Universidade de Aveiro Departamento de Eletrónica, Telecomunicações e Informática
2014

Hugo Miguel Moreira de Almeida

Planeamento de Redes de Transporte de dados para o SKA (Square Kilometre Array)

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Doutor Paulo Monteiro, Professor Associado do Departamento de Eletrónica Telecomunicações e Informática da Universidade de Aveiro e coorientação do Doutor Rui Ribeiro, Professor Auxiliar do Departamento de Eletrónica Telecomunicações e Informática da Universidade de Aveiro.

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A todos o meu muito obrigado.

palavras-chave

Redes de transmissão óptica; SKA; DWDM; Sistemas de Detecção Directa; Sistema Duobinario.

resumo

O SKA (Square Kilometre Array) pretende ser o maior e mais sensível radiotelescópio do mundo com uma dimensão de um quilómetro quadrado (um milhão de metros quadrados) de área efetiva, esperando que seja capaz de esclarecer algumas das principais questões sobre o universo. Este projeto encontra-se atualmente na fase preparatória já tendo sido estabelecidas as regiões e as distribuições das várias antenas e a localização das unidades de processamento de sinal e armazenamento.

Por forma a atender os requisitos científicos, o SKA é compreendido por milhares de recetores de ondas de rádio (antenas) que necessitam de ser interligados a uma unidade de processamento e armazenamento de dados central. As distâncias de transmissão e a sua capacidade dependem da configuração e do género de antenas.

Esta dissertação pretende apresentar um planeamento e otimização de Redes de Transporte entre as antenas e as unidades de processamento central, por forma apresentar uma solução económica e com eficiência espectral.

keywords

Optical transmission networks; SKA; DWDM; Direct Detection systems; Duobinary system.

abstract

The SKA (Square Kilometre Array) will be the world's largest and most sensitive radio telescope with a square kilometre (one million square metres) of collecting area, expecting to be able to clarify some of the main questions about the universe. This project is currently in the preparatory phase, having already established the regions and distributions of the various antennas and the location of signal processing and storage units.

In order to satisfy the scientific requirements, the SKA is comprised of thousands of radio wave receivers (antennas) that need to be connected to a processing unit and data centre storage. Transmission distances and capacity depend on the configuration and type of antennas.

This dissertation intends to submit a planning and optimization of transport networks between the antennas and the central processing units, in order to present an economic and spectral efficiency solution.

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Acronyms

16QAM	16 Quadrature Amplitude Modulation
APD	Avalanche Photodiode
ASE	Amplified Spontaneous Emission
ASKAP	Australian Square Kilometre Array Pathfinder
ASIC	Application-Specific integrated Circuit
ATM	Asynchronous-transfer-mode
AWG	Arrayed waveguide grating
BER	Bit Error Rate
CD	Chromatic Dispersion
CFP	Central Form-factor Pluggable
CMOS	Complementary Metal-Oxide-Semiconductor
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	Central Signal Processing
CWDM	Coarse Wavelength Division Multiplexing
DDBH	Digital Data Back Haul
DFB	Distributed Feedback Laser
DP-16QAM	Dual-Polarization 16 Quadrature Amplitude Modulation
DP-QPSK	Dual-Polarization Quadrature Phase Shift Keying
DRA	Distributed Raman Amplifier
DWDM	Dense Wavelength Division Multiplexing
EDF	Erbium Doped Fibre
EDFA	Erbium Doped Fibre Amplifier
ICT	Integrated Coherent Transmitter
ICTON	International Conference on Transparent Optical Networks
IEEE	Institute of Electrical and Electronics Engineer
IM-DD	Intensity Modulation – Direct Detection
ISI	Inter-symbol Interference
ITU-T	International Telecommunication Unit - Telecommunication Standardization Sector

LEAF	Large Effective Area Fiber
MeerKAT	The South African precursor array being built on site in the Karoo
MSA	Multi-Source Agreement
MZM	Mach-Zehnder Modulator
NF	Noise Figure
NRZ	Non-Return-to-Zero
NZDSF	Non-Zero Dispersion-Shifted Fibre
OA	Optical Amplifiers
ODB	Optical Duobinary Modulation
OIF	Optical Internetworking Forum
OFC	Optical Fiber Communication Conference
OOK	On-off Keying
OSNR	Optical Signal-to-Noise Ratio
PD	Photodiodes
PIC	Photonic Integrated Circuit
PMD	Polarization Mode Dispersion
QSFP	Quad (4-channel) Small Form-factor Pluggable
QFSK	Quadrature Phase Shift Keying
ROSA	Receive Optical Sub-Assembly
SADT	Signal and Data Transport Synchronisation and Timing
SBS	Stimulated Brillouin Scattering
SONET	Synchronous Optical Networking
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
SFP	Small Form-factor Pluggable
SFP+	Enhanced Small Form-factor Pluggable
SKA	Square Kilometre Array
SKAO	Square Kilometre Array Organization
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifier

TIA/EIA	Telecommunications Industry Association / Electronics Industries Alliance
TOSA	Transmit Optical Sub-Assembly
UK	United Kingdom
VOA	Voltage Optical Attenuator
XFP	10 Gigabit Small Form-factor Pluggable
XPM	Cross Phase Modulation
WDM	Wavelength Division Multiplexing

Chapter 1
Introduction

SKA (Square Kilometre Array) is a worldwide science project which aims to be the key of unanswered questions about the universe such as how the first stars and galaxies formed after Big Bang and how they have evolved since then, the origin and evolution of cosmic magnetism and dark energy, prove the gravity of black holes or even be able clarify if life exists beyond Earth [1].

Around 100 organizations across 20 countries have been participating in the design and development of SKA. The SKAO (SKA Organization, responsible for coordinating the global activities including all engineering science work) headquarters is located at Jodrell Bank Observatory, [1], near Manchester UK.

The SKA will use thousands of linked radio wave receptors in three configurations (SKA low, mid and survey) in order to enable the monitoring of the sky in maximum detail and survey the entire sky thousands of times faster than any other currently existing system. The members of the SKA Organisation decided to distribute these three configurations in two sites, one between Western Australia at the Murchison Radio Observatory (near Boorlardy Station) and the other in Karro Central Astronomy Advantage Area (extended eventually to other countries in Southern Africa). South Africa's Karoo desert will cover the core of high and mid frequencies (SKA-mid), which will have telescopes spread all over the continent). Australia's Murchison region will cover the low frequency range and the survey instrument (SKA-low and SKA-survey) [1] [2].

This project will be built in two main phases, between 2018 and the mid 2020's. The SKA Phase 1 (SKA1) will be the installation phase of the telescopes. In Australia will be host low-frequency telescopes with more than 900 stations, each containing approximately 300 individual dipole antennas capturing frequencies from 50MHz to 350MHz (forming the SKA1-low) as well a 96-dish SKA1-survey telescope, incorporating the already exiting 36-dish ASKAP (Australia Square Kilometre Array Pathfinder) [3]. South Africa will host an array of 254 dishes, incorporating the 64-dish of South African MeerKAT precursor telescope [4]. The SKA Phase 2 (SKA2), estimated to start in 2022, shall become fully operation in mid of 2020's. At the end of this phase several thousand mid frequency telescopes and aperture arrays will be adding to the millions of low frequency antennas [2].

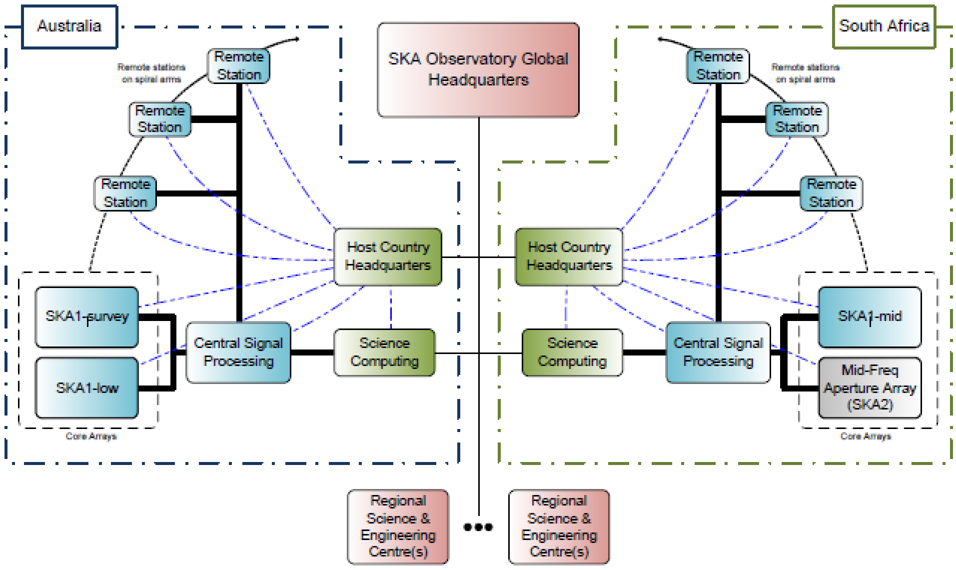

Figure 1 - Schematic diagram of SKA Observatory, showing the distribution of the telescopes and the entities at regional and global centres [1]

1.1 Motivation

The SKA project is currently at a preparatory stage and there are some aspects of implementation which require an intensive study to discover the best solution in each case. This Dissertation is intended to choose the right option for transmission between the Central Science Processor facility (CSP) and the antennas. The chosen solution must be the most efficient and the least costly, since it will be repeated for thousands of antennas and will have a big impact on the final project budget.

1.2 Objectives

This dissertation aims to focus on the planning and optimization of transmission data for the SKA, with the following main objectives:

- Identification of use cases for data transport;
- Study of the appropriate techniques depending on the optical transmission rate and transmission distance;
- Study VPIphotonics simulator for simulation of optical communication systems;
- Simulate identified scenarios and respective optimization;

- Definition of specifications for optical systems used in different scenarios.

1.3 Stucture

This document is structured as follows:

Chapter 1 Introduction presents the framework, the motivation of the project and the main objectives and contributions of this dissertation.

Chapter 2 State of the Art presents a summary of theoretical concepts needed in this dissertation (DWM, modulation formats modelling) and also the main technologies and devices that exist today on the market that can be used in this project.

Chapter 3 Architecture presents the expected distribution of the antennas for the various configurations of the SKA, an optimization from the viewpoint of the cost of the distribution of antennas and the CSP, and descriptions of the studied solutions, both for mid-SKA1 and SKA1-survey.

Chapter 4 Simulations presents the implementation through VPI simulations of the solutions previously presented.

Chapter 5 Conclusions and Future work appointing the main conclusions of the Dissertation and to define the future work that will be done for the continuation of the project.

1.4 Contributions

As a result of achieving the objectives proposed above, this Dissertation provides the following set of contributions:

- Identification and characterization of optical devices which can be used in SKA transport solutions (transceivers, amplifiers, multiplexers, optical fibres);
- Study the best location (in terms of costs) of Central Science Processor facility (CSP) and antennas for SKA1-mid and SKA1-survey;
- Study of Dense Wavelength Division Multiplexing (DWDM) solution, using Intensity Modulation – Direct Detection (IM-DD) and Optical Duobinary Modulation (ODB) for the transmission of CSP-antenna link (studying the effects of fibre dispersion, link amplification and integration of all channels) for SKA-mid and SKA1-survey;

- Contribution in the realization of the Horizon Scan Report for Signal and Data Transport (SADT) Consortium (SKA group responsible for the design of the transport networks);
- Contribution in a publication on the 16th International Conference on Transparent Optical Networks (ICTON): ‘’*Challenges in Digital Data Backhaul Networks for Square Kilometre Array Radio Telescope*’’ [5].

Chapter 2
State of Art

2.1 Wavelength Division Multiplexing

Many different wavelengths can be sent along a single fibre simultaneously. This technique of combining multiple wavelengths in the same fibre is named Wavelength Division Multiplexing (WDM), and it upgrades the capacity of point-to-point fibre optic transmission links (for example if one wavelength supports an independent network channel of few gigabits per second, WDM can dramatically increase the capacity with each additional wavelength channel). WDM provides also a much easier and low cost protection for switching to a backup path, because in case there are many channels carried on the same fibre, it will be only necessary to switch a single fibre. Another advantage of WDM is the possibility to carry different transmission formats, allowing digital and analogue information to be transmitted simultaneously without the need of a common signal structure. WDM also avoids the use of electronic means to switch optical signal at a node, it can be done with pure optical end-to-end connections between users (using *ligthpaths* which are routed and switched at intermediate nodes in the network) [6] [7].

The original use of WDM was achieved with wavelengths that were separated from several 10's ups to 200 nm in order not to impose strict wavelengths-tolerance in different sources and receivers. With the DFB lasers, with narrow bandwidth and high wavelength stability the channel spacing could be less than a few nanometres [7].

2.1.1 WDM link

WDM networks require a variety of passive and/or active devices to combine, attenuate, add, drop, and amplify the optical power of the different wavelengths. Passive devices are the components used to split or combine optical signals, not needing external control. Active components are devices controlled electronically, such as tunable optical filters, tunable sources, multiplexers and de-multiplexers, optical switches and optical amplifiers. The simple WDM link can be described by the follow scheme (Figure 2):

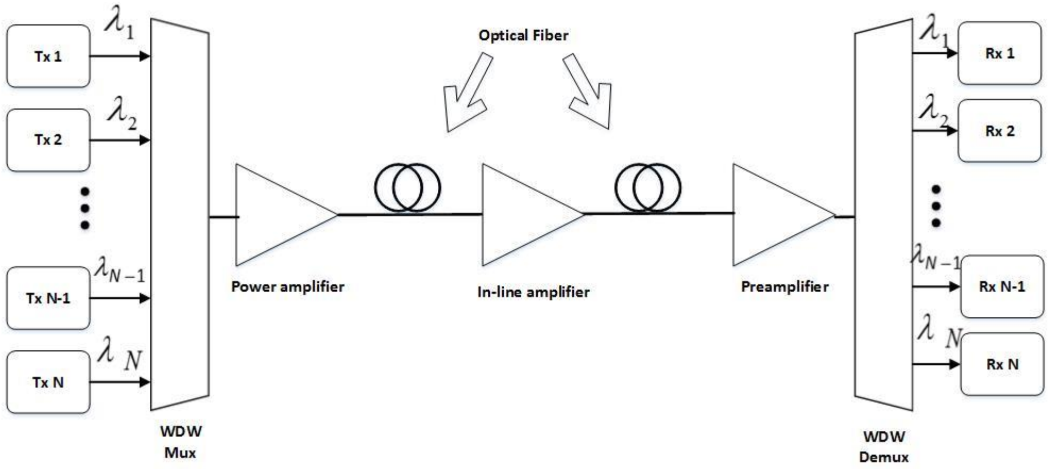

Figure 2 - Implementation of a simple WDM link

The transmitter has a series of fixed-wavelength or a tunable modulated light sources, each with a unique wavelength. The multiplexer is used to combine the optical outputs into a continuous spectrum of signals and couple them onto a fibre. Along the link several amplifiers can be used to compensate for the attenuation that the signal takes along the transmission. The distance between the amplifiers is called 'span'. The de-multiplexer has the function of separating the signals into detection channels for signal processing.

At the transmission level it is very important to ensure that the multiplexer has a low insertion loss from each optical source to the multiplexer output. At the receiver the photo-detectors are sensitive for the bid range of wavelengths, which could include the WDM channels, so it is important to give good channel isolation for the different used wavelengths [7].

2.1.2 WDM Technologies

There are two main types of WDM technologies: Dense Wavelength Division Multiplexing (DWDM) and Coarse Wavelength Division Multiplexing (CWDM).

DWDM enables large channel counts within a limited spectral band. DWDM technologies are capable of multiplexing 32, 64 or 128 wavelengths into a fibre, and with amplification DWDM links can achieve thousands of kilometres. The main disadvantage is the need of high-precision filters to select one specific wavelength without interfering with neighbouring wavelengths (due to tight spectrum), which may increase the cost of the system.

CWDM match the basic capabilities of DWDM but at lower capability and lower cost. It was created to respond to diverse customer needs in metropolitan regions and it is intended for short distances. It uses a wide-range frequency and spreads wavelength while supporting a few channels, this being more adequate for metro carriers [8].

2.1.3 Performance Measurements

As the optical signal travels along the link, it becomes attenuated due the loss of mechanism of the fibre, at connectors and other components and also due to factors such as chromatic dispersion, polarization mode dispersion nonlinear effects on the fibre and various electrical and optical noises. The optical power level at the end of a link defines the signal-to-noise-ratio (SNR) at the receiver, which is used to measure the performance of the system. In digital systems a photo-detector in the receiver produces an electrical current proportional to the incident optical power level. This current is compared with a threshold to determine if the bit is 1 or 0. Various noise and interference effects cause deviations and can lead to errors in the interpretation of the signal [7].

2.1.3.1 Bit error rate

The most common quality measurement for digital links is bit error rate (BER) [9]. It is also known as error probability, which is commonly abbreviated as P_e. BER is defined as the number of bit errors N_e divided by the number of total bits N_t sent during an interval of time. So a BER value of 10^{-12} means that on average one error occurs for every trillion pulses sent. The SNR (or Q) and BER can be related (using Gaussian approximation) through the expression:

$$BER \approx \frac{1}{\sqrt{2\pi}} \int_{0}^{\infty} \exp\left(-\frac{x^2}{2}\right) dx \approx \frac{1}{\sqrt{2\pi}} \frac{e^{-Q^2/2}}{Q} \tag{2.1}$$

This approximation is reasonably accurate for Q > 3. Figure 3 shows how the BER varies with the Q parameter. The BER improves as Q increases and becomes lower than 10^{-12} for $Q > 7$.

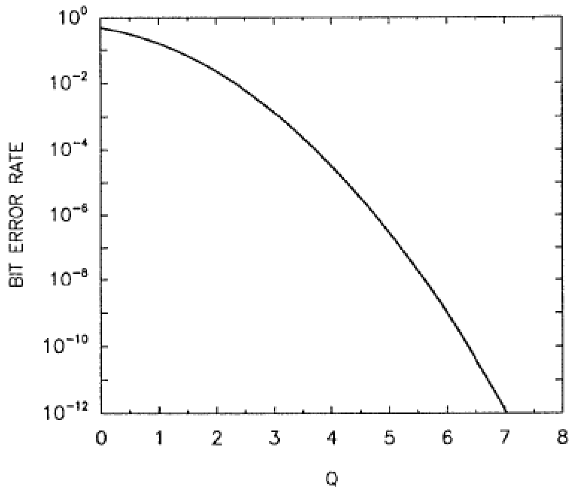

Figure 3 - Bit error vs Q parameter [9]

The value of Q can be defined by

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \tag{2.2}$$

where I_1 and I_0 the average signal currents for 1 and 0 bits and σ_1 and σ_0 are the corresponding detected root-mean-square (rms) noise values.

2.1.3.2 Eye diagram

The eye diagram is a simple but powerful method to evaluate the data-handling ability of a digital transmission system. A great deal of system performance information can be deduced from eye pattern display, such as [7]:

- The width of the eye opening defines the interval over which the receiver signal can be sampled without error due to interference from adjacent pulses (known as inter-symbol interference).
- The height of the eye opening (the distance between the top of the eye and the maximum signal level) gives the degree of distortion. The more the eye is closed, the more difficult is to distinguish between 1s and 0s of the signal.
- Timing jitter is related with the timing errors of the arrived impulses at the receiver. The amount of time uncertainty ΔT at threshold level indicates de amount of jitter. Thus timing jitter is given by $\textit{Timing jitter (\%)} = \frac{\Delta T}{Tb} \times 100$, where T_b is the bit interval.

- The rise time is defined by the interval between the point where rising edge of the signal reaches 10 percent of its final amplitude to the time where it reaches 90 percent of its final amplitude. However in measuring optical signals these points are often obscured by noise and jitter effects, so it used the values between 20 percent and 80 percent with the following relationship $T_{10\text{-}90}=1.25\times T_{20\text{-}80}$

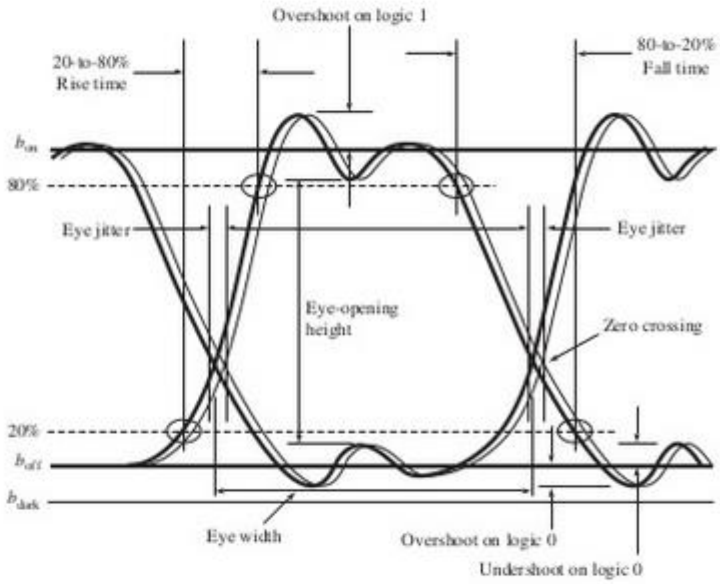

Figure 4 - Eye diagram with the fundamental measurement parameters [7]

2.1.3.3 Optical Signal-to-Noise Ratio

BER is determined mostly by optical signal-to-noise ratio [7], or OSNR, which is what is measured when a WDM link is installed or is in operation. The OSRN only depends on the average of optical signal power P_{signal} and average optical power noise P_{noise} and not on data format or pulse shape. The TIA/EIA-526-10 standard defines *OSNR* over a spectral gain reference spectral bandwidth B_{ref} as

$$OSNR(dB) = 10\log\frac{P_{signal}}{P_{noise}} + 10\log\frac{B_m}{B_{ref}} \qquad (2.3)$$

where B_m is the noise-equivalent measurement bandwidth of the instrument (such as a spectrum analyser) used.

The parameter Q can be related with $OSNR$ with the follow expression:

$$Q = \frac{2\sqrt{B_0 / B_e}OSNR}{1+\sqrt{1+4(OSNR)}} \tag{2.4}$$

2.1.4 Performance Impairments

Signal impairment effects are inherent in optical fibre transmission links and can seriously degrade network performance. These main effects are [7]:

- Dispersion, which spread out a pulse as it travels along a link, leading to interference between adjacent pulses (called inter-symbol interference) limiting the distance a pulse can travel. There are three main types:
  - i) Modal dispersion, which only occurs in multimode fibres in which each module travels at a different velocity;
  - ii) Chromatic dispersion (CD) originates from the fact that each wavelength travels at slightly different velocity in the fibre;
  - iii) Polarization Mode Dispersion (PMD) caused due the fact that two fundamental orthogonal polarization modes in a fibre travel at slightly different speeds owing to fibre birefringence.
- Nonlinear effects which arise at high optical power levels, can be qualified in two categories:
  - i) Nonlinear inelastic scattering processes, which are interactions between optical signal and molecular or acoustic vibrations on fibre;
  - ii) Nonlinear variations of refractive index in silica fibre that occurs because the refractive index is dependent on the intensity changes of the signal.
- Non-uniform gain across the desired wavelength range of optical amplifiers in WDM links (which can be mitigated using grating filters or variable optical attenuators named VOAs);
- Reflections for the connectors or splitters that cause instabilities in laser source and can be eliminated using optical isolators.

2.1.4.1 Chromatic Dispersion

Chromatic Dispersion is the combination between the index of refraction of silica (material dispersion) and the frequency dependent wave guidance in the fibre core and fibre cladding (waveguide dispersion). Index refractive varies with wavelength and consequently each wavelength within an optical pulse will see a slightly different refractive index and will travel at a slightly different speed through the fibre. Waveguide dispersion is an effect that occurs due to the fact that various frequency components of a pulse travelling at slightly different group velocities in a fibre, arriving at different times at the fibre end.

Chromatic Dispersion is generally referred to as dispersion since it has a great impact on the design of single-mode fibres, and is measured in units of picoseconds per kilometre of fibre per nanometre of optical source spectral width (ps/km.nm).

The accumulated dispersion increases with distance along a link. So a transmitter signal has to be designed to tolerate the total dispersion, or incorporate some method of compensation dispersion. Although the exact calculation of the dispersion effect is quite complex, it can be done a basic estimation of what limitation dispersion is imposed on link performance by specifying that the accumulated dispersion should be less than a fraction of bit period. For example Bellcore/Telcordia standard GR-253-CORE specifies for a 1-dB performance penalty the accumulation dispersion should be less than 0.206 of a bit period: $|D_{CD}| LB\Delta\lambda < 0.206$, where D_{CD} is the chromatic dispersion, *LB* is the used bandwidth and $\Delta\lambda$ is the spectral width of the light source [7].

2.1.4.2 Polarization Mode Dispersion

Polarization Mode Dispersion (PMD) occurs from the light signal energy at a given wavelength in a single-mode fibre that actually occupies two orthogonal polarization. At the start of the fibre the two polarization states are aligned, after this the fibre material is not perfectly uniformed throughout its lengths and the refractive index is not perfectly uniform across any given cross-sectional area (known as birefringence of the material). Consequentially each polarization mode will travel at slightly different velocity and the polarization operation will rotate with distance. The result difference in propagation times between two orthogonal polarization modes will cause a pulse spreading. PDM is not constant, varying with the temperature and stress changes in the fibre. Pulse spreading Δt_{PMD} resulting from polarization mode dispersion is given by

$$\Delta t_{PMD} = D_{PMD} \times \sqrt{fiberlength} \quad (2.5)$$

The typical value is $D_{PMD} = 0.05 ps/\sqrt{km}$ [7] [9].

2.1.4.3 Nonlinear Effects

As referred before, the nonlinear effects have two categories [7]: nonlinear inelastic scattering processes which are simulated Raman scattering (SRS) and simulated Brillouin scattering (SBS), and nonlinear variations of refractive index which are self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM).

The SBS, SRS and FWM processes results in gains or losses in a wavelength channel that are dependent on the optical signal intensity, providing some gains for some channels while depleting power from others producing crosstalk between the wavelength channels. Both SPM and XPM affect only the phase of signals which causes chirping in digital pulses (this can worsen pulse broadening due to dispersion, particularly in very high-rate systems).

2.2 Optical Modulation Formats and Detection Schemes

2.2.1 Intensity modulation with direct detection (IM-DD)

This IM-DD can be characterized by the follow scheme:

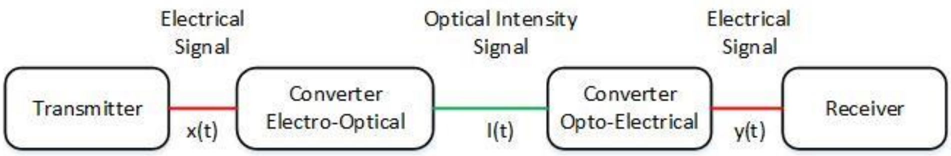

Figure 5 - Block diagram of an optical intensity direct detection communication system

The simpler approach for transmitter data over a fibre optic link is to use the on-off keying (OOK) by modulating the output of the transmitter with zeros and ones.

The main problem of the IM-DD system is the chromatic dispersion. The maximum reach of direct modulation lasers is limited to few kilometres which limits significantly the system robustness to the chromatic dispersion. Experimentally, it was used as a direct modulation of a DFB laser for a 10 Gbps system using a standard single mode fibre (SSMF) and it was observed a penalty of 1dB after a transmission of 3.6 km [10]. The maximum transmission distance lmax for an optical power penalty of 1 dB is given by [10]:

$$l\max = \frac{c}{2\lambda^2 B^2 D} \tag{2.6}$$

where c is the speed of light, λ the wavelength, B the transmission rate and D the total dispersion of fibre value.

Considering λ=1552.5 nm and for dispersion values of 4 ps/nm.km and 17 ps/nm.km it was obtained the follow responses:

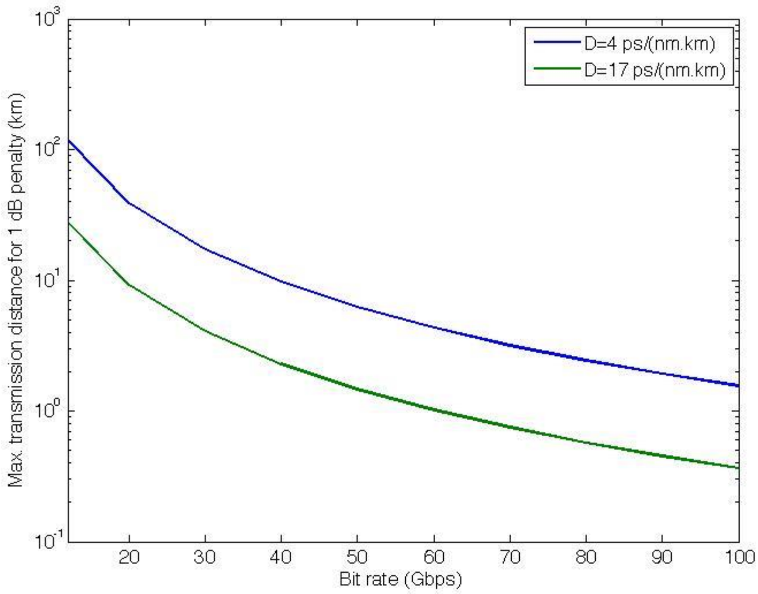

Figure 6 - Maximum transmission distance for 1 dB penalty

Observing the Figure 6, for a bit rate of 90Gbit/s (SKA1-mid bit rate) was obtained maximum reach of 0.5 and 2 km for 4 ps/(nm.km) and 17 ps/(nm.km), respectively. To obtain higher distances the penalty value can be relaxed. A possibility to increase the transmission distances even more is to use inverse multiplexing by transmitting in parallel several wavelengths in the same fibre (WDM).

2.2.2 Optical Duobinary (ODB) Modulation

Optical Duobinary (ODB) scheme belongs to a class of correlating coding formats. These formats are the most conveniently when it comes employing the signalling set {0, ±|E|} taking advantage of the direct detection optical receivers, which automatically convert the three optical symbols to the two electrical symbols {0, $|E|^2$}. Optical Duobinary is also named phase shaped binary transmission (PSBT) or phased amplitude-shift signalling (PASS) [11].

Duobinary Modulation is an approach for transmitting R b/s using less than R/2 Hz of bandwidth, using inter-symbol interference (ISI) controls can be subtracted out to recover the original values.

The main advantages of ODB signals is their low spectral occupancy and high tolerance to residual chromatic dispersion and narrowband optical filtering compared to binary signalling formats. This is due to the Duobinary being encoded {1 0 1} with a bit pattern of {1 0 -1}. In time the domain of the Duobinary encoding lets the two 1-bit between 0-bit interference be destructive. Conventional OOK or NRZ let the pulses interference be constructive, which raises the 0-bit level and closed the eye. The next figure shows the dispersion effects of a NRZ sequence vs. Duobinary sequence.

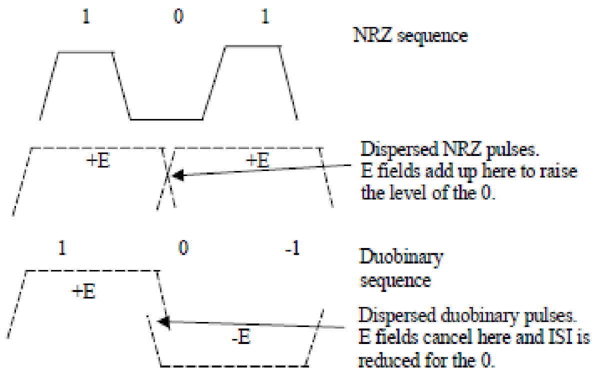

Figure 7 - Effects of dispersion on NRZ and Duobinary sequences [11]

The DB transmitters use a differential pre-coding version of the data signal in the input (decoding at the receiver is also possible but is preferable pre-coding at the transmitter to avoid error propagation after detection). This is done using an exclusive-OR (XOR) or using an *and gate* followed by a Divide-by-2-counter. The second option is the most suitable to implement at higher data rates since it avoids the use of 1-bit delay feedback path used by XOR. This pre-coded sequence is converted into a three-level electrical signal using a low pass electrical filter. This low pass filter (LPF) can be implemented by a delay/add circuit, resulting in a better back-to-back sensitivity or it can be chosen to increase the Chromatic Dispersion tolerance (generally with a roll-off characteristics and a 3-dB bandwidth of about 25% of bitrate). The main job of this filter is to convert the signal from Binary to Duobinary and to trim high-frequency components in Duobinary signal spectrum. The last step is to modulate the light with a three-level Duobinary signal, which implies a three-level optical signal. This result is achieved using a Mach-

Zehnder (MZ) modulator biased at its null point. With 0 input no light is transmitted but +1 and -1 are transmitted as respectively +E and –E electrical fields. Then the three-level signal electricity is filed and transformed in two-level signal in terms of optical power [11] [12] [13].

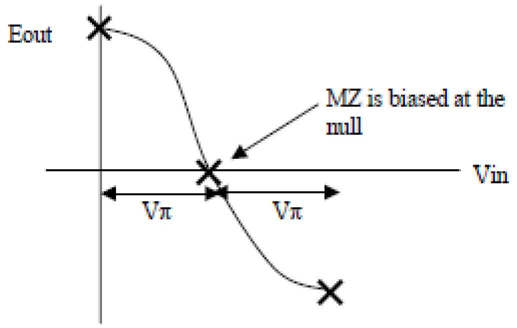

Figure 8 - Baising of the Mach-Zehnder modulator [11]

The complete Duobinary transmission is shown in Figure 9. An inverter is added to the input of the differential encoder to avoid the inversion of the signal during the process (this invertor can be placed either at the receiver or the transmitter) and can be implemented by reversing the differential lines to form the data source to the AND gate. The complete Doubinary modulator transmitter and the exact sequence of transformations that occur in data path at each state are presented in the figure and table below [11].

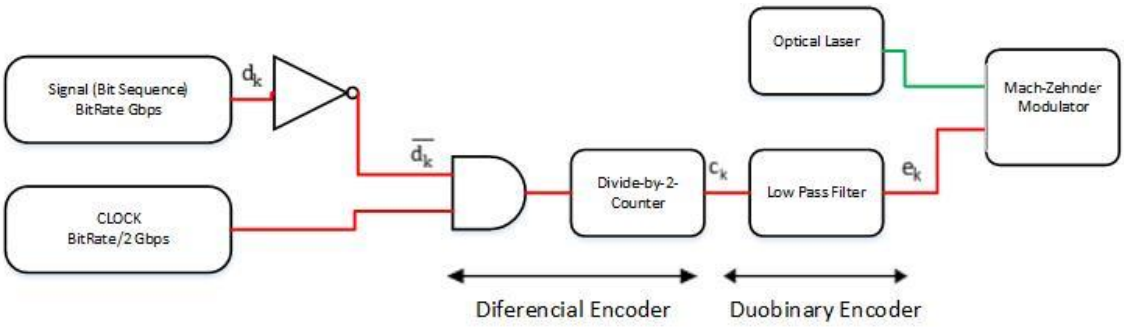

Figure 9 - Complete Duobinary modulator transmitter

K	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
d_K		0	1	0	1	1	1	0	0	0	0	1	0	1	0	1	0
$\overline{d_k}$		1	0	1	0	0	0	1	1	1	1	0	1	0	1	0	1

Diff encoder $c_k = c_{k-1} \oplus \overline{d_k}$	0	1	1	0	0	0	0	1	0	1	0	0	1	1	0	0	1
Bit to voltage mapper v_k	-1	1	1	-1	-1	-1	-1	1	-1	1	-1	-1	1	1	-1	-1	1
Duobinary encoder $e_k = v_{k-1} + v_k$		0	1	0	-1	-1	-1	0	0	0	0	-1	0	1	0	-1	0
Electric field		0	+E	0	-E	-E	-E	0	0	0	0	-E	0	+E	0	-E	0
Optical power		0	E^2	0	E^2	E^2	E^2	0	0	0	0	E^2	0	E^2	0	E^2	0
Receiver bits		0	1	0	1	1	1	0	0	0	0	1	0	1	0	1	0

Table 1 - A transformation example of data in a Duobinary system [11]

2.3 Standardization for 100G and beyond

There are three main companies (IEEE, ITU, OIF) which define the technical standard specifications used by all the optical industry. These standards ensure that all of the industry is focused on building and using common interfaces, allowing a further depending and improvement of components, increasing the competition and lowering prices.

IEEE 802.3 committee and ITU-T have different but complementary responsibilities in standard creation. IEEE is responsible for standards relating with the Ethernet interface (client side), whereas the ITU-T is responsible for the standards relating to the transport between the interfaces (line side), such as framing, optical characteristics, FEC [14].

Figure 10 - IEEE logo [16]

In 2010, IEEE has published to the client side 100Gb/s Ethernet (GbE) the IEEE standard 802.3ba (a standard defined for 10 km and 40 km reach, using four channels at 25 Gb/s) [15]. Recently, IEEE approved the development of a new standard, IEEE P802.3bs, to 400 Gb/s Ethernet specification, having the following main goals: provide physical layer specifications, define media access control (MAC) parameters, preserve Ethernet frame format using Ethernet MAC, provide appropriate support for OTN, achieving a Bit Error Rate better or equal than 10^{-13} [16].

Figure 11 - ITU logo [17]

ITU-T published in 2009 the standard G.709, which defined the line side bitrate of 112 Gb/s (OTU4 bitrate), the OTN multiplex with the client data and standard Reed Solomon FEC [15]. More recently ITU-T group SG15 propose to define standards for Beyond 100G systems (B100G) [17], to correspond (point of view of line side), to the IEEE 400Gb/s standard.

Figure 12 – OIF logo [18]

OIF is an international non-profit organization with more than 90 members companies including world's leading optics carriers and vendors, which propose the deployment of interoperable, cost-effective and robust optical internetworks and their associated technologies [18]. For 100G systems OIF proposed a generation of 100G Long-Haul DWDM transceiver architecture technology (standards such as OIF-FD-100G-DWDM-01.0 [19], OIF-MSA-100GLH-EM-02.0 [18]). Currently OIF has developed the first generation 400G Client Modules using 16x25G/28G and second generation using 10x40G or 8x56G defining the standard called MSA 400G [20].

2.4 Transmitter and Receiver Technologies

The SKA telescope requires large data transmission that calls for innovative technological solutions. Thus it is presented below the principal transceiver types presented existing on the market. The competing technologies CFP and CFP2; CFP4 and QSFP28 Multi-Source Agreement (MSA), include XFP and SFP+, Cisco's silicon photonic CPAK solution and photonic integrated circuits (PICs). The competing factors are bit rate, power efficiency, size and cost.

2.4.1 Transceiver CFP Multi-Source Agreement (MSA)

The CFP Multi-Source Agreement (MSA) [21] defines (hot) pluggable optical transceivers to enable 40Gb/s and 100Gb/s applications, including next-generation High Speed Ethernet (40GbE and 100GbE). The CFP MSA is composed by the following companies: Avago Technologies, Finisar, Fujitsu, JDSU, Oclaro and Sumitomo Electric.

To 100Gb/s applications, the CFP interconnects can support both 10x10 Gb/s and 4x25Gb/s variants and are capable of achieving 100 m reach for MMF (Multi-Mode Fibre) named 100GBASE-SR10, and for SMF (Single Mode Fibre) can achieve 10 km reach (named 100GBASE-LR10 and 100GBASE-LR4 for 10x10Gbit/s and 4x25Gbit/s, respectively) and 40 km reach (named 100GBASE-ER10 and 100GBASE-ER4 for 10x10Gbit/s and 4x25Gbit/s, respectively) [22].

Pluggable CFP, CFP2, CFP4 and QSFP28 transceivers permit a single line card to support transceivers with different performance and cost points.

CFP2; CPF4 and QSFP28 modules were recently defined by MSA and are very attractive for applications having high demand in terms of module density. A current challenge with the CFP2 module is fitting the ASIC (Application-Specific integrated Circuit) and optics within the CFP2 power constraints of 12 W. Moving the ASIC out of the CFP2 module and placing it on the host card is a consideration for such applications. This strategy, however, can produce a very challenging high-speed and pluggable analogue interface between the CFP2 and host card [23].

Recently MSA proposed new transceiver modules with more reduced size and power, the CFP4 (6W) and 100G QSFP28 (3.5W) [24]. Figure 13 depicts the MSA CFPx 100G module evaluation in terms of layout and power consumption.

Figure 13 - The MSA CFPx 100G module evaluation [21]

2.4.2 SFP+ and XFP Transceivers

SFP+ (Small Form-Factor Pluggable +) and XFP (10Gb Small Form-Factor Pluggable) are transceivers with a maximum transmission rate of approximately 10 Gb/s. To transmit higher bit rates one can resort to WDM as exemplified in the following figure for an aggregated capacity of 100 Gb /s using 10 transceivers.

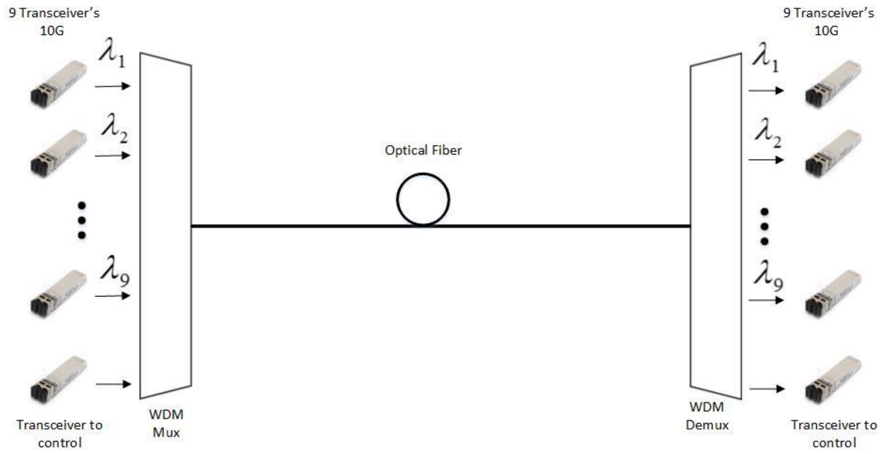

Figure 14 - WDM solution of SKA1-mid using 10 transceivers

SFP+ is an extension of SFP standard (which supports only 4.25 Gb/s), generally using Fast Ethernet or Gigabit Ethernet applications. XFP transceiver is a separate standard that also support 10 Gb/s speeds, but it is a slightly older standard. SFP+ moves the chip for the clock and data recovery into a line card on the host device, making SFP+ smaller than XFP, enabling greater port density.
These transceivers are hot-swappable, so it is easy to change interfaces on the fly an upgrade or maintenance because there is no need to shut down a switch to swap out a module. They are also OSI Layer 1 devices, transparent to data and do not examine or alter data any way and in spite of being used more with Ethernet, they are also compatible with other standards such as Fibre Channel, ATM, SONET or Token Ring [25].
As CFP transceivers, SFP+ and XFP transceivers were standardised by multisource agreements (MSAs), so connectors, physical dimensions and signalling are interchangeable.

In Attachment C is an example of SFP+ available on the market.

2.4.3 CMOS Photonic Technology

This technology uses the CMOS fabrication process to print multiple circuit components onto silicon wafers, making them more compact and energy efficient.
Cisco has the "CPAK" silicon photonic product range [26]. CPAK is a Cisco in-house product line, and claiming be a smaller, faster and a more power-efficient solution than any other on the market. This product complies with IEEE standard interfaces, being

interoperable with any IEE-compliant 100GBASE-LR4 or 100GBASE-SR10 form factors. CPAK products are designed for a variety of client-side applications, and the first available modules will be Cisco CPAK 100GBASE-SR10 and CPAK 100GBASE-LR4, where short range (SR) at 10.3125 Gbps data rate per lane and long range (LR) at 25.78125 Gbps data rate per lane.

2.4.4 Photonic Integrated Circuits (PICs) or other integrated technologies

Some companies offer PIC technology as a solution for the transmission and reception claiming to provide higher density, lower power and cost.

Infinera uses semiconductor technology to deliver large scale Photonic Integrated Circuits, offering commercially available 500Gb/s FlexCoherent super-channels [27].

NeoPhotonics announced an Integrated Coherent Transmitter (ICT) for next generation small form factor, combining narrow line width tunable laser with a dual polarization QPSK modulator in a single compact package. This modulation section uses PIC Integration to combine onto a single chip and consists of four InP based Mach-Zehnder modulators including integrated phase and balance control along with VOA functionality and monitor photodiodes [28].

2.4.5 TOSA (Transmit Optical Sub-Assembly) and ROSA (Receive Optical Sub-Assembly) technology

TOSA/ROSA are PIC sub-assemblies integrating several transceiver functionalities which can perform the transmission/reception and multiplexing/de-multiplexing of several channels in the same package. These modules have a low power consumption, and a maximum reach of 40 km unamplified links. Companies like Avago Technologies [29], Enablence Technologies [30] and Kaiam Corporation [31] commercialize this type of technology.

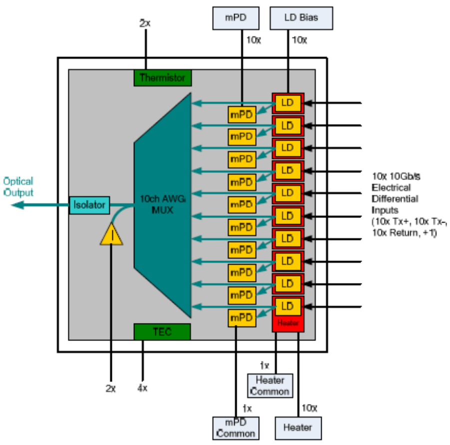

Figure 16 – Scheme of Enablence Technologies ROSA module [27]

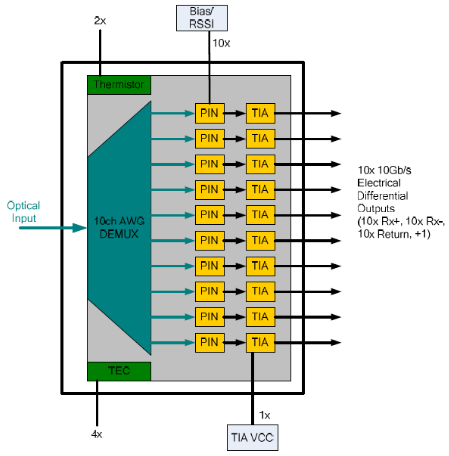

Figure 15 - Scheme of Enablence Technologies TOSA module [27]

The table of the main companies and their transceivers can be consulted in Attachment A.

2.5 WDM Multiplexers and De-multiplexers

The WDM multiplexer and de-multiplexer are key components at WDM transmission. The combination of impendent signals at different wavelengths onto the same fibre can be achieving by different filters: thin-film filters, fibre Bragg gratings, array waveguide gratings, diffraction gratings and interleavers [7].

The multiplexers available on the market are mostly AWG whose operation is explained below.

2.5.1 Array waveguide gratings

An array waveguide grating (AWG) are composed by two identical star couples and an interconnection of uncoupled waveguides called grating array (the length of these waveguides are chosen to have a difference in length of ΔL). Considering an AWG as a de-multiplexing, the

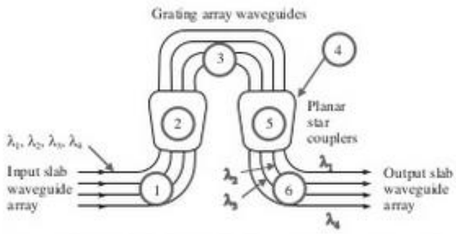

Figure 17 - Typical arrayed waveguide grating and the various key operating regions

signal with several wavelengths pass through the first star couple and are split in several wavelengths. These wavelengths are equally precisely spaced due to the arrayed waveguides (in region 3, Figure 17). As result, the second star couple will focuses each wavelength into a different exit and then separating completely the several wavelengths. These devices are widely used because has a dense channel spacing (25 GHz) and can support to 40 channels [7] [9] .

In Attachment C is an example of AWG multipliers/de-multiplexers available on the market.

2.6 Optical Amplifiers (OA)

The SKA1's DDBH requires very high capacities. Although the majority of dishes of SKA1-mid and SKA1-survey are in the central core region, there are a small percentage of dishes which will be located beyond 40 km and maybe 100 km away from this region. For these cases the cumulative losses (mainly by scattering and absorption mechanisms in an optical fibre which progressively attenuated the signal along the fibre) make the signal too weak to be detected, having to be amplified before be detected at the receiver so it can properly interpret it [7] [9].

2.6.1 General Concepts

In this section are shown the main basic concepts needed to use and implement systems with optical amplifiers.

2.6.1.1 Gain

The gain of an amplifier [7] is roughly defined as

$$G = \frac{P_{out}}{P_{in}} \tag{2.7}$$

The gain value can range depending of type of amplifier and the wavelength used, and is measure under small-signal conditions ($P_{out} < 0$ dB) and is expressed in dB by

$$G(dB) = P_{out}(dB) - P_{in}(dB) \tag{2.8}$$

2.6.1.2 Amplifier Noise

During the amplification the spontaneous emission of amplifier add noise to the signal, degrading the signal-to-noise-ratio (SNR) [9]. This SNR degradation is quantified by a parameter name amplifier Noise Figure (NF) and is defined by the following formula:

$$NF = 10\log\left(\frac{SNR_{in}}{SNR_{out}}\right) \tag{2.9}$$

2.6.1.3 Amplifier Applications

There are three common applications of optical amplifiers: in-line optical amplifiers, preamplifier and power amplifier (Figure 18).

The most common usage of long-haul systems is the in-line optical amplifiers. This application is utilized for the cases which are not necessary to regenerate completely the signal, but just simple amplification of the signal at periodic locations along the transmitter path.

The preamplifier configuration (amplifier placed before the receiver) is used to minimize the signal-to-noise ratio degradation caused by thermal noise in the receiver, improving then the receiver sensitivity.

The power amplifier (also named postamplifier or booster, amplifier placed after the transmitter) gives a boost to the light level at the beginning of a fibre link, increasing the transmission distance by 100 km or more depending on amplifier gain and fibre losses.

A mixed configuration (preamplifier and power amplifier used together) can improve the systems even more, being capable, for example, to transmit distances of 200 to 250 km between amplifiers in submarine communication systems [7] [9].

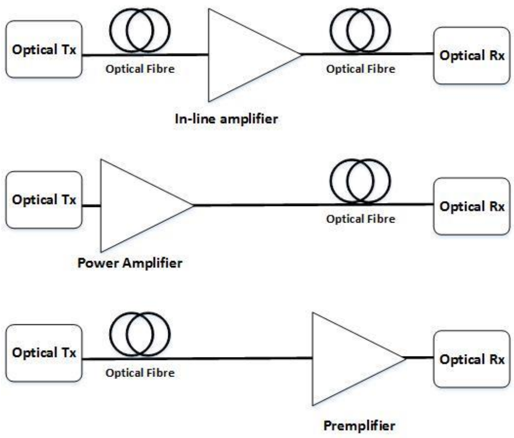

Figure 18 - Three possible applications of optical amplifiers: in-line amplifier, power amplifier and preamplifier [7]

2.6.2 Amplifier Types

There are mainly three types of Optical Amplifiers: SOA, EDFA and Raman Amplifier.

2.6.2.1 SOA

Semiconductor optical amplifiers (SOA) are basically InGaAsP laser that operate below its threshold point. Since these amplifiers are based on semiconductor technology they are easily integrated in the same way as other optical devices and circuits, enabling them to be used in switching and signal processing. Furthermore, they have a huge operational wavelength range (from 1280 nm in the O-band to 1650 nm in the U-band). However the SOA rapid carrier response causes fluctuations of gain value with the signal rate for bit rates up to several gigabits per second. When a broad spectrum of wavelengths are amplified, due the fluctuation caused in several wavelengths this give rises to crosstalk effects, not very suitable for WDM applications [7].

2.6.2.2 EDFA

Erbium-doped amplifier (EDFA), traditionally classified as lumped amplifiers, consists nominally of 10 to 30 m length of optical fibre (named Erbium-doped fibre, EDF) whose core is doped with ionized atoms (ions, Er^{3+}) of the rare earth elements erbium. These modules (EDF) are placed approximately after each 80 km span of transmission line, so the span can be amplified back to the required level power at the end of each span. EDFA has typical a Noise Figure (NF) of 5-6 dB. Originally the operation of EDFA was limited to the C-band (1350 to 1560 nm), but with the recent improvements in erbium-doped fibre designs and the use of high-power pump lasers operating at wavelengths different than used by C-band allowed the extension of EDFAs to the L-band (1570 to 1605 nm), generally with an optical amplification up to 35nm [7].

2.6.2.3 Raman Amplifier

Raman amplifier makes use of the transmission fibre (which can be any type of fibre) as the medium of amplification the signal (this process is named Distributed Raman Amplification, DRA).

Unlike EDFA, which needs a special EDF to provide amplification, the Raman amplifier can be used in any fibre and pump the transmission fibre itself to provides amplification for the signal propagation along the fibre (this process is named Distributed Raman Amplification, DRA).

Since gain occurs along the transmission, DRA can prevent the attenuation of the signal to very low powers where noise is significant, improving the Optical Signal to Noise Ratio (OSNR) of the transmitted signal. DRA allows the launch of the signal with less power, important in cases where the fibre is an issue.
Raman amplifiers have far broader spectrum amplification comparatively with EDFAs with a wide amplification bandwidth of 100 nm, being capable of amplifying all communication windows. Then, Raman amplifiers improve the Noise Figure (6 to 3 dB) and reduce the nonlinear penalty of fibre systems, allowing longer amplifier spans, higher bit rates, closer channel spacing, and operation near the zero-dispersion wavelength [32] [33] [34].
However Raman has lower power efficiency, requiring a much higher output of power to pump modules that are typical power levels of EDFA based systems. The high launch power requires a special handling in optical connectors and splitters to avoid equipment being damaged, and requires many safety measurements as part of open circuit detection and automatic shutdown. DRA generate Amplified Spontaneous Emission (ASE) along the transmission line. This means that event in case of fibre break, ASE power can still propagate along the system within the C-Band [32].

2.6.2.4 Hybrid Raman-EDFA amplification

Hybrid amplification combines the best characteristics of EDFA and Raman amplifier. In a hybrid, Raman is used in the first amplification stage (the stage that Noise Figure performance is the most important characteristic), whereas the EDFA is used in the second stage, boosting the signal to a higher level due its power efficiency [35].

The table of the main companies and their optical amplifiers which can be used in SKA DWDM solution (focus to EDFA, Raman and hybrid amplifiers) can be consulted in Attachment B.

2.7 Optical Fibre

It is important to know the principal available types of optical fibre to choose the suitable option for each configuration. Then it is presented the main SMF (Single Mode Fibres) standards and the optical fibres available on the market which can be used in this Dissertation.

2.7.1 Optical Fibre Standards

The International Telecommunications Union - Telecommunication Standardization Sector (ITU-T) and Telecommunications Industry Associations (TIA/EIA) have published standards for both multi and single-mode optical fibres used in telecommunications. In SKA1 will be used single-mode fibres, so the standards will be focused on these types of fibre.

The principal types of standards single-mode fibres are [7]:

Standard Designation	Specifications
ITU-T G.652. Standard single-mode fibre	This fibre works with single modes installed in telecommunications networks since 1990s, which has a Ge doped silica core with a diameter between 5 and 8 µm. Since the first applications was used 1310-nm laser sources, this fibres was optimized zero-dispersion value at this wavelength.
ITU-T G.652.C. Low-water-peak-fibre	This standard was created for fibres with reduced water concentration in order to eliminate the high attenuation from 1360 to 1460 nm (E-band). The main use of this fibre is for low-cost short-reach CWDM applications in E-band.
ITU-T G.653. Dispersion-shifted fibre (DSF)	DSF was developed for third window transmission where the zero dispersion fibre point is shifted to 1550 nm. The fibre attenuation is about one-half compare to 1310 nm. This fibre type became obsolete

	with the use of DWDM at long haul systems (due to the high inter-channel impairments) and with introduction of G.655 NZDSF.
ITU-T G.655. Nonzero dispersion-shifted fibre (NZDSF)	NZDSF was introduced in mid of 1990's and it has a nonzero dispersion value over entire C-band (spectral operating region for erbium-doped optical fibre amplifiers), contrary to the case of G.653 fibres in which the dispersion varies negative to positive values in this spectral range.
ITU-T G.655b. Advanced nonzero dispersion-shifted fibre (A-NZDSF)	A-NZDSF appeared in October 2000 to extend WDM applications to S-band. The principal characteristic is that has a nonzero dispersion value over entire S-band and C-band, been an improved of G.555 fibre, once this presents variations in the S-band dispersion.
ITU-T G.656. Nonzero dispersion-shifted fibre (NZDSF) for wideband optical transport [36]	This standard single-mode optical fibre has a positive chromatic dispersion coefficient greater than some non-zero value throughout wavelength range of 1460-1625 nm, which reduces the growth of nonlinear effects, particularly detrimental in DWDM. This fibre uses non-zero dispersion to reduce four-wave mixing and cross-phase modulation over a wider wavelength range that the fibre ITU-T G.655. Then is used for DWDM and also CWDM systems.
ITU-T G.657. Bending-loss intensive	This standard improve bending

single mode optical fibre [37]	performance compared with the ITU-T G.652 single-mode fibres. This is done by means of two categories of single-mode fibres, one is category A, fully compliant with ITU-T G.652 single-mode fibres and the category B is not necessarily compliant with the Recommendations of ITU-T G.652 but capable of low values of macro bending losses at low bend radii. These category B fibres are system compatible with ITU-T G.657.A (and ITU-T G.652.D) fibres in access networks.

Table 2 - ITU-T Standard single-mode fibres

Thus it is possible to conclude that the most suitable fibres for WDM solutions are standards of ITU-T G.655 and ITU-T G.656 (NZ-DSF), with the possibility of also using ITU-T G.652 (SMF) but with systems of dispersion compensation, since unlike the NZ-DSF fibres, the SMF has a high dispersion value at 1550 nm (wavelength which is more frequently used for WDM systems).

2.7.2 Available Fibres on the market

Following are presented the fibres available on the market which can be used for this project: the standard SMF and NZ-DSF.

2.7.2.1 Corning SMF-28e+ optical fibre

This fibre, is ITU-T G.652.D fully backward compatible with standards single-mode fibre. The main optical communications can be found in the respective datasheet [38], which features a maximum attenuation of 0.2 dB/km, a dispersion not exceeding 18 ps/nm.km and a Mode-field Diameter (MFD) of 9.2±0.4 µm for a wavelength at 1550 nm and a PDM (Polarization Mode Dispersion) Link Design Value $PMD_Q \leq 0.06 ps/\sqrt{km}$.

2.7.2.2 Corning LEAF (Large Effective Area Fibre)

Large Effective Area Fibre [39] is the most widely deployed ITU G.655 compliant NZ-DSF fibre. Compared to other non-zero dispersion-shifted fibres, LEAF fibre has a large effective area, allowing higher levels of optical power to be transmitted while minimizing nonlinear impairments that can degrade transmission-system performance. This fibre has low chromatic dispersion, which simplifies dispersion compensation and lowers the cost of network installation and operation for long-haul carriers. These characteristics also allow improvement of optical signal-to-noise ratio, longer amplifier spacing and maximum dense wavelength division multiplexing (DWDM) channel plan. In addition, this fibre has low polarization mode dispersion (PMD), which enables high-data-rate transmission [40].

Corning LEAF is also compatible with installed base fibres and components, having a slightly larger mode-field diameter improving its splicing performance especially when connecting to standard single-mode fibre.

As it can be observed at Figure 19, LEAF fibre increases the area where the light can propagate, reducing nonlinear effects [41].

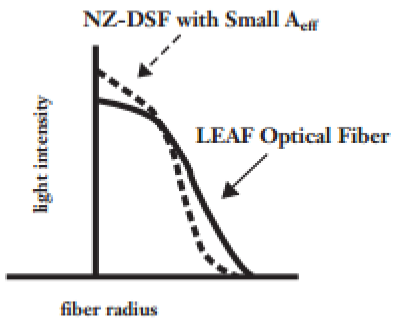

Figure 19 - Compared Light Intensity of NZ-DSF and LEAF Optical [37]

The main optical communications can be found in the respective datasheet [39], which features a maximum attenuation of 0.19 dB/km, a chromatic dispersion of 4 ps/nm.km and a Mode-field Diameter (MFD) of 9.6±0.4 µm at 1550 nm of wavelength and a PDM (Polarization Mode Dispersion) Link Design Value of $PMD_Q \le 0.04 ps/\sqrt{km}$.

Chapter 3
Architecture

As mentioned before, this Dissertation intends to study the best solution for the transmission between the various antennas and the CSP (Central Signal Processing, responsible for correlating all the signals of three types of antenna after the delay correction). This connection is established by Digital Data Back Haul (DDBH) infrastructures. The DDBH requirements are directly related with the transmission distance and capacity which are different for the three configurations. The transmission reach and the bit rate in each configuration can be consulted in following table:

Approx. Distance range (km)	SKA mid (bit rate ≅ 90 Gbps)	SKA low (bit rate ≅ 10 Gbps)	SKA survey (bit rate ≅ 864 Gbps)
10	158	24	6
20	9	6	6
30	5	3	3
40	3	0	3
50	3	3	3
60	3	0	
70	0	3	
80	1		
90	2		
100	0		
110	1		
120	2		
130	0		
140	0		
150	0		
160	3		

Table 3 - Estimated SKA DDBH link requirements [5]

From the data presented in Table 3 it is possible to conclude that the antennas stations distribution is not uniform: a high number of antennas are concentrated with distances equal or low than 10 km (forming a core of dishes).

3.1 Study of best SKA configuration

The configuration of cable paths are not yet definitely established. For this reason the University of Manchester (Bassem Alachckar and Richard Oberland) created a matlab program that calculates the best configuration depending on cost (of cabling and trenching). Then, this program assumes that the CSP is connected to all antennas but, to avoid enhancement of trenching, the CSP is only established directly with nearby antennas, connecting with the others through these. The algorithm used to construct the web of links is based on spanning tree.

This program takes as input an excel file with the geographic or Cartesian coordinates estimated for the antennas and the CSP. Using the location information of all antennas and CSP, the program creates an array with the information of each direct link between all antennas and CSP and the respective length (array named LinkLength). Then, this array is sorted in ascending order (according to the lengths) and links with greater lengths are deleted, leaving only the shorter connections necessary to ensure the links between all antennas (assuming N as the number of antennas plus CSP, this list has N- 1 links). Thus, all antennas are connected (directly or indirectly) allowing saving cost in terms of trenching since in this way a trench is avoided for each connection CSP-antenna, allowing multiple links in each trench.

Figure 20 shows the determination of network connections for a case of 4 points. The eliminated connection was A1-A2 and not A3-A4, because although connection A3-A4 has a lower value than A1-A2, the first one cannot be eliminated (it is required that all antennas haves a connection with at least another one).

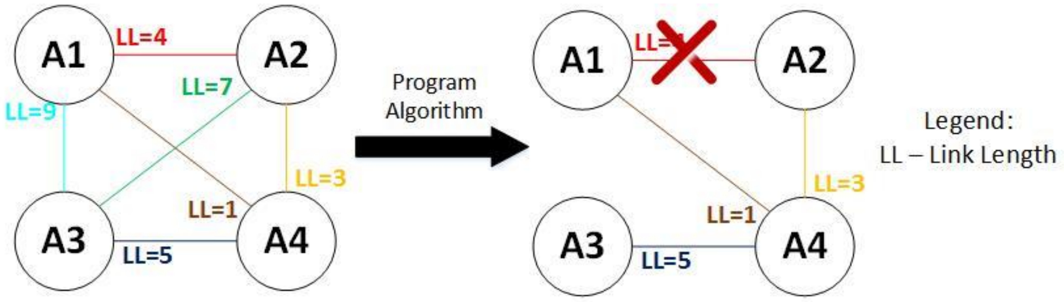

Figure 20 - Determination of network connections (example for 4 points)

This program assumes that the coordinates of the CSP location are the first point of the excel file. Then, assuming that for each CSP-antenna link it is used an independent cable, the program determines an array (designed NumberofCables) with the number of links repeated of LinkLength to CSP connect with all antennas directly, in order to determine the maximum number of cables required. So, the choice of the location of CSP has an impact on *NumberofCables* and consequently in the *CablingCost*.

Figure 21 shows the impact of the choice of the CSP location for the case of Figure 20.

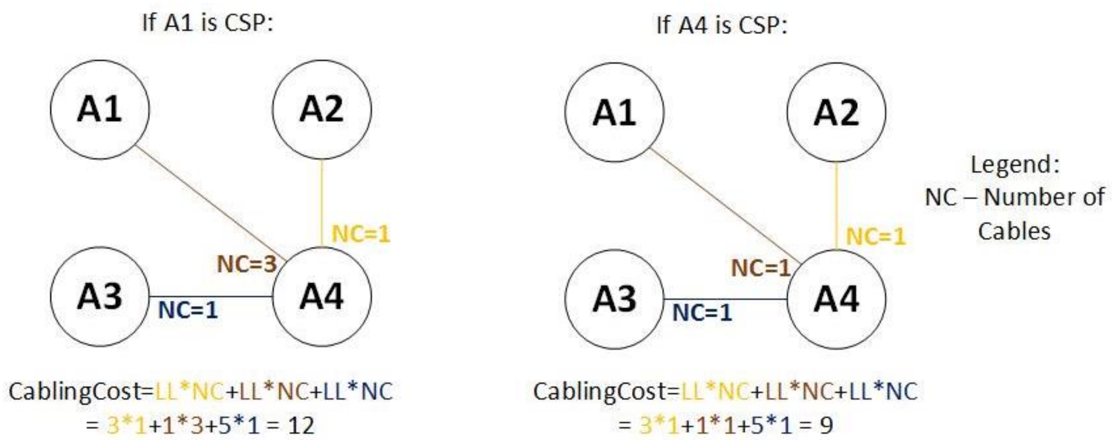

Figure 21 - Impact of CSP choice location in terms of Cabling Cost

Hence, the total cost of the configuration is given by

$$\begin{aligned} TotalCost &= TrenchingCost + CablingCost = \\ &= \sum_{i=1}^{N-1} ShortDist(i) \times TrenchingCost + ShortDist(i) \times NumberofCables(i) \times CablingCost \end{aligned} \tag{3.1}$$

where N is the number of antennas plus CSP.

Running this program for SKA1-mid data (considering Trench Cost = 10 euros and Cabling Cost = 5 euros) is obtained the follow results:

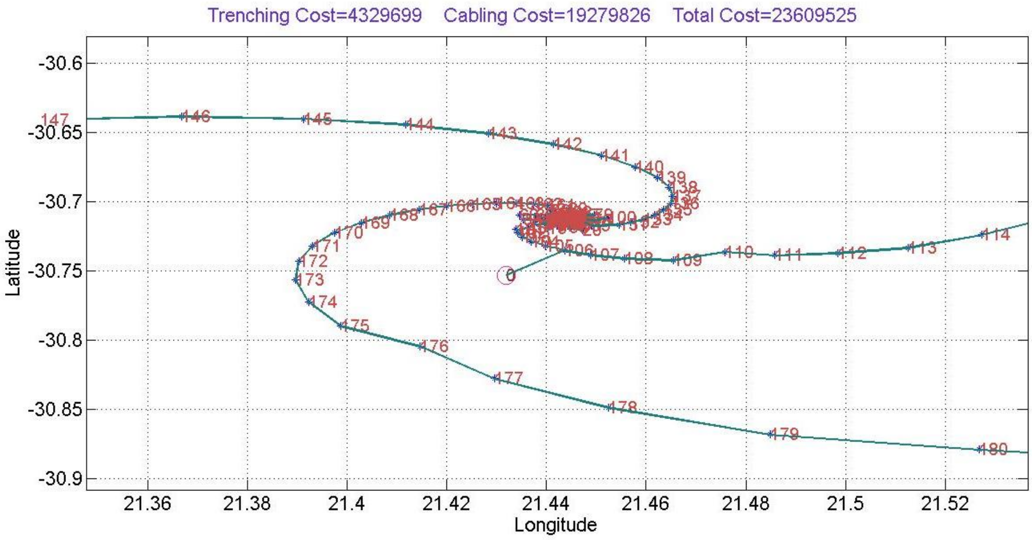

Figure 22 – SKA1-mid program results (zoom on CSP location)

Since the location of CSP has a big impact in Cabling Cost, it is possible to reduce the costs by choosing another CSP location where the size of the cable is the smallest.
Then the programme was changed not to assume the CSP as the first point of the excel file but to do the calculations for the other points and choose the one which allows the lower cabling cost value. With this change we obtained the following result:

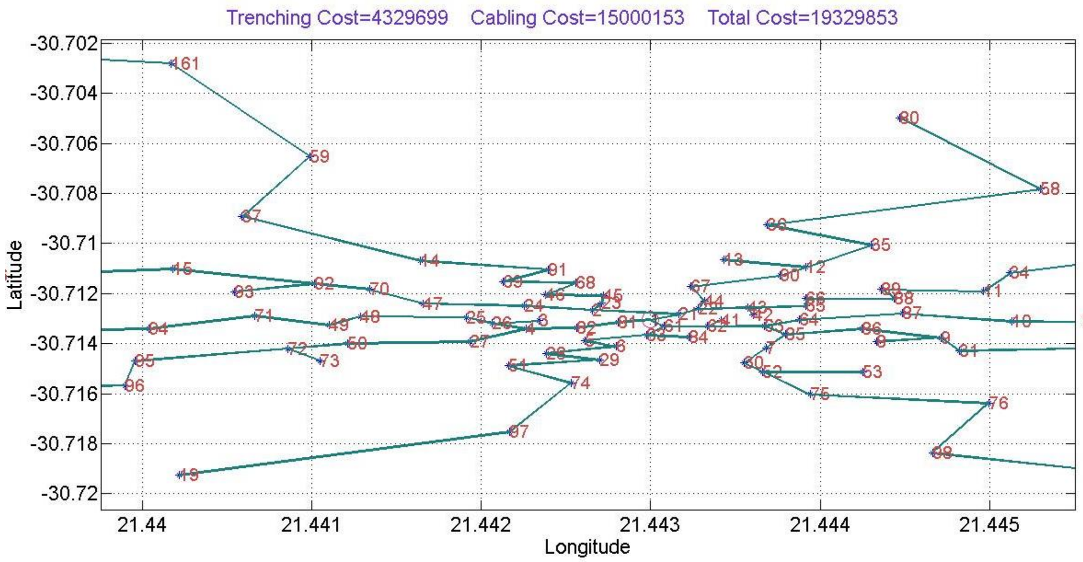

Figure 23 - SKA1-mid program results after optimization

These results were obtained using the values of the excel file, assuming antenna 1 as the new CSP facility and older CSP as an antenna, which may not be exactly correct. However it is possible to conclude that if it has chosen a CSP location closer to the core of antennas and not close to one of the arms as before it is possible a significant reduction on cable length, having a great impact on the final cost (in this case the configuration achieved a saving of approximately 4.276 million of euros).

Using the same configuration for the SKA1-survey was obtained the follow results:

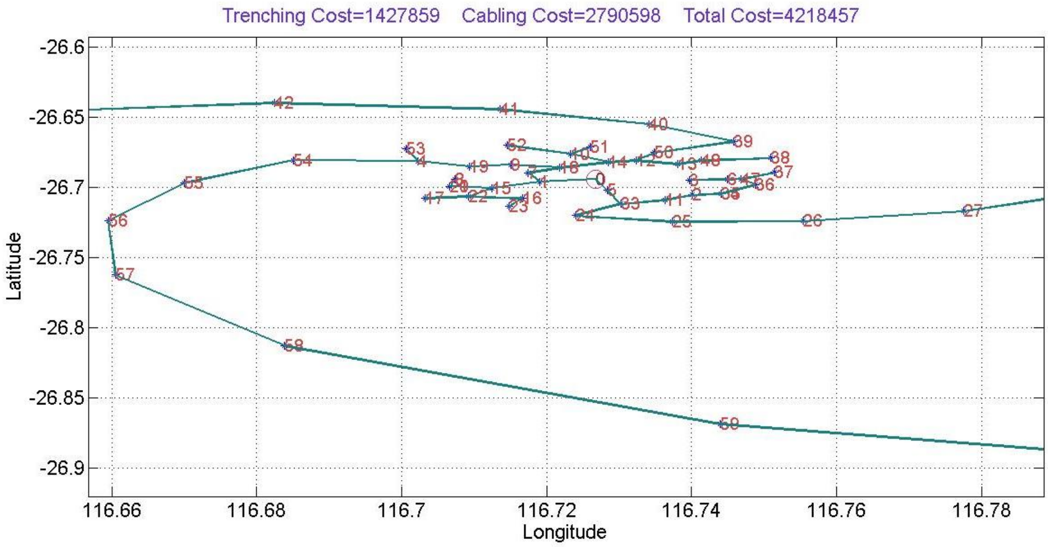

Figure 24 - SKA1-survey program results (zoom on CSP location)

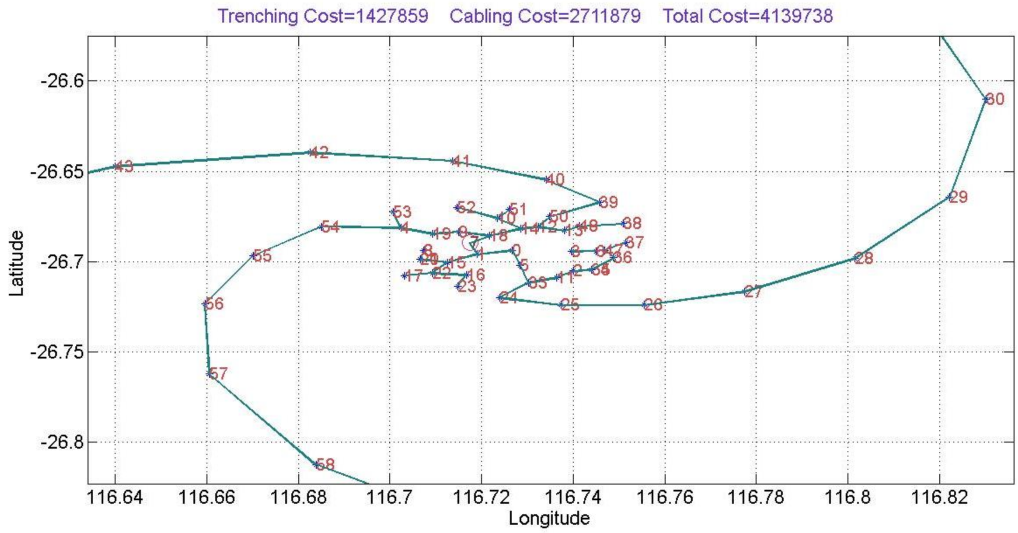

Figure 25 - SKA1-survey program results after optimization

Where the CSP location was already close to the core the optimization does not have a big impact, though it is still possible to save around 78.7 thousands euros.

It is important to note that despite being an improvement there are other factors that are required to determine the choice of CSP location, but from the point of view of cost optimization this being one possible solution.

3.2 DWDM Solution

DDBH transmission has a similar distance to some common access networks. However the first one requires much higher transmission capacities and is mostly unidirectional (only needs low capacity bidirectional for control and monitoring the remote antennas). Then it is necessary to find a solution that is able to reach high transmission rates and at the same time be possible to use standard technologies, in order to make the cheapest possible solution.

The found solution was to use DWDM (Dense Weigh Division Multiplexing), allowing the transmission of multiple channels through only one cable, and simultaneously achieving the required transmission rate and using a standard technology available on the market (section 2.4).

For SKA1-mid was studied 2 solutions: carrier 10 channels at 10 Gbps and 4 channels at 25 Gbps. For SKA1-survey the solution found was to use 35 channels at 25 Gbps.

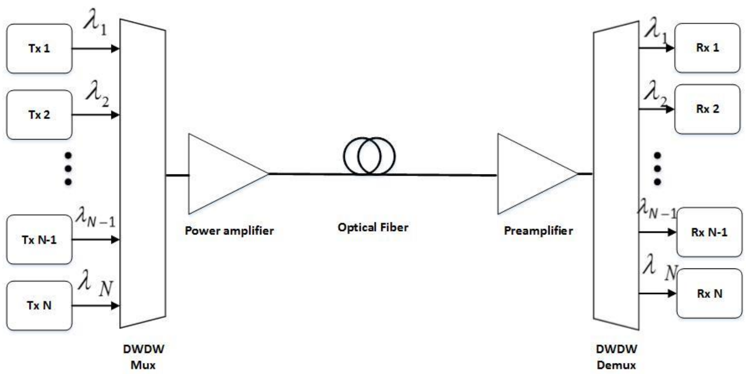

Figure 26 - DWDM Solution for SKA

3.2.1 DWDM 10 Channels at 10 Gbps (SKA1-mid)

This solution uses 9 channels to transmit 90 Gbps (transmission rate of SKA1-mid) and an additional one for control. There are transceivers standard on the market that can be used in this solution such as transceivers SFP + or XFP (chapter 2.4.2). In order to transmit the signal to all the antennas (SKA1-mid maximum reach is 160 km) was first assumed a back-to-back system (in order to simulate and test the characteristics of the transceiver) and then the assessment of the system for different fibre lengths in order to study the transmission impairments and how to mitigate them.

3.2.2 DWDM 4 Channels at 25 Gbps (SKA1-mid)

In this solution the Duobinary Modulation was used instead of NRZ due to the higher tolerance to the fibre dispersion.

It was used transceivers with the following characteristics: transmitter with an output power of -1 dBm and with 30 dB of extinction ratio and receiver with a BER of 10^{-12} back-to-back for a input receiver power of -14 dBm (this input power value is for NRZ modulation, so it was necessary to determine the new value of input power for a Duobinary system in order to use the same receiver and obtain a BER value of 10^{-12} back-to-back).

As done to the DWDM 10 Channels at 10 Gbps, the transmitter and receiver were firstly simulated in back-to-back configuration and then with all transmission elements (fibre, amplifiers, multiplexers and de-multiplexers) to verify the transmission possibility to all antennas of SKA1-mid.

3.2.3 DWDM 35 Channels at 25 Gbps (SKA1-survey)

Using as reference the study done to the 4 channels at 25Gbps solution, it was used a similar configuration but with an aggregated transmission capacity of 875 Gbps, (35 channels), slightly higher than 864 Gbps required for SKA1-survey.

Chapter 4
Simulation of Transmission Solutions for SKA

4.1 SKA1-mid: 10 Channels at 10 Gbps

This solution was done by using as reference the transceiver Cisco 10GBASE DWDM SFP+ transceiver (Attachment C) for the transmitter and the receiver.

4.1.1 Transmitter

According the datasheet of transceiver Cisco 10GBASE DWDM SFP+ ([42]), the transmitter has the follow characteristics:

Parameter	Symbol	Minimum	Typical	Maximum	Units	Notes and Conditions
Transmitter						
Transmitter extinction ratio		9			dB	
Transmitter optical output power	Pout	-1.0		3.0	dBm	Average power coupled into single-mode fiber

Figure 27 - Transmitter characteristics of the transceiver Cisco 10GB DWDM SFP+ [42]

To simulate this transmitter it was used the follow VPI scheme:

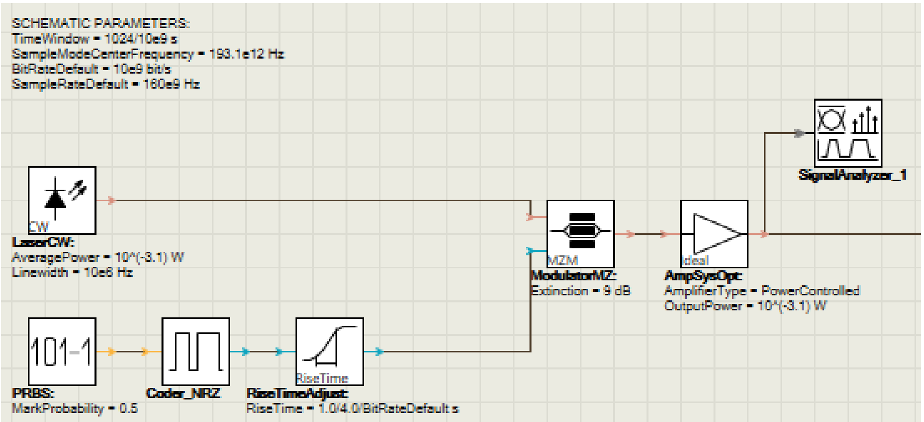

Figure 28 - Block diagram of the transmitter used in the simulation

The transmitted signal has an $AveragePower = -1\,\text{dBm} = -31\,\text{dBW} = 10^{-3.1}$ W (minimum value) with an $ExtinctionRatio = 9\,\text{dB}$. At transmitter side, a PRBS block was used and it was followed by a NRZ Pulse and a Rise Time block of 25ps to turn the signal in a similar way to a response that can be obtained in practice. The optical signal used was a LaserCW with an Average Power of -1 dBm. The modulation is done with a MZ modulator with an Extinction Ratio of 9 dB. An ideal amplifier (with no noise) were used to ensure the power at the modulator output of -1 dBm (value confirmed at NumericalAnaliser1). The output signal (SignalAnaliser1) is presented in the Figure 29.

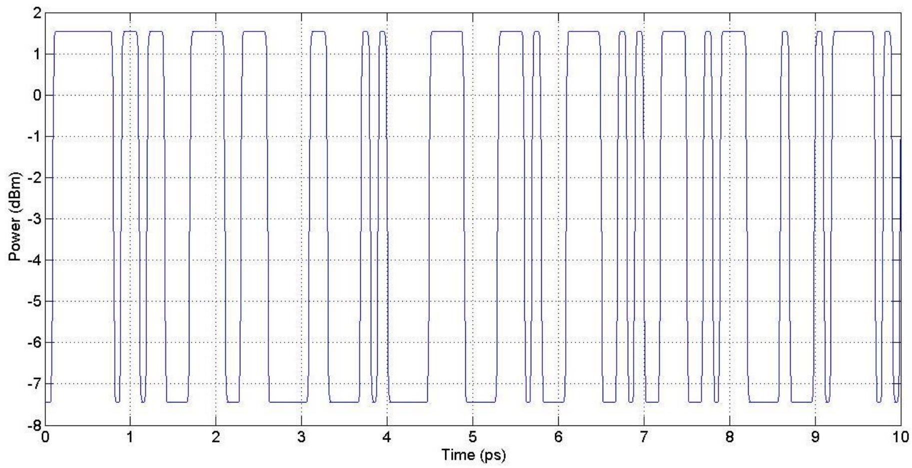

Figure 29 - Output Signal of the transmitter

4.1.2 Receiver

According the datasheet the receiver of transceiver Cisco has the following characteristics ([42]):

Receiver Performance at 10G LAN and 10G WAN Rates (NO-FEC Applications)						
Optical input power	Pin	-23.0		-7.0	dBm	At BER=1E-12, back-to-back, unamplified link

Figure 30 - Receiver characteristics of the transceiver Cisco 10GB DWDM SFP+ [42]

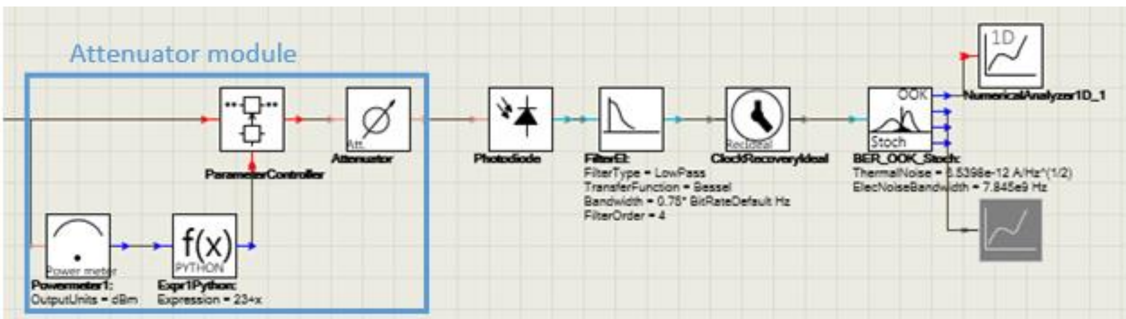

Figure 31 - Block diagram of the receiver used in the simulation

The set of blocks called Attenuator Module serves to define, at the level of the receiver input, a minimum input power value of -23 dBm described in datasheet. The module Powermeter1 measures current power (in dBm's) of the signal and uses Expr1Python to set the required value of the -23 dBm (thus in Expr1Phyton is used the expression 23 + x, with x meaning the current power signal).

The other blocks of Figure 31describes the receiver itself, where the BER_OOK_Block determines (in order of *ThermalNoise* and *ElecNoiseBandwidth*) the BER value of 10^{-12} for a power receiver of -23dBm, which can be viewed at NumericalAnalyzer1D_3.

The Equivalent Noise Bandwidth can be determined using the Equivalent Noise bandwidth ratio to the -3dB filter bandwidth (*ENB_r*) [43]:

$$ENB_r = \frac{NoiseBandwidth}{Bandwidth(-3\,\mathrm{dBm})} \tag{4.1}$$

Once the filter used was a Bessel filter order 4 with a bandwidth of 7.5 (0.75×10) GHz, Equivalent Noise bandwidth ratio of Bessel filter order 4 is equal to

$ENB_r(Bessel, order4) \approx 1.046$ [44].

Then:

$$ENB_r = \frac{NoiseBandwidth}{Bandwidth(-3\,\mathrm{dBm})} \Leftrightarrow 1.046 = \frac{ElecNoiseBandwidth}{Bandwidth(FilterEl)} \Leftrightarrow$$

$$\Leftrightarrow \frac{ElecNoiseBandwidth}{7.5\times 10^9} = 1.046 \Leftrightarrow ElecNoiseBandwidth = 7.845\mathrm{GHz}$$

It's also known that $Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \approx \frac{I_1 - I_0}{2\sigma}$ and Q=7 for BER=10^{-12} (chapter 2.1.3.1)

The responsivity of a photodiode is characterized by

$$\Re = \frac{I}{P} \tag{4.2}$$

As the diode responsivity is defined as 1:

$$\Re = \frac{I}{P} = 1 \Leftrightarrow I = P$$

Then

$$Q = \frac{I_1 - I_0}{2\sigma} = \frac{P_1 - P_0}{2\sigma} \tag{4.3}$$

Using the definition of extinction ratio ($ExtRatio$), is possible to relate the power bit 1 and 0 by:

$$10\log\left(\frac{P_1}{P_0}\right) = ExtRatio \Leftrightarrow \frac{P_1}{P_0} = 10^{\frac{ExtRatio}{10}} \tag{4.4}$$

Relating power of bit 1 and 0 with the average power (P_{avg}), using the formula (4.4):

$$P_{avg} = \frac{P_1 + P_0}{2} = \frac{1}{2}P_1\left(1 + \frac{P_0}{P_1}\right) = \frac{1}{2}P_1\left(1 + 10^{-\frac{ExtRatio}{10}}\right) \Leftrightarrow P_1 = \frac{2P_{avg}}{\left(1 + 10^{-\frac{ExtRatio}{10}}\right)}$$

$$P_1 - P_0 = P_1\left(1 - \frac{P_0}{P_1}\right) = P_1\left(1 - 10^{-\frac{ExtRatio}{10}}\right) = 2P_{avg}\frac{\left(1 - 10^{-\frac{ExtRatio}{10}}\right)}{\left(1 + 10^{-\frac{ExtRatio}{10}}\right)} \qquad (4.5)$$

Then using formulas (4.3) and (4.5):

$$Q = \frac{P_1 - P_0}{2\sigma} = \frac{\left(1 - 10^{-\frac{ExtRatio}{10}}\right)}{\left(1 + 10^{-\frac{ExtRatio}{10}}\right)}\frac{P_{avg}}{\sigma} \Leftrightarrow \sigma = \frac{\left(1 - 10^{-\frac{ExtRatio}{10}}\right)}{\left(1 + 10^{-\frac{ExtRatio}{10}}\right)}\frac{P_{avg}}{Q} \qquad (4.6)$$

The rout-mean-square of noise values can be related with the thermal noise and the equivalent noise bandwidth as follows [43]:

$$\sigma^2 = ThermalNoise^2 \times ElecNoiseBandwidth \Leftrightarrow$$

$$\Leftrightarrow ThermalNoise = \frac{\sigma}{\sqrt{ElecNoiseBandwidth}} \qquad (4.7)$$

Relating (4.6) and (4.7):

$$\Leftrightarrow ThermalNoise = \frac{\sigma}{\sqrt{ElecNoiseBandwidth}}$$

$$\Leftrightarrow ThermalNoise = \frac{\frac{\left(1 - 10^{-\frac{ExtRatio}{10}}\right)}{\left(1 + 10^{-\frac{ExtRatio}{10}}\right)}\frac{P_{avg}}{Q}}{\sqrt{ElecNoiseBandwidth}} \qquad (4.8)$$

As the medium optical input power of the receiver is -23 dBm:

$$10\log\left(\frac{P_{avg}(W)}{10^{-3}}\right) = -23\text{dBm} \Leftrightarrow P_{avg}(\text{W}) = 10^{-2.3} \times 10^{-3} = 10^{-5.3}\ \text{W}$$

Then, using the values Q=7 for BER=10^{-12}, $ElecNoiseBandwidth = 7.845\text{GHz}$, $P_{avg}(W) = 10^{-5.3}$ W and *ExtRatio=9* dB and the formula (4.8):

$$ThermalNoise = \frac{\dfrac{\left(1-10^{-\frac{ExtRatio}{10}}\right)}{\left(1+10^{-\frac{ExtRatio}{10}}\right)} \dfrac{P_{avg}}{Q}}{\sqrt{ElecNoiseBandwidth}} = \frac{\dfrac{\left(1-10^{-0.9}\right)}{\left(1+10^{-0.9}\right)} \dfrac{10^{-5.3}}{7}}{\sqrt{7.845 \times 10^{9}}} \approx 6.276 \times 10^{-12} \text{ A}/\sqrt{\text{Hz}}$$

Using the back-to-back configuration (Figure 32) it was verified by simulation the *ElecNoiseBandwidth* and *ThermalNoise* values:

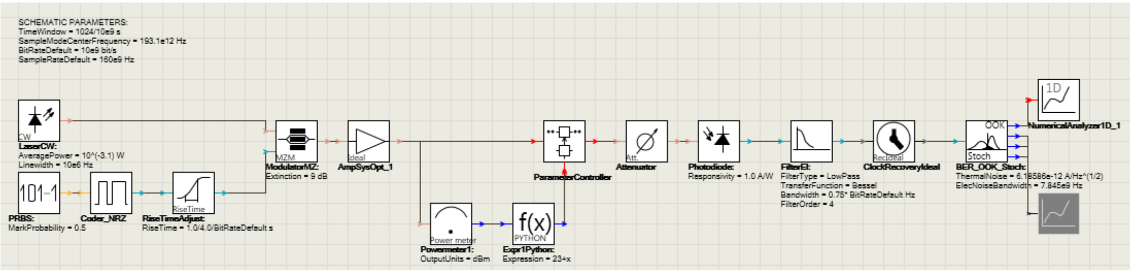

Figure 32 - Back-to-Back configuration

Setting $ElecNoiseBandwidth = 7.845\text{GHz}$ and $ThermalNoise = 6.186 \times 10^{-12} \text{ A}/\sqrt{\text{Hz}}$ of BER_OOK_Block was obtained a BER value of approximately 4.524×10^{-12}.

To obtain a BER value of 1×10^{-12}, by simulation was determined a $ThermalNoise = 6.186 \times 10^{-12} \text{ A}/\sqrt{\text{Hz}}$ (values used in simulation, Figure 32).

The difference in values between the theoretical and the obtained by simulation is:

$$\delta(\%) = \frac{ThN_{theor} - ThN_{simul}}{ThN_{theor}} \times 100 = \frac{6.276 \times 10^{-12} - 6.186 \times 10^{-12}}{6.276 \times 10^{-12}} \times 100 \approx 1.434\%$$

This discrepancy can be explained by the interference inter-symbol and the fact that the BER value is determined by a semi-analytical method (using the theoretical relation but also the Gaussian distribution).

4.1.3 Transmission assessment for different fibre lengths

After determining the right amount of Thermal Noise, the Attenuator Module is replaced by the fibre in order to take into account the fibre dispersion and nonlinear effects.

It was used a fibre with attenuation 0.22 dB/km, dispersion of 17 ps/nm.km (common values for standard fibres) and taking into account the nonlinear effects (2.6×10^{-20} m^2/W).

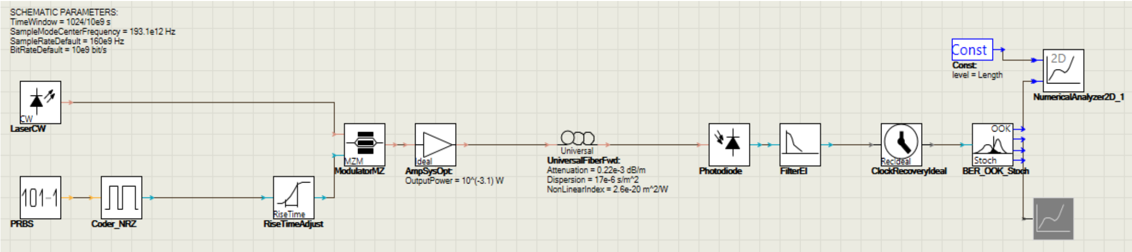

Figure 33 - Simulation scheme of the system using fibre

For different fibre lengths, it was obtained the follow graphic (SignalAnalyser2D_1):

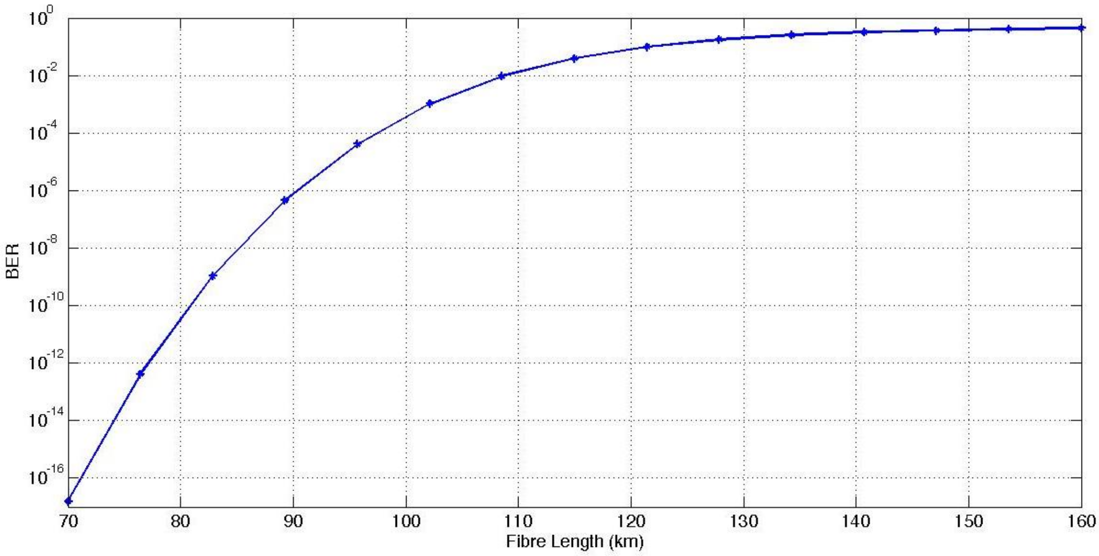

Figure 34 – BER depending on the fibre length

It is possible to observe that the BER of 10^{-12} is obtained for a fibre length of approx. 75 km. Once this BER value has been determined for a receiver power input of -23 dBm and as the fibre has an attenuation of 0.22 dB/km, it was expected that to achieved the BER value of 10^{-12} the fibre length would be

$$Pout\_Tx(\text{dBm}) - FibreAtt(\text{dB/km}) \times FibreLength(\text{km}) = -23\text{dBm} \Leftrightarrow$$

$$\Leftrightarrow FibreLength(\text{km}) = \frac{23dBm + Pout\_Tx(\text{dBm})}{FibreAtt(\text{dB/km})} = \frac{23-1}{0.22} \approx 100\text{km}$$

This discrepancy of values (100 to 75 km) is due to the fact that there are more fibre characteristics to take into account in addition of attenuation, such as the dispersion and nonlinear effects.

4.1.4 Dispersion effect

In order to find suitable values for the dispersion, it was used a similar scheme, shown in Figure 33 but with the Modulator Module before the fibre to ensure that the receiver input power has a range of [-22, -21, -20, - 19, -15] dBm. For the used fibre it has only been considered the effect of dispersion (this parameter ranging from 7 to 17 ps/nm.km) not including the nonlinear effects ($NonLinearIndex = 0\,\mathrm{m}^2/\mathrm{W}$) and attenuation (0 dB/km). Thus was obtained the following response:

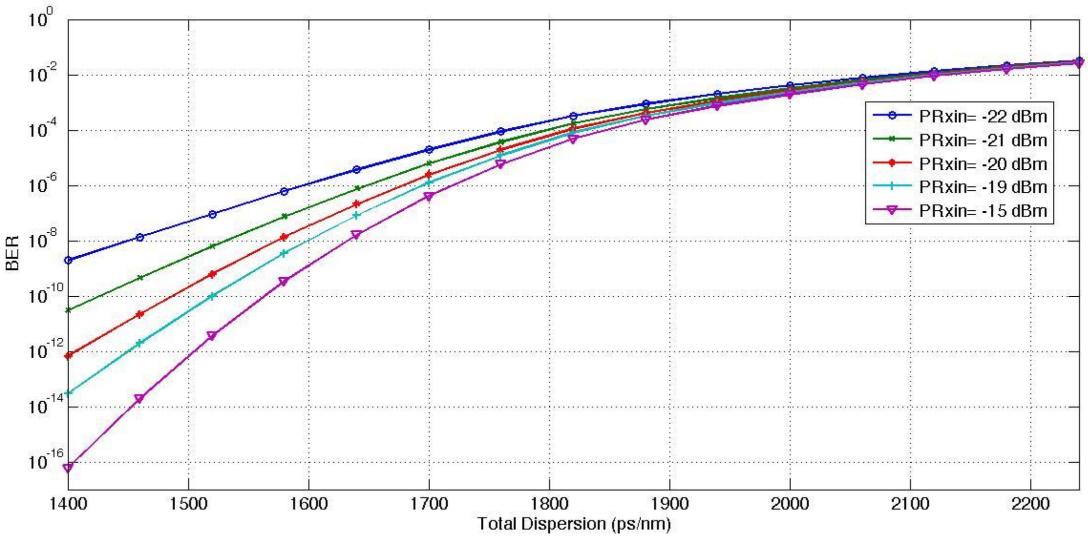

Figure 35 – BER depending on the fibre dispersion

For low dispersion values the BER is influenced by the thermal noise and for high dispersion values the BER is influenced by interference inter-symbol. It was chosen as reference the receiver power input of -19 dBm (having a maximum normalized dispersion of approximately $1210/160 \approx 7.6\,\mathrm{ps/nm.km}$ to a BER value of 10^{-12}, considering a fibre length of 160 km).

4.1.5 Amplification

Once the maximum coefficient of dispersion value has been determined, it is now necessary to add amplifiers to the schematic to amplify the signal to the antennas whose distances are greater than 75 km (Figure 34).

With the addition of the amplifiers was taken into account the nonlinear effects of the fibre, the dispersion (7.6 ps/nm.km), the attenuation (0.22 dB/km) and the noise of amplifiers (using a Noise Figure value of 6 dB, common in EDFA amplifiers).

Therefore, it was used the power amplifier configuration (amplifier before fibre), preamplifier configuration (amplifier after fibre) and both configurations simultaneously.

4.1.5.1 Power amplifier configuration

In this configuration an amplifier was added before the fibre as it can be observed in following figure:

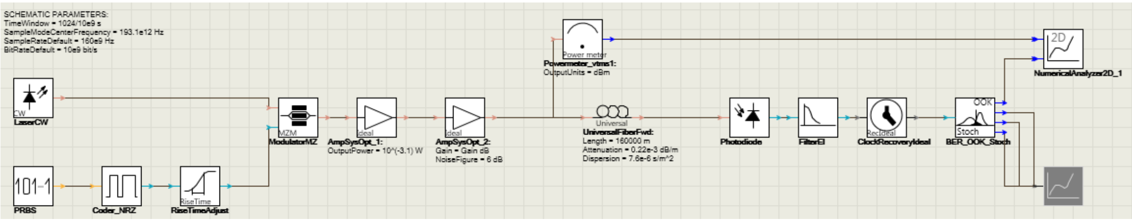

Figure 36 – Simulation scheme used for the study of power amplifier configuration

Thus varying the amplifier gain (from 0 to 25 dB) it is possible to observe the BER obtained (graphic obtained through NumericalAnalizer2D_1 block):

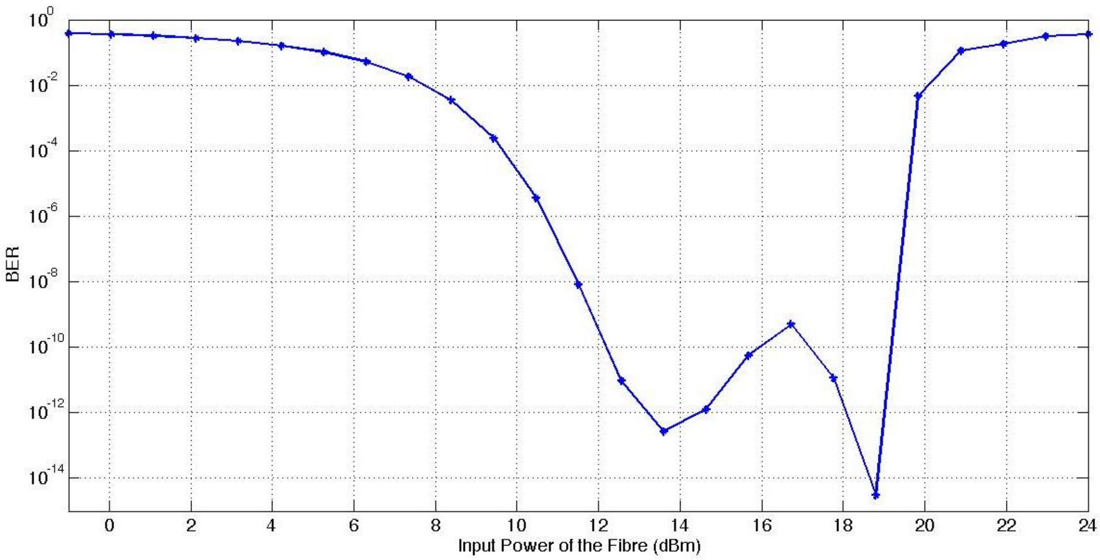

Figure 37 - BER depending on the input power of the fibre

Once the fibre length used was 160 km with an attenuation of 0.22 dB/km, the total attenuation of the fibre is:

$$TotalFibreAtt(\text{dB}) = FibreLength(\text{km}) \times FibreAtt(\text{dB/km}) = 160 \times 0.22 = 35.2\,\text{dB}$$

So it was expected to obtain a BER value close to 10^{-12} for an input power of receptor of -19 dBm (Figure 35), which correspond to an input fibre power of

$$\begin{aligned}
&Pin_Fibre(\text{dBm}) - TotalFibreAtt(\text{dB}) = Pin_Rx(\text{dBm}) \Leftrightarrow \\
&\Leftrightarrow Pin_Fibre(\text{dBm}) = TotalFibreAtt(\text{dB}) + Pin_Rx(\text{dBm}) \Leftrightarrow \\
&\Leftrightarrow Pin_Rx(\text{dBm}) = 35.2 - 19 = 16.2\,\text{dBm}
\end{aligned}$$

However, observing the Figure 37 it is possible to conclude that the nonlinear effects of the fibre begin to influence at an input fibre power of $\approx$ 13.8 dB, causing a non-monotonic response. Nonetheless it was achieved BER values below 10^{-12} to a power input fibre ranging between 18 and 19 dBm (corresponding an amplifier gain of

$$\begin{aligned}
&Gain_PowerAmp(\text{dB}) = Pin_Fibre(\text{dB}) - Pout_Tx(\text{dBm}) \Leftrightarrow \\
&\Leftrightarrow Gain_PowerAmp(\text{dB}) = [18,19] - (-1) = [19,20]\,\text{dB}
\end{aligned}$$

Thus it is possible to conclude that using just one amplifier with a gain range of [19,20] dB is possible to have BER values lower that 10^{-12}, but this amplifier is very low tolerant to gain variation, so this is not the ideal configuration to implement in practice.

The BER increases from 3×10^{-15} to 3×10^{-3} when the fibre input power increases from 18.8 to 19.8 dBm, respectively. This significant increase in BER is mainly due to the signal distortions (mainly by the fibre nonlinearities) as can be observed from the eye diagrams at the input of the decision circuit depicted in Figure 38 and Figure 39 for the transmitted output powers 18.8 and 19.8 dBm, respectively.

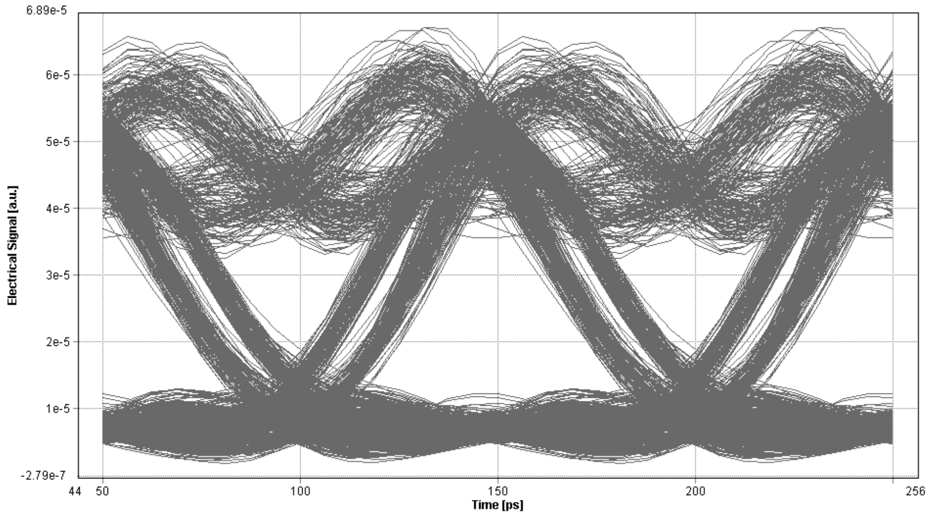

Figure 38 - Eye Diagram for an input fibre power of 18.8 dBm (BER=3×10^{-15})

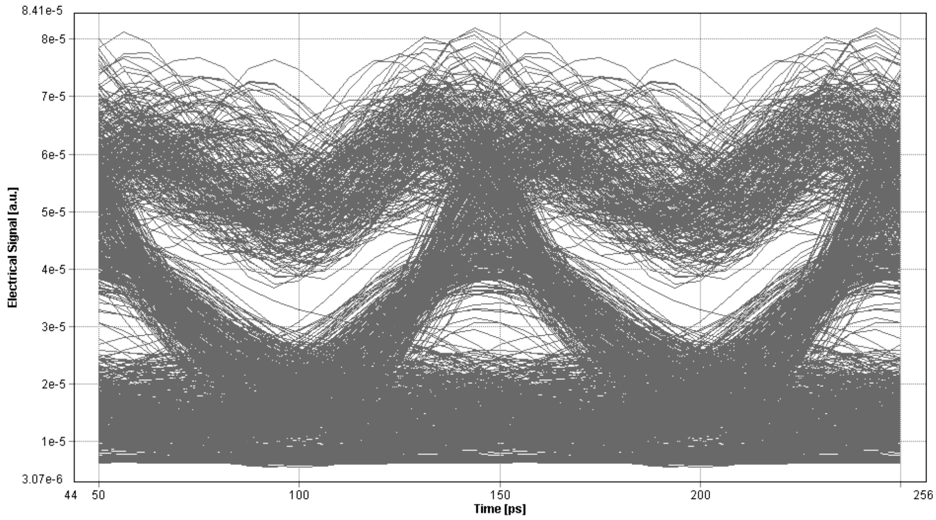

Figure 39 - Eye Diagram for an input fibre power of 19.8 dBm (BER=3×10^{-3})

4.1.5.2 Preamplifier Configuration

The preamplifier configuration was also studied (placing the amplifier after the fibre) and it is presented in the following figure.

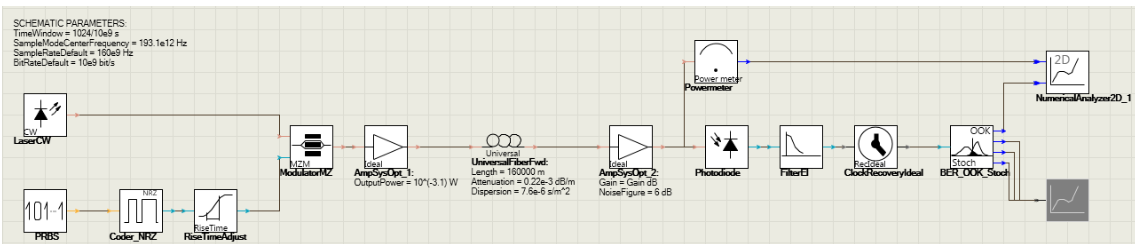

Figure 40 – Simulation scheme used for study of preamplifier configuration

Varying the gain of the amplifier (from 0 to 25 dB), the following BER values were obtained at the receiver output:

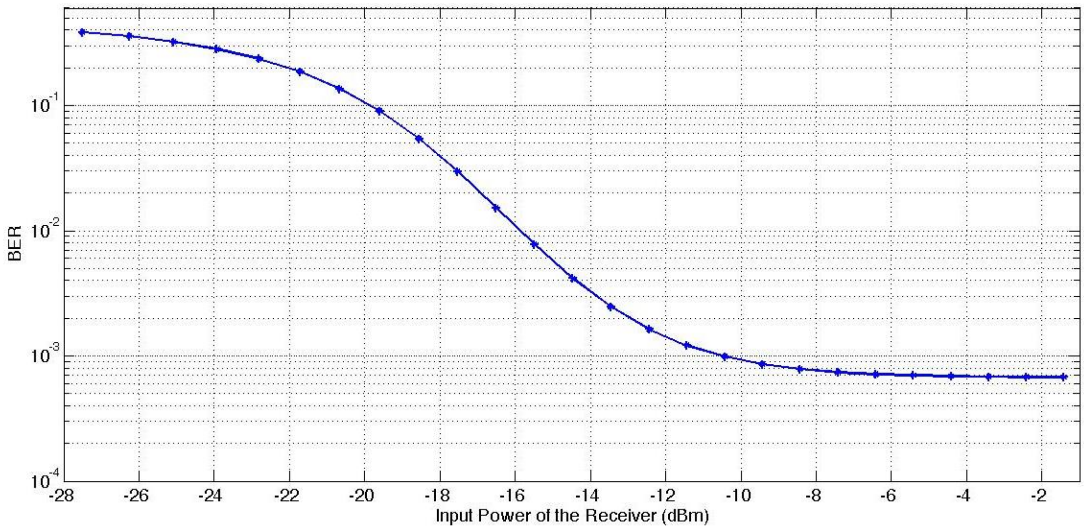

Figure 41 - BER depending on the input power of the receiver

It would be expected to a power value of -19 dBm, a corresponding BER value of 10^{-12}. This is not what is observed at Figure 41 because the noise of the amplifier is quite high when the amplifier input power is very low. In this case there is no amplification before this amplifier and the signal was attenuated, having a power value of:

$$\begin{aligned} &Pout\_Fibre(\text{dBm}) = Pout\_Tx(\text{dBm}) - TotalFibreAtt(\text{dB}) = \\ &= Pout\_Tx(\text{dBm}) - FibreLength(\text{km}) \times FibreAtt(\text{dB/km}) = \\ &= 1 - (160 \times 0.22) = -36.2\,\text{dB} \end{aligned}$$

Thus it is possible to conclude that with only one amplifier, using preamplifier configuration, it is not possible to achieve BER values lowers than 10^{-12} for antennas with greater distances.

4.1.5.3 Power amplifier and preamplifier configuration

This configuration was used in order to obtain a correct signal power at the fibre input (two amplifiers allow a lower post amplifier gain and consequently a lower power input, reducing the fibre nonlinear effects) and at the fibre output (the use of the post amplifier allow a higher power at the input of preamplifier, reducing the influence of amplifier noise).

So it was used in the following configuration:

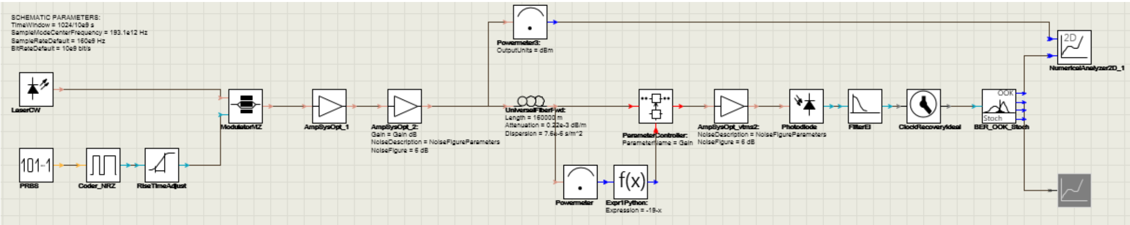

Figure 42 – Simulation scheme used for the study of power amplifier and preamplifier configurations

Thus, ranging the gain of the power amplifier (from 0 to 25 dB), and also ranging the gain of the preamplifier with the Exp1Phyton block (using the expression -19-x, ensuring a power input of the receiver of -19 dBm) it was obtained the following graphic:

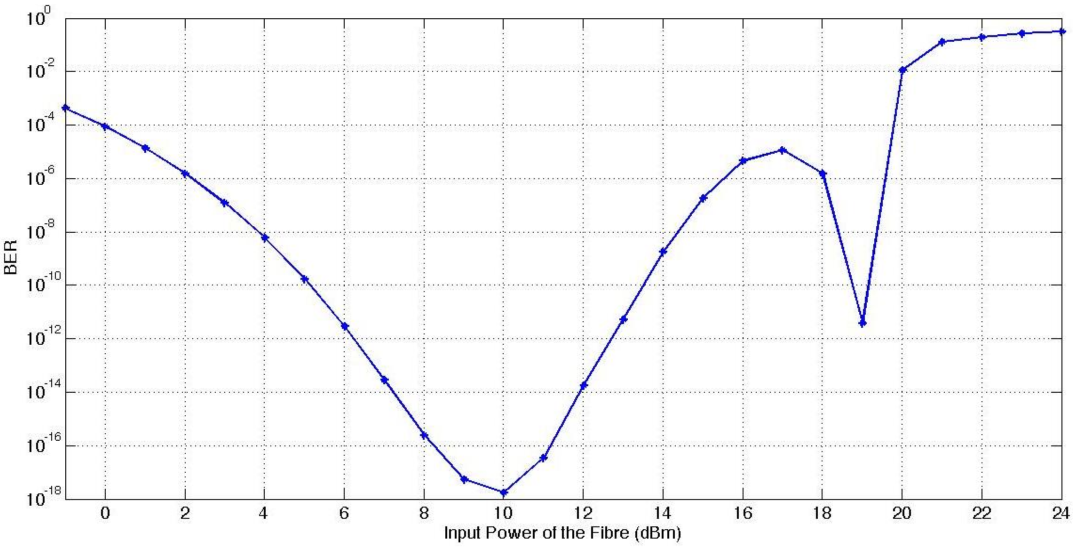

Figure 43 - BER depending on the power output of the first amplifier (at the input of the fibre)

It is thus possible to conclude that the required power input of the fibre for BER values lower or equal to 10^{-12} is between 9 and approximately 13 dBm. To this range the corresponding gain range of first amplifier is equal to:

$$Gain\_PowerAmp(\text{dB}) = Pin\_Fibre(\text{dB}) - Pout\_Tx(\text{dBm}) \Leftrightarrow$$
$$\Leftrightarrow Gain\_PowerAmp(\text{dB}) = [9,13] - (-1) = [10,14]\,\text{dB}$$

For these values, the second amplifier gain range is:

$$Gain\_PreAmp(\text{dB}) = Pin\_Fibre(\text{dB}) - FibreLength(\text{km}) \times FibreAtt(\text{dB/km}) \Leftrightarrow$$
$$\Leftrightarrow Gain\_PreAmp(\text{dB}) = 19 - [9,13] + 0.22 \times 160 = [7.2,3.2]\,\text{dB}$$

Then, it is possible to conclude that the best configuration to achieve the best values using both power amplifier and preamplifier.

So, after concluding that the dispersion fibre value should be lower than 7.6 ps/nm.km and a pre and post amplifiers should be used, it is now important to study the DWDM configuration.

4.1.6 Study of DWDM 10x10 Configuration

Having an idea of the features and elements to be used for a system with a satisfactory BER value, it is now time to simulate the DWDM system with 10 signals, each signal with a transmission rate of 10 Gb/s.

Then it is necessary to use a multiplexer and de-multiplexer, using as reference the multiplexer and de-multiplexer of Cisco named Cisco ONS 15216 Mux/De-mux 40-Channel Patch Panel (Attachment C), which allows the use of the following 40 channels with respective frequencies:

Cisco Product Number 15216-MD-40-ODD			Cisco Product Number 15216-MD-40-EVEN		
Channel Id	Frequency (THz)	Wavelength (nm)	Channel Id	Frequency (THz)	Wavelength (nm)
1	195.9	1530.33	1	195.85	1530.72
2	195.8	1531.12	2	195.75	1531.51
3	195.7	1531.90	3	195.65	1532.29
4	195.6	1532.68	4	195.55	1533.07
5	195.5	1533.47	5	195.45	1533.86
6	195.4	1534.25	6	195.35	1534.64
7	195.3	1535.04	7	195.25	1535.43
8	195.2	1535.82	8	195.15	1536.22
9	195.1	1536.61	9	195.05	1537.00
10	195.0	1537.40	10	194.95	1537.79
11	194.9	1538.19	11	194.85	1538.58
12	194.8	1538.98	12	194.75	1539.37
13	194.7	1539.77	13	194.65	1540.16
14	194.6	1540.56	14	194.55	1540.95
15	194.5	1541.35	15	194.45	1541.75
16	194.4	1542.14	16	194.35	1542.54
17	194.3	1542.94	17	194.25	1543.33
18	194.2	1543.73	18	194.15	1544.13
19	194.1	1544.53	19	194.05	1544.92
20	194.0	1545.32	20	193.95	1545.72
21	193.9	1546.12	21	193.85	1546.52
22	193.8	1546.92	22	193.75	1547.32
23	193.7	1547.72	23	193.65	1548.11
24	193.6	1548.51	24	193.55	1548.91
25	193.5	1549.32	25	193.45	1549.72
26	193.4	1550.12	26	193.35	1550.52
27	193.3	1550.92	27	193.25	1551.32
28	193.2	1551.72	28	193.15	1552.12
29	193.1	1552.52	29	193.05	1552.93
30	193.0	1553.33	30	192.95	1553.73
31	192.9	1554.13	31	192.85	1554.54
32	192.8	1554.94	32	192.75	1555.34
33	192.7	1555.75	33	192.65	1556.15
34	192.6	1556.55	34	192.55	1556.96
35	192.5	1557.36	35	192.45	1557.77
36	192.4	1558.17	36	192.35	1558.58
37	192.3	1558.98	37	192.25	1559.39
38	192.2	1559.79	38	192.15	1560.20
39	192.1	1560.61	39	192.05	1561.01
40	192.0	1561.42	40	191.95	1561.83

Figure 44 - Table of available channels by the device Cisco ONS 15216 Mux/Demux 40-Channel Patch Panel [45]

The scheme used to study the DWDM 10x10Gb/s configuration is presented below (showing for just one channel):

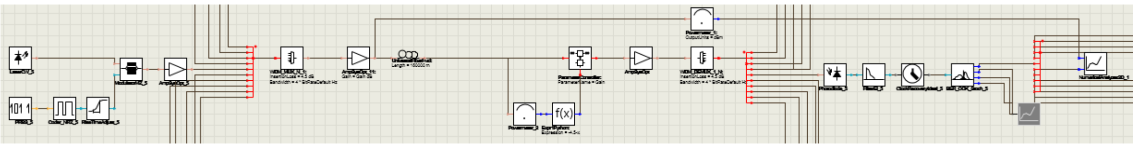

Figure 45 – Simulation scheme used for the solution DWDM 10x10Gb/s

The insertion loss used to the multiplexer and de-multiplexer was 4.5 dBm (value based on datasheet Cisco ONS 15216 Mux/De-mux 40-Channel Patch Panel [42]).

Then, the characteristics used to perform this simulation were the same than used in previous simulations (193.1 THz centre frequency which corresponds approximately to 1552.524 nm and a bit rate of 10 Gb/s).

The major difference is the power values involved, due to the multiplexing and de-multiplexing, a gain of 10 dB after the multiplex was added, and subtracted 10 dB after de-multiplexer, requiring an adjustment of the amplifiers gain. Then, the expression used in order to obtain a power of -19 dBm at the receiver input per channel must be adjusted. Taking into account that the multiplexer and de-multiplexer has an insertion loss of 4.5 dBm each, the expression used to determine the gain of the amplifier after the fibre is -4.5-x to obtain a power of -19 dBm, once the de-multiplexer will attenuate a value of 14.5 dBm (10 dBm due to the de-multiplexing of the 10 channels and 4.5 dBm due the multiplex/de-multiplexer insertion loss).

So, by varying the gain value of the first amplifier it is possible to observe the BER values at the output of the receiver for each channel.

For the subsequent simulations was considered the fibre parameters of the LEAF fibre from Corning (chapter 2.7.2) which have a dispersion range of [3.78, 5.05] ps/nm.km and an attenuation range of [0.216, 0.22] dB/km for a frequency range of [192.3, 194.1] THz (having an attenuation value of 0.217 dB/km to a frequency of 193.1 THz, value used in following calculations). This fibre, due its larger effective area, is affected by nonlinear effects only for much larger powers comparing with other fibres, so it was necessary to vastly increase the power input to see the nonlinear effects (the increasing of BER, instead decreasing), supporting much more input power and consequently allow amplifiers with greater gain.

It was used the 10 channels with different spacing: 100 GHz and 200 GHz, assuming as reference the frequency 193.1 THz.

So, for a channel spacing of 100 GHz (channels between 192.7 and 193.6 THz), using LEAF fibre it was obtained the following graphic:

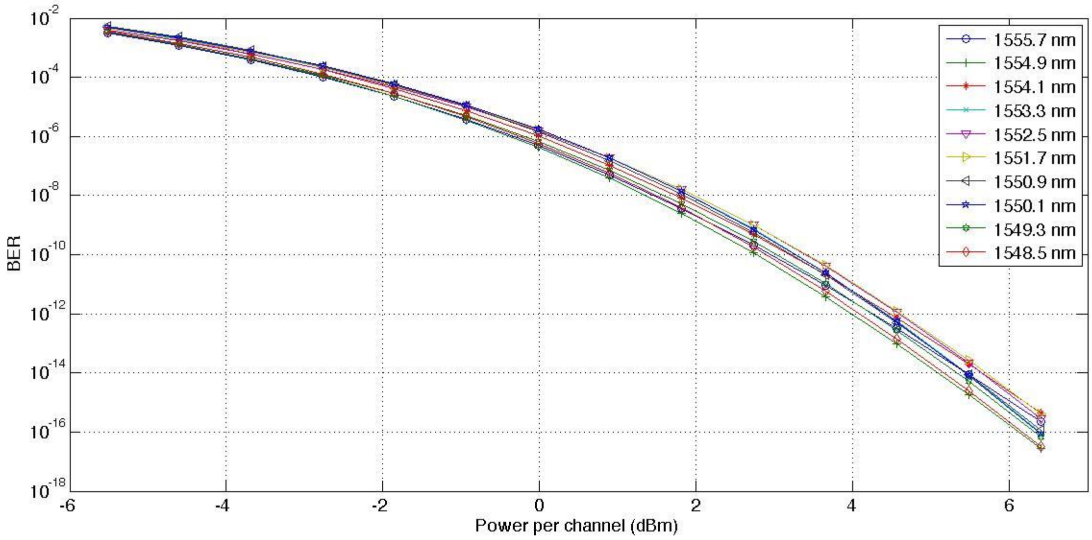

Figure 46 - BER depending on the power output of the first amplifier (at the input of the fibre) using 10 signals with a frequency spacing channel of 100 GHz

It is possible to verify that for a power greater than approx. 4.5 dBm, all channels have a BER lower than 10^{-12}. The power amplifier gain to this value is equal to:

$$Gain\_PowerAmp(\mathrm{dB}) = Pin\_Fibre_{perChan}(\mathrm{dB}) - \left(Pout\_Tx(\mathrm{dBm}) - MuxInsLoss(\mathrm{dB})\right) =$$
$$= 4.5 - (-1 - 4.5) = 10\,\mathrm{dB}$$

For this value, the preamplifier gain is:

$$Gain\_PreAmp(\mathrm{dB}) = Pin\_Rx(\mathrm{dB}) - Pin\_Fibre(\mathrm{dB}) + TotalFibreAtt(\mathrm{dB}) + DemuxInsLoss(\mathrm{dBm}) =$$
$$= -19 - 4.5 + 160 \times 0.217 + 4.5 = 15.72\,\mathrm{dB}$$

Doing the simulation to the spacing channels of 200 GHz (192.9 to 193.5 THz) it was obtained the following results:

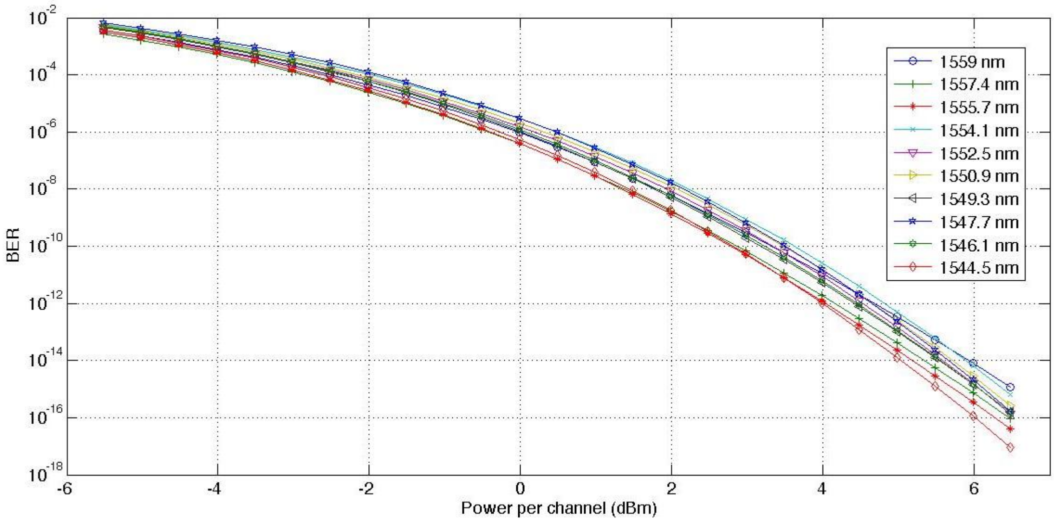

Figure 47 - BER depending on the power output of the first amplifier (at the input of the fibre) using 10 signals with a frequency spacing channel of 200 GHz

The results obtained are practically the same, with a minimal power of approximately 4.8 dB for a BER equal or lower than 10^{-12}, which correspond to a power amplifier gain:

$$Gain\_PowerAmp(\mathrm{dB}) = Pin\_Fibre_{perChan}(\mathrm{dB}) - \left(Pout\_Tx(\mathrm{dBm}) - MuxInsLoss(\mathrm{dB})\right) = \\ = 4.8 - (-1 - 4.5) = 10.3\,\mathrm{dB}$$

And the preamplifier gain is equal to:

$$Gain\_PreAmp(\mathrm{dB}) = Pin\_Rx(\mathrm{dB}) - Pin\_Fibre(\mathrm{dB}) + TotalFibreAtt(\mathrm{dB}) + DemuxInsLoss(\mathrm{dBm}) = \\ = -19 - 4.8 + 160 \times 0.217 + 4.5 = 15.42\,\mathrm{dB}$$

Using 2 amplifiers the total input power of fibre is:

$$Pin\_Fibre_{allChan}(\mathrm{dB}) = Pin\_Fibre_{perChan}(\mathrm{dB}) + 10\log\left(numofChan\right) = \\ = 4.8 + 10\log(10) = 14.8\,\mathrm{dB}$$

In order to reduce this value it was used a configuration with 3 amplifiers, dividing one power amplifier and one fibre with length L in two power amplifiers, both with same gain, and two fibres with length L/2 (amplifier1, fibre1, amplifier2, fibre2). Doing this modification for the 200 GHz spacing configuration the follow response was obtained:

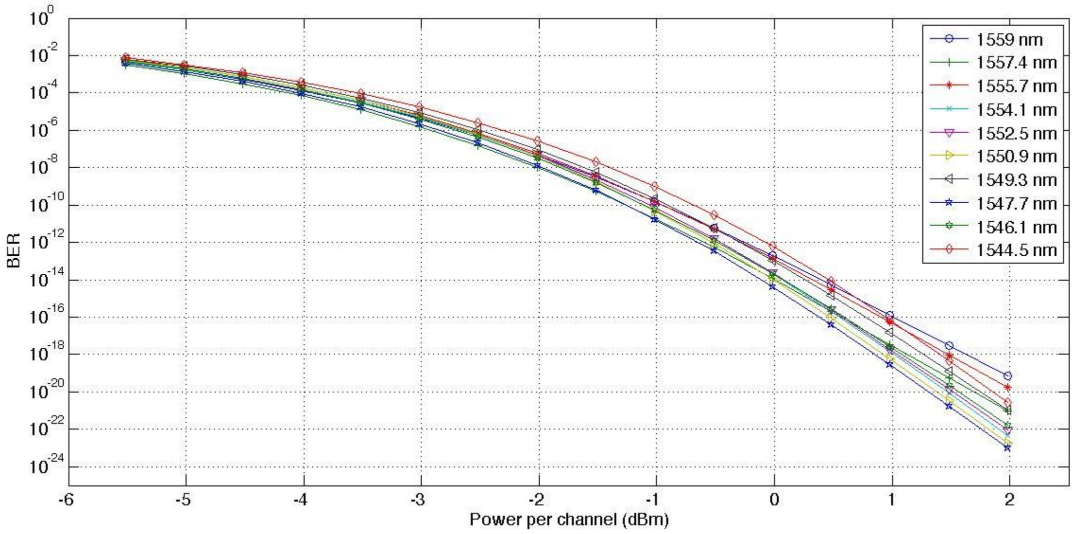

Figure 48 - BER depending on the power output of the first amplifier (at the input of the fibre) using 10 signals with a frequency spacing channel of 200 GHz, using 3 amplifier configuration

It is possible to conclude that with 3 amplifiers was achieved a BER value lower than 10^{-12} for a total input power of the fibre (all the channels) of approximately 9.8 dBm, which correspond to a power amplifier with a gain of:

$$Gain\_PowerAmp(\mathrm{dB}) = Pin\_Fibre_{perChan}(\mathrm{dB}) - \left(Pout\_Tx(\mathrm{dBm}) - MuxInsLoss(\mathrm{dB})\right) =$$
$$= 0.2 - (-1 - 4.5) = 5.3\,\mathrm{dB}$$

The preamplifier gain, for this power value is equal to:

$$Gain\_PreAmp(\mathrm{dB}) = Pin\_Rx(\mathrm{dB}) - Pin\_Fibre(\mathrm{dB}) + TotalFibreAtt(\mathrm{dB}) + DemuxInsLoss(\mathrm{dBm}) =$$
$$= -19 - (-0.2) + 160 \times 0.217 + 4.5 = 20.42\,\mathrm{dB}$$

Defining the first amplifier gain as 20 dB and the second amplifier gain varying to the input of the receiver to be -19 dBm was ranged the length of the fibre to determine the maximum distance which this configuration can be achieved:

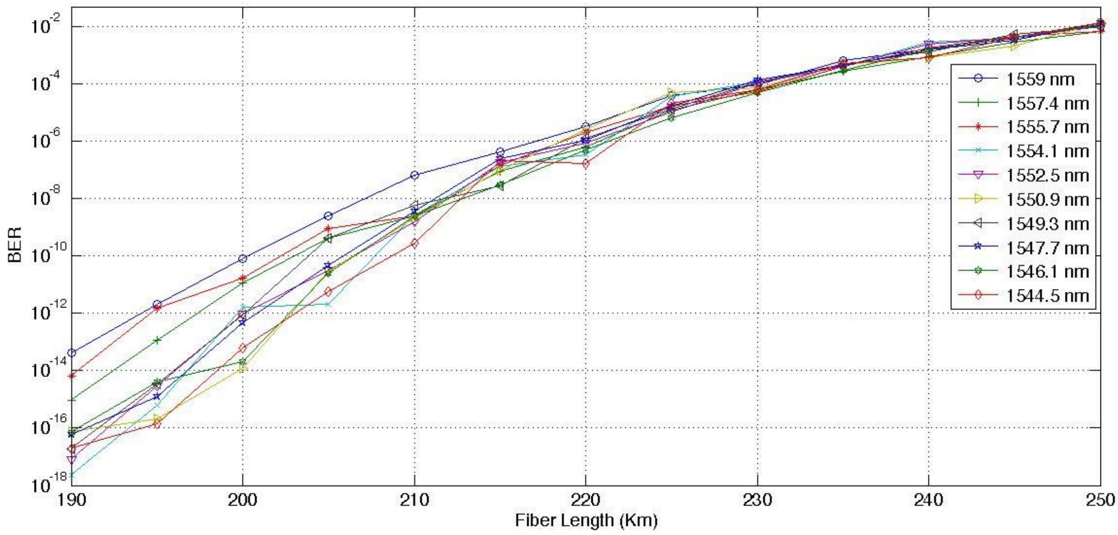

Figure 49 - BER depending on the fibre length using 10 signals with a frequency spacing channel of 200 GHz

Observing Figure 49 it is possible to conclude that the maximum distance to a BER of 10^{-12} is approx. 195 km.

4.2 SKA1-mid: 4 Channels at 25 Gbps

For this solution it was considered a transmitter with an output power of -1 dBm and an extinction ratio of 20 dB, and a receiver which for an input power of -14 dBm providing a BER of 10^{-12} (values assuming a NRZ signal, modulated by an NRZ transmitter, in a back-to-back system).

4.2.1 Transmitter

To simulate the Duobinary transmitter was used the follow block diagram:

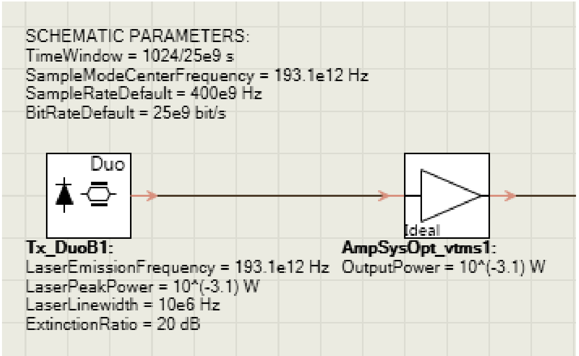

Figure 50 - Duobinary transmitter scheme

Tx_DuoB1 is the transmitter itself and the block AmpSysOpt_1 (ideal power amplifier, without noise) serves only to ensure that the transmitter output signal power is exactly the intended (in this case -1 dBm).

Thus the scheme of the transmitter Tx_DuoB1, a transmitter model available on VPI, is described by following figure:

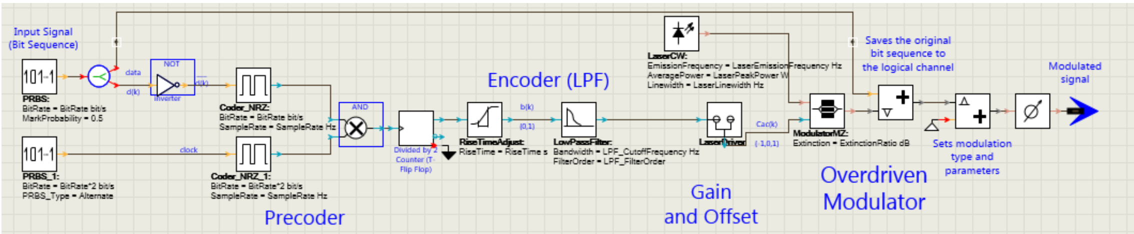

Figure 51 - Tx_DuoB1 Block Diagram

The main characteristics of Tx_BuoB1 are:

SampleRate	400 GHz
BitRate	25 Gbits/s
RiseTime	25 ps
LaserEmissionFrequency	193.1 THz
LaserPeakPower	10^(-3.1) W
LaserLinewidth	10 MHz
LPF_CutoffFrequency	6.5 GHz
LPF_FilterOrder	5
ExtinctionRatio	20 dB

Table 4 - Tx_DuoB1 characteristics

Some of these values were defined as input (case of Extinction Ratio or Laser Peak Power), other values (such as LPF Cut-off Frequency and LPF_FilterOrder) are optimized (chapter 4.2.3)

4.2.2 Receiver

The receiver used in simulation is similar to the one used for the 10 channels at 10Gbps. The only difference is the BiteRateDafault used (in this case is 25 Gbps, changing the Bandwidth of the receptor).

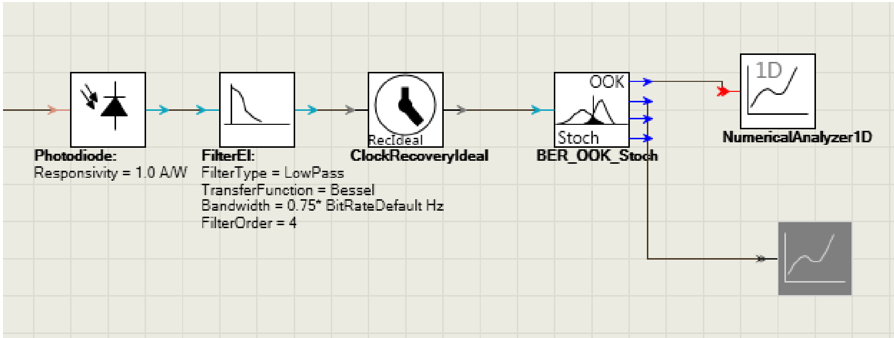

Figure 52 - Diagram block used for the receiver simulation

4.2.3 Receiver optimization without thermal noise and determination of Duobinary system sensitivity

Once having defined the receiver configuration, it is now necessary to optimize their parameters taking into account the fibre length of the DDBH links.

In order to do that, it was added the fibre (just to simulate the effect of dispersion, without considering the attenuation, nonlinear effects or the thermal noise of the receiver). So the following scheme was used:

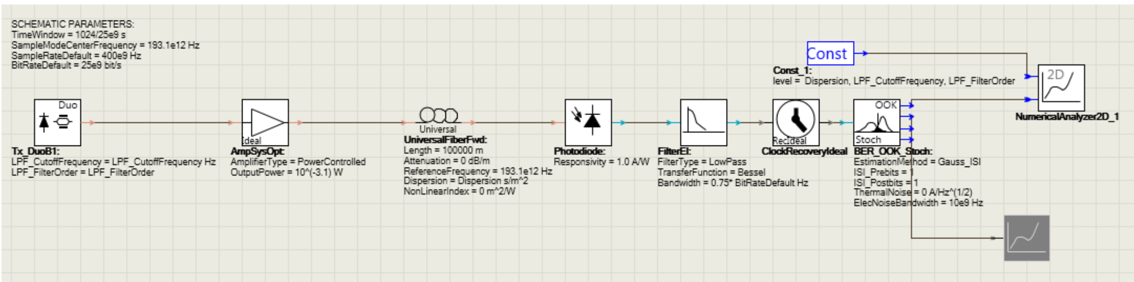

Figure 53 – Simulation scheme used to optimize de Duobinary transceiver

Using this scheme it was varied the *LPF_CutoffFrequency* and *LPF_FilterOrder* of Tx_DuoB1_1 and dispersion of fibre. The thermal noise of BER_OOK_Block_1 was not considered ($ThermalNoise = 0\,\text{A}/\sqrt{\text{Hz}}$), neither the nonlinear effects of the fibre ($NonLinearIndex = 0\text{m}^2/\text{W}$). So, varying the dispersion of the fibre (considering $LPF\_CutoffFrequency = 0.25 \times 25 = 6.25\text{Gbps}$), was obtained the following graphic:

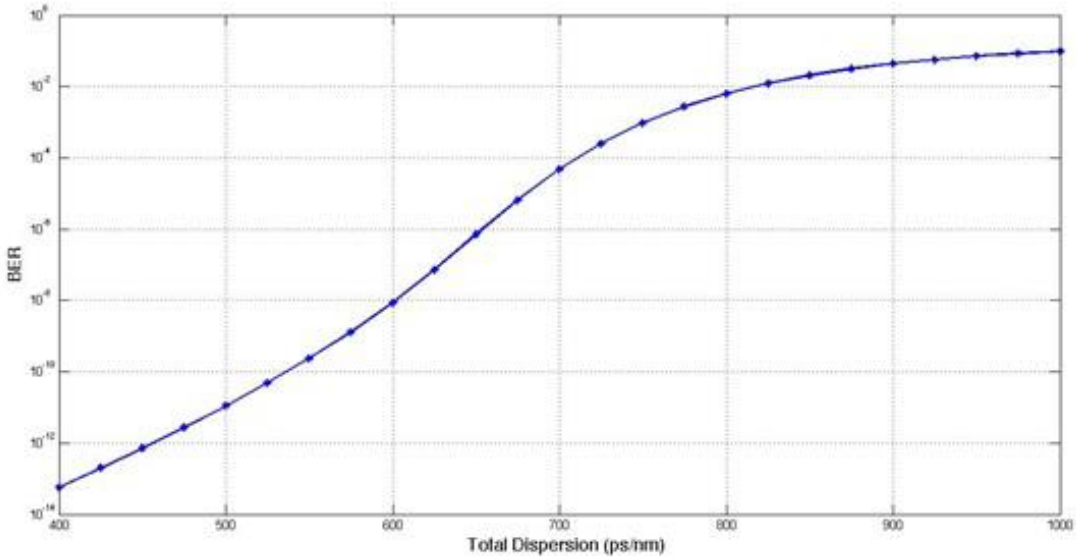

Figure 54 - BER depending on the dispersion for a LPF_Cutoff Frequency of 6.25 GHz

In order to optimize the other values, a dispersion value of 7.2 ps/nm.km (with 100 km of fibre length, value that corresponds to a BER of 10^{-3}) was used. So with this dispersion was varied the value of *LPF_CuttoffFrequency* (to filters from 1 to 7) in order to obtain the lowest BER value:

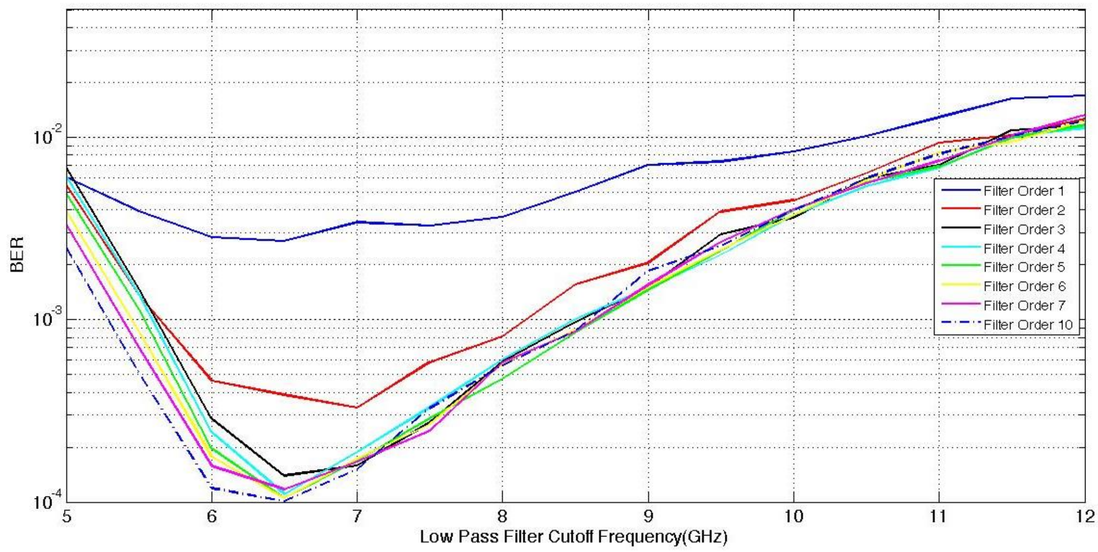

Figure 55 – BER depending on the low pass filter cut-off frequency to several filter orders

From Figure 55 it is observed that the optimal value of *LPF_CutoffFrequency* is 6.5 GHz (0.26×25 GHz). In terms of the filter's order, it is observed that with an order greater than 4, the BER values obtained are fairly low. So between the presented range, it was chosen the order 5, since it has a low BER value and is still a relatively low order (less complex filter compared to higher orders).

Once obtained the optimum characteristics of the transmitter (*LPF_CutoffFrequency* = 6.5 GHz, *LPF_FilterOrder* = 5) is now necessary determine the Thermal Noise and Electrical Equivalent Noise Bandwidth values to obtain a BER value of 10^{-12} to the Duobinary back-to-back system.

It is known the input receiver power of NRZ system to obtain a BER value of 10^{-12} (-14 dBm), but this value is not known for a Duobinary system. So, once the receiver for a Duobinary system and a NRZ system is the same, it is necessary to determine the characteristics of receiver (*ThermalNoise* and *ElecNoiseBandwidth*) to then, using that receiver, achieve the new input power of receiver in order to obtain a BER of 10^{-12} to a Duobinary back-to-back system.

The Filter used in the receiver is a Bessel Filter order 4 with a cut-off frequency of $0.75 \times 25 \times 10^9 = 18.75\text{GHz}$, so using the formula (4.1) and knowing that the Equivalent

Noise bandwidth ratio of Bessel filter order 4 $ENB_r(Bessel,order4) \approx 1.046$ [44], it possible to determine the *ElecNoiseBandwidth*:

$$ENB_r = \frac{NoiseBandwidth}{Bandwidth(-3\,\text{dBm})} \Leftrightarrow 1.046 = \frac{ElecNoiseBandwidth}{Bandwidth(FilterEl)} \Leftrightarrow$$

$$\Leftrightarrow \frac{ElecNoiseBandwidth}{18.75 \times 10^9} = 1.046 \Leftrightarrow ElecNoiseBandwidth = 19.6125\text{GHz}$$

Once the filter used was a Bessel filter order 4 with a bandwidth of 18.75 (0.7525) GHz, As the medium optical input power of the receiver is -14 dBm:

$$10\log\left(\frac{P_{avg}(\text{W})}{10^{-3}}\right) = -14\,\text{dBm} \Leftrightarrow P_{avg}(\text{W}) = 10^{-1.4} \times 10^{-3} = 10^{-4.4}\ \text{W}$$

Then, using the values Q=7 for BER=10^{-12}, $ElecNoiseBandwidth = 19.6125\text{GHz}$, $P_{avg}(\text{W}) = 10^{-4.4}$ W and *ExtRatio*=20 dB and the formula (4.8):

$$ThermalNoise = \frac{\dfrac{\left(1-10^{-\frac{ExtRatio}{10}}\right)}{\left(1+10^{-\frac{ExtRatio}{10}}\right)}\dfrac{P_{avg}}{Q}}{\sqrt{ElecNoiseBandwidth}} = \frac{\dfrac{\left(1-10^{-2}\right)}{\left(1+10^{-2}\right)}\dfrac{10^{-4.4}}{7}}{\sqrt{19.6125 \times 10^9}} \approx 3.98 \times 10^{-11}\ \text{A}/\sqrt{\text{Hz}}$$

This value was verified in simulation with a back-to-back NRZ system. Using $ElecNoiseBandwidth = 19.6125\text{GHz}$, to obtain a BER value of 10^{-12} by simulation, was obtained $ThermalNoise = 3.72 \times 10^{-11}\ \text{A}/\sqrt{\text{Hz}}$, corresponding to an error of

$$\delta(\%) = \frac{ThN_{theor} - ThN_{simul}}{ThN_{theor}} \times 100 = \frac{3.98 \times 10^{-11} - 3.72 \times 10^{-11}}{3.98 \times 10^{-11}} \times 100 \approx 6.53\%.$$

As described before, this error can be explained by the interference inter-symbol and the fact that the BER value is determined by a semi-analytical method (using the theoretical relation but also the Gaussian distribution).

Once determined the receiver parameters ($ElecNoiseBandwidth = 19.6125\text{GHz}$ and $ThermalNoise = 3.72 \times 10^{-11}\ \text{A}/\sqrt{\text{Hz}}$), it is now necessary to obtain the sensitivity for the Duobinary system (the new input power of the receiver to obtain a BER value of 10^{-12}). So, it was used the follow simulation scheme:

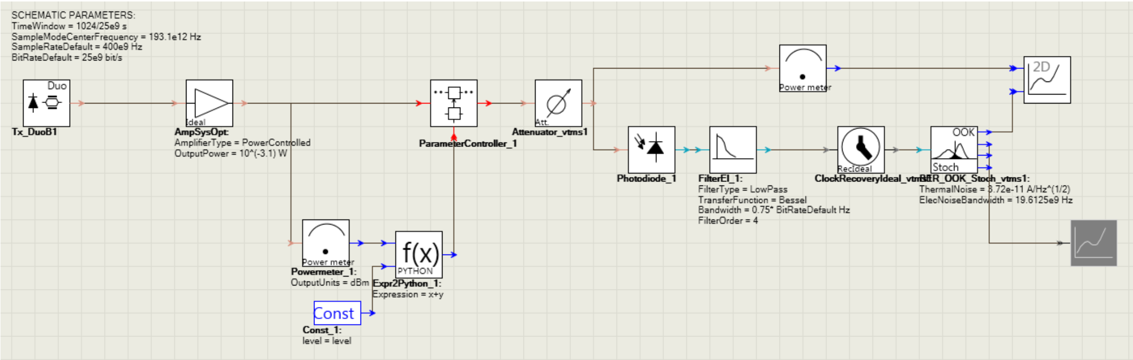

Figure 56 - Diagram block used to determine the sensitivity of the Duobinary system

The set of blocks Powermeter_1, Expre2Phyton_1 and Powermeter_Controlled_1 was used to insert the necessary attenuation in order to the input receiver power be equal to –level (being level the value introduced in block Const_1). So ranging the level value it was obtained the follow graphic:

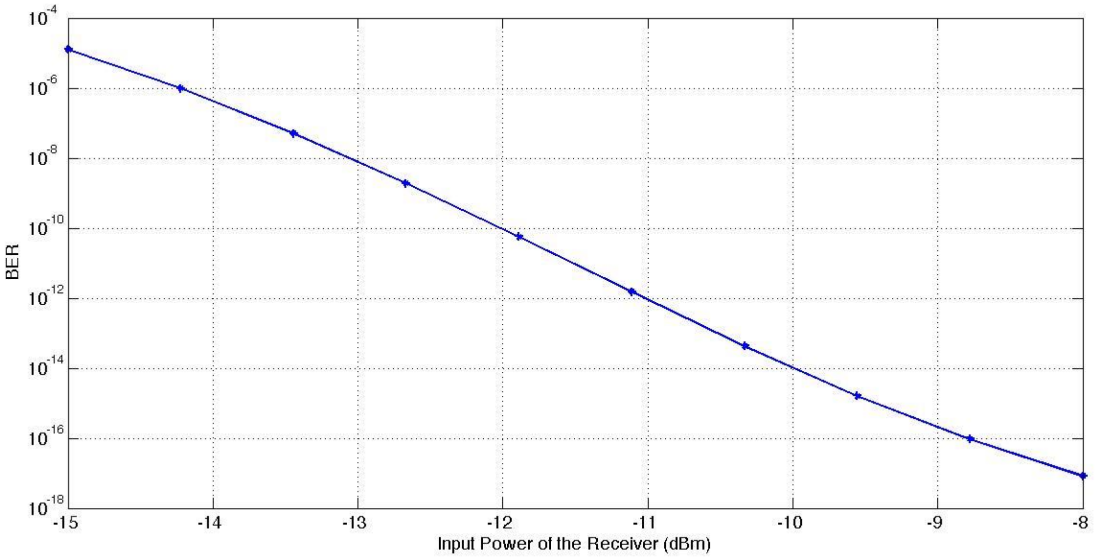

Figure 57 - Determination of Duobinary system sensitivity

Then, observing the Figure 57 it is possible to conclude that to obtain a BER value of 10^{-12} using a receiver with $ElecNoiseBandwidth = 19.6125GHz$ and $ThermalNoise = 3.72 \times 10^{-11}$ A/$\sqrt{\text{Hz}}$ (to a back-to-back system), the receive input power to the Duobinary system must be -11 dBm (sensitivity of the system: BER value of 10^{-12} to a input receive power of -11 dBm).

4.2.4 Dispersion effect

Using again the example of Figure 53, but now using the Thermal Noise and Electrical Equivalent Noise Bandwidth values previously determined and with modulation module (set of blocks Powermeter_1, Expre2Phyton_1 and Powermeter_Controlled_1 and Const_1 using in Figure 57) to define the several values of input power of receiver, it was varied the value of fibre dispersion and progressively reducing the value of the receiver input power:

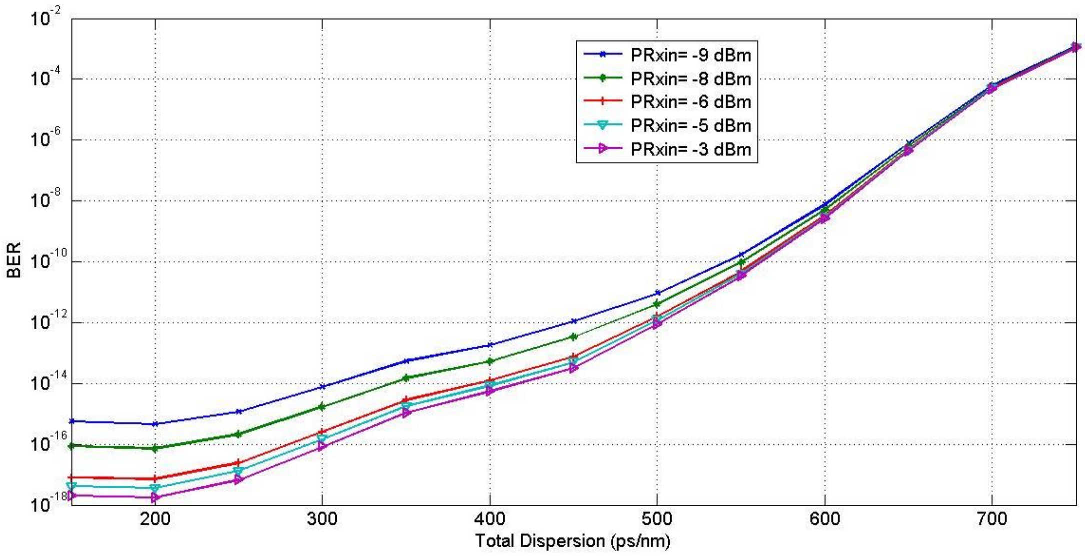

Figure 58 - Determination of dispersion value

Then, using a receiver power input of -5 dBm, to obtain a maximum BER value of 10^{-12} the maximum total dispersion value is 500 ps/nm.

4.2.5 Amplification

For the amplification study it was considered a fibre length of 100 km, a dispersion of 5ps/nm.km and an attenuation of 0.22 dB/km. The amplifiers used has a Noise Figure of 6 dB.

4.2.5.1 Power amplifier configuration

In this configuration it was added an amplifier before the fibre as can be observed in the following figure:

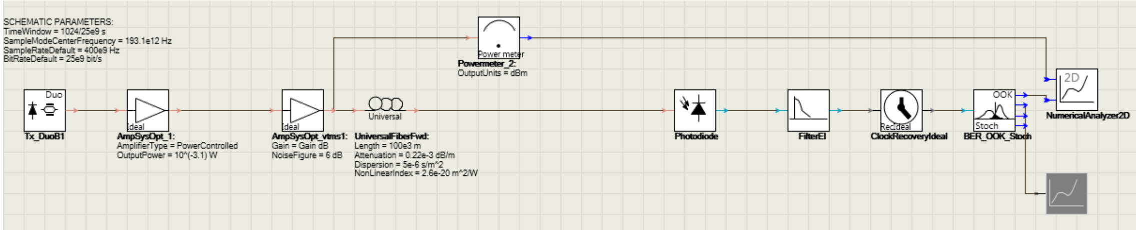

Figure 59 – Simulation scheme used for the study of power amplifier configuration

Thus varying the amplifier gain (from 0 to 20 dB) it is possible to observe the BER obtained (graphic obtained through NumericalAnalizer2D_1 block):

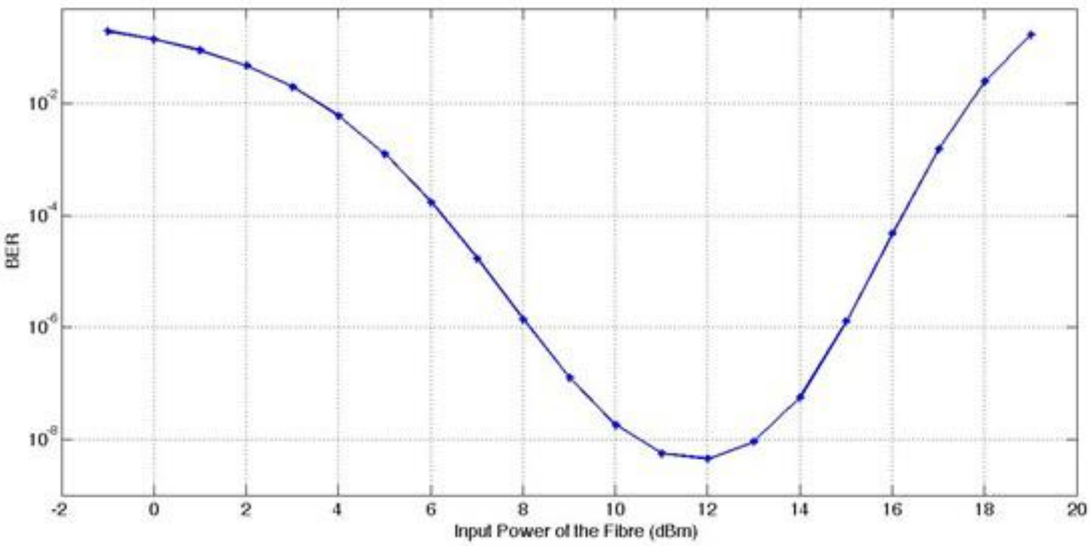

Figure 60 - BER depending on the input power of the fibre

Once the fibre length used was 100 km and had an attenuation of 0.22 dB/km, the total attenuation of the fibre is:

$$TotalFibreAtt(\text{dB}) = FibreLength(\text{km}) \times FibreAtt(\text{dB/km}) = 100 \times 0.22 = 22\text{dB}$$

So, to obtain a BER value close to 10^{-12} it was necessary to have a fibre input power of:

$$Pin\_Fibre(\text{dBm}) - TotalFibreAtt(\text{dB}) = Pin\_Rx(\text{dBm}) \Leftrightarrow$$
$$\Leftrightarrow Pin\_Fibrer(\text{dBm}) = TotalFibreAtt(\text{dB}) + Pin\_Rx(\text{dBm}) \Leftrightarrow$$
$$\Leftrightarrow Pin\_Rx(\text{dBm}) = 22 - 5 = 17\text{dBm}$$

From Figure 60, it can be observed that for fibre input powers higher than 12 dBm, the BER increases with increase of fibre input power instead of continuing decrease due to fibre nonlinear effects.

Then it is possible to conclude that using just one amplifier it is not possible to have a BER equal or lower than 10^{-12}.

4.2.5.2 Preamplifier Configuration

The preamplifier configuration was also studied (placing the amplifier after the fibre) as detailed in the following figure.

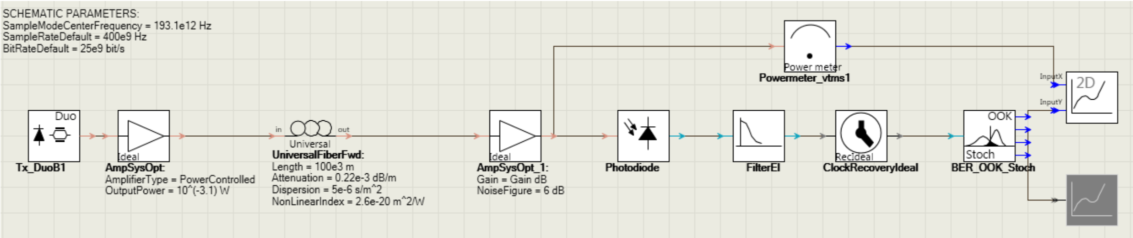

Figure 61 – Simulation scheme used for the study of the preamplifier configuration

Ranging the gain of the amplifier (from 0 to 22 dB) was obtained as function of receiver power output the following BER values:

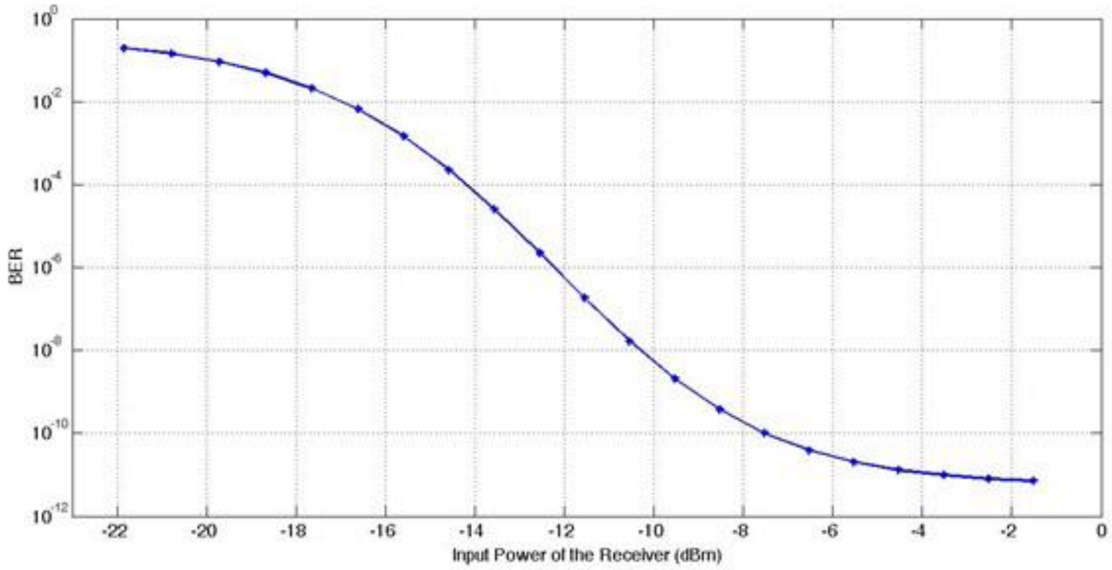

Figure 62 - BER depending on the receiver input power

It is expected that for a power value of -5 dBm, a corresponding BER value of 10^{-12} is required. This is not what is observed at Figure 62 because the noise of the amplifier is quite high when the power input of amplifier is very low (in this case there is no amplification before the signal be attenuated by the fibre, having a power value of:

$$
\begin{aligned}
&Pout\_Fibre(\mathrm{dBm}) = Pout\_Tx(\mathrm{dBm}) - TotalFibreAtt(\mathrm{dB}) = \\
&= Pout\_Tx(\mathrm{dBm}) - FibreLength(\mathrm{km}) \times FibreAtt(\mathrm{dB/km}) = \\
&= 1 - (100 \times 0.22) = -21\mathrm{dB}
\end{aligned}
$$

Thus it is possible to conclude that with only one amplifier, using preamplifier configuration, it is not possible to obtain a BER value equal or lower than 10^{-12} (considering a length fibre of 100 km).

4.2.5.3 Power amplifier and preamplifier configuration

Using only power amplifier or preamplifier configuration it was not possible to achieve BER values lower than 10^{-12} (for the reasons mentioned above). Then, it was used a configuration with two amplifiers to reduce the effects of fibre nonlinearities and noise amplifier.

So it was used the following configuration:

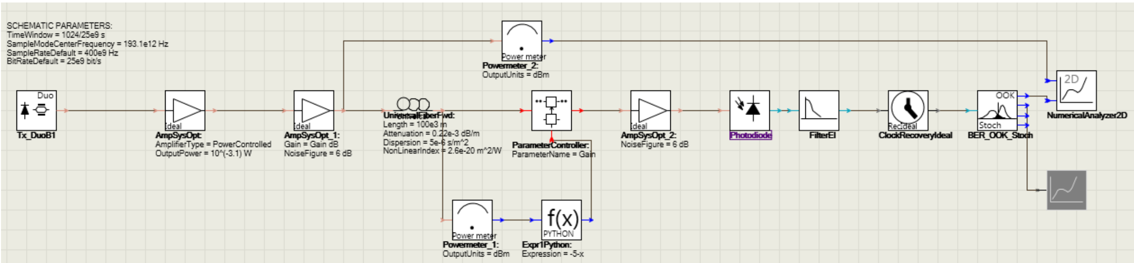

Figure 63 – Simulation scheme used for the study of power amplifier and preamplifier configurations

Thus, varying the gain of the power amplifier (from 0 to 16 dB), and also varying the gain of the preamplifier with the Exp1Phyton block (using the expression -5-x, ensuring a power input of the receiver of -5 dBm).

Then, it was obtained the following graphic:

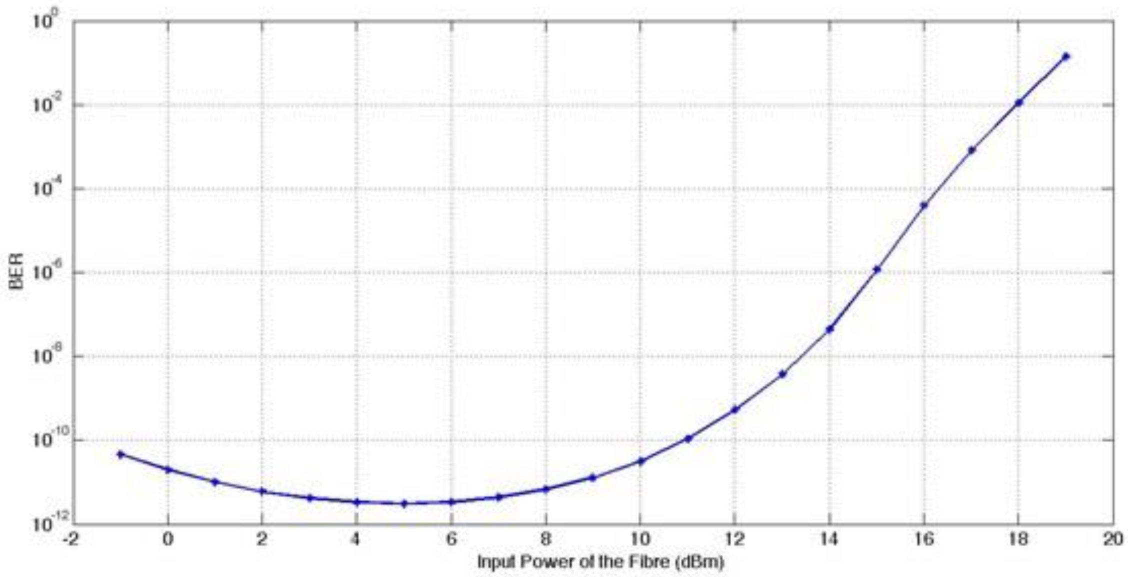

Figure 64 - BER depending on the power output of the first amplifier (at the input of the fibre)

It is possible to conclude that the required power input of the fibre for the best BER value is 4.5 dBm (achieving a BER value close to 10^{-12}).

Then, it is possible to conclude that the best configuration to achieve the best values is using both a power and pre amplifier.

To improve these results it is necessary to use filters to minimize the effects of the noise amplifier, especially for the amplifier placed after the fibre. But once it is decided to use wavelength multiplexing, using multiplexers and de-multiplexers which already have built-in filters, it is not necessary to study this scheme with filters.

So, after concluding that the dispersion fibre value should be lower than 5 ps/nm.km to a length of 100 km and a configuration with pre and post amplifiers should be used, it is now important to study the DWDM configuration.

4.2.6 Study of DWDM 4x25 Gbps Configuration

For study the DWDM system the following VPI block diagram was used:

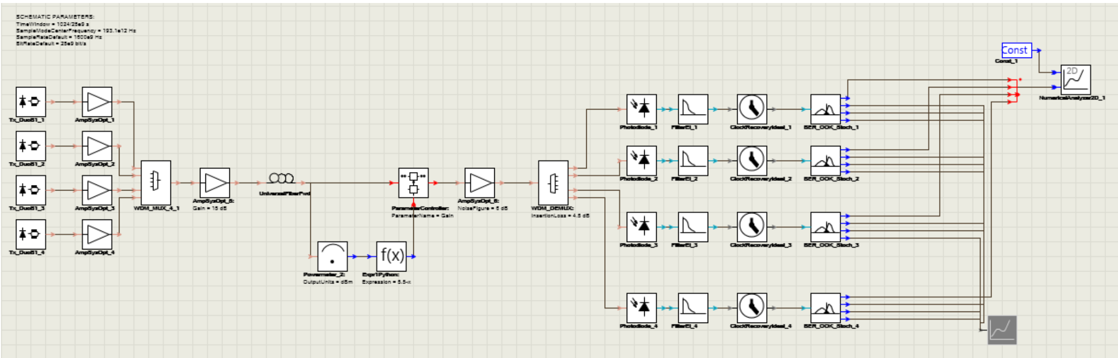

Figure 65 - 4x25 Gbps DWDM scheme using ODB modulation

To achieve this solution it was considered optical amplifiers with a NF (Noise Figure) of 6 dB, multiplexer and de-multiplex, each one with an insertion loss of 4.5 dB. Once it was used a multiplexer and de-multiplexer of 4 channels, it had a power impact of $P\_SeparationChan(\text{dBm}) = 10 \times \log(4) = 6\,\text{dBm}$. As done before, the preamplifier (amplifier after the fibre) ranges in order to ensure that the input power of each receiver is -5 dBm. This value is controlled by Expr1PhytonControl block which applies the equation 5.5-x, where 5.5 dBm is the necessary output power of preamplifier to the input power of receiver be -5 dBm, as proved in following formula:

$$Pin\_Rx(\text{dBm}) = Pout\_PreAmp(\text{dBm}) - P\_SeparationChan(\text{dBm}) - MuxInsLoss(\text{dBm}) \Leftrightarrow$$
$$\Leftrightarrow Pin\_Rx(\text{dBm}) = 5.5 - 10 \times \log(4) - 4.5 = -5\,\text{dBm}$$

Once the maximum total dispersion determined was 500 ps/nm (5 ps/nm.km to 100 km of fibre) and the attenuation 0.22 dB/km, for these simulations was used the LEAF fibre of Corning (chapter 2.7.2.2) which has a dispersion range of [3.78, 5.05] ps/nm.km and an attenuation range of [0.216, 0.22] dB/km for a frequency range of [192.3, 194.1] THz. The gain of the first amplifier (power amplifier) was set equal to 15 dB and the length was ranged (15 points between 60 and 205 km).

4 channels with different spacing of 200 GHz where used, and it was obtained the following response:

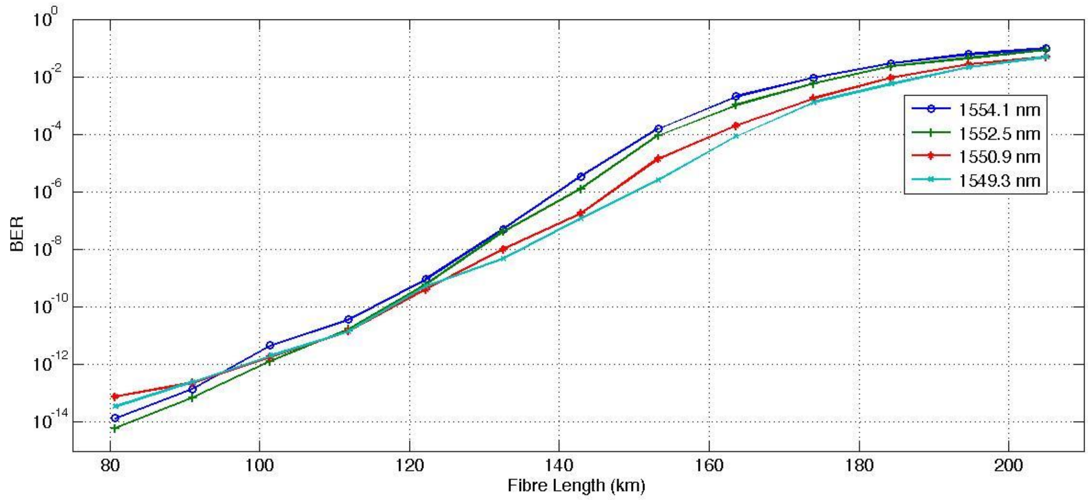

Figure 66 - BER depending on the fibre length for 4 channels at 25 Gbps using ODB

From Figure 66 it is concluded that, using OBD (Optical Duobinary modulation), it is possible to transmit up to 95 km with a BER value of approximately 10^{-12}, using a power amplifier with a gain of 15 dB, corresponding a input power of fibre of:

$$Pin\_Fibre(dBm) = Pout\_Tx(dBm) - MuxInsLoss(dB) + Gain\_PoweAmp(dB) \Leftrightarrow$$
$$\Leftrightarrow Pin\_Fibre(dBm) = -1 - 4.5 + 15 = 9.5\,dBm$$

The second amplifier (preamplifier) has a gain of:

$$Gain\_PreAmp(\text{dB}) = Pin\_Rx(\text{dB}) - Pin\_Fibre(\text{dB}) + TotalFibreAtt(\text{dB}) + DemuxInsLoss(\text{dBm}) =$$
$$= -5 - 9.5 + 95 \times 0.217 + 4.5 = 10.615\text{dB}$$

With the use Forward Error Correction (FEC) it is possible to extend the transmission distance up to 160 km (maximum reach of SKA1-mid) or longer distances.

This system can be optimized by changing the bandwidth of the transmitter filter. So, defining the fibre length as 160 km (maximum reach of SKA1-mid) the filter bandwidth was varied and the following graphic was obtained:

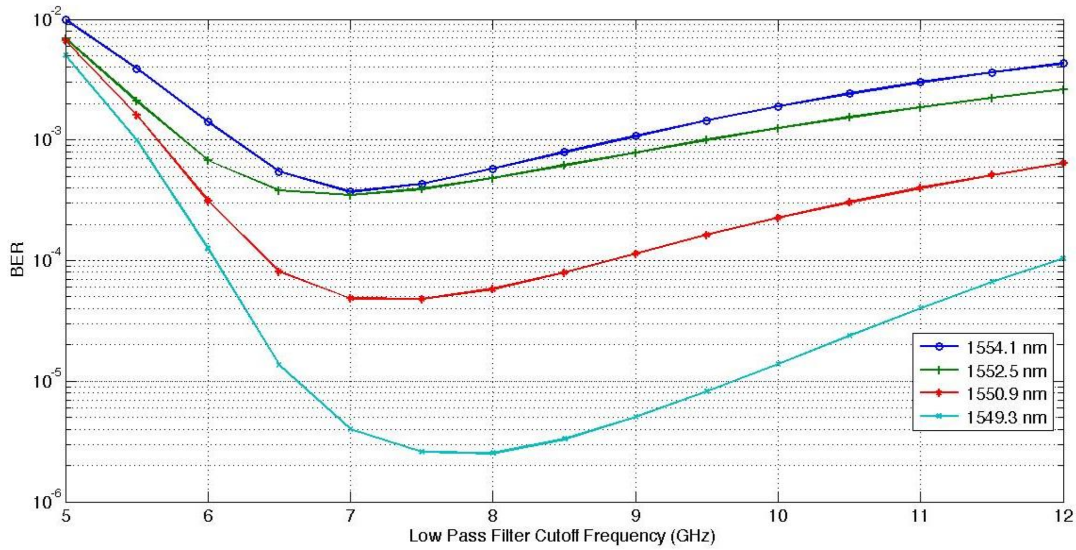

Figure 67 - BER depending on the low pass filter cut-off frequency for 4 channels at 25 Gbps using ODB

Then, using the LPF Cut-off Frequency value of 7 GHz, was obtained the following response:

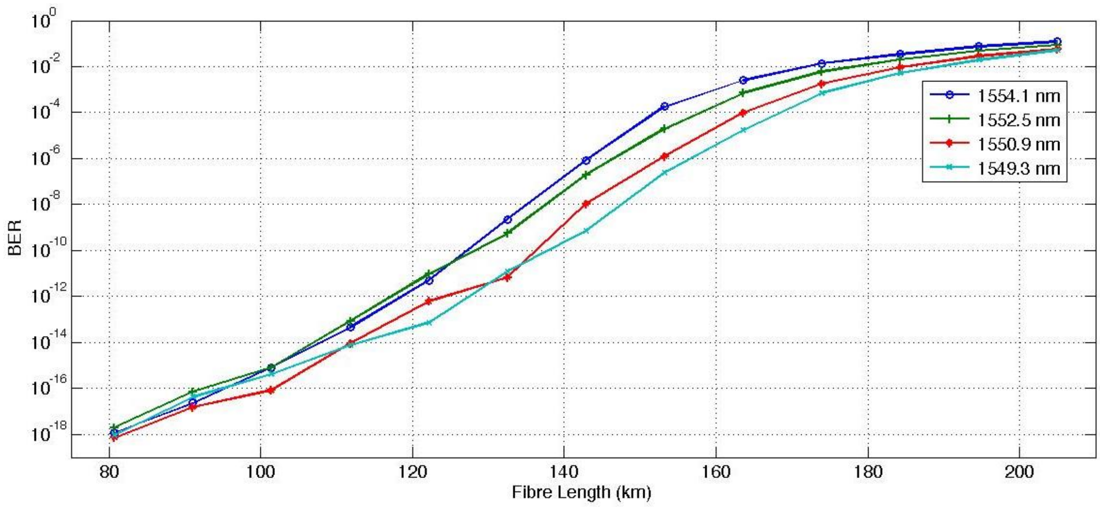

Figure 68 - BER depending on the fibre length (LPF cut-off frequency of 7 GHz) for 4 channels at 25 Gbps using ODB

Observing the results of Figure 68 it can be concluded that with ODB 4x25Gbps system it is possible to achieve a maximum distance of approximately 120 km.

The first amplifier has a gain of 15 dB, corresponding an input power of fibre of:

$$Pin\_Fibre(\text{dBm}) = Pout\_Tx(\text{dBm}) - MuxInsLoss(\text{dB}) + Gain\_PowerAmp(\text{dB}) \Leftrightarrow$$
$$\Leftrightarrow Pin\_Fibre(\text{dBm}) = -1 - 4.5 + 15 = 9.5\,\text{dBm}$$

The second amplifier (preamplifier) has a gain of:

$$Gain\_PreAmp(\text{dB}) = Pin\_Rx(\text{dB}) - Pin\_Fibre(\text{dB}) + TotalFibreAtt(\text{dB}) + DemuxInsLoss(\text{dBm}) =$$
$$= -5 - 9.5 + 120 \times 0.217 + 4.5 = 16.04\,\text{dB}$$

The following graphic presents the results of ranging the extinction ratio of the transmitter (to a fibre length of 160 km):

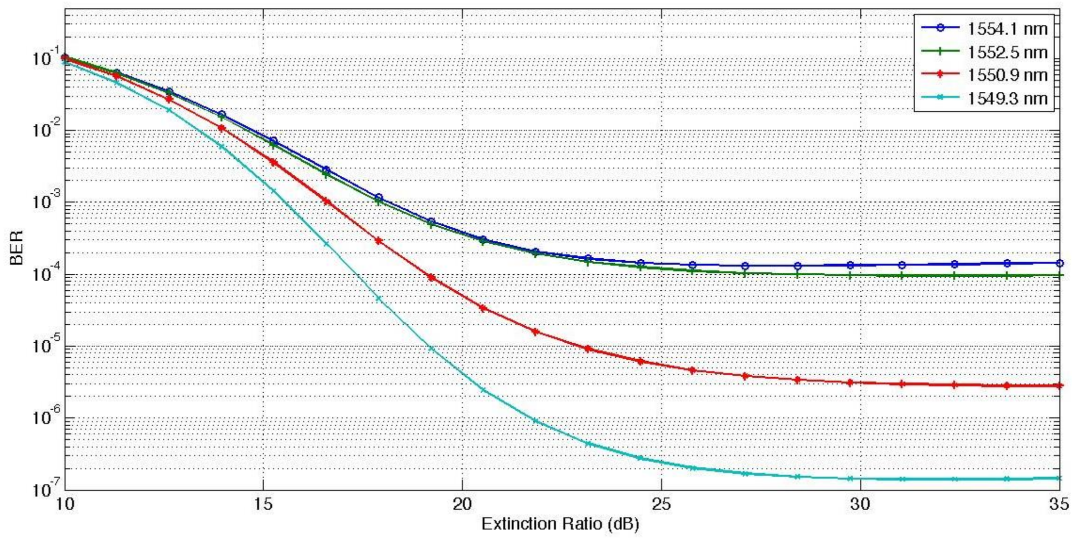

Figure 69 - BER depending on the extiction ratio for 4 channels at 25 Gbps using ODB

The Figure 69 shows that the extinction ratio does not influence the sensitivity of the system from around 25 dB.

4.3 SKA1-survey: 35 Channels at 25Gbps

SKA1-survey has a transmission rate of 864 Gbps and a maximum reach of approximately 50 km. So, using exactly the same transmitter and receiver used to SKA1-mid with 4channels at 25 Gbps (point 4.2), but now using more channels (864 Gbps/25Gbps = 34.56 Channels, so it was used 35 channels). Then, using the same configuration with the same characteristics of used in the Figure 65 (but now with 35

Channels with a spectral spacing of 100 GHz with a range [192, 195.4] THz), was varying the length of the fibre, as shown in the follow graphic:

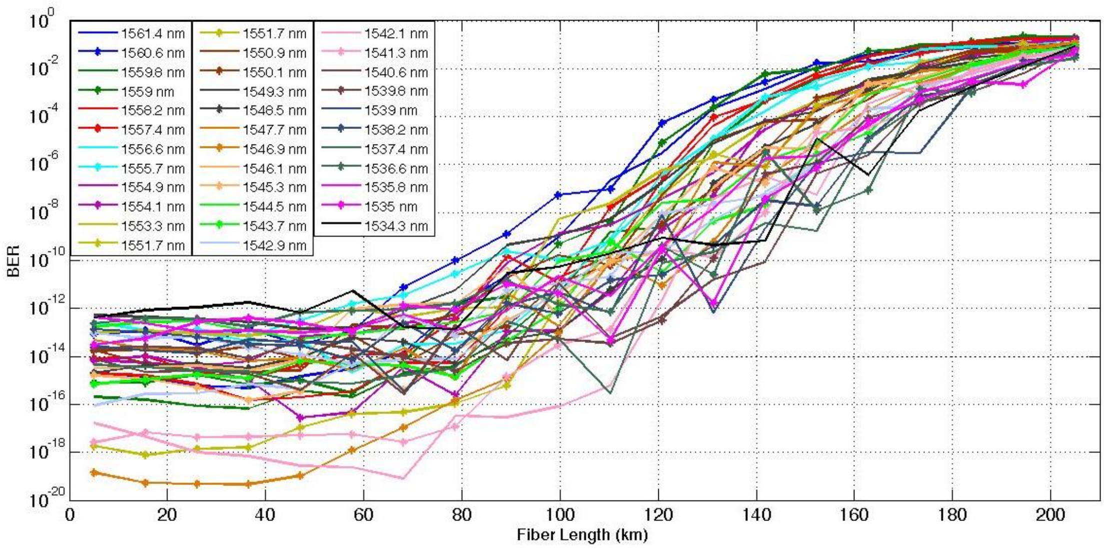

Figure 70 - BER depending on the fibre length for 35 channels at 25 Gbps using ODB

It was used a power amplifier gain of 10 dB and, as done before, the preamplifier ranges in order to ensure that the input power of each receiver is -5 dBm.

Then, the first amplifier has a gain of 10 dB, corresponding an input power of fibre of:

$$Pin\_Fibre(\text{dBm}) = Pout\_Tx(\text{dBm}) - MuxInsLoss(\text{dB}) + Gain\_PoweAmp(\text{dB}) \Leftrightarrow$$
$$\Leftrightarrow Pin\_Fibre(\text{dBm}) = -1 - 4.5 + 10 = 4.5\,\text{dBm}$$

The second amplifier (preamplifier) has a gain of:

$$Gain\_PreAmp(\text{dB}) = Pin\_Rx(\text{dB}) - Pin\_Fibre(\text{dB}) + TotalFibreAtt(\text{dB}) + DemuxInsLoss(\text{dBm}) =$$
$$= -5 - 4.5 + 50 \times 0.217 + 4.5 = 10.35\text{dB}$$

The maximum reach of SKA1-survey is 50 km, so the results of Figure 70 satisfy the requirements (BER values are equal or lower than 10^{-12} at this distance).

However it is possible to improve this system, obtaining the transmitter cut-off frequency for the lowest BER value. Then ranging the transmitter filter cut-off frequency (to a fibre length of 50 km, maximum reach of SKA1-survey) was obtained the following response:

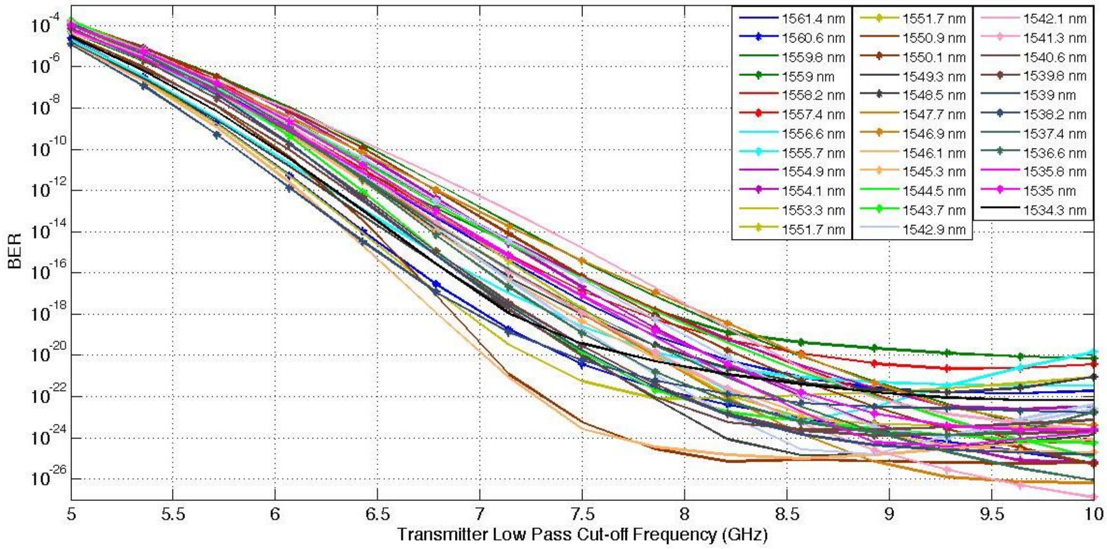

Figure 71 - BER depending on the low pass filter cut-off frequency for 35 channels at 25 Gbps using ODB

Observing Figure 71 it is possible to conclude that the sensitivity of the system improves for the transmitter with a low pass filter cut-off frequencies up to 8.2 GHz (from this value the BER remains approximately constant).

So using a transmitter with a low pass filter cut-off frequency of 8.2 GHz was obtained this new response:

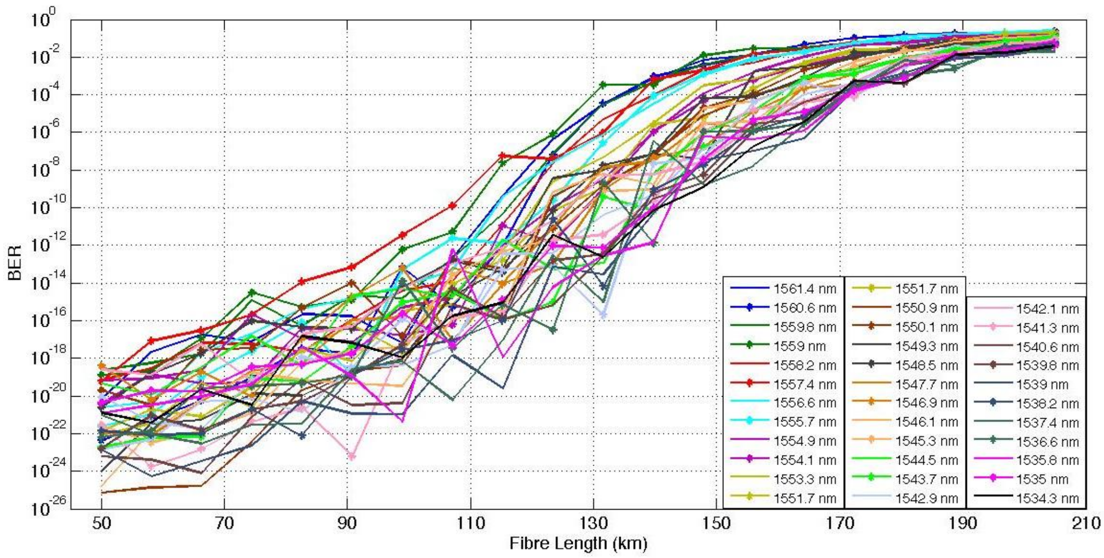

Figure 72 - BER depending on the fibre length (LPF Cut-off Frequency of 8.2GHz) for 35channels at 25 Gbps using ODB

With the new value of the transmitter with a low pass filter cut-off frequency the system improved, presenting a BER values lower or equal than 10^{-12} to distances up to approximately 95 km.

Ranging the extinction ratio of the transmitter (to a fibre length of 160 km) was obtained the following graphic:

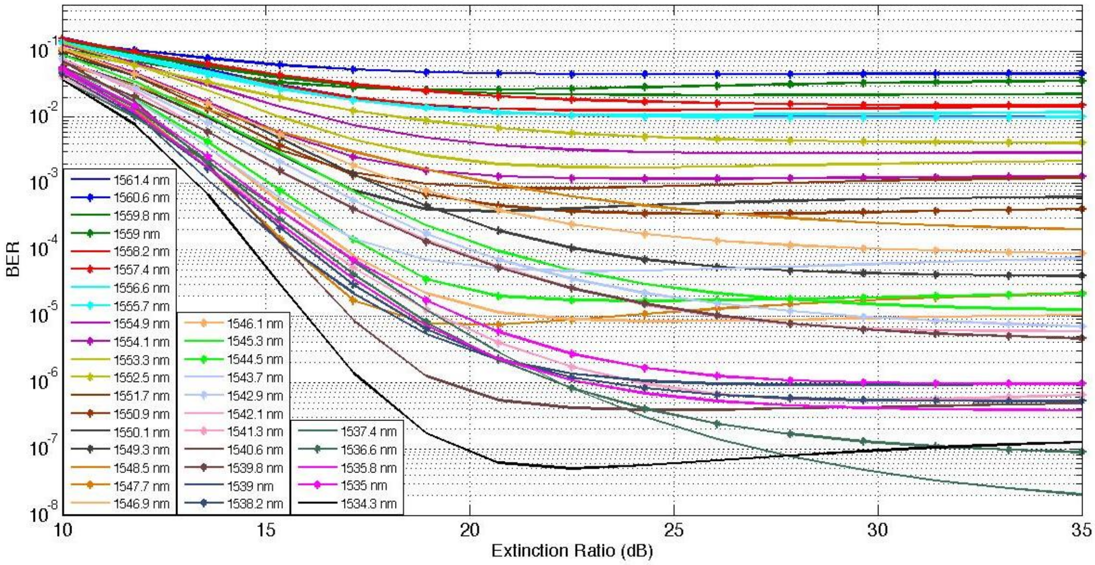

Figure 73 - BER depending on the extinction ratio for 35 channels at 25 Gbps using ODB

As the system 4 channels at 25 Gbps, the sensitivity of the system remains constant for extinction ratio values equal or greater than 25 dB.

Chapter 5
Conclusion and future work

5.1 Conclusion

The choice of technology to be used by DDBH (Digital Data Back Haul) and the location of antennas and CSP (Central Signal Processor) is still under discussion. However this Dissertation presents some possible solutions.

In terms of cost, the CSP location must be closer to the core of the antennas, since it significantly reduces the transmission requirements between the antennas and CSP.

The DWDM technology proved to be a good solution from an economic standpoint, since it allows the use of existing standard products on the market presenting a competitive price, and enables the transmission of a high data rate using only one fibre (instead of 4, 10 or even 35 fibres), which reduces the number of fibres and consequently reduces the cost. This solution has also proved to be spectrally efficient, being able to transmit with low Bit Error Rate (BER) over relative long distances.

To SKA1-mid it was proved that it is possible to transmit through the multiplexing of 10 channels at 10 Gb/s (using for example transceivers SFP+, multiplexing and amplification) with a maximum reach of 195 km (more than 160 km, maximum reach for SKA1-mid) and a Bit Error Rate (BER) lower or equal than 10^{-12}. To achieve these results it was determined that the fibre should have a maximum normal dispersion value of 7.2 ps/nm.km. Thus it was used LEAF fibre (Non Zero – Dispersion Shift Fibre with a large effective area). Also studied was the solution 4 channel at 25 Gb/s using Duobinary Modulation in the transmitter (this modulation has low spectral occupancy, high tolerance due to residual chromatic dispersion and narrowband optical filtering compared to binary signalling formats, such as Non-Return to Zero modulation). Even so, with a 4x25 Gbps solution it was obtained a maximum reach less than obtained to 10x10 Gbps (120 km vs 195 km), revealing that for higher transmission rates is more difficult to transmit over longer distances with a low bit error rate. So, in order to use this solution, for antennas with a distance range between 120 and 160 km, it is necessary to use Forward Error Correction (FEC).

Taking advantage of the study done for SKA1-mid for a configuration of 4 channels at 25 Gbps Duobinary Modulation, instead of 4, it was used 35 channels to achieve the transmission rate used in SKA1-survey (864 Gbps). Then it was possible to achieve BER values lower or equal than 10^{-12} with a maximum reach of 95 km (twice the maximum reach of SKA1-survey, 50 km). Thus, despite this solution causing interference inter-channels due to the amount of multiplexed channels, visible in the results obtained, it satisfies the requisites stipulated.

5.2 Future work

For future work there is practical interest in:

- Study of DWDM systems using transceivers with higher transmission rates (e.g. 40 Gb/s and 100 Gb/s);
- Study amplitude and phase modulation formats and coherent detection systems as a possible solution;
- Study the best deployment system configuration on the desert taking into account the high temperature variations, localisation of the link devices such as the multiplexers and de-multiplexers and the optical amplifiers, the ideal location of the fibres.

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Attachment A. List of Transceivers and respective manufactures on the market which can be used in DWDM SKA solution

Manufacturer	Products	Comments
Avago Technologies	100G QSFP28 SR4, 100G CPF4 LR4 up to 10 km [46]	
Liverage Technology Inc.	40G QSFP (LR 40 km) [47]	Expressed interest in adapting the product to the SKA
	10G SFP+, XFP to 40 km for SMF [47]	
Fujitsu (Optical Components Limited)	100G OIF 168 pin Coherent Transceivers (0 to 70 °C); Dispersion tolerance: +-55000ps/nm [48]	
	100G CFP Coherent Transceiver (0 to 70 °C) up to 600 km (+-10000ps/nm) [48]	Under development
	100G CFP Transceiver up to 40km (-5 to 70 °C); +3.3V single power supply; 145×77×14 mm [48]	
	100G CFP2 Transceivers up to 40 km (-5 to 70°C) [48]	10 km available, 40 km under development
	100G CFP4 transceivers up to 40 km (-5 to 70°C) [48]	Demonstrated a prototype at OFC. The electrical interface is a 25G x 4 lane electrical interface

		compliant with the OIF CEI-28G-VSR specification.
	10G XFP transceivers with APD and maximum dispersion tolerance of 1600ps/nm (-5 to 70 °C); 3.5W power consumption [48]	
	10G SFP+, XFP with APD, Dispersion tolerance: -400ps/nm to +800ps/nm [48]	
Source Photonics	SFP+ 10Gb/s range (up to 40 km); XFP 10Gb/s range (up to 40 km) temperature range: (-5 to 70 °C) [49]	
Optoway	10Gb/s DWDM SFP+ with extended temperature range (-40 to 85 °C), optical link budget of 23 dB up to 80 km [50]	
Oclaro	Coherent CFP2 Transceiver DWDM Module and 100G MSA DWDM: CD tolerance -40,000 to 40,000 ps/nm, DP-QPSK modulation format; 10G XFP DWDM: up to 80 km, available at 850nm VCSEL, 1310nm DFB-LD or 1550nm ILM TOSA; 40 Gb/s 300-Pin MSA range [51]	The coherent CFP2 was presented at OFC2014

Finisar	100G DWDM CFP up to 30 km (for amplified, FEC-based applications), four 28Gb/s 1550nm tunable transmitters [52]	
CISCO	Cisco CFP-100G-ER4, 40 km on SMF, G.652 terminated with SC/PC optical connectors [53]; Cisco 10GBase DWDM SFP+, 40 non-tunable wavelengths at 1530 nm to 1565 nm, max power consumption: 1.5 W [42]	CISCO presented more advanced products in CMOS Photonics CPAK 100GBASE-SR10 and CPAK 100GBASE-LR4
OPLINK	Presented 4x28G metro DWDM CFP transceiver with OOK modulation format and direct detection receiver with MLSE, OPLINK claims these transceivers can reach transmission distances of several hundred Kilometres [54]. TXP1XGHL2xx DWDM XFP provide a quick and reliable interface for 10Gbps DWDM applications, fibre channel data from 9.95 Gb/s to 11.09 Gb/s; operate from +1.8V, +3.3V and +5.0V power supplies; temperature range	

	of -5 °C to +70 °C (commercial); transmission distance up to 80 km [55]	
CIVCOM	Coherent 100Gbps CFP (bit rate at 111.18 Gbps) based on DP-16QAM for Metro applications up to 1400 km, coverage full C-band, up to CD of ±25,000ps/nm [56]	
Cube Optics	SFP+ transceivers: CSS-850A14D0-xx C [57], CSS-851A23D0-xx [58] for DWDM solutions, optical link budget of 14 and 23 dBs respectively, 45 DWDM channels (range between 1529 to 1564 nm), Data rates from 1.0625 to 10.5 Gb/s bit rates , temperature range: 0 to 70 °C CSS-852A14D0-xx [59], CSS-853A23D0-xx [60] for CWDM solutions, optical link budget of 14 and 23 dBs respectively, Data rates from 1.0625 to 11.1 Gb/s bit rates, 18 CWDM channels wavelength (20 nm spacing), case operation temperature range: -5 to 70 °C	

Table 5 - Summary of transceiver manufacture and their products

Attachment B. List of Optical Amplifiers available on the market which can be used in DWDM SKA solution

Company	Product	Details
IPG Photonics	RAR Series Raman Amplifiers	Up to 20 dB amplification, models amplify over range 1260nm to 1700m with 100nm optical bandwidth for an individual amplifier; Amplifiers come in a rack mountable case. The pump diodes reliability corresponds to a MTTF of 5,000,000 hours. These modules make use of an Ytterbium fibre laser and Raman wavelength shifters to achieve the desired pump wavelength. It appears that the unit makes use of a counter pumping scheme as well as polarization scrambling of the pump signal which leads to low pump noise signal transfer and polarization insensitive operation (important feature) [61].
AOC Technologies Inc.	EDFA-Pre-Amplifier Series	Amplifies signals in almost all C-band (1530nm to 1560nm), with a rated gain of 20 dB,

		operation temperature of -5 to 55 ˚C and a power consumption of 20 W [62].
LiComm	C+L-band Raman 2U-Shelf ORA-BFD Series	Amplification over C band, L band and C+L band. Designed for ultra-long haul, long haul and wide bandwidth DWDM systems. Supports 10Gbps and 40Gbps systems [63].
Amonics	AEDFA-CL-23-B-FA (C+L band EDFA)	C+L band EDFA, small signal gain (-30 dBm signal) 32 dB. Amplification wavelength 1528nm to 1562nm and 1570nm to 1603nm. Amonics also distribute Raman amplifiers [64].
Finisar	Specialize in EDFA, Raman amplifier and Hybrid Raman and EDFA module [65].	

Table 6 - Optical Amplifiers present on the market

Attachment C. Devices used as reference in the simulations

Cisco 10GBASE Dense Wavelength-Division Multiplexing (DWDM) SFP+ [42] allow service to provide 10-Gigabit LAN,WAN and optical transport network (OTN) services. The CISCO DWDM SFP+ main features are:

Figure 74 - CISCO 10GBASE DWDM SFP+ Transceiver [39]

- Support digital monitoring capability;
- Hot-swappable input/output devices plugs into a router or an Ethernet SFP+ to link the port with the network; Cisco quality identification (ID) feature;
- Commercial operational temperature range (COM): 0 to 70°C (32 to 158°F);
- Maximum power consumption per Cisco SFP+ module: 1.5W;
- Receiver optical input wavelength range: 1530 nm to 1565 nm, supporting 40 non-tunable ITU 100-GHz wavelengths;
- Transmitter optical output power range: -1 dBm to 3 dBm;
- Input power range: -7 to -23 dBm at BER=1E-12, back to back, unamplified link;

Cisco ONS 1516 Mux/De-mux 40 Channel Path Panel [45] is a passive dense wavelength-division multiplexing (DWDM) system, which uses active-temperature-controlled and filter AWG technology. It has 40 channels for multiplexer and 40 for de-multiplexer (with a frequency range of between 191.95 and 195.9 GHz), covering the even and odd numbered channels specified by de ITU grid. Cisco also has a Mux/De-mux Patch Panel 50-GHz Interleaver De-Interleaver to satisfy the possible need to upgrade the Mux/De-mux from 40 to 80 channels in a 4 rack unit (RU).

Figure 75 - Cisco ONS 15216 Mux/Demux 40-Channel Patch Panel [42]

The main features of these products are:

- Cost effective for DWDM applications;
- Low optical insertion loss (4.5 dBm to 6 dBm);
- Entire unit comes preassembled;
- No electrical power requirements, improving the efficiency;
- Integrated cable routing guides to maintain bend radius for prevent fibres from being pinched;
- Patch panel front door and USB port for passive inventory.