Comparative Analysis, Design and Optimisation of a 48 Channel DWDM System using Various Design Parameters

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ABSTRACT

In the current era, there is an ever-growing demand for data hungry applications and services that need large amounts of bandwidth to send digital information at very high speeds. In order to meet this challenge for higher bandwidth capacity, Dense Wave Division Multiplexing (DWDM) is used as the strategy to transmit multiple high-bit rate channels at extremely narrow channel spacings over a single fiber core. However, this gives rise to detrimental transmission impairments such as linear effects and non-linear effects. The dissertation minimises the impairments by optimally designing a new DWDM system that produces a detectable and acceptable quality of signal at the receiver.

In this dissertation, a comparative analysis is performed on the simulative design of a 48-channel DWDM system that has a 25 Gb/s bit rate and a 100 km transmission distance. The research mitigates the effects of transmission impairments such that an error-free matched communication link is produced for equally spaced (ES) channels of 100 GHz, 50 GHz, 25 GHZ and 12.5 GHz and 6.25 GHz. Various design parameters are used to create the comparative analysis model to optimise the 48 channel DWDM network. The design is simulated using the Optisystem simulation platform and the signal analysis is based on the bit error rate (BER) and quality (Q) factor of the received signal's eye diagrams.

It is established in the desertion that modified networks with matched active components has ES frequency channels that are aligned to each other and has a higher optical signal to noise ratio (OSNR) than mismatched networks. The maximum signal power and OSNR of the 3-erbium doped fiber amplifier (EDFA)-post symmetric compensation technique is always higher than the 1-EDFA post compensation technique for all channel spacings in any type of network. Modified duobinary return to zero (MDRZ) when compared to non-return to zero (NRZ) and return to zero (RZ) has a greater dispersion tolerance, higher fiber non-linearity tolerance and a higher acceptable signal transmission over longer distances with the least amount of errors. The optimised design parameter configurations produce the highest signal performance (highest Q factor > 6 and lowest BER > 10^{-9}) and the highest bandwidth efficiency for the RZ Modulation (at 100 GHz, 50 GHz and 25 GHz channel spacings) and MDRZ Modulation (at 12.5 and 6.25 GHz channel spacing).

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LIST OF ACRONYMS

Acronyms	Description
ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
BW	Bandwidth
CD	Chromatic Dispersion
CW	Continuous Wave
DCF	Dispersion-Compensating Fiber
DEMUX	Demultiplexer
DSF	Dispersion-Shifted Fiber
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-Doped Fiber Amplifier
ER	Extinction Ratio
ES	Equally Spaced
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FWM	Four-Wave Mixing
GUI	Graphical User Interface
IP	Internet Protocol
ITU	International Telecommunication Union
LAN	Local Area Network
LED	Light-Emitting Diode
MAN	Metropolitan Area Network
MDRZ	Modified Duobinary Return to Zero
MOA	Mode of Operation
MQW	Multiquantum Well
MZ	Mach-Zehnder
MUX	Multiplexer

LIST OF ACRONYMS

Acronyms	Description
NRZ	Nonreturn To Zero
NZDSF	Nonzero Dispersion Shifted Fiber
OC	Optical Carriers
O/E/O	Optical/Electrical/Optical
OSNR	Optical Signal-To-Noise Ratio
PCM	Pulse Code Modulation
PDH	Plesiochronous Digital Hierarchy
PMD	Polarization Mode Dispersion
PSD	Power Spectral Density
RoF	Radio over fiber
RZ	Return to Zero
SBS	Stimulated Brillouin Scattering
SDH	Synchronous Digital Hierarchy
SMF	Single-Mode Fiber
SOA	Semiconductor Optical Amplifier
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
STM	Synchronous Transport Module
TDM	Time Division Multiplexing
WDM	Wavelength Division Multiplexing
XPM	Cross Phase Modulation

CHAPTER 1

GENERAL INTRODUCTION TO THE RESEARCH IN DENSE WAVE DIVISION MULTIPLEXING

1.1 Introduction

The explosion in the demand for information brought about by the internet is creating enormous needs for capacity expansion in the next generation telecommunication networks. The demand for increasing bandwidth (voice, video, and data traffic) continues to drive the demand for ongoing evolution in fiber optical networks. Even though optical networks were widely regarded as the ultimate solution to the bandwidth needs of future communication systems, the telecommunications industry is still struggling to keep up with the growth pace of bandwidth requirements. To fulfil the enormously increasing capacity requirements, especially in long haul optical link communications, it had become imperative to increase the number of channels as well as the data rate per channel. Therefore, to reach the future customer demands, more capacity is needed, so carriers had three possible solutions: Firstly, install a new fiber infrastructure with or secondly, invest in new Time Division Multiplexing (TDM) technology to achieve faster bit rates or thirdly, deploy dense wavelength division multiplexing (DWDM). This dissertation focuses on the latter.

1.2 Research Motivation

DWDM is an extension of wavelength division multiplexing (WDM) optical networking systems and its capability to transmit multiple ultra-high bit rate channels at narrow channel spacings is an attractive approach to meet the challenges of current optical communication systems and thereby increase the capacity of future optical networks.

In this dissertation, the capability and limitations of DWDM systems to scale WDM channels to even more high dense dimensions are exploited to further increase the transmission capacity gains of existing communication systems. The use of line encoding modulation formats to improve the quality of signal (QoS) is explored by minimising the performance degradations caused by the reductions in channel spacings. The availability and versatility of the Optisystem platform is utilised to simulate and evaluate the transmission of a such a DWDM signal for various design parameters. Evaluation of signal quality and performance limitations is possible due to eye diagram and bit error rate (BER) tools found within the Optisystem platform.

The literature review shows that there is very little research that has been done by other researchers in finding out the impact of varying the channel spacings of a 48-channel x 25Gbps DWDM system from 100 GHz, 50 GHz, 25 GHz, 12.5 GHz, and 6.25 GHz with modulation formats of non-return to zero (NRZ), return to zero (RZ) and modified duobinary return to zero (MDRZ) for the novel post symmetric compensation optical link setup. Furthermore, the international telecommunication union (ITU) standard supported by ITU-T G.694.1 only recommends fixed channel spacings ranging from 12.5 GHz to 100 GHz as stated in [2, 18, 50]. Therefore, there is an untapped channel spacing of 6.25 GHz that is used in this dissertation to further expand the channel capacity of the ITU frequency grid and for that purpose, it is essential to design and analyse a pilot network that is able to test the limitations of its transmission parameters.

1.3 Research Objectives

1. Simulate and evaluate the performance analysis of the 48 Channel DWDM system with a bit rate of 25 Gb/s.
2. Simulate and evaluate the effect of varying the channel spacing (100 GHz, 50 GHz, 25 GHZ, 12.5 GHz and 6.25 GHz) with respect to the above bit rate.
3. Simulate and evaluate the effect of varying the modulation format (NRZ, RZ, MD-RZ) with respect to the above bit rate and channel spacings to optimise signal quality.
4. Validate the most optimal specification from the given parameters of the 48 channel DWDM system that provides the best spectral bandwidth efficiency and signal performance.

1.4 Research Methodology

A quantitative research approach was taken to collect information from various literature reviews and other related work done previously. This helped synthesise a comparative research study, which justified the research approach and the design parameters used to optimise a 48-channel DWDM network. The research approach was as follows:

1. A 32 channel DWDM design model was recreated and verified on the Optisystem platform using the parameters from existing literature reviews. This served as a pilot

to help one understand the procedure to design a DWDM network using the Optisystem simulation platform. The 32-channel model was then modified to design a novel comparative study that helped understand the transmission capabilities and limitations of increasing bit rates at different transmission distances when using the NRZ and RZ modulation formats in combination with a 1-erbium doped fiber amplifier (EDFA) post compensation technique [1].

2. A novel comparative study of a 48 channel DWDM network was done using mismatched active components. This helped understand the increasing and decreasing effects of linear and non-linear losses for various channel spacings using the NRZ and RZ modulation formats in combination with a novel 3-EDFA post symmetric dispersion compensation technique [2].
3. The parameters collected from the calculations, literature reviews and the previous comparative studies were then used to simulate numerous 48-channel DWDM network models using various design parameters. In this dissertation, the comparative study and optimisation of the 48 channel DWDM networks was done using matched active components for each of the varied parameters. The simulated results helped validate the most optimal design specification that gave the best signal performance when using the NRZ, RZ and MDRZ modulation formats at very narrow channel spacings in combination with the 3-EDFA post symmetric dispersion compensation technique.
4. In each of the above comparative studies, the optical signal-to-noise ratio (OSNR), received power and optical link loss calculations were done manually and then verified using the Optisystem platform.
5. The performance of the signals for each channel was evaluated by the analysis of the quality factor (Q) and bit error rate (BER) of eye diagrams.

1.5 Publications

Parts of the work presented in this dissertation have been presented and submitted by the Author at two conferences:

1. J.Z. Mohan and O. A. Sokoya, "Comparison of NRZ and RZ in a 32x5Gbps and a 32x10Gbps DWDM Networks for 100km and 500km," *Proceedings of The Southern Africa*

Telecommunication Networks and Applications Conference (SATNAC), Hermanus, Western Cape, South Africa, 2018, pp. 142-148

2. J.Z. Mohan and O. A. Sokoya, "Performance Analysis of a 48 x 25Gb/s DWDM system at Various Channel Spacings with NRZ and RZ," *Proceedings of The Southern Africa Telecommunication Networks and Applications Conference (SATNAC)*, Ballito, KwaZulu Natal, South Africa, 2019, pp. 172-177

1.6 Original Research Contributions

- The dissertation extends the work done in [1, 2, 13, 16 – 29] by performing an investigation of a 32 channel and a 48 Channel DWDM system at different bit rates (5, 10, and 25 Gb/s), for different channel spacings (6.25 GHz, 12.5 GHz, 25 GHZ, 50 GHz and 100 GHz), different transmission distances (100 km and 500 km) and different modulation formats (NRZ, RZ, MDRZ).
- The dissertation modifies the existing OSNR and received power equations for the current design setups. It explores the effects of three modulation formats (NRZ, RZ and MDRZ), transmission impairments caused by non-linear effects such as Four wave mixing (FWM) and the impact of using a novel dispersion compensation technique (i.e. a post symmetric compensation technique with three EDFAs) on the current design setup. Furthermore, the dissertation implements novel ideas to combat the effects of FWM and thereby enhance signal quality by modifying certain design parameters of the above-mentioned channel spacings. The post symmetric compensation technique with the three EDFAs is a modified setup of the post compensation technique shown in [1]. This all then leads to the following research contributions:
    - Improves the QoS of the existing 48 channel networks operating at 100 GHz channel spacing to the point that there are no bit errors received by the optical receiver for any channel within that network i.e. achieves a BER = 0 for the received signals.
    - Produces an acceptable QoS for each of the signals transmitted in 100 GHZ, 50 GHZ, 25 GHZ, 12.5 GHz and 6.25 GHZ channel spacings where Quality factor > 6 and BER > 10^{-9} and in each instance, the optical receiver is able to detect each of these signals successfully.

- ❖ Produces an acceptable QoS for the 6.25 GHz channel spacing with the least amount of errors since there was very little research done by other researchers at this channel spacing. This allows the potential for the ITU Frequency grid to be expanded to 6.25 GHz channel spacing.

1.7 Dissertation Overview

This dissertation is divided into six chapters.

Chapter 1 enumerates some of the challenges faced in an optical communication networks due to future bandwidth requirements that demands growth in optical communication systems. The motivation that led to the topic choice of this research is described. A research plan showing the direction and approach of the research is listed and explains with regards to the intermediate objectives and the research methodology. The original contribution to the engineering body of knowledge is enumerated and explained. The publications that resulted due to the research of this dissertation is also mentioned.

Chapter 2 is a literature survey on fiber optic communication with the focus being on DWDM fiber optic communication systems. The evolution of fundamental concepts that led to the development of DWDM communication is explained. The advantages and performance limitations factors affecting DWDM system is described. A small sample of all the literature surveys done for this research is shown to understand the limitations of DWDM systems and the extent of work done by other researchers. The fundamental building blocks, components and its design properties used for this research are also explained.

Chapter 3 analyses the performance of a 48 x 25 Gb/s DWDM system at various channel spacings (100 GHz, 50 GHz, 25 GHz, 12.5 GHz and 6.25 GHz) using NRZ and RZ modulation formats with a multiplexer (MUX) and demultiplexer (DEMUX) that has equally spaced (ES) channels. Various design parameters such as the bandwidth of the MUX and DEMUX, type of filter used in the MUX and DEMUX, the extinction ratio (ER) of the WDM transmitter and the MDRZ advanced modulation format are compared to optimise the DWDM system for bandwidth efficiency. The simulated results of the designed networks are analysed, compared and discussed for signal performance variations in the above-mentioned design parameters. Optimised design parameters are found for each channel spacing.

Chapter 4 illustrates the simulation results of the 48 channel DWDM system in the form of eye diagrams that represented the quality of the received signals. The results for all 48 channels for each type of network used in this dissertation is tabulated and represented on a Q factor vs BER chart. It also illustrates the eye diagram for the channel with the highest Q factor for analysis.

Chapter 5 analyses and discusses the results obtained in chapter 4. The results in chapter 4 are tabulated in this chapter for the purpose of comparing the effect of varying the design parameters on the signal performance of each type of network.

In Chapter 6, the final conclusions and future recommendations are drawn in this dissertation.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, a literature review is done to obtain the necessary background information on the evolution of transmission media and the fundamental concepts in fiber optic communications with the main focus being on dense wave division multiplexing (DWDM) technology. Literature reviews were compiled from credible online sources, various textbooks, equipment specification datasheets, equipment manufacturer manuals, research journals and conference article entries. Also, later in this chapter, the literature for the design and performance measuring criteria of DWDM system components used in this dissertation is expatiated.

2.2 Evolution of Fundamental Concepts in Fiber Optical Communication

The rapid growing increase in the usage of new applications, broadband data services, advanced internet traffic, changing patterns of usage and redistribution of services such as data, voice and video always causes a bandwidth bottleneck in telecommunications networks. This meant that the nature of communication systems is always in a state of ongoing evolution [3]. Fiber optic communication started replacing analogue electrical communication (copper cables) for long haul communication between the 1950s and 1960s with the introduction of pulse code modulation (PCM) [3]. PCM involved sampling, quantizing, and coding analogue telephone voice signals to produce a compressed binary digital signal [4], [5]. Fiber optic communication systems used optical multiplexing techniques that made use of carrier waves in specific regions of the optical spectrum to modulate light waves that allowed the transmission of digital signals up to a few gigahertz or gigabits per second [6]. The earliest fiber systems operated around 850 nm, the first window in the optical spectrum. A second window (S band), at 1310 nm, started being used due to its lower attenuation characteristics. The third window (C band) at 1550 nm had an even lower optical loss. Today, a fourth window (L band) near 1625 nm is under development and early deployment [3], [6].

By the 1970s and 1980s, optical communication systems used hierarchical multiplexing techniques such as Plesiochronous Digital Hierarchy (PDH) and Synchronous Digital Hierarchy

(SDH) respectively. PDH was a four-group multiplexing system that used multiple stages of multiplexing or de-multiplexing to move from a lower bit rate channel to a higher bit rate channel or vice versa. PDH was not fully synchronous and was plesiochronous in nature, which according to the ITU-T G.702 recommendations [8], meant that signals were transmitted nominally at the same bit rate but were not synchronized to each other by a common master clock. The maximum data rate for a PDH carrier signal was an E4 (European standard, level 4), which was 140 Mb/s [4], [7]. Unlike PDH, SDH used a repeated hierarchy of fixed length frames, which carried isochronous traffic channels that were able to encompass asynchronous transfer mode (ATM) frames, PDH frames, IP Packets and ethernet frames. SDH eliminated mountains of multiplexers by allowing a single stage of multiplexing and de-multiplexing to transfer multiple digital bit streams synchronously over an optical fiber cable using a single master clock thereby reducing the hardware complexities of PDH technology. The maximum data rate for SDH carrier signal was a STM256 (Synchronous Transport Module, level 256), which was 40 Gb/s [7].

PDH and SDH were both time division multiplexed (TDM) systems that increased the capacity of a long haul transmission link by slicing the time into smaller intervals so that the bits from multiple input sources can be transmitted on a single trunked wavelength carrier (either 1310 nm or 1550 nm) for each fiber core in a single mode fiber (SMF) optic cable link, effectively increasing the number of bits transmitted per second [5], [7]. This meant that for a full duplex communication system, a pair of fiber cores would be needed to send and receive a signal between two terminal equipment. However, to increase the bandwidth and channel capacity of the network, one would need to increase the number of fibers cores used. And whenever the bandwidth in the existing fiber cores of a fiber cable were exhausted, one would need to replace the fiber optic infrastructure with a fiber cable that had a larger number of fiber cores, which ultimately was a costly affair [3].

The need to increase bit rates and bandwidths without changing the existing fiber optic infrastructure led to the development of wavelength division multiplexing (WDM) in the late 1980s using two widely spaced wavelengths in the 1310nm and 1550nm regions. This technology was able to propagate two carrier waves, each having its own wavelength, to transmit and receive signals over a single fiber core [3].

WDM formed the foundation building block that led to the development of Dense Wavelength Division Multiplexing (DWDM), which had been used since 1999 [5]. In DWDM, several carrier waves can be transmitted over multiple wavelengths that are on the same fiber core with minimal losses and interactions between each wavelength. Each carrier wave has its own frequency that corresponded to a different wavelength. DWDM uses a transmitter that had different light sources to emit different wavelengths of light pulses. These wavelengths are narrowly spaced apart at a typical frequency spacing of 100 GHz or less in the C and L frequency bands. These emitted signals are then coupled as a composite signal and injected into a single optical fiber core by a multiplexer (MUX). After transmission on the fiber, a de-multiplexer (DEMUX) separates the composite signal into the different wavelength signals. The DEMUX then sends each of these signals towards its own photodetector at the receiving end. See Figure 2.1 [3].

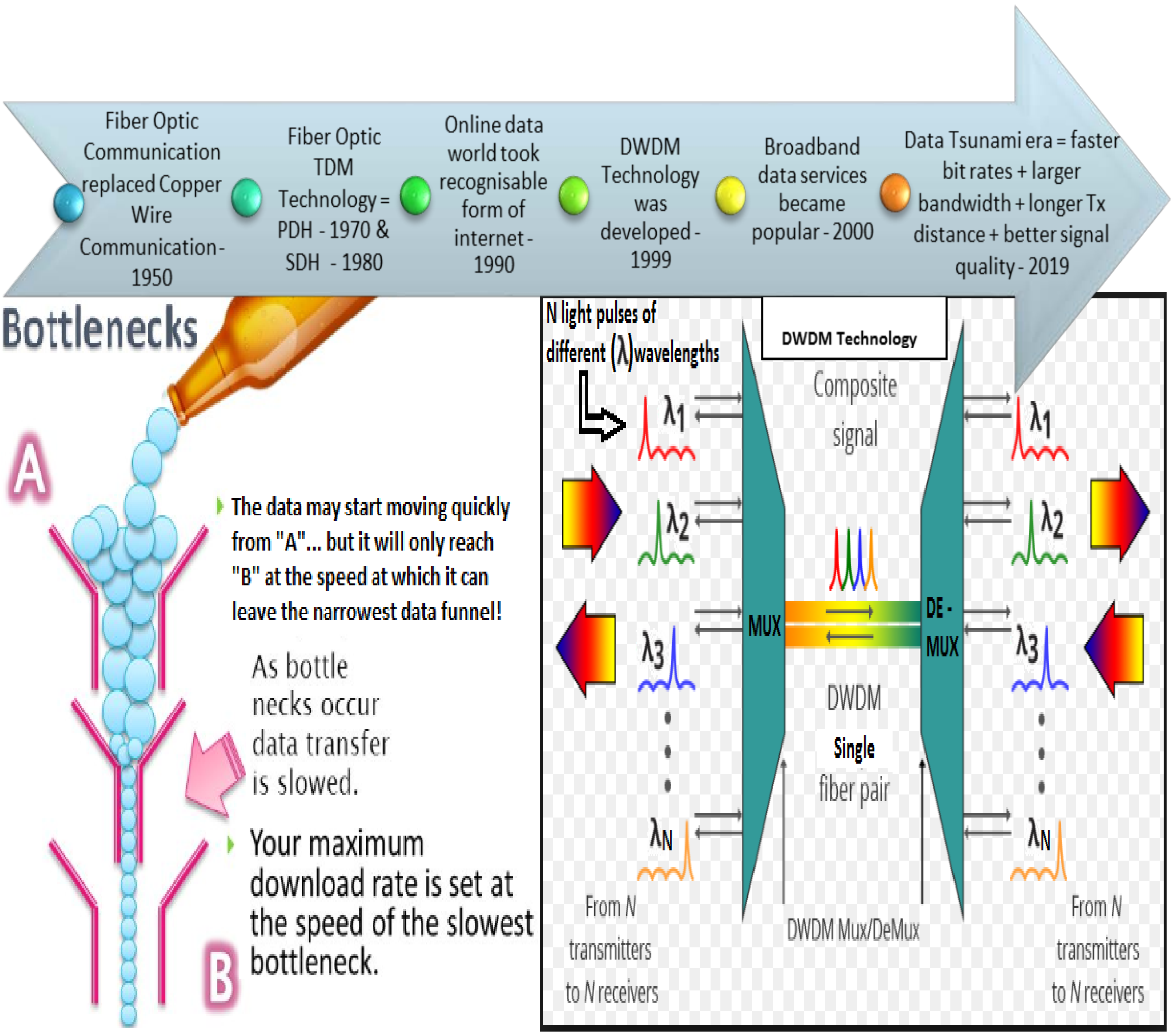

Figure 2.1: Timeline and Overview of DWDM Communication System [3]

DWDM technology eases the bandwidth bottleneck by increasing channel capacity and bit rate without needing to change the existing fiber optic infrastructure to increase bandwidth. However, due to the “Data Tsunami” era, there is a greater demand to increase transmission distance and channel capacity of data traffic at even higher bit rates, smaller channel spacings and higher quality of service (QoS). This gives rise to linear effects (attenuation and dispersion) and non-linear effects. In DWDM, four-wave mixing (FWM) is the most critical type of non-linear effect. All these unwanted effects must be managed and optimised for efficient spectral efficiency by line encoding modulation formats, which has a direct effect on the accuracy and performance of a DWDM signal. The focus of this dissertation is to use three type of line encoding modulations formats namely, non-return to zero (NRZ), return to zero (RZ) and Modified duobinary return to zero (MDRZ) to minimise the effects of attenuation, dispersion and FWM when decreasing channel spacings from 100 GHz to 6.25 GHz.

2.3 Advantages of DWDM

DWDM has the ability to provide potentially limitless transmission capacity, which is dependant only by the properties of the equipment that make up the system. The money invested on the existing fiber infrastructure can not only be retained, but can also be optimised. This is because as demands increase, additional capacity can be added, either by simple equipment upgrades or by increasing the number of wavelengths on the fiber, thereby increasing the bandwidth without the need for high costly upgrades. Besides Bandwidth, DWDM’s most enthralling technical advantages were as follows [3]:

- Transparency – DWDM provisions for TDM and other data formats such as ATM, Gigabit Ethernet, PDH and SDH fiber channels with open interfaces transparently over its shared architectural physical layer [3].
- Cost-effective integration – By using DWDM as a transportation layer for TDM, existing SDH equipment investments can be preserved. Not only can one integrate existing SDH equipment to DWDM equipment effortlessly, but one can also eliminate layers of SDH multiplexing equipment that would be needed for future SDH requirements by interfacing directly to DWDM equipment from ATM and packet switches [3].
- Scalability – DWDM leverages the large amount of dark fibers found within many metropolitan and enterprise networks to swiftly meet the rapid demand for capacity on point-to-point links and on spans of existing SDH rings [3].

- Dynamic provisioning – DWDM provides fast, simple, and dynamic provisioning of network connections, which equips service providers with the capability to deliver a high-bandwidth of services to customers within a matter of days [3].

2.4 Performance limitation factors affecting DWDM systems

Fiber optic transmission presents several limitations that must be dealt with when designing a DWDM system. These fall into two broad categories namely linear effects and non-linear effects. These effects had several causes, not all of which affect DWDM. The following section only discusses those causes that were relevant to DWDM.

2.4.1 Linear effects

- **Attenuation –** This is the deterioration of the signal strength, or the loss of optical power as the signal is transmitted through the fiber. Attenuation in a fiber optic link occurs due to the internal and external factors of the fiber optic link.
  - *Internal factors* such as Rayleigh scattering and absorption are caused by density variations and impurities found within the fiber optic glass of the cable, respectively. These factors are directly dependant on the length of the fiber and the wavelength of the light, therefore an increase in these parameters will increase the attenuation. In this dissertation, the attenuation due to internal factors of the fiber will be found in the non-zero dispersion shifted fiber (NZDSF) and the dispersion compensated fiber (DCF). This attenuation loss is measured in decibels per kilometre (dB/km) [3], [9].
  - *External factors* such as link loss mechanisms are caused by the insertion loss of active components and the noise figure of the optical amplifier in the fiber optic link. Active components that exhibit loss in this dissertation include the Lithium-niobate Mach–Zehnder Modulator (Linb MZM), WDM transmitter, WDM MUX and DEMUX, connector and the optical receiver. The attenuation (or loss) of these factors, for a given wavelength, is defined as the ratio between the input power and the output power of the fiber being measured. It is expressed in decibels (dB) [3], [9].
- **Chromatic dispersion –** This is the spreading phenomena of light pulses as they travelled down the fiber. Chromatic dispersion (CD) occurs in DWDM because a single

light pulse that is transmitted through a fiber core is composed of multiple wavelengths, each travelling at different speeds through the fiber. The interaction between the dissimilar propagation speeds widens the light pulse when it arrives at the receiver, which in turn causes a reduction in the optical signal-to-noise ratio (OSNR) and an increase in the number of bit errors. The CD coefficient (referred as D) of a given fiber is the normalised value that represents the relative arrival delay (in ps) of two wavelength components separated by one nanometre (nm) per each kilometre (km) of transmission, expressed in $\mathrm{ps/(nm\,x\,km)}$ [3], [9]. For the ITU G.655D compliant [10] non-zero dispersion shifted fiber (NZDSF) used in this dissertation, the chromatic dispersion coefficient (D) for a centre wavelength of 1550 nm is chosen using the expression shown below in (2.1), which is taken from [10]. The expression in (2.1) is chosen since the wavelength range used for the design in this dissertation is from 1460 nm to 1550 nm:

$$D(\lambda)_{1460nm\ to\ 1550nm} = \begin{cases} D_{min}(\lambda)\,, & \dfrac{7.00}{90}(\lambda - 1460) - 4.20 \\ D_{max}(\lambda)\,, & \dfrac{2.91}{90}(\lambda - 1460) + 3.29 \end{cases} \quad (2.1)$$

- **Polarization Mode Dispersion**

  Unlike CD, Polarization mode dispersion (PMD) is the smearing of a signal, which is caused by an interaction between pulses that happens over time. This interaction happens due to the ovality of the fiber shape from external stressors or because of the lack of maintenance done to create a consistent birefringence pattern along the length in the fiber’s perpendicular polarisation modes during the manufacturing process. Birefringence is the phenomenon where light is divided into two different pathways. Most SMF have two polarisation states, one is vertical and the other is horizontal [3], [11]. For this dissertation, we assume that PMD is negligible.

2.4.2 Non-linear effects

As opposed to linear effects that can be compensated, non-linearities are increasingly additive effects formed by the continuous interaction of the light signal with the fiber medium through which it travels, which results in deleterious changes to the light signal. The high-power level and the large number of optical channels used in the

DWDM system are the main causes to non-linear effects, which are the fundamental limiting factors that determines the total quantity of data that can be transmitted in optical fiber. There are different types of nonlinear effects namely, stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), self-phase modulation (SPM), Cross-phase modulation (XPM), and four-wave mixing (FWM). In DWDM, FWM is the most critical of these types [3], [11].

- **Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS)**

  SBS is a backscattering phenomenon that is evident when an induced periodic change in the fiber refractive index causes a loss of power and scattering of signal, however it only occurs when a few channels are transmitted. SRS is a scattering effect (formed only when using the Raman optical amplifier) that causes a transfer of signal power from a shorter wavelength to a longer wavelength signal; and in the process of doing so, scatters the light in all directions. SBS and SRS are not applicable for the design used in this dissertation since many channels are amplified using the EDFA instead of the Raman [3], [11].

- **Self-Phase Modulation (SPM) and Cross-Phase Modulation (XPM)**

  SPM produces a time varying phase change in the same channel and XPM produces a phase change on another channel; both SPM and XPM are formed by high signal intensities that changes the fiber's refractive index and causes spectral broadening of the optical signal [3], [11].

- **Four Wave Mixing (FWM)**

  FWM is an interference phenomenon that degrades the performance of a DWDM system because it produces a number of new unwanted signal frequency $(f_N \equiv f_{ijk})$ from a combination of three different signal frequencies f_i, f_j and f_k as shown below in [3], [12]:

$$(f_N \equiv f_{ijk} = f_i \pm f_j \pm f_k) \tag{2.2}$$

where *i, j* and *k* vary from 1 to *N* and *N* is the total number of DWDM channels.

This creates a large number of unwanted FWM components (N_{FWM}), which can be calculated using the expression shown in (2.3), which is taken from [12]:

$$N_{FWM} = \frac{N^2.(N-1)}{2} \quad (2.3)$$

The new unwanted channels are ghost channels, which are formed when any combination of the three different channels produced a fourth channel. Due to the high-power levels, ghost channels may either be a new sideband frequency to one of the other frequencies or it may overlap with one of the other frequencies [3]. The effect of FWM on a 3 channel WDM system is illustrated in [3] as an example. By using the equation above, for a 3 channel (λ1, λ2, λ3) system, $N_{FWM} = 9$.

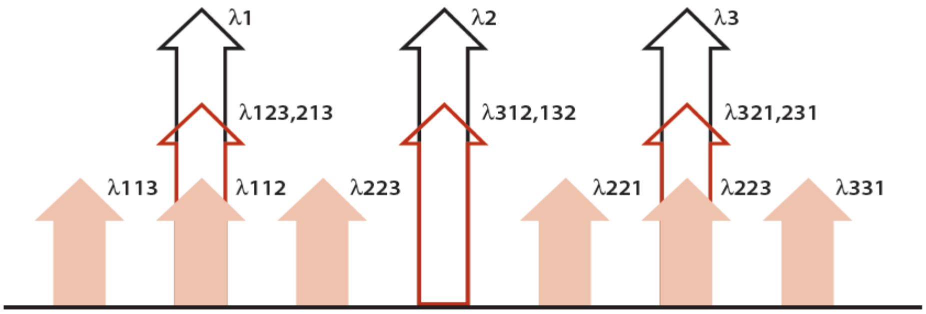

Figure 2.2: Illustration of FWM on a three channel WDM system [3]

The three different channels induce a fourth channel known as ghost channel. Due to high power levels, FWM effects produce several ghost channels (some of which overlap actual signal channels), depending on the number of actual signal channels. Similarly, it could be deduced that for a 48 channel DWDM system used in this dissertation, there are a potential of 54144 unwanted FWM frequency components or ghost channels that will degrade system performance as the channel spacing is decreased. Therefore, FWM is one of the most adverse nonlinear effects in DWDM systems. FWM effects limit the channel capacity of DWDM systems and it increases due to the following factors [3], [12]:

- Increase in the length of the fiber
- Increase in the number of channels
- Increase in power levels
- Decrease in chromatic dispersion
- Decrease in channel spacings

Dispersion-shifted fiber (DSF) is one of the types of fibers that is greatly affected by the effects of FWM due to its zero-dispersion property near 1550nm, making it unsuitable for DWDM systems. Manufacturers subsequently created the non-dispersion-shifted fiber (NZDSF) with the above point in mind because this fiber had a certain amount of chromatic dispersion (CD) that occurs around 1550 nm region. This leads to different wavelengths having different group velocities, and thereby causes a reduction in the non-linear effects of FWM [3].

2.5 Exploring the limitation and extent of existing research

The need for a DWDM system is application dependent with varying parameters such as signal data rate and number of users. The research of this dissertation led to the publication of two conference articles.

The first article in [1] dealt with the analysis of a 32 channel DWDM network for bit rates of 5 Gb/s and 10 Gb/s, a channel spacing of 100 GHz and transmission distances of 100km and 500km. The Q factor of the NRZ and RZ modulation formats were compared in combination with a post compensation technique that used 1 EDFA. The obtained results showed that the NRZ modulation technique performed better in producing a higher quality of signal for long haul DWDM links. Long haul links have non-linear losses that affected the transmitted signals because it produced noise. In the 5 Gb/s DWDM network for small distances such as 100 km, the RZ technique had a better performance due to the higher Q-factor and lower BER for short distances. However, for the 5 Gb/s network at 500 km and the 10 Gb/s DWDM networks for both 100km and 500km, NRZ modulation was the preferred choice because of its low BER, high Q-factor and higher eye heights.

The second article in [2] dealt with the performance analysis of a 48 channel DWDM network, which had mismatched active components, that evaluated the effect of linear and non-linear losses for channel spacings of 100 GHz, 50 GHz, 25 GHZ and 12.5 GHz and 6.25 GHz when using the NRZ and RZ modulation formats in combination with a post symmetric dispersion compensation technique that used 3 EDFAs. The modifications of the optical link by adding symmetric EDFAs significantly improved signal quality because it compensated for the increased dispersion and in turn also lowered the effects of non-linearities to a certain extent for smaller channel spacings. Non-linear effects of FWM was mostly supressed at a 100GHz channel spacing for NRZ. The obtained results showed that the NRZ modulation technique at a channel spacing of 100GHz performed better than RZ. Lower channel spacings for both NRZ and RZ for 50GHz, 25GHz, 12.5GHz and 6.25GHz were highly susceptible to non-linear losses that produced noise.

In addition to the literature surveys done by the author in the two published conference articles researched in [1] and [2]; the following represents some of the many other literature surveys done to explore the extent of the work done by other researchers in the topic of point-to-point DWDM systems for long-haul communications:

Subash and Babu [13] performed an iterative analysis to obtain an optimized DWDM system in terms of data rate, channel spacing and number of channels. The system was designed and analysed for three channel numbers of 16, 32 and 64. For each of these three channels, the output was analysed by varying the bit rate by 5 Gb/s, 10 Gb/s and 20 Gb/s and channel spacing by 30 GHz, 40 GHz and 50 GHz.

Kaur and Sharma [16] presented an intensive review of the DWDM and its hard-core analysis. The most exponential changes in communication engineering had taken place in the last several decades with the advent of DWDM to explore the untapped potential of unlimited bandwidth on a fiber pair. Originally applied to solve the problem of fiber saturation in long-distance networks, DWDM was becoming the leading player in all-topical networks. DWDM was insensitive to bit rate and permits communication networks to enhance its transmission capacity without installing new fibers. This was done at a decreased cost and with much greater flexibility than other communication systems. DWDM installs narrowly spaced channels onto the same fiber and improve capacity on existing fiber routes by factors of 16, 32, 40, or more.

Antil et al. [17] provided an overview of DWDM networks and its current technologies. Analysis of applications and roles of current network protocols in the future DWDM frameworks were also provided. The article covered the functions and applications of DWDM system components. The operation of each component was discussed individually. The interaction of all the components associated with a DWDM system was critical to system design. Fiber optic terminology like attenuation, dispersion and optical signal to noise ratio (OSNR) were factors that measure the quality of the optical signal. These key factors help to design and optimise a DWDM system. During the design process from transmitter to receiver, the strength (power level) and quality (OSNR and dispersion) of every optical signal must be maintained. Optical amplifiers extended the reach of DWDM systems by overcoming losses owing to attenuation, but could cause OSNR problems. Dispersion compensation devices and dispersion compensated fibres reduced the amount of dispersion of a span, hence it increased the transmission distance.

Sajjan et al. [18] gave a detailed description about link design and optical power budget calculations in a DWDM network. Power budget analysis involved the description of gain accumulation in the signal due to erbium-doped fiber amplifiers (EDFAs), attenuation calculation owing to fiber and insertion losses caused by reconfigurable optical add-drop multiplexers (ROADMs) and dispersion compensation modules (DCMs). For DWDM network design, it was very necessary to obtain optimised power values at the EDFA nodes that were well within the range specified. Power management was an important task to achieve optical receive power for better bit error rate (BER). Output power at the optical amplifier (OA) correlated to the number of channels passing through them. Dispersion compensation was also very much necessary so that signal was efficiently detectable at the receiver. Placement of DWDM components in a network required the analysis of the distance between two nodes, type of data rate, technical specifications of the component, their gain and insertion losses. DWDM network setup required various network components to make the system work. Optimal optical power requirements were the major constraints in these kinds of networks. The DWDM system considered in this article was designed to carry 80 channels in a 1550nm band. This provided 50 GHz channel spacing (approx. 0.4 nm), with 80 channels in a single mode fiber. DWDM channel spectrum had been defined in ITU-T recommendation G.694.1. The power management in a DWDM network was dependent on the number of channels which were supported by the setup. The amplifiers used to boost the signal power were fixed gain amplifiers. The power measurement at each component of DWDM system was calculated separately. Calculations were accounted to the 80-channel DWDM system and calculations were done with respect to the individual channels. Insertion loss of the network elements and attenuation through the fiber link were considered during calculation. The relationship between the optical power at input and output of each component in DWDM system were discussed and was made feasible to carry all 80 channels without violating the power requirements and constraints for the amplifiers as well as other components used in the network.

Saxena and Saxena [19] studied the relationship and calculations between different parameters related optical strength of light signal. They established that Optical Power debugging played an important role for smooth and efficient functioning of a DWDM system. They then evaluated the ideal and actual optical power of the light signal at input points of DWDM components. Experimental results show that at many points, the actual value of optical power of light signal differed from ideal value, which caused a failure of the network design and led to traffic outage and hardware fault of DWDM components. They had also described difference between ideal and actual value with the help of attenuation. Therefore, the article concluded the importance of optical power debugging for better performance of DWDM system having fixed gain amplifiers.

Moses and Lakshmy [20] aimed to find the most efficient amplifier with respect to transmission and to identify the significant degradation factors that influenced transmission distance. Raman-EDFA showed better performance than any other amplifiers mentioned. The main factor that had limited transmission was amplifier-produced noise, the amount of which was more in the case of the semiconductor optical amplifier (SOA). The main factor that held down a transmission system with a discrete Raman amplifier was inter channel crosstalk, which was a product of the Four Wave Mixing (FWM) non-linear effect. It was also necessary to note that the difference in accumulated inter channel crosstalk was mostly explained by the signal intensity difference at the amplifier output. At the same time, it was established that the non-linear response of the SOA and the small effective area together with the high non-linear coefficient of the discrete Raman amplifier made a serious impact on the quality of transmission and limited the total achievable length of the link. The parameters of SOA were adjusted so that it produced higher amplification with less signal distortions.

Kaur and Sarangal [21] investigated the performance of a 32-channel DWDM system with post-dispersion compensation using dispersion compensated fiber (DCF) at different bit rates (10, 20 and 40 Gbps). The simulation results showed that if the DCFs were incorporated in system through the dispersion compensation technique, then the DWDM systems had good signal performances, low bit error rates and were able to fully exploit the high-speed data rates.

The analysis and design of a 32-Channel with 40 Gb/s point-to-point DWDM system was proposed by Pal and Revathi [22]. By varying the modulation format, it was seen that the Q-factor, bit error rate (BER), eye height, threshold performance gave the best result in the return-to-zero (RZ) modulation scheme, then non-return-to-zero (NRZ), and finally Mach Zehnder (MZ) modulation. MZ modulator had high extinction ratio and high-speed performance. Varying channel frequency from 100 GHz to 50 GHz produced inter-symbol interference (ISI). For single mode fiber (SMF), the DCF length was less. It produced very good BER and Q factor, as well as good eye height. At 50 km SMF and 10 km DCF, it produced optimum results.

Cho and Kim [23] proposed the simulation and optimization of a 32-channel DWDM system for different modulation formats, channel spacings and line widths in the 1550 nm transmission window using Optisystem 12.0. On the criterion of Q factor and BER, it was observed that RZ modulation format, channel spacing 150 MHz and line width 0.3 MHz gave the optimised performance. It was also observed that DCF and EDFA should also be used at the appropriate place for the optimum performance.

Chaudhary et al. [24] demonstrated an error free transmission of a 32 x 45 Gb/s DWDM system that had a channel spacing of 200 GHz with distance of 100 km based on DWDM/EDFA signals; NRZ modulation format of the optical signal was used. The dispersion management was fully treated by DCF as a compensator with the in-line optical amplifiers such as EDFA to improve the optical signal-to-noise ratio (OSNR), and reduce the nonlinear effects in transmission system. The optimum fiber length to this system was 100 km transmission distance with the average power of -10 dBm, and the average noise power was -37 dBm for all 32-channels. This meant that the DWDM system had a good performance, and fully exploited the high speed, low error rate, availability of multiple channels on a single fiber, and the major contribution was the development of the multi-destination communication over the light wave DWDM system. This scheme was very attractive for the upgrading of current optical networks. Expenditures may be reduced by adding more bandwidth to the 45 Gb/s DWDM system and increasing the capacity of existing systems. Finally, the 32 x 45 Gb/s channels were successfully transmitted using DWDM/EDFA architecture.

Senthamizhselvan et al. [25] analysed the performance of a DWDM based fiber optic communication system at different modulation schemes, various power level and different number of data channels. It was established in this article that non-linear optical effects degraded the performance of DWDM systems. These included cross phase modulation (XPM), self-phase modulation (SPM), four-wave mixing (FWM), stimulated brillouin scattering (SBS) and stimulated Raman scattering (SRS). Analysis was performed on a DWDM system with NRZ, RZ modulation schemes and DCF. The performance of RZ modulation was shown to be better than NRZ modulation. The bit error rate was greatly reduced by using RZ modulation. The SMF signal dispersion was compensated by using DCF with dispersion coefficient of -83.75 ps/nm/km. The DCF along with SMF was used for length of 100km at 1550nm to reduce the dispersion of optical signal. The performance of improved detected signals was evaluated by the analysis of quality factor and BER. The simulation studies were carried out using Optisystem platform from Optiwave.

Singh and Bhagat [26] performed an analysis of a DWDM transmission system using different modulation formats (NRZ and RZ), power levels (5, 8, 10, 12, 15 and 20 dBm), data transmission rates (2.5, 5 and 10 Gb/s) and a number of information channels (8, 16, 24, and 32) at the input. A single mode fiber of length 100 km at 1550 nm wavelength was used along with a dispersion compensating fiber to reduce dispersion. The performance of the signal received at the receiver was analysed based on the quality factor and BER. It was found that the presence of non-linear effects in optical fiber, namely FWM, SPM, XPM, SRS, and SBS, degraded the performance of the DWDM transmission system. From the results presented, it may be concluded that RZ modulation format showed a better performance as compared to that of NRZ modulation format. This is because the quality of signal received in the case of RZ modulation format was better than that of NRZ modulation format. Moreover, it could be concluded that by varying the number of input channels in a DWDM system, the quality of the signal received at the receiver end remained the same and showed negligible degradation. Furthermore, as the transmission power level was increased up to 10 dBm, the quality of the received signal improved, but as the transmission power level was further increased the quality of the received signal degraded due to the increased efficiency of non-linear effects.

An increase in the data transmission rate degraded the performance of the received signal. Thus, it may be concluded that for faithful transmission in case of DWDM transmission system, the RZ modulation format must be used and the transmitting power levels should be kept close to 10 dBm for each input channel.

Kaur et al. [27] investigated an 8 channel DWDM system for a fiber based on optical add/drop multiplexers (OADMs) at 1550 nm window at different data rates i.e. 5, 10, 15 Gb/s. In addition, the system was examined at different distances i.e. 800, 960, 1120, 1200, 1440 kms. Finally, the system was examined with a frequency of 193.1 THz at different channel spacing of 20, 40, 80, 100 GHz. Various performance parameters such as different data rates, distances, and channel spacings were varied to investigate the system performance in terms of the BER and quality factor. The comparison of output power at different channel spacings, distances and data rate were made and an improved eye diagram was observed at a maximum distance of 1440 kms.

Rajalakshmi at al. [28] simulated a 32-channel DWDM network using the RZ and NRZ modulation formats at the data rate of 40 Gb/s. The transmitter used was a 32-channel WDM transmitter at a frequency spacing of 100 GHz. The transmission loop was a 50km SMF optical link with 10 km of DCF and two EDFAs. The receiver was a 32-channel WDM demultiplexer and BER testers. The important feature of EDFA was the ability to pump the devices at different wavelength, which was very suitable for DWDM. It had a very low coupling loss, compatible–sized fiber transmission medium and a very low dependence of gain on light polarization. EDFAs were highly transparent to signal format and bit rate. They were immune to interference effects between different channels, thus only EDFAs were used for long distance transmission. The simulated results were tested using BER analysers. It was analysed for different modulation formats with PIN receivers using an Optisystem simulation tool.

Choudhary et al. [29] performed a comparative analysis of a 16-channel DWDM optical communication system for different dispersion compensation schemes, namely pre-, post- and mix-dispersion compensation schemes using DCF. They also used different modulation formats, namely non-return-to-zero (NRZ), carrier suppressed return-to-zero (CS-RZ), duobinary return-to-zero (DRZ) and modified duobinary return-to-zero (MDRZ) at different bit rates of 10 Gb/s, 20Gb/s and 40 Gb/s for the comparison. They observed that at a high bit rate, the MDRZ format gave a better performance than the other formats. The mix-dispersion compensation scheme showed a better performance as compared to pre- and post-compensation schemes. It gave better results at high bit rate (40Gb/s) when used with the MDRZ modulation format. The results were based on the quality factor, BER and eye opening of the received signal.

It can be seen by the work done in [13, 16 – 29] that there was very little research done for DWDM systems operating at very narrow channel spacings of 12.5 GHz and 6.25 GHz channel spacings with a 25 Gb/s bit rate. This dissertation focuses on achieving an optimised system performance for a 48 channel DWDM system model that has a bit rate of 25 Gb/s for channel spacings of 6.25 GHz, 12.5 GHz, 25 GHz, 50 GHz and 100 GHz.

2.6 DWDM System Design Components

The design of the DWDM communication system comprises mainly of nonlinear devices and non-gaussian noise sources. Therefore, the analysis of such a communication system would have been tremendously time-intensive since it is a highly multifaceted system. As a result, these tasks are performed efficiently and effectively with the help of an optical communication system design platform.

Optisystem is used as the design platform since it is an innovative optical communication system simulation package with a graphical user interface (GUI). It helped virtually design, simulate, test, and optimise the DWDM optical link in the physical layer of a broad spectrum based on the realistic modelling of a DWDM fiber optic network. Optisystem version 7.0 is used for this design.

The various components that determines the performance characteristics of the designed DWDM system is explained in the following sections.

2.6.1 WDM Transmitter

DWDM systems require multiple transmitters for each wavelength channel and different parameters for each one of them. In order to reduce the time consumption of designing multiple transmitters, a WDM transmitter is used. The WDM Transmitter array encapsulated different components that comprised the design of multiple WDM transmit channels. This allows the selection of different line coding modulation formats and laser modulation scheme types for multiple channels in one single component [29].

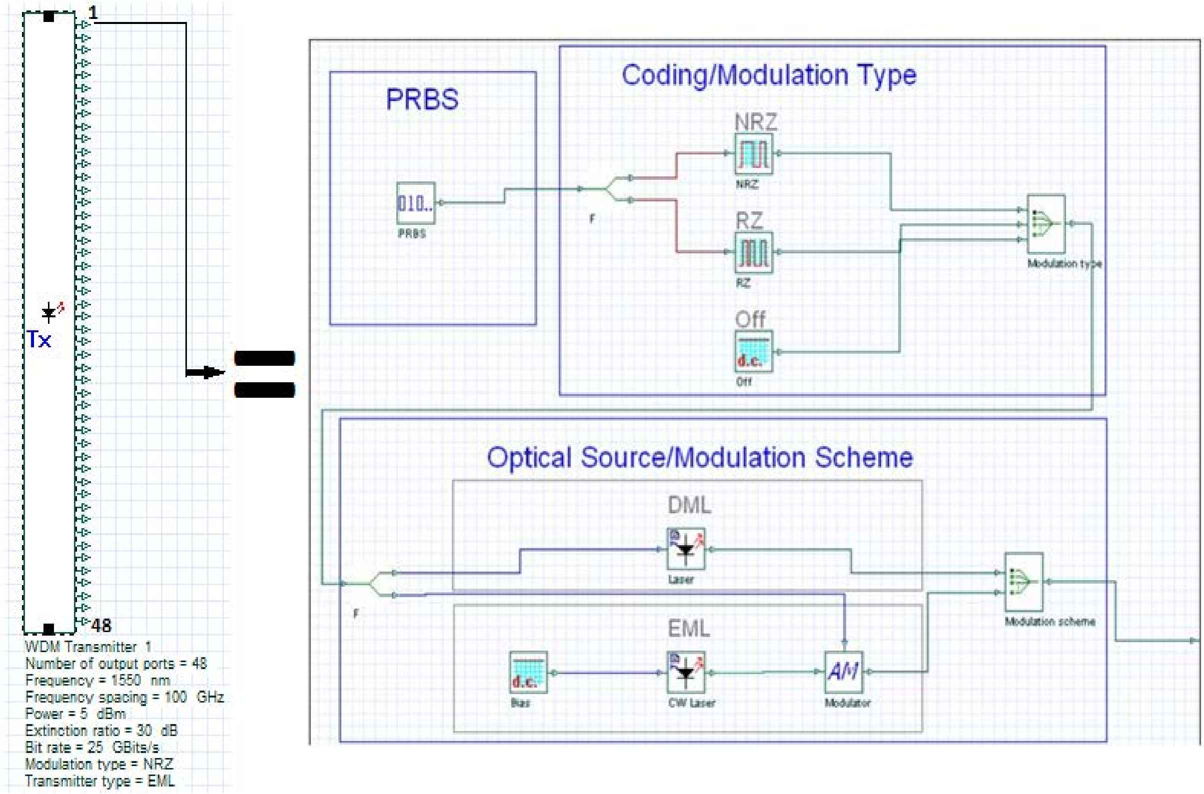

Figure 2.3: A 48 port WDM Transmitter and the Block Diagram of a single channel in a WDM Transmitter

Figure 2.3 shows a 48 port WDM transmitter on the left and the equivalent block diagram of a single channel (which in this case is the 1st channel) of the WDM Transmitter on the right. The most important components and parameters that make up the WDM transmitter is shown in the sections that follow.

2.6.1.1 Pseudo-Random Bit Sequence Generator (PRBS)

The first stage is the PRBS; which creates a bit sequence that is designed to approximate the characteristics of random data. A different seed of leading and trailing zeros is generated for each bit sequence for each WDM channel [29]. The WDM transmitter had a built-in PRBS that automatically generates a random seed of data for each channel port. When using the external PRBS generator, one needs to set the individual bit rate parameter of each channel, whereas with the WDM transmitter, one is able to set and apply one-bit rate for all channels.

2.6.1.2 Light Source

There are two types of light sources namely, light emitting diodes (LEDs) and laser diodes [29], [3]. A laser diode is the preferred light source since it is a pure light source that provides coherent energy with little distortion. Even though lasers are more expensive than LEDs, laser diodes are the preferred choice because they offer a better performance than LEDs. It has much higher transmission speeds, is able to use precise wavelengths, has a narrower spectrum width, enough power, and has the ability to control chirp (the change in frequency of a signal over time) [3]. Chirp is undesirable because a pulse with a broad range of wavelengths is susceptible to dispersion through the optical fiber transmission [3].

2.6.1.3 Modulation scheme type of transmitting light source

There are two modulation schemes for the laser diode, namely a direct modulated laser (DML) and an external modulated laser (EML) [29]. For DML, the bias current applied to the laser is itself modulated by an electrical data signal. This variance of the DML's electrical current (input signal) causes an undesirable wavelength chirp effect, which in turn causes an excessive chromatic dispersion at high speeds. For EML, the bias current to the laser is held constant, and the constant light output from the laser is modulated by the electrical data signal. This provides a constant level of optical power for the light-wave output data signal [31]. Compared to a DML, an EML is the preferred choice since it limited chirp effects and has a smaller chromatic dispersion with a stable wavelength under high-speed operation. This is because the input signal to the laser section is not modulated and therefore did not change [32]. C-band wavelengths with a centre frequency of 1550nm are assigned to the CW lasers to modulate the data.

2.6.1.4 Extinction Ratio

Extinction Ratio (E_r) is a measure of the quality of the laser. This defines the power penalty ratio of the laser, which is the ratio of the optical power measured at the centre of the transmitted 1 level state ($P1$) to that of the optical power measured at the transmitted 0 level state ($P0$) and is measured in decibels (dB) [33], [34]. The expression shown below is taken from [33]:

$$E_r = 10.\log_{10}\left(\frac{P1}{P0}\right) \tag{2.4}$$

The transmitted 1-level state is defined as when the light pulse is 'on' and produces a 'high' state. Transmitted 0-level state is defined as when there is 'no light pulse' and produces a 'low state'. Even though in an ideal working environment, the 0-level state should have no power, however the laser needs a small amount of power to be emitted at the 0-level state for it to be biased, thus $P0$ > 0. Usually for an optical transmitter, the Extinction Ratio or transmission power is kept high enough for the transmission signal to be distinguished at the receiver [33], [34]. In this dissertation, a very high 30 dB extinction ratio is used in combination with a Bessel filter, which makes the power penalty close to 0 for most of the network designs. Signal propagation over length of fiber in a DWDM system causes dispersion and this significantly decreases the extinction ratio. However, the 4th order Bessel filter does not require for a maximum or minimum channel extinction ratio to be set for its operation. For any other order of the Bessel filter, an extinction ratio > 10dB would suffice [33].

The effect of varying the extinction ratio in combination with a rectangular filter is evaluated for a 25 GHz channel spacing for the purpose of eliminating four wave mixing (FWM). This is because a rectangular filter had the property to eliminate frequency harmonics without affecting lower harmonics and signal propagation over a length of fiber in a DWDM system. Signal propagation through a fiber causes dispersion. This dispersion significantly decreases the extinction ratio. Therefore, in theory if the extinction ratio is also decreased, it should increase the power and dispersion in the system. Therefore, in theory, an increase in dispersion should decrease the effects of FWM.

2.6.1.5 Line coding Modulation format used in WDM Transmitter: NRZ and RZ

For a digital laser to transmit analogue information signals in the electrical domain over an optical passband domain, these analogue signals have to be converted to a digital format by means of using a line coding technique. The digital format consists of a sequence of voltage pulses that is either a high (logic level 1) or a low (logic level 0 – no pulse). The digital signal transmission rate is the bit rate of the signal and had the unit, bits per second (b/s). Each bit time slot had the period T with its unit in seconds (s), where $\mathrm{T} = 1/\text{bit rate}$ [35]. The duty cycle (d_c) of the pulse is a fraction of the bit width (T_b) of the data over the time slot period (T), where $d_c = T_b\ /\ \mathrm{T}$ [35]. Two common methods of coding data information in a digital signal are non-return to zero (NRZ) and return to zero (RZ) coding [35]. Modulation of a signal format using line coding techniques in a DWDM system is important to eliminate the direct current (DC) component of a signal. This decreases the dependence on the low end of the frequency spectrum in a baseband signal where there is very little or no transmission capability at and near zero frequency (DC). For this reason, the polar format of the NRZ and RZ is used. This is shown in Figure 2.4 [35]. The zero-mean and vanishing spectral density point at zero frequency is the spectral null (Δf_{null}) at DC [36].

The differences between NRZ and RZ are further explained in Table 2.1 and are illustrated in Figure 2.4:

Table 2.1: Differences between NRZ and RZ

NRZ	RZ
1. The definition of NRZ and RZ differs with regards to their modulation techniques as stated in [35].	
NRZ is a non-linear modulation technique in which the pulse does not return to zero, but rather remains on when successive ones are transmitted.	RZ is a linear modulation form of pulse amplitude modulation, in which the pulse returns to the zero state when transmitting a one.
2. The baseband signal power spectral density (PSD) of NRZ and RZ is shown in [35]. The RZ pulse width is half the NRZ pulse width, however, the RZ pulse spectral width is much wider than the NRZ spectral width because:	
The bit width of NRZ is the same as its time slot width, where T = Tb and $d_c = 1$. The spectral width to the first null is $\Delta f_{null} = 1/T$.	The bit width of RZ is half of the time slot width, where Tb = T/2 and $d_c = 0.5$. The spectral width to the first null is $\Delta f_{null} = 2/T$.
3. The transmit signal spectrum for NRZ and RZ is shown in [37] and is centred at the carrier frequency of the light source, which in this dissertation is set at 193 THz for 1550 nm wavelength. RZ has a wider spectral width and is less tolerant to dispersion than NRZ because:	
NRZ transmitter has a finite bandwidth.	RZ transmitter has a larger bandwidth.
4. The mode of operation (MOA) for NRZ and RZ is shown in [37]. The transmission of a long string of 1s and 0s produces a condition in which the receiver may lose its amplitude reference for optimum discrimination and	

transitioning between successive received signals of 1s and 0s. This means that the effects of fiber losses are more reduced in RZ than NRZ because:	
With NRZ, its MOA never demands for a return to a zero-level state before a new set of 1s and 0s are transmitted. Minimal transitioning and discrimination between the successive transmission of a long string of either 1s or 0s.	With RZ, its MOA demands for a return to a zero-level state before a new set of 1s and 0s were transmitted, which maximises the discrimination and eases the transitioning between each state.

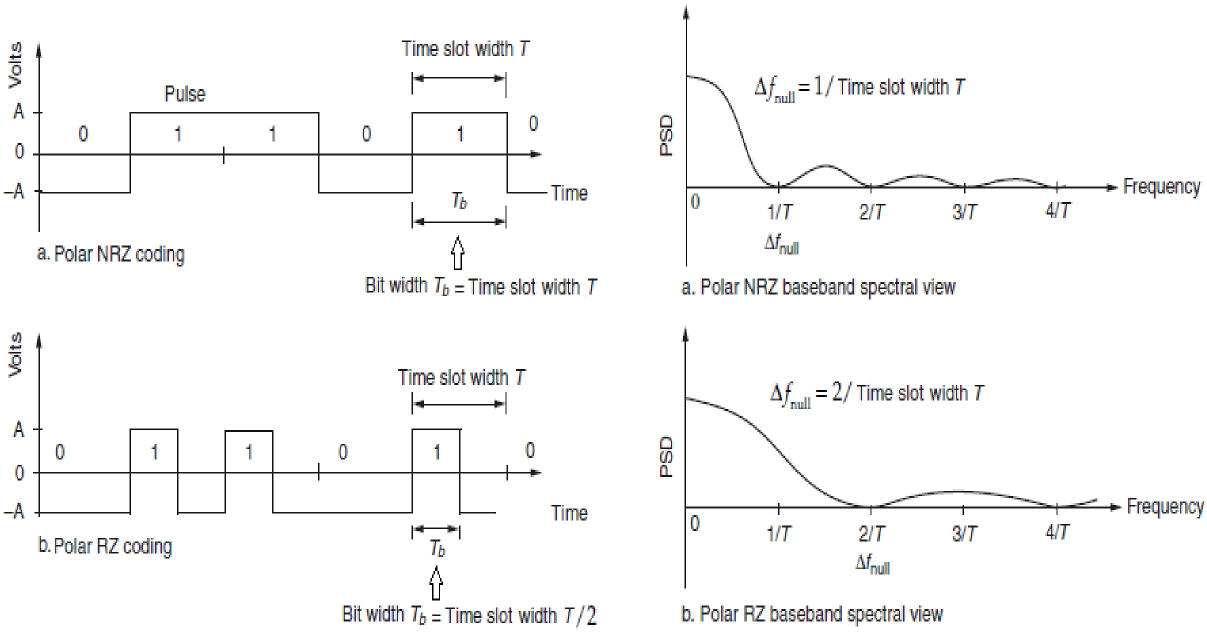

Figure 2.4: Illustration of the differences between NRZ and RZ Signals [35]

2.6.2 Continuous Wave (CW) Laser Array with Equally Spaced (ES) channels

The CW Laser Array ES is an array of CW lasers and is equivalent to the conventional CW Laser Array component. The emission frequencies are equally spaced (ES). However, the CW Laser Array ES model is easier to set up for WDM systems, because it only requires the initial laser emission frequency and spacing. The signal output power is the same for all the output signals. This type of laser is used as the optical source when there is a need to use advanced modulation techniques such as the modified duo binary return to zero (MDRZ) line coding modulation format. This is because the properties of the WDM transmitter in Optisystem does not support the usage of the MDRZ format. For this purpose, each channel of the CW laser array has to be connected to its own MDRZ subsystem. The left part of Figure 2.5 shows the 48th channel of the CW laser array connected to its MDRZ subsystem. The internal design components that make up the MDRZ subsystem is shown on the right.

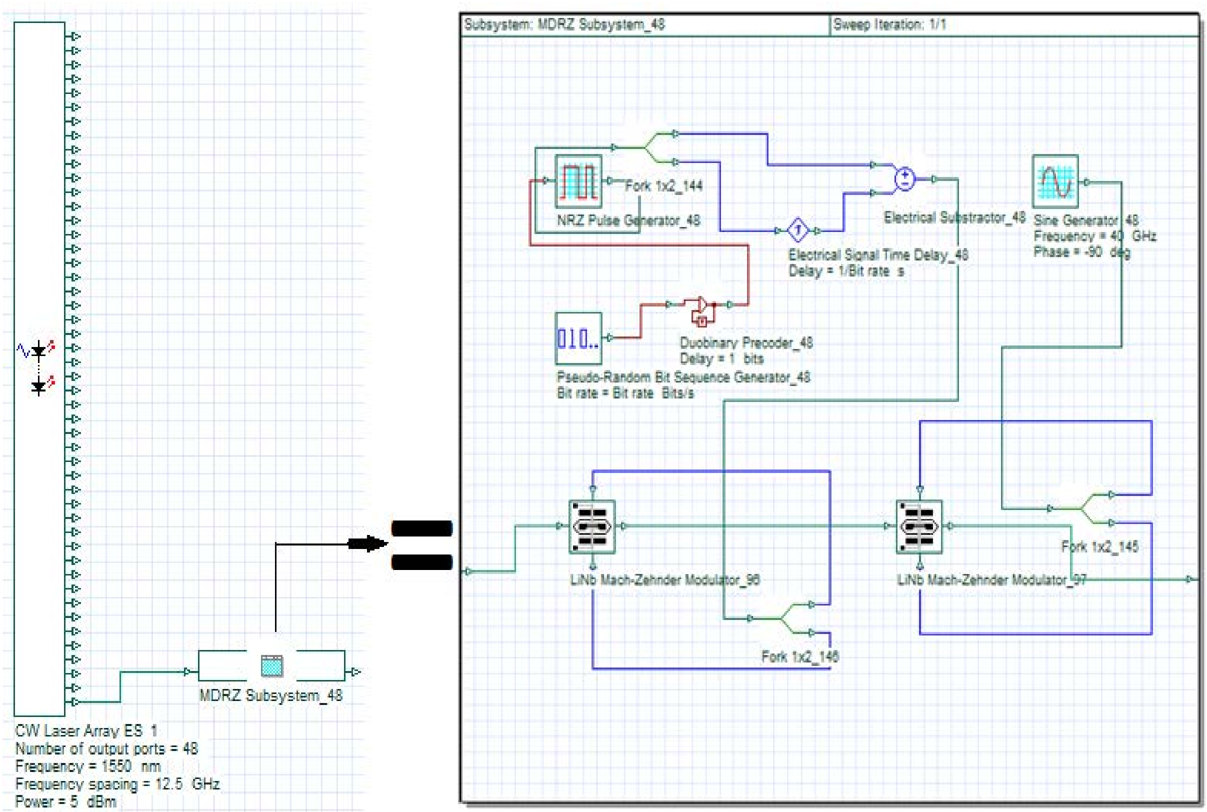

Figure 2.5: 48 port CW Laser Array and Design components of MDRZ modulation subsystem

2.6.2.1 Advanced Line coding Modulation format: MDRZ

The selection of the most optimum signal format for a transmission system is of great importance to maintain a low channel crosstalk penalty. This is because the modulation format used, bandwidth of the specified format and the channel spacing are closely interrelated. An advanced modulation formatting technique is used to enhance bandwidth utilisation of the DWDM system while sustaining a high quality of service (QoS) [38]. The desire to achieve an acceptable system performance for narrow channel spacings (< 25 GHz) for the optical modulation bandwidths with transmission rates (≥ 25 Gb/s) leads to the choice of using the modified duobinary return to zero (MDRZ), which is an advanced modulation format that implements forward error correction (FEC) [38]. FEC code is a system of adding redundant data (parity data) to an information signal, such that it can be recovered by a receiver even when a number of errors (up to the capability of the code being used) are introduced, either during the process of transmission, or on reception [39].

MDRZ effectively suppresses the discrete frequency tones of RZ signal spectrum and provides the advantage of a smaller timing jitter and amplitude distortion. Moreover, when compared to NRZ and RZ, MDRZ signals provides smooth operation even at relatively higher average channel powers. MDRZ format has a much narrower optical bandwidth over the NRZ and RZ formats, which leads to a greater chromatic dispersion tolerance and higher fiber non-linearity tolerance. It thus should be able to achieve an acceptable signal transmission over longer distances. In this format, the phases of two groups of "ones" that wrap an isolated "zero" are flipped, leading to a reduced generation of ghost pulses caused by intra-channel four-wave mixing (FWM) [38].

In order to produce the MDRZ modulation format, it requires the use of two optical Lithium Niobate Mach-Zehnder modulators (Linb MZM); one generated NRZ duo-binary signal and the other carved the NRZ data to a RZ by means of an electrical signal [38]. The MZM produces an intensity modulating signal that uses a simple drive circuit for the modulating voltage [40]. The MZM structure consists of an input optical branch, which could split the incoming light into two arms followed by an output optical branch [40].

The designed diagram of the MDRZ subsystem is shown in Figure 2.5. Each channel of the CW laser array is connected to the input of the first Linb MZM within each MDRZ Subsystem. The first step to create the MDRZ subsystem is to generate the NRZ duobinary signal, and this is achieved by combining a pseudo random bit sequence generator to a duobinary precoder, the NRZ generator and an electrical time delay-and subtractor circuit. The pseudo random bit sequence generator used in this dissertation has a bit rate of 25 Gb/s and is connected to a duobinary precoder with a delay of 1 bit. The precoder avoids recursive decoding in the receiver, error propagation and reduces hardware complexity. The precoder is composed of an exclusive-or gate with a 1-bit delayed feedback path. The output of the NRZ duobinary signal block is split and fed into the two independent optical arms of the first Linb MZM, which subsequently is recombined by the output optical branch to feed the input port of the second Linb MZM. In the second Linb MZM, an electrical signal is split and fed to both optical arms to control the degree of interference at the output optical branch and therefore controls the output intensity. The second MZM is driven by a sinusoidal electrical signal with 40 GHz frequency and phase of −90°. In the MDRZ, the phase between 0 and π for the "1" bits are alternated and the phase of all the "0" bits are kept constant, which introduces a 180° phase variation between all the consecutive "1s". This leads to the suppression of the duobinary carrier signal. The optical power and phase of the modulator output are determined in response to the modulating voltage waveforms. The modulator's transfer function relates the effective drive voltage to the applied drive voltage [38]. The output of the 2nd Linb MZM is then connected to the WDM MUX.

2.6.3 WDM Multiplexer (MUX) ES and WDM De-multiplexer (DEMUX) ES

The MUX takes transmitted optical wavelengths from multiple fibers of the WDM transmitter and converges them into one beam that is sent over the optical link. At the receiving end of the system, the DEMUX separates the received beam from the optical link into its wavelength components and couples them to individual fibers, which are then sent to its own photodetector. Demultiplexing must be done before the light is detected, because photodetectors are inherently broadband devices that could not selectively detect a single wavelength [3]. The WDM MUX ES and WDM DEMUX ES components used in this dissertation respectively multiplexes and demultiplexes a user-defined number of WDM signal channels [29]. The centre frequencies of the internal filters for both the MUX and DEMUX are equally spaced (ES). The WDM MUX ES and WDM DEMUX ES are both equivalent to the conventional WDM MUX and WDM DEMUX components respectively [29]. However, the WDM MUX ES and WDM DEMUX ES are easier to set up for WDM systems, since it only requires the filter centre frequency and the spacing. The most important parameters that could be set for the MUX and DEMUX is the centre frequency of the first filter (1550nm), frequency spacing between adjacent filters (either 100 GHz, 50 GHz, 25 GHz, 12.5 GHz, or 6.25 GHz), 3 dB filter bandwidth (which in this case refers to a range of values depending on the frequency spacing used), insertion loss of the DEMUX (5dB), and the internal optical filter type (which in this case is either a Bessel or rectangular filter).

2.6.3.1 Bessel Filter

The Bessel filter used in the MUX, DEMUX and photodetector is a type of low pass linear filter that provides a maximally flat phase response and almost constant propagation group delay across the entire pass band of the frequency spectrum. This preserves the wave shape of the transmitted filtered signal in the pass band. However, it offers a slower transition from pass-band to stop-band than any other forms of filters of the same order [11]. All harmonics outside the pass band are either eliminated or reduced in power level, which is dependent on the order of the Bessel transfer function. Bessel filter has a Bessel frequency transfer function of $H(N)$, which is given by [30] and is shown in (2.5):

$$H(N) = \alpha . \left(\frac{\left(\frac{(2N)!}{(2^n . N!)} \right)}{B_N} \right) \quad (2.5)$$

where α is the insertion loss parameter, *N* is the order parameter of the filter, and B_N is an Nth-order Bessel polynomial expression is shown in (2.6) with the following form:

$$B_N = \sum_{k=0}^{N} \left(\left(\frac{(2N-k)!}{\left(2^{(N-k)}. k!. ((N-k)!)\right)} \right) . \left(j. \left(2. \frac{(f - f_c). \left(\sqrt{((2N-1). ln2)} \right)}{B} \right) \right)^k \right) \quad (2.6)$$

where f_c is the filter centre cut-off frequency parameter defined by the -3dB point, f is the frequency of the signal being filtered and B represents the bandwidth parameter [30].

2.6.3.2 Rectangular Filter

It is a low pass optical filter with a linear phase response; it is able to remove all frequencies above a given bandwidth and leaves the low frequencies alone. This property enables the filter to eliminate unwanted frequency harmonics above a given cut off frequency, without affecting lower frequencies. The real time filters of the Optisystem platform can only approximate an ideal rectangular filter since it has an infinite delay and is non-causal [29], which means that the output at any time interval is dependent on past, present and anticipated values of the input from the future [41]. The transfer function $H(f)$ is given by [30]:

$$H(f) = \begin{Bmatrix} \alpha, & f_c - \frac{B}{2} < f < f_c + \frac{B}{2} \\ d, & otherwise \end{Bmatrix} \quad (2.7)$$

where α is the parameter Insertion loss, d is the parameter Depth, f_c is the filter center frequency defined by the parameter Frequency, B is the parameter Bandwidth, and f is the frequency.

2.6.4 Optical Link

The optical link consists of three components:

- The fiber optic transmission medium component – transports the composite beam of light from the MUX to the DEMUX in a point-to-point link.
- The optical amplification component – amplifies the gain of the composite light signal.
- The dispersion compensation technique – reduces the effects of linear and non-linear losses.

The main components and theoretical design method of the fiber optic link is discussed in the following sections.

2.6.4.1 Fiber optic transmission medium

There are two type of fibers namely, multi-mode fiber (MMF) and single mode fiber (SMF). MMF has a large core diameter either 50 microns or 62.5 microns and operates at wavelengths of either 850nm or 1300nm [9]. The large core size of MMF makes them susceptible to modal dispersion, has a relatively high attenuation and a low bandwidth, which limits its transmission of light to only short distances. SMF has a very small core size of 9 microns and operates at wavelengths of 1310nm and 1550nm [9]. The small core size of SMF limits the transmission of light to only one mode of propagation, which eliminates modal dispersion and increases the transmission capabilities for long haul communication [9]. The multiplexed optical signal in the DWDM system is launched over SMF due to its higher performance with respect to bandwidth and attenuation [9]. DWDM systems in this dissertation operates in the C-band (1530nm to 1565nm) since it has the least attenuation and has the highest availability of optical amplifiers operating at the centre wavelength of 1550nm. The International Telecommunication Union (ITU) distinguishes SMF into three main categories, namely the G.652 for conventional SMF, G.653 for dispersion shifted fiber (DSF) and the G.655 for non-zero dispersion shifted fiber (NZDSF) [22]. However, within the C band, conventional SMF (ITU G.652 compliant [44]) undergo high dispersion, which severely limits its transmission distance. Both DSF and NZDSF minimises the effects of dispersion and operates at the 1550nm wavelength. Even though DSF (ITU G.653 compliant [45]) had a zero-dispersion point at the 1550nm region, there are unwanted non linearities (such as FWM) in this fiber near the zero-dispersion point for which there is no effective compensation. For this reason, the ITU G.655D compliant [10], NZDSF is the preferred choice since it has a low positive chromatic dispersion

(CD) property (~4 ps/nm.km at 1550 nm) that is sensibly selected to be small enough to enable high-speed transmission over long distances, and at the same time be large enough to suppress FWM. In addition, to further suppress the unwanted effects of dispersion over the link, a dispersion compensating fiber (DCF) is used. Dispersion compensating fiber (DCF) has a negative dispersion property and a negative dispersion slope that compensates for the positive dispersion and slope of installed fibers. The length of the DCF is designed in such a way that it cancels out the dispersion gathered in the SMF [3]. A combination of the NZDSF and a DCF is used as the preferred choice to compensate losses that arise due to CD and FWM for the fiber optic transmission medium.

2.6.4.2 Optical Amplification

Optical amplifiers (OAs) magnify and regenerate light signals directly without any need for an optical to electrical conversion. In doing so, OAs lessen the effects of dispersion and attenuation for longer transmission distances, which makes it essential for any long-haul optical network. There are currently three types of OAs available, namely semiconductor optical amplifiers (SOAs), erbium doped fiber amplifiers (EDFAs), and raman optical amplifiers (ROA). The focus of this dissertation is on the EDFA, since it is the best known, cost-effective and most frequently used optical amplifier suited for DWDM systems. This is due to the operational frequency of the erbium ion (used in EDFAs) being within the C band, which is a low loss optical window of silica based fiber [49]. EDFA uses an internal fiber (doped with erbium ions) as a gain medium to boost an optical signal. The input signal is multiplexed with a pump laser from the EDFA before it is sent into the doped fibers. The interaction of the multiplexed signal with the doped erbium ions in the fiber amplifies the signal. Subsequently, this process releases natural emissions within the EDFA that adds noise to the signal, which determines the noise figure [3]. The EDFA used in this dissertation has a gain of 21 dB and a noise figure of 6 dB.

There are two types of compensation techniques used in this dissertation, namely the post compensation and the post symmetric compensation. They both make use of EDFAs to compensate the losses of the fiber. For the post compensation technique, a single EDFA is used as a pre-amplifier to boost the signal pulses at the receiver's side, as can be seen in Figure 3.3. For the post symmetric compensation technique shown in Figure 3.4, three EDFAs are placed strategically in the optical link. The first is placed before the NZDSF, this acts as a post-amplifier, which boosts the signal at the transmitter's side. The second is placed in between the NZDSF and DCF, which acts as an in-line amplifier that recovers the signal before it is degraded significantly. And finally, the third amplifier is placed after DCF, which acts as pre-amplifier that performs the same function as the amplifier used in the post compensation technique [11].

2.6.5 Optical Receiver

The optical receiver component used in this dissertation consists of a built-in selector to choose between a P-N junction type (PIN) photodetector and an avalanche photodetector (APD), one Bessel filter and a 3R regenerator. This can be seen in Figure 2.6.

Photodetectors receive demultiplexed optical signals and interpret the information signals found within the received signals [5]. They can do this function because they are optoelectronic devices that convert the received optical signal into an electrical signal for the purpose of decoding the optical signal to the actual information signal [5]. For such applications, photo-detectors have high sensitivity, high responsivity and minimum noise [5]. There are two types of photodetectors that can be used in Optisystem namely, PIN type and the APD photodetector [29]. The fundamental concept of a PIN photodiode is built on the P-N junction which has the (p) type material connected to a lightly doped (n) type material with a wide depletion region; this allows longer wavelengths of light to pass through. This depletion region is called the intrinsic region (i) and subsequently it makes a low resistance contact with less noise on a signal passing through. It has a heavily doped (n+) layer near the intrinsic region; and thus, forms the P-I-N assembly [20]. However, an avalanche photodetector (APD) requires a higher operating voltage and this is due to its output being non-linear. This in turn causes APDs to produce a higher level of noise than a PIN diode [21].

The 3R regenerator component is used to recover the binary data from the electrical signal, regenerate the original bit sequence and modulate the electrical signal to be used for bit error rate (BER) analysis. It performs the 3R functions such as re-shaping, re-timing and re-amplification of the electrical signal [29].

The component properties of the optical receiver used in this dissertation allows the user to select the internal component parameters such as the -3dB cut-off frequency of the filter (set as 0.75 x bit rate), order of the low pass Bessel filter function (set as = 4), insertion loss of the filter (set as 3dB), user-defined centre frequency of the internal filter (set as 1550nm), reference bit rate to use for the decision instant calculation (which in this dissertation is 25 Gb/s) and the receiver sensitivity parameter (set as -18 dBm) [29]. The received signal of the optical receiver is analysed using eye diagram analysers.

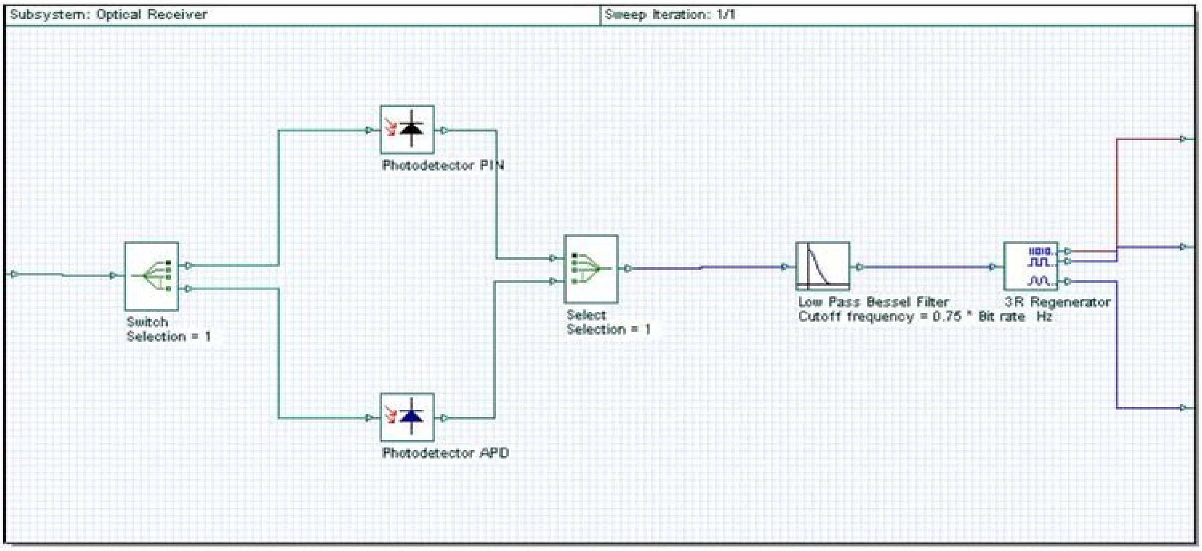

Figure 2.6: Internal setup of Optical Receiver

2.7 Theoretical Concepts for the Design of the Optical Transmission Link

The theoretical design method of the optical transmission link involves obtaining the length of dispersion compensation fiber (DCF), the initial span loss before amplification, the minimum launch power of transmitter, power budget, power margin, the total span loss after amplification, and the received signal power. The theoretical formulas for each of the above parameters is summarised below with relevance to a 100 km transmission distance. The same parameters for the optical link used in [1] and is used in the design of the optical link used for the 48 channel DWDM networks.

When designing DWDM networks for long-haul communications, a DCF needs to be used. A DCF with a negative dispersion component must be added to a DWDM system for the purpose of compensating the positive dispersion component of the non-zero dispersion shifted fiber (NZDSF), which subsequently decreases the chromatic dispersion (CD) of the system. The dispersion coefficient of the DCF and NZDSF is assumed as -147 ps/nm.km and 4 ps/nm.km, respectively [1].

The length of the DCF is calculated using the expression in (2.8):

$$(D_{NZDSF})(L_{NZDSF}) = -(D_{DCF})(L_{DCF}) \tag{2.8}$$

where L_{NZDSF}, D_{NZDSF} L_{DCF} and D_{DCF} are the respective lengths and dispersion coefficients of corresponding fibers.

The initial span loss (P_{Si}) for both NRZ and RZ before amplification is calculated by adding the various linear and nonlinear losses, which is shown by the following expression in [1] :

$$P_{Si} = \alpha_{NZDSF} + \alpha_{DCF} + \alpha_C \tag{2.9}$$

where α_{DSF}, α_{DCF} and α_C are the losses of the NZDSF, DCF, connectors, and safe margin (SM), respectively. To compensate for unpredictable losses due to non-linear effects and temperature fluctuations when employing the DCF, a safe margin of 6 dB is used.

If P_T is the power of the WDM transmitter and in Optisystem, the NRZ WDM transmitter has an internal optical attenuation ($\alpha_{T\ NRZ}$) and the RZ WDM system has an optical attenuation ($\alpha_{T\ RZ}$); then the minimum launch power (P_{TMIN}) that is transmitted into the WDM MUX is the difference between transmitter power (P_T) and its internal optical attenuation (either $\alpha_{T\ NRZ}$ or $\alpha_{T\ RZ}$).

To ensure that the 100km fiber span has sufficient power for correct operation, the span's power budget (P_B) is calculated. This is the maximum amount of power that can be transmitted over a span. From a design perspective, the power budget (P_B) is the difference between the minimum transmitter launch power (P_{TMIN}) and the minimum receiver sensitivity (P_{RMIN}) [1]. The receiver's sensitivity level (P_{RMIN}) indicates the minimum signal power required by the photodetector to detect the signal with the least errors. Based on the parameters of the photodetector, the receiver sensitivity is -18 dBm, therefore, the signal power received at the detector for the NRZ and RZ should be above the receiver sensitivity to prevent receiver saturation and ensure system viability [1].

The next calculation involves the power margin (P_M), which represents the amount of power available to operate the receiver or it can be referred to as the maximum allowable power loss over the span. P_M is the difference between power budget (P_B) and the total span losses (Psi). The P_M has to be greater than zero for the power budget to be adequate to operate the receiver without further amplification [1].

Once amplifiers are added to the span, the total span loss after amplification ($P_{S\,EDFA}$) is calculated by obtaining the difference between the total gain after amplification ($N.G_{EDFA}$) and the initial span loss (P_{Si}). The gain of the amplifier is G_{EDFA} and the number of amplifiers used in the network is Na.

To calculate the received signal power (P_R) at the photodetector after amplification, the following expression in [1] is used:

$$P_R(dBm) = P_{TMIN} - Psi + (Na\,.G_{EDFA}) - \alpha_{MUX} - \alpha_{DEMUX} \qquad (2.10)$$

where P_{TMIN} , Psi , α_{MUX}, α_{DEMUX}, Na and G_{EDFA} are minimum transmitter launch power, total initial span loss, losses of multiplexer, demultiplexer, number of EDFAs used and gain of EDFA, respectively. This equation assumes that all amplifiers has the same gain. The set parameters values listed in Table 2 of [1] are used to find the power received at the photodetector for the 100km transmission link.

2.8 Measuring system performance

The performance of the signal is evaluated using three measurements, namely the optical signal to noise ratio (OSNR), Quality (Q) factor and Bit error rate (BER).

2.8.1 Optical Signal to Noise Ratio (OSNR)

$OSNR$ measures the signal quality of an optical transmission system, which is the digital equivalent to the analogue signal to noise ratio (SNR) of an electrical transmission system. The addition of components such as an amplifier in a long-haul transmission system causes performance degradation in the OSNR. The final OSNR at the receiver is used from [1] and is shown below:

$$OSNR\ (dB) = P_{TMIN\ dB} - NF_{dB} - P_{Si} - 10\log[h.v] - 10\log[\nabla f] - 10\log[Na] \qquad (2.11)$$

where P_{TMIN} is transmitter launch power, NF is noise figure, P_{Si} is total loss for single span (100km), $h\ (= 6.6260 \times 10^{-34}\ J/s)$ is planks constant, $v\ (= 193.4\,Thz)$ is optical signal frequency, $\nabla f\ (= 12.5\ Ghz)$ is optical bandwidth of 0.1nm measuring NF and Na is number of amplifier stages.

OSNR can also be calculated as the difference between the Signal power (Ps) and the noise power (Pn) received at the optical receiver as shown in (2.12), which is essentially found at the output of the demultiplexer.

$$OSNR\ (dB) = 10\log\left({}^{Ps}/_{Pn}\right) = Signal\ Power(dB) - Noise\ Power(dB) \quad (2.12)$$

2.8.2 Quality (Q) factor

The Quality of the signal (QoS) in the eye pattern of a digital signal is represented by the Quality (Q) factor. Q-factor is the ratio of the signal difference between the mean value of the signals for 1 level state and 0 level state to the sum of the noise value at those signal levels. The Q factor expression shown below is taken from [2]:

$$Q = \frac{\mu 1 - \mu 0}{|\sigma 1 + \sigma 0|} \quad (2.13)$$

where $\mu 0$, $\mu 1$, $\sigma 0$ and $\sigma 1$ denotes respectively, the average signal values for the 1 and 0 levels, and the standard deviations of the sampled noise values for signal at 1 and 0 levels in the eye diagram [10]. The wider the eye opening (eye height), the greater is the difference between signal to noise values of at the 1 level and 0 level states, which results in better BER performance.

2.8.3 Bit Error Rate (BER)

Bit error rate (BER) is the percentage that shows the number of error bits received in relation to the total number of bits received. Normally, the total number of bits transmitted is larger than the BER of the information signal. The BER may be improved by optimising the signal strength. This can be done by applying compensation techniques or line coding modulation that is able to enhance the signal, or by choosing filter and other active parameters that is able to minimise bit errors [39].

Based on the Gaussian approximation for the noise distribution in the received signal, the relationship between Q-factor and BER for this model is given in [10] and [2]:

$$BER = \frac{1}{2}\, erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{1}{Q\sqrt{2\pi}}\, e^{-\frac{Q^2}{2}} \quad (2.14)$$

where BER is the bit error rate, Q is the linear quality factor and '$erfc$' is the complementary error function, which is taken from [2] and given by the expression:

$$erfc\ (x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2}\, dt \ \approx \ \frac{e^{-x^2}}{x\sqrt{\pi}} \tag{2.15}$$

The variable x of (2.15) will be replaced by $\frac{Q}{\sqrt{2}}$ when substituting (2.15) in (2.14).

The Forward Error Communication (FEC) threshold sets the minimum acceptable BER value for an optical link to be > 10^{-9} . This provides a minimum Q factor of 6 for an error free optical communication. This can be obtained in terms of Q-factor using the following expressions in [38]:

$$Q\ (dB) = 20.\log(2^{\frac{1}{2}}.erfc^{-1}(2.BER)) \tag{2.16}$$

And if Q in linear format is known then Q (dB) can be calculated using (2.17) :

$$Q\ (dB) = 20.\log\ (Q_{linear}) \tag{2.17}$$

So, throughout this paper Q-factor of 6 and BER of 10^{-9} are considered as the reference criteria and the performances of various parameters are evaluated using these two criteria.

2.8.4 Overall Signal Performance and Bandwidth Efficiency

The total average Q factor ($Avg.Q$) of a DWDM System for a total number of N channels is equal to a ratio between the sum of the Q factors for the number of recognisable channels ($\sum_{k=1}^{N}(Q_k)$) in the system (where Q > 0 and BER < 1) and the total number of transmitted channels (N) in the system. This gives an indication of the overall signal performance of that system, which is shown in (2.18):

$$Avg.Q(N)_{DWDM\ System} = \frac{\sum_{k=1}^{N}(Q_k)}{N} \tag{2.18}$$

The Bandwidth or spectral efficiency shows a percentage of the total Bandwidth that is utilised in the designed spectral frequency band, which has recognisable signals at the receiver (where Q > 0 and BER < 1). Each frequency in the spectral band is sent over its own channel. Therefore, Bandwidth efficiency is a percentage of the ratio between the total number of channels that can produce a recognisable signal at the optical receiver and the total number of transmitted channels (N) in that DWDM system. This is shown in (2.19):

$$BW\ Efficiency\ (\%) = \frac{Total\ No.of\ recognisable\ channels\ at\ the\ receiver}{N}\ X\ 100 \qquad (2.19)$$

2.9 Summary

In this chapter, the literature reviews substantiated DWDM as the best fiber optic technology to meet the current bandwidth requirements. The performance limitations of DWDM was explored and it was established that CD and FWM were the most critical limiting factors that deteriorates a DWDM signal. The various design components of the DWDM system, their properties, functionalities, limitations and benefits were discussed with the focus being on the optimisation of a 48 channel DWDM system. The theoretical design method of designing and measuring the performance of the optical transmission link was also enumerated.

CHAPTER 3

DESIGN OF A 48 X 25Gb/s DWDM SYSTEM

3.1 Introduction

In this chapter, the design methodology and parameters of the 48-channel DWDM system are discussed using references to the system components and theoretical concepts explained in Chapter 2. The design is performed using the Optisystem v7.0 simulation platform. The set and varied parameters used to simulate, model and optimise the existing 48 channel DWDM network is enumerated.

The design process of the DWDM network systems in this dissertation mainly consists of three main design blocks, namely the transmitter block, the optical transmission link and the receiver block. The set parameters of all components in each block are calculated using the theoretical concepts of the literature review that was discussed in Chapter 2 and are exhibited in this chapter.

The varied parameters that are chosen to create a comparative model between the compensation techniques and modulation types used in the design is also enumerated in this chapter. These are used to optimise the signal performance of the 48 channel DWDM network for various narrow channel spacings. The block diagrams of the designed network models, compensation techniques and modulation types are also illustrated in this chapter.

3.2 Design Methodology

The numerous 48 channel DWDM networks that are designed in this dissertation have a bit rate of 25 Gb/s for a transmission distance of 100 km and centre wavelength of 1550 nm. The performance analysis of these networks is done by varying the channel spacing from 100 GHZ, 50 GHz, 25 GHz, 12.5 GHz and 6.25 GHz. The 1550 nm wavelength is a low attenuation window in the C band and this is chosen according to the ITU standard DWDM wavelength grid since it has a huge bandwidth and the operational wavelength of many optical components are in this band [26].

Furthermore, various design parameters such as the modulation type, extinction ratio of the transmitter, filter type and bandwidth of the multiplexer, filter type and bandwidth of the demultiplexer and the dispersion compensation techniques of the optical link are varied and compared to discover the system with the most optimal signal performance. The system performance is based on the results of Q factor, minimum BER and eye height of the received signal, which is represented by eye diagrams. The Optisystem v7.0 is used as the design simulation platform to analyse the 48-channel DWDM networks as explained in section 2.5 of chapter 2. Eye diagram analysers are connected to each optical receiver to evaluate the system performance. The impact of the varied design parameters on the effects of non-linearities on the system performance of the 48 channel DWDM network at various channel spacings is also observed and evaluated. The study then determines the best design parameters for the most optimised DWDM network with the highest bandwidth efficiency across all 48 channels for each channel spacing.

Figure 3.1 shows the block diagram of the 48 channel DWDM network. This shows the different components that make up the network, the design parameters used and the two types of dispersion compensation techniques used for the optical link. Figure 3.2 shows an example of the 48 Channel DWDM Network Design using the NRZ modulation scheme for a 100 GHz channel spacing. The same design setup is used for the RZ modulation scheme and for all other channel spacings of 50 GHz, 25 GHz, 12.5 GHz and 6.25 GHz.

The design of the two types of dispersion compensation techniques of the optical link, namely the Post Compensated Optical Link Design with 1 EDFA and the Post Symmetric Optical Link Design with 3 EDFAs were shown in Figure 3.3 and Figure 3.4 respectively. The design of both dispersion compensation techniques uses the post compensation design technique, that has the NZDSF placed before the DCF, as the foundation. The post compensated optical link with one EDFA (placed after the DCF) is shown in Figure 3.3. The post symmetric compensated optical link with three EDFAs shown in Figure 3.4 is designed to have a total of three symmetrically distributed EDFA optical amplifiers placed before and after the NZDSF and the DCF. The post symmetric compensation technique is used to further compensate for the signal degradation that occurs due to non-linear effects when decreasing channel spacings.

In order to improve the system performance such that the least amount of BER is achieved for each of the channel spacings for the NRZ and RZ modulation schemes, the MUX and DEMUX bandwidths are varied. The methodology used to vary the bandwidth of the MUX and DEMUX is by comparing the system performance of the initially used bandwidth of MUX and DEMUX of 80 GHz with a varied bandwidth parameter that is half of the used channel spacing until an acceptable system performance is achieved. If signal quality is not improved by varying the MUX and DEMUX bandwidths, then the extinction ratio is decreased from 30 dB to 5 dB and the Bessel filter in the MUX and DEMUX is replaced with a rectangular filter.

If the signal quality could not be improved with the NRZ and RZ modulation schemes, further improvement of the signal quality is done using an advanced MDRZ modulation scheme. Figure 3.5 shows the design of a 48 channel DWDM network design using the advanced MDRZ modulation scheme. In this network, a 48 output CW laser array is connected to 48 MDRZ subsystems. The MDRZ subsystem allows the use of the MDRZ modulation method. Figure 2.5 shows the internal design setup of the MDRZ subsystem. Each of these MDRZ subsystems are connected to a 48 input WDM MUX with equally spaced channels. See Figure 3.5. The single output port of the MUX is then connected to a post symmetric optical link with 3 EDFAs. The single output of the optical link is connected to the single input of a WDM DEMUX that has 48 output ports. A 2nd order Bessel filter is used for both the MUX and DEMUX.

3.3 Design Parameters

The design parameters are divided into two groups, namely set parameters and varied parameter. Set design parameters are the common constant parameters used for all configurations of the 48 channel DWDM network. The varied design parameters are the various parameter configurations that are changed to optimise signal performance and bandwidth efficiency for all 48 channels of the designed DWDM networks.

3.3.1 Set Design Parameters

The main steps of designing this network, consists of a transmitter block, optical transmission link, and receiver block, respectively.

3.3.1.1 Design of the Transmitter block

The transmitter block consists of the WDM transmitter, which has the modulation type used by the transmitter and the WDM MUX.

For the design of NRZ and RZ DWDM networks, a 48-output port WDM transmitter with a bit rate of 25 Gb/s and a transmitting power of 5 dBm is chosen. The transmitter type chosen for the Optisystem platform is an externally Modulated Laser (EML). C-band wavelengths with a centre frequency of 1550nm are assigned to the lasers to modulate the data. The WDM transmitter has a default extinction ratio of 30 dB and an internal modulation selector that allows the option to switch between NRZ and RZ modulation schemes. The WDM transmitter of NRZ and RZ are connected to a 48 input WDM MUX with equally spaced channels.

For the WDM transmitter, the following set values are chosen:

- Power (P_T = 5 dB), internal attenuation for NRZ ($\alpha_{T\ NRZ}$ = 4.27 dB) and internal attenuation for RZ ($\alpha_{T\ RZ}$ = 9.49 dB).
- Minimum launch power, (P_{TMIN}) for NRZ = 0.73 dB and (P_{TMIN}) for RZ = - 4.49 dB

For the MDRZ DWDM networks, a 48 output CW laser array is connected to 48 MDRZ subsystems. The MDRZ subsystem allows the use of the MDRZ modulation method. Each channel of the CW laser array is connected to its own MDRZ Subsystem. The internal design setup and theoretical explanation of the MDRZ system is shown in section 2.5.2.1 of chapter 2. The output of the MDRZ subsystem produces a bit rate of 25 Gb/s and a modulated MDRZ signal with a total insertion loss of 10 dB (5dB insertion loss for each MZM). Refer to Figure 2.5 to see the internal design setup of the MDRZ subsystem. Each of the outputs from the MDRZ subsystem is connected to its own input port on the 48 port WDM MUX.

The 48-channel multiplexer has an insertion loss of 5 dB and has an internal selector to change the filter type of the MUX. As a default, it uses a 2nd order Bessel filter but it has the option to change to a rectangular filter. The multiplexer combines the 48 channels into a single output port which is then connected to an optical link.

Each channel is launched into the optical fiber with a relatively low power (P_{TMIN}) to minimise the nonlinear effects as discussed in section 2.6 of chapter 2.

3.3.1.2 Design of the Optical Transmission Link

The communications link is designed using a non-zero dispersion shifted fiber (NZDSF) as the transmission medium due to its low attenuation, low dispersion coefficient and subsequently its ability to minimise FWM at the operating wavelength of 1550 nm.

The chromatic dispersion coefficient of the NZDSF with 1550nm wavelength has to be in the range between $D_{min}(\lambda)$ $(= 2.8\frac{ps}{nm}/km)$ and $D_{max}(\lambda)$ $(= 6.2\frac{ps}{nm}/km)$ which is calculated using (2.1) from section 2.3.1 of chapter 2. Therefore, a mid-value of 4 ps/nm/km is chosen for the dispersion coefficient of NZDSF. Given that the dispersion coefficient of -147 ps/nm/km is chosen for the DCF, the length of the DCF is calculated using (2.8) from section 2.6 of chapter 2.

The optical link has the following common design components, which can also be seen in Figure 3.1:

- NZDSF length of 100km, attenuation of 0.19 dB/km, dispersion coefficient of 4 ps/nm/km, a PMD coefficient of 0.04 ps/sqrt(km) and an effective area of 72 um^2.
- DCF length of 2.7 km, attenuation of 0.24 dB/km, dispersion coefficient of -147 ps/nm/km, a PMD coefficient of 0.04 ps/ sqrt(km) and an effective area of 27 um^2.
- EDFA with gain of 21 dB and a noise figure of 6 dB
- Connectors with insertion loss of 0.75 dB
- Post compensation technique uses 1 EDFA and 6 connectors
- Post symmetric compensation technique uses 3 EDFAs and 7 connectors
- Initial span loss for both NRZ and RZ before amplification is calculated using (2.9): ($P_{Si} = 24.15\ dB$).
- Span loss after amplification for NRZ and RZ is calculated using the following expression in (3.1):

$$Ps_{EDFA} = (Psi + n\,.\,\alpha_C) - (Na\,.\,G_{EDFA}) \tag{3.1}$$

where P_{si}, n, α_C, Na and G_{EDFA} represents the total initial span loss before amplification, number of extra connectors added after amplification, loss of connectors, number of EDFAs used and gain of EDFA, respectively. For 1 EDFA no extra connectors were added after amplification. However, when 3 EDFAs were added, there is one extra connector added. Therefore, $Ps_{for\ 1\ EDFA} = 3.15\ dB$ and $Ps_{for\ 3\ EDFA} = -38.1\ dB$. Thus, the span loss for 1 EDFA is much greater than the span loss for 3 EDFAs.

3.3.1.3 Design of the Receiver Block

The receiver is composed of two parts: a DEMUX with 48-output channels that has an insertion loss of 5 dB, and 48 photodiodes. For simplicity, 25 optical receivers are used evenly to represent the 48 channel outputs i.e. optical receivers were placed in Channel 1, 2, 4, 6..., and so forth till channel 48 as can be seen in Figure 3.1 and Figure 3.2.

One photodiode is connected for each output channel of the DEMUX. Each Photodiode is connected to its own eye-diagram analysers. The PIN photodiode is chosen as the photodetector, because of its lower cost and minimal sensitivity to the noise level in comparison to avalanche photodiodes (APDs). These types of photodiodes need to be reverse biased to operate; they provide better performances for wide bandwidth and high dynamic range applications. For each channel of the DEMUX, a PIN photodiode with an insertion loss of 3 dB and a dark current of 10 nA is used to change the received signals into their electrical equivalents. An eye-diagram analyser has been used to analyse the detected signals of each channel. The receiver also operates at a centre frequency of 1550nm and has a power sensitivity of -18 dBm.

The received signal power at the photodetector is calculated using (2.10):

- For 1 EDFA: ($P_{R\ for\ NRZ} = -12.42\ dBm$), ($P_{R\ for\ RZ} = -17.64\ dBm$)
- For 3 EDFA: ($P_{R\ for\ NRZ} = 28.83\ dBm$), ($P_{R\ for\ RZ} = 23.61\ dBm$)

Therefore, it is evident that for both 1 EDFA and 3 EDFA networks, the signal could be detected using both NRZ and RZ modulation formats since all power received is greater than the receiver’s power sensitivity. But it could be noticed that the power received for 3 EDFAs is far greater than for 1 EDFA.

3.3.2 Varied design parameters

This section shows all the various combination of parameters used to optimise the 48 channel DWDM network at channel spacing of 100GHz, 50 GHz, 25 GHz, 12.5 GHz, and 6.25 GHz.

3.3.2.1 100 GHz channel spacing

- Modulation Type of either NRZ or RZ for the following MUX/DEMUX Bandwidth Configuration with ER = 30 dB using Bessel Filter:

a) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 80 GHz with 1 EDFA and 3 EDFAs

b) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 50 GHz with 3 EDFAs

c) MUX Bandwidth of 50 GHz and DEMUX Bandwidth of 80 GHz with 3 EDFAs

3.3.2.2 50 GHz channel spacing

- Modulation Type of NRZ and RZ for the following MUX/DEMUX Bandwidth Configuration with ER = 30 dB using Bessel Filter:

  a) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 80 GHz with 1 EDFA and 3 EDFA

  b) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 50 GHz with 3 EDFAs

  c) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 25 GHz with 3 EDFAs

  d) MUX Bandwidth of 50 GHz and DEMUX Bandwidth of 80 GHz with 3 EDFAs

3.3.2.3 25 GHz channel spacing

- Modulation Type of NRZ and RZ for the following MUX/DEMUX Bandwidth Configuration with ER = 30 dB using Bessel Filter:

  a) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 80 GHz with 1 EDFA and 3 EDFAs

  b) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 25 GHz with 3 EDFAs

  c) MUX Bandwidth of 25 GHz and DEMUX Bandwidth of 80 GHz with 3 EDFAs

  d) MUX Bandwidth of 12.5 GHz and DEMUX Bandwidth of 80 GHz with 3 EDFAs

  e) MUX Bandwidth of 25 GHz and DEMUX Bandwidth of 25 GHz with 3 EDFAs

- Modulation Type of MDRZ for the following MUX/DEMUX Bandwidth Configuration, with ER = 5dB using Rectangular Filter:

  f) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 25 GHz with 3 EDFAs

  g) MUX Bandwidth of 25 GHz and DEMUX Bandwidth of 25 GHz with 3 EDFAs

3.3.2.4 12.5 GHz channel spacing

- WDM Transmitter Modulation Type of NRZ and RZ for the following MUX/DEMUX Bandwidth Configuration with ER = 30 dB using Bessel Filter:

a) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 80 GHz with 1 EDFA and 3 EDFAs
b) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 12.5 GHz with 3 EDFAs
c) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 6.25 GHz with 3 EDFAs
d) MUX Bandwidth of 12.5 GHz and DEMUX Bandwidth of 80 GHz with 3 EDFAs
e) MUX Bandwidth of 6.25 GHz and DEMUX Bandwidth of 80 GHz with 3 EDFAs
f) MUX Bandwidth of 3.125 GHz and DEMUX Bandwidth of 80 GHz with 3 EDFAs

- Modulation Type of MDRZ for the following MUX/DEMUX Bandwidth Configuration with ER = 30dB using Bessel Filter:

g) MUX Bandwidth of 3.125 GHz and DEMUX Bandwidth of 80 GHz with 3 EDFAs

3.3.2.5 6.25 GHz channel spacing

- Modulation Type of NRZ and RZ for the following MUX/DEMUX Bandwidth Configuration with ER = 30dB using Bessel Filter:

a) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 80 GHz with 1 EDFA and 3 EDFAs
b) MUX Bandwidth of 80 GHz and DEMUX Bandwidth of 6.25 GHz with 3 EDFAs
c) MUX Bandwidth of 6.25 GHz and DEMUX Bandwidth of 80 GHz with 3 EDFAs
d) MUX Bandwidth of 3.125 GHz and DEMUX Bandwidth of 80 GHz with 3 EDFAs

- Modulation Type of MDRZ for the following MUX/DEMUX Bandwidth Configuration with ER = 30dB using Bessel Filter:

e) MUX Bandwidth of 3.125 GHz and DEMUX Bandwidth of 80 GHz with 3 EDFAs

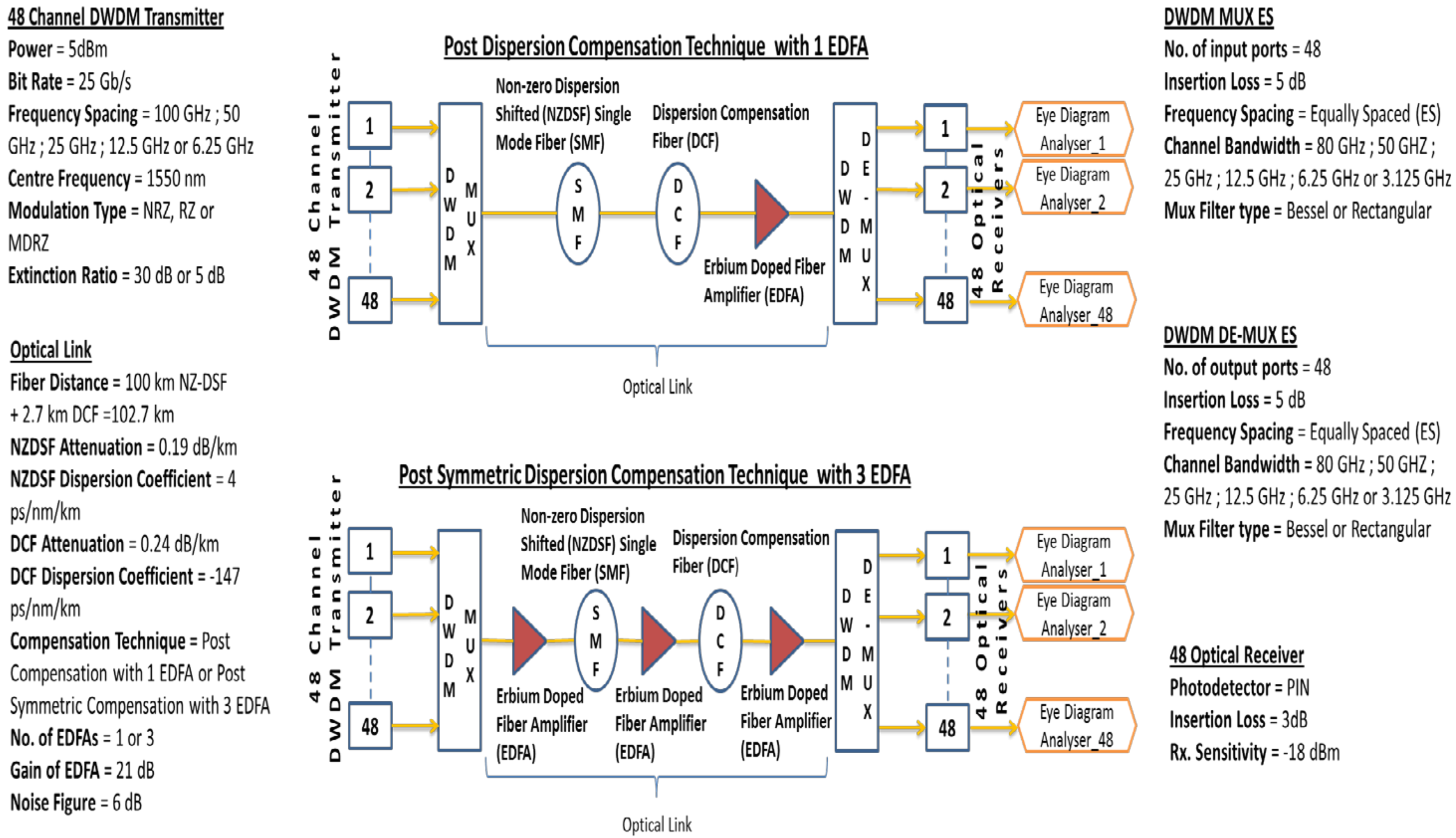

Figure 3.1: Block Diagram Design of 48 Channel DWDM system with bit rate of 25 Gb/s and various other design parameters

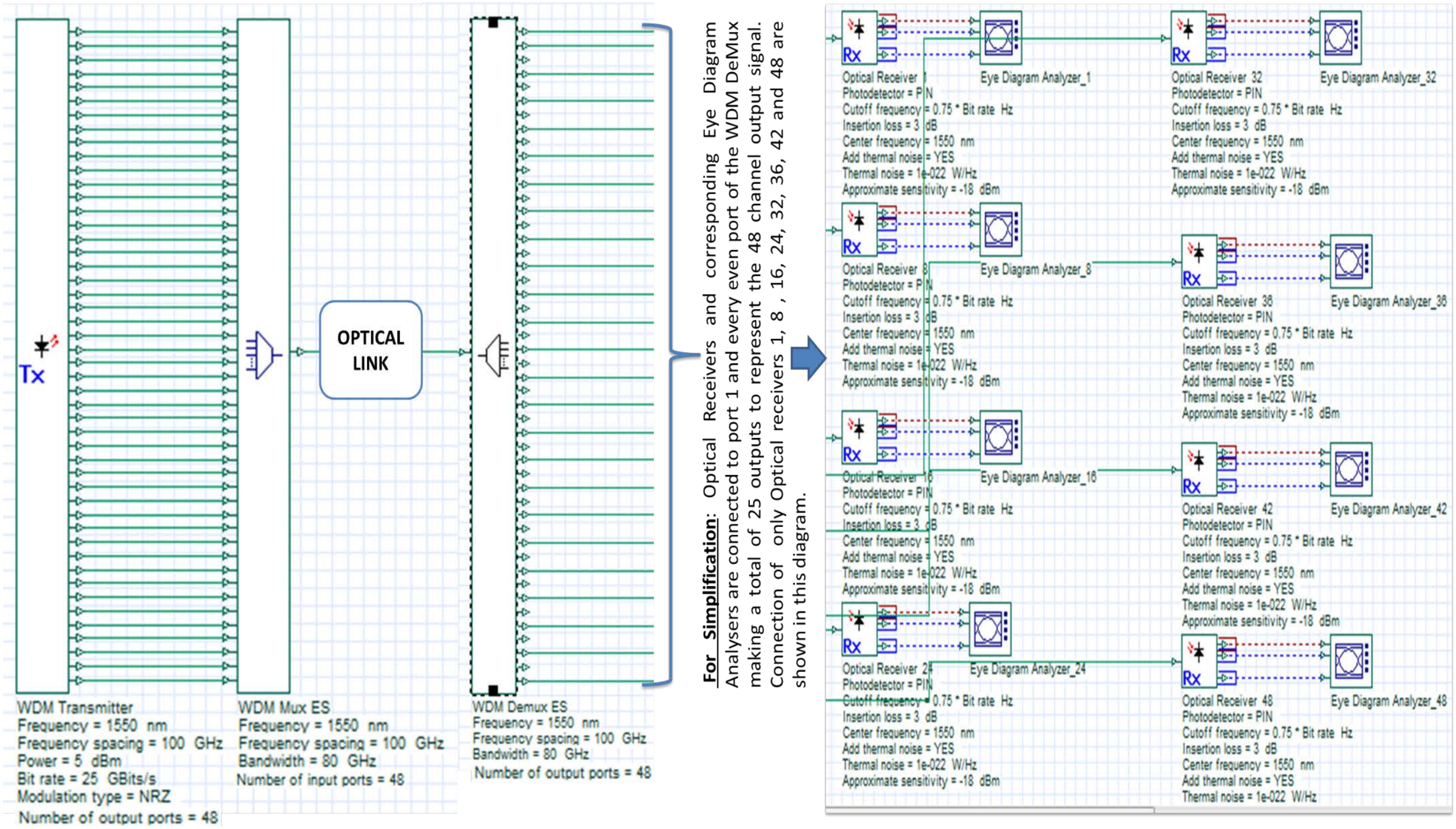

Figure 3.2: 48 Channel DWDM Network Design using either NRZ or RZ Modulation

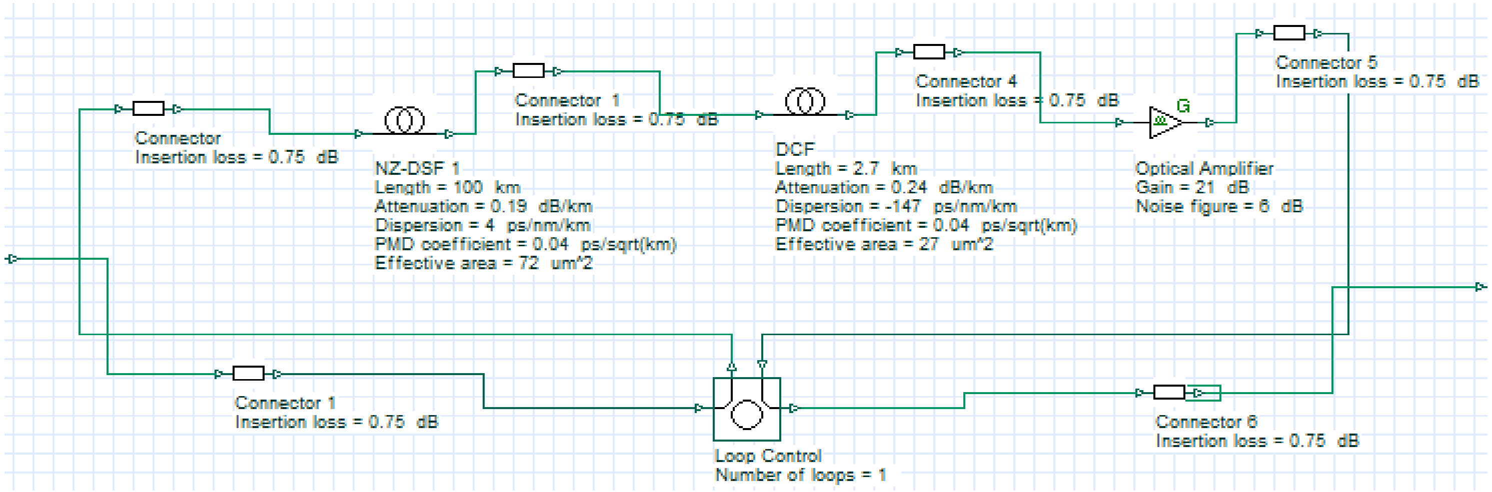

Figure 3.3: Post Compensated Optical Link Design with 1 EDFA

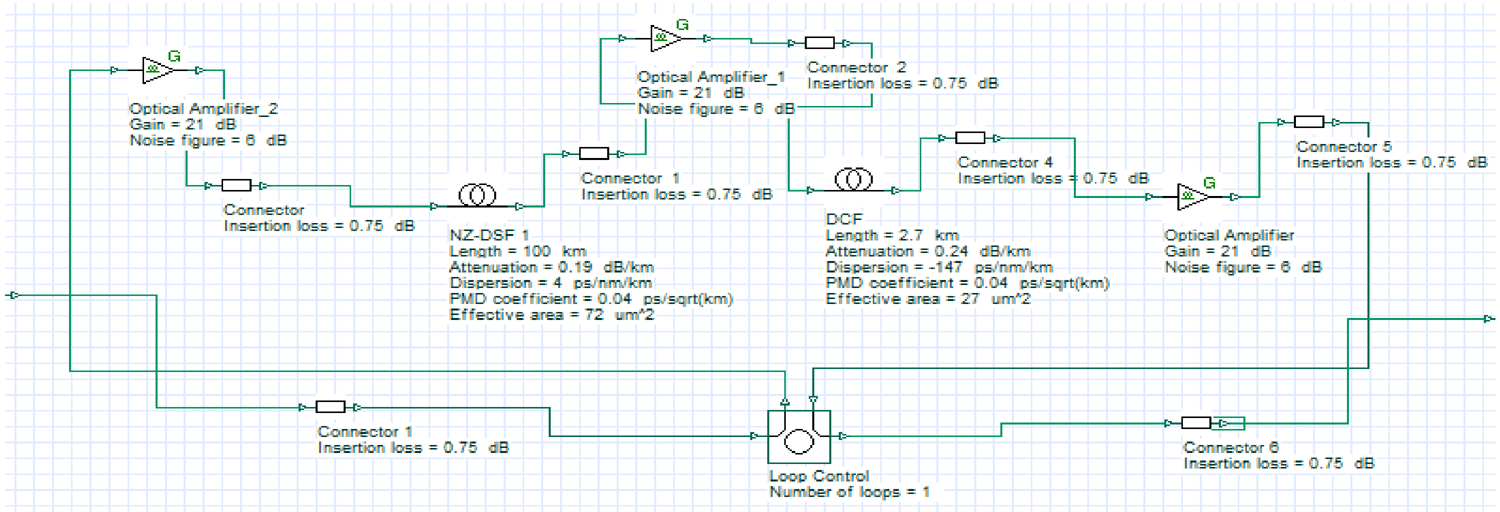

Figure 3.4: Post Symmetric Optical Link Design with 3 EDFAs

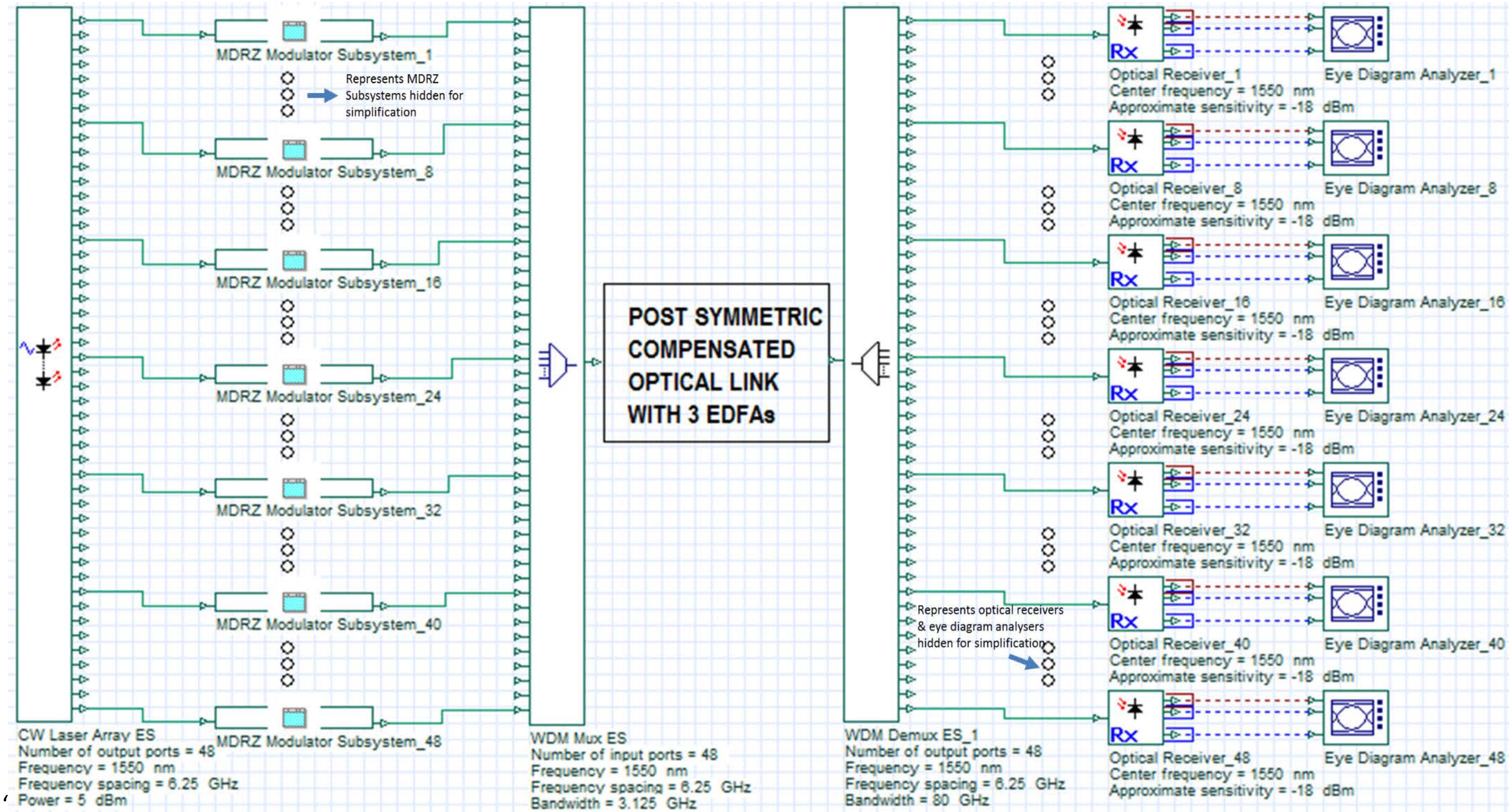

Figure 3.5: 48 Channel DWDM Network Design using MDRZ Modulation

3.4 Summary

In this chapter, the simulation and design process of the 48-channel DWDM system design was shown using the Optisystem simulation platform. The system basically consisted of 48 closely spaced DWDM channels. Each channel was able to transmit at a 25 Gb/s data rate for a 100 km distance at various narrow channel spacings of 100 GHz, 50 GHz, 25 GHz, 12.5 GHz and 6,25 GHz.

The WDM transmitter and WDM MUX used for optimisation were completely matched in frequency. This matched network was used to produce equally spaced channels as opposed to the unmatched active components (WDM transmitter and WDM MUX) network used in [2]. This was done to reduce the non-linear effects of FWM

Various design parameters were used to model and optimise the existing 48 channel fiber optic network such that an acceptable system performance could be achieved for future growth in end-user requirements. The optimisation of the 48-channel network was done using various parameters in different combinations. Three of the line encoding techniques (NRZ, RZ and MDRZ) were used in numerous DWDM networks with different filter types in the MUX and DEMUX. The two types of filter types were the Bessel and rectangular filter. The BW of the MUX/DEMUX filter and the ER of the transmitter were also varied to obtain an optimised network that had the most acceptable signal performance with the least amount of non-linearities for each of the above-mentioned channel spacings. A comparative model of two dispersion compensation techniques was also done for each channel spacing to evaluate a reduction in linear effects (CD) and non-linear effects (FWM). The two compensation techniques used in the design process were the 1 EDFA post compensation technique and the 3 EDFA post symmetric compensation techniques.

CHAPTER 4

SIMULATION RESULTS FOR THE 48 CHANNEL DWDM NETWORKS

4.1 Introduction

This chapter shows the simulation results of the 48 channel DWDM system designed in Chapter 3. The Optisystem v7.0 platform is used to simulate the 48-channel DWDM systems. For simplification, the results of 25 optical receivers are analysed evenly to represent the 48 channel outputs i.e. the analysis of the received signals from optical receivers placed in Channel 1, 2, 4, 6..., and so forth till channel 48 was done.

Eye diagram results of each channel is simulated by varying parameters such as channel spacings, modulation formats, filter types and BW parameters of the filters in the MUX/DEMUX for each network combination. The eye diagram results represent the BER eye height and Q factor measurements of the received signal for each channel in the DWDM system. For simplification and analysis of each network, the BER and Q factor measurements are tabulated and compiled in an excel spread sheet. Subsequently, this tabulated data is then graphically represented in the form of a Q factor vs BER comparative charts. These charts are an equivalent representation of the numerous tables of data that is recorded for each varied parameter combination of the 48 channel DWDM network shown in section 3.3.2 of chapter 3. The comparative chart shows the inversely proportional relationship between Q factor and BER for each combination of the varied parameters. The BER vs Q factor charts are used to verify the effect that each modified parameter (used in this design) has on the overall signal performance and bandwidth efficiency of the entire system. The blue bar pillars on the chart represent the quality factor on a linear scale for each channel within that network and the orange line showed the BER on a logarithmic scale for that corresponding channel in relation to the other channels within that network.

The eye diagrams results shown in this chapter illustrates each of the channels that has the highest signal performance (highest Q factor, lowest BER and its corresponding eye height) of the received signal for channel spacings of 100GHz NRZ, 100GHz RZ, 50GHz NRZ, 50GHz RZ, 25GHz NRZ, 25GHz RZ, 12.5GHz NRZ, 12.5GHz RZ, 6.25GHz NRZ and 6.25GHz RZ respectively.

4.2 The 48 Channel x 25 Gbps at 100 GHz Spacing using NRZ

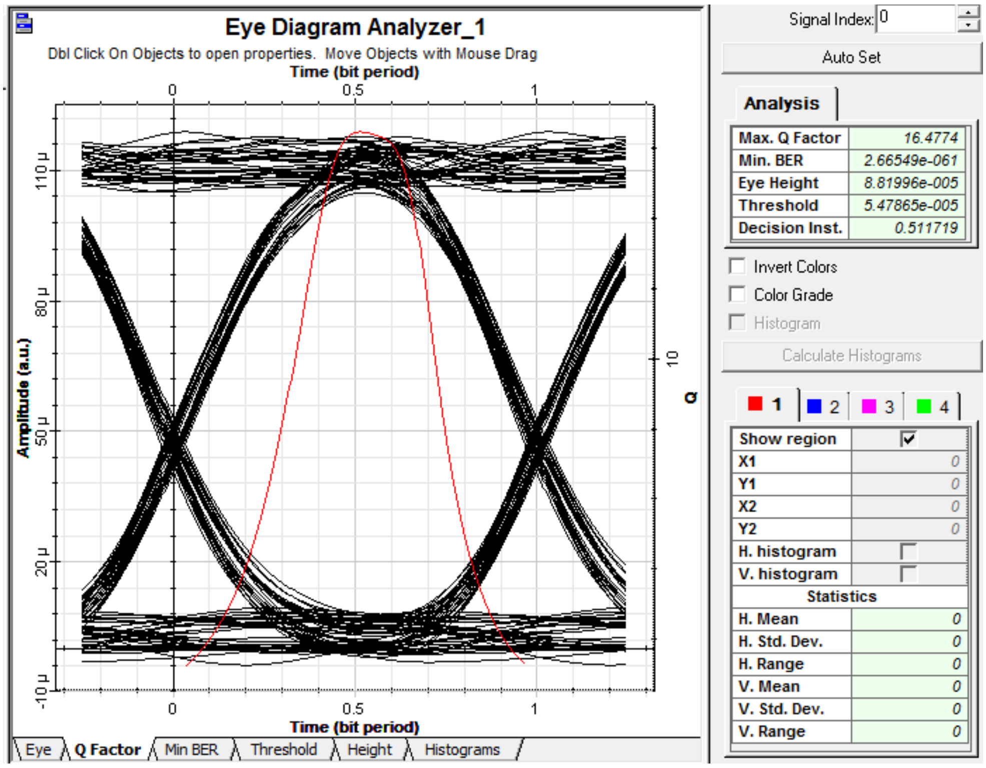

Figure 4.1: Eye Diagram of 100 GHz Channel Spacing Using NRZ, 1 EDFA, MUX BW = 80 GHz and DEMUX BW = 80 GHz

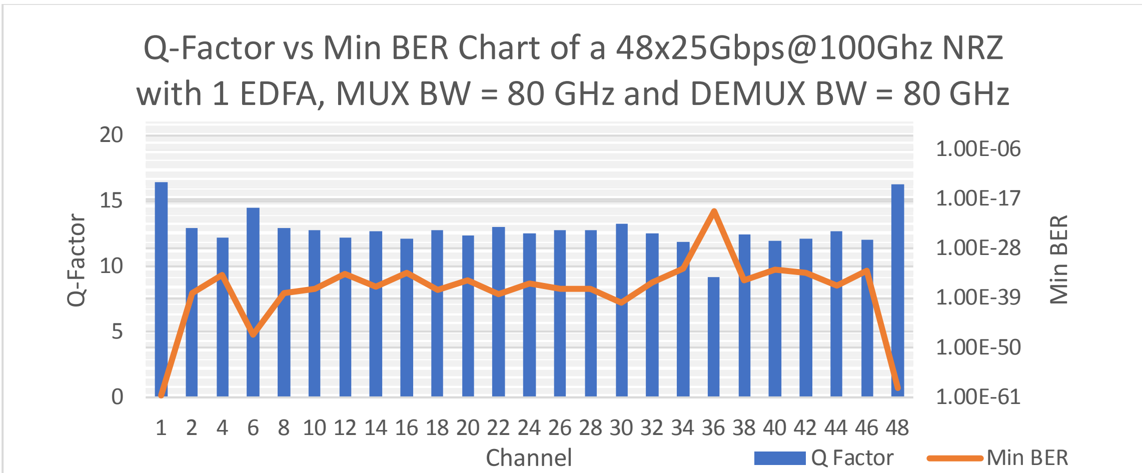

Figure 4.2: Q Factor vs BER Graph of 100 GHz Spacing Using NRZ, 1 EDFA, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.1 and Figure 4.2 represented the signal data for a DWDM network with 100 GHz channel spacing using NRZ and 1 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.2 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 1, which can be seen to have the lowest BER as well. Figure 4.1 showed the eye diagram of channel 1 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

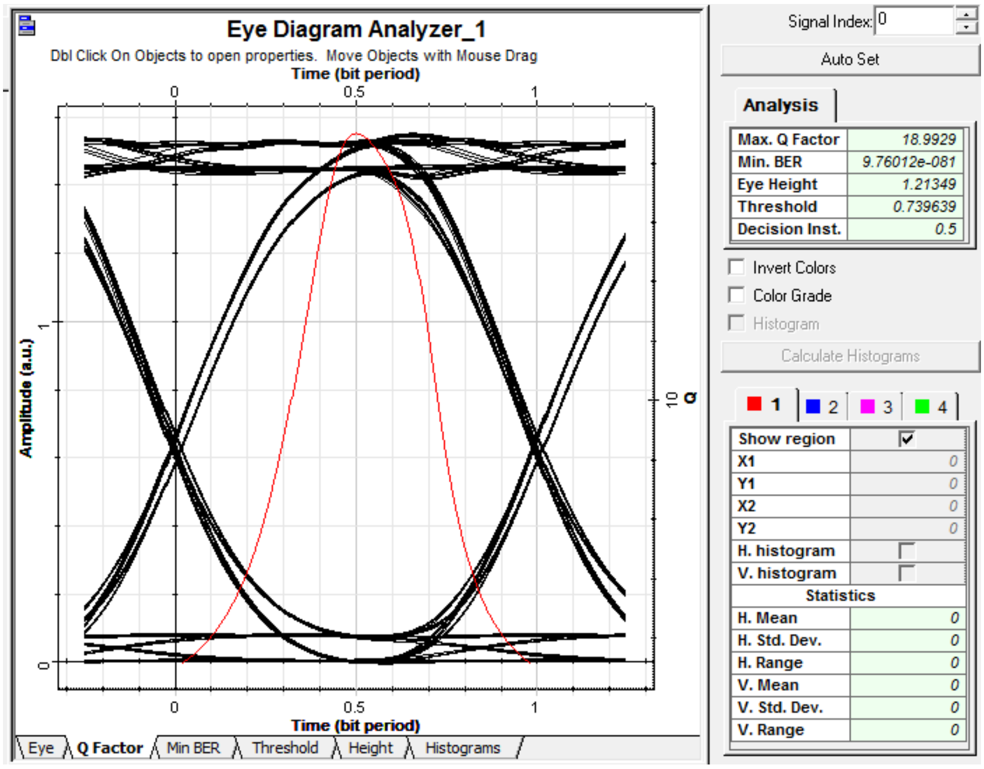

Figure 4.3: Eye Diagram of 100 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

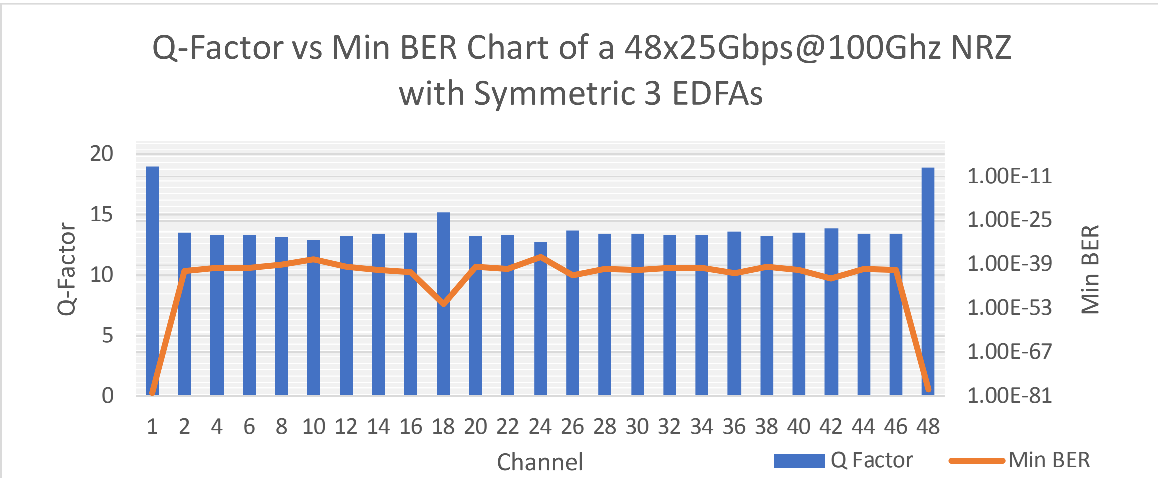

Figure 4.4: Q factor vs BER Graph of 100 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.3 and Figure 4.4 represented the signal data for a DWDM network with 100 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.4 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 1, which had the lowest BER as well. Figure 4.3 showed the eye diagram of channel 1 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

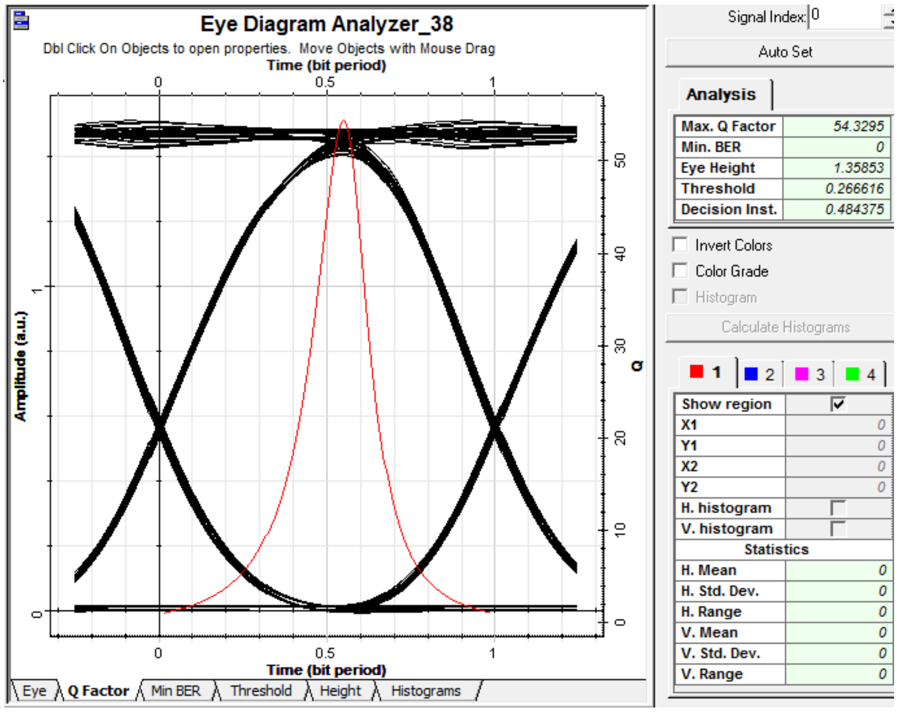

Figure 4.5: Eye Diagram of 100 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 50 GHz

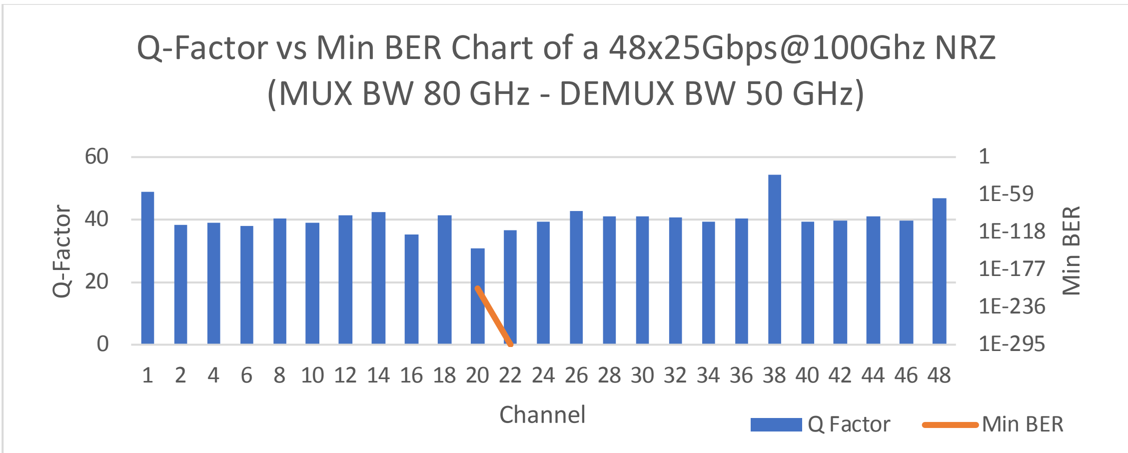

Figure 4.6: Q Factor vs BER of 100 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 50 GHz

Figure 4.5 and Figure 4.6 represented the signal data for a DWDM network with 100 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 50 GHz. Figure 4.6 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 38, which had the lowest BER as well. The Min BER is truncated at channel 20 and 22 because they had the highest BER and the lowest Q in comparison to all other channels. BER for all other channels was almost = 0 and negligible. Figure 4.5 showed the eye diagram of channel 38 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

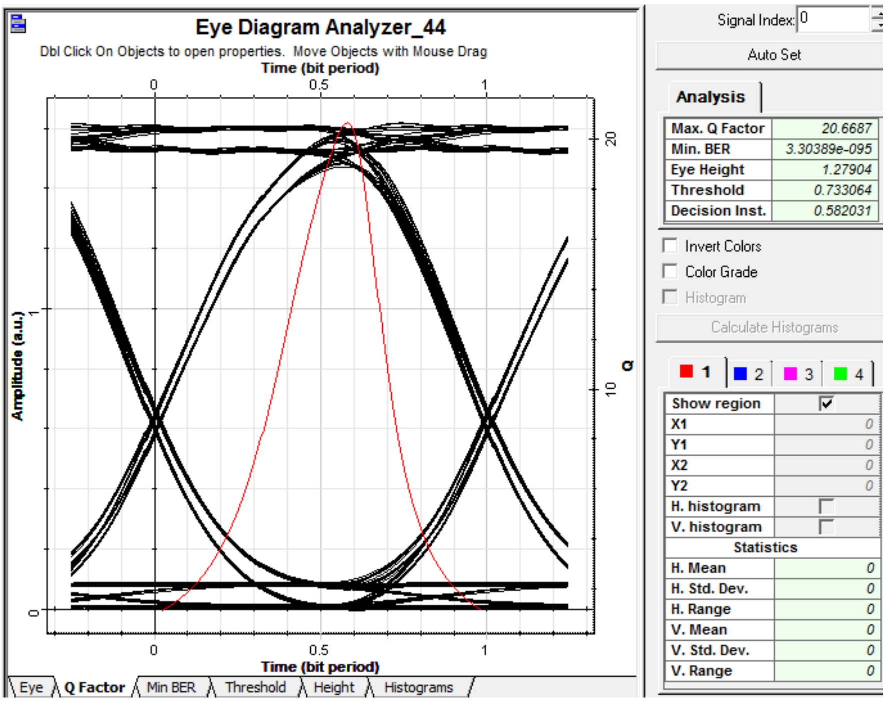

Figure 4.7: Eye Diagram of 100 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 50 GHz and DEMUX BW = 80 GHz

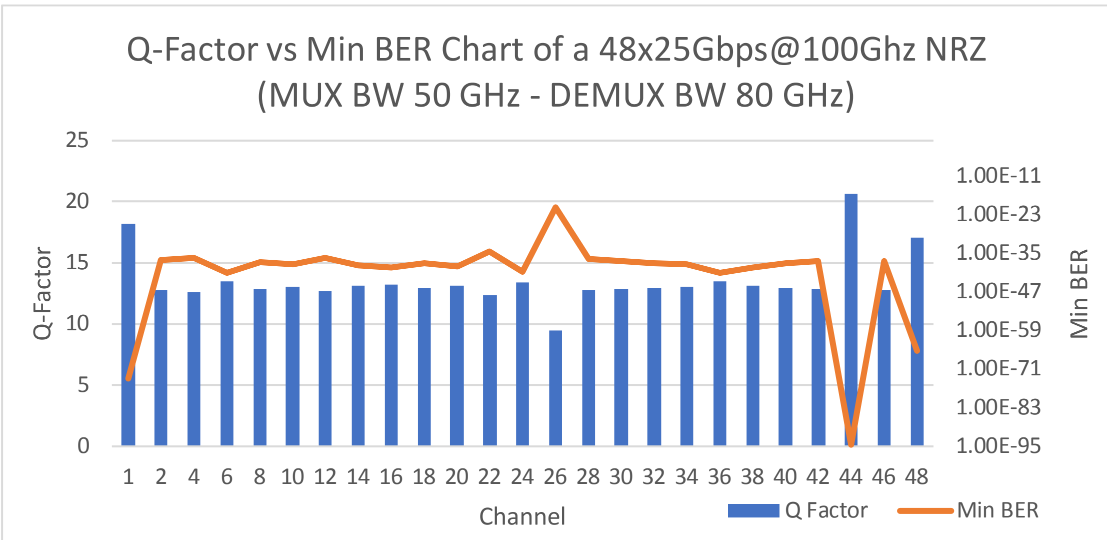

Figure 4.8: Q Factor vs BER of 100 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 50 GHz and DEMUX BW = 80 GHz

Figure 4.7 and Figure 4.8 represented the signal data for a DWDM network with 100 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 50 GHz and DEMUX BW = 80 GHz.

Figure 4.8 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 44, which had the lowest BER as well. Figure 4.7 showed the eye diagram of channel 44 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

4.3 The 48 Channel x 25 Gbps at 100 GHz Spacing using RZ

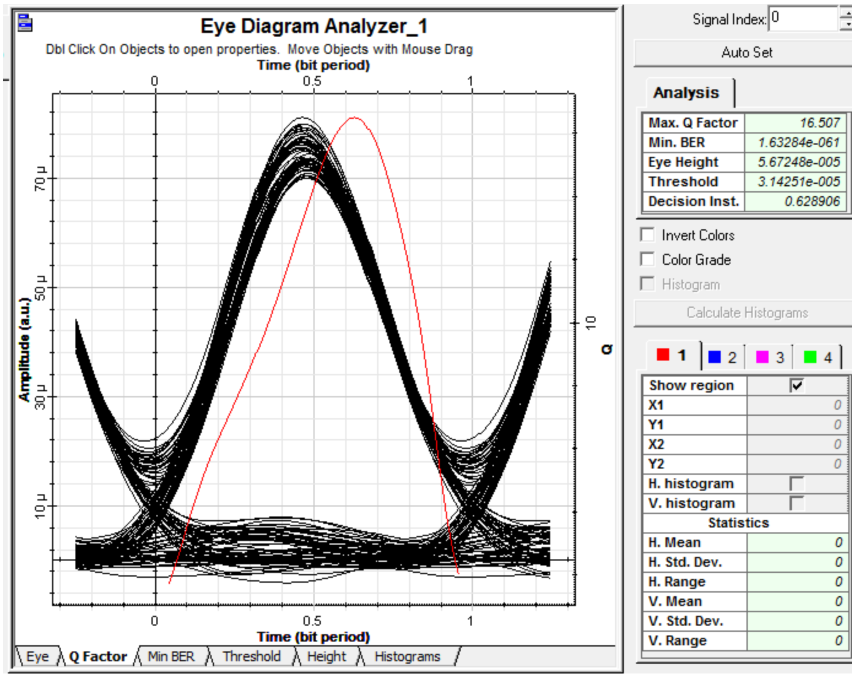

Figure 4.9: Eye Diagram of 100 GHz Channel Spacing Using RZ, 1 EDFA, MUX BW = 80 GHz and DEMUX BW = 80 GHz

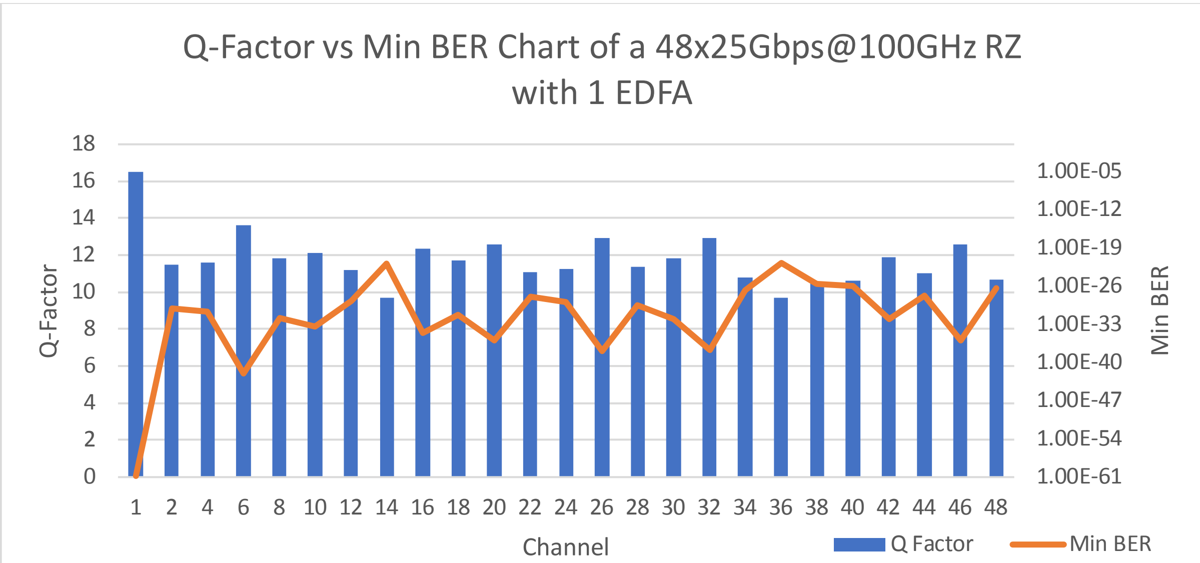

Figure 4.10: Q Factor vs BER of 100 GHz Channel Spacing Using RZ, 1 EDFA, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.9 and Figure 4.10 represented the signal data for a DWDM network with 100 GHz channel spacing using RZ and 1 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.10 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 1, which had the lowest BER as well. Figure 4.9 showed the eye diagram of channel 1 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

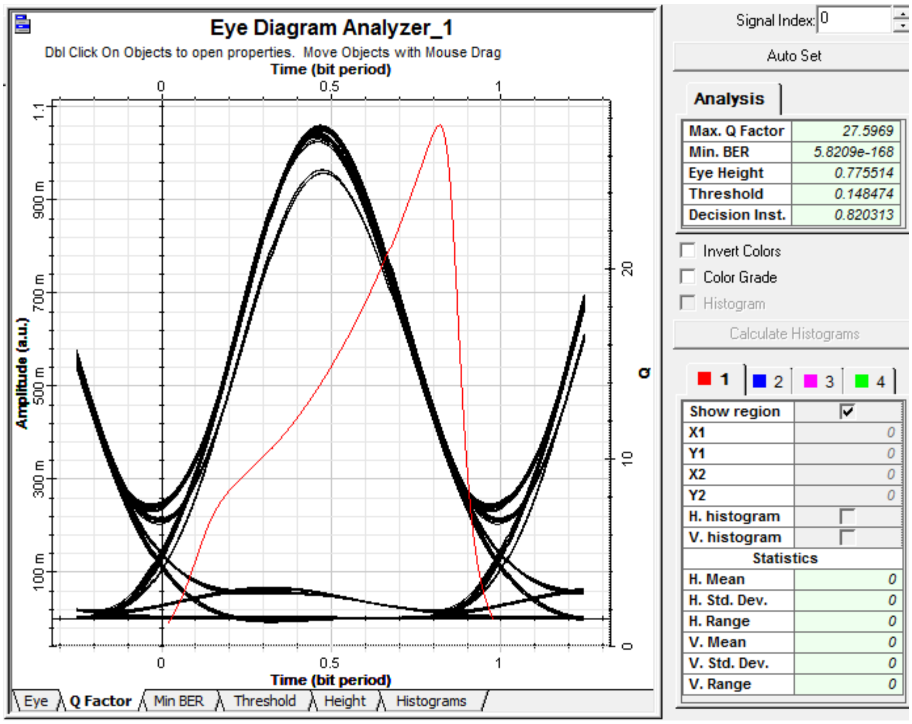

Figure 4.11: Eye Diagram of 100 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

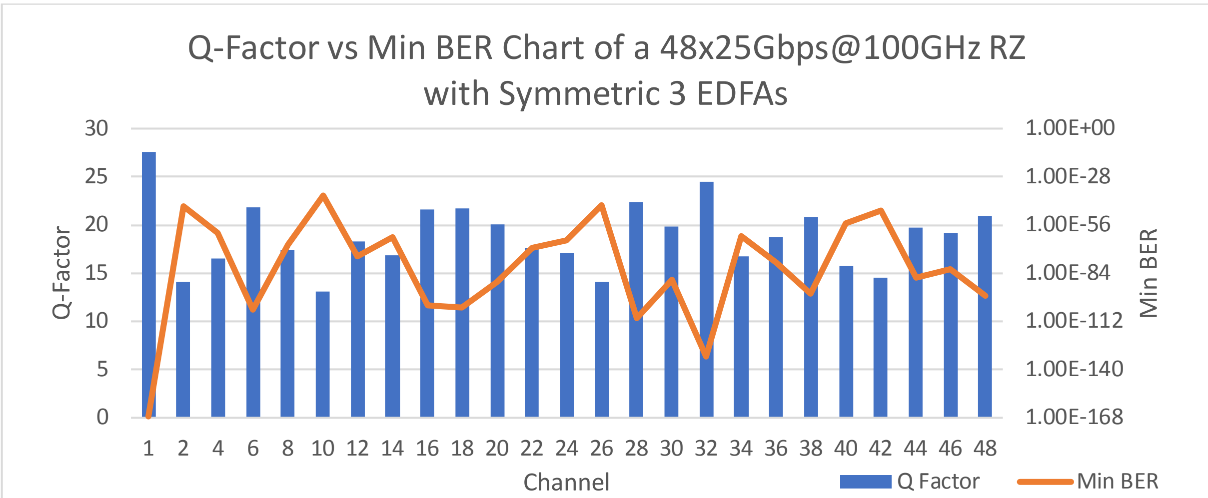

Figure 4.12: Q factor vs BER of 100 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.11 and Figure 4.12 represented the signal data for a DWDM network with 100 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.12 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 1, which had the lowest BER as well. Figure 4.11 showed the eye diagram of channel 1 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

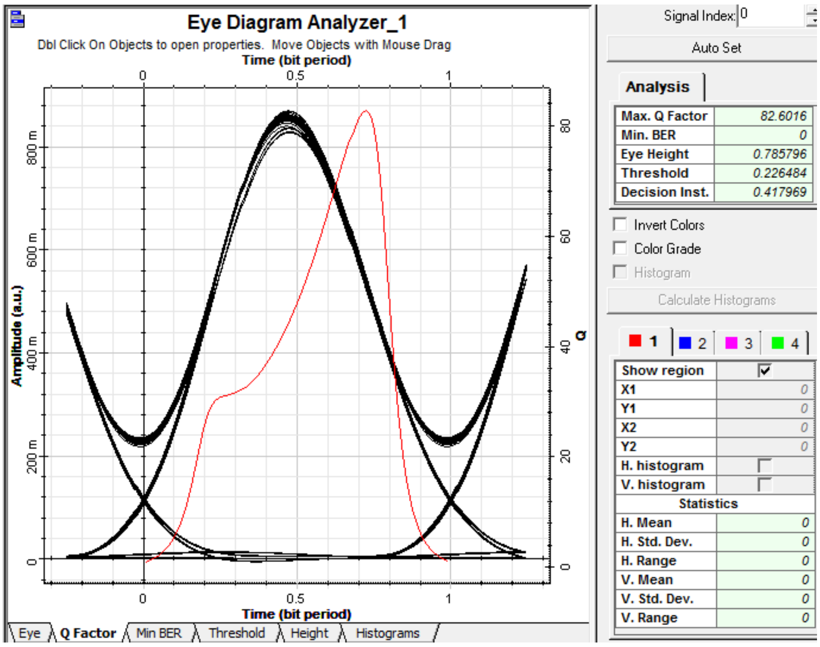

Figure 4.13: Eye Diagram of 100 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 50 GHz

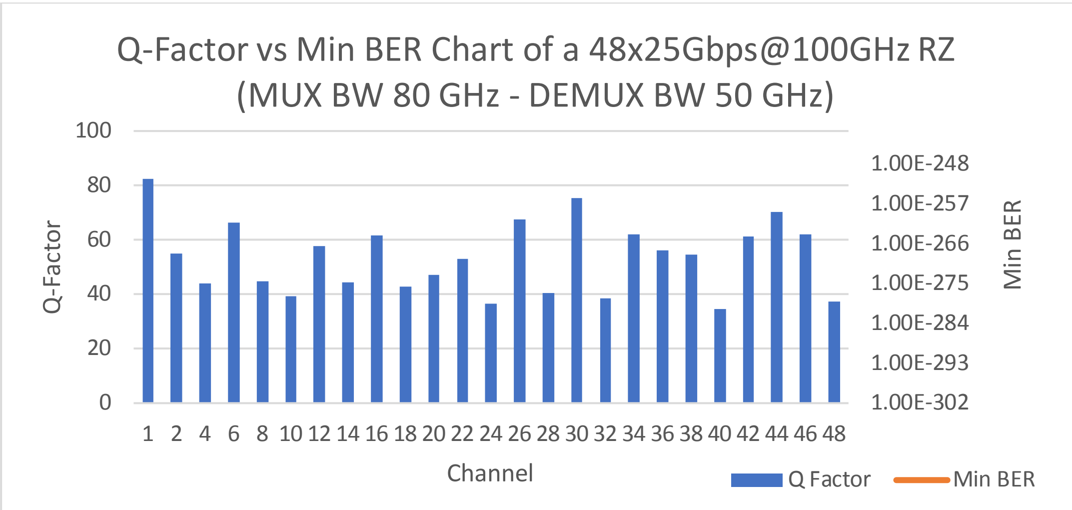

Figure 4.14: Q Factor vs BER of 100 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 50 GHz

Figure 4.13 and Figure 4.14 represented the signal data for a DWDM network with 100 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 50 GHz. Figure 4.14 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 1, which had the lowest BER as well. All Q factors for all channels in this system are so high that the BER for this system = 0, BER for all channels in this system is negligible. Figure 4.13 showed the eye diagram of channel 1 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

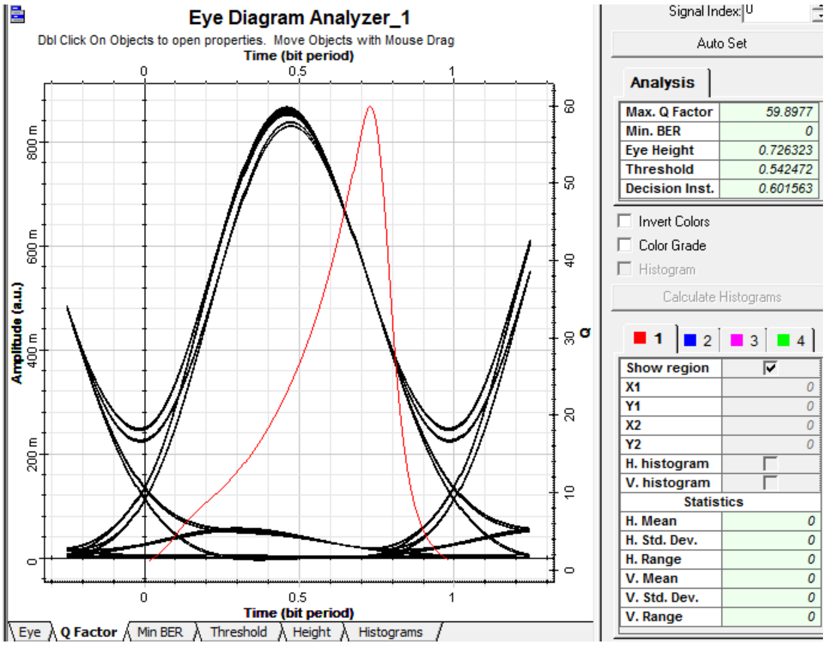

Figure 4.15: Eye Diagram of 100 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 50 GHz and DEMUX BW = 80 GHz

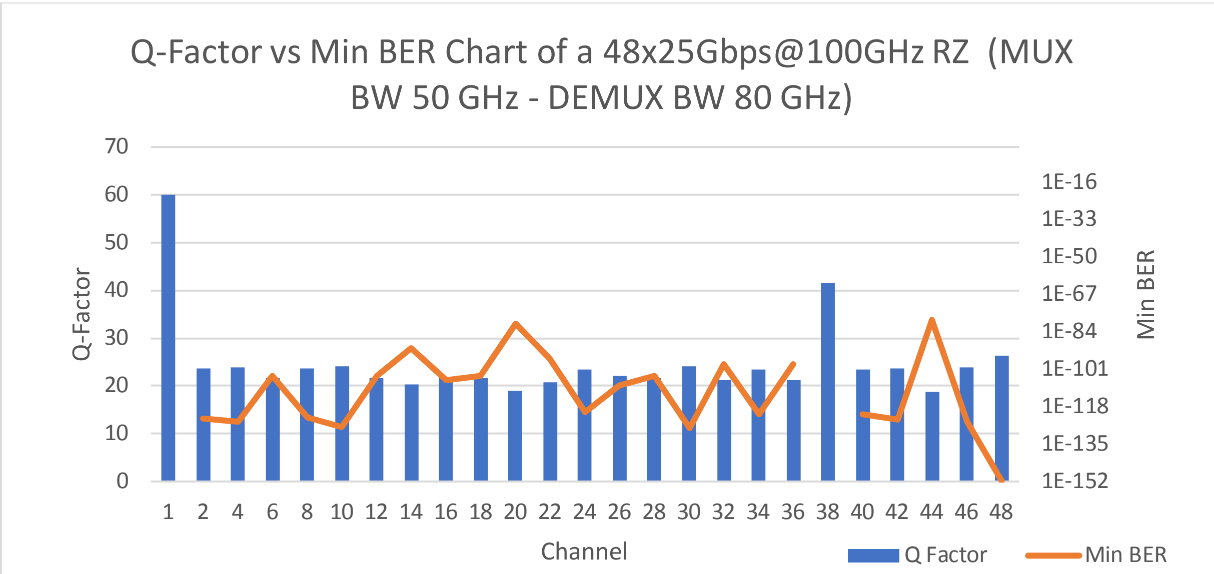

Figure 4.16: Q Factor vs BER of 100 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 50 GHz and DEMUX BW = 80 GHz

Figure 4.15 and Figure 4.16 represented the signal data for a DWDM network with 100 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 50 GHz and DEMUX BW = 80 GHz.

Figure 4.16 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 1, which had the lowest BER as well. Figure 4.15 showed the eye diagram of channel 1 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

4.4 The 48 Channel x 25 Gbps at 50 GHz Spacing using NRZ

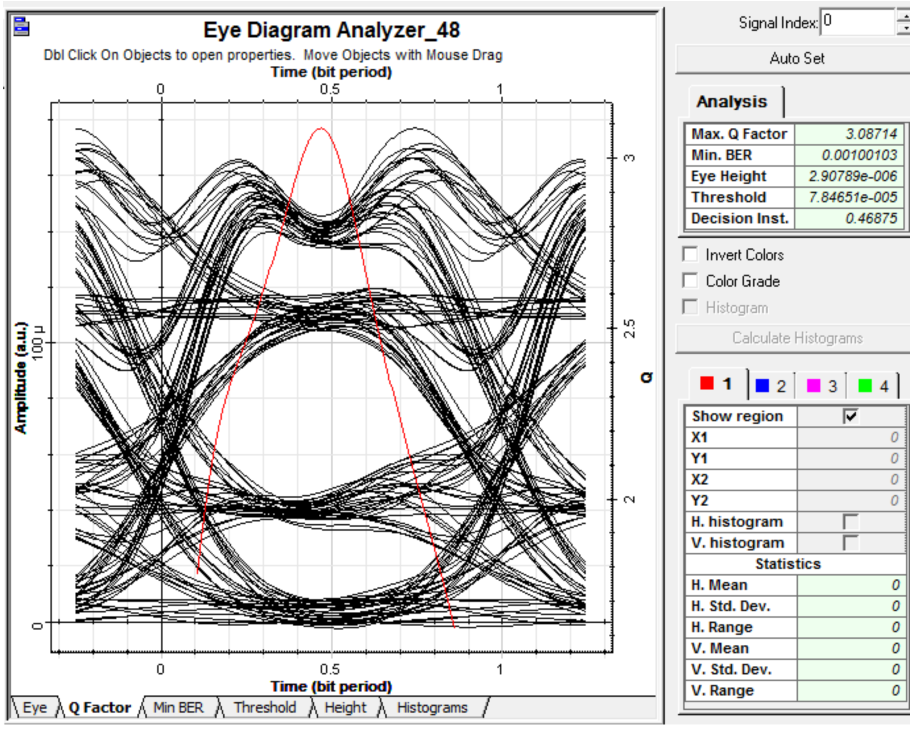

Figure 4.17: Eye Diagram of 50 GHz Channel Spacing Using NRZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

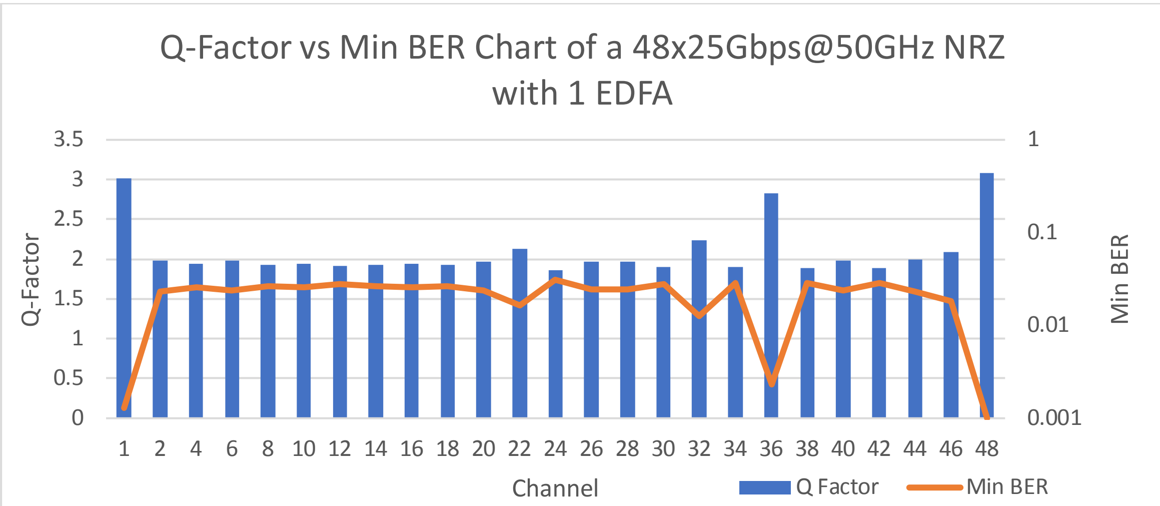

Figure 4.18: Q factor vs BER of 50 GHz Spacing Using NRZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.17 and Figure 4.18 represented the signal data for a DWDM network with 50 GHz channel spacing using NRZ and 1 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.18 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 48, which had the lowest BER as well. Figure 4.17 showed the eye diagram of channel 48 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

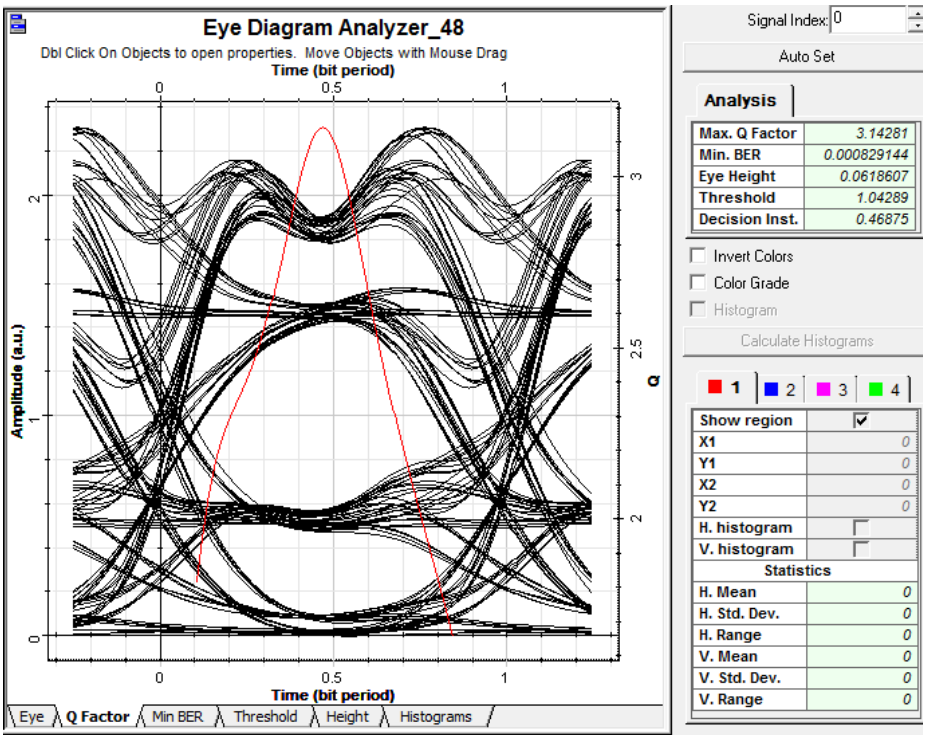

Figure 4.19: Eye Diagram of 50 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

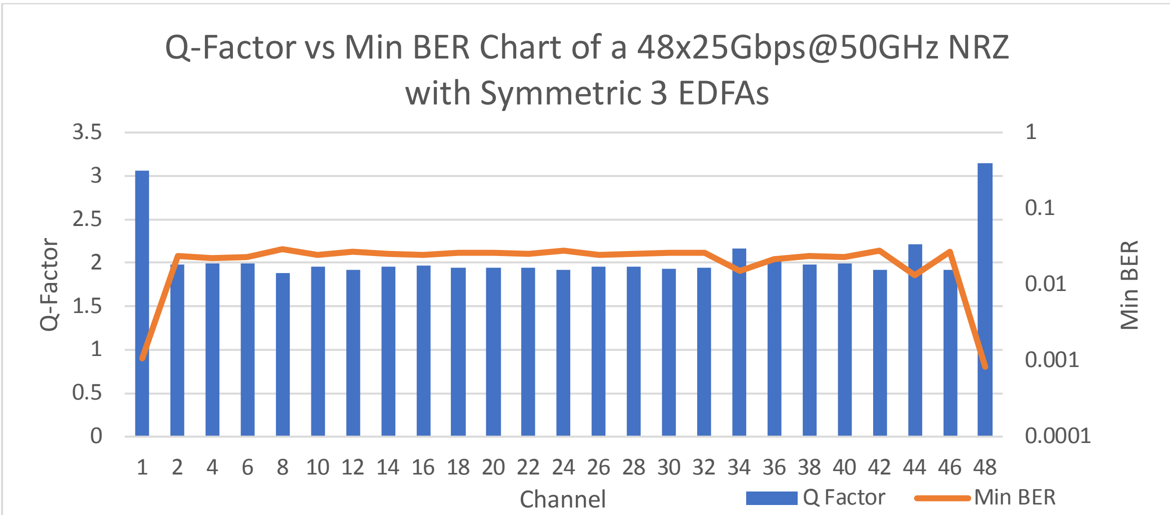

Figure 4.20: Q Factor vs BER of 50 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.19 and Figure 4.20 represented the signal data for a DWDM network with 50 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.20 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 48, which had the lowest BER as well. Figure 4.19 showed the eye diagram of channel 48 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

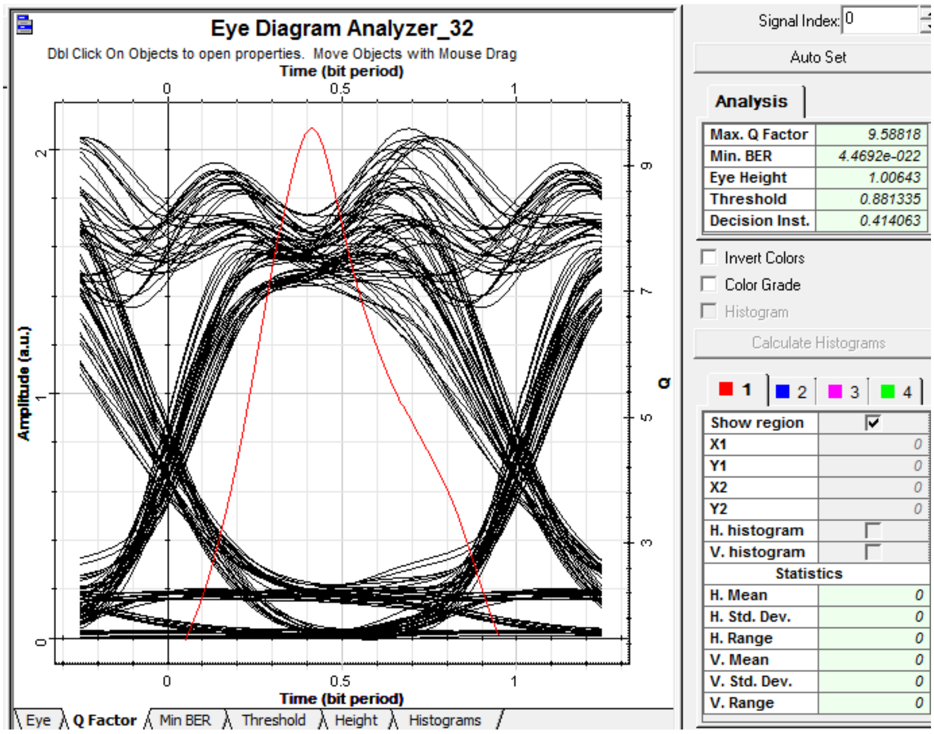

Figure 4.21: Eye Diagram of 50 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 50 GHz

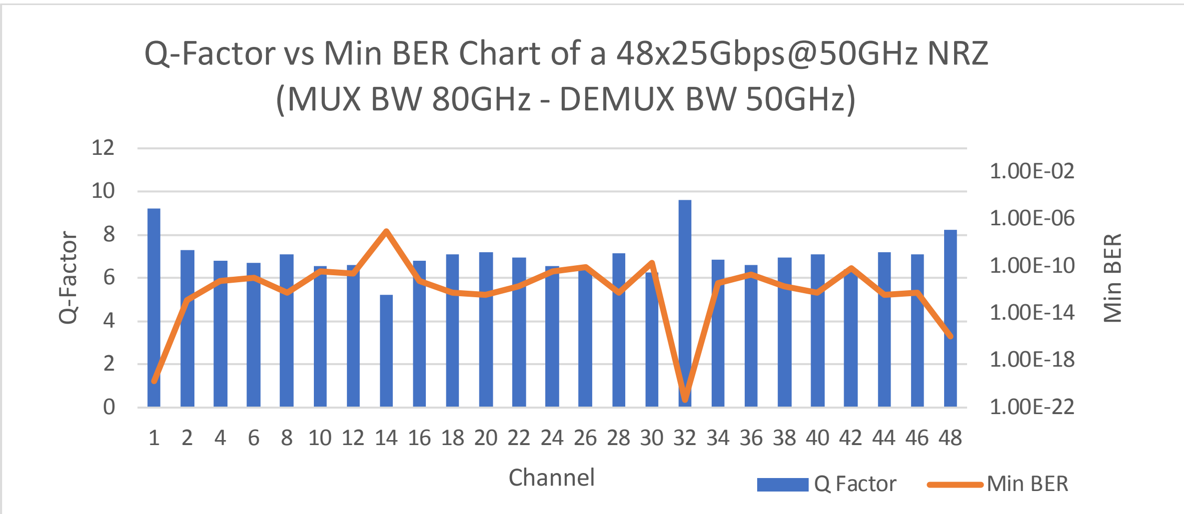

Figure 4.22: Q Factor vs BER of 50 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 50 GHz

Figure 4.21 and Figure 4.22 represented the signal data for a DWDM network with 50 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 50 GHz.

Figure 4.22 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 32, which had the lowest BER as well. Figure 4.21 showed the eye diagram of channel 32 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

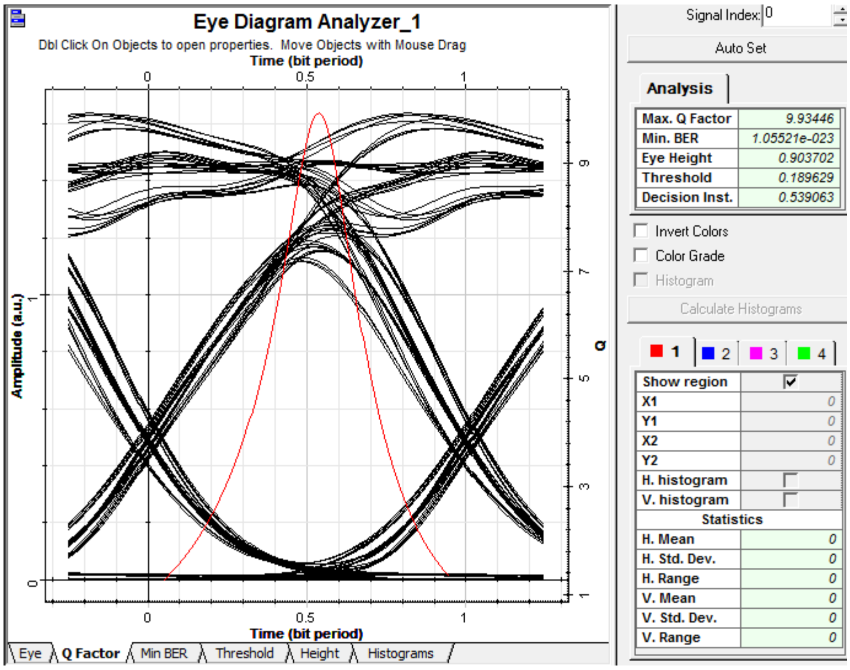

Figure 4.23: Eye Diagram of 50 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 25 GHz

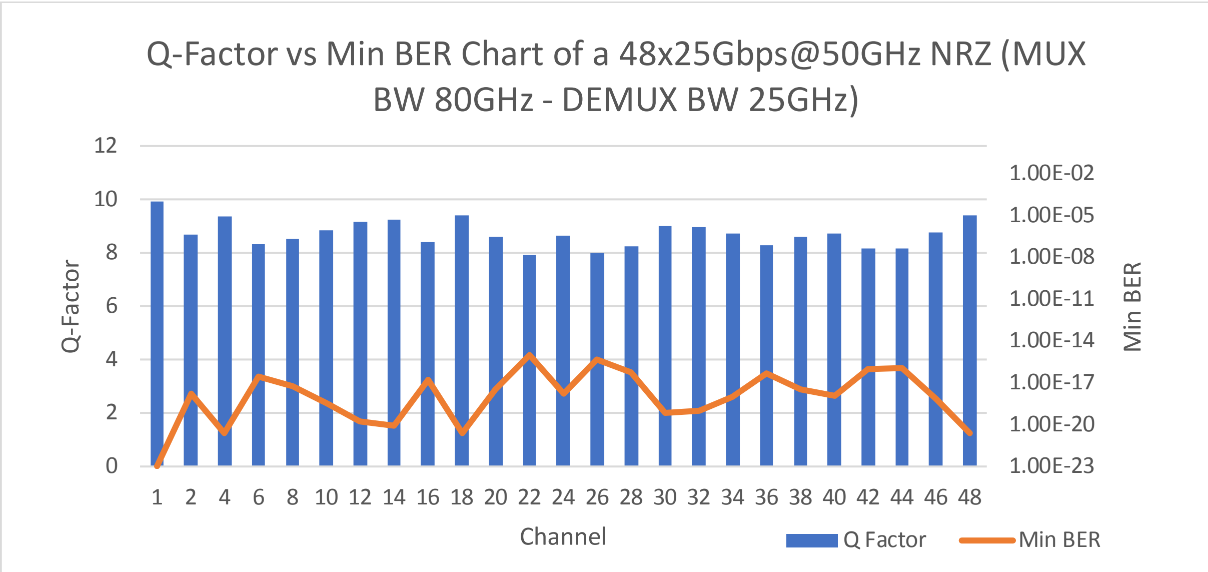

Figure 4.24: Q Factor vs BER of 50 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 25 GHz

Figure 4.23 and Figure 4.24 represented the signal data for a DWDM network with 50 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 25 GHz.

Figure 4.24 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 1, which had the lowest BER as well. Figure 4.23 showed the eye diagram of channel 1 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

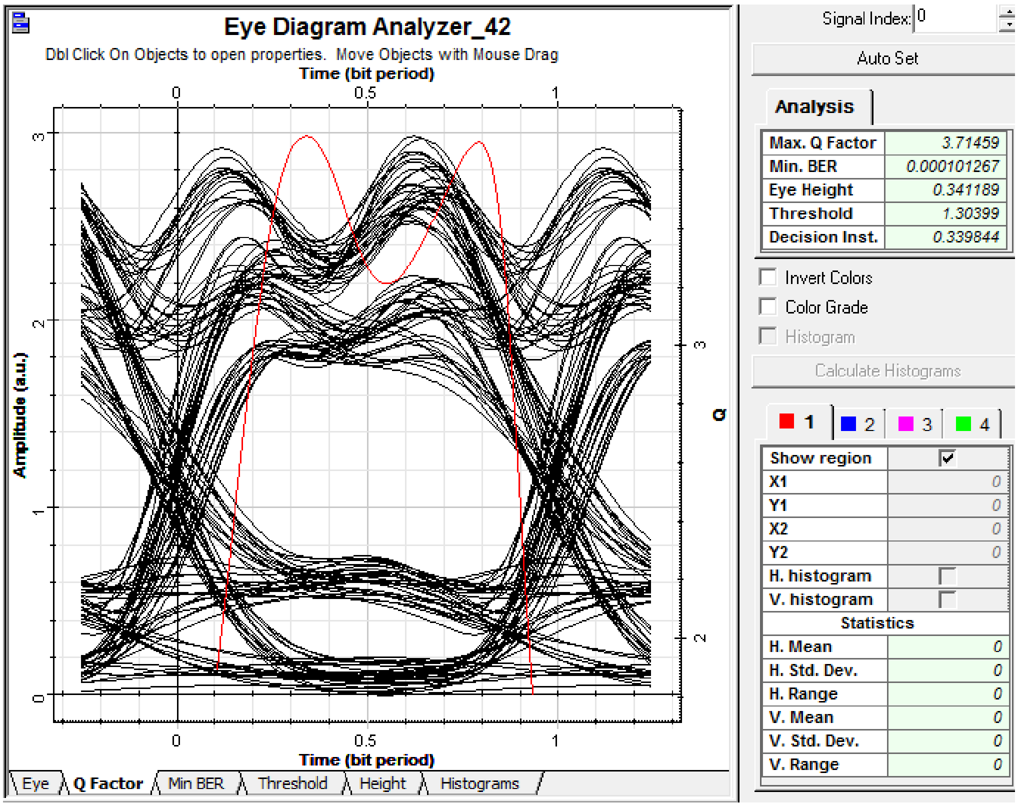

Figure 4.25: Eye Diagram of 50 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 50 GHz and DEMUX BW = 80 GHz

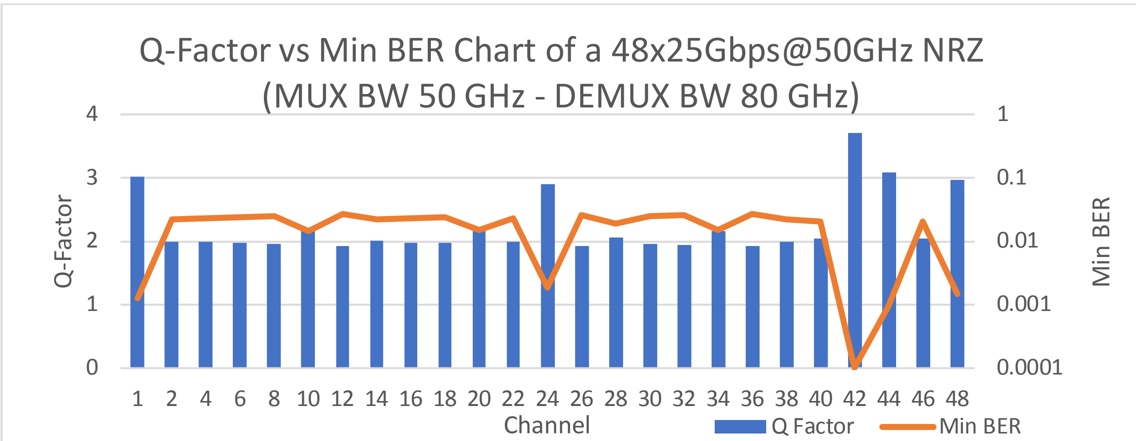

Figure 4.26: Q Factor vs BER of 50 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 50 GHz and DEMUX BW = 80 GHz

Figure 4.25 and Figure 4.26 represented the signal data for a DWDM network with 50 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 50 GHz and DEMUX BW = 80 GHz.

Figure 4.26 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 42, which had the lowest BER as well. Figure 4.25 showed the eye diagram of channel 42 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

4.5 The 48 Channel x 25 Gbps at 50 GHz Spacing using RZ

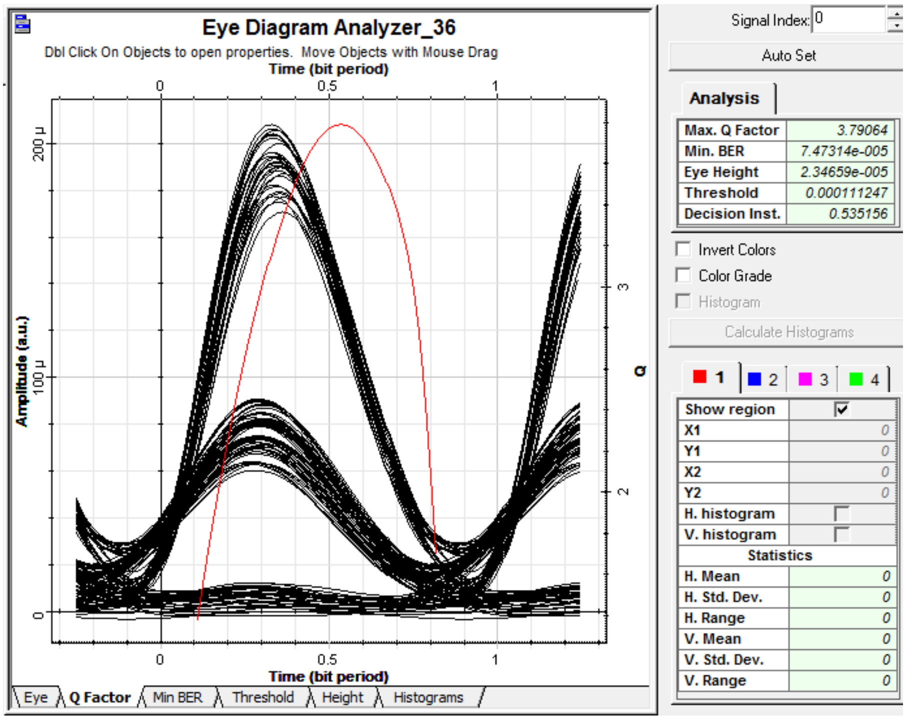

Figure 4.27: Eye Diagram of 50 GHz Channel Spacing Using RZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

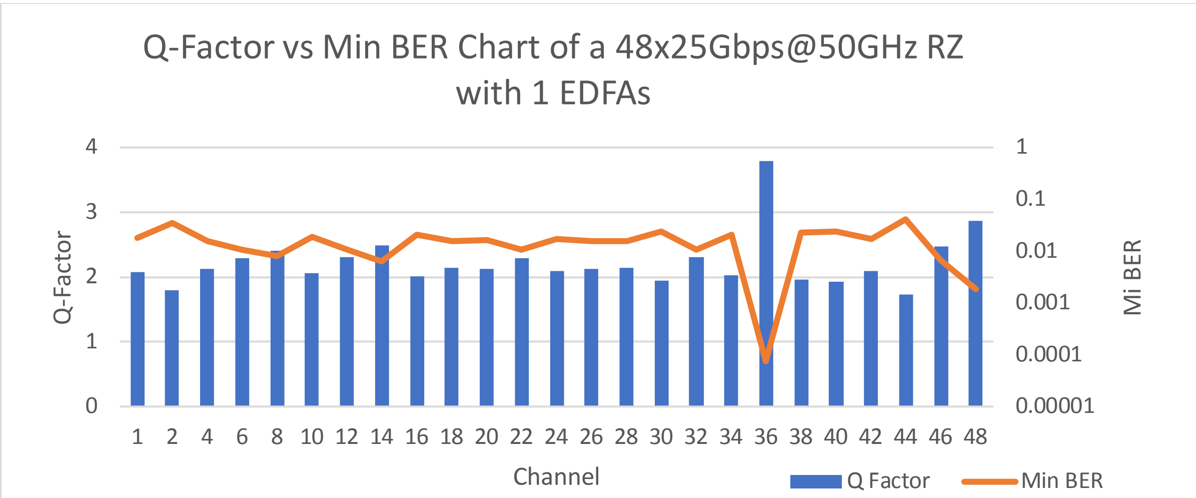

Figure 4.28: Q factor vs BER of 50 GHz Spacing Using RZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.27 and Figure 4.28 represented the signal data for a DWDM network with 50 GHz channel spacing using RZ and 1 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.28 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 36, which had the lowest BER as well. Figure 4.27 showed the eye diagram of channel 36 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

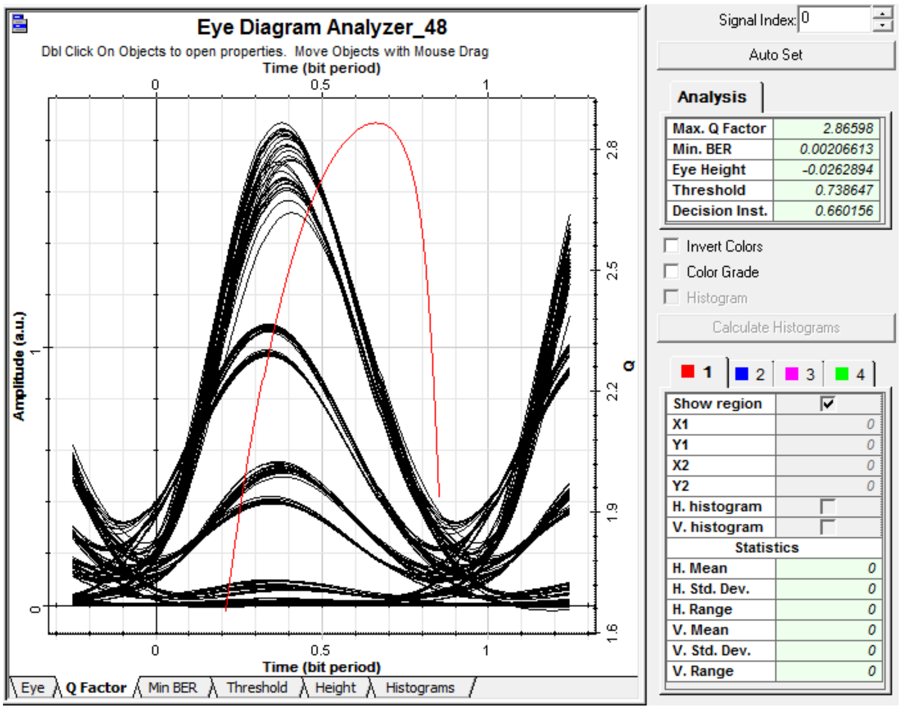

Figure 4.29: Eye Diagram of 50 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

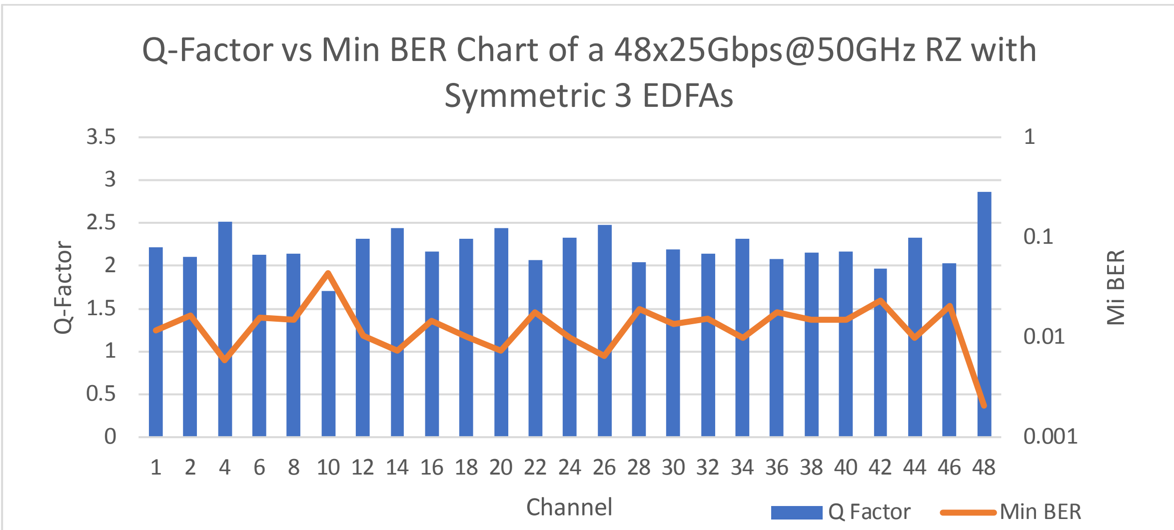

Figure 4.30: Q factor vs BER of 50 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.29 and Figure 4.30 represented the signal data for a DWDM network with 50 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.30 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 48, which had the lowest BER as well. Figure 4.29 showed the eye diagram of channel 48 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

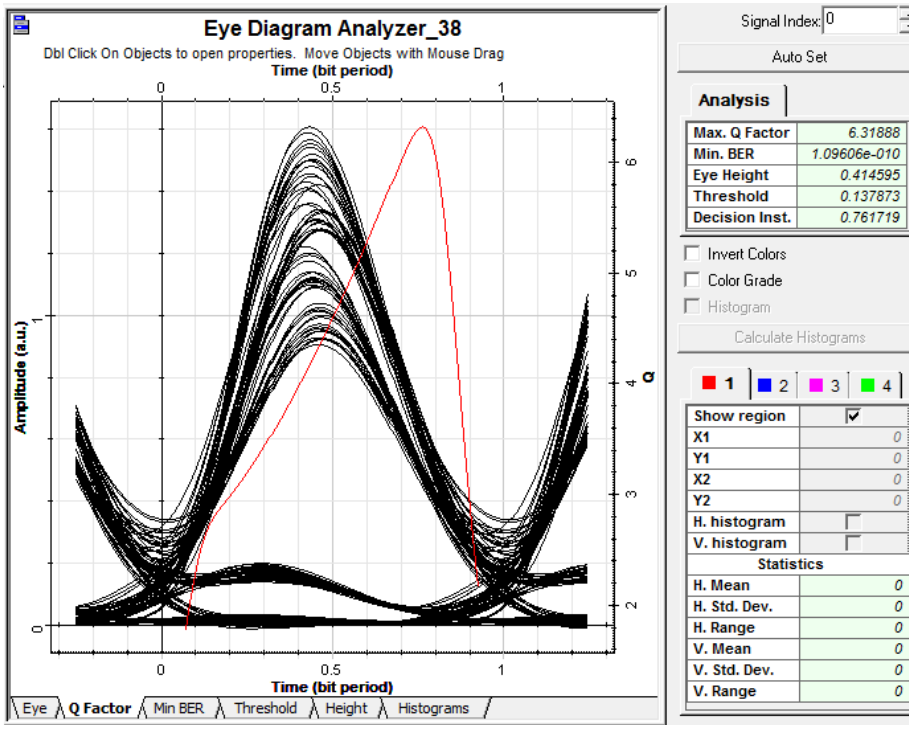

Figure 4.31: Eye Diagram of 50 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 50 GHz

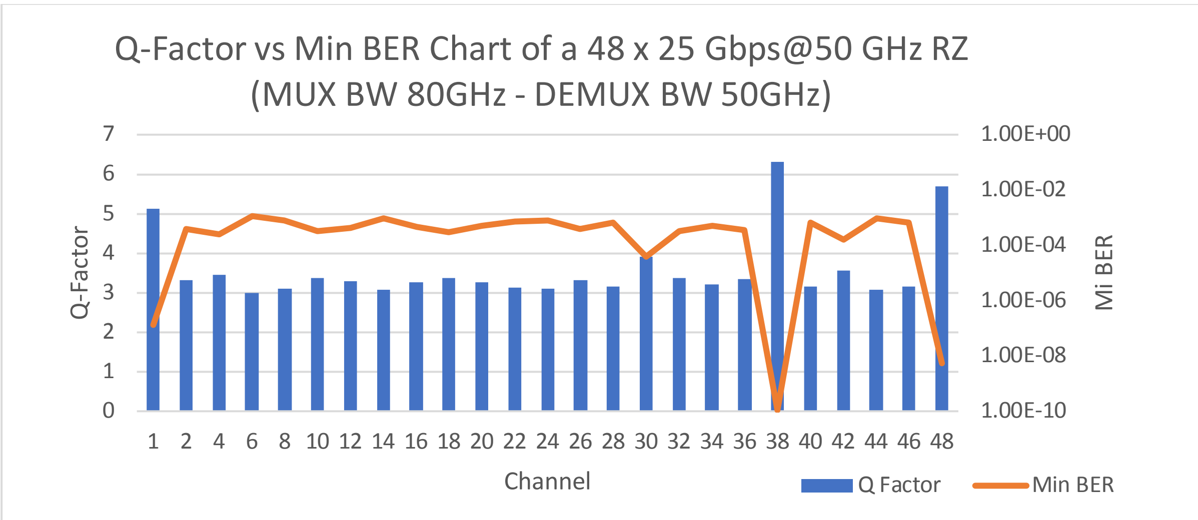

Figure 4.32: Q Factor vs BER of 50 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 50 GHz

Figure 4.31 and Figure 4.32 represented the signal data for a DWDM network with 50 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 50 GHz.

Figure 4.32 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 38, which had the lowest BER as well. Figure 4.31 showed the eye diagram of channel 38 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

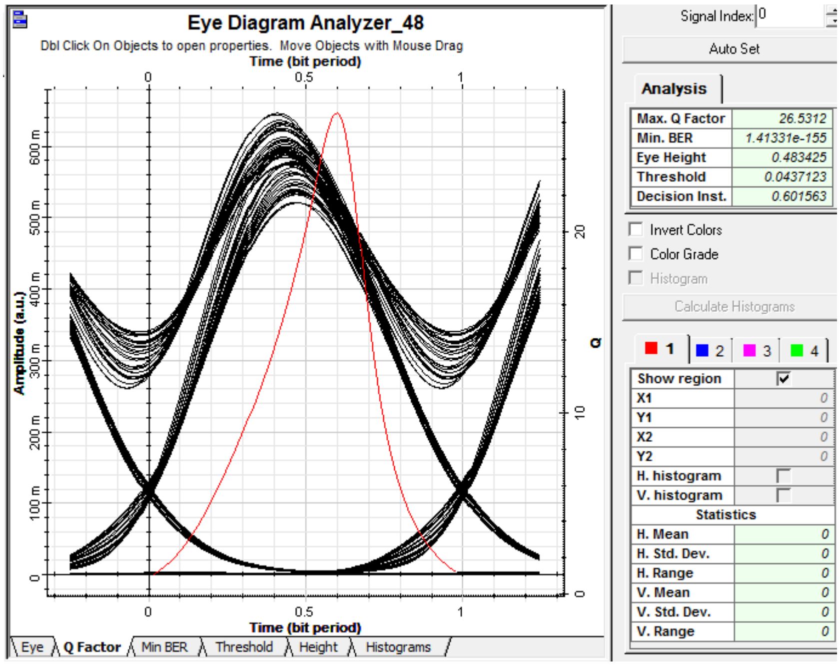

Figure 4.33: Eye Diagram of 50 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 25 GHz

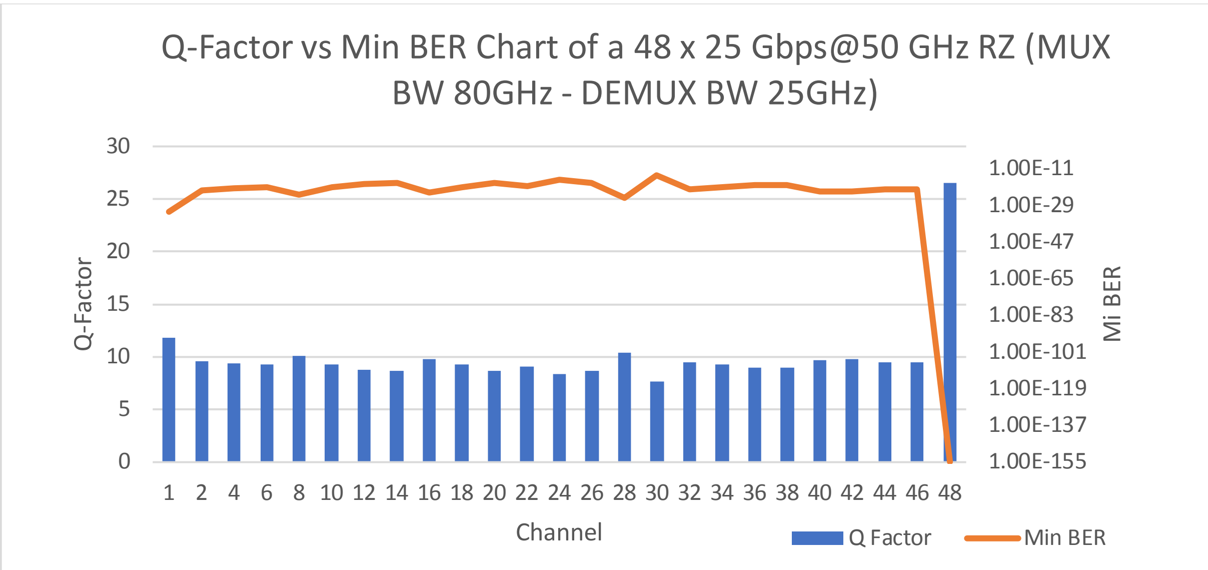

Figure 4.34: Q factor vs BER Diagram of 50 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 25 GHz

Figure 4.33 and Figure 4.34 represent the signal data for a DWDM network with 50 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 25 GHz.

Figure 4.34 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 48, which had the lowest BER as well. Figure 4.33 showed the eye diagram of channel 48 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

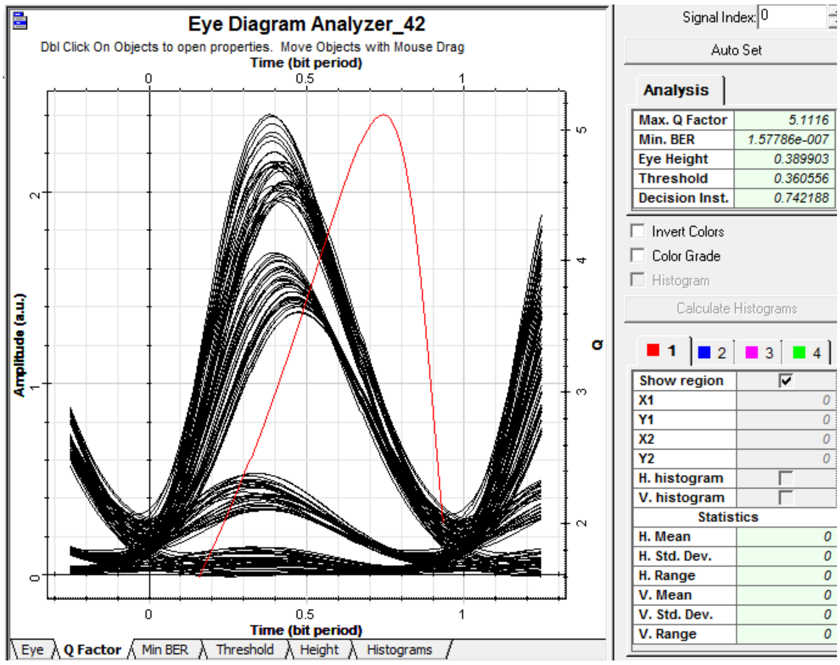

Figure 4.35: Eye Diagram of 50 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 50 GHz and DEMUX BW = 80 GHz

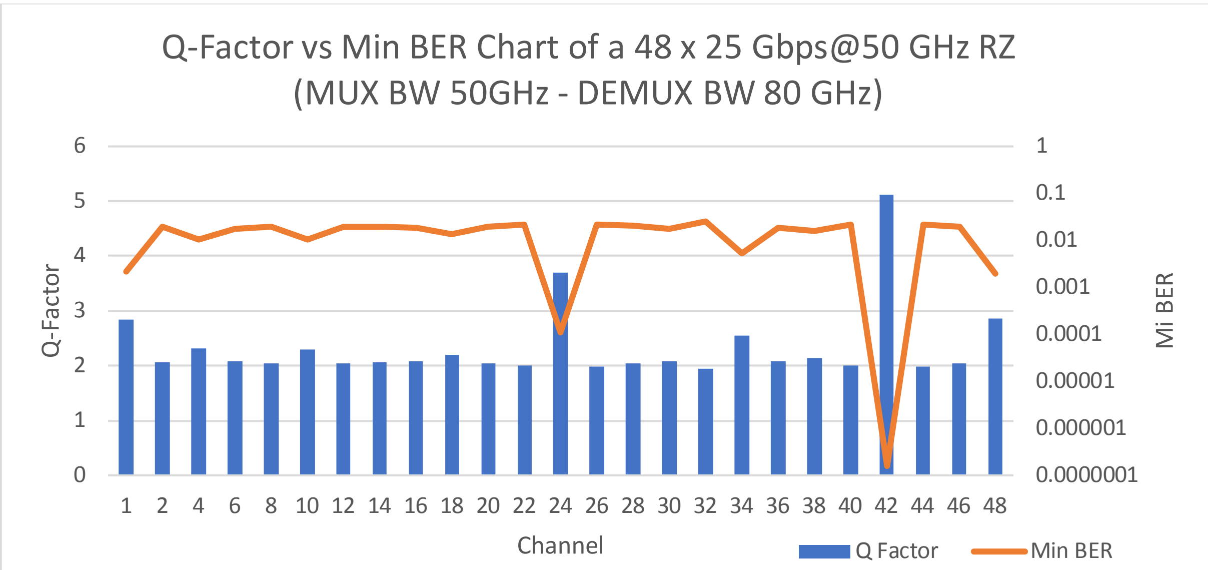

Figure 4.36: Q Factor vs BER of 50 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 50 GHz and DEMUX BW = 80 GHz

Figure 4.35 and Figure 4.36 represented the signal data for a DWDM network with 50 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 50 GHz and DEMUX BW = 80 GHz.

Figure 4.36 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 42, which had the lowest BER as well. Figure 4.35 showed the eye diagram of channel 42 with its Q factor, BER and eye height. The BW efficiency was 100% because all transmitted channels were received.

4.6 The 48 Channel x 25 Gbps at 25 GHz Spacing using NRZ

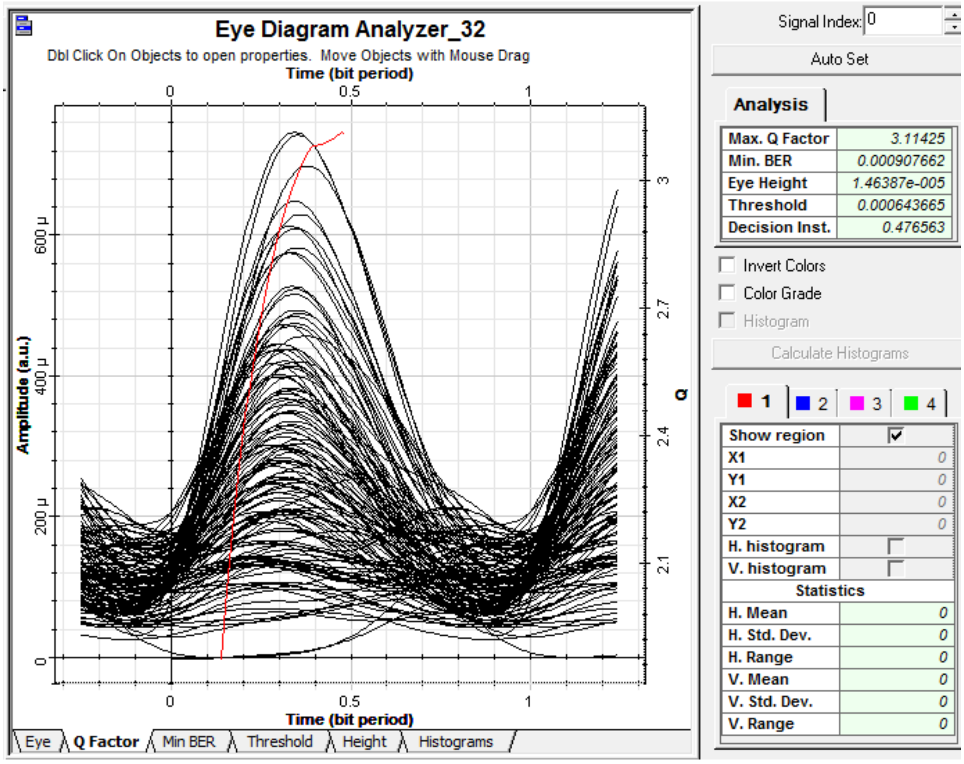

Figure 4.37: Eye Diagram of 25 GHz Channel Spacing Using NRZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

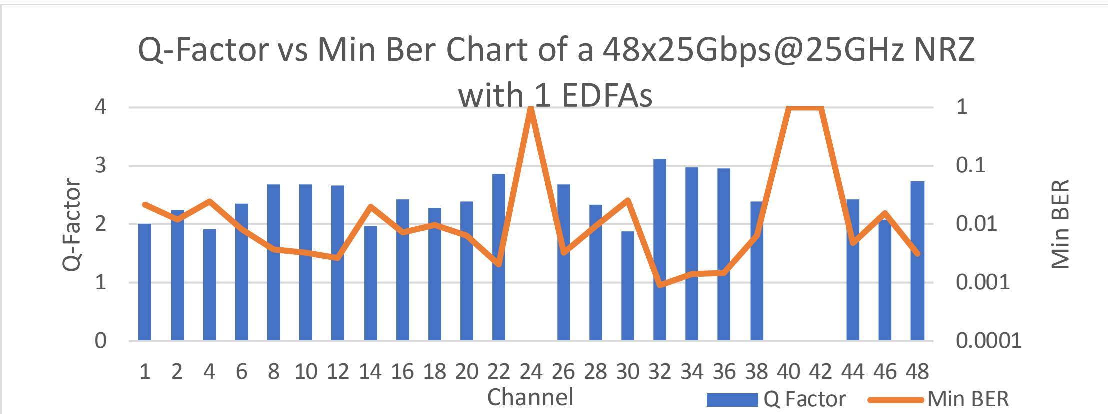

Figure 4.38: Q factor vs BER of 25 GHz Spacing Using NRZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.37 and Figure 4.38 represented the signal data for a DWDM network with 25 GHz channel spacing using NRZ and 1 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.38 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 32, which had the lowest BER as well. Figure 4.37 showed the eye diagram of channel 32 with its Q factor, BER and eye height. The BW efficiency was 93.75% because only 45 out of the 48 channels were received. Three channels did not have a recognisable signal since the BER = 1 and Q = 0.

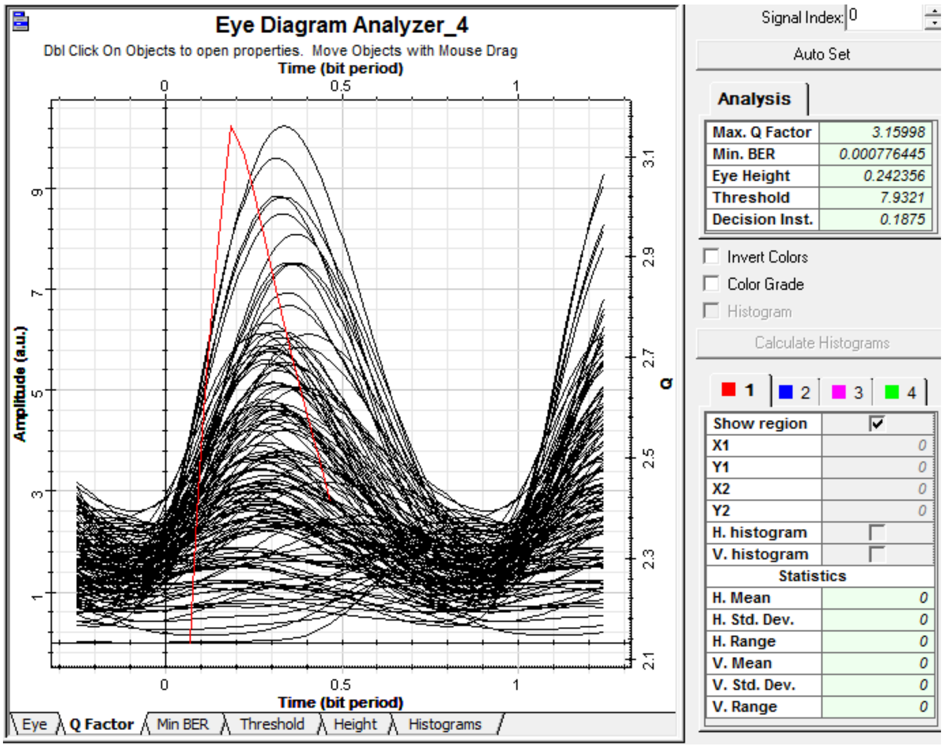

Figure 4.39: Eye Diagram of 25 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

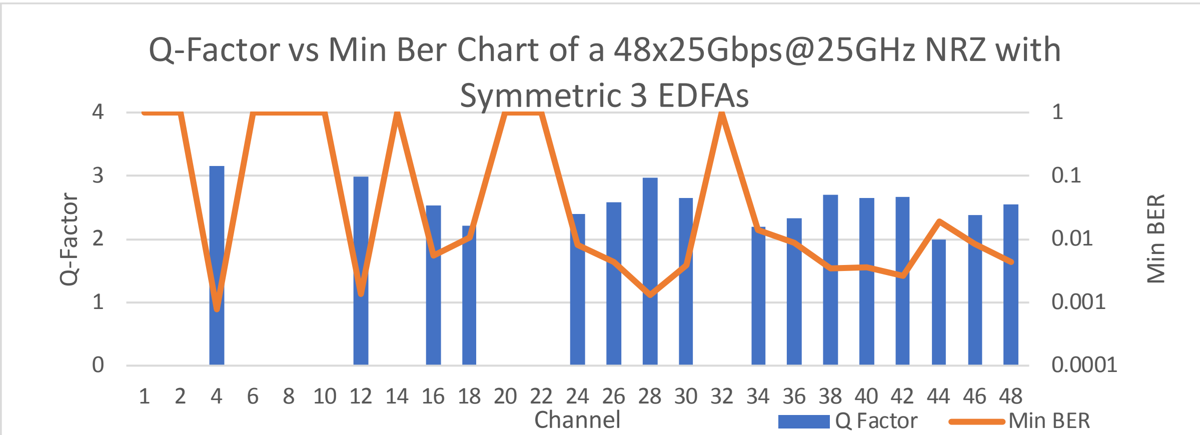

Figure 4.40: Q Factor vs BER of 25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.39 and Figure 4.40 represented the signal data for a DWDM network with 25 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.40 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 4, which had the lowest BER as well. Figure 4.39 showed the eye diagram of channel 4 with its Q factor, BER and eye height. The BW efficiency was 81.25% since only 39 out of 48 channels were recognisable. Nine channels had BER = 1 and Q = 0.

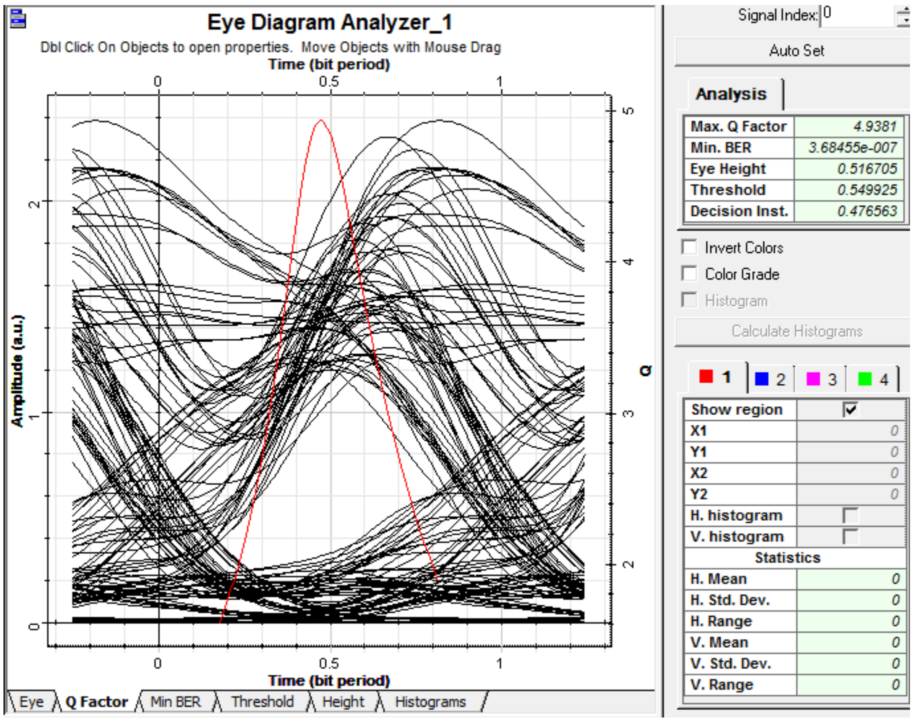

Figure 4.41: Eye Diagram of 25 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 25 GHz

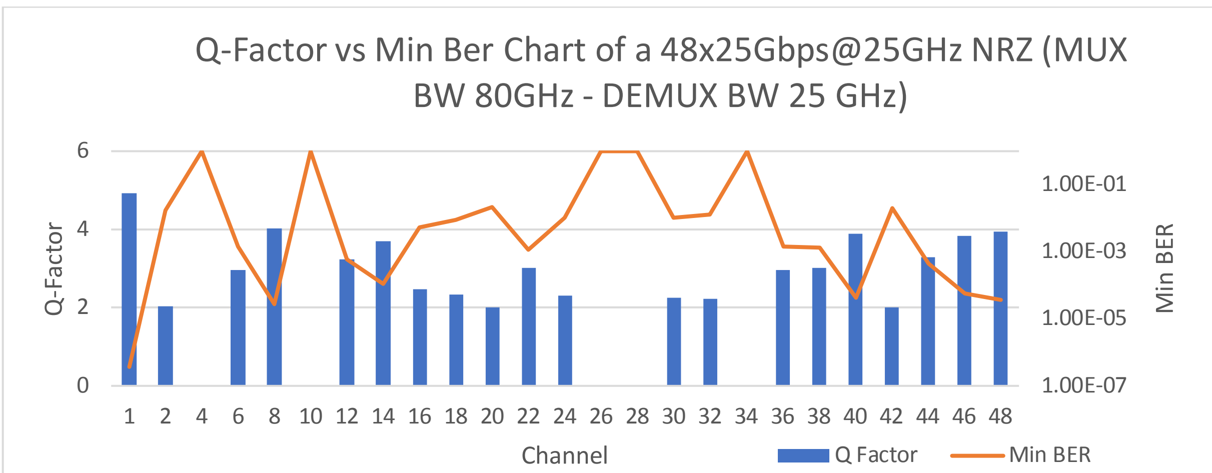

Figure 4.42: Q Factor vs BER of 25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 25 GHz

Figure 4.41 and Figure 4.42 represented the signal data for a DWDM network with 25 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 25 GHz.

Figure 4.42 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 1, which had the lowest BER as well. Figure 4.41 showed the eye diagram of channel 1 with its Q factor, BER and eye height. The BW efficiency was 89.58% because only 43 out of 48 channels was recognisable. Five of the channels had BER = 1 and Q = 0.

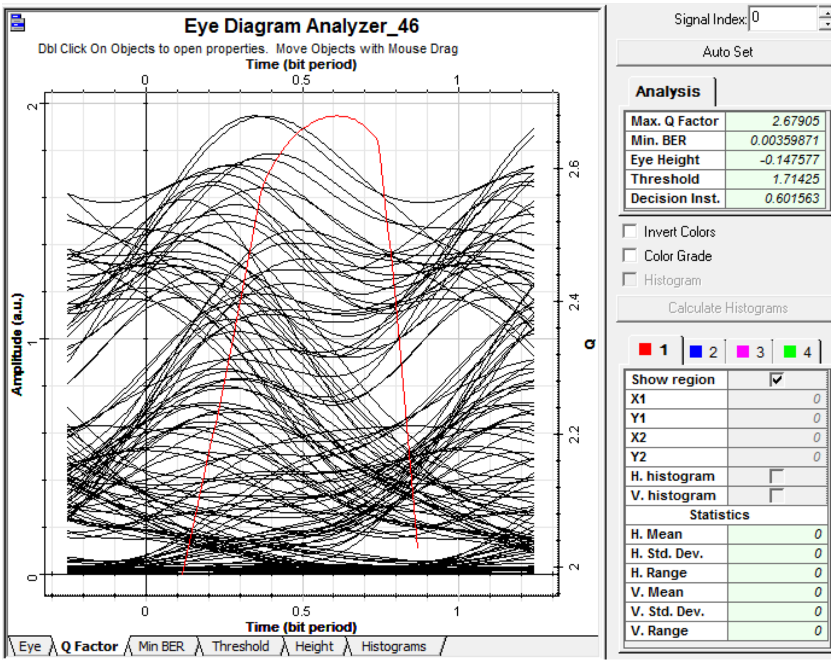

Figure 4.43: Eye Diagram of 25 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 12.5 GHz

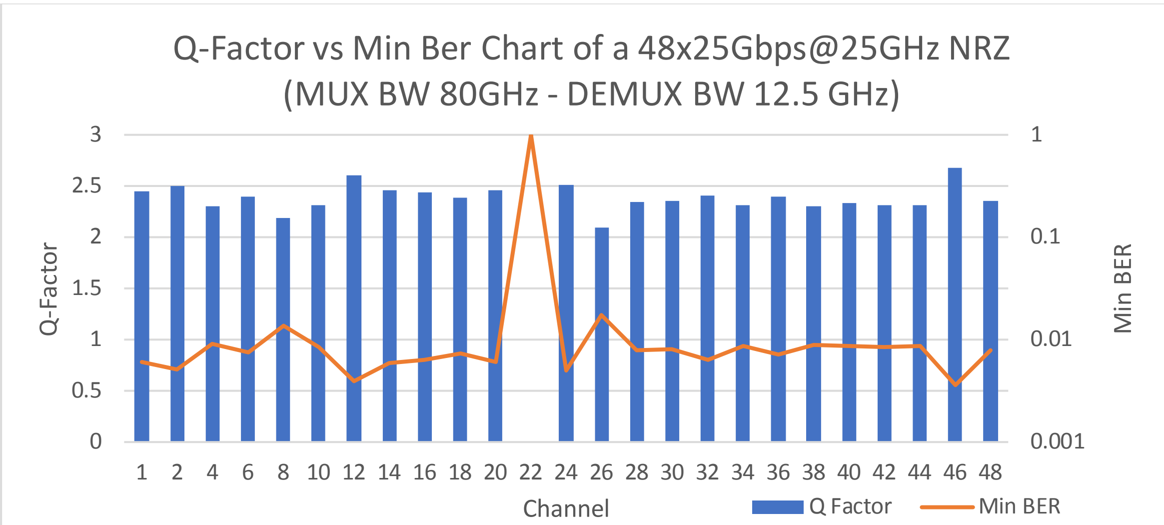

Figure 4.44: Q Factor vs BER of 25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 12.5 GHz

Figure 4.43 and Figure 4.44 represented the signal data for a DWDM network with 25 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 12.5 GHz.

Figure 4.44 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 46, which had the lowest BER as well. Figure 4.43 shows the eye diagram of channel 46 with its Q factor, BER and eye height. The BW efficiency was 97.91% because 47 out of 48 channels were recognisable. One channel had BER = 1 and Q = 0.

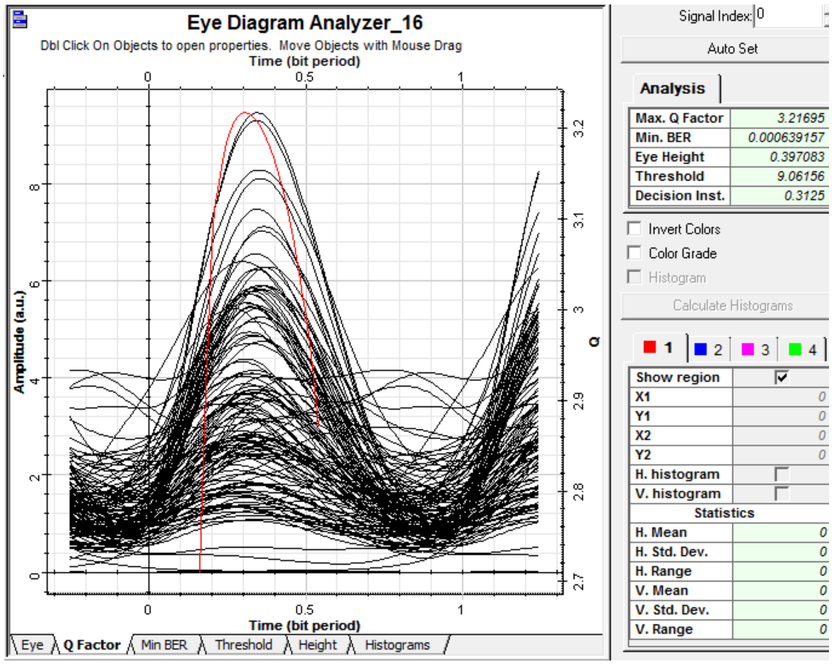

Figure 4.45: Eye Diagram of 25 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 25 GHz and DEMUX BW = 80 GHz

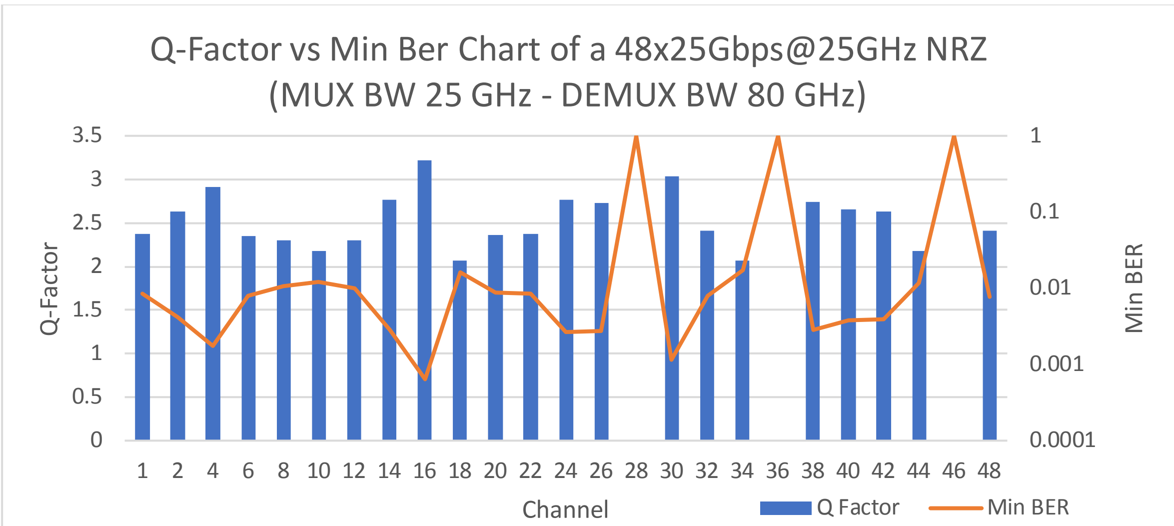

Figure 4.46: Q Factor vs BER of 25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 25 GHz and DEMUX BW = 80 GHz

Figure 4.45 and Figure 4.46 represented the signal data for a DWDM network with 25 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 25 GHz and DEMUX BW = 80 GHz.

Figure 4.46 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 16, which had the lowest BER as well. Figure 4.45 showed the eye diagram of channel 16 with its Q factor, BER and eye height. The BW efficiency was 93.75% because 45 out of 48 channels were transmitted. Three channels had a BER = 1 and Q = 0.

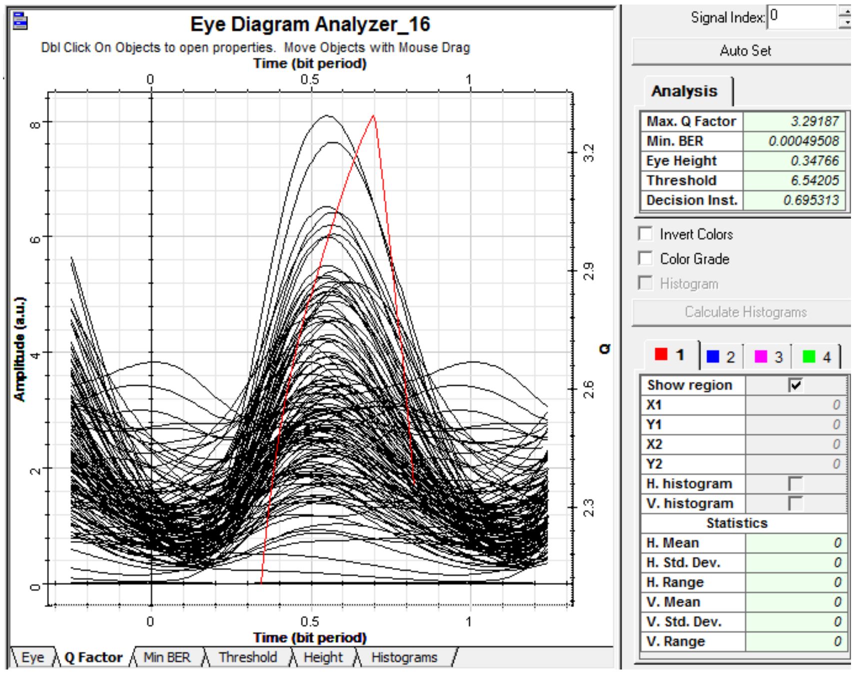

Figure 4.47: Eye Diagram of 25 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 12.5 GHz and DEMUX BW = 80 GHz

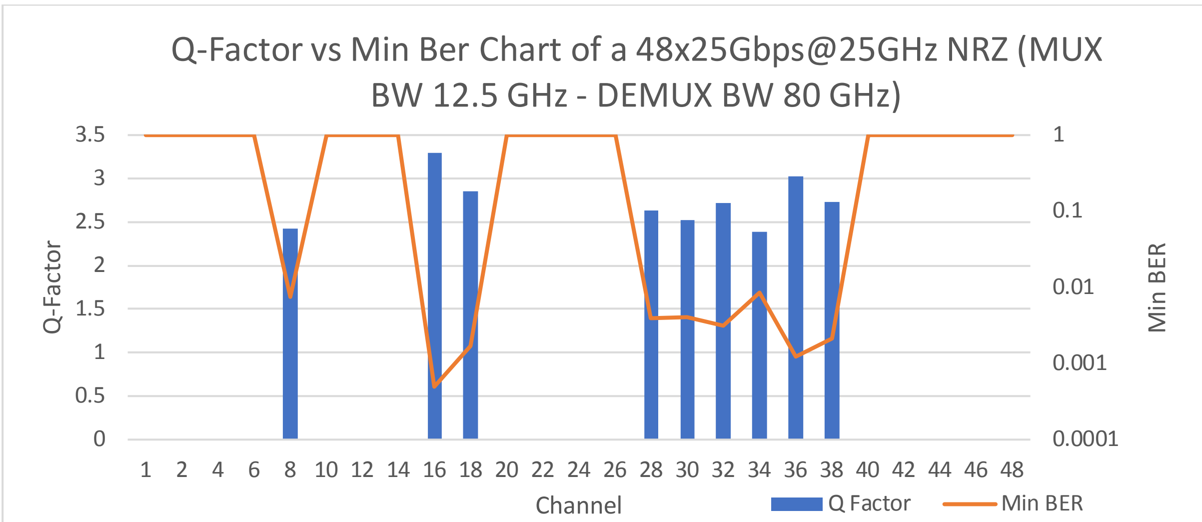

Figure 4.48: Q Factor vs BER of 25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 12.5 GHz and DEMUX BW = 80 GHz

Figure 4.47 and Figure 4.48 represented the signal data for a DWDM network with 25 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 12.5 GHz and DEMUX BW = 80 GHz.

Figure 4.48 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 16, which had the lowest BER as well. Figure 4.47 showed the eye diagram of channel 16 with its Q factor, BER and eye height. The BW efficiency was 66.66% because 32 out of 48 channels were recognisable. Sixteen channels had BER =1 and Q = 0.

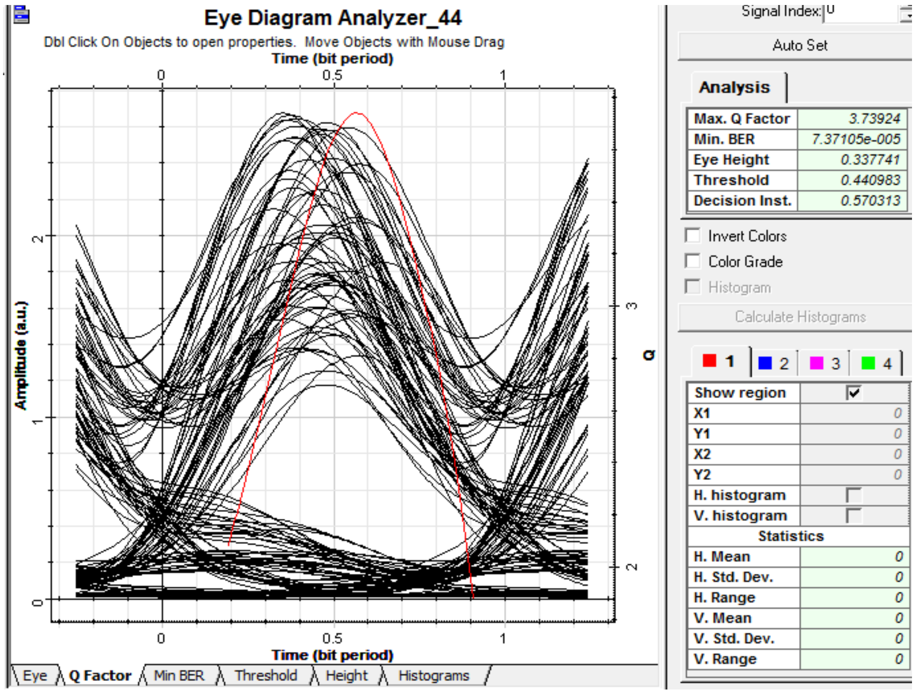

Figure 4.49 Eye Diagram of 25 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 25 GHz and DEMUX BW = 25 GHz

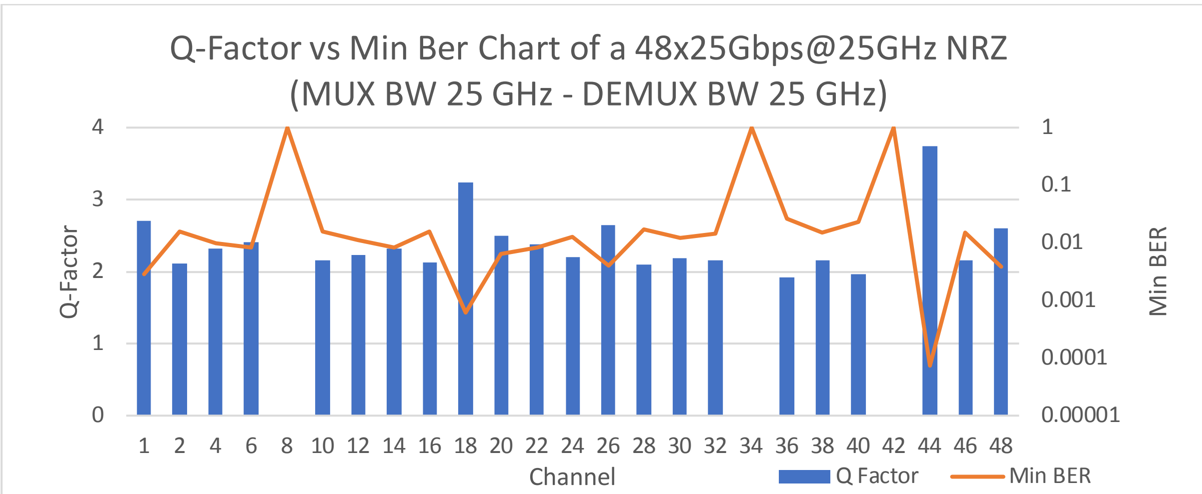

Figure 4.50: Q Factor vs BER of 25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 25 GHz and DEMUX BW = 25 GHz

Figure 4.49 and Figure 4.50 represented the signal data for a DWDM network with 25 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 25 GHz and DEMUX BW = 25 GHz.

Figure 4.50 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 44, which had the lowest BER as well. Figure 4.49 showed the eye diagram of channel 44 with its Q factor, BER and eye height. The BW efficiency was 93.75% because 45 out 48 channels were recognisable. Three channels had a BER = 1 and Q = 0.

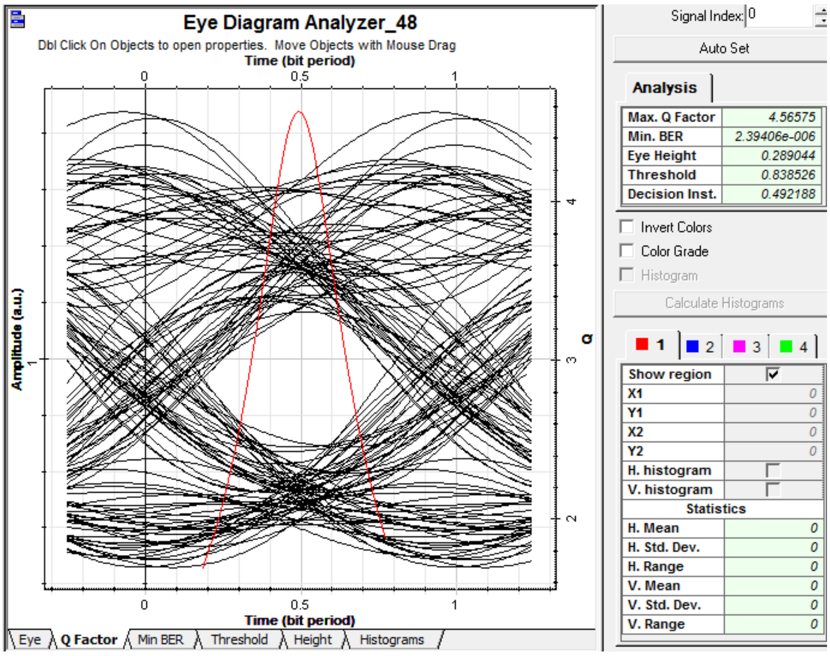

Figure 4.51: Eye Diagram of 25 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, ER = 5dB, Rectangular Filter, MUX BW = 80 GHz and DEMUX BW = 25 GHz

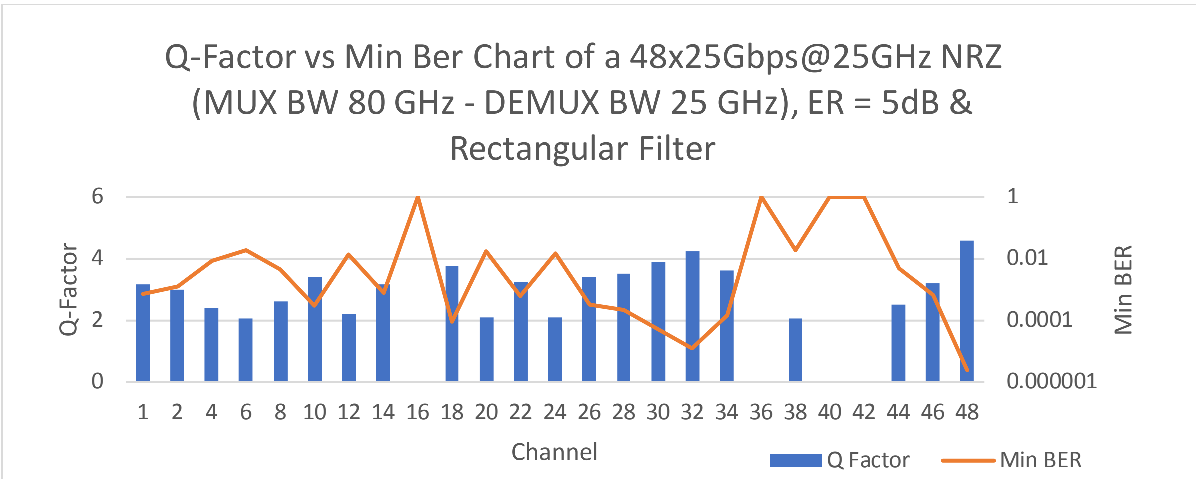

Figure 4.52: Q Factor vs BER of 25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, ER = 5dB, Rectangular Filter, MUX BW = 80 GHz and DEMUX BW = 25 GHz

Figure 4.51 and Figure 4.52 represented the signal data for a 25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, ER = 5dB and a Rectangular Filter. The MUX BW = 80 GHz and DEMUX BW = 25 GHz.

Figure 4.52 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 48, which had the lowest BER as well. Figure 4.51 showed the eye diagram of channel 48 with its Q factor, BER and eye height. The BW efficiency was 91.66% because 44 out of 48 channels had a recognisable signal. Four channels had BER =1 and Q = 0.

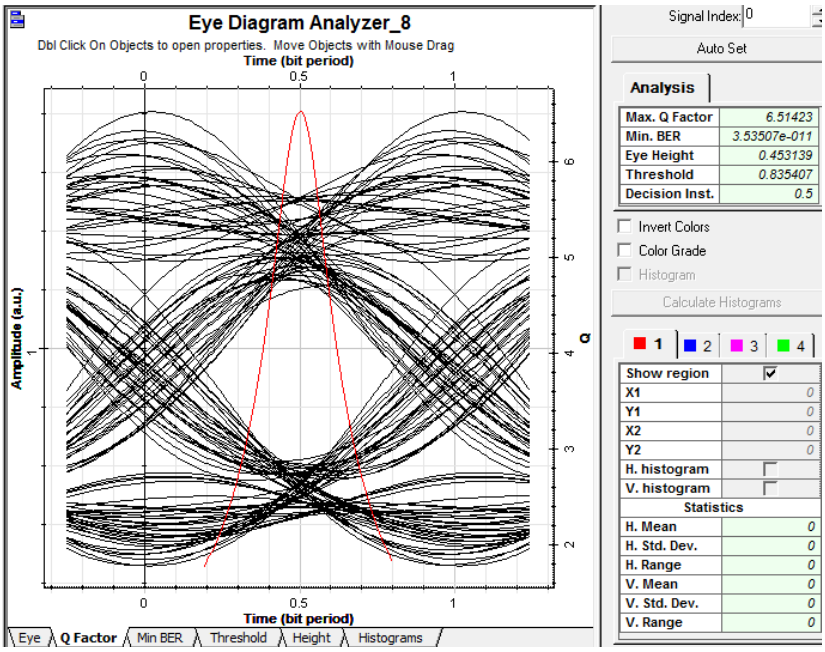

Figure 4.53: Eye Diagram of 25 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, ER = 5dB, Rectangular Filter, MUX BW = 25 GHz and DEMUX BW = 25 GHz

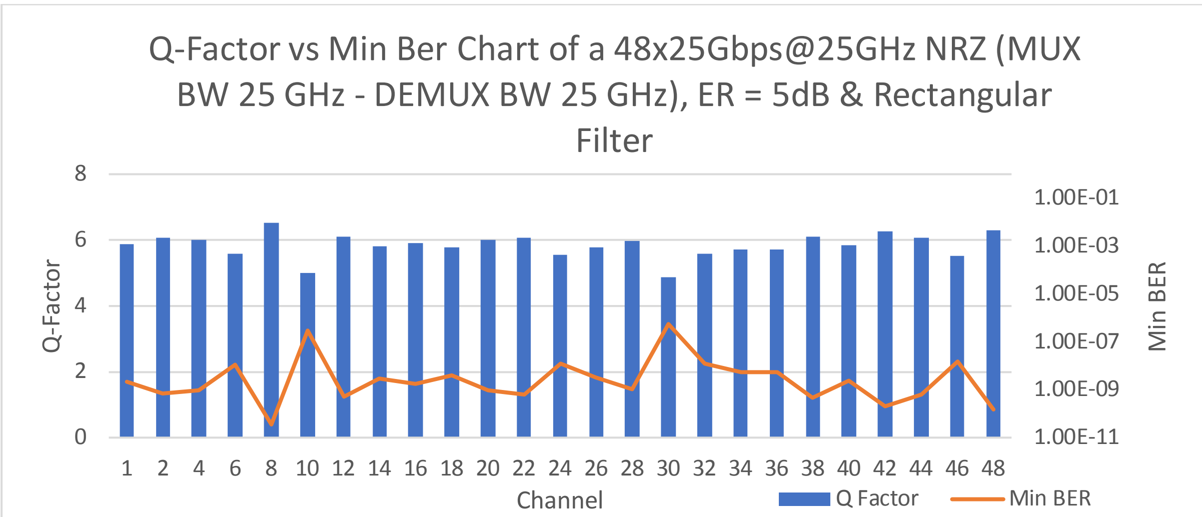

Figure 4.54: Q Factor vs BER of 25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, ER = 5dB, Rectangular Filter, MUX BW = 25 GHz and DEMUX BW = 25 GHz

Figure 4.53 and Figure 4.54 represented the signal data for a 25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, ER = 5dB and a Rectangular Filter. The MUX BW = 25 GHz and DEMUX BW = 25 GHz.

Figure 4.54 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 8, which had the lowest BER as well. Figure 4.53 showed the eye diagram of channel 8 with its Q factor, BER and eye height. The BW efficiency was 100% since all transmitted channels were received.

4.7 The 48 Channel x 25 Gbps at 25 GHz Spacing using RZ

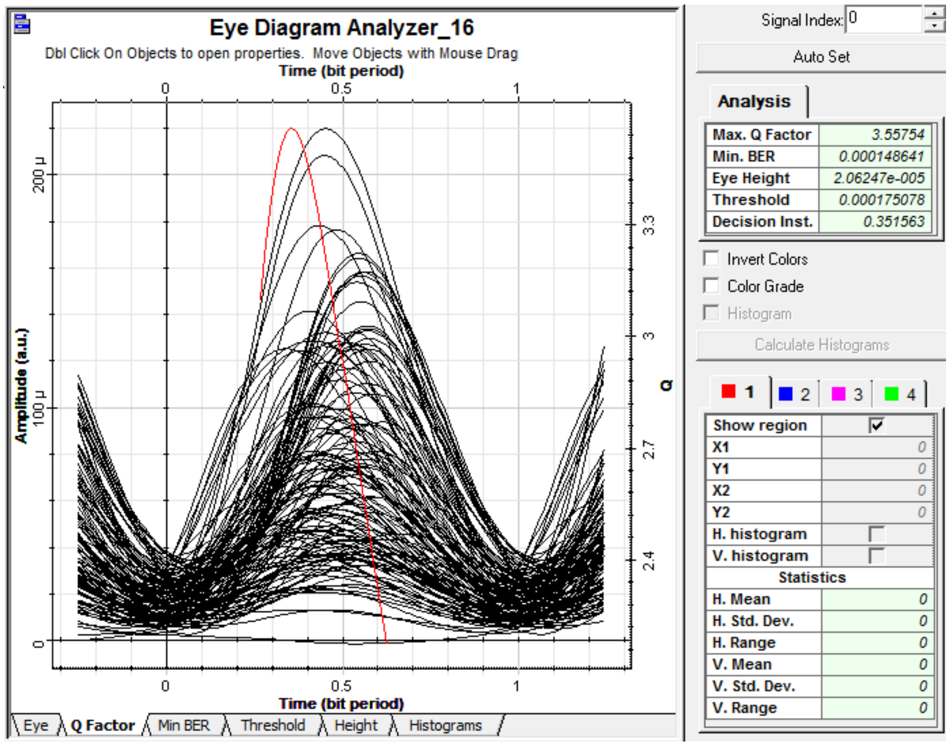

Figure 4.55: Eye Diagram of 25 GHz Channel Spacing Using RZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

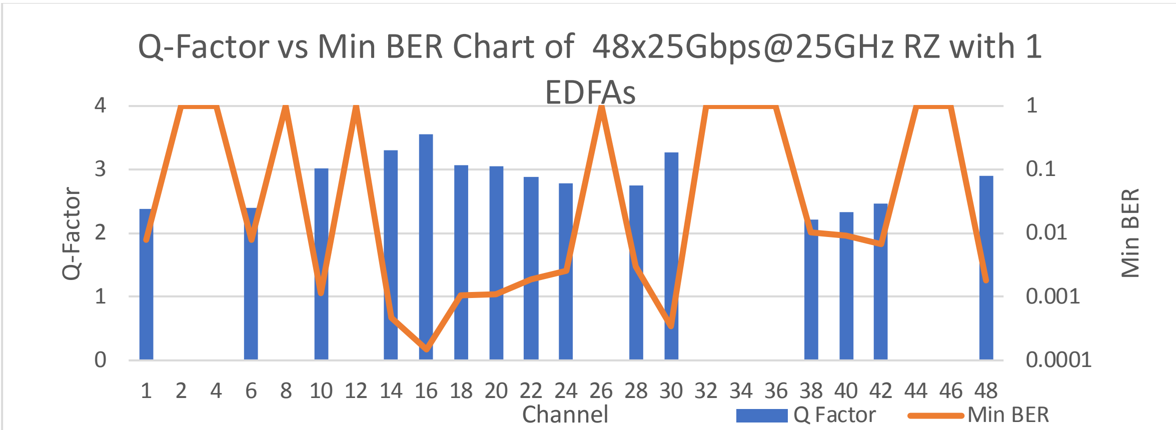

Figure 4.56: Q Factor vs BER of 25 GHz Spacing Using RZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.55 and Figure 4.56 represented the signal data for a DWDM network with 25 GHz channel spacing using RZ and 1 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.56 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 16, which had the lowest BER as well. Figure 4.55 showed the eye diagram of channel 16 showing its Q factor, BER and eye height. The BW efficiency was 79.16% because 38 out of 48 channels were recognisable. Ten channels had BER =1 and Q = 0.

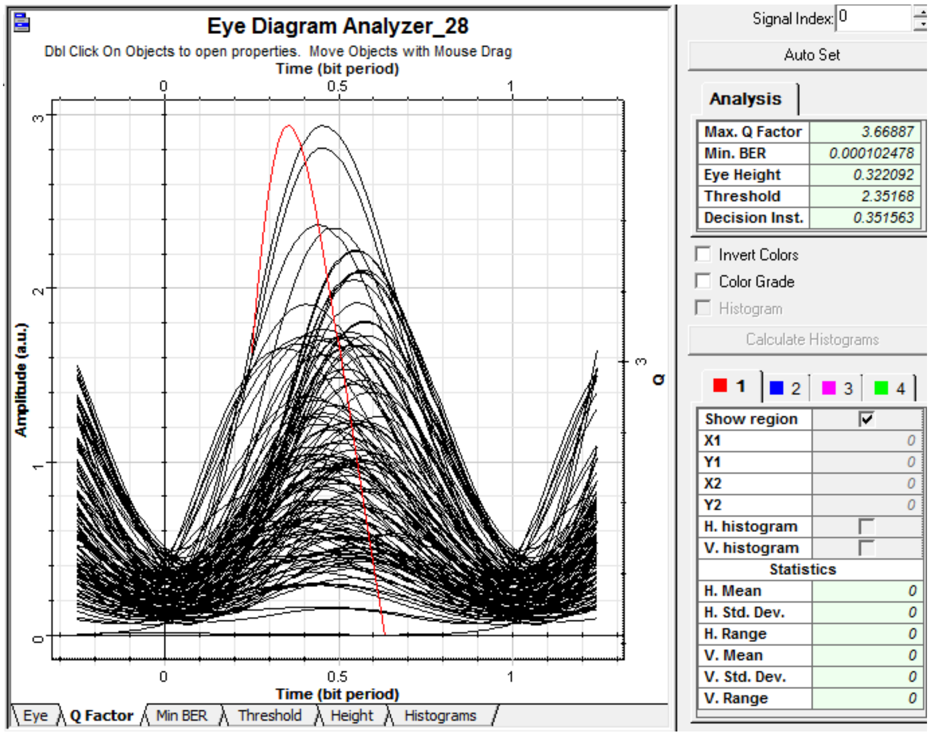

Figure 4.57: Eye Diagram of 25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

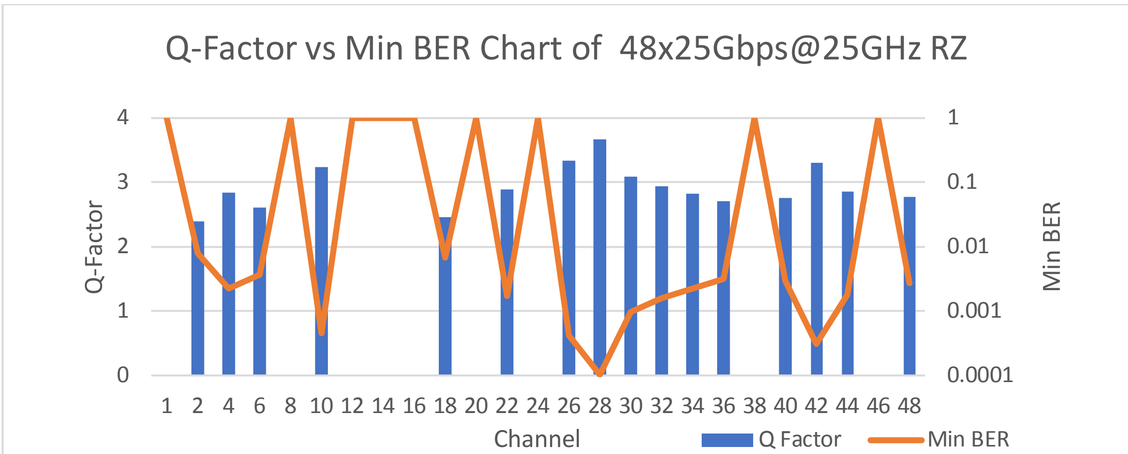

Figure 4.58: Q Factor vs BER of 25 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.57 and Figure 4.58 represented the signal data for a DWDM network with 25 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.58 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 28, which had the lowest BER as well. Figure 4.57 showed the eye diagram of channel 28 with its Q factor, BER and eye height. The BW efficiency was 83.33% because 40 out of 48 channels were recognisable. Eight channels had BER =1 and Q = 0.

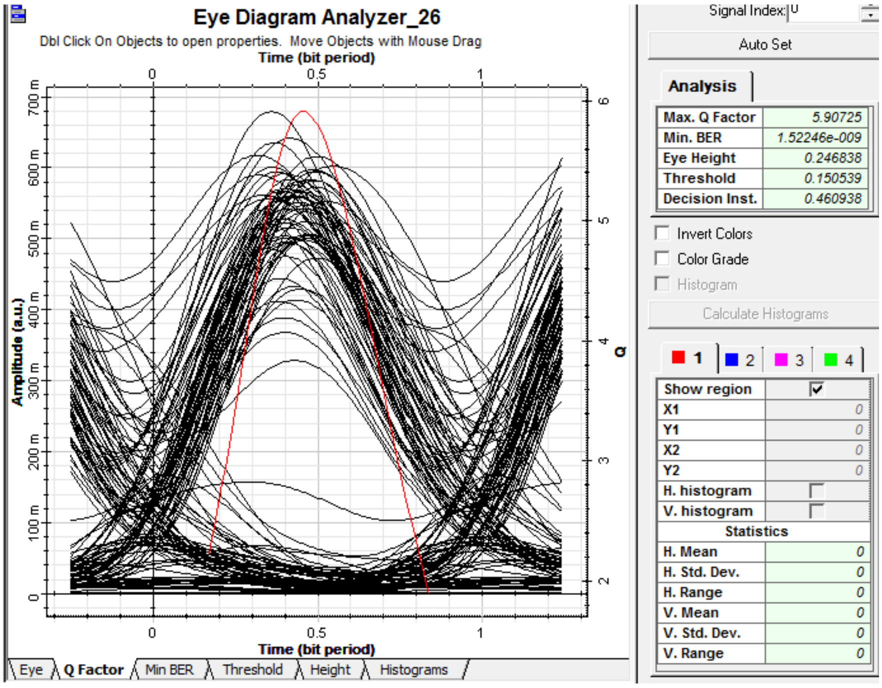

Figure 4.59: Eye Diagram of 25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 25 GHz

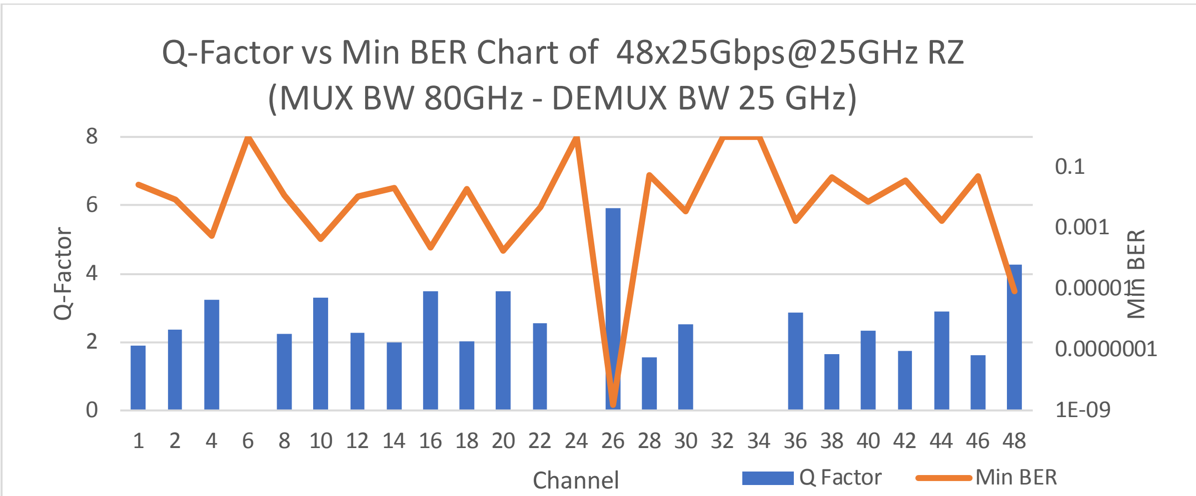

Figure 4.60: Q Factor vs BER of 25 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 25 GHz

Figure 4.59 and Figure 4.60 represented the signal data for a DWDM network with 25 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 25 GHz.

Figure 4.60 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 26, which had the lowest BER as well. Figure 4.59 showed the eye diagram of channel 26 with its Q factor, BER and eye height. The BW efficiency was 91.66% because 44 out of 48 channels were recognisable. Four channels had BER =1 and Q = 0.

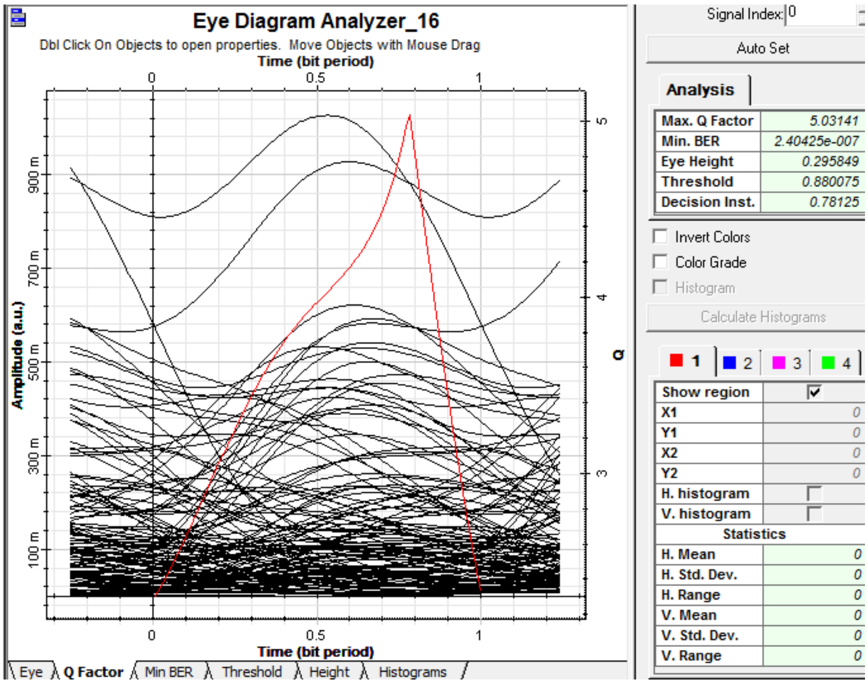

Figure 4.61: Eye Diagram of 25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 12.5 GHz

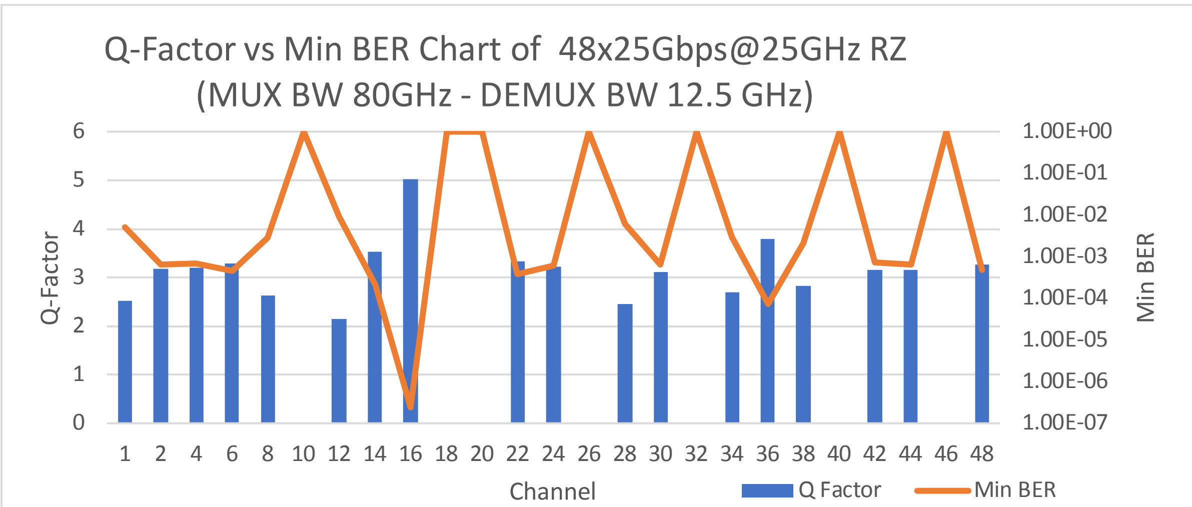

Figure 4.62: Q Factor vs BER of 25 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 12.5 GHz

Figure 4.61 and Figure 4.62 represented the signal data for a DWDM network with 25 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 12.5 GHz.

Figure 4.62 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 16, which had the lowest BER as well. Figure 4.61 showed the eye diagram of channel 16 with its Q factor, BER and eye height. The BW efficiency was 85.41% because 41 out of 48 channels were recognisable. Seven channels had BER =1 and Q = 0.

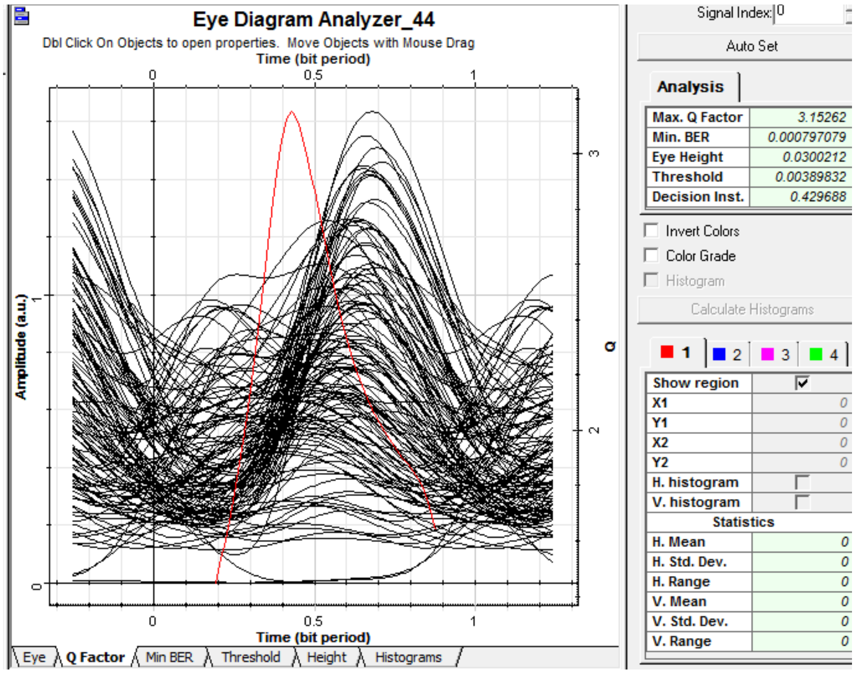

Figure 4.63 Eye Diagram of 25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 25 GHz and DEMUX BW = 80 GHz

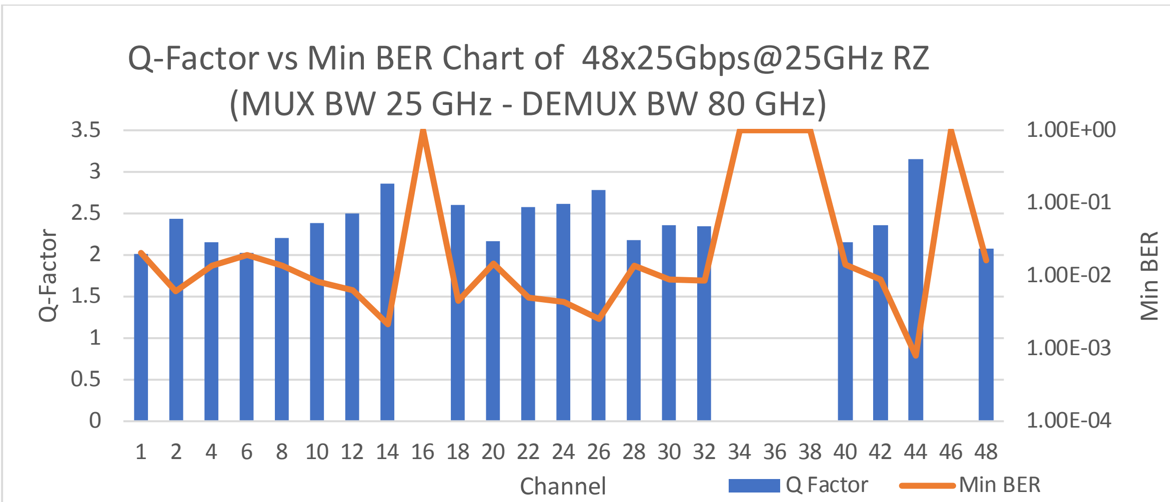

Figure 4.64: Q Factor vs BER of 25 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 25 GHz and DEMUX BW = 80 GHz

Figure 4.63 and Figure 4.64 represented the signal data for a DWDM network with 25 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 25 GHz and DEMUX BW = 80 GHz.

Figure 4.64 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 44, which had the lowest BER as well. Figure 4.63 showed the eye diagram of channel 44 with its Q factor, BER and eye height. The BW efficiency was 89.58% because 43 out of 48 channels were recognisable. Five channels had BER =1 and Q = 0.

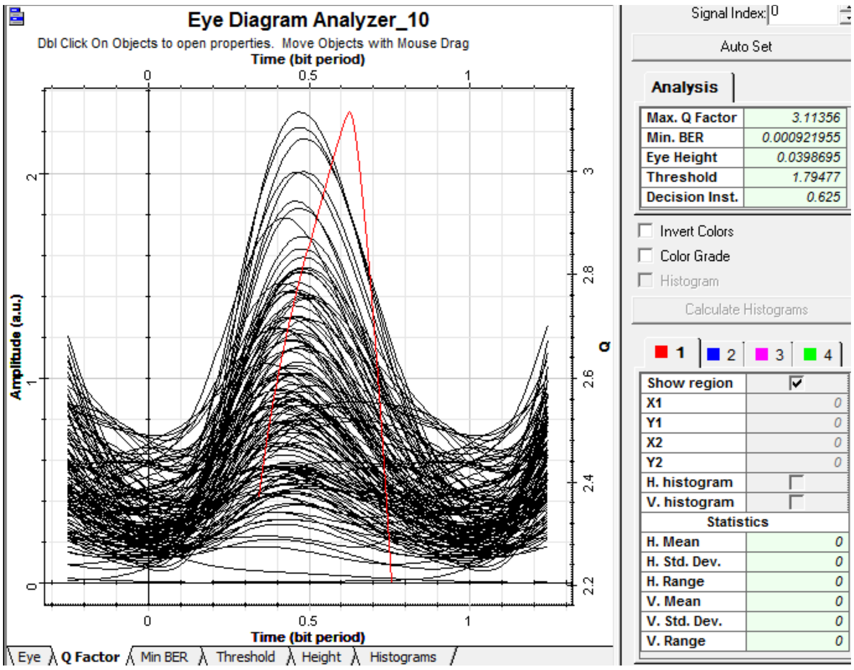

Figure 4.65: Eye Diagram of 25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 12.5 GHz and DEMUX BW = 80 GHz

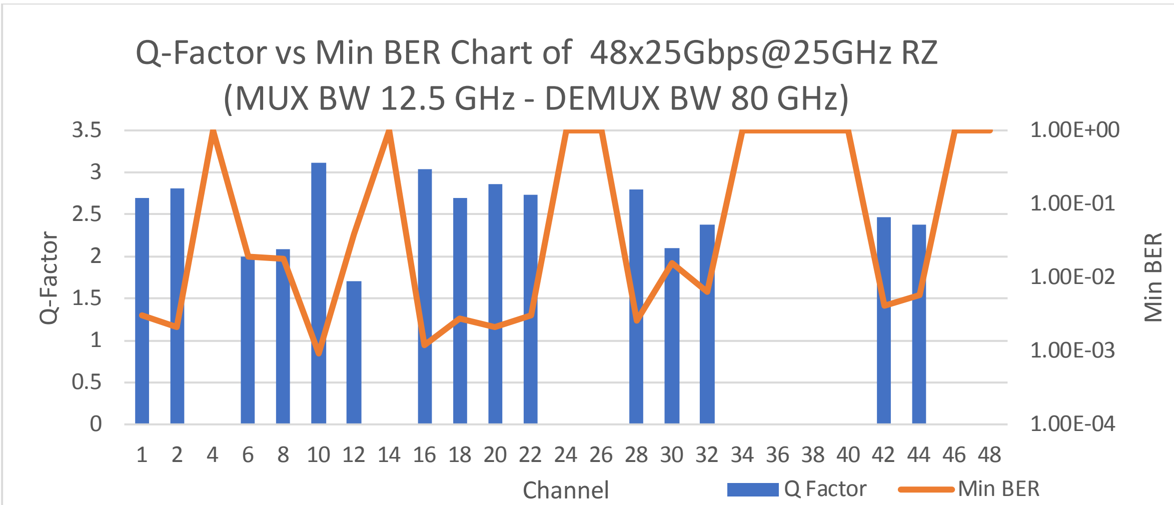

Figure 4.66: Q Factor vs BER of 25 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 12.5 GHz and DEMUX BW = 80 GHz

Figure 4.65 and Figure 4.66 represented the signal data for a DWDM network with 25 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 12.5 GHz and DEMUX BW = 80 GHz.

Figure 4.66 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 10, which had the lowest BER as well. Figure 4.65 showed the eye diagram of channel 10 with its Q factor, BER and eye height. The BW efficiency was 79.16% because 38 out of 48 channels were recognisable. Ten channels had BER =1 and Q = 0.

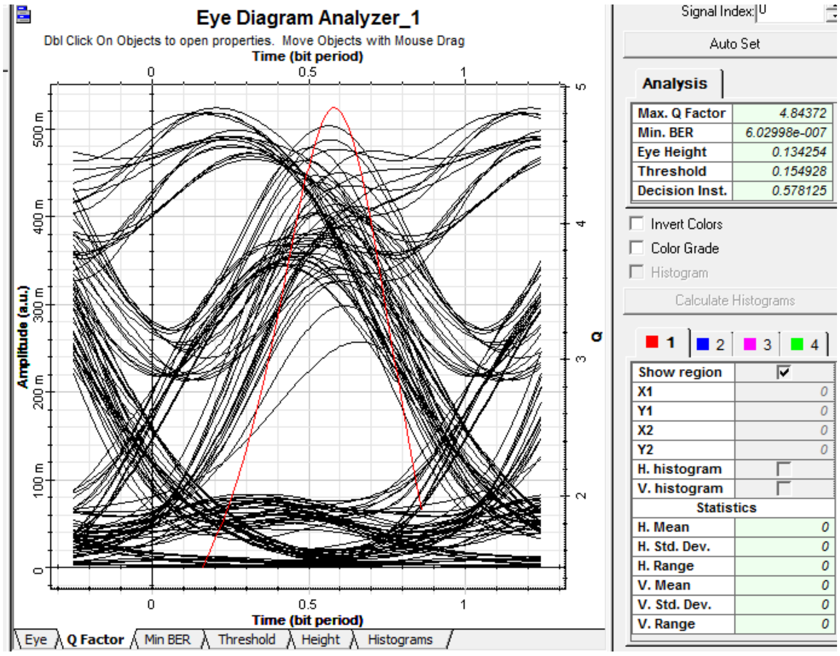

Figure 4.67:Eye Diagram of 25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 25 GHz and DEMUX BW = 25 GHz

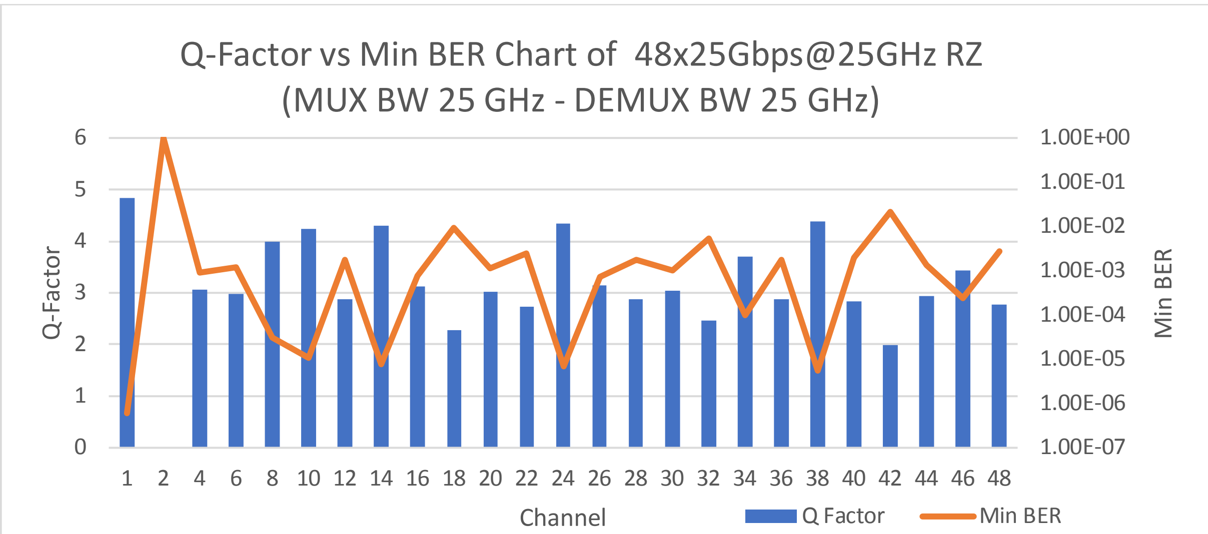

Figure 4.68: Q factor vs BER of 25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 25 GHz and DEMUX BW = 25 GHz

Figure 4.67 and Figure 4.68 represented the signal data for a DWDM network with 25 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 25 GHz and DEMUX BW = 25 GHz.

Figure 4.68 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 1, which had the lowest BER as well. Figure 4.67 showed the eye diagram of channel 1 with its Q factor, BER and eye height. The BW efficiency was 97.91% because 47 out of 48 channels were recognisable. One channel had BER =1 and Q = 0.

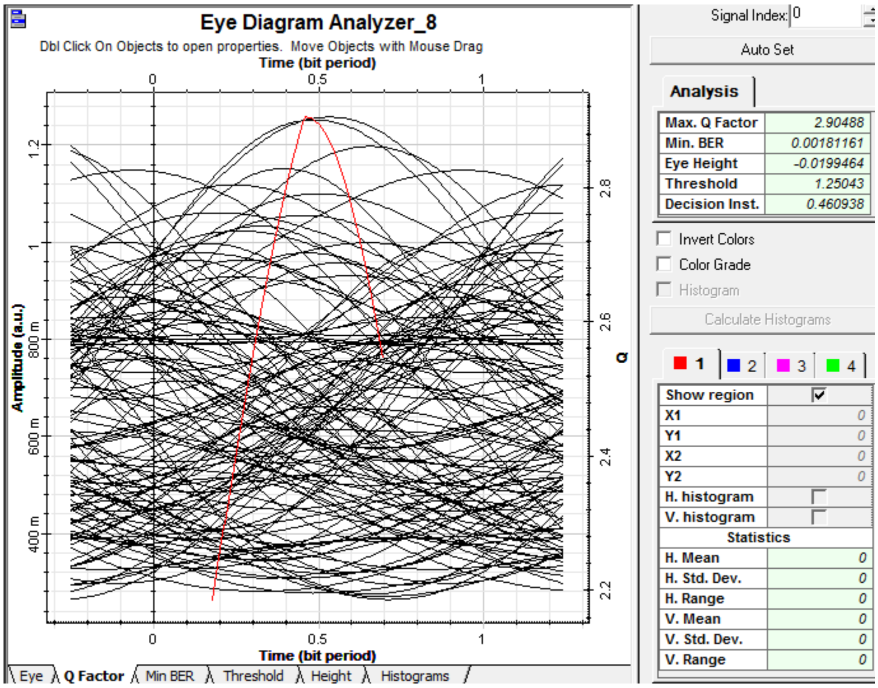

Figure 4.69: Eye Diagram of 25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, ER = 5dB, Rectangular Filter, MUX BW = 80 GHz and DEMUX BW = 25 GHz

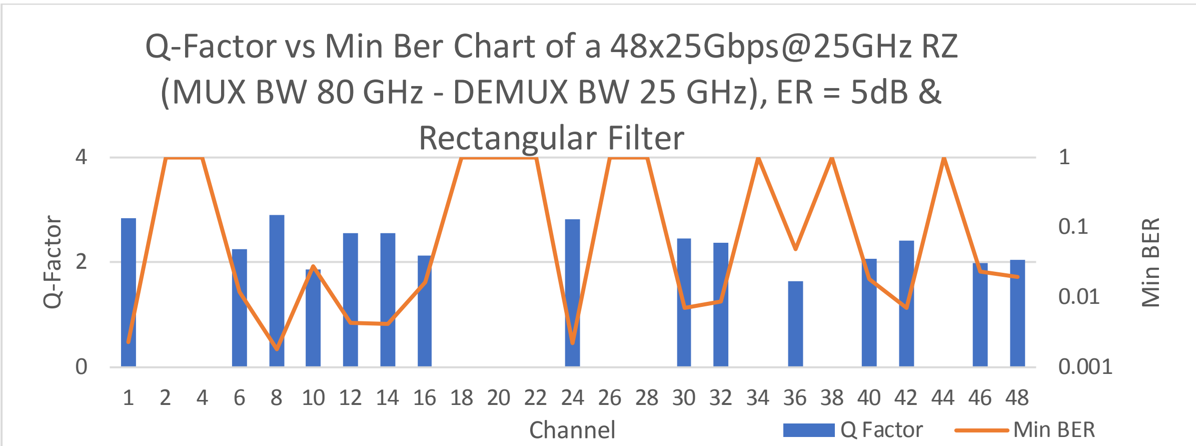

Figure 4.70: Q Factor vs BER of 25 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, ER = 5dB, Rectangular Filter, MUX BW = 80 GHz and DEMUX BW = 25 GHz

Figure 4.69 and Figure 4.70 represented the signal data for a DWDM network with 25 GHz Spacing using RZ, Post Symmetric Dispersion with 3 EDFAs, ER = 5dB and a Rectangular Filter. The MUX BW = 80 GHz and DEMUX BW = 25 GHz.

Figure 4.70 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 8, which had the lowest BER as well. Figure 4.69 showed the eye diagram of channel 8 with its Q factor, BER and eye height. The BW efficiency was 79.16% because 38 out of 48 channels were recognisable. Ten channels had BER =1 and Q = 0.

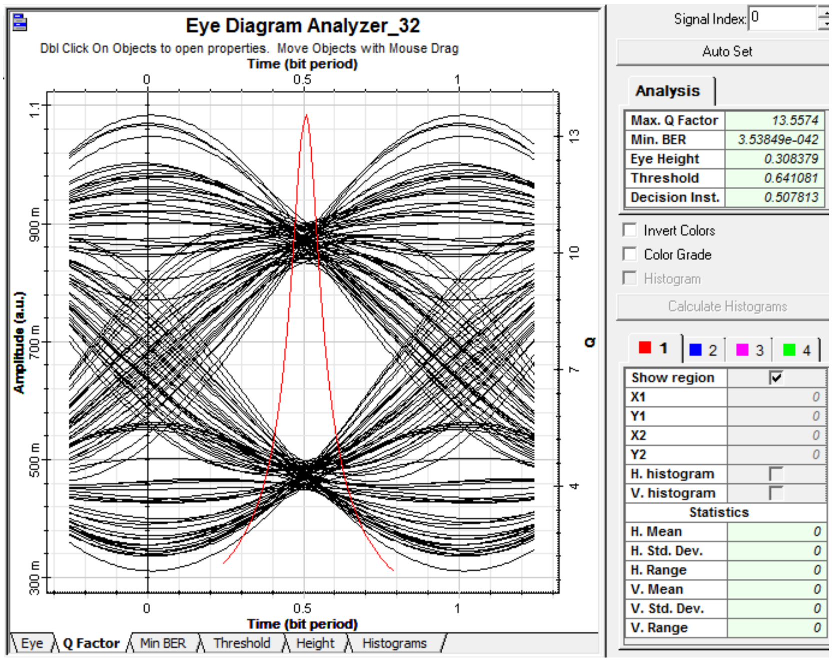

Figure 4.71: Eye Diagram of 25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, ER = 5dB, Rectangular Filter, MUX BW = 25 GHz and DEMUX BW = 25 GHz

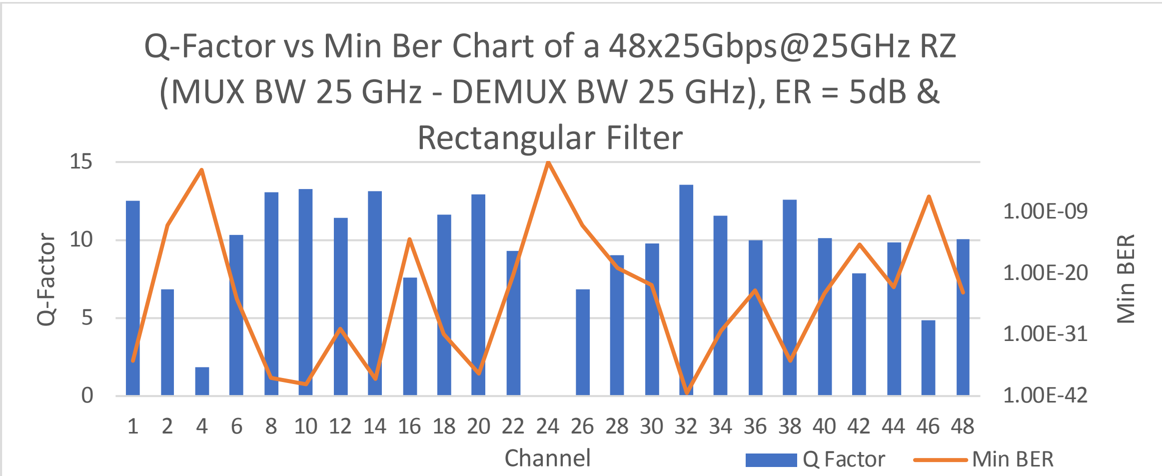

Figure 4.72: Q factor vs BER of 25 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, ER = 5dB, Rectangular Filter, MUX BW = 25 GHz and DEMUX BW = 25 GHz

Figure 4.71 and Figure 4.72 represented the signal data for a DWDM network with 25 GHz Spacing using RZ, Post Symmetric Dispersion with 3 EDFAs, ER = 5dB and a Rectangular Filter. The MUX BW = 25 GHz and DEMUX BW = 25 GHz.

Figure 4.72 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 32, which had the lowest BER as well. Figure 4.71 showed the eye diagram of channel 32 with its Q factor, BER and eye height. The BW efficiency was 97.91% because 47 out of 48 channels were recognisable. One channel had BER =1 and Q = 0

4.8 The 48 Channel x 25 Gbps at 12.5 GHz Spacing using NRZ

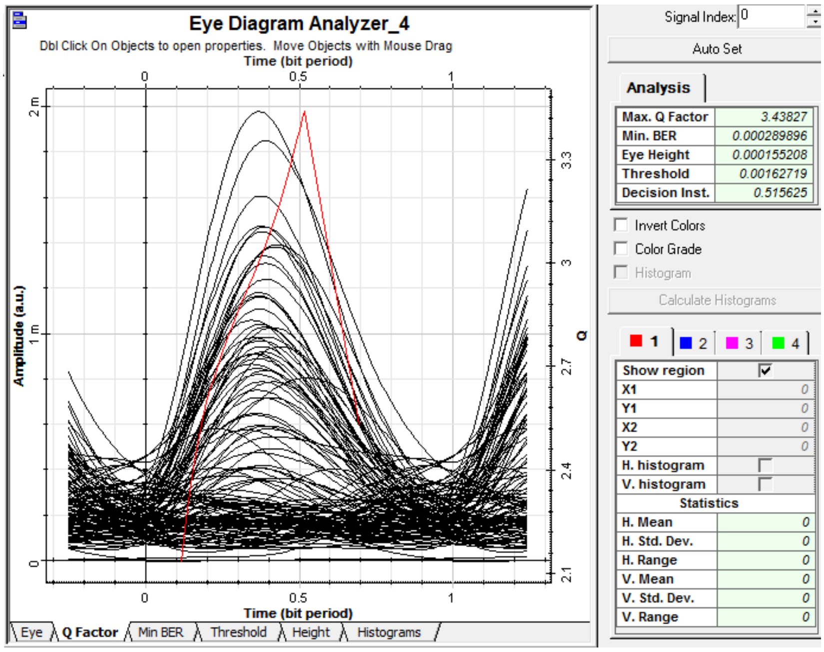

Figure 4.73: Eye Diagram of 12.5 GHz Channel Spacing Using NRZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

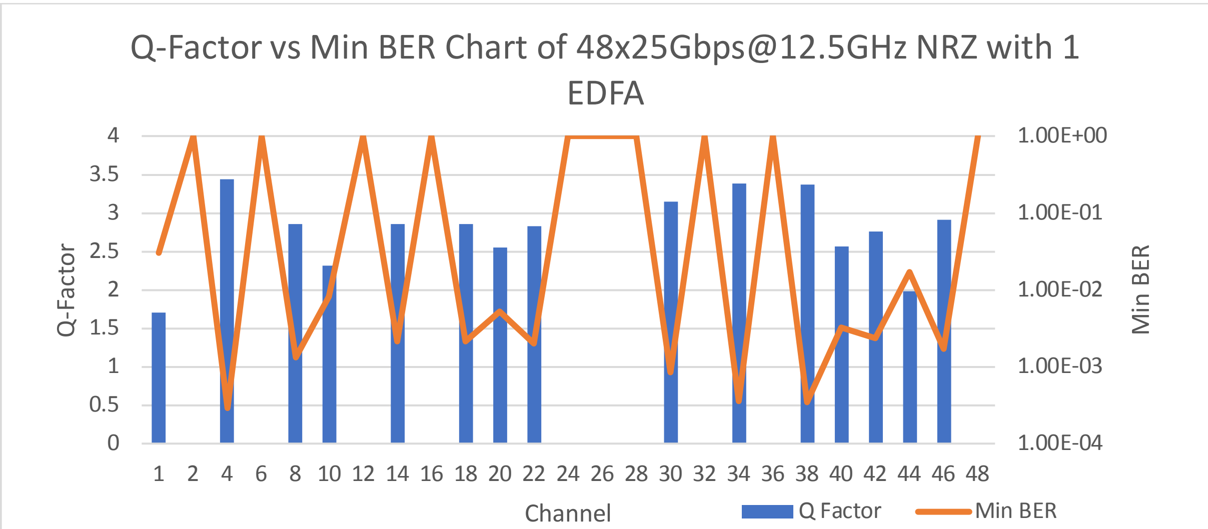

Figure 4.74: Q factor vs BER of 12.5 GHz Spacing Using NRZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.73 and Figure 4.74 represented the signal data for a DWDM network with 12.5 GHz channel spacing using NRZ and 1 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.74 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 4, which had the lowest BER as well. Figure 4.73 showed the eye diagram of channel 4 with its Q factor, BER and eye height. The BW efficiency was 81.25% because 39 out of 48 channels were recognisable. Nine channels had BER =1 and Q = 0.

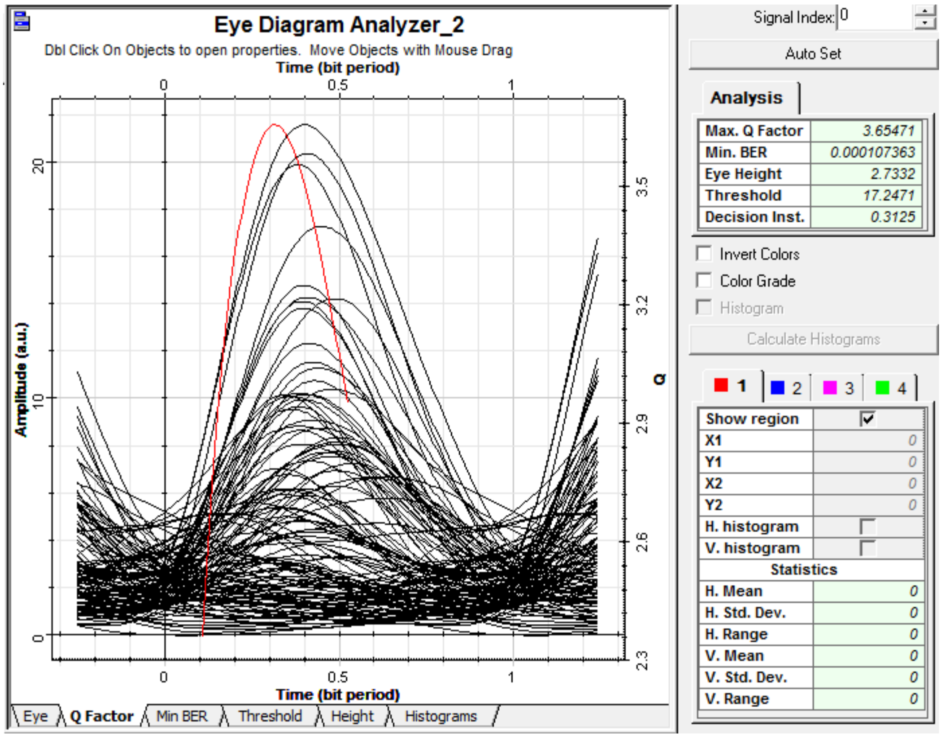

Figure 4.75: Eye Diagram of 12.5 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

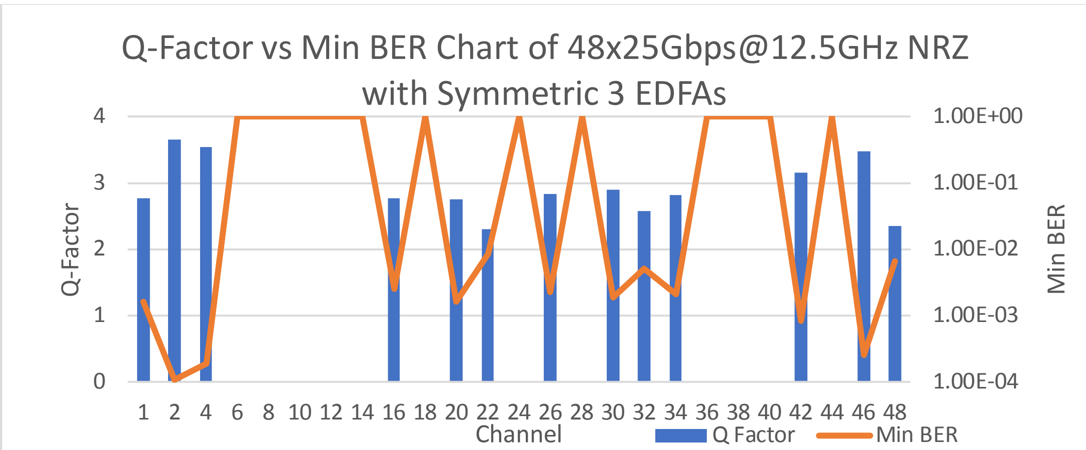

Figure 4.76: Q factor vs BER of 12.5 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.75 and Figure 4.76 represented the signal data for a DWDM network with 12.5 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.76 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 2, which had the lowest BER as well. Figure 4.75 showed the eye diagram of channel 2 with its Q factor, BER and eye height. The BW efficiency was 75% because 36 out of 48 channels were recognisable. Twelve channels had BER =1 and Q = 0

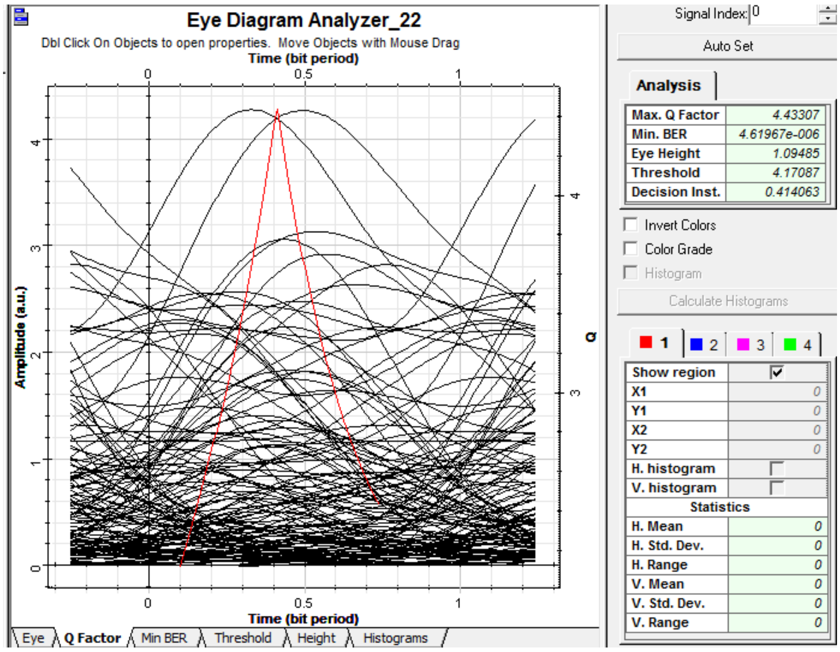

Figure 4.77: Eye Diagram of 12.5 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 12.5 GHz

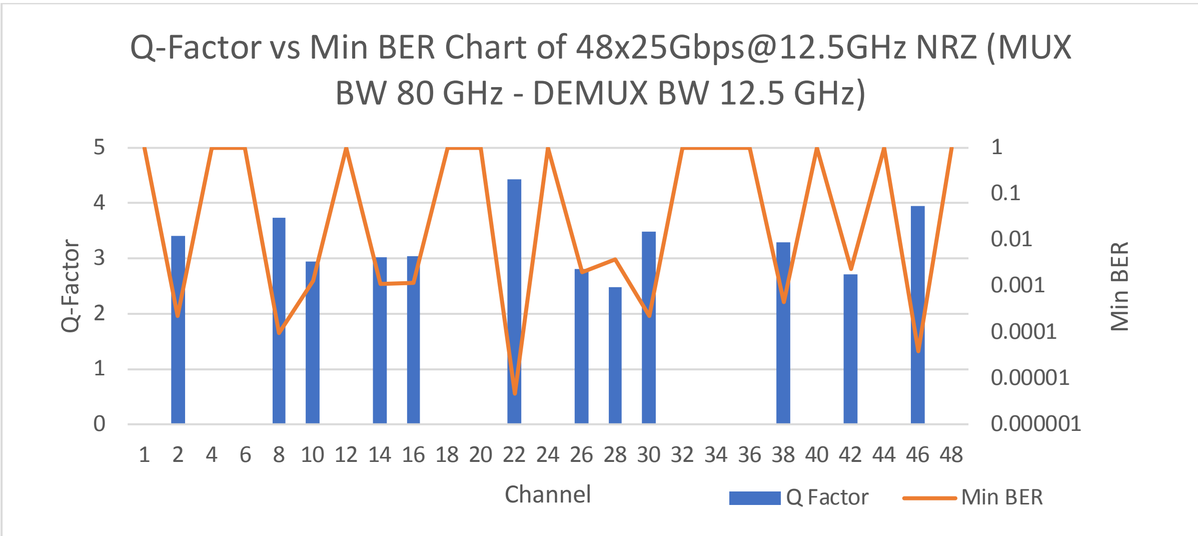

Figure 4.78: Q Factor vs BER of 12.5 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 12.5 GHz

Figure 4.77 and Figure 4.78 represented the signal data for a DWDM network with 12.5 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 12.5 GHz.

Figure 4.78 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 22, which had the lowest BER as well. Figure 4.77 showed the eye diagram of channel 22 with its Q factor, BER and eye height. The BW efficiency was 72.91% because 35 out of 48 channels were recognisable. Thirteen channels had BER =1 and Q = 0

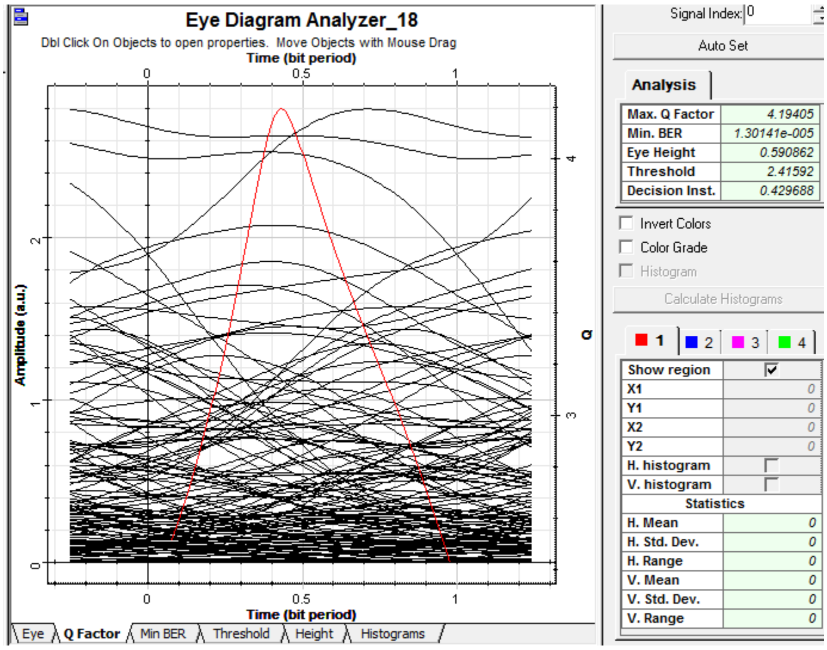

Figure 4.79: Eye Diagram of 12.5 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 6.25 GHz

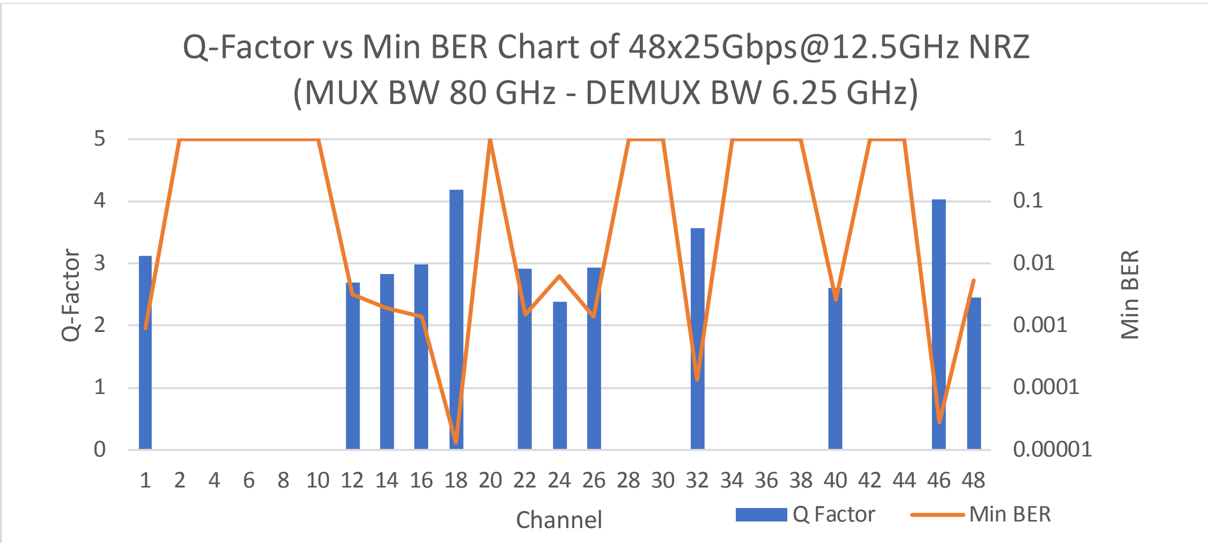

Figure 4.80: Q Factor vs BER of 12.5 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 6.25 GHz

Figure 4.79 and Figure 4.80 represented the signal data for a DWDM network with 12.5 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 6.25 GHz.

Figure 4.80 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 18, which had the lowest BER as well. Figure 4.79 showed the eye diagram of channel 18 with its Q factor, BER and eye height. The BW efficiency was 72.91% because 35 out of 48 channels were recognisable. Thirteen channels had BER =1 and Q = 0

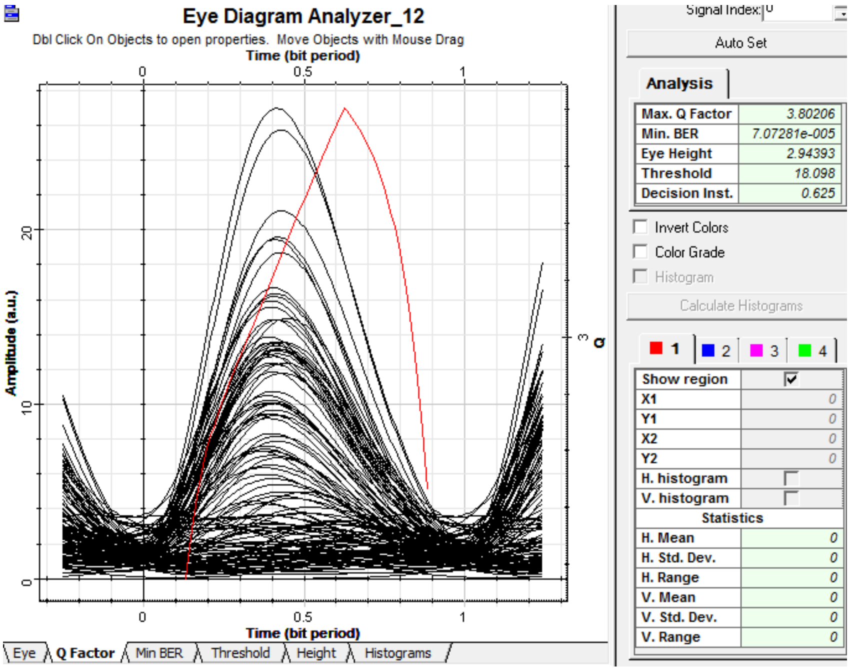

Figure 4.81: Eye Diagram of 12.5 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 12.5 GHz and DEMUX BW = 80 GHz

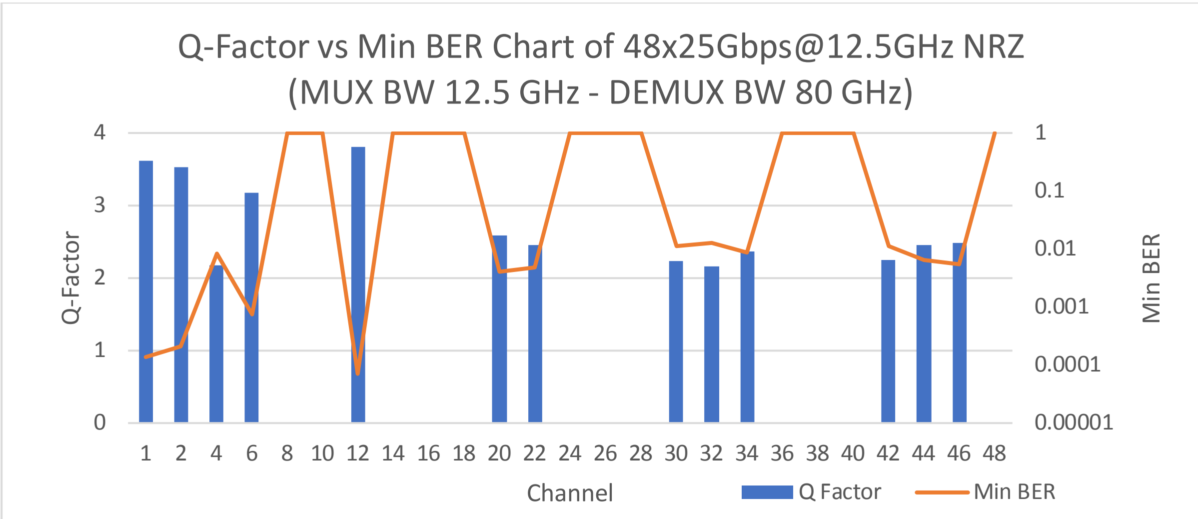

Figure 4.82: Q Factor vs BER of 12.5 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 12.5 GHz and DEMUX BW = 80 GHz

Figure 4.81 and Figure 4.82 represented the signal data for a DWDM network with 12.5 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 12.5 GHz and DEMUX BW = 80 GHz.

Figure 4.82 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 12, which had the lowest BER as well. Figure 4.81 showed the eye diagram of channel 12 with its Q factor, BER and eye height. The BW efficiency was 75% because 36 out of 48 channels were recognisable. Twelve channels had BER =1 and Q = 0

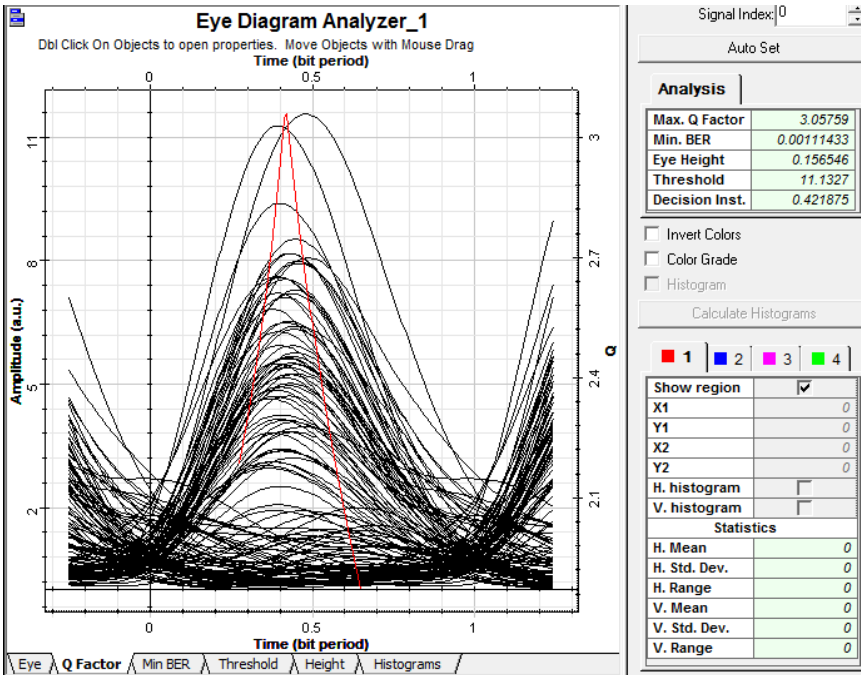

Figure 4.83: Eye Diagram of 12.5 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 6.25 GHz and DEMUX BW = 80 GHz

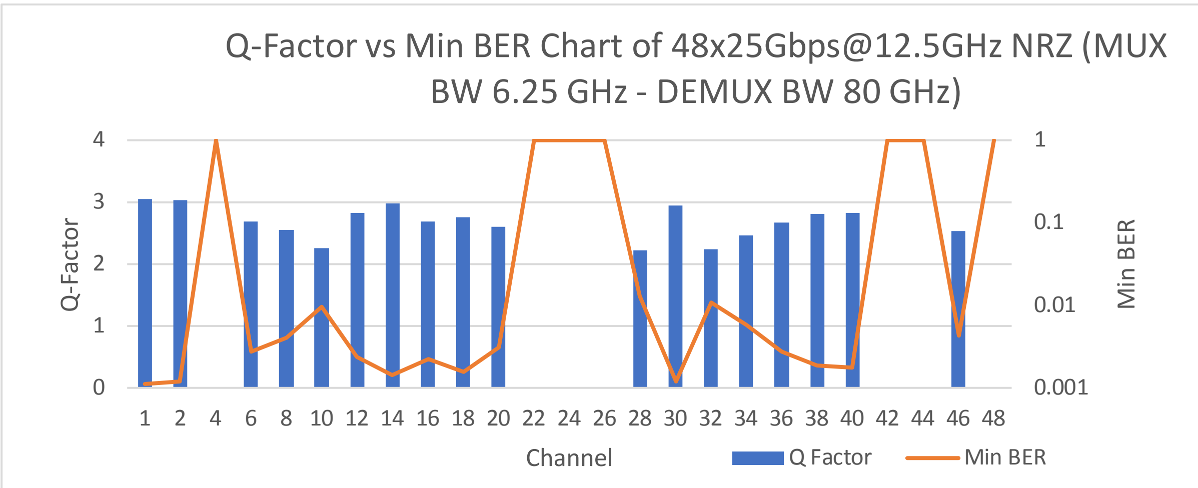

Figure 4.84: Q factor vs BER of 12.5 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 6.25 GHz and DEMUX BW = 80 GHz

Figure 4.83 and Figure 4.84 represented the signal data for a DWDM network with 12.5 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 6.25 GHz and DEMUX BW = 80 GHz.

Figure 4.84 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 1, which had the lowest BER as well. Figure 4.83 showed the eye diagram of channel 1 with its Q factor, BER and eye height. The BW efficiency was 85.41% because 41 out of 48 channels were recognisable. Seven channels had BER =1 and Q = 0

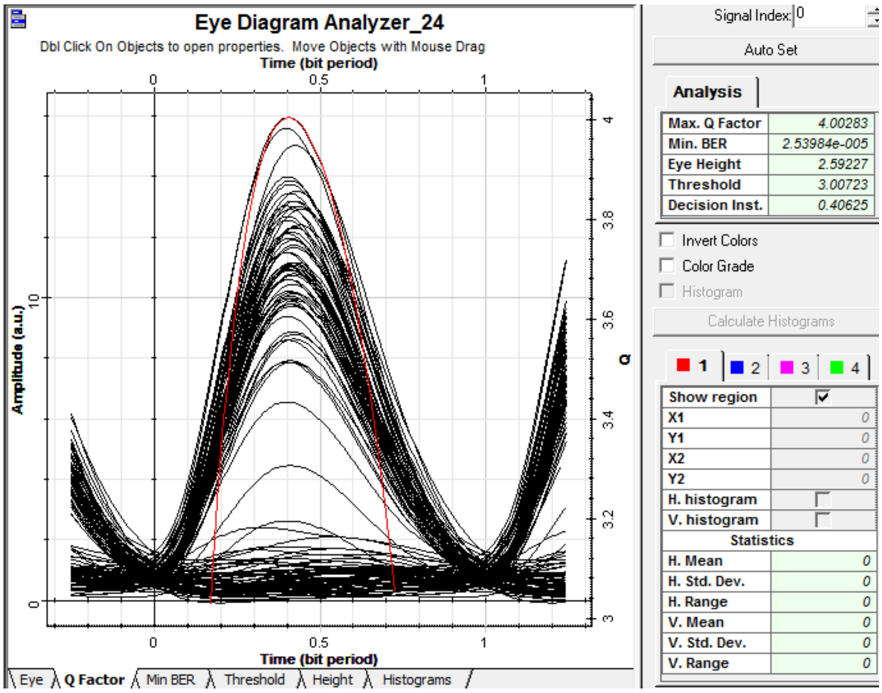

Figure 4.85: Eye Diagram of 12.5 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 3.125 GHz and DEMUX BW = 80 GHz

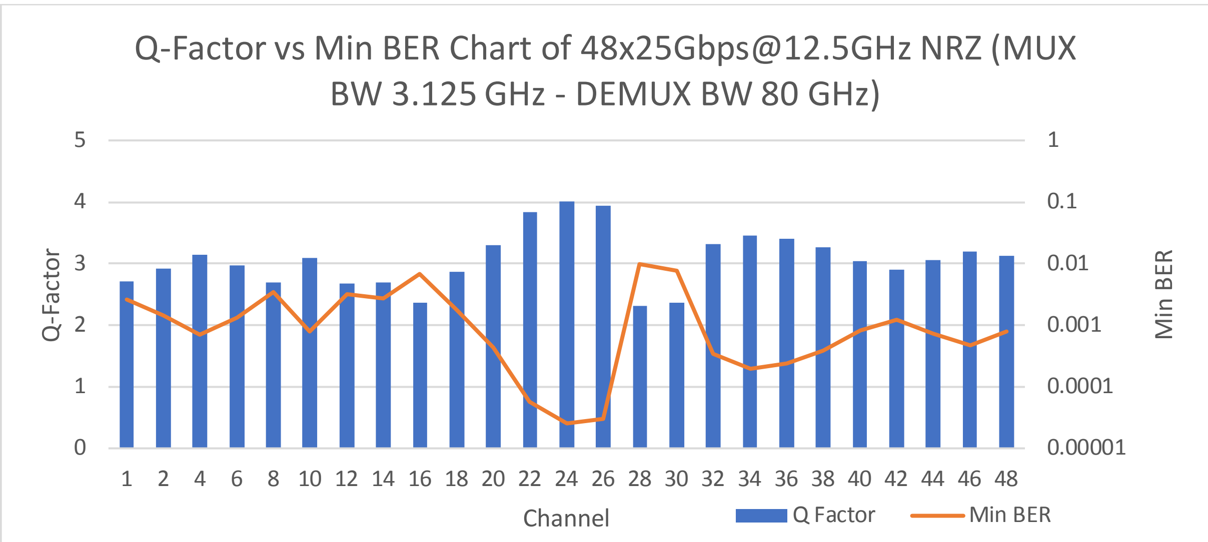

Figure 4.86: Q factor vs BER of 12.5 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 3.125 GHz and DEMUX BW = 80 GHz

Figure 4.85 and Figure 4.86 represented the signal data for a DWDM network with 12.5 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 3.125 GHz and DEMUX BW = 80 GHz.

Figure 4.86 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 24, which had the lowest BER as well. Figure 4.85 showed the eye diagram of channel 24 with its Q factor, BER and eye height. The BW efficiency was 100% since all transmitted channels were received.

4.9 The 48 Channel x 25 Gbps at 12.5 GHz Spacing using RZ

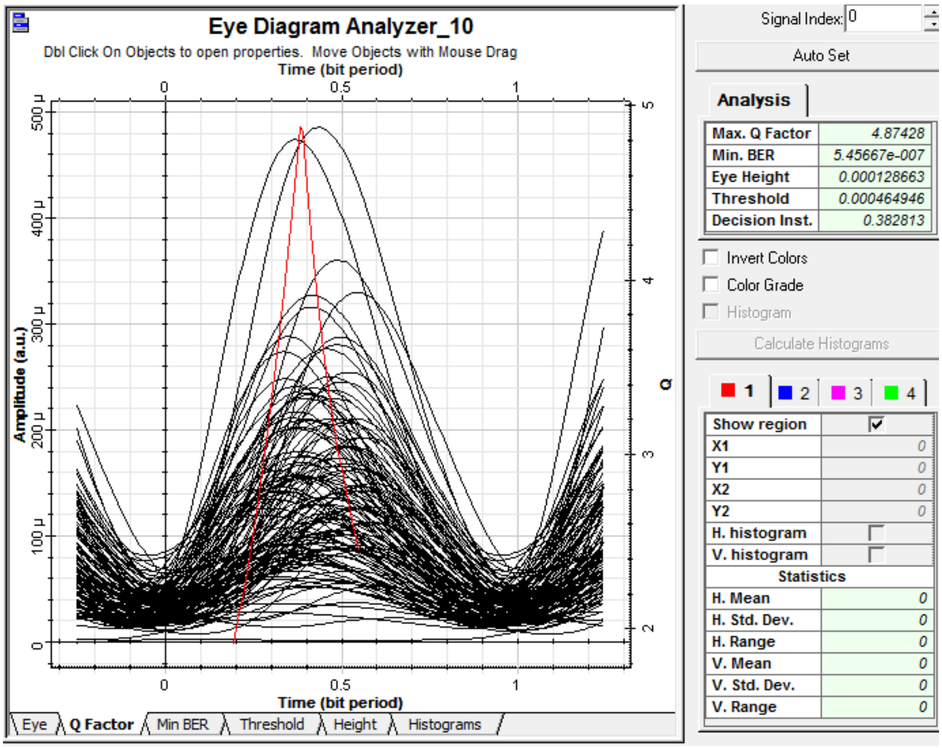

Figure 4.87: Eye Diagram of 12.5 GHz Channel Spacing Using RZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

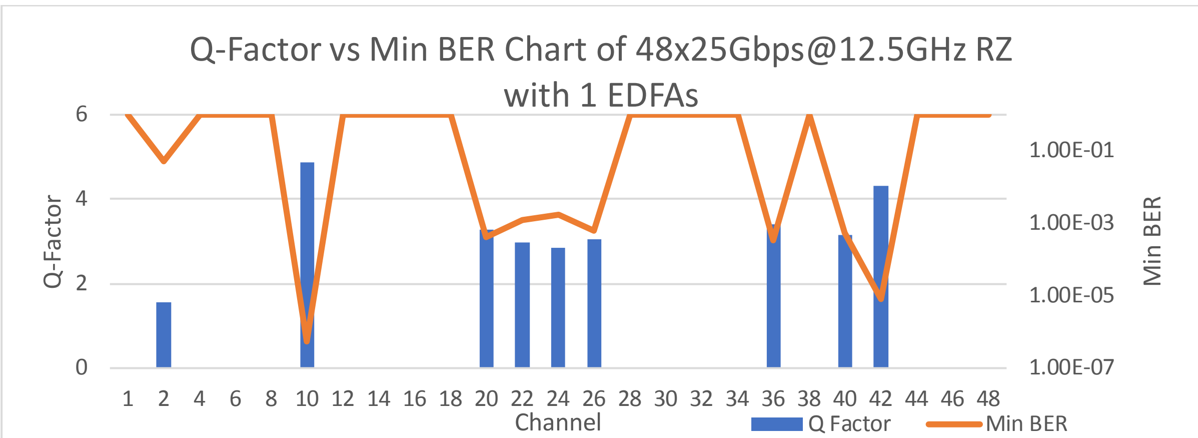

Figure 4.88: Q Factor vs BER of 12.5 GHz Spacing Using RZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.87 and Figure 4.88 represented the signal data for a DWDM network with 12.5 GHz channel spacing using RZ and 1 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.88 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 10, which had the lowest BER as well. Figure 4.87 showed the eye diagram of channel 10 with its Q factor, BER and eye height. The BW efficiency was 66.66% because 35 out of 48 channels were recognisable. Sixteen channels had BER =1 and Q = 0

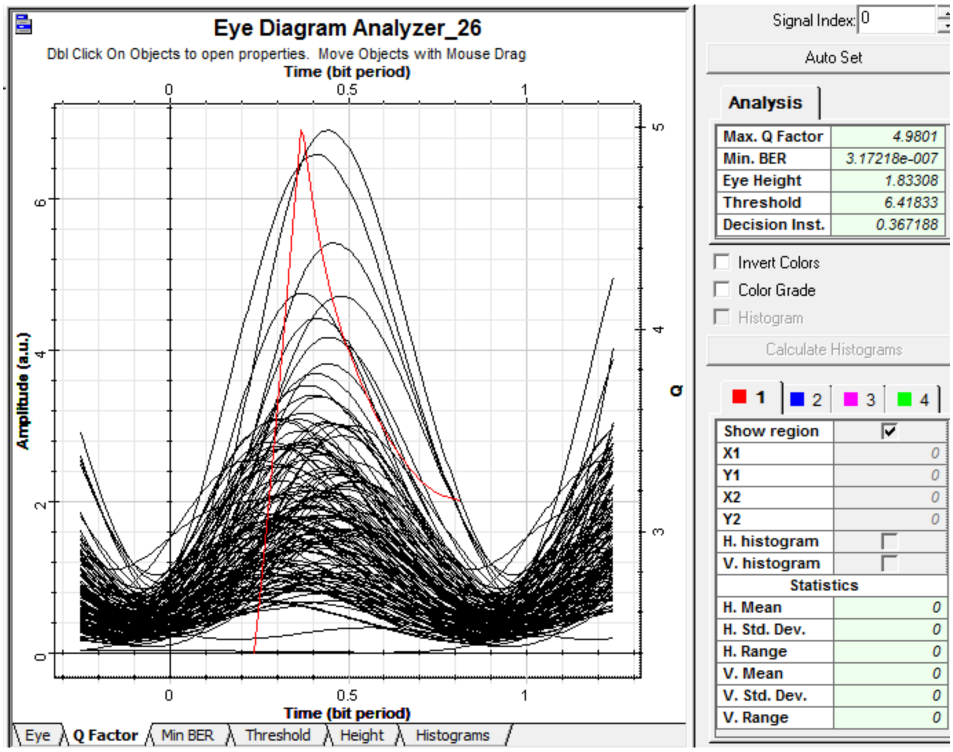

Figure 4.89: Eye Diagram of 12.5 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

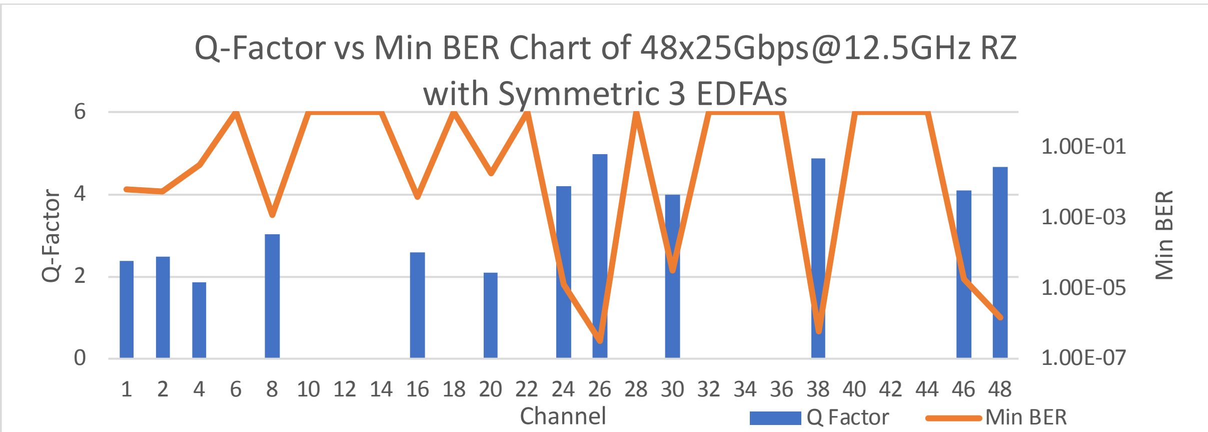

Figure 4.90: Q Factor vs BER of 12.5 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.89 and Figure 4.90 represented the signal data for a DWDM network with 12.5 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.90 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 26, which had the lowest BER as well. Figure 4.89 showed the eye diagram of channel 26 with its Q factor, BER and eye height. The BW efficiency was 72.91% because 35 out of 48 channels were recognisable. Thirteen channels had BER =1 and Q = 0

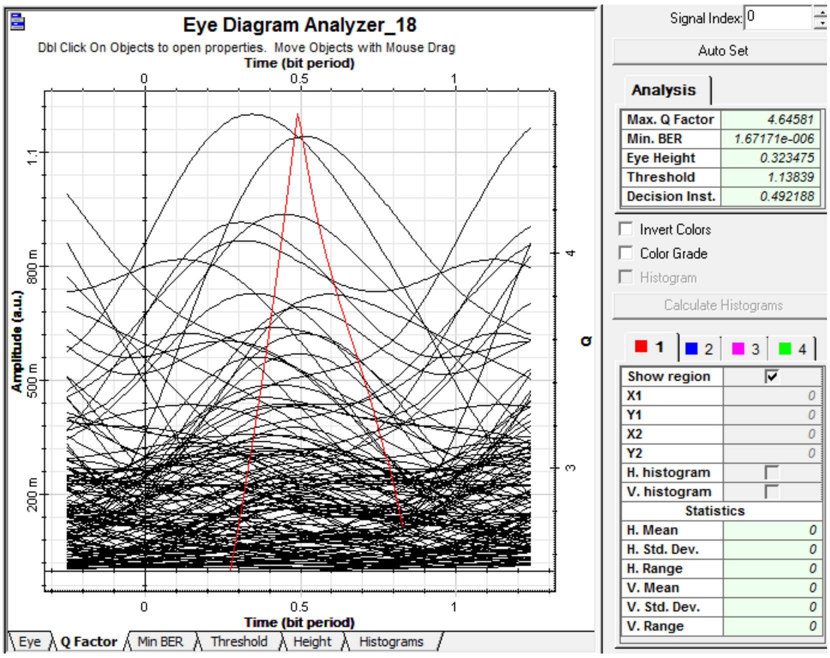

Figure 4.91: Eye Diagram of 12.5 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 12.5 GHz

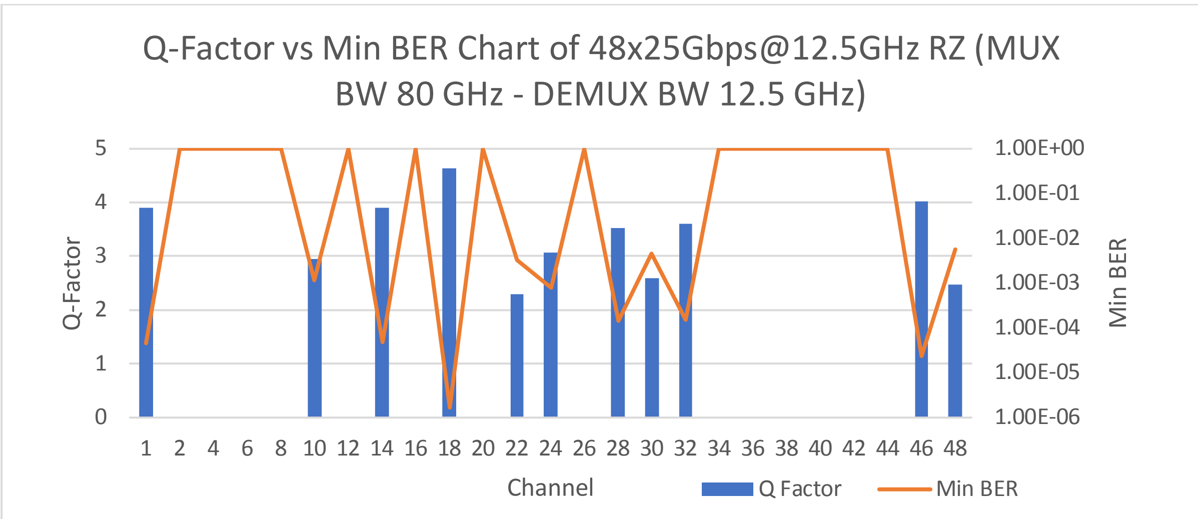

Figure 4.92: Q Factor vs BER of 12.5 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 12.5 GHz

Figure 4.91 and Figure 4.92 represented the signal data for a DWDM network with 12.5 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 12.5 GHz.

Figure 4.92 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 18, which had the lowest BER as well. Figure 4.91 showed the eye diagram of channel 18 with its Q factor, BER and eye height. The BW efficiency was 70.83% because 34 out of 48 channels were recognisable. Fourteen channels had BER =1 and Q = 0

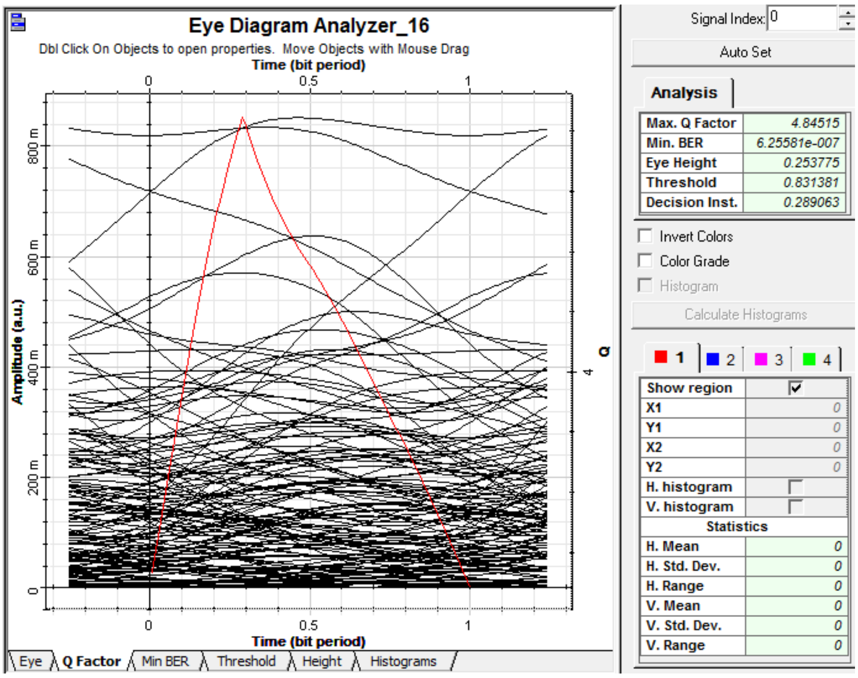

Figure 4.93: Eye Diagram of 12.5 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 6.25 GHz

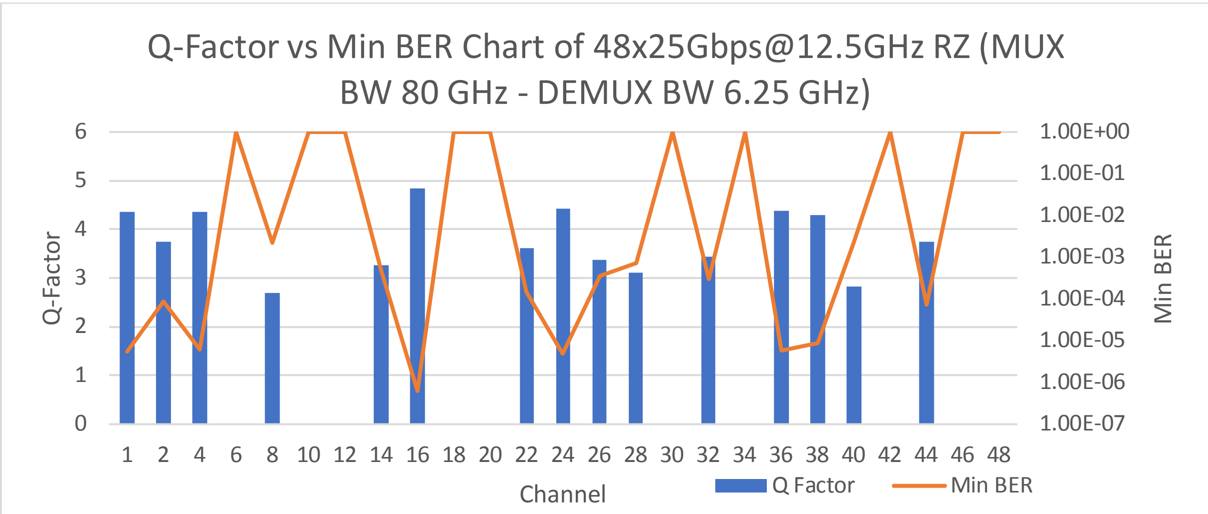

Figure 4.94: Q Factor vs BER of 12.5 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 6.25 GHz

Figure 4.93 and Figure 4.94 represented the signal data for a DWDM network with 12.5 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 6.25 GHz.

Figure 4.94 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 16, which had the lowest BER as well. Figure 4.93 showed the eye diagram of channel 16 with its Q factor, BER and eye height. The BW efficiency was 79.16% because 38 out of 48 channels were recognisable. Ten channels had BER =1 and Q = 0.

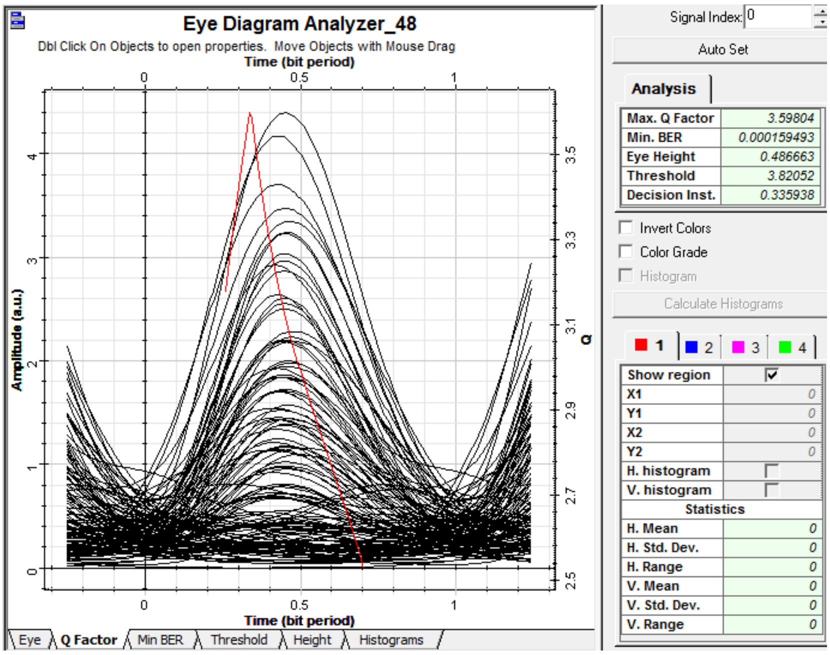

Figure 4.95: Eye Diagram of 12.5 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 12.5 GHz and DEMUX BW = 80 GHz

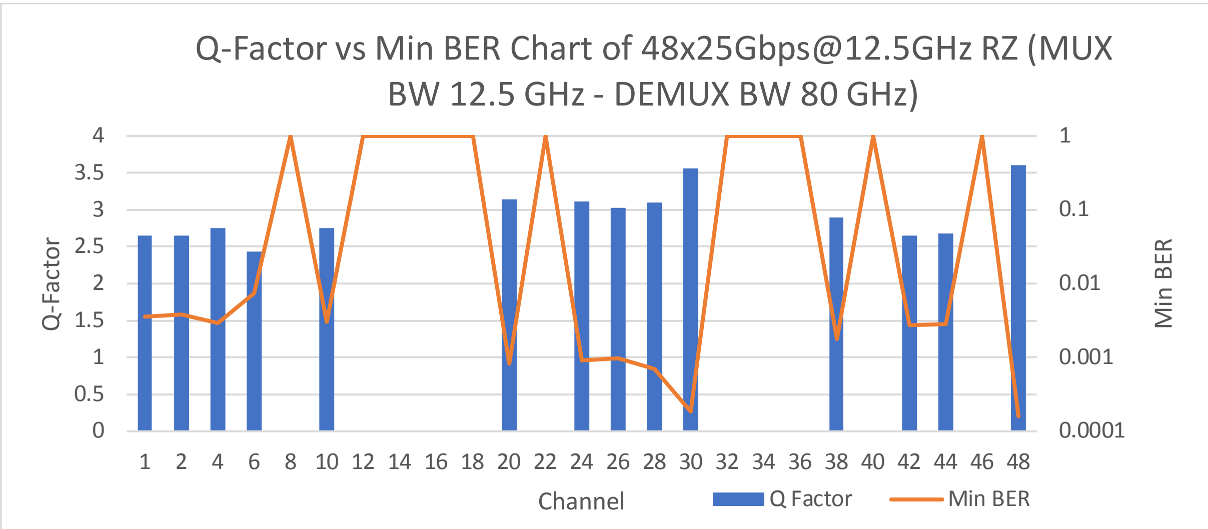

Figure 4.96: Q factor vs BER of 12.5 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 12.5 GHz and DEMUX BW = 80 GHz

Figure 4.95 and Figure 4.96 represented the signal data for a DWDM network with 12.5 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 12.5 GHz and DEMUX BW = 80 GHz.

Figure 4.96 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 48, which had the lowest BER as well. Figure 4.95 showed the eye diagram of channel 48 with its Q factor, BER and eye height. The BW efficiency was 77.08% because 37 out of 48 channels were recognisable. Eleven channels had BER =1 and Q = 0.

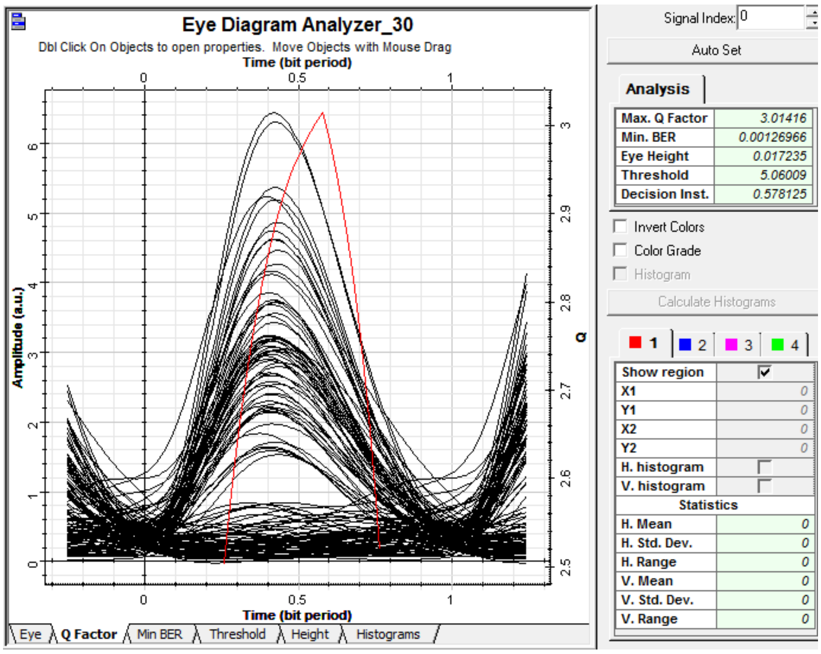

Figure 4.97: Eye Diagram of 12.5 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 6.25 GHz and DEMUX BW = 80 GHz

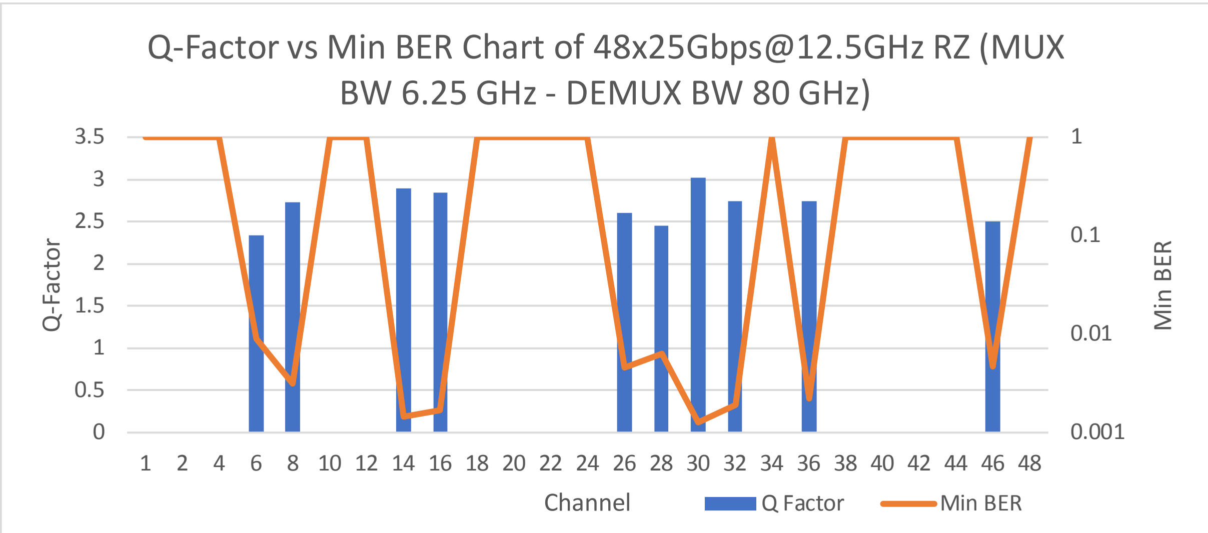

Figure 4.98: Q Factor vs BER of 12.5 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 6.25 GHz and DEMUX BW = 80 GHz

Figure 4.97 and Figure 4.98 represent the signal data for a DWDM network with 12.5 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 6.25 GHz and DEMUX BW = 80 GHz.

Figure 4.98 shows the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 30, which had the lowest BER as well. Figure 4.97 shows the eye diagram of channel 30 with its Q factor, BER and eye height. The BW efficiency was 68.75% because 33 out of 48 channels were recognisable. Fifteen channels had BER =1 and Q = 0.

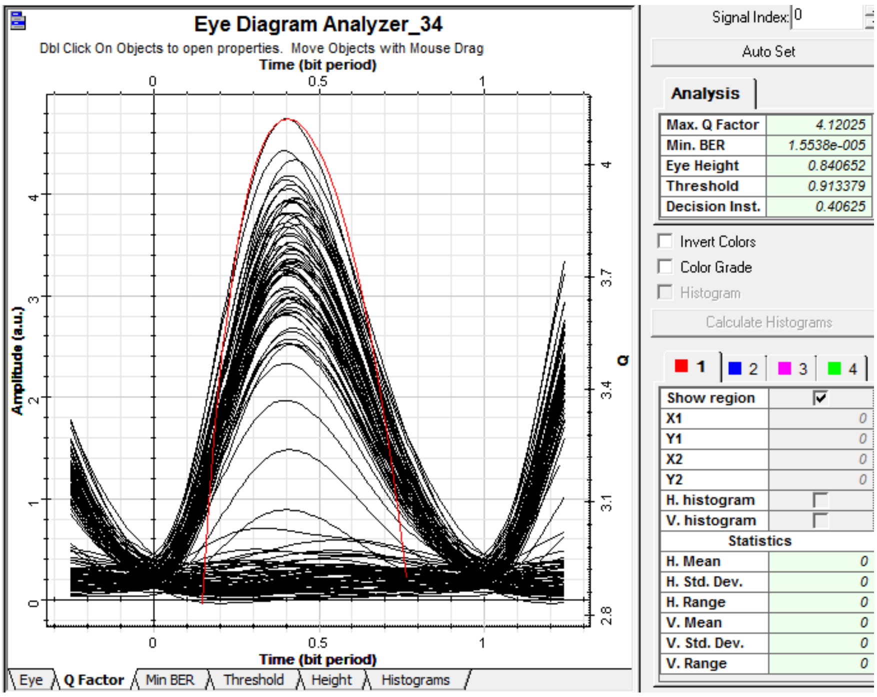

Figure 4.99: Eye Diagram of 12.5 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 3.125 GHz and DEMUX BW = 80 GHz

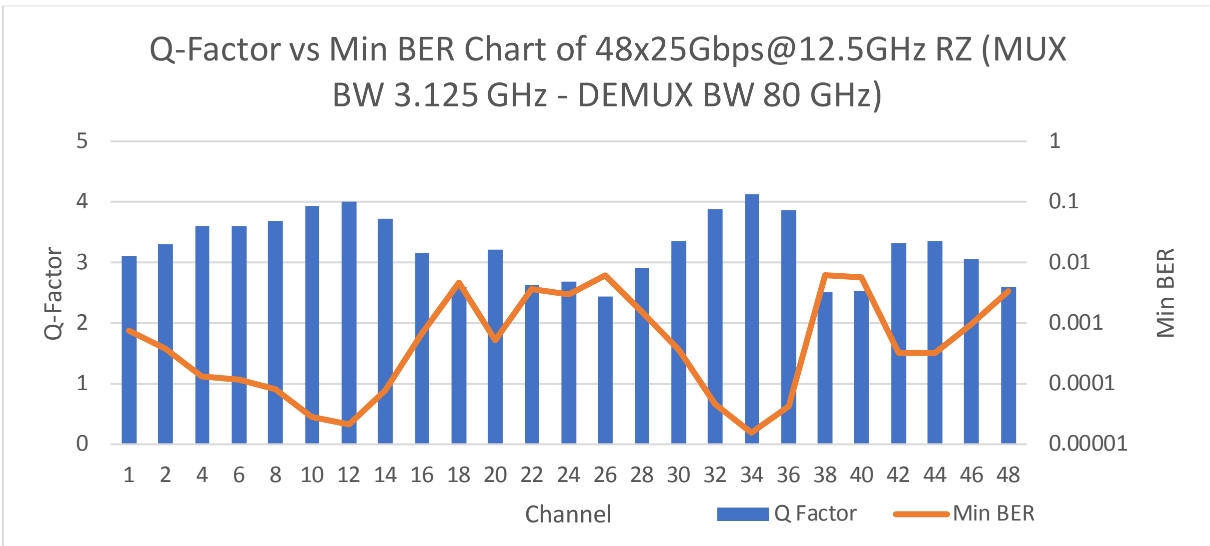

Figure 4.100: Q Factor vs BER Diagram of 12.5 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 3.125 GHz and DEMUX BW = 80 GHz

Figure 4.99 and Figure 4.100 represented the signal data for a DWDM network with 12.5 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 3.125 GHz and DEMUX BW = 80 GHz.

Figure 4.100 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 34, which had the lowest BER as well. Figure 4.99 showed the eye diagram of channel 34 with its Q factor, BER and eye height. The BW efficiency was 100% since all channels transmitted were received.

4.10 The 48 Channel x 25 Gbps at 12.5 GHz Spacing using MDRZ

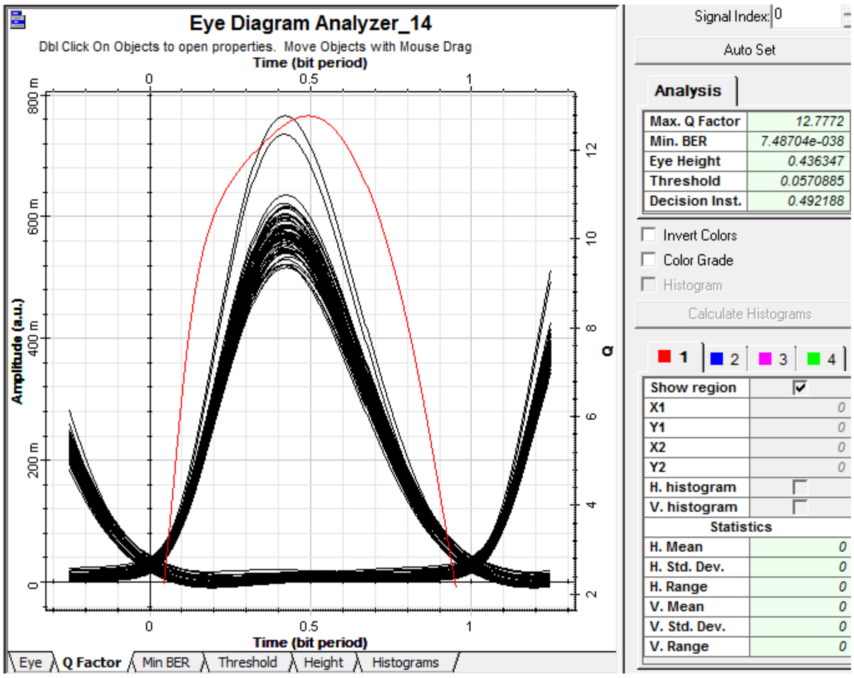

Figure 4.101: Eye Diagram of 12.5 GHz Channel Spacing Using MDRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 3.125 GHz and DEMUX BW = 80 GHz

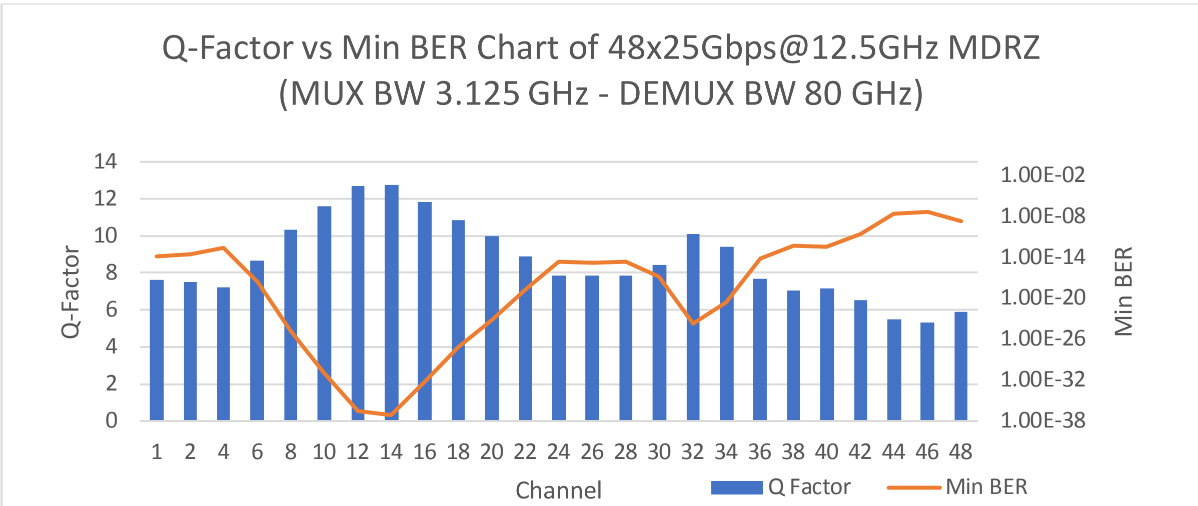

Figure 4.102: Q Factor vs BER of 12.5 GHz Spacing Using MDRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 3.125 GHz and DEMUX BW = 80 GHz

Figure 4.101 and Figure 4.102 represented the signal data for a DWDM network with 12.5 GHz channel spacing using MDRZ and 3 EDFA. The MUX BW = 3.125 GHz and DEMUX BW = 80 GHz.

Figure 4.102 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 14, which had the lowest BER as well. Figure 4.101 showed the eye diagram of channel 14 with its Q factor, BER and eye height. The BW efficiency was 100% since all transmitted channels were received.

4.11 The 48 Channel x 25 Gbps at 6.25 GHz Spacing using NRZ

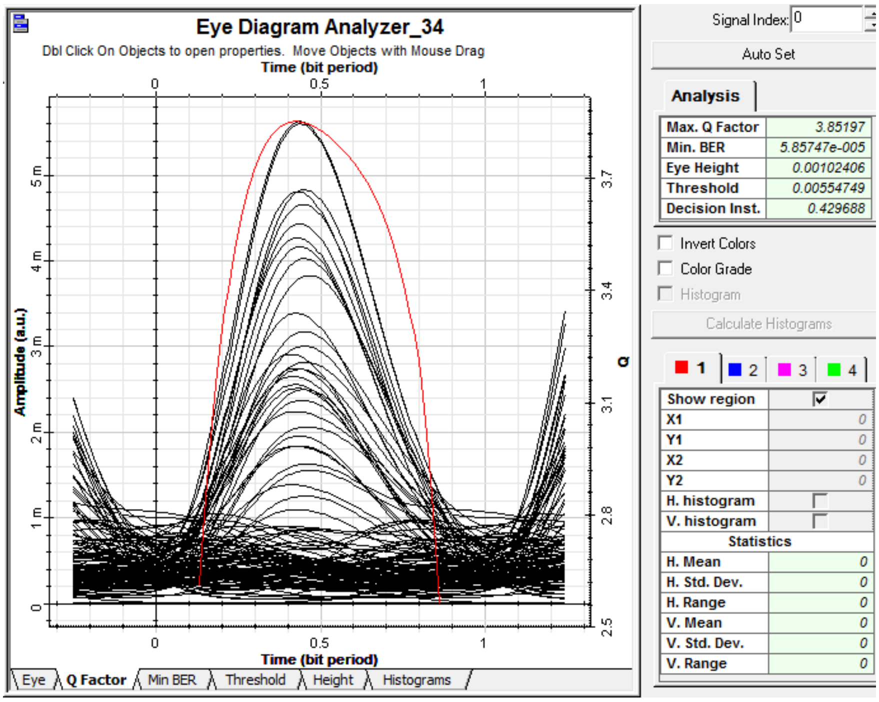

Figure 4.103: Eye Diagram of 6.25 GHz Channel Spacing Using NRZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

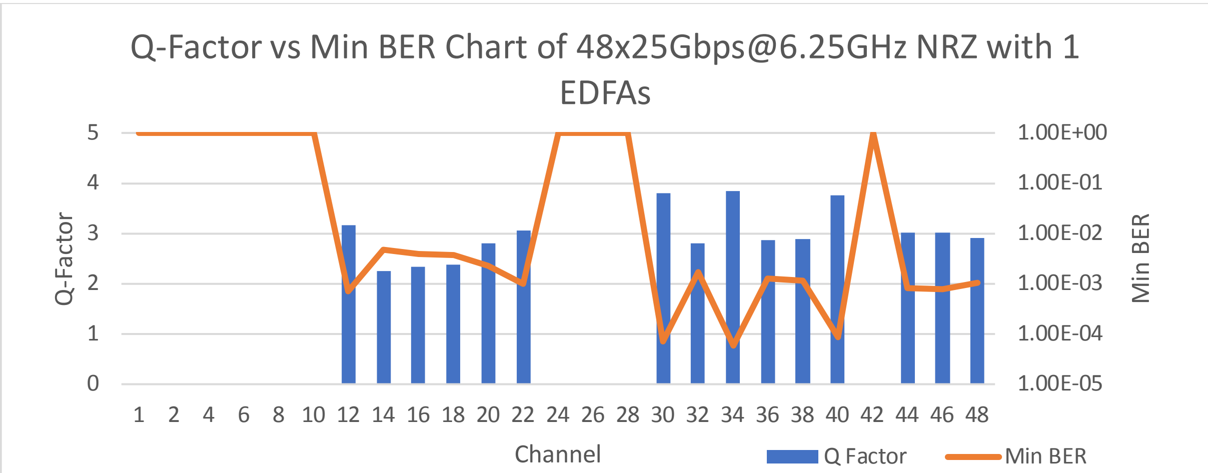

Figure 4.104: Q factor vs BER of 6.25 GHz Spacing Using NRZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.103 and Figure 4.104 represented the signal data for a DWDM network with 6.25 GHz channel spacing using NRZ and 1 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.104 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 34, which had the lowest BER as well. Figure 4.103 showed the eye diagram of channel 34 with its Q factor, BER and eye height. The BW efficiency was 79.16% because 38 out of 48 channels were recognisable. Ten channels had BER =1 and Q = 0.

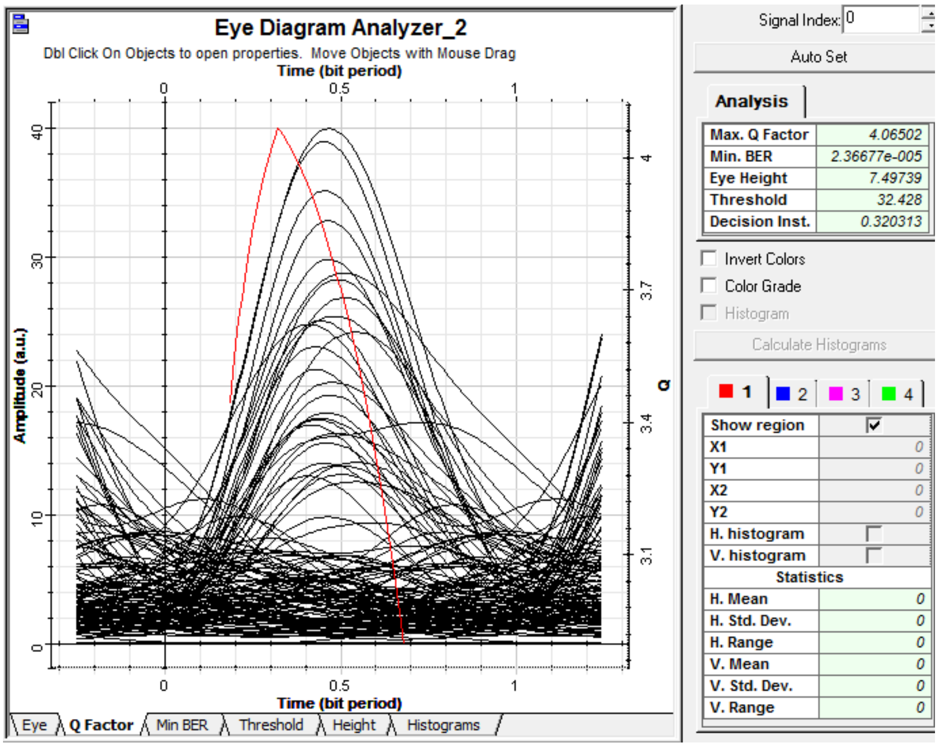

Figure 4.105: Eye Diagram of 6.25 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

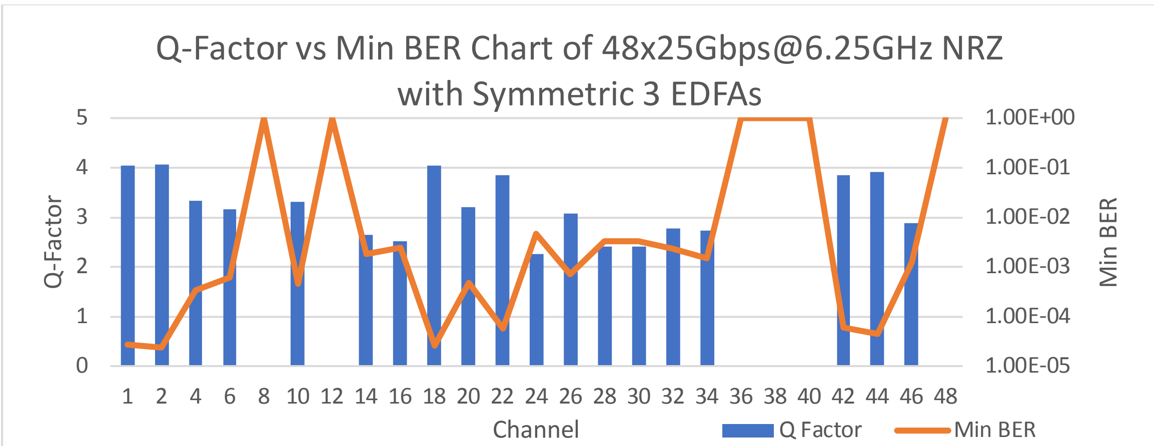

Figure 4.106: Q factor vs BER of 6.25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.105 and Figure 4.106 represented the signal data for a DWDM network with 6.25 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.106 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 2, which had the lowest BER as well. Figure 4.105 showed the eye diagram of channel 2 with its Q factor, BER and eye height. The BW efficiency was 89.52% because 43 out of 48 channels were recognisable. Five channels had BER =1 and Q = 0.

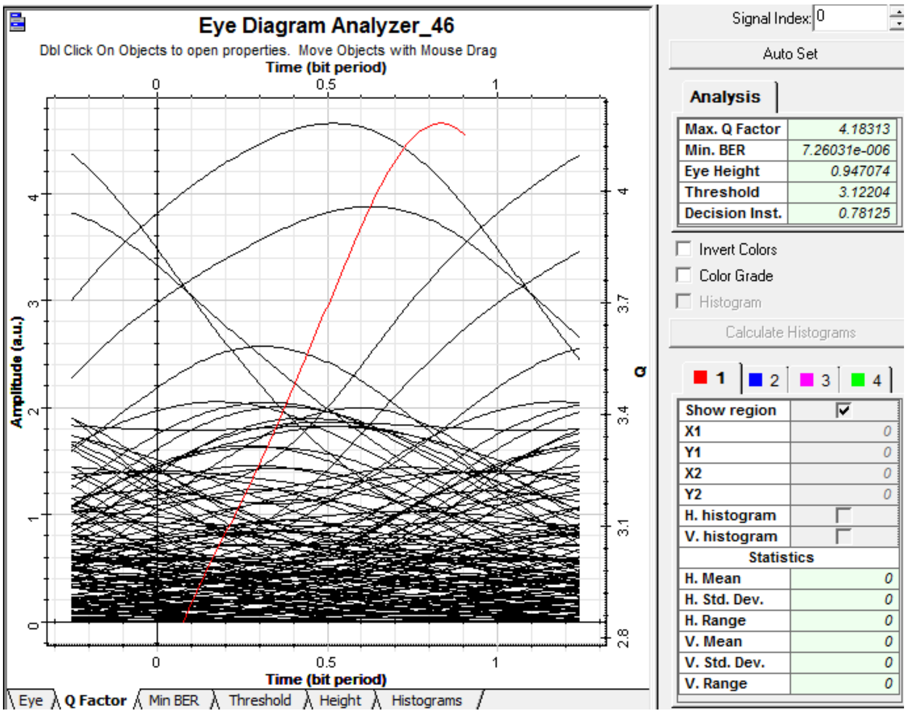

Figure 4.107: Eye Diagram of 6.25 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 6.25 GHz

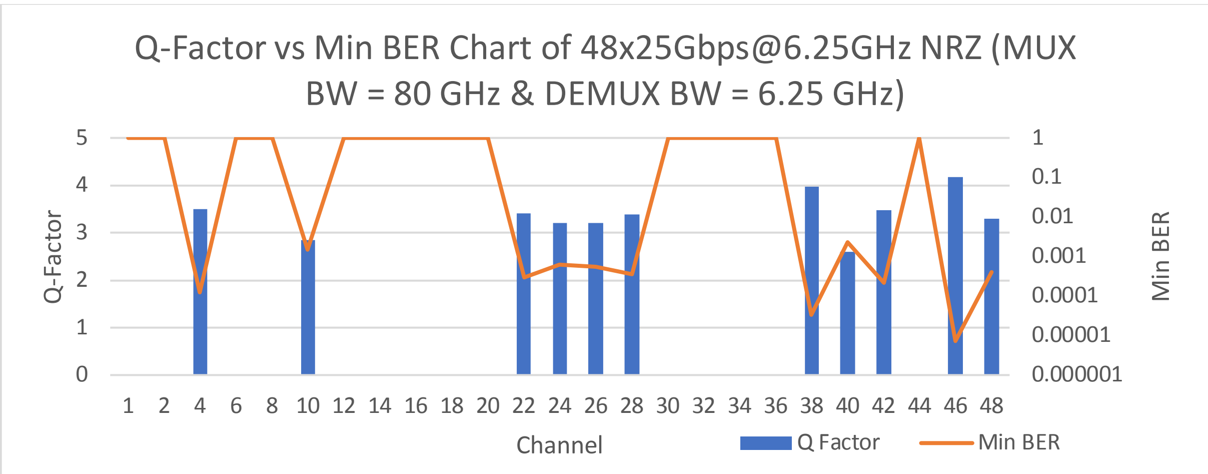

Figure 4.108: Q Factor vs BER of 6.25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 6.25 GHz

Figure 4.107 and Figure 4.108 represented the signal data for a DWDM network with 6.25 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 6.25 GHz.

Figure 4.108 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 46, which had the lowest BER as well. Figure 4.107 showed the eye diagram of channel 46 with its Q factor, BER and eye height. The BW efficiency was 75% because 36 out of 48 channels were recognisable. Twelve channels had BER =1 and Q = 0.

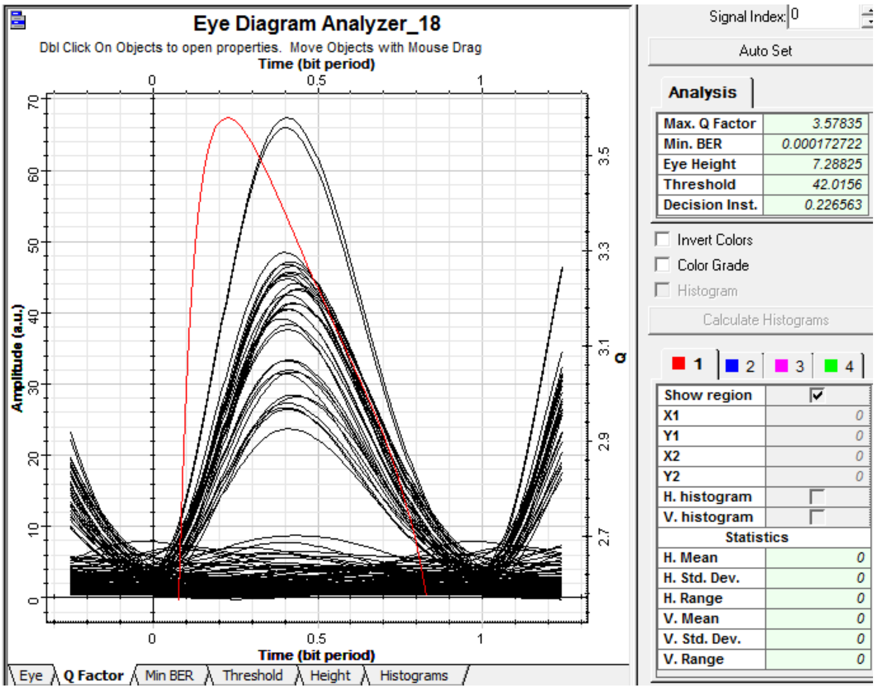

Figure 4.109: Eye Diagram of 6.25 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 6.25 GHz and DEMUX BW = 80 GHz

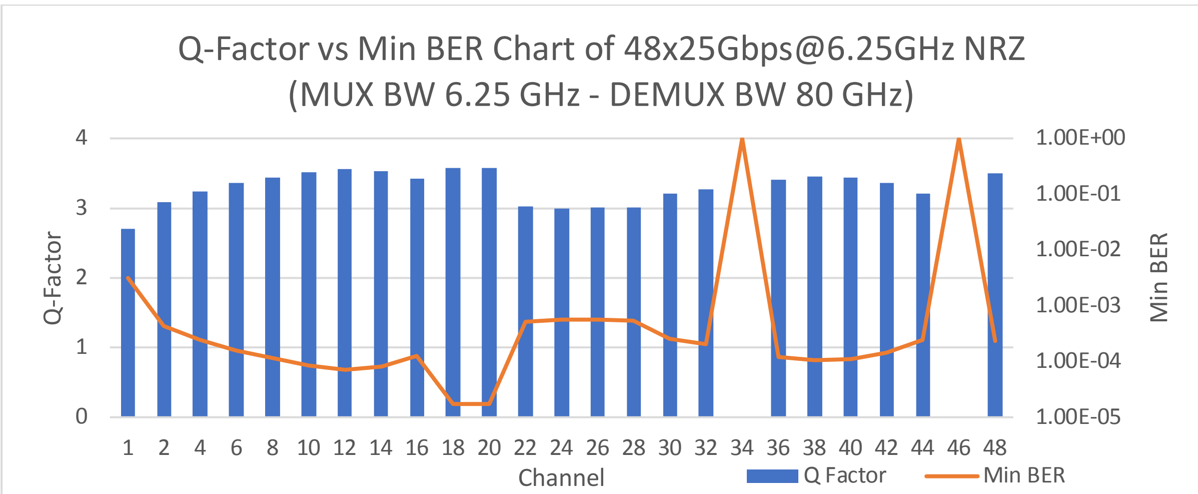

Figure 4.110: Q Factor vs BER of 6.25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 6.25 GHz and DEMUX BW = 80 GHz

Figure 4.109 and Figure 4.110 represented the signal data for a DWDM network with 6.25 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 6.25 GHz and DEMUX BW = 80 GHz.

Figure 4.110 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 18, which had the lowest BER as well. Figure 4.109 showed the eye diagram of channel 18 with its Q factor, BER and eye height. The BW efficiency was 95.83% because 46 out of 48 channels were recognisable. Two channels had BER =1 and Q = 0.

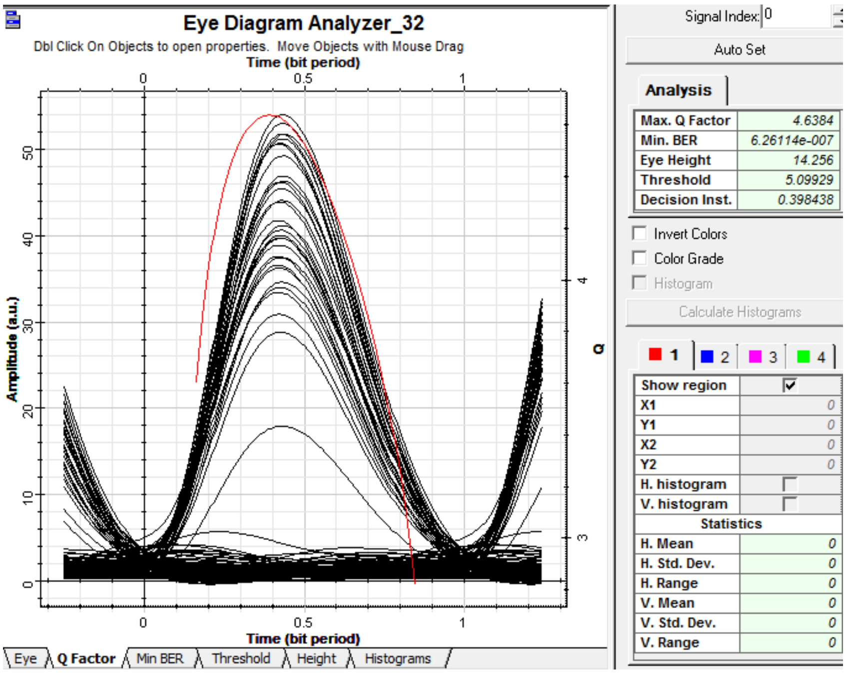

Figure 4.111: Eye Diagram of 6.25 GHz Channel Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 3.125 GHz and DEMUX BW = 80 GHz

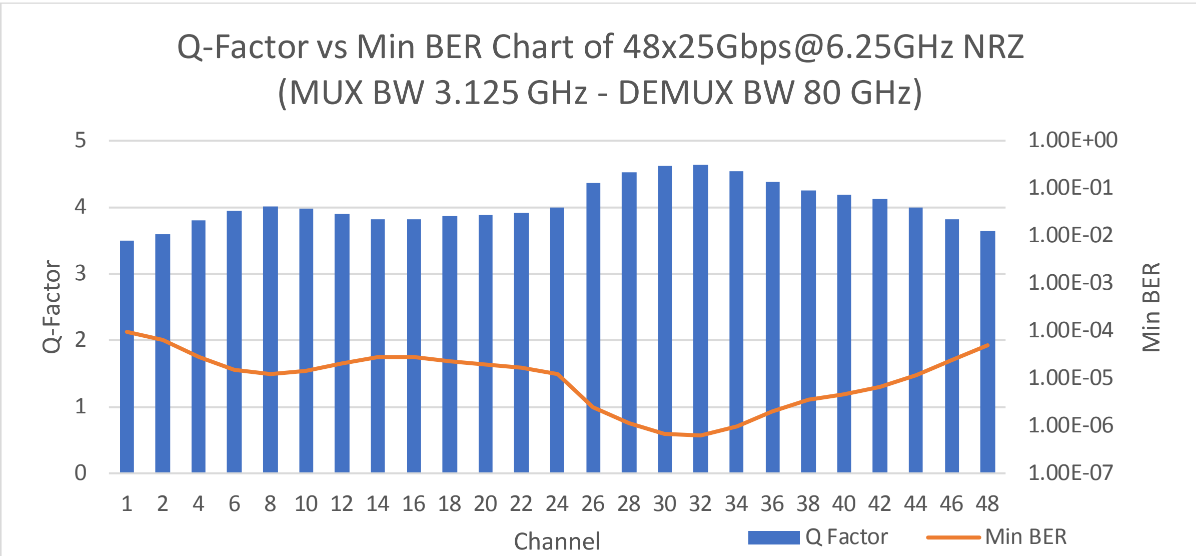

Figure 4.112: Q Factor vs BER of 6.25 GHz Spacing Using NRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 3.125 GHz and DEMUX BW = 80 GHz

Figure 4.111 and Figure 4.112 represented the signal data for a DWDM network with 6.25 GHz channel spacing using NRZ and 3 EDFA. The MUX BW = 3.125 GHz and DEMUX BW = 80 GHz.

Figure 4.112 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 46, which had the lowest BER as well. Figure 4.111 showed the eye diagram of channel 46 with its Q factor, BER and eye height. The BW efficiency was 100% since all transmitted channel were received.

4.12 The 48 Channel x 25 Gbps at 6.25 GHz Spacing using RZ

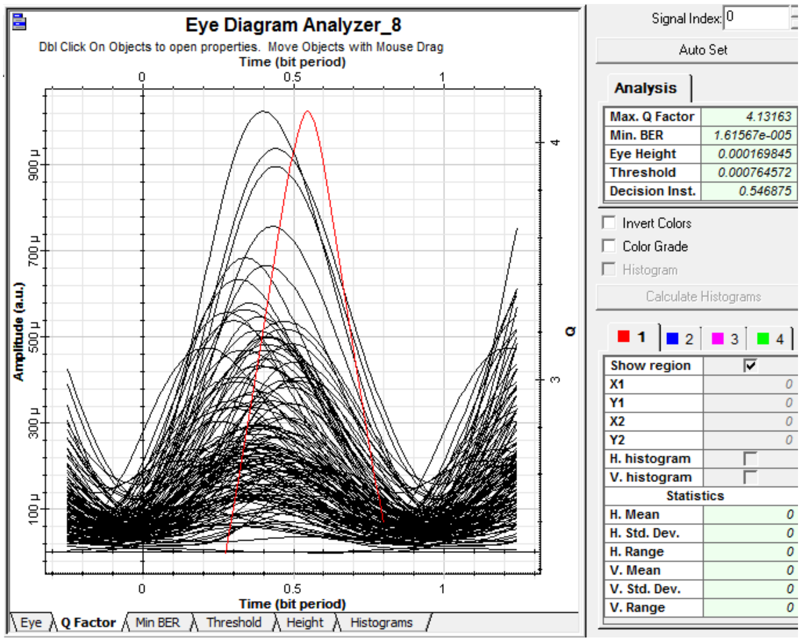

Figure 4.113: Eye Diagram of 6.25 GHz Channel Spacing Using RZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

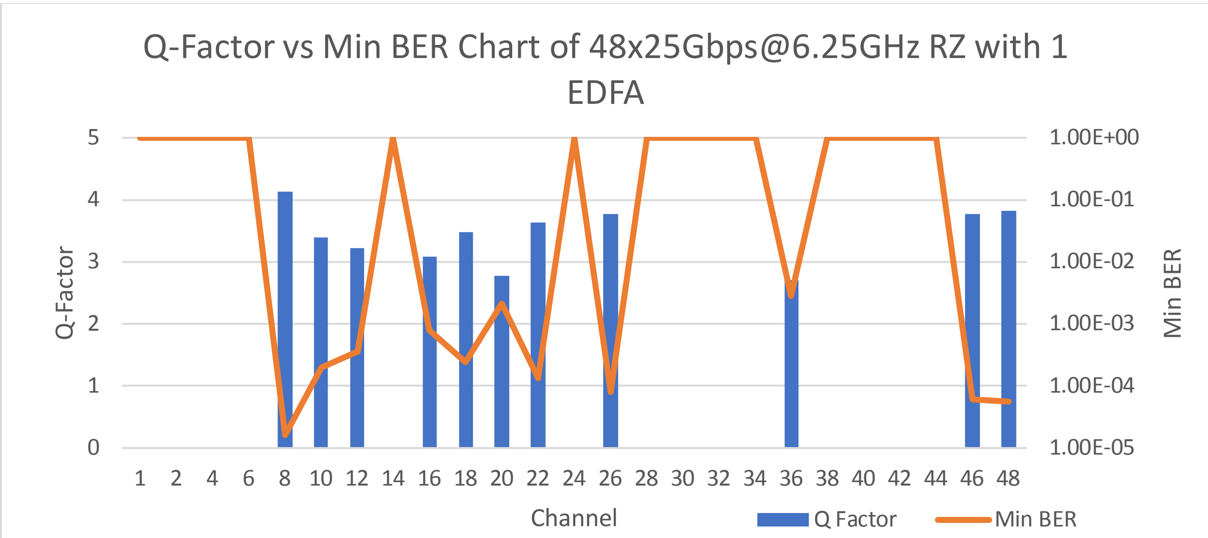

Figure 4.114: Q Factor vs BER of 6.25 GHz Spacing Using RZ, 1 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.113 and Figure 4.114 represented the signal data for a DWDM network with 6.25 GHz channel spacing using RZ and 1 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.114 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 8, which had the lowest BER as well. Figure 4.113 showed the eye diagram of channel 8 with its Q factor, BER and eye height. The BW efficiency was 70.83% because 34 out of 48 channels were recognisable. Fourteen channels had BER =1 and Q = 0.

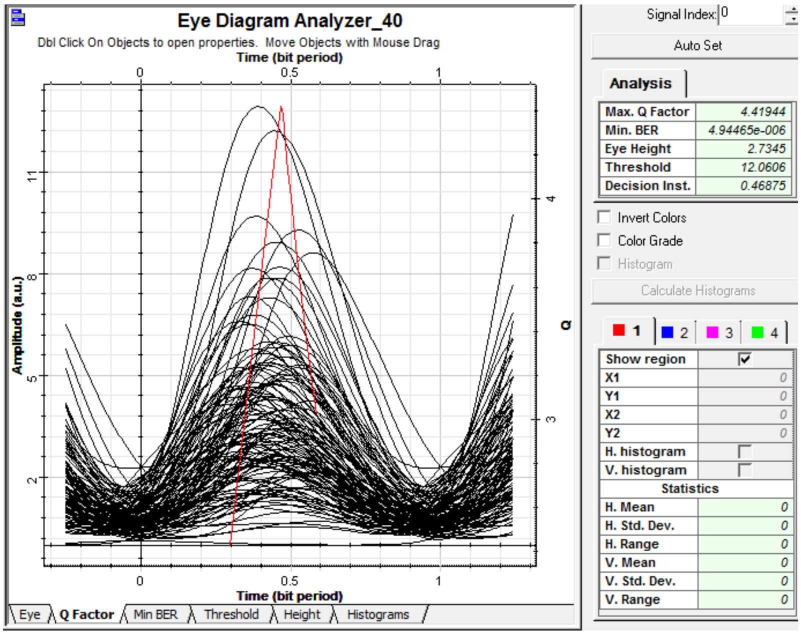

Figure 4.115: Eye Diagram of 6.25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

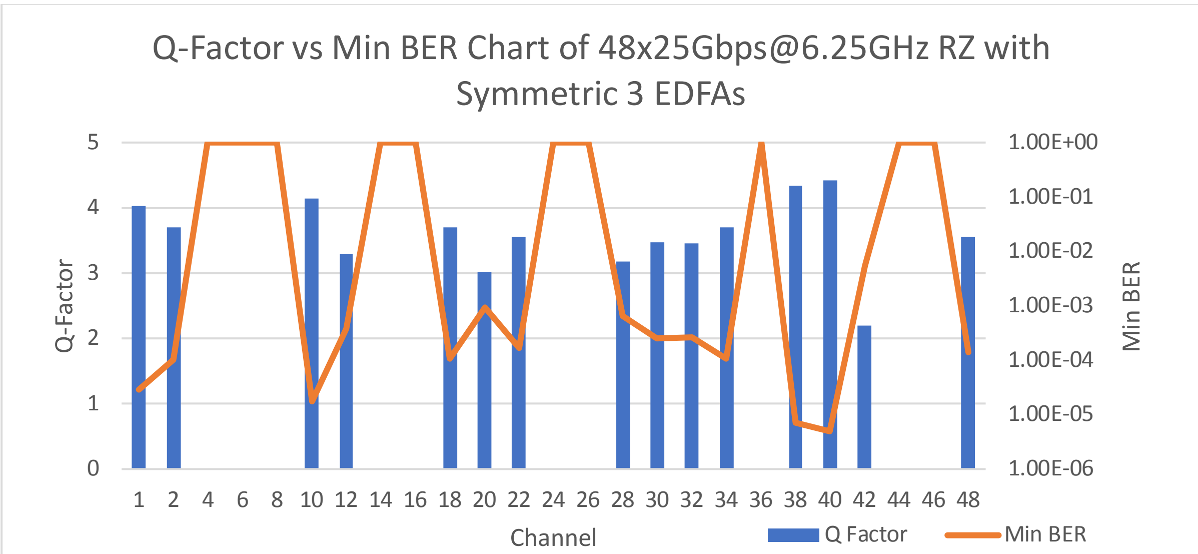

Figure 4.116: Q factor vs BER of 6.25 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 80 GHz

Figure 4.115 and Figure 4.116 represented the signal data for a DWDM network with 6.25 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 80 GHz.

Figure 4.116 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 40, which had the lowest BER as well. Figure 4.115 showed the eye diagram of channel 40 with its Q factor, BER and eye height. The BW efficiency was 79.16% because 38 out of 48 channels were recognisable. Ten channels had BER =1 and Q = 0.

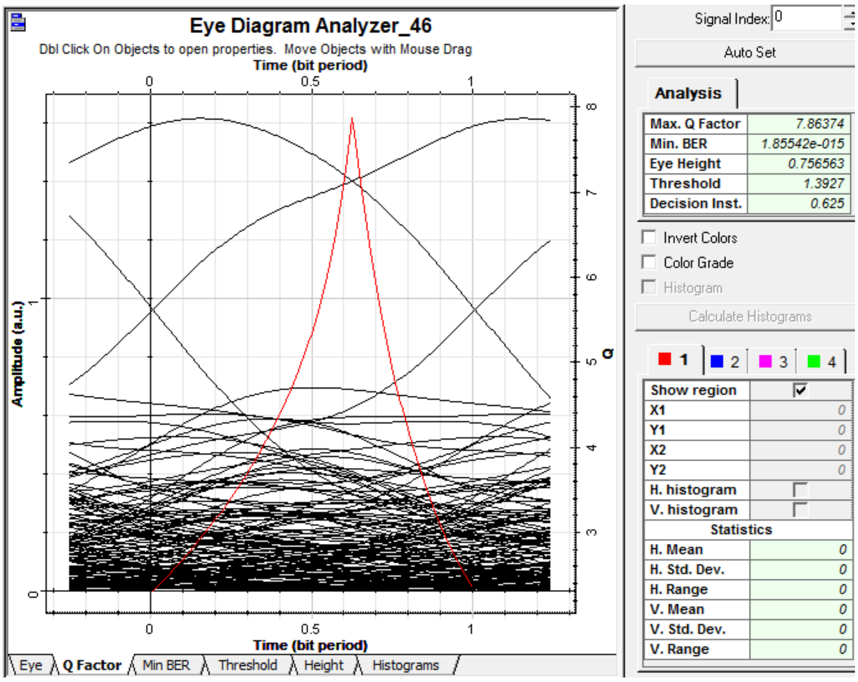

Figure 4.117: Eye Diagram of 6.25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 6.25 GHz

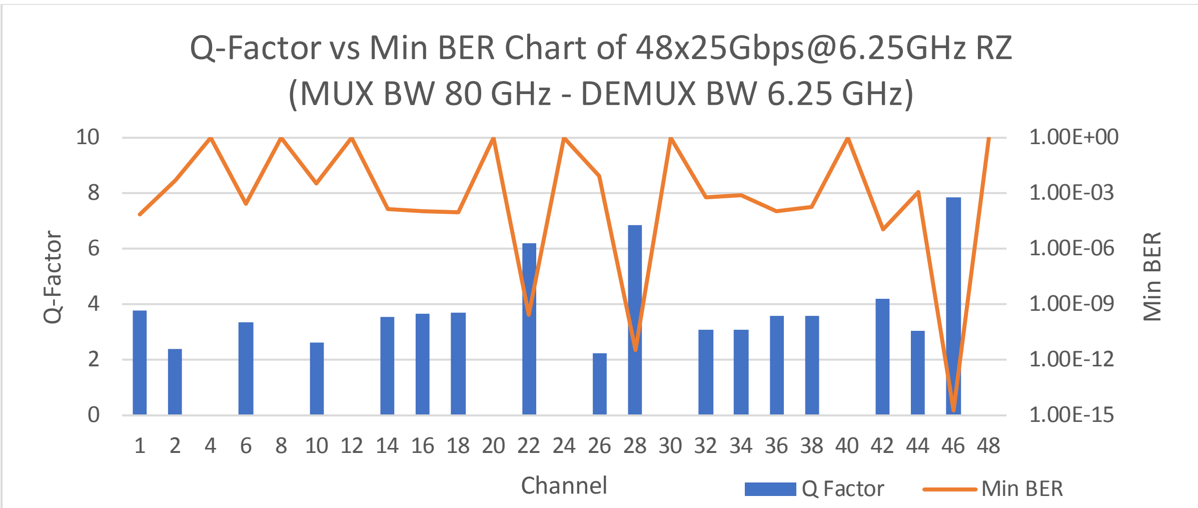

Figure 4.118: Q factor vs BER of 6.25 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 80 GHz and DEMUX BW = 6.25 GHz

Figure 4.117 and Figure 4.118 represented the signal data for a DWDM network with 6.25 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 80 GHz and DEMUX BW = 6.25 GHz.

Figure 4.118 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 46, which had the lowest BER as well. Figure 4.117 showed the eye diagram of channel 46 with its Q factor, BER and eye height. The BW efficiency was 85.41% because 41 out of 48 channels were recognisable. Seven channels had BER =1 and Q = 0.

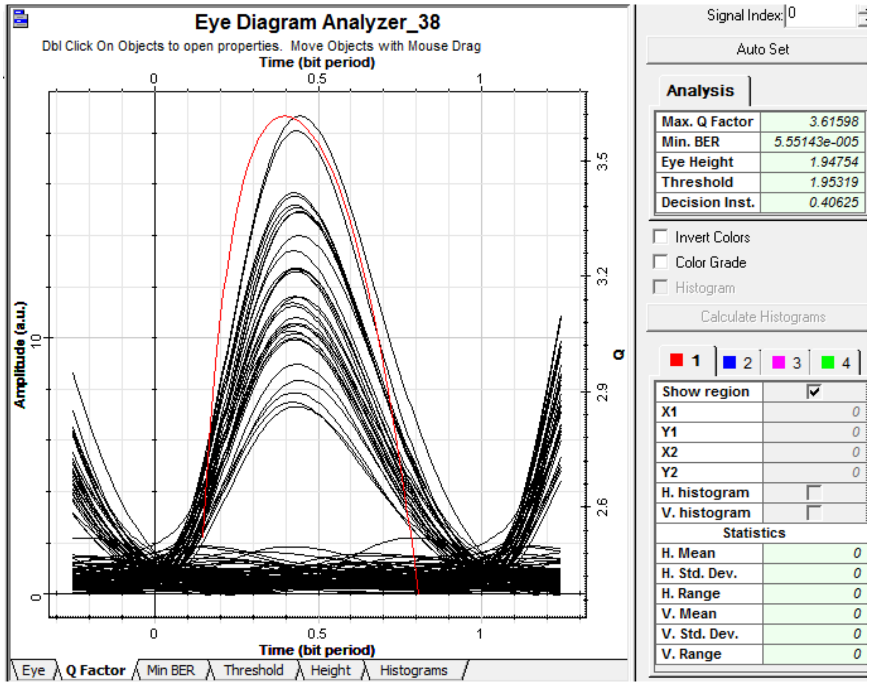

Figure 4.119: Eye Diagram of 6.25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 6.25 GHz and DEMUX BW = 80 GHz

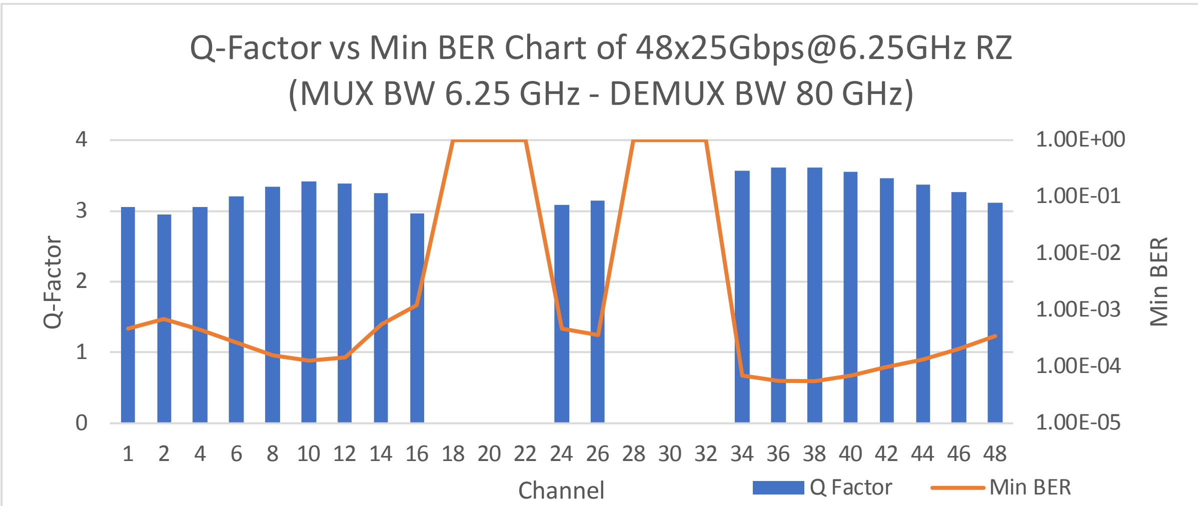

Figure 4.120: Q Factor vs BER of 6.25 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 6.25 GHz and DEMUX BW = 80 GHz

Figure 4.119 and Figure 4.120 represented the signal data for a DWDM network with 6.25 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 6.25 GHz and DEMUX BW = 80 GHz.

Figure 4.120 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 38, which had the lowest BER as well. Figure 4.119 showed the eye diagram of channel 38 with its Q factor, BER and eye height. The BW efficiency was 87.5% because 42 out of 48 channels were recognisable. Six channels had BER =1 and Q = 0.

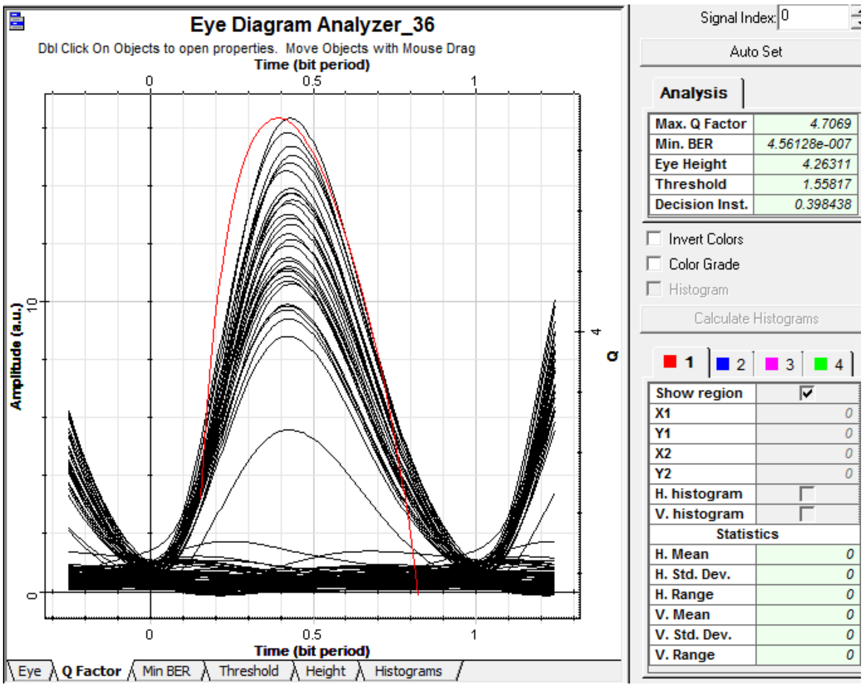

Figure 4.121: Eye Diagram of 6.25 GHz Channel Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 3.125 GHz and DEMUX BW = 80 GHz

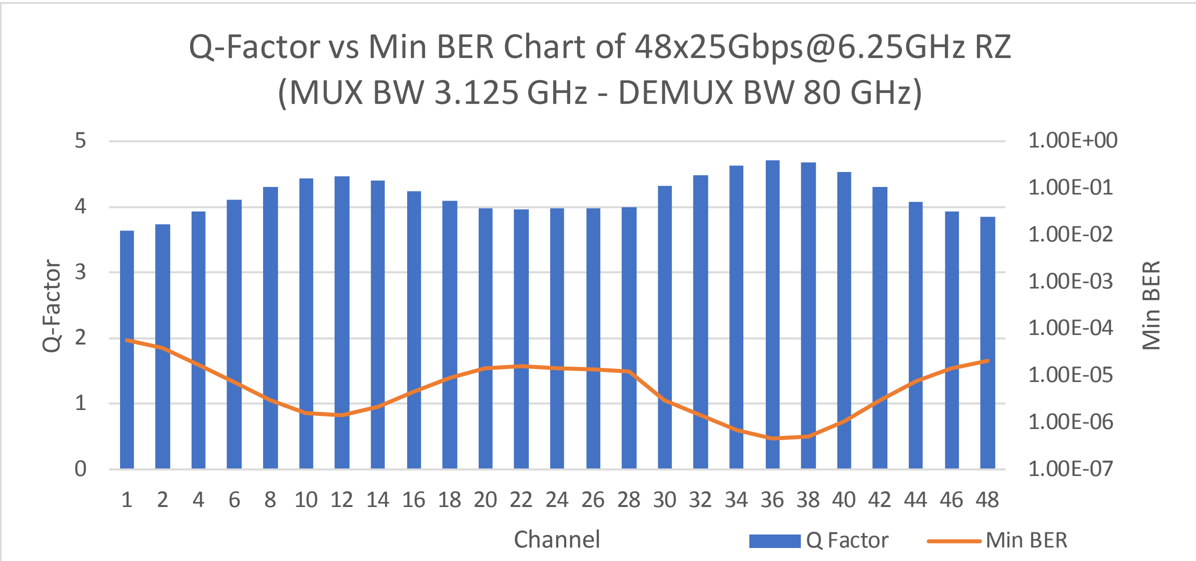

Figure 4.122: Q factor vs BER of 6.25 GHz Spacing Using RZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 3.125 GHz and DEMUX BW = 80 GHz

Figure 4.121 and Figure 4.122 represented the signal data for a DWDM network with 6.25 GHz channel spacing using RZ and 3 EDFA. The MUX BW = 3.125 GHz and DEMUX BW = 80 GHz.

Figure 4.122 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 36, which had the lowest BER as well. Figure 4.121 showed the eye diagram of channel 36 with its Q factor, BER and eye height. The BW efficiency was 100% since all transmitted channels were received.

4.13 The 48 Channel x 25 Gbps at 6.25 GHz Spacing using MDRZ

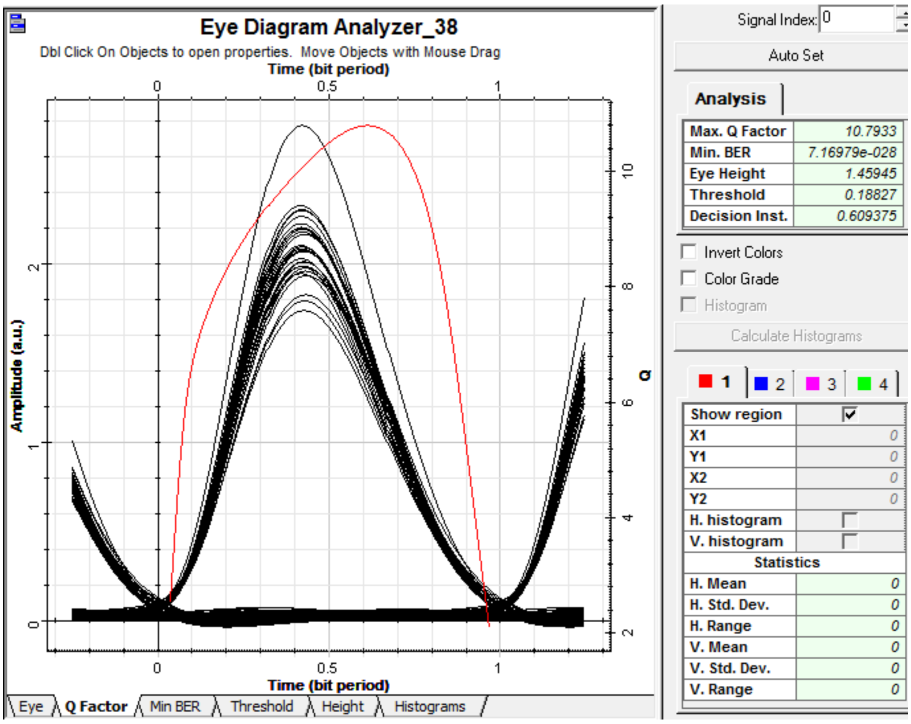

Figure 4.123: Eye Diagram of 6.25 GHz Channel Spacing Using MDRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 3.125 GHz and DEMUX BW = 80 GHz

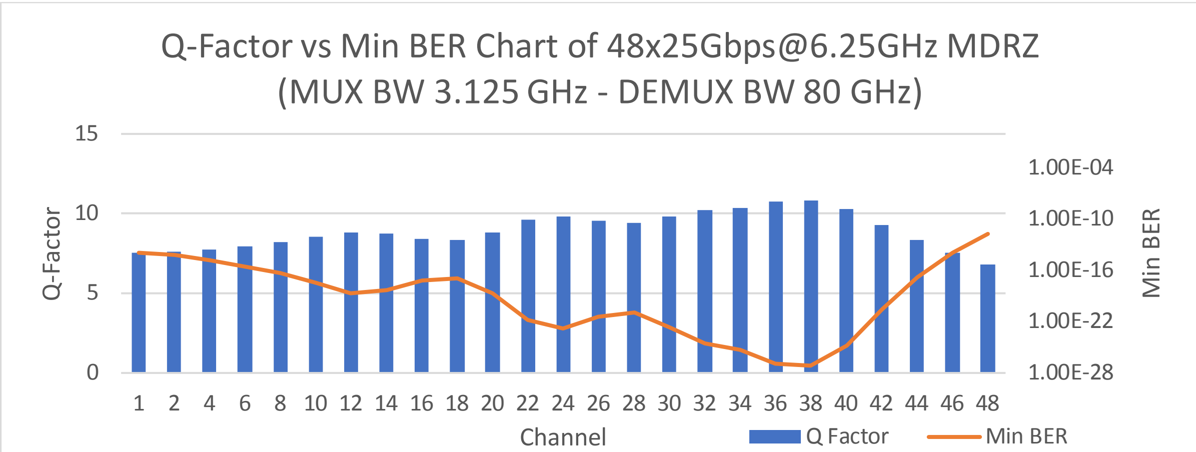

Figure 4.124: Q Factor vs BER of 6.25 GHz Spacing Using MDRZ, Post Symmetric Dispersion with 3 EDFAs, MUX BW = 3.125 GHz and DEMUX BW = 80 GHz

Figure 4.123 and Figure 4.124 represented the signal data for a DWDM network with 6.25 GHz channel spacing using MDRZ and 3 EDFA. The MUX BW = 3.125 GHz and DEMUX BW = 80 GHz.

Figure 4.124 showed the Q Factor vs BER Graph of this network. It can be seen from this chart that the highest quality factor was shown in channel 38, which had the lowest BER as well. Figure 4.123 showed the eye diagram of channel 38 with its Q factor, BER and eye height. The BW efficiency was 100% since all transmitted channels were received.

4.14 Summary

The chapter analysed eye-diagram results of each channel in the DWDM system. The eye diagrams were a representation of the simulated received signals in each combination case of the varied parameters. The eye diagram data showed the Q factor, minimum BER and eye height of the received signal of all 48 channels for every channel spacing, modulation format and design parameter combinations of the designed networks.

Since BER was inversely proportional to the Q factor, the channels with the highest Q factor had the lowest BER and vice versa was also true. The channels with the highest Q was used for analysis for all networks to compare the maximum signal performance of that network to the other networks. A signal with a BER = 1 indicated that the bit errors received at the optical receiver were too high and the signal was not recognisable. Therefore, the Q factor will be = 0 for such signals. This is clearly shown on the comparative charts. The BW efficiency of each network was calculated using (2.19) shown in section 2.8.4 of chapter 2. This indicated the number of channels that would provide a recognisable signal at the optical receiver. For such signals BER < 1 and Q > 0. BW efficiency was also an indication of how much of the bandwidth of the 48 channels were utilised to send a signal that could be recognised by the receiver. However, a recognisable signal at the optical receiver was not always an acceptable signal that would be able to transmit information with the least amount of errors.

The minimum BER required for an acceptable signal must be > 10^{-9} for the optical receiver to detect the information signal with the least amount of bit errors. The Q factors for such signals would be > 6.

The eye height of an eye diagram illustrated the size of the vertical eye opening of a received signal. The more noise there is in a received signal, the more closure there will be in the eye opening. The eye height is therefore an indication of the amount of noise in the received signal. Furthermore, the OSNR value of high-speed data signals are directly impacted by the amount of eye closure. This means that a higher eye height of a received signal will have a higher OSNR and vice versa.

CHAPTER 5

DISCUSSION OF RESULTS FOR THE 48 CHANNEL DWDM NETWORKS

5.1 Introduction

This chapter analysed and discussed all the results obtained for the designed 48 channel DWDM network models from Chapter 4. The tabulated OSNR results of the mismatched active component design from [2] was compared with the tabulated OSNR results of the matched active component design for each channel spacing of the 48-channel network used in this dissertation. In both cases, the OSNR was used to compare and evaluate the signal performance of the 1 EDFA post compensation technique with that of the 3 EDFA post symmetric compensation technique. See Table 5.1

Furthermore, in this chapter, the results of all the eye diagrams with the highest Q factor and lowest BER illustrated in chapter 4 was tabulated for signal performance comparison of each channel spacings and parameter combinations. The section analysed and compared the effectiveness of using the NRZ, RZ and MDRZ modulation formats at various channel spacings using the 3 EDFA Post Symmetric Compensation Technique. This was done to find the most optimised design parameter for maximum signal performance of a matched 48 Channel DWDM system.

5.2 Comparison of OSNR for Post Compensation Technique (with 1 EDFA) vs Post Symmetric Compensation Technique (with 3 EDFAs)

The signal power received at the optical receiver was calculated using (2.10) shown in section 2.7 of chapter 2. The calculated signal power was found to be equal to the maximum signal power measured in Optisystem. The noise power was measured placing a WDM analyser at the output of the WDM DEMUX. The OSNR was calculated using (2.12) found in section 2.8.1 of chapter 2.

The mismatched frequencies between the 48 channel WDM transmitter and WDM MUX for networks used in [2] increased the chromatic distortion (CD), which then significantly decreased signal power and its OSNR. However, this was done to decrease the non-linear effects of FWM because FWM effects were inversely dependant on CD. There was a definite and clear improvement in OSNR when using matched components than as opposed to using mismatched components for all channel spacings as shown in Table 5.1. This was because matched active components used frequency channels that were aligned to each other and the BW of each channel did not overlap with each other.

From section 3.3.1.2 of chapter 3, it had been established that the span loss for 1 EDFA is much greater than the span loss for 3 EDFAs and power received at the photodetector for 3 EDFAs was far greater than for 1 EDFA. The received signal for 3 EDFA was more easily detected and had a higher signal quality than with 1 EDFA.

Furthermore, Table 5.1 shows the maximum signal power and OSNR of the post Symmetric 3 EDFA technique, which was always higher than the 1 EDFA post compensation technique for all channel spacings in any type of network. The addition of the 3 symmetric EDFAs in all networks compensated for the increased attenuation and dispersion introduced when the bit rate and number of channels were increased as shown from the design done in [1]. It can also be seen that the NRZ format always displayed a higher signal to noise ratio than the RZ. This was because NRZ was more robust to impacts of chromatic dispersion as compared to RZ. Linear and non-linear losses were mostly supressed at 100GHz channel spacing for NRZ. NRZ had higher signal power and lower noise power than RZ due to NRZ eliminating more effects of CD.

Table 5.1: OSNR Comparison of Post Compensation Technique with 1 EDFA vs Post Symmetric compensation Technique with 3 EDFAs [2]

Channel Spacing (GHz)	Optical Link	Mod. Type	Max Signal Power (dBm)	Max Noise Power (dBm)	Max OSNR (dB)
100	1 EDFA (WDM Tx & WDM MUX mismatched)	NRZ	-43.83	-38.28	0
		RZ	-48.24	-38.28	0
	Symmetric Post Comp. 3 EDFAs (WDM Tx & WDM MUX mismatched)	NRZ	-2.98	-16.13	13.64
		RZ	-8.43	-16.13	9.11
	1 EDFA (Matched)	NRZ	-12.38	-38.28	26.01
		RZ	-17.70	-38.28	20.66
	Symmetric Post Comp. 3 EDFAs (Matched)	NRZ	28.87	-16.13	45.11
		RZ	23.54	-16.13	39.76
50	1 EDFA (WDM Tx & WDM MUX mismatched)	NRZ	-43.22	-38.28	24.39
		RZ	-46.64	-38.28	19.01
	Symmetric Post Comp. 3 EDFAs (WDM Tx & WDM MUX mismatched)	NRZ	-2.41	-16.13	43.55
		RZ	-7.53	-16.13	38.17
	1 EDFA (Matched)	NRZ	-12.41	-38.28	26.08
		RZ	-17.81	-38.28	20.58
	Symmetric Post Comp. 3 EDFAs (Matched)	NRZ	28.87	-16.13	45.23
		RZ	23.53	-16.13	39.77
25	1 EDFA (WDM Tx & WDM MUX mismatched)	NRZ	-25.67	-38.28	24.81
		RZ	-31.80	-38.28	18.67
	Symmetric Post Comp.	NRZ	15.58	-16.13	43.92

	3 EDFAs (WDM Tx & WDM MUX mismatched)	RZ	10.03	-16.13	38.36
	1 EDFA (Matched)	NRZ	-12.36	-38.28	26.15
		RZ	-19.64	-38.28	19.90
	Symmetric Post Comp. 3 EDFAs (Matched)	NRZ	28.93	-16.13	45.34
		RZ	22.69	-16.13	39.18
12.5	1 EDFA (WDM Tx & WDM MUX mismatched)	NRZ	-19.03	-38.28	23.67
		RZ	-23.89	-38.28	18.62
	Symmetric Post Comp. 3 EDFAs (WDM Tx & WDM MUX mismatched)	NRZ	22.22	-16.13	42.78
		RZ	17.91	-16.13	37.73
	1 EDFA (Matched)	NRZ	-11.53	-38.28	27.35
		RZ	-17.33	-38.28	22.12
	Symmetric Post Comp. 3 EDFAs (Matched)	NRZ	29.60	-16.13	46.62
		RZ	23.98	-16.13	41.49
6.25	1 EDFA (WDM Tx & WDM MUX mismatched)	NRZ	-13.42	-38.28	24.86
		RZ	-18.58	-38.28	19.69
	Symmetric Post Comp. 3 EDFAs (WDM Tx & WDM MUX mismatched)	NRZ	27.38	-16.13	45.51
		RZ	22.12	-16.13	38.25
	1 EDFA (Matched)	NRZ	-7.77	-38.28	31.55
		RZ	-14.20	-38.28	24.94
	Symmetric Post Comp. 3 EDFAs (Matched)	NRZ	33.69	-16.13	50.49
		RZ	27.25	-16.13	44.05

5.3 Signal performance comparison of NRZ, RZ and MDRZ at various channel spacings for maximum optimisation of a 48 Channel DWDM system

The section showed the tabulated results of all eye diagrams with the highest Q factor illustrated in chapter 4 for signal performance comparison of each channel spacings and parameter combinations. Table 5.2, Table 5.3, Table 5.4, Table 5.5 and Table 5.6 showed the tabulated results of the 100 GHz, 50 GHz, 25 GHz, 12.5 GHz and 6.25 GHz channel spacing respectively.

The average Q-factor of a network was an indication of the overall signal performance of the system and was calculated using (2.18) shown in section 2.8.4 of chapter 2. The overall signal performance of a system was deemed acceptable and optimised only if the average Q factor of the system was > 6. For this to be true, almost all channels had to perform with a Q factor that was either ≈ or ≥ 6, which was the minimum Q factor needed to obtain a BER of $\geq 10^{-9}$. This was needed to produce an acceptable signal that can be detected at the optical receiver with the least amount of bit errors. The BW efficiency of each network was an indication of the number of channels that were received by the optical receiver that had some recognisable signal. For this to happen, BER must be < 1 and Q factor must be > 0. The BW efficiency was calculated using (2.19) shown in section 2.8.4 of chapter 2.

Table 5.2: Results of 100GHz channel spacing with various design parameters and modulation types

Channel Spacing (GHz)	Various Design Parameters	Mod Type	Avg. Q-Factor of all 48 Channels (Overall Performance)	Channel	Highest Q-Factor	Min. BER	Eye Height	BW Eff. (%)
100 GHz MUX BW = 80 GHz DEMUX BW = 80 GHz	Symmetric Post Comp. 3 EDFAs (WDM Tx & WDM MUX Mismatched)	NRZ	10.97	48	20.34	2.76E-92	8.25E-04	97.9
		RZ	4.77	48	24.20	8.53E-130	6.66E-04	100
	1 EDFA (Matched)	NRZ	12.77	1	16.47	2.67E-61	8.82E-05	100
		RZ	11.76	1	16.50	1.63E-61	5.67E-05	100
	Symmetric Post Comp. 3 EDFAs (Matched)	NRZ	13.88	1	18.99	9.76E-81	1.21	100
		RZ	18.83	1	27.59	5.82E-168	0.77	100

100 GHz Symmetric Post Comp. 3 EDFAs (Matched)	*MUX BW = 80 GHz DEMUX BW = 50 GHz*	*NRZ*	*40.68*	*38*	*54.32*	*0*	*1.35*	*100*
		RZ	*53.37*	*1*	*82.60*	*0*	*0.78*	*100*
	MUX BW = 50 GHz DEMUX BW = 80 GHz	NRZ	13.52	44	20.66	3.30E-95	1.27	100
		RZ	24.67	1	59.89	0	0.72	100

Table 5.2 showed the summarised results of the eye diagram for the 100GHz channel spacing with various design parameters and modulation types. A post symmetric compensation technique with 3 EDFAs using MUX BW = 80 GHz and DEMUX BW = 50 GHz was the most optimised network with highest signal performance. This was underlined and highlighted in italics in Table 5.2. For this network configuration, the RZ (Avg. Q= 53.37) performed better than NRZ (Avg. Q = 40.68). The BER for NRZ and RZ is equal to 0.

Table 5.3: Results of 50GHz channel spacing with various design parameters and modulation types

Channel Spacing (GHz)	Various Design Parameters	Mod Type	Avg. Q-Factor of all 48 Channels (Overall Performance)	Channel	Highest Q-Factor	Min. BER	Eye Height	BW Eff. (%)
50 GHz MUX BW = 80 GHz DEMUX BW = 80 GHz	Symmetric Post Comp. 3 EDFAs (WDM Tx & WDM MUX mismatched)	NRZ	1.04	1	4.15	1.61E-05	6.16E-02	66.6
		RZ	1.33	18	3.09	9.66E-04	1.22E-05	75
	1 EDFA (Matched)	NRZ	2.08	48	3.08	1.00E-03	2.91E-06	100
		RZ	2.22421	36	3.79	7.47E-05	2.35E-05	100
	Symmetric Post Comp. 3 EDFAs (Matched)	NRZ	2.06	48	3.14	8.29E-04	6.19E-02	100
		RZ	2.22573	48	2.8	2.07E-03	-0.026	100

50 GHz Symmetric Post Comp. 3 EDFAs (Matched)	MUX BW = 80 GHz DEMUX BW = 50 GHz	NRZ	7.03	32	9.58	4.47E-22	1.00	100
		RZ	3.56	38	6.31	1.10E-10	0.41	100
	MUX BW = 80 GHz DEMUX BW = 25 GHz	*NRZ*	*8.72*	*1*	*9.93*	*1.06E-23*	*0.90*	*100*
		RZ	*10.02*	*48*	*26.53*	*1.41E-155*	*0.48*	*100*
	MUX BW = 50 GHz DEMUX BW = 80 GHz	NRZ	2.23	42	3.71	1.01E-04	0.34	100
		RZ	2.34	42	5.11	1.58E-07	0.38	100

Table 5.3 showed the summarised results of the eye diagram for the 50 GHz channel spacing with various design parameters and modulation types (NRZ and RZ). A post symmetric compensation technique with 3 EDFAs using MUX BW = 80 GHz and DEMUX BW = 25 GHz was the most optimised network with the highest signal performance. This was underlined and highlighted in italics in Table 5.3. For this network configuration, RZ (Avg. Q= 10.02) performed better than NRZ (Avg. Q = 8.72). The BER of RZ was lower than NRZ.

Table 5.4: Results of 25 GHz channel spacing with various design parameters and modulation types

Channel Spacing (GHz)	Various Design Parameters	Mod. Type	Avg. Q-Factor of all 48 Channels (Overall Performance)	Channel	Highest Q-Factor	Min. BER	Eye Height	BW Eff. (%)
25 GHz MUX BW = 80 GHz DEMUX BW = 80 GHz	Symmetric Post Comp. 3 EDFAs (WDM Tx & WDM MUX mismatched)	NRZ	2.27	4	4.34	6.23E-06	3.34E-01	91.6
		RZ	2.50	4	5.00	2.36E-07	2.77E-01	97.9
	1 EDFA (Matched)	NRZ	2.16	32	3.11	9.08E-04	1.46E-05	93.75
		RZ	1.69	16	3.55	1.49E-04	2.06E-05	79.16
	Symmetric Post Comp. 3 EDFAs (Matched)	NRZ	1.63	4	3.15	7.76E-04	0.24	81.25
		RZ	1.86	28	3.66	1.02E-04	0.32	83.33

25 GHz Symmetric Post Comp. 3 EDFAs (Matched)	MUX BW = 80 GHz DEMUX BW = 25 GHz	NRZ	2.41	1	4.93	3.68E-07	0.51	89.58
		RZ	2.24	26	5.90	1.52E-09	0.24	91.66
	MUX BW = 80 GHz DEMUX BW = 12.5 GHz	NRZ	2.28	46	2.67	3.60E-03	-0.14	97.91
		RZ	2.26	16	5.03	2.40E-07	0.29	85.41
	MUX BW = 25 GHz DEMUX BW = 80 GHz	NRZ	2.21	16	3.21	6.39E-04	0.39	93.75
		RZ	1.91	44	3.15	7.97E-04	3.00E-02	89.58
	MUX BW = 12.5 GHz DEMUX BW = 80 GHz	NRZ	0.98	16	3.29	4.95E-04	0.34	66.66
		RZ	1.51	10	3.11	9.22E-04	3.99E-02	79.16
	MUX BW = 25 GHz DEMUX BW = 25 GHz	NRZ	2.09	44	3.73	7.37E-05	0.33	93.75
		RZ	3.13	1	4.84	6.03E-07	0.13	97.91
25 GHz ER = 5dB & Rectangular Filter Symmetric Post Comp. 3 EDFAs (Matched)	MUX BW = 80 GHz DEMUX BW = 25 GHz	NRZ	2.56	48	4.56	2.39E-06	0.28	91.66
		RZ	1.39	8	2.90	1.81E-03	-1.99E-02	79.16
	MUX BW = 25 GHz DEMUX BW = 25 GHz	*NRZ*	*5.83*	*8*	*6.51*	*3.54E-11*	*0.45*	*100*
		RZ	*9.59*	*32*	*13.55*	*3.54E-42*	*0.30*	*97.91*

Table 5.4 showed the summarised results of the eye diagram for the 25 GHz channel spacing with various design parameters and modulation types (NRZ and RZ). A post symmetric compensation technique with 3 EDFAs, an ER =5dB and a rectangular filter using MUX BW = 25 GHz and DEMUX BW = 25 GHz was the most optimised network with highest signal performance. This was underlined and highlighted in italics in Table 5.4. For this network configuration, RZ (Avg. Q= 9.59) performed better than NRZ (Avg. Q = 5.83). BER of RZ is lower than NRZ. Further improvement of this network can be done in the future for the average Q of NRZ to be also greater than 6 by using MDRZ or by decreasing the BW of the filter, but this was not the focus of this dissertation.

Table 5.5: Results of 12.5 GHz channel spacing with various design parameters and modulation types

Channel Spacing (GHz)	Various Design Parameters	Mod Type	Avg. Q-Factor of all 48 Channels (Overall Performance)	Channel	Highest Q-Factor	Min. BER	Eye Height	BW Eff. (%)
12.5 GHz MUX BW = 80 GHz DEMUX BW = 80 GHz	Symmetric Post Comp. 3 EDFAs (WDM Tx & WDM MUX mismatched)	NRZ	2.56	1	3.27	1.91E-04	6.20E-02	95.8
		RZ	2.77	1	3.89	4.09E-05	1.33E-01	97.9
	1 EDFA (Matched)	NRZ	1.66	4	3.43	2.90E-04	1.55E-04	81.2
		RZ	1.17	10	4.87	5.46E-07	1.29E-04	66.6
	Symmetric Post Comp. 3 EDFAs (Matched)	NRZ	1.51	2	3.65	1.07E-04	2.73	75
		RZ	1.65	26	4.98	3.17E-07	1.83	72.9
12.5 GHz Symmetric Post Comp. 3 EDFAs (Matched)	MUX BW = 80 GHz DEMUX BW = 12.5 GHz	NRZ	1.57	22	4.43	4.62E-06	1.09	72.9
		RZ	1.48	18	4.64	1.67E-06	0.32	70.8
	MUX BW = 80 GHz DEMUX BW = 6.25 GHz	NRZ	1.46	18	4.19	1.30E-05	0.59	72.9
		RZ	2.26	16	4.84	6.26E-07	0.25	79.1
	MUX BW = 12.5 GHz DEMUX BW = 80 GHz	NRZ	1.41	12	3.80	7.07E-05	2.94	75
		RZ	1.64	48	3.59	1.59E-04	0.48	77.0
	MUX BW = 6.25 GHz DEMUX BW = 80 GHz	NRZ	1.92	1	3.05	1.11E-03	0.15	85.4
		RZ	1.07	30	3.01	1.27E-03	1.72E-02	68.7
	MUX BW = 3.125 GHz DEMUX BW = 80 GHz	NRZ	3.06	24	4.00	2.54E-05	2.59	100
		RZ	3.24	34	4.12	1.55E-05	0.84	100
		MDRZ	*8.66*	*14*	*12.77*	*7.49E-38*	*0.43*	*100*

Table 5.5 showed the summarised results of the eye diagrams for the 12.5 GHz channel spacing with various design parameters and modulation types. A post symmetric

compensation technique with 3 EDFAs and a MDRZ line coding modulation scheme using MUX BW = 3.125 GHz and DEMUX BW = 80 GHz was the most optimised network with highest signal performance. This was underlined and highlighted in italics in Table 5.5. For this network configuration, MDRZ (Avg. Q= 8.66) performed better than NRZ (Avg. Q = 3.06) and RZ (Avg. Q = 3.24). The BER of MDRZ is lower than that of NRZ and RZ.

Table 5.6: Results of 6.25 GHz channel spacing with various design parameters and modulation types

Channel Spacing (GHz)	Various Design Parameters	Mod Type	Avg. Q-Factor of all 48 Channels (Overall Performance)	Channel	Highest Q-Factor	Min. BER	Eye Height	BW Eff. (%)
6.25 GHz MUX BW = 80 GHz DEMUX BW = 80 GHz	Symmetric Post Comp. 3 EDFAs (WDM Tx & WDM MUX mismatched)	NRZ	3.329	26	3.77	7.82E-05	7.35E-03	100
		RZ	1.868	26	3.65	1.27E-04	5.83E-04	79.1
	1 EDFA (Matched)	NRZ	1.79	34	3.85	5.86E-05	1.02E-03	79.1
		RZ	1.51	8	4.13	1.62E-05	1.70E-04	70.8
	Symmetric Post Comp. 3 EDFAs (Matched)	NRZ	2.41	2	4.06	2.37E-05	7.49	89.5
		RZ	2.14	40	4.41	4.94E-06	2.73	79.1
6.25 GHz Symmetric Post Comp. 3 EDFAs (Matched)	MUX BW = 80 GHz DEMUX BW = 6.25 GHz	NRZ	1.48	46	4.18	7.26E-06	0.94	75
		RZ	2.67	46	7.86	1.86E-15	0.75	85.4
	MUX BW = 6.25 GHz DEMUX BW = 80 GHz	NRZ	3.03	18	3.57	1.73E-04	7.28	95.8
		RZ	2.49	38	3.61	5.55E-05	1.94	87.5
	MUX BW = 3.125 GHz DEMUX BW = 80 GHz	NRZ	4.04	32	4.63	6.26E-07	14.25	100
		RZ	4.19	36	4.70	4.56E-07	4.26	100
		MDRZ	*8.93*	*38*	*10.7*	*7.17E-28*	*1.45*	*100*

Table 5.6 showed the summarised results of the eye diagrams for the 6.25 GHz channel spacing with various design parameters and modulation types. A post symmetric

compensation technique with 3 EDFAs and a MDRZ line coding modulation scheme using MUX BW = 3.125 GHz and DEMUX BW = 80 GHz was the most optimised network with highest signal performance. This was underlined and highlighted in italics in Table 5.6. For this network configuration, MDRZ (Avg. Q= 8.93) performed better than NRZ (Avg. Q = 4.04) and RZ (Avg. Q = 4.19). The BER of MDRZ was lower than that of NRZ and RZ.

5.3.1 Comparison of Post Compensation Technique with 1 EDFA vs Post Symmetric Compensation Technique with 3 EDFAs

The common parameters used for all networks compared in this section was that they all had Bessel Filters in the MUX and DEMUX, all MUX's had a Bandwidth of 80 GHz, DEMUX's had a Bandwidth of 80 GHz, and ER was 30 dB.

- **For the 100 GHz channel spacing, using MUX BW = 80 GHZ and DEMUX BW = 80 GHZ** (See Table 5.2 for results):
  - For the 48 Channel network with mismatched components, the Avg. Q-Factor of NRZ = 10.97 and RZ = 4.77, which were both lower than that of the 48-channel network with matched components (Avg. Q of NRZ = 13.88 and RZ = 18.83). This means that overall signal performance of the matched network was better since it can lower the effect of chromatic distortion.
  - The highest Q factor when using 1 EDFA for RZ (= 16.50) was higher than NRZ (= 16.47). The min. BER when using 1 EDFA of RZ (= 1.63E-61) was lower than NRZ (= 2.67E-61). Similarly, the highest Q factor when using 3 EDFAs of RZ (= 27.59) was higher than that of NRZ (= 18.99). The min. BER when using 3 EDFAs of RZ (= 5.82E-168) was lower than that of NRZ (= 9.76E-81). The RZ modulation scheme when using 3 EDFAs had the lowest BER. The min BER of the post symmetric compensation technique with 3 EDFAs produced less bit errors than the post compensation technique of using 1 EDFA for both NRZ and RZ. Furthermore from Figure 5.1, it was noticed that the highest Q and Average Q of NRZ and RZ was higher in the post symmetric compensation (3 EDFAs) than the post compensation (1 EDFA) technique. The RZ modulation scheme when using 3 EDFAs had the best overall signal performance since the Avg. Q of RZ was also the best overall.

- For the 48-channel network with matched components, when using 1 EDFA, the Avg. Q factor of NRZ modulation scheme (= 12.77) was higher than that of RZ (= 11.76). Similarly, when using 3 EDFAs, the Avg. Q-Factor of 48 Channels of the RZ modulation scheme (= 18.83) was higher than that of NRZ (= 13.88). The signal performance of the post symmetric compensation technique with 3 EDFAs was higher than the post compensation technique of using 1 EDFA for both NRZ and RZ. Furthermore, it can be established that the RZ modulation scheme, when using 3 EDFAs, had the highest signal performance.

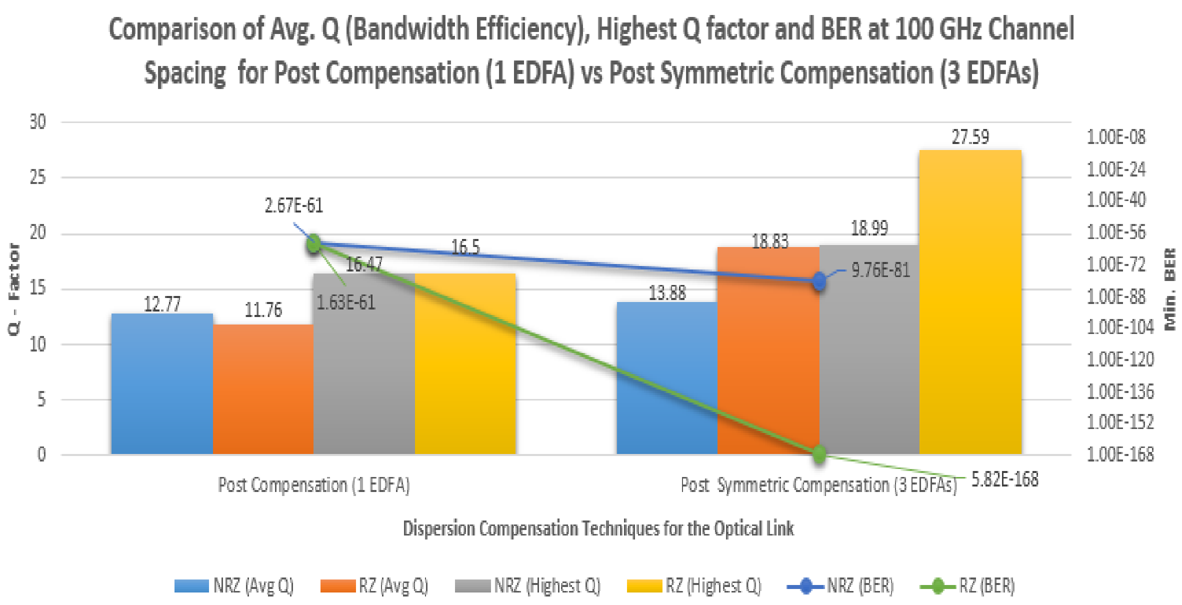

Figure 5.1: Comparison of Signal Performance of 1 EDFA vs 3 EDFAs for 100GHz spacing

- **For the 50 GHz channel spacing, using MUX BW = 80 GHZ and DEMUX BW =80 GHz** (See Table 5.3 for results):
  - For the 48 Channel network with mismatched components, the Avg. Q-Factor of NRZ = 1.04 and RZ = 1.33, which were both lower than that of the 48-channel network with matched components (Avg. Q of NRZ = 2.06 and RZ = 2.225). This means that overall signal performance of the matched network was better since it can lower the effect of chromatic distortion.

    However, further improvements were done on the matched network for it have an acceptable Q > 6 and BER value > 10^{-9}. This was done in section 5.3.2.

- The highest Q factor, when using 1 EDFA, of RZ (= 3.79) was higher than NRZ (= 3.08). Therefore, when using 1 EDFA, the min. BER of RZ (= 7.47E-05) was lower than NRZ (= 1.00E-03). The RZ modulation scheme when using 1 EDFA had the highest Q factor and lowest BER than the NRZ. This was because a decrease in channel spacings increases the effects of non-linear losses and RZ was more robust to the effects of non-linear losses than NRZ.
- The highest Q factor, when using 3 EDFAs, of RZ (= 2.86) was lower than that of NRZ (= 3.14). Therefore, when using 3 EDFAs, the min. BER of RZ (= 2.07E-03) was higher than that of NRZ (= 8.29E-04). The NRZ modulation scheme had the highest Q factor and lowest BER when using 3 EDFAs than the RZ. This was because, when the symmetric EDFAs were added, the effects of non-linear losses were minimised significantly. This meant that dispersion was the only linear loss left in the network and NRZ was more robust to impacts of chromatic dispersion than RZ. However, these were just an indication of the individual signal performance of the channel with the highest Q in both compensation techniques. The best overall performance would be determined after considering the average Q of the system as well.
- For the matched 48-Channel network, when using 1 EDFA, the Avg. Q-Factor of the NRZ modulation scheme (= 2.224) was higher than that of RZ (= 2.08). Similarly, when using 3 EDFAs, the Avg. Q-Factor of the RZ modulation scheme (= 2.225) was higher than that of NRZ (= 2.06). Therefore, the signal performance of the post symmetric compensation technique with 3 EDFAs using the RZ modulation technique was slightly higher than that of the post compensation technique with 1 EDFA. However, when considering the fact that the RZ modulation scheme using 3 EDFAs only had a slightly higher overall signal performance (avg. Q) than NRZ, as could be seen from Figure 5.2, and NRZ showed a higher Q factor when compared to RZ when using 3 EDFAs; the NRZ modulation scheme was believed to showcase the best overall signal performance for the post symmetric compensation technique.

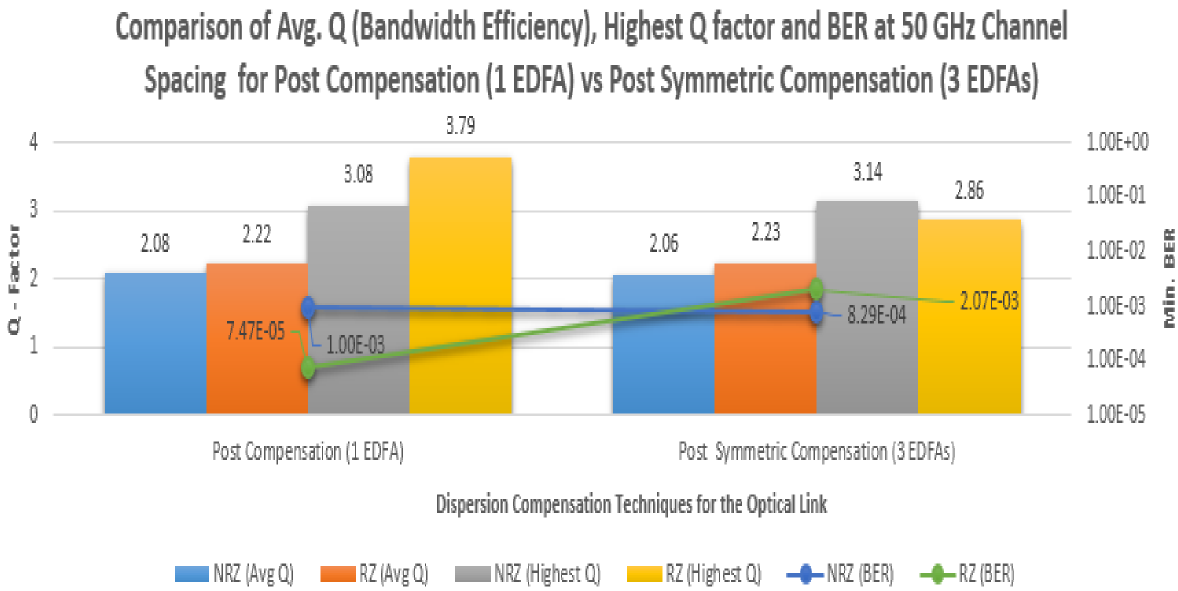

Figure 5.2: Comparison of Signal Performance of 1 EDFA vs 3 EDFAs for 50GHz spacing

- **For the 25 GHz channel spacing, using MUX BW = 80 GHZ and DEMUX BW =80 GHz** (See Table 5.4 for results):
  - For the 48 Channel network with mismatched components, the Avg. Q-Factor of NRZ = 2.27 and RZ = 2.50, which were both higher than that of the 48-channel network with matched components (Avg. Q of NRZ = 1.63 and RZ = 1.86). This means that overall signal performance of the mismatched network was better since at narrow channel spacings of 25 GHz, it increases the effect of chromatic distortion due to an overlap in channel bandwidths. An increase in chromatic dispersion in narrow channel spacings greatly reduces the effects of non-linear losses such as FWM. Therefore, further improvements on the design parameters of the matched network had to be done to produce a far greater signal performance with an acceptable Q and BER. This was done in section 5.3.2.
  - The highest Q factor, when using 1 EDFA, of RZ (= 3.55) was higher than NRZ (= 3.11). The min. BER, when using 1 EDFA, of RZ (= 1.49E-04) was lower than NRZ (= 9.08E-04). And, the highest Q factor, when using 3 EDFAs, of RZ (= 3.66) was higher than that of NRZ = 3.15. The min. BER, when using 3 EDFAs, of RZ (= 1.02E-04) was lower than that of NRZ (= 7.76E-04). The RZ modulation scheme when using 3 EDFAs had the highest quality factor and the lowest BER. The highest quality factor

of the post symmetric compensation technique with 3 EDFAs was higher than that of the post compensation technique of using 1 EDFA for RZ.

- The Avg. Q-Factor of the matched 48 Channels, when using 1 EDFA, for the NRZ modulation scheme (= 2.16) was higher than that of RZ (= 1.69). Similarly, the Avg. Q-Factor of 48 Channels, when using 3 EDFAs, of the RZ modulation scheme (= 1.86) was higher than that of NRZ (= 1.63). The NRZ modulation scheme had the highest performance for system when using 1 EDFA and RZ had the highest performance for a system when using 3 EDFAs, which can be seen in Figure 5.3. However, since the RZ modulation scheme had the highest quality factor and the lowest BER, the best overall signal performance was achieved using the RZ with the post symmetric compensation technique.

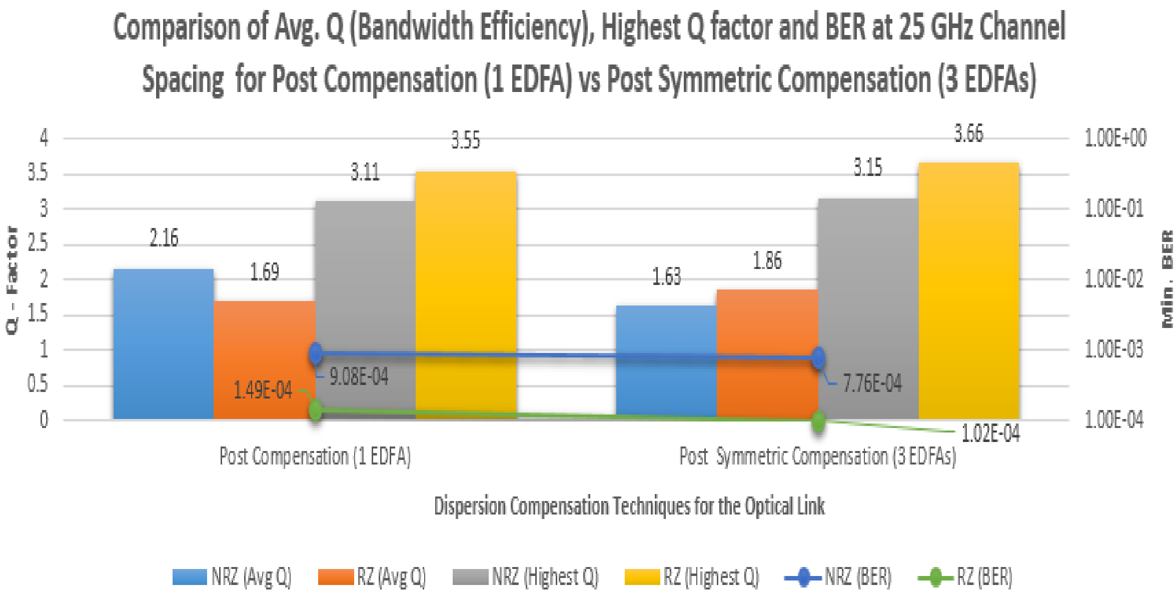

Figure 5.3: Comparison of Signal Performance of 1 EDFA vs 3 EDFAs for 25GHz spacing

- **For the 12.5 GHz channel spacing, using MUX BW = 80 GHZ and DEMUX BW =80 GHz** (See Table 5.5 for results):
  - For the 48 Channel network with mismatched components, the Avg. Q-Factor of NRZ = 2.56 and RZ = 2.77, which were both higher than that of the 48-channel network with matched components (Avg. Q factor of NRZ = 1.51 and RZ = 1.65). This means that overall signal performance of the mismatched network was better since at narrow channel spacings of 12.5 GHz, it increases the effect of chromatic distortion due to an overlap in channel bandwidths. An increase in chromatic dispersion in narrow channel spacings greatly reduces the effects of non-linear losses such as FWM. Therefore, further improvements on the design parameters of the matched network had to be done to produce a far greater signal performance with an acceptable Q and BER. This was done in section 5.3.2 and section 0.
- The highest Q factor, when using 1 EDFA, of RZ (= 4.87) was higher than NRZ (= 3.43). The min. BER, when using 1 EDFA, of RZ (= 5.46E-07) was lower than NRZ (= 2.90E-04). When using 3 EDFAs, the highest Q factor of RZ (= 4.98) was higher than that of NRZ (= 3.65). The min. BER, when using 3 EDFAs, of RZ (= 3.17E-07) was lower than that of NRZ (= 1.07E-04). The RZ modulation scheme when using 3 EDFAs had the highest quality factor and the lowest BER. The highest quality factor of the post symmetric compensation technique with 3 EDFAs was higher than that of the post compensation technique of using 1 EDFA for RZ.
- For the 48 Channel matched network, when using 1 EDFA, Avg. Q-Factor of the NRZ modulation scheme (= 1.66) was higher than that of RZ (= 1.17). Similarly, when using 3 EDFAs, the Avg. Q factor of the RZ modulation scheme (= 1.65) was higher than that of NRZ (= 1.51). The NRZ modulation had the highest signal performance when using 1 EDFA and RZ had the highest signal performance when using 3 EDFAs, which can be seen in Figure 5.4. However, since the RZ modulation scheme had the highest quality factor and the lowest BER, the best overall signal performance was achieved using the RZ format with the post symmetric compensation technique.

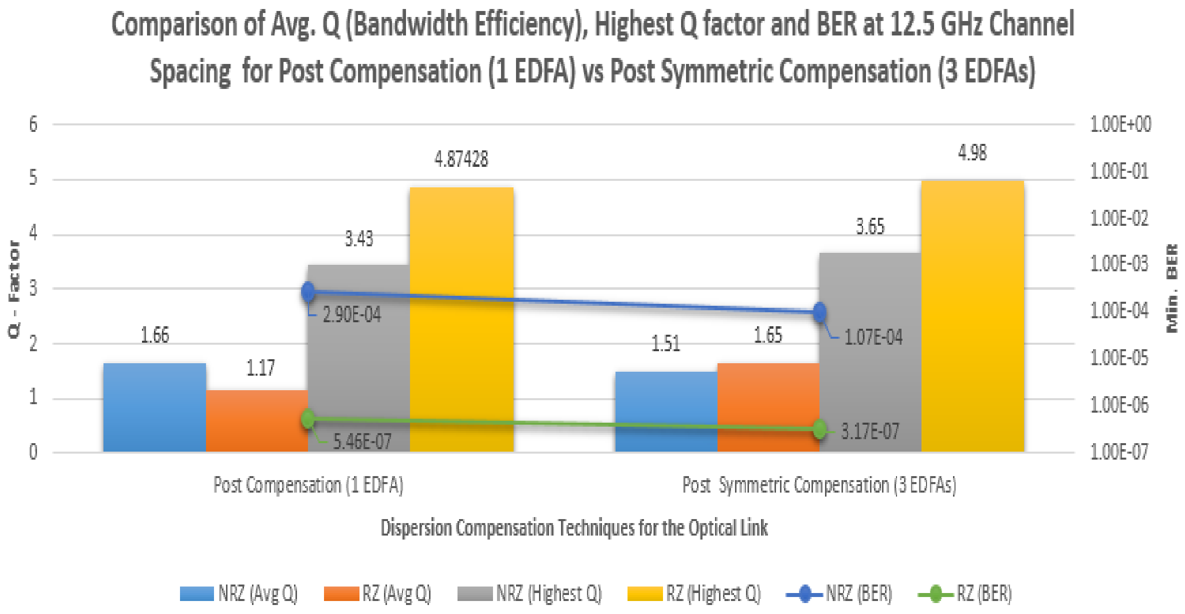

Figure 5.4: Comparison of Signal Performance of 1 EDFA vs 3 EDFAs for 12.5 GHz spacing

- **For the 6.25 GHz channel spacing, using MUX BW = 80 GHZ and DEMUX BW = 80 GHz** (See Table 5.6 for results):
  - For the 48 Channel network with mismatched components, the Avg. Q-Factor of had NRZ = 3.329, which was higher than that of the NRZ (= 2.41) of the 48-channel network with matched components. However, the Avg. Q-Factor of RZ (=1.868) of the mismatched components was lower than that of the RZ (=2.14) of the 48-channel network with matched components. This means that for very narrow channel spacings of 6.25 GHZ, the overall signal performance of the NRZ mismatched network was better due to NRZ being more robust to impacts of chromatic dispersion as compared to RZ. At very narrow channel spacings for a mismatched network, there was a massive overlap in channel bandwidths and increased effect of chromatic distortion. An increase in chromatic dispersion in narrow channel spacings greatly reduced the effects of non-linear losses such as FWM. Therefore, further improvements on the design parameters of the matched network had to be done to produce a far greater signal performance with an acceptable Q and BER. This was done in section 5.3.2 and section 5.3.3.
  - The highest Q factor, when using 1 EDFA, of RZ (= 4.13) was higher than NRZ (= 3.85). However, when using 3 EDFAs, the highest Q factor of RZ (= 4.41) was higher

than that of NRZ (= 4.06). The RZ modulation scheme when using the post symmetric compensation technique with 3 EDFAs had the highest quality factor than that of the post compensation technique of using 1 EDFA for both NRZ and RZ.

- For the 48 Channels matched network, when using 1 EDFA, the Avg. Q-Factor of the NRZ modulation scheme (= 1.79) was higher than that of RZ (= 1.51). However, when using 3 EDFAs, the Avg. Q-Factor of the RZ modulation scheme (= 2.14) was lower than that of NRZ (= 2.41). Both the NRZ and RZ modulation schemes had avg. Q factors that showed the highest signal performance in the post symmetric compensation technique with 3 EDFAs than the post compensation technique of using 1 EDFAs for both NRZ and RZ, as can be seen in Figure 5.5.

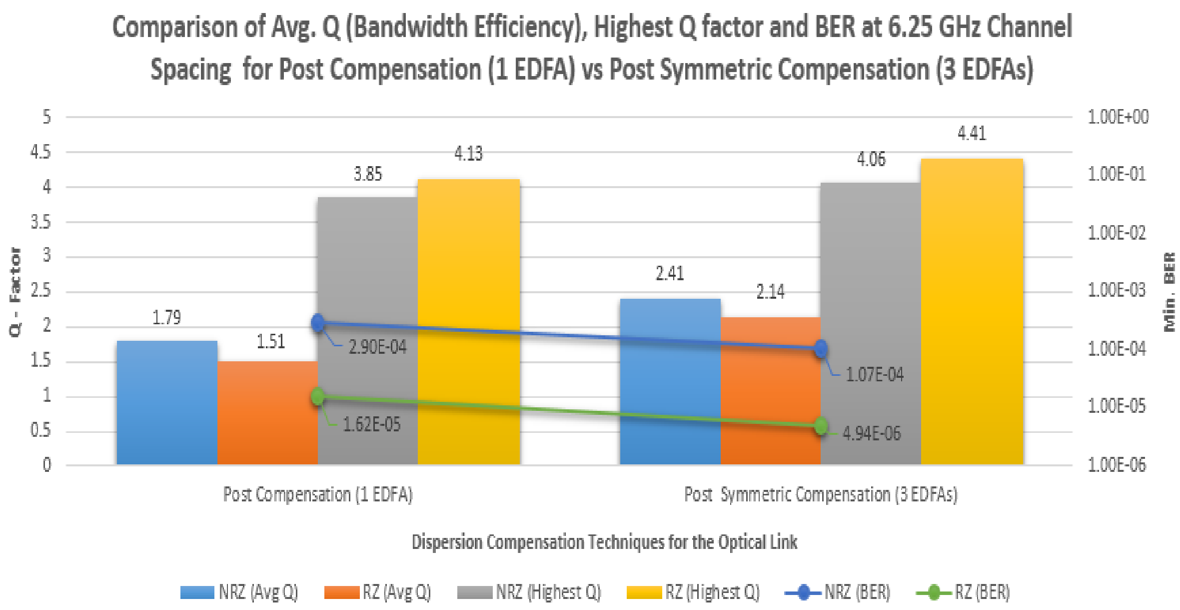

Figure 5.5: Comparison of Signal Performance of 1 EDFA vs 3 EDFAs for 6.25 GHz spacing

5.3.2 Optimisation of DWDM System by varying different parameters for RZ and NRZ Modulation formats

The common parameters used for all networks in this section was the 2nd order Bessel Filters in the MUX and DEMUX, a Post Symmetric Compensation Technique with 3 EDFAs in the optical link and an ER of 30 dB at the WDM transmitter.

- **For the optimisation of the 100 GHz channel spacing,** see Table 5.2 and Figure 5.6**:**
  - ➢ The Avg. Q-Factor of 48 Channels (Bandwidth Efficiency) of the following networks were compared:
    - ❖ MUX BW = 80 GHz and DEMUX BW = 80 GHz,
    - ❖ MUX BW = 50 GHz and DEMUX BW = 80 GHz,
    - ❖ MUX BW = 80 GHz and DEMUX BW = 50 GHz.
  - ➢ There was a definite improvement when decreasing the DEMUX BW from 80 GHZ to 50 GHz and not much improvement when decreasing the MUX BW from 80 GHZ to 50 GHz.
    - ❖ When MUX BW = 80 GHz and DEMUX BW = 80 GHz was used, the Avg. Q-Factor of 48 Channels of the RZ modulation scheme (= 18.83) was higher than that of NRZ (= 13.88).
    - ❖ When MUX BW = 50 GHz and DEMUX BW = 80 GHz was used, the Avg. Q-Factor of 48 Channels of the RZ modulation scheme (= 24.67) was higher than that of NRZ (= 13.52).
    - ❖ Similarly, when using MUX BW = 80 GHz and DEMUX BW = 50 GHz, the Avg. Q-Factor of 48 Channels of the RZ modulation scheme (= 53.37) was higher than that of NRZ (= 40.68). Therefore, the RZ modulation scheme when using MUX BW = 80 GHz and DEMUX BW = 50 GHz, had the highest signal performance.
  - ➢ There was definite improvement in the quality factor of NRZ and RZ modulation scheme when decreasing the DEMUX BW from 80 GHz to 50 GHz, and finally to 25 GHz. However, there was not much improvement in quality factor when decreasing MUX BW from 80 GHz to 50 GHz.
    - ❖ The highest Q factor of RZ (= 27.59), when using MUX BW = 80 GHz and DEMUX BW = 80 GHz, is higher than the Q of NRZ (= 18.99).

- ❖ Similarly, the highest Q factor of RZ (= 59.89), when using MUX BW = 50 GHz and DEMUX BW = 80 GHz, is higher than the Q of NRZ (= 20.66).
- ❖ The RZ modulation scheme had the highest Q factor (=82.6), when using MUX BW = 80 GHz and DEMUX BW = 50 GHz, which was higher than the Q of NRZ (= 54.32) for that same bandwidth configuration. This bandwidth configuration produced the best QoS.

- ➢ The min. BER of both RZ and NRZ (= 0), when using MUX BW = 80 GHz and DEMUX BW = 50 GHz. However, there is a min. BER of NRZ (= 3.30E-95) and RZ (= 0) when using MUX BW = 50 GHz and DEMUX BW = 80. The min BER for both NRZ and RZ, when using MUX BW = 80 GHz and DEMUX BW = 50 GHz, was the lowest compared to all other bandwidth configurations.
- ➢ For the 100 GHz channel spacing, with the NRZ and RZ modulation scheme, the signal quality was already of an acceptable level; however, when the MUX and DEMUX bandwidth was reduced 50 GHz, the system performance was significantly improved.
- ➢ Nevertheless, the RZ modulation scheme, when using MUX BW = 80 GHz and DEMUX BW = 50 GHz, had the highest bandwidth efficiency (=100 %) and the best overall signal performance for a channel spacing of 100 GHZ with a Q > 6 and a BER = 0 is greater than 10^{-9}. This is illustrated in Figure 5.6.

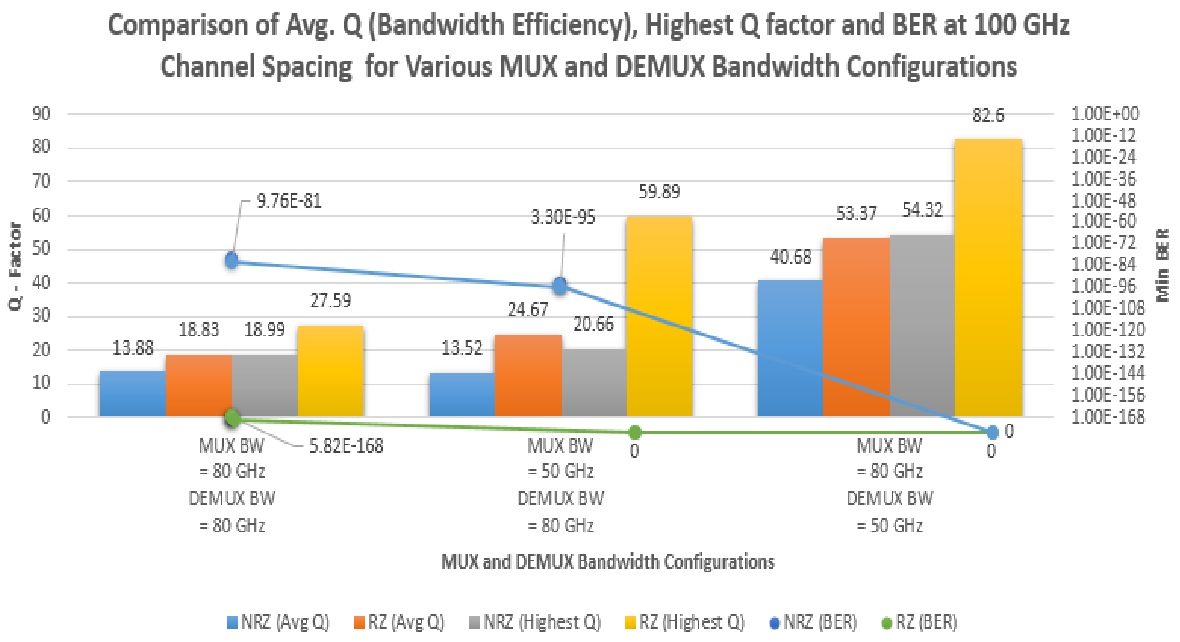

Figure 5.6: Comparison of Signal Performance of 100GHz spacing for Various MUX/DEMUX BW Configurations

- **For the optimisation of the 50 GHz channel spacing**, see Table 5.3 and Figure 5.7:
  - The Avg. Q-Factor for 48 Channels of the following networks were compared:
    - MUX BW = 80 GHz and DEMUX BW = 80 GHz,
    - MUX BW = 50 GHz and DEMUX BW = 80 GHz,
    - MUX BW = 80 GHz and DEMUX BW = 50 GHz,
    - MUX BW = 80 GHz and DEMUX BW = 25 GHz
  - There was definite improvement in bandwidth efficiency and signal performance in NRZ and RZ modulation scheme when decreasing the DEMUX BW from 80 GHz to 50 GHz, and finally to 25 GHz. However, there was not much improvement in bandwidth efficiency when decreasing MUX BW from 80 GHz to 50 GHz.
    - When using MUX BW = 80 GHz and DEMUX BW = 80 GHz, the Avg. Q-Factor of NRZ (= 2.06) was lower than that of RZ (= 2.22).
    - When using MUX BW = 50 GHz and DEMUX BW = 80 GHz, the Avg. Q-Factor of NRZ (= 2.23) was lower than that of RZ (= 2.34).
    - When using MUX BW = 80 GHz and DEMUX BW = 50 GHz, the Avg. Q-Factor of NRZ (= 7.03) was higher than that of RZ (= 3.56).
    - Finally, when using MUX BW = 80 GHz and DEMUX BW = 25 GHz, the Avg. Q-Factor of NRZ (= 8.72) was lower than that of RZ (= 10.02).
  - There was definite improvement in the quality factor in NRZ and RZ modulation scheme when decreasing the DEMUX BW from 80 GHz to 50 GHz, and finally to 25 GHz. However, there was not much improvement in the quality factor when decreasing MUX BW from 80 GHz to 50 GHz.
    - When using MUX BW = 80 GHz and DEMUX BW = 80 GHz, the highest Q factor of NRZ (= 3.14) was higher than the Q of RZ (= 2.86).
    - Similarly, when using MUX BW = 50 GHz and DEMUX BW = 80 GHz, the highest Q factor of RZ (= 5.11) was higher than the Q of NRZ (= 3.71).
    - When using MUX BW = 80 GHz and DEMUX BW = 50 GHz, the highest Q factor of NRZ (= 9.58) was higher than the Q of RZ (= 6.31).
    - Finally, when using MUX BW = 80 GHz and DEMUX BW = 25 GHz, the highest Q factor of RZ (= 26.53) was higher than the Q of NRZ (= 9.93).
  - The min. BER of both RZ and NRZ (= 0) when using MUX BW = 80 GHz and DEMUX BW = 50 GHz. However, when using MUX BW = 50 GHz and DEMUX BW = 80 GHz,

the min. BER of NRZ = 3.30E-95 and RZ = 0. The min BER for both NRZ and RZ, when using MUX BW = 80 GHz and DEMUX BW = 50 GHz, was comparatively lower than when using MUX BW = 50 GHz and DEMUX BW = 80 GHz.

- For the 50 GHz channel spacing, the DEMUX bandwidth had to be reduced to 25 GHz to achieve an acceptable system performance. BW Efficiency was always maintained at 100%.
- Therefore, the RZ modulation scheme, when using MUX BW = 80 GHz and DEMUX BW = 25 GHz, had the best overall signal performance for a channel spacing of 50 GHZ with the highest Q factor being > 6 and lowest BER > 10^{-9}. This is illustrated in Figure 5.7.

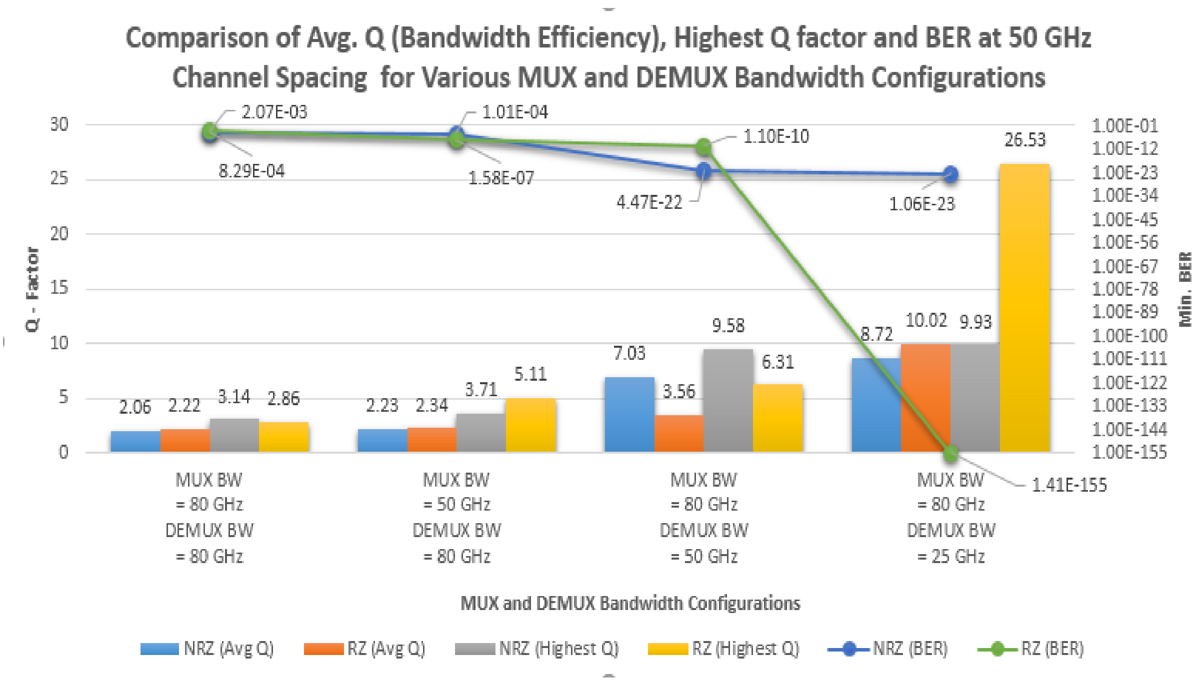

Figure 5.7: Comparison of Signal Performance of 50GHz spacing for Various MUX/DEMUX BW Configurations

- **For the optimisation of the 25 GHz channel spacing**, see Table 5.4 and Figure 5.8:
  - The Avg. Q-Factor for 48 Channels of the following networks were first compared:
    - MUX BW = 80 GHz and DEMUX BW = 80 GHz,
    - MUX BW = 80 GHz and DEMUX BW = 25 GHz,
    - MUX BW = 80 GHz and DEMUX BW = 12.5 GHz,
    - MUX BW = 25 GHz and DEMUX BW = 80 GHz,
    - MUX BW = 12.5 GHz and DEMUX BW = 80 GHz,
    - MUX BW = 25 GHz and DEMUX BW = 25 GHz,
  - The trial to improve the bandwidth efficiency and signal performance in NRZ and RZ modulation scheme was done by decreasing the MUX and DEMUX BW from 80 GHz to 12.5 GHz.
    - When using MUX BW = 80 GHz and DEMUX BW = 80 GHz, the Avg. Q-Factor of NRZ (= 1.63) was lower than that of RZ (= 1.86).
    - When using MUX BW = 80 GHz and DEMUX BW = 25 GHz, the Avg. Q-Factor of NRZ (= 2.41) was higher than that of RZ (= 2.24). This bandwidth configuration showed a slight improvement in signal performance however it was still not anywhere near the acceptable value.
    - When using MUX BW = 80 GHz and DEMUX BW = 12.5 GHz, the Avg. Q-Factor of NRZ (= 2.28) was higher than that of RZ (= 2.26).
    - When using MUX BW = 25 GHz and DEMUX BW = 80 GHz, the Avg. Q-Factor of NRZ (= 2.21) was higher than that of RZ (= 1.91).
    - When using MUX BW = 12.5 GHz and DEMUX BW = 80 GHz, the Avg. Q-Factor of NRZ (= 0.98) was lower than that of RZ (= 1.51).
    - Finally, when using MUX BW = 25 GHz and DEMUX BW = 25 GHz, the Avg. Q-Factor of NRZ (= 2.09) was lower than that of RZ (= 3.13).
  - There was definite improvement in the quality factor and BER in NRZ and RZ modulation scheme when decreasing the DEMUX BW from 80 GHz to 25 GHz, and finally the MUX BW to also 25 GHz. However, there was no improvement when decreasing to 12.5 GHz.
    - When using MUX BW = 80 GHz and DEMUX BW = 25 GHz, the highest Q factor of NRZ (= 4.93) was lower than the Q of RZ (= 5.9). The BER of NRZ (3.68E-07) is higher than that of RZ (1.52E-09).

❖ Similarly, when using MUX BW = 25 GHz and DEMUX BW = 25 GHz, the highest Q factor of RZ (= 4.84) was higher than the Q of NRZ (= 3.73). The BER of RZ (6.03E-07 is lower than the BER of NRZ (7.37E-05).

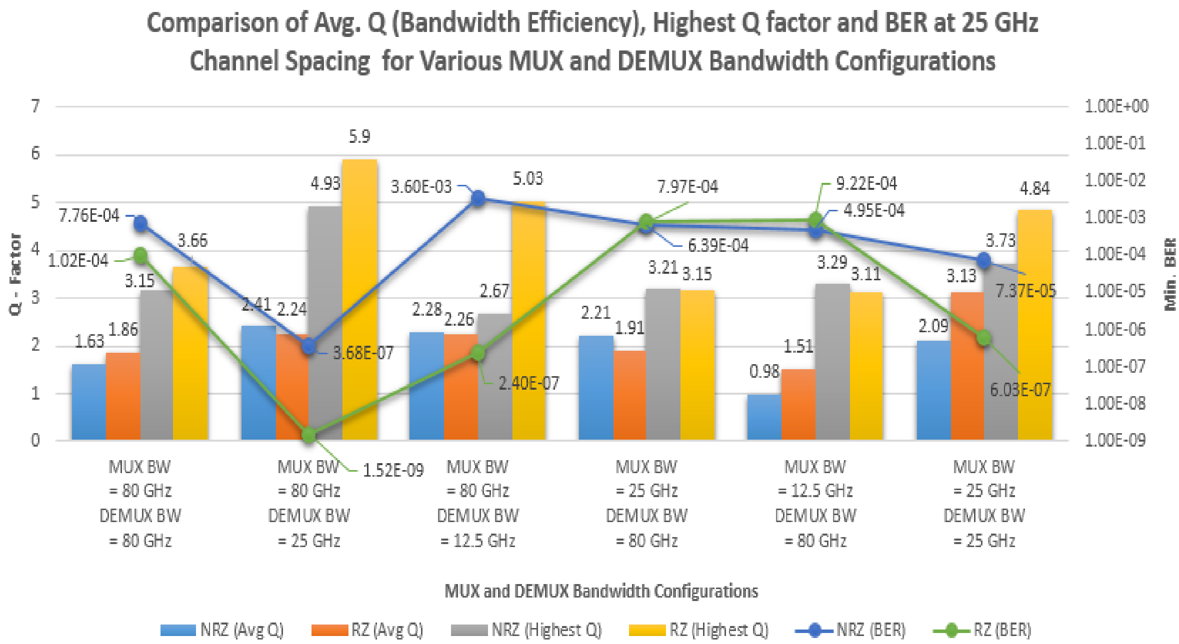

Figure 5.8: Comparison of Signal Performance of 25GHz spacing for Various MUX/DEMUX BW Configurations

➢ In order to try improve the system performance further, the extinction ratio of the WDM transmitter was decreased and a rectangular filter was used in the MUX and DEMUX instead of the Bessel filter. There was a definite improvement in bandwidth efficiency and signal performance in NRZ and RZ modulation scheme when decreasing the extinction ratio from 30 dB to 5dB and changing the filter type from a Bessel filter to a rectangular filter, as can be seen in Figure 5.9.

❖ When using MUX BW = 80 GHz and DEMUX BW = 25 GHz while using a 5dB ER with rectangular filer, the Avg. Q-Factor of NRZ (= 2.56) is higher than that of RZ (= 1.39). The highest Q for NRZ (= 4.56), was higher than the highest Q for RZ (= 2.9). However, all these values were not acceptable since Q < 6.

❖ However, when using MUX BW = 25 GHz and DEMUX BW = 25 GHz while using a 5dB ER with rectangular filer, the Avg. Q-Factor of NRZ (= 5.83) was lower than that of RZ (= 9.59). The highest Q factor for NRZ (=6.51) was lower than that of RZ (=13.55). The BER of RZ (=3.54E-42) was lower than that of NRZ (=3.54E-11). Both signals were acceptable signals since Q > 6 and BER > 10^{-9}.

➢ It is therefore established that the RZ modulation scheme, when using MUX BW = 25 GHz and DEMUX BW = 25 GHz, had the best bandwidth efficiency (=100%) and the best signal performance for a channel spacing of 25 GHZ when using a 5dB extinction ratio in combination with a rectangular filter.

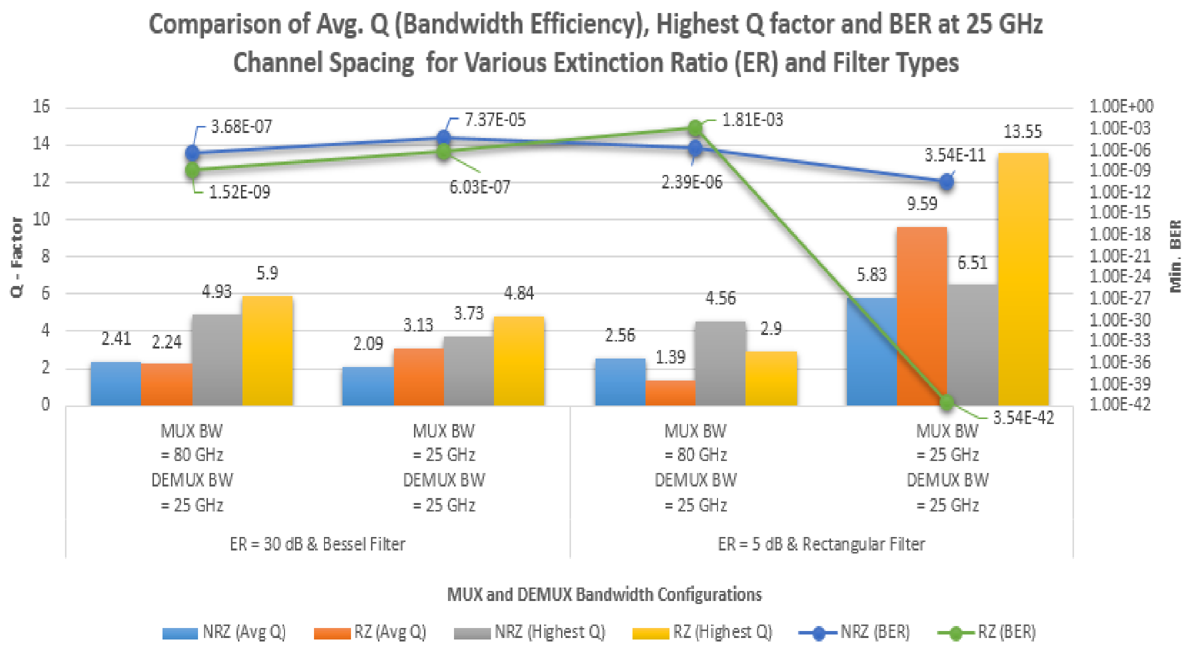

Figure 5.9: Comparison of Signal Performance of 25GHz spacing for Various MUX/DEMUX BW Configurations

- **For the optimisation of the 12.5 GHz channel spacing**, see Table 5.5 and Figure 5.10:

  ➢ The Avg. Q-Factor for 48 Channels of the following networks were first compared:

    ❖ MUX BW = 80 GHz and DEMUX BW = 80 GHz,

    ❖ MUX BW = 80 GHz and DEMUX BW = 12.5 GHz,

    ❖ MUX BW = 80 GHz and DEMUX BW = 6.25 GHz,

    ❖ MUX BW = 12.5 GHz and DEMUX BW = 80 GHz,

    ❖ MUX BW = 6.25 GHz and DEMUX BW = 80 GHz,

    ❖ MUX BW = 3.125 GHz and DEMUX BW = 80 GHz.

- The trial to improve the bandwidth efficiency and signal performance in NRZ and RZ modulation scheme was done by decreasing the MUX and DEMUX BW from 80 GHz to 3.125 GHz.
  - When using MUX BW = 80 GHz and DEMUX BW = 80 GHz, the Avg. Q-Factor of NRZ (= 1.51) was lower than that of RZ (= 1.65).
  - When using MUX BW = 80 GHz and DEMUX BW = 12.5 GHz, the Avg. Q-Factor of NRZ (= 1.57) was higher than that of RZ (= 1.48).
  - When using MUX BW = 80 GHz and DEMUX BW = 6.25 GHz, the Avg. Q-Factor of NRZ (= 1.46) was lower than that of RZ (= 2.26).
  - When using MUX BW = 12.5 GHz and DEMUX BW = 80 GHz, the Avg. Q-Factor of NRZ (= 1.41) was lower than that of RZ (= 1.61).
  - When using MUX BW = 6.25 GHz and DEMUX BW = 80 GHz, the Avg. Q-Factor of NRZ (= 1.92) was higher than that of RZ (= 1.07).
  - Finally, when using MUX BW = 3.125 GHz and DEMUX BW = 80 GHz, the Avg. Q-Factor of NRZ (= 3.06) was lower than that of RZ (= 3.24). This bandwidth configuration showed a slight improvement in signal performance however it was still not anywhere near the acceptable value.
- There was definite improvement in the quality factor and BER in NRZ and RZ modulation scheme when decreasing the MUX BW from 80 GHz to 3.125 GHz while maintaining the DEMUX BW at 80 GHz. However, there was no improvement when decreasing DEMUX BW to 6.25 GHz.
  - When using MUX BW = 3.125 GHz and DEMUX BW = 80 GHz, the highest Q factor of NRZ (= 4) was lower than the highest Q of RZ (= 4.12). The BER of NRZ (2.54E-05) is higher than that of RZ (1.55E-05)
- In order to try improve the system performance further, an advanced modulation method (MDRZ) was used. The optimisation of the 12.5 GHz channel spacing by using the MDRZ modulation format was done in section 5.3.3.

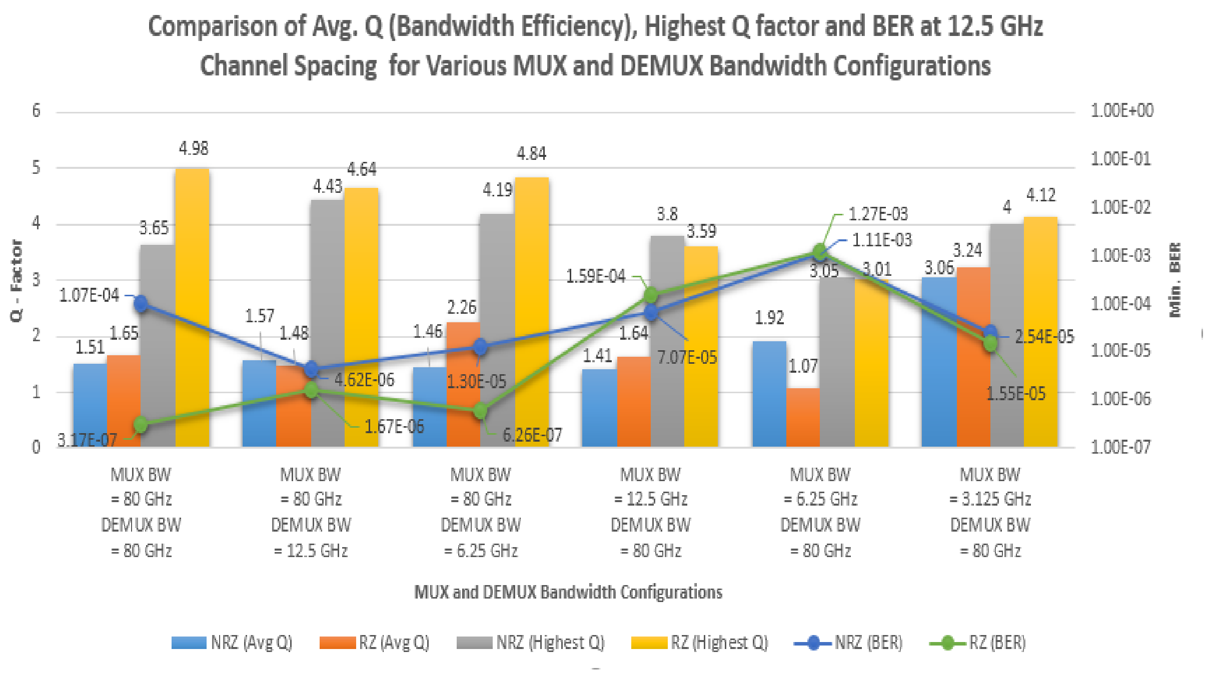

Figure 5.10: Comparison of Signal Performance of 12.5GHz spacing for Various MUX/DEMUX BW Configurations

- **For the optimisation of the 6.25 GHz channel spacing**, see Table 5.6 and Figure 5.11:
  - ➢ The Avg. Q-Factor for 48 Channels of the following networks were first compared:
    - ❖ MUX BW = 80 GHz and DEMUX BW = 80 GHz,
    - ❖ MUX BW = 80 GHz and DEMUX BW = 6.25 GHz,
    - ❖ MUX BW = 6.25 GHz and DEMUX BW = 80 GHz,
    - ❖ MUX BW = 3.125 GHz and DEMUX BW = 80 GHz.
  - ➢ The trial to improve the bandwidth efficiency and signal performance in NRZ and RZ modulation scheme was done by decreasing the MUX and DEMUX BW from 80 GHz to 3.125 GHz.
    - ❖ When using MUX BW = 80 GHz and DEMUX BW = 80 GHz, the Avg. Q-Factor of NRZ (= 2.41) was higher than that of RZ (= 2.14).
    - ❖ When using MUX BW = 80 GHz and DEMUX BW = 6.25 GHz, the Avg. Q-Factor of NRZ (= 1.48) was lower than that of RZ (= 2.67).
    - ❖ When using MUX BW = 6.25 GHz and DEMUX BW = 80 GHz, the Avg. Q-Factor of NRZ (= 3.03) was higher than that of RZ (= 2.49).
    - ❖ Finally, when using MUX BW = 3.125 GHz and DEMUX BW = 80 GHz, the Avg. Q-Factor of NRZ (= 4.04) was lower than that of RZ (= 4.19). This

showed a slight improvement in signal performance however it was still not acceptable.

- There was definite improvement in the overall performance (Avg. Q) of the system when decreasing the MUX BW from 80 GHz to 3.125 GHz while maintaining the DEMUX BW at 80 GHz.
    - When using MUX BW = 3.125 GHz and DEMUX BW = 80 GHz, the highest Q factor of NRZ (= 4.63) was lower than the highest Q of RZ (= 4.7). The BER of NRZ (6.26E-07) is higher than that of RZ (4.56E-07)

- In order to try improve the system performance further, an advanced modulation method (MDRZ) was used. The optimisation of the 6.25 GHz channel spacing by using the MDRZ modulation format was done in section 5.3.3.

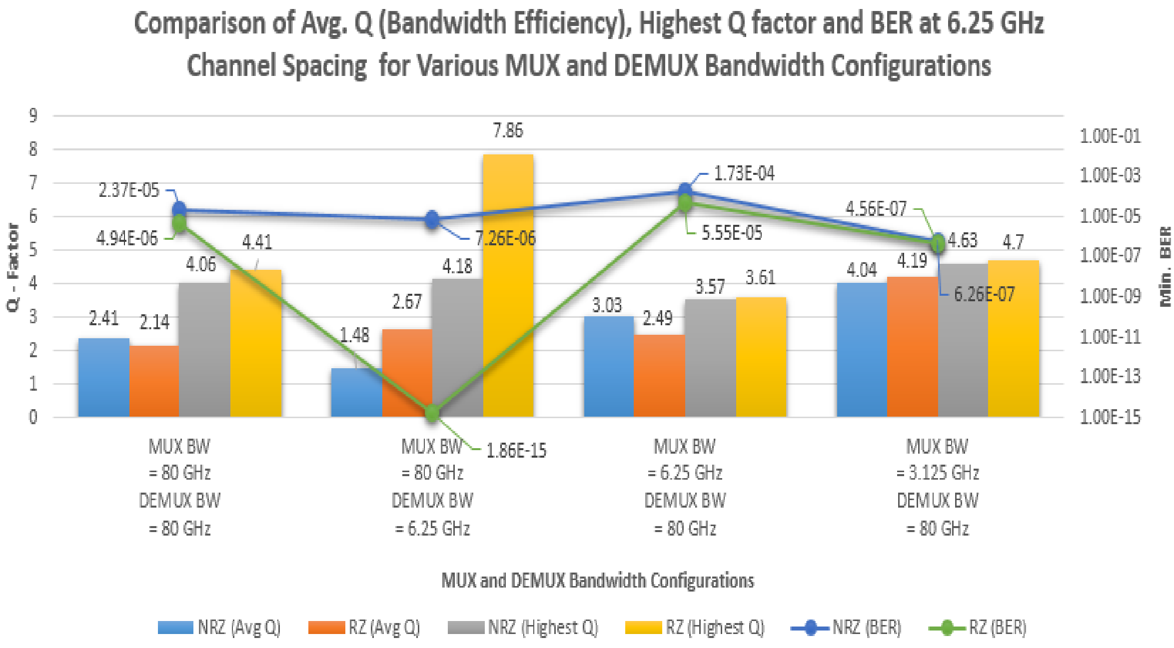

Figure 5.11: Comparison of Signal Performance of 6.25GHz spacing for Various MUX/DEMUX BW Configurations

5.3.3 Optimisation of 12.5 GHz and 6.25 GHz Channel spacing using MDRZ

The optimisation of both the 12.5 GHz spacing and the 6.25 GHz spacing was done using the advanced modulation format, MDRZ. The performance of both the above channel spacing was done using the filter bandwidth parameter of MUX BW = 3.125 GHz and DEMUX BW = 80 GHz. This was because, this parameter showed the best performance in comparison to the other filter bandwidth configurations discussed in section 5.3.2.

For the 12.5 GHz spacing: MDRZ had the highest Average Q (= 8.66) and the highest Q (= 12.77), which were higher when compared to the average Q of NRZ (= 3.06), highest Q of NRZ (= 4), average Q of RZ (= 3.24) and the highest Q of RZ (= 4.12). The BER of the MDRZ signal (= 7.49E-38) was lower than the BERs of the NRZ (= 2.54E-05) and RZ (= 1.55E-05). The comparison is shown in Figure 5.12.

For the 6.25 GHz spacing: MDRZ had the highest Average Q (= 8.93) and the highest Q (= 10.79), which were higher when compared to the average Q of NRZ (= 4.04), highest Q of NRZ (= 4.63), average Q of RZ (= 4.19) and the highest Q of RZ (= 4.7). The BER of the MDRZ signal was 7.17E-28, which was lower the NRZ and RZ BERs of 6.26E-07 and 4.52E-07 respectively. The comparison is shown in Figure 5.13.

The MDRZ format provided an acceptable signal that had a Q > 6 and BER > 10^{-9} for both 12.5 GHz and 6.25 GHz channel spacing. Therefore, it was established that the MDRZ modulation scheme had the best bandwidth efficiency (=100%) and the best signal performance when using MUX BW = 3.125 GHz and DEMUX BW = 80 GHz for both channel spacings of 12.5 GHZ and 6.25 GHZ. This was because the MDRZ format had a much narrower optical bandwidth over the NRZ and RZ formats. This led to a greater chromatic dispersion tolerance, higher fiber non-linearity tolerance and thereby achieved an acceptable signal transmission over longer distances.

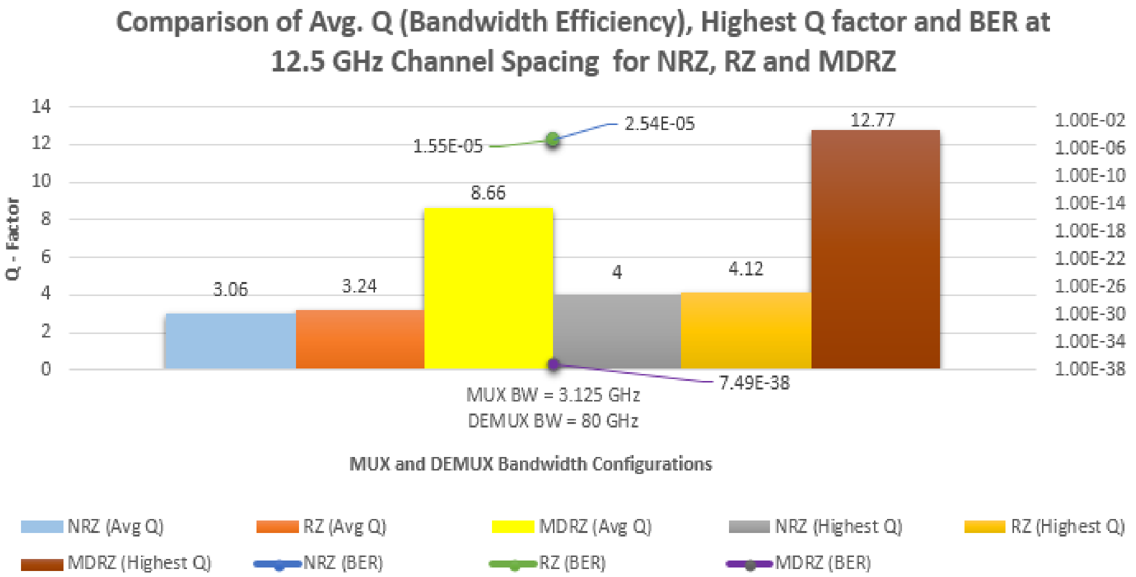

Figure 5.12: Comparison of Signal Performance of 12.5GHz spacing using various Line Coding Modulation Formats

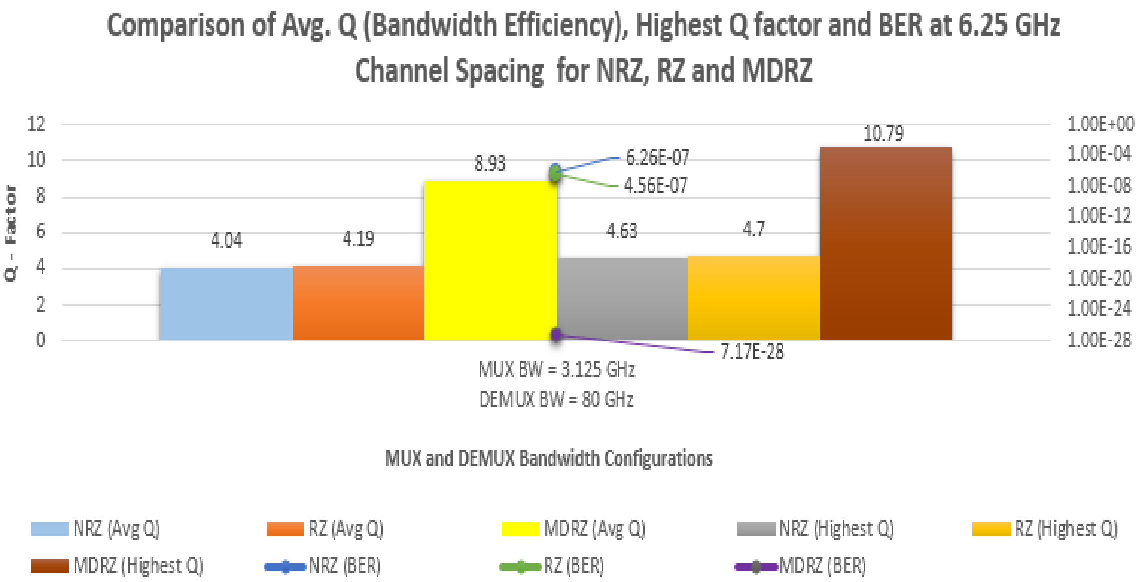

Figure 5.13: Comparison of Signal Performance of 6.25GHz spacing using various Line Coding Modulation Formats

5.4 Summary

The simulation, design and comparative analysis of the 48-channel DWDM system with a 25 GB/s bit rate was performed using the Optisystem simulation platform. The optimised 48 channel DWDM network models produced point to point communication link with minimal bit errors for channel spacings of 100 GHz, 50 GHz, 25 GHZ and 12.5 GHz and 6.25 GHz. In this chapter, the analysis and discussion of the various design parameters used to optimise the network was done to validate the best configuration that provided an acceptable system performance for future growth in end-user requirements.

Networks with matched active components (WDM transmitter and WDM MUX) had equally spaced frequency channels that were aligned to each other and had a higher OSNR than mismatched networks. This was because mismatched networks with misaligned frequency channels increased the levels of linear losses (CD) and this level increased further for narrower channel spacings. Matched networks minimised the effects of chromatic dispersion for wide channel spacings. However, unmodified mismatched networks had a better signal performance at smaller channel spacings because of their increased effects of CD. This minimised the effects of non-linear losses such as FWM.

The maximum signal power and OSNR of the 3 EDFA-post Symmetric compensation technique was always higher than the 1 EDFA-post compensation technique for all channel spacings in any type of network. The addition of the 3 symmetric EDFAs in all networks compensated for the increased attenuation and dispersion introduced when the bit rate was increased, number of channels were increased and the channel spacings were decreased. The 3 EDFA-post symmetric compensation technique produced less bit errors than the 1 EDFA-post compensation technique since it minimised the effects of CD and FWM to some extent. However, this could only be achieved when used in combination with the NRZ and RZ modulation formats.

NRZ was more robust to impacts of CD as compared to RZ. Therefore, it had a greater signal performance for wider channel spacing that had a high amount of CD and a low amount of FWM harmonic components. RZ was more robust to the effects of non-linear losses than NRZ.

This meant that the RZ modulation scheme produced a higher overall signal performance at smaller channel spacings that had a larger amount of FWM harmonic components.

However, the capabilities of NRZ and RZ were limited; because they minimised the effects of CD and FWM respectively but they compromised on signal quality and BER at lower channel spacings. For this purpose, the signal performance of the 48 channel DWDM network was optimised for each channel spacing using various design parameters that produced networks that had the least amount of bit errors for the optical receiver to detect and decode any signal in a channel successfully.

The MDRZ modulation format implemented FEC at very narrow bandwidths and at very narrow channel spacings. This led to a greater CD tolerance, higher fiber non-linearity tolerance and achieved an acceptable signal transmission over longer distances with the least amount of errors.

The decreased extinction ratio of the transmitter in combination with a rectangular filter increased signal power and dispersion, which subsequently decreased the effects of FWM. Simultaneously, the rectangular filter eliminated low power frequency harmonics of FWM without affecting the lower harmonics and signal propagation over the length of fiber in a DWDM system, which also caused dispersion.

Varying the filter bandwidth configurations of the MUX and DEMUX decreased the finite passband of a 2nd order Bessel filter, which meant that all FWM harmonic products outside this band is eliminated or the power of the harmonic components was decreased significantly.

The signal performance was evaluated using eye diagrams that analysed the Q factor and BER. For each of the optimised parameters below, the signal detected by the receiver had a Q factor > 6 and the BER > 10^{-9}. The optimised parameter designs and configurations for each channel spacing that had the highest signal performance and bandwidth efficiency were as follows:

- For 100 GHz: The RZ format with MUX BW = 80 GHz and DEMUX BW = 25 GHz produced an avg. Q = 53.37, highest Q= 82.60 and BER = 0.

- For 50 GHz: The RZ format with MUX BW = 80 GHz and DEMUX BW = 25 GHz produced an avg. Q = 10.02, highest Q = 26.53 and BER = 1.41 x 10^{-155}.
- For 25 GHz: The RZ format with MUX BW = 25 GHz and DEMUX BW = 25 GHz; used together with a 5dB extinction ratio in combination with a rectangular filter produced an avg. Q = 9.59, highest Q = 13.55 and BER = 3.54 x 10^{-42}.
- For 12.5 GHz: The MDRZ format with MUX BW = 3.125 GHz and DEMUX BW = 80 GHz produced an avg. Q = 8., highest Q = 12.77, and BER = 7.49 x 10^{-38}.
- 6.25 GHz: The MDRZ format with MX BW = 3.125 GHz and DEMUX BW = 80 GHz produced an avg. Q = 8.93, highest Q = 10.79, and BER = 7.17 x 10-28.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This dissertation focused on achieving an acceptable signal performance for a 48 channel DWDM network model with a 25 Gb/s bit rate and a 100 km transmission distance for channel spacing of 100 GHz, 50 GHz, 25 GHz, 12.5 GHz and 6.25 GHz. This chapter concludes all the summaries and lessons learnt from Chapter 1 to Chapter 5. It also gives possible recommendations of how to decrease non-linear effects to further improve the current DWDM network design. Furthermore, an overview of the current maximum bandwidth potential of the designed DWDM network model is given with an oversight into future applications of the design.

6.2 Chapter Conclusions

In Chapter 1, a brief overview of some of the challenges faced in an optical communication networks due to future bandwidth requirements was enumerated. The motivation to this dissertation established that the usage of DWDM technology was an attractive strategy to meet the challenges of current optical communication systems and thereby increase the capacity of future optical networks. The objectives of this dissertation focused essentially on creating a pilot network that was be able to test the limitations of the untapped channel spacing of 6.25 GHz to further expand the channel capacity of the ITU frequency grid.

In Chapter 2, the literature review explored the performance limitations of DWDM technology and it was established that CD and FWM were the most critical limiting factors that deteriorates a DWDM signal. The various design components of the DWDM system, their properties, functionalities, limitations and benefits were discussed with the focus being on the optimisation of a 48 channel DWDM system. The theoretical design method of designing and measuring the performance of the optical transmission link was also enumerated.

In Chapter 3, the simulation and design process of the 48-channel DWDM system design was shown using the Optisystem simulation platform. The various design parameters used to model and optimise the existing 48 channel fiber optic network was calculated and enumerated such that an acceptable system performance was achieved for future growth in end-user requirements. The optimisation of the 48-channel network was done using various parameters in different combinations. Three of the line encoding techniques (NRZ, RZ and MDRZ) were used in numerous DWDM networks with different filter types (Bessel and rectangular) in the MUX and DEMUX to minimise the effects of linear and non-linear losses. The BW of the filter used in the MUX/DEMUX and the extinction ratio of the transmitter were also varied to obtain an optimised network that had the most acceptable signal performance with the least amount of non-linearities for each of the channel spacings. Furthermore, a comparative model of two dispersion compensation techniques (1 EDFA post compensation and the 3 EDFA post symmetric compensation) was also done for each channel spacing to evaluate a reduction in linear effects (CD) and non-linear effects (FWM).

In chapter 4, the eye-diagram results of each channel in the DWDM system was illustrated and analysed. The results showed that since BER was inversely proportional to the Q factor, the channels with the highest Q factor had the lowest BER and vice versa was also true. The channels with the highest Q was used for analysis for all networks to compare the maximum signal performance of that network to the other networks. The BW efficiency of each network was calculated to have an indication of the overall signal performance for each type of network. The minimum BER required for an acceptable signal was greater than 10^{-9} for the optical receiver to detect the information signal with the least amount of bit errors. The Q factors for such signals was greater than 6.

In Chapter 5, the analysis and discussion of the various design parameters, used to optimise the DWDM network models, validated the best system configuration that could provide an acceptable signal quality for future growth in end-user requirements. It was established that networks that have matched active components with equally spaced frequency channels minimise the effects of CD at wide channel spacings and therefore have a higher OSNR than mismatched networks. The maximum signal power and OSNR of the 3 EDFA-post symmetric compensation technique is always higher than the 1 EDFA-post compensation technique for all channel spacings in any type of network. NRZ is more robust to the effects of linear losses (CD) as compared to RZ and has a greater signal performance for wider channel spacing. RZ is more robust to the effects of non-linear losses (FWM) than NRZ and produces a higher overall signal performance at smaller channel spacings. The MDRZ modulation format implements

FEC at very narrow bandwidths and at very narrow channel spacings. This leads to a greater CD tolerance and a higher fiber non-linearity for MDRZ than for NRZ and RZ. The usage of a rectangular filter, a decrease in the ER of the transmitter and a decrease in the BW of the MUX/DEMUX filter are the parameter variances that substantially decreased the effects of FWM. The optimised parameter designs and configurations for each channel spacing has the highest signal performance and BW efficiency for the RZ modulation format at 100 GHz, 50 GHz and 25 GHz channel spacing. Similarly, the MDRZ has the highest signal performance and BW efficiency for channel spacings of 12.5 GHz and 6.25 GHz.

6.3 Recommendations

FWM could be further reduced in future applications without varying the bandwidth filter.

- One possible way is to use irregular channel spacings in the design to decrease the possibility of FWM forming multiple harmonic products [3], [6].
- The second possibility is to either lower the signal power in the fiber or design the non-zero dispersion shifted fiber to have a larger cross-sectional area. This reduces the signal power density and should avoid FWM cross-talk interference [3], [6].
- Lastly, the use of polarisation-multiplexed DWDM channels to polarise DWDM channels is another possibility that may suppress FWM harmonics and reduce FWM component power and cross talk [3], [6]. This is because each channel's polarisation state would be in an orthogonal state to the adjacent channel's polarisation state.

6.4 Current Potential of Designed DWDM Network Model and Future Work

The maximum bit rate capacity of the DWDM network model designed in this dissertation is 1200 Gb/s or 1.2 Tb/s. This is because each channel in the 48 channel DWDM system has a bit rate of 25 Gb/s. Furthermore, the total channel bandwidth utilised by the designed model in the optical spectrum is only 300 GHz (2.4 nm) because each channel of the 48 channel DWDM system used a channel spacing of 6.25 GHz (0.05 nm). This meant that for the 6.25 GHz channels spacing, the 48 channel DWDM system only uses 2.4 nm of wavelength from the C Band's (1530nm to 1565nm) maximum range of 35 nm [3], [6]. Therefore, for the 6.25 GHz channel spacing in the C band, the current 25 Gb/s bit rate per channel designed model has the potential of providing good signal quality performance for a maximum transmission capability of 700 DWDM channels with a total bit rate capacity of 17.5 Tb/s over a single fiber core. This DWDM model should be currently sufficient to manage the demands for high data rate applications and provide reasonable flexibility for broadband communication.

This flexibility should also open doors for the application of DWDM in possible radio-over-fiber (RoF) systems, which is the future of broadband wireless communication systems such as mobile communications and hotspots in suburban areas [51], [52]. The use of DWDM in RoF systems is advantageous because it simplifies the network topology by allowing the potential to allocate different wavelengths to individual base stations without changing the existing fiber infrastructure. This provides simpler network management and enables easier network or service upgrades [51].

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