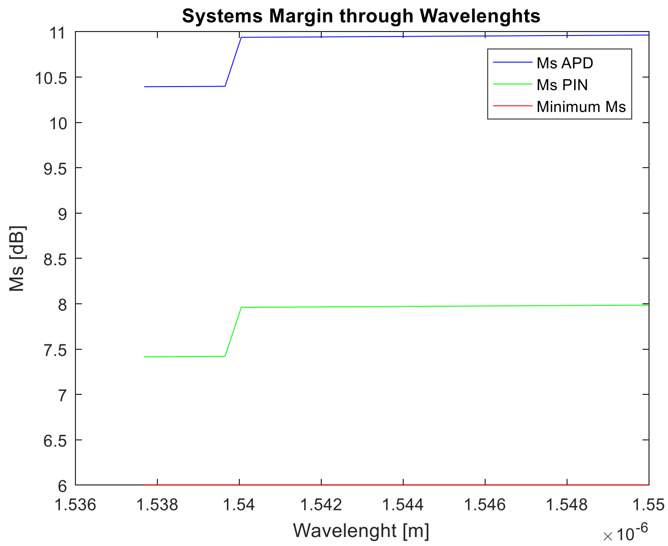

Figure 3.34 Graphical analyses of the system's margin per wavelength in the FCCN system

In Figure 3.34 the red line represents the minimum system's margin, it is possible to conclude that the system's margin for APD and PIN receivers is higher than the minimum required margin for all wavelengths. Thus, it is possible to conclude that the system complies with the minimum required system's margin.

3.3.2.2 Project with External Modulation

The use of external modulation will, in theory, have a higher system margin, which comes from the fact that the chirp parameter is set as zero. Therefore, the power penalty due to chromatic dispersion will be lower than with internal modulation. Figure 3.35 represents the values that were obtained by the receiver with external modulation. Besides the values that are returned by the receiver, the rest of the values of the system will not be altered.

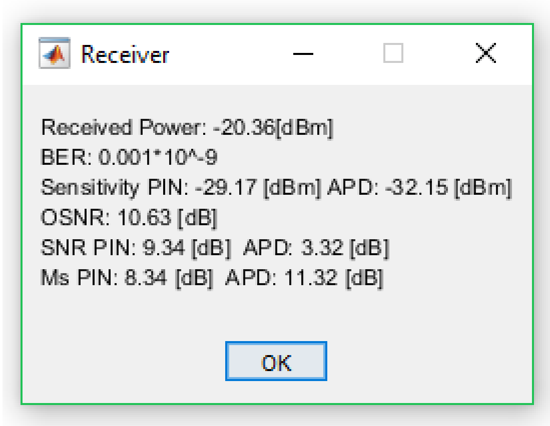

Figure 3.35 Receiver message box in FCCN system with external modulation

The system's margin, observed in Figure 3.32 and Figure 3.35, is higher with external modulation, following the theoretical analysis that was set beforehand. It can be concluded that the use of external modulation can be beneficial to the system, in this case, the system margin is significantly higher than the minimum value for this parameter, $M_s > 6[dB]$. However, in some cases the differences between both techniques can make one of the receiver's types comply with the minimum margin and the other does not. Figure 3.36 contains the graphical representation of the system's margin for each channel, which agrees with the previous conclusion that the system has a higher system margin with external modulation, than with internal modulation.

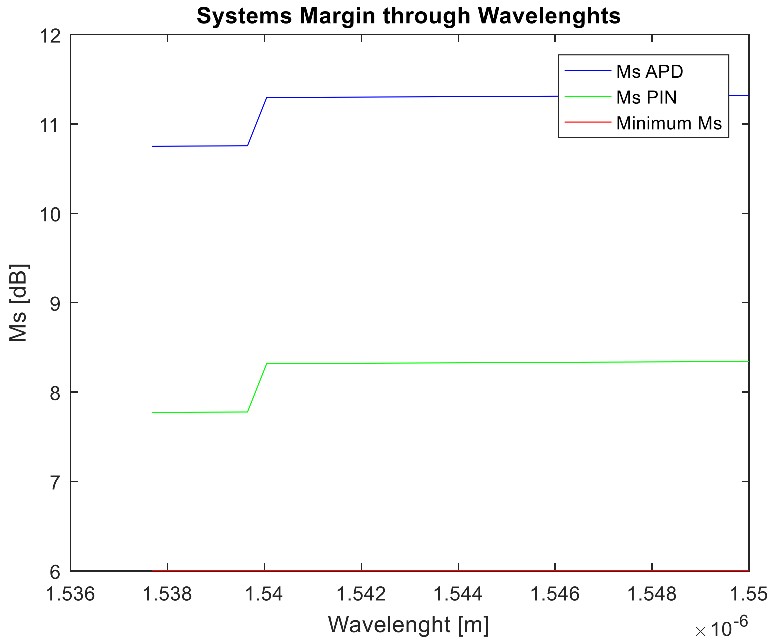

Figure 3.36 Graphical analyses of the system's margin per wavelength in the FCCN system with external modulation

Chapter 4

4. Conclusions

The project planning tool developed in this project was implemented as a library for MATLAB's Simulink. This implementation was tested against its own theoretical design and against another simulator of fibre optics communications planning tool. Those tests stated the viability of the program and its main goal that was providing a free developing tool for MATLAB's Simulink.

The project was also tested with a real-life project that was already implemented and with some values were given to the University. The simulation of the project proved the resourcefulness of the program against a real-life project and how it's simulation can be build using the provided tools. The project was also provided with a simple construction of the systems' components. Even though the simulation was not made to the signal level, the information provided by the simplification of the system was enough to provide a simple and precise conclusion about the viability of the system.

The analyses of the test concluded that the noise power is propagated throughout the system, resulting in the decrease of the $OSNR$ throughout the system. The tests, also provided a clear explanation between the different types of receivers and a comparison between internal and external modulation.

The simulator also did not provide an economic analysis of the system, since it opted for a more open approach to each equipment, providing the possibility to compare two types of receivers at the same time or test any type of fibre simply by inserting the values, for example. However, standard values were inserted for known types of fibres and there was no access to the equipment's cost.

The outputs provided by the simulator are more than sufficient for a user to identify the main parameters of his system. The outputs being an excel spreadsheet with the main matrix that transmits the values throughout the fibre, a text base document with detailed information on each channel, and the Simulink outputs, which consist of a graphical analysis of the $OSNR$ and the power throughout the system. The system also provides a comparison of the SNR of the system for the different channels, if the user is using more than one channel, and the systems margin for the different channels and receivers.

The non-linear effects that can occur in a fibre optics system were implemented in the simulator. However, the FWM was not included due to the excessive complexity of its implementation without a simulation of the communication at the signal level.

In conclusion, the simulator provides the ability to construct systems combining professional and academic components in a free access developing tool. The use of Simulink simplifies the construction of systems by simply dragging each model and add it to the system. This tool also provides the ability for students to understand and compare their results with the results provided by this simulator, from the insertion of each component and their benefits and problems for the systems, as each parameter that is taken into account by this program.

3.4 Future Work

The development of the program was made with the possibility to grow, there were always possibilities for its improvement by adding complexity to the simulator. The suggestions aim to add more complexity and versatility to the program, providing the capacity to construct even more complex systems, since this project was planned to be the foundation for a much bigger project than the one built by students throughout the years. The suggestions are the following:

- Adding multiple types of modulation.
- Adding more models with equipment predefined from the suppliers.
- The continuous improving the interface according to the user perspective.
- Introducing standard market cost for the main components.
- The insertion of Passive optical network (PON) technology.
- Identifying and correct possible errors reported by the user.
- Providing the most cost efficient solution for the system.
- Adding other types of fibres, such as DCF.

References

[1] International Telecommunications Union, “Statistics,” ITU, 2016. [Online]. Available: http://www.itu.int/ict/statistics. [Accessed 02 10 2016].

[2] TeleGeography, “Submarine cable map,” TeleGeography, 2016. [Online]. Available: http://www.submarinecablemap.com/. [Accessed 16 09 2016].

[3] G. P. Oslin, The Story of Telecommunications, Mercer University Press, 1999.

[4] R. W. Burns, Communications: An international history of the formative years, The Instutuition of Electrical Engineers, 2004.

[5] J. Hecht, City of Light: The Story of Fiber Optics, Oxford University Press, 2004.

[6] Corning, “Smithsonian features Corning’s optical fiber,” [Online]. Available: https://www.corning.com/worldwide/en/innovation/culture-of-innovation/cornings-invention-of-the-first-low-loss-optical-fiber-featured-in-new-smithsonian-innovation-wing.html. [Accessed 05 09 2016].

[7] Organisation for Economic Co-operation and Development , “Statistics News Releases,” Organisation for Economic Co-operation and Development , 2016. [Online]. Available: http://www.oecd.org/std/statisticsnewsreleases.htm. [Accessed 13 11 2016].

[8] O. f. E. C.-o. a. D. (OECD), “http://www.oecd.org,” OECD, 02 02 2017. [Online]. Available: http://www.oecd.org/internet/broadband/oecdbroadbandportal.htm. [Accessed 07 02 2017].

[9] G. P. AGRAWAL, Fiber-Optic Communication Systems, John Wiley & Sons, Inc., 2002.

[10] L. N. Binh, Optical Fiber Communication Systems with MATLAB and Simulink Models, CRC Press, 2015.

[11] R. Borkowski, E. P. D. SIlva, J. C. M. Diniz, S. Gaiarin, M. Iglesias, M. Piels and D. Zibar, “Robochameleon,” DTU, [Online]. Available: http://dtu-dsp.github.io/Robochameleon/. [Accessed 30 02 2017].

[12] G. M. d. S. Horta, “Planning tool for fiber optic communication systems:Access and Transport network,” ISCTE-IUL, Lisboa, 2015.

[13] VPIphotonics, “Link Configurator,” VPIphotonics, [Online]. Available: http://www.vpiphotonics.com/Tools/LinkConfigurator/. [Accessed 18 11 2016].

[14] Synopsys, “Receiver Sensitivity,” Synopsys, [Online]. Available: https://optics.synopsys.com/rsoft/application-gallery/optsim-receiver-sensitivity.html. [Accessed 02 12 2016].

[15] P. S. J. R. F. C. Gonçalo Horta, “Efficient planning tool for fiber optic communication systems access and transport nertwork,” ISCTE-Instituto Universitário de Lisboa, Lisboa, 2016.

[16] A. Cartaxo, Sistemas de Telecomunicações por fibra óptica, Lisboa: AEIST.

[17] T. Janevski, “NGN Architectures, Protocols and Services,” John Wiley & Sons, Inc., 2014.

[18] V. Alwayn, “Fiber-Optic Technologies,” Cisco Press, 23 04 2004. [Online]. Available: http://www.ciscopress.com/articles/article.asp?p=170740&seqNum=7. [Accessed 02 12 2016].

[19] Corning, “Corning SMF-28 Ultra Optical Fiber,” 2014. [Online]. Available: https://www.corning.com/media/worldwide/coc/documents/Fiber/SMF-28%20Ultra.pdf. [Accessed 02 12 2016].

[20] Corning, “Corning LEAF fibre,” 2014. [Online]. Available: https://www.corning.com/media/worldwide/coc/documents/Fiber/LEAF%20optical%20fiber.pdf. [Accessed 02 12 2016].

[21] G. P. Agrawal, in *LIGHTWAVE TECHNOLOGY Telecommunication Systems*, Rochester, NY, John Wiley & Sons, Inc., 2005.

[22] J. A. Salla, A. C. González, J. F. Borrull, J. R. d. F. Moneo, I. J. Prades, E. M. Badosa, E. P. Aguilera, R. T. Fernández and J. M. Soler, “JOptics Curso de Óptica,” DTU, [Online]. Available: http://www.ub.edu/javaoptics/. [Accessed 07 12 2016].