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# Bandwidth and availability enhancement in dense wavelength division multiplexing optical networks.



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|---|---|
| Item Type | Thesis |
| Authors | Mkhwanazi, Mnotho |
| Publisher | Tshwane University of Technology |
| Rights | CC0 1.0 Universal |
| Download date | 2025-12-16 12:37:44 |
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# BANDWIDTH AND AVAILABILITY ENHANCEMENT IN DENSE WAVELENGTH DIVISION MULTIPLEXING OPTICAL NETWORKS

by

**Mnotho Philani Mkhwanazi**

Submitted in the fulfilment of the requirements for the degree of

**MASTER OF ENGINEERING: ENGINEERING MANAGEMENT**

in the

Department of Industrial Engineering

FACULTY OF ENGINEERING AND THE BUILT ENVIRONMENT

**TSHWANE UNIVERSITY OF TECHNOLOGY**

Supervisor: Prof Khumbulani Mpofu

Co-Supervisor: Dr Vusi Malele

November 2023

C2 General

# DECLARATION

I hereby declare that this dissertation is my work and that every secondary material used has been properly referenced or cited. Furthermore, this work has never been published in its entirety or in part for any other degree at any other university. Professor Khumbulani Mpofu and Doctor Vusi Malele of the Tshwane University of Technology supervised the research.

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Co-Supervisor: Dr Vusi Malele Date



C2 General

# DEDICATION

This dissertation is dedicated to my parents, Bethuel and Goodness Mkhwanazi, to my wife, Nombuso Mkhwanazi, to my children, Londeka and Kwanda Mkhwanazi, to my brothers and sisters, and to the entire Mkhwanazi family. I value your contribution to my life; no words can ever express my gratitude and love for you.



C2 General

## ACKNOWLEDGEMENT

I want to begin by thanking the Almighty God for the greatest gift of all, the gift of life. All the glory and honour belong to Him because He is the source of my life, and it is through His endless blessings and mercy that I am who I am today.

I would like to express my heartfelt gratitude to my supervisor, Professor Khumbulani Mpofu and my co-supervisor, Doctor Vusi Malele, for their exceptional support, motivation, guidance, and belief in me throughout the entire journey of my research. I would also like to thank the Industrial Engineering Department at Tshwane University of Technology for providing me with all the resources I needed to make my postgraduate programme a success.

Furthermore, I would like to thank my colleagues for their encouragement and for allowing me to bounce ideas off them throughout my studies. A special thanks to Mr Piet van der Merwe, my line manager, and Mr Hussain Nabee, my executive head of department, for giving me time and space, as well as encouragement, to pursue my studies. I acknowledge and appreciate the financial support provided by my employer, Vodacom, through the learning and development internal bursary scheme.

Finally, I would like to extend my sincere gratitude to my wife, Nombuso Mkhwanazi, and my children, Londeka and Kwanda, for their constant encouragement during my years of study and throughout the research and writing of this thesis. I am indebted to you for allowing me the time and space I needed to focus on this research. Thank you.



C2 General

# ABSTRACT

Since the introduction of 3G technology and, more recently, the emergence of 5G applications and services, mobile network subscribers have increased rapidly over the years and are more reliant on their mobile devices than in the past. This phenomenon has compelled mobile network operators to implement technologies capable of handling the traffic surge. Mobile devices are being used for both recreational and business purposes, prompting mobile network operators to give prominence to bandwidth and network availability as major contributors to customer satisfaction. Techniques and strategies that promote high bandwidth and network availability demand the adoption of advanced data-transmission technologies. One such technology is Dense Wavelength Division Multiplexing (DWDM). This study delved deeper into DWDM technology, which is a transmission technology used in the optical networks of large mobile network operators around the world.

The goal of this research was to investigate techniques and strategies to enhance bandwidth and network availability in DWDM optical networks. The study used a pragmatic approach that included quantitative and qualitative research methods. A desk research strategy was used to conduct a comprehensive literature review for the study. Secondary data for the desk research was acquired from various academic research databases, the internet, and data sheets from various DWDM vendors. The simulation was performed using the 1830 Engineering and Planning Tool, Release: 22.12.0, which is a Nokia proprietary planning tool for DWDM optical networks.

The study found that Flex-Grid technology proved to be crucial in DWDM optical network capacity enhancement. 100/200/400 *Gbit/s* lambdas were simulated, and Flex-Grid technology outperformed Fixed-Grid in terms of spectral efficiency, number of transponders used, and power consumption. Transponder type, modulation scheme, baud rate, and optical signal-to-noise ratio margin were identified to be factors influencing a lambda's reach. The verdict was that the Quadrature Phase Shift Keying modulation scheme is suitable for long-distance transmission, while higher-order modulation schemes like 16-Quadrature Amplitude Modulation are suited to higher line rate transmission over short distances. The study further found that a Reconfigurable Optical Add-Drop Multiplexer (ROADM) with colourless, directionless,




C2 General

and contentionless (CDC) features enabled effective and improved lambda restoration. The research demonstrated that combining Flex-Grid technology with CDC ROADM reduced Operational expenditure (OPEX) costs. On the simulated network, Service Level Agreement 2 with a mean time-to-repair of eight hours was recommended, which led to an OPEX saving of R26 346 600 per annum on dark-fibre leases. Another cost-cutting effort was comparing the power consumption of Fixed-Grid and Flex-Grid transponders. When using Flex-Grid transponders, power consumption was reduced by 69%. Finally, while the Flex-Grid technology and CDC ROADM features can be deployed separately, the study recommends that they be deployed together to produce the most resilient, flexible, bandwidth-ready, and future-proof DWDM optical network.



C2 General

## List of Contents





C2 General

C2 General

C2 General

C2 General

## List of Figures





C2 General

C2 General

## List of Tables





C2 General

## List of Symbols

***c***: Speed of light = 299792458m/s

***dB***: Decibel

***Gbit/s***: Gigabit per second

***GHz***: Gigahertz

***km***: Kilometre

***nm***: Nanometre

***v***: Frequency

$\boldsymbol{v_{lower}}$**:** Lower boundary frequency

$\boldsymbol{v_{upper}}$**:** Upper boundary frequency

***λ***: Wavelength/Lambda



C2 General

## List of Abbreviations

**2G:** Second-generation cellular technology

**3G:** Third-generation of wireless mobile telecommunications technology

**5G:** Fifth-generation cellular network technology

**APS:** Automatic Protection Switching

**ASON:** Automatically Switched Optical Network

**BSC:** Base Station Controller

**CAPEX:** Capital Expenditure

**CDC:** Colourless, Directionless, Contentionless

**CDC:** Colourless, Directionless, Contentionless

**CM:** Coherent Modulation

**CWDM:** Coarse Wavelength Division Multiplexing

**DFA:** Dark Fibre Africa

**DMT:** Discrete Multi-Tone

**DPSK:** Differential Phase Shift Keying

**DSP:** Digital Signal Processing

**DWDM:** Dense Wavelength Division Multiplexing

**EDFA:** Erbium-Doped Fibre Amplifier

**EON:** Elastic Optical Networks

**EPT**: 1830 Engineering and Planning Tool

**ESNC-P:** Electrical Sub-Network Connection Protection

**FEC:** Forward Error Correction

**FOADM:** Fixed Optical Add/Drop Multiplexer

**GMPLS:** Generalised Multi-Protocol Label Switching



C2 General

**GMRE:** GMPLS Routing Engine

**HD-FEC:** Hard-Decision Forward Error Correction

**IP/MPLS:** Internet Protocol / Multiprotocol Label Switching

**ITU:** International Telecommunication Union

**KZN:** KwaZulu-Natal

**LAN:** Local Area Network

**LH:** Long Haul

**LSP:** Label Switched Path

**LTE:** Long-Term Evolution

**MNO:** Mobile Network Operator

**MSC:** Mobile Switching Centre

**MSC:** Multicast Switch

**NG:** Next Generation

**NLD:** National Long Distance (fibre route)

**NRZ:** Non-Return-to-Zero

**OCh:** Optical Channel

**ODU:** Optical Data Unit

**O-E-O:** Optical-Electrical-Optical

**OOK:** On-Off Keying

**OPEX:** Operational Expenditure

**OSNR:** Optical-Signal-to-Noise Ratio

**OTN:** Optical Transport Network

**OTN:** Optical Transport Network

**PAM:** Pulse Amplitude Modulation

**PMD:** Polarisation-Division Multiplexed



C2 General

**PRC:** Protection Restoration Combined

**PSS:** Photonic Service Switch

**QAM:** Quadrature Amplitude Modulation

**QoS:** Quality of Service

**QPSK:** Quadrature Phase Shift Keying

**ROADM:** Reconfigurable Optical Add/Drop Multiplexer

**SD-FEC:** Soft-Decision Forward Error Correction

**SDH:** Synchronous Digital Hierarchy

**SLA:** Service Level Agreement

**SONET:** Synchronous Optical Network

**SSS:** Selective Spectrum Switch

**VPLS:** Virtual Private LAN Service

**WSS:** Wavelength Selective Switch



C2 General

## Glossary of Terms

**C-Band:** 1530 *nm*-to-1565 *nm* spectrum

**CellC:** South African MNO.

**Core:** is the backbone of the mobile network; it backhauls data traffic generated from the access network between the BSC and the MSC as well as interlinks the MSCs.

**Degree:** A fibre-optic route in a DWDM system

**Heatless switch:** Switching traffic without service disruption

**L-Band**: 1565 to 1625 spectrum

**Metro:** a group of sites that form a core of the transmission network in a city, e.g., the KwaZulu-Natal (KZN) metro.

**MNO**: Organisations that run mobile networks such as Vodacom, MTN, Telkom, and CellC, in the South African context.

**MTN:** South African MNO.

**Network congestion:** when the network nodes and links are overloaded with traffic.

**NLD:** Fibre route that interconnects different regions; this fibre can be self-provided by the operator, or it can be leased from fibre suppliers.

**Nominal route:** A route configured as a primary route for the traffic

**Self-healing:** is the ability of the optical transmission network to restore services over alternative routes during a network failure.

**Self-provide:** Optical fibre route belonging to the MNO.

**Span:** An optical link between two DWDM systems

**Telkom Mobile:** South African MNO.

**Traffic:** the amount of data transmitted over a transmission medium.

**Vodacom:** South African MNO.



C2 General

# CHAPTER 1: INTRODUCTION

## 1.1. Background and Motivation

The telecommunications industry has evolved significantly over the years, making it a crucial player in enabling a wide range of data-driven applications in business, social media, and entertainment. From the launch of third-generation (3G) technology until the present, when fifth-generation (5G) technology is gaining traction, there has been a huge increase in the volumes of data traffic in mobile networks. The rise in data volumes over the years can be attributed to mobile-device users accessing various online services (Zdravecký, et al., 2022). The telecommunications industry has seen a massive increase in mobile devices over the years (Alvarez, 2022). Figure 1.1 depicts the rise in mobile-device subscriptions per 100 people in various countries. The increase in mobile devices suggested that subscribers relied on their devices for both business and recreational purposes more than ever before. A recent example was during the Covid-19 epidemic in 2020, when more people were working from home. Outdoor leisure activities were prohibited, resulting in subscribers spending even more time on their mobile devices. During this time, many telecommunication operators reported a 50% increase in traffic (Feldmann, et al., 2021).

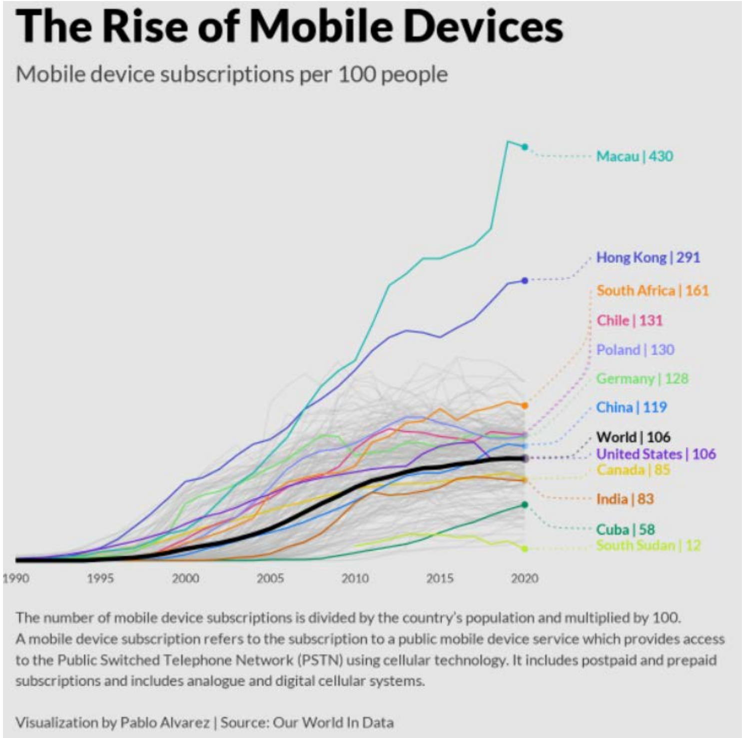


**Figure 1.1:** The Rise of Mobile Devices **(Alvarez, 2022)**



C2 General

The global number of mobile devices is expected to reach 18.22 billion by 2025, a 4.2 billion increase over the 2020 tally (Laricchia, 2023). This situation has compelled mobile network operators (MNOs) to prioritise bandwidth and network availability to improve customer satisfaction and, as a result, market share. High bandwidth demands have driven MNOs to switch to technologies capable of transmitting data at high rates and at a reduced cost (Ujjwal, 2017). Optical communication addresses this data traffic increase adequately due to its ability to cope with high data volumes (Nance-Hall, et al., 2021). The increasing demand for bandwidth capacity drives the rapid development of optical fibre communication technology (Zhang, et al., 2021). Dense Wavelength Division Multiplexing (DWDM) technology represents a substantial leap in optical communication as it allows several optical channels to share a single fibre-optic cable. The International Telecommunication Union – Telecommunication (ITU-T) standardised the successful commercialisation of DWDM systems as the core network infrastructure (Zdravecký, et al., 2022). MNOs primarily use DWDM technology in their core networks to send large amounts of data between mobile switching centres (MSCs) and base station controllers (BSCs). Because DWDM technology can be deployed across vast distances, it is also used to transport data between places that may be hundreds of kilometres apart.

## 1.2. Problem Statement

Mobile subscriber’s increased usage of data-driven applications in business, social media, and entertainment has resulted in an increase in data traffic that MNOs must manage. This increase requires MNOs to design their networks to support current and future bandwidth demands. The growing demand for bandwidth capacity also propels the rapid advancement of optical-fibre communication technology (Nance-Hall, et al., 2021). MNOs deploy DWDM technology in their core networks because it can transmit massive amounts of data; nevertheless, this technology requires ongoing innovation to ensure that more data can be transported in a single wavelength.

Along with meeting growing bandwidth demands, network availability is equally important to MNOs. Optical networks carry a wide range of communication services; a single fibre cut can disrupt lambdas provisioned on the affected route, putting many vital services at risk (Liu, 2019). Poor network availability has the potential to



C2 General

negatively affect the user experience and, as a result, customer satisfaction. When network disruptions linger for an extended period, it results in significant revenue loss and even penalties stemming from service level agreement (SLA) breaches. The ultimate price for poor bandwidth and network availability is subscribers switching to a rival MNO for a better user experience.

## 1.3. Aim and Objectives of the Study

The aim of this research was to investigate mechanisms for improving bandwidth and network availability in DWDM optical networks. Leading MNOs control some of the world's largest optical networks; therefore, this study will provide insights into the most recent enhancements in DWDM optical networks. The focus areas were techniques for dealing with ever-increasing bandwidth demands, as well as network survivability techniques that enhance network availability. The research objectives are:

i. To conduct a comparative study on Fixed-Grid and Flex-Grid technology as it relates to bandwidth enhancement and spectral efficiency.
ii. To analyse protection and restoration mechanisms that enhance survivability in DWDM optical networks.
iii. To simulate lambdas with line rates exceeding 100 *Gbit/s* on a single-carrier wavelength using Flex-Grid technology.
iv. To simulate lambda restoration using CDC ROADM features.
v. To investigate measures to reduce Operational Expenditure (OPEX) cost for DWDM optical networks.

## 1.4. Research Questions

RQ1: What is the role of DWDM optical networks in the telecommunications sector?

RQ2: How do DWDM systems affect mobile network bandwidth and network availability?

RQ3: Is it possible to enhance bandwidth and network availability in DWDM optical networks by deploying CDC ROADM and Flex-Grid technology concurrently?

## 1.5. Significance and Implications of the Study

The telecommunications sector has evolved from the days of copper as the primary transmission medium to the now preferred medium, optic fibre. Optical fibre communication has become increasingly popular for long-distance data transport in



C2 General

recent years, due to several advantages, such as low loss, efficient amplification, and low interference (Anjana, et al., 2021). Leading MNOs use optic-fibre-based DWDM technology in their metros and core networks. The research provides a thorough understanding of DWDM optical networks as they relate to mobile networks and, by extension, subscribers. MNOs will benefit from this research because they have the largest DWDM optical network footprint. The study also targets small and medium-sized network operators, such as those used by banks and municipalities. In some instances, small and medium-sized optical networks may not justify financial investment in newer features, but they can already implement strategies learned from this study to ensure their long-term viability. A small network today will evolve into a large network in the future.

South Africa’s telecommunications and technology industry is one of the sectors that are growing rapidly in the country (Teuteberg & Aina, 2021). In 2020, this country had a population of 58.8 million people and 95.96 million mobile cellular subscriptions (www.statista.com, 2022). Figure 1.1 reflects the increase in mobile-device subscriptions per 100 people in different countries, with South Africa showing strong growth in this area. As a result, this research is also significant in the context of the South African telecommunications sector. In this country, the four primary participants in the mobile network area are Vodacom, MTN, Telkom Mobile, and CellC. Figure 1.2 shows the market share that each of these organisations enjoys. Market leaders Vodacom and MTN have 73% of the market, while the other two smaller MNOs, Telkom Mobile and CellC, share 27% of the market (Msomi, 2022). Each of these organisations ought to focus on bandwidth and network availability to maintain market share, as these two variables have a direct impact on customer satisfaction.



C2 General

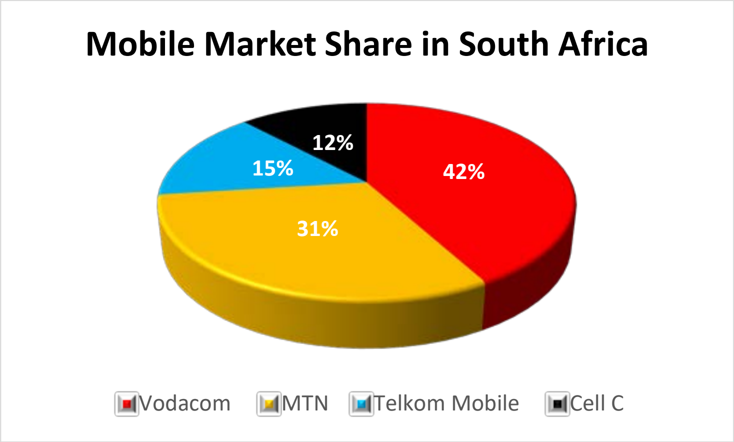


**Figure 1.2:** Mobile Market Share in South Africa **(Msomi, 2022)**

One of the advantages of a modernised DWDM optical network is lower operational OPEX. Almost every organisation is constantly seeking innovative methods to cut OPEX. A self-healing network takes care of that component by requiring fewer labour hours to manage network outages. Modernised DWDM systems reroute wavelengths automatically, eliminating the need for costly and time-consuming manual adjustments that were required in prior generations (Eisenach, 2021). While all the technologies and features outlined in the study help MNOs, subscribers are the ultimate beneficiaries. The successful deployment of the most recent DWDM technology advancements ensuring bandwidth and network availability is vital as the world embraces the 5G era.

### 1.6. Research Scope

Since the telecommunications sector is a fiercely contested terrain, primary data is particularly difficult to obtain due to non-disclosure agreements and confidentiality. As a result, secondary data and a simulation were used in the study. To counteract the effect of bias, this study reviewed literature from 102 different publications. While mobile networks are made up of various subnetworks, this research focuses on the transmission aspect of the backbone infrastructure, which includes core and metro optical networks, as shown in Figure 2.1. The study is focused on the bandwidth and network availability of this portion of the mobile network, with DWDM as a transmission technology of interest. The research does not cover the access network.



C2 General

## 1.7. Research Framework

Figure 1.3 outlines the framework of the study. The framework shows the various steps and the rationale used in carrying out this research.

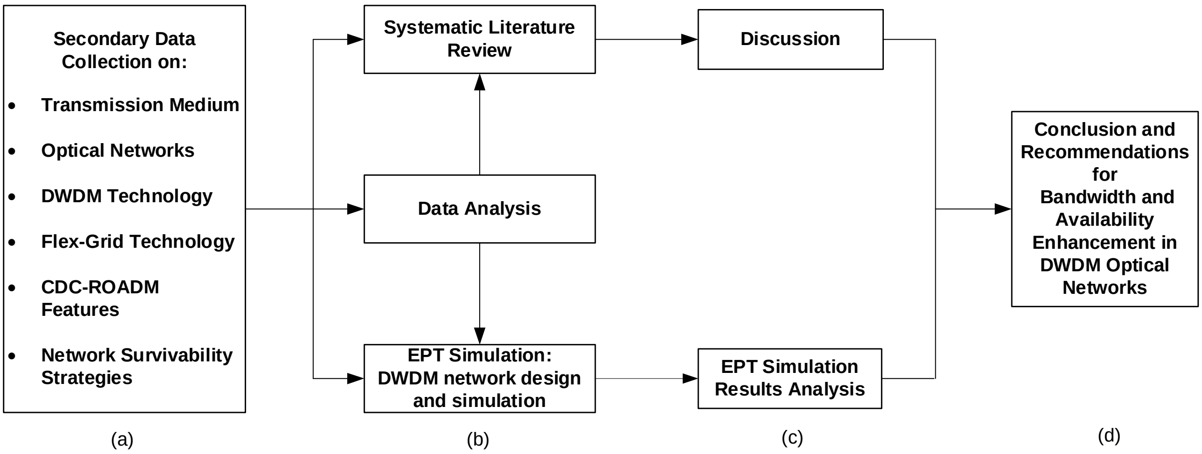


**Figure 1.3:** Research Framework

(a) Presents the knowledge areas of the secondary data that was collected for the study.

(b) This section highlights the thorough data analysis conducted of the literature, as well as the simulated DWDM optical network.

(c) Discusses the results from the analysis of the literature as well as the EPT simulation.

(d) The study is concluded by presenting the major findings concerning bandwidth and network availability in DWDM optical networks, as well as the recommendations.

## 1.8. Research Outline

Chapter 1: Introduction

The introductory chapter explained the context and rationale for doing this research. It highlighted the background, problem statement, objectives, and significance of the study. This chapter also outlined research questions that helped focus the research, set limits, and served as a frame of reference for the study.



C2 General

Chapter 2: Literature Review

This chapter reviewed the literature on DWDM optical networks. The focus was on fundamental mobile network architecture, various transmission media, DWDM technology, and its components. Furthermore, the chapter investigated the advancement of DWDM functionalities such as colourless, directionless, contentionless, and Flex-Grid technology in enhancing bandwidth and network availability.

Chapter 3: Research Methodology

The methodology employed in the study was discussed in depth in Chapter 3. The chapter discussed the rationale for the use of a desktop research approach paired with the EPT simulation. A systematic literature review method was used, with search terms indicated, as well as the inclusion and exclusion criteria of literature sources outlined.

Chapter 4: Results and Discussion

This chapter discussed the findings of the study, it presented the findings of the EPT simulation. Chapter 4 also examined OPEX reduction initiatives in a DWDM network that uses CDC-F ROADMs. All findings were compared to the previously defined research objective and research questions, which ultimately informed the conclusions.

Chapter 5: Conclusion

The researcher concluded and made recommendations after reviewing the findings. This chapter also suggested future research areas for other academics to pursue.

## 1.9. Chapter 1 Summary

The first chapter of this dissertation established the context and rationale behind carrying out this research. The background of the study highlighted the global rise of mobile devices, both now and in the future. With more mobile devices in the hands of subscribers, mobile network operators must ensure that network services and products are accessible and reliable. The problem statement explained how bandwidth and network availability are crucial to providing subscribers with a decent user experience. This chapter also discussed the research questions, objectives, the scope, and the significance of the study.



C2 General

# CHAPTER 2: LITERATURE REVIEW

## 2.1. Introduction

This chapter presents an overview of the various research studies undertaken in the field of optical networks. One of the most critical requirements for optical networks is the ability to increase bandwidth swiftly in response to increased heterogeneous traffic transmitted resulting from the many internet services available today (Ibrahimov, 2023). This chapter delves into the preferred technologies and strategies for enhancing bandwidth and network availability in optical networks, with a particular focus on DWDM optical networks. The research relied on accredited articles and datasheets from a variety of DWDM vendors.

## 2.2. Transmission Medium

Before deploying any network, numerous factors must be considered, one of which is the appropriate transmission medium to use. In mobile networks, common transmission media include fibre optic, microwave, infrared, radio waves, twisted pair cable, and coaxial cable. Fibre optics and microwave transmission are the two most used transmission media in mobile networks. This research focuses on fibre optics. Fibre optics is the technology that transmits information as light pulses along a glass or plastic fibre. The global market for fibre-optic communication products and technologies has experienced rapid growth in recent years (Jinkai, et al., 2021). Lately, optical fibre communication has become increasingly popular for long-distance data transport due to various advantages, such as efficient amplification, high data rates, and low attenuation (Anjana, et al., 2021). The pursuit for faster speeds, more efficiency, and greater capability drives substantial innovation in optical communications (Kareem, et al., 2021). In mobile networks, fibre optics are most used in metro and core networks, while microwave transmission remains popular in access networks. Figure 2.1 shows a generic representation of a mobile network from end users to the core network, with access and metro networks in between. The geographical area, number of network nodes, and quantity of traffic of core, metro, and access networks varied significantly (Welch, et al., 2021). The core network is a network node cluster consisting of large-size, high-capacity routers for quicker traffic redirection, while metro nodes connect voice, data, and media to the core network

(Herrera, et al., 2021). The last link in the network chain that connects subscribers to the core and metro networks is the access network, also known as the last mile.

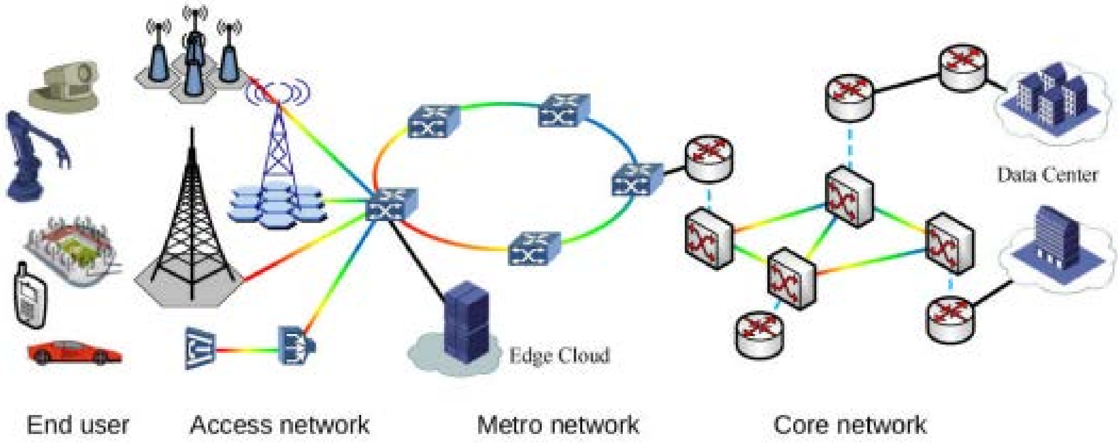


**Figure 2.1:** Basic Mobile Network Architecture **(Herrera, et al., 2021)**

It is simple to grasp how a fibre cable works once one understands how it is put together. Figure 2.2 shows all the distinct components of a fibre-optic cable, including the various diameters. The fibre-optic cable is composed of the core, cladding, primary coating, and jacket. The core is the primary component of the fibre optic cable located in the centre; it is made of glass and is where light travels. The cladding is the glass layer outside of the core that is responsible for retaining light signals inside the core during transmission (Hui, 2020). The core and the cladding are made of different types of glass, which is why they can work well together.

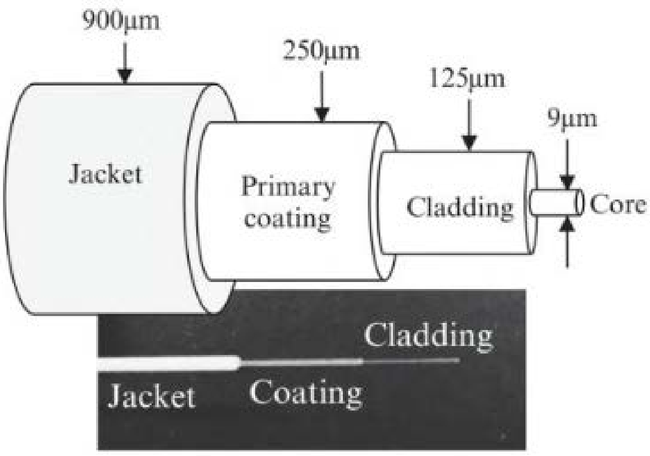


**Figure 2.2:** Fibre Optic Cable **(Hui, 2020)**



C2 General

Outdoor fibre-optic cables are typically laid underground; however, in some cases, overhead installation is required. Both scenarios expose the fibre cable to extreme weather conditions, underlining the significance of all the layers that protect its core area. Figure 2.3 shows a fibre-optic cable that is used outdoors as well as one that is intended for indoor usage. Indoor fibre-optic cables are called *patch chords*.

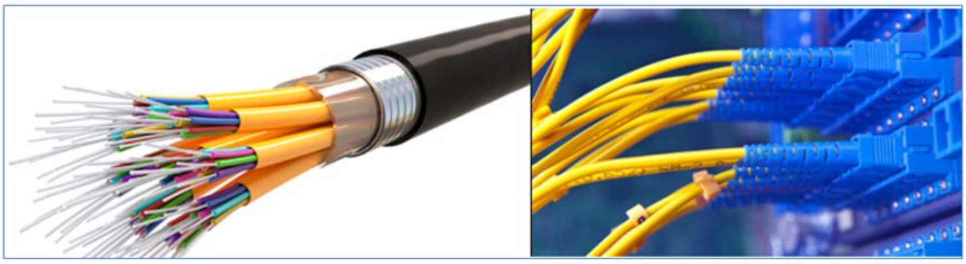


**Figure 2.3:** Fibre-Optic Cable

There are two types of fibre-optic cables, single-mode and multi-mode fibres. A single-mode fibre-optic cable is used for longer distances, due to the smaller diameter of the glass fibre core and low attenuation. A multimode fibre-optic cable is used for shorter distances because the larger core opening enables light signals to bounce and reflect more along the way (English, 2021). When it comes to fibre routes, MNOs have several procurement options to select from, namely:

- Purchase (the MNO pays a once-off fee)
- Leased (the MNO pays a monthly fee)
- Self-provided (the MNO builds the route themselves)
- Co-build (two or more MNOs build the route)
- Swap deals (the MNO offers one route in return for another from a different operator).

## 2.3. Dense Wavelength Division Multiplexing (DWDM) Technology

Because of the large increase in data transmission, the physical transport layer's bandwidth requirements have increased. DWDM technology is used to increase the transmission capacity of the optical medium (Zdravecký, et al., 2022). DWDM is the optical multiplexing technology used to enhance bandwidth over existing fibre networks (Zola & Burke, 2021). Figure 2.4 shows the basic functionality of a DWDM system. This technology combines and transmits multiple signals simultaneously at



C2 General

different wavelengths on the same fibre. Each input is generated by a distinct optical source with a specific wavelength. The transmitter converts the electrical signal into an optical signal. The converted optical signal is then transmitted over the fibre-optic cable. At the receiver, the signal is converted from optical back to an electrical signal.

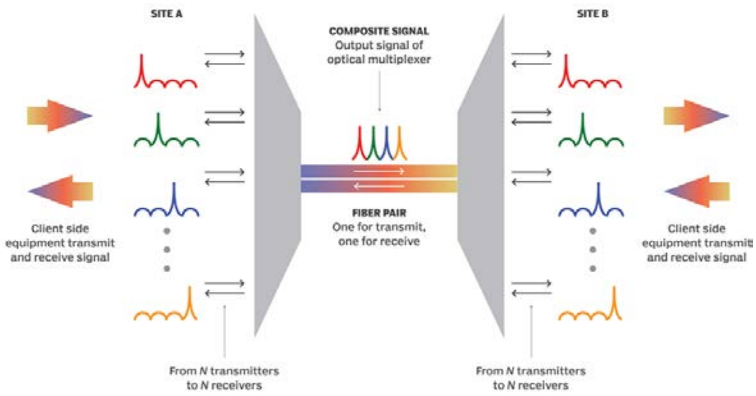


**Figure 2.4:** DWDM System Basic Functionality **(Zola & Burke, 2021)**

Light waves do experience attenuation along the fibre and at the optical fibre's junction during their propagation. As a result, for long-distance transmission, an amplifier that amplifies attenuated light waves is required (Simanjuntak, et al., 2022). The ability to cover vast distances and transmit massive amounts of data makes DWDM technology the most advanced multiplexing technique available (Lazim, et al., 2022).

DWDM systems can operate in both the C-band and the L-band. The C-band is preferred over the L-band due to its lower attenuation during data transmission (Zdravecký, et al., 2022). For this study, the focus is on the C-band. The range of the C-band is 1530 *nm* to 1565 *nm* and is based on the ITU-T G.694.1 standard. Table 2.1 shows the different frequency bands used for data transmission.

**Table 2.1:** Optical Wavelength Bands **(Anjana, et al., 2021)**

| **Optical Wavelength Band** | **Band Descriptor** | **Wavelength Range (*nm*)** |
|---|---|---|
| O-band | Original | 1260 to 1360 |
| E-band | Extended | 1360 to 1460 |
| S-band | Short | 1460 to 1530 |
| **C-band** | **Conventional** | **1530 to 1565** |
| L-band | Long | 1565 to 1625 |
| U-band | Ultra-long | 1625 to 1675 |



C2 General

When using 50 *GHz* spacing, a typical DWDM system comprises 88 wavelength channels or 44 channels when using 100 *GHz* spacing. (Mahajan, 2018) details the mathematics behind the C-band's 88 channels. It is derived by calculating the frequency at both the upper and lower boundary of the C-band to be able to work out the total bandwidth and subsequently the spacing.

$$c = \lambda v \qquad \text{(Eq. 2.1)}$$

Where C = speed of light in a vacuum = $299792458 m/s$

λ = wavelength

v = frequency

<u>Lower boundary</u>

$$v_{lower} = 299792458 m/s \div 1530 nm$$
$$= 196.1\ THz$$

<u>Upper boundary</u>

$$v_{upper} = 299792458 m/s \div 1565 nm$$
$$= 191.7\ THz$$

$$\begin{aligned}
C - Band\ available\ spectrum &= v_{lower} - v_{upper} \\
&= 196.1 THz - 191.7 THz \\
&= 4.4 THz \\
For\ 50 GHz\ channel\ spacing &= 4.4 THz \div 50 GHz \\
&= 88\ wavelength\ channels
\end{aligned}$$

$$\begin{aligned}
For\ 100 GHz\ channel\ spacing &= 4.4 THz \div 100 GHz \\
&= 44\ wavelength\ channels
\end{aligned}$$

When designing a DWDM system for 88 channels at 50 *GHz* spacing, odd and even wavelengths/channels are combined into one system. A 44-channel DWDM system with 100 *GHz* spacing is deployed, with either odd or even wavelength/channels. Figure 2.5 exhibits a typical 44-channel static filter DWDM module with all 44 even wavelength/channels displayed. To set up an 88-channel DWDM system, an identical module with 44 odd channels will be added to the one shown in Figure 2.5.

**Figure 2.5:** 44 Channel Static Filter DWDM Module **(Source: Nokia)**



C2 General

### 2.3.1. Key Components for DWDM Systems

Transponder – is required to tune the incoming signal as a requirement of an optical line system that supports C-band deployment (Papageorgiou, 2018). The incoming signal is tuned by first converting the optical signal to an electrical signal and then regenerating the optical signal with a lambda wavelength. A transponder is responsible for this optical-electrical-optical (O-E-O) wavelength conversion.

Multiplexer/Demultiplexer – a multiplexer is an optical add filter that combines multiple wavelengths produced by different optical transmitters operating on different fibres into a single composite signal that is then transmitted on a single channel (Anjana, et al., 2021). Wavelength demultiplexers are typically built by connecting a multiplexer in an inverted arrangement, allowing a composite signal to be isolated into multiple wavelengths and terminated at their corresponding transponders (Bakery, 2018).

Optical Add/Drop Multiplexer (OADM) – is one of the most important components of a DWDM network. It is a type of optical add-drop multiplexer that allows individual or multiple wavelengths carrying data to be added or dropped on an incoming fibre link. An OADM card has add/drop ports that can be interconnected to allow pass-through traffic from one direction to another. Traffic can also be destined for a local add/drop block (Papageorgiou, 2018).

Optical Amplifier – due to DWDM systems being deployable over long distances, amplification is required along the way. The further an optical signal travels the more attenuation it experiences. The optical signal must be amplified to restore its strength so that it can be detected at the receiver end (Lacerda Jr, et al., 2017). Erbium-doped fibre amplifiers (EDFAs) are the most preferred optical amplifier. EDFA amplifiers are widely used in current systems and are still being studied in the field of research (Lazim, et al., 2022). The principle behind their operation is based on stimulated emission. Depending on where it is connected in the DWDM system, the EDFA can perform various amplification functions. Figure 2.6 shows different amplifier placements in the DWDM system, namely:

i. The power amplifier, also called the booster amplifier
ii. In-line amplifier



C2 General

iii. Pre-amplifier

A standard EDFA can cover a distance of up to 70-80 *km* depending on the span loss on the fibre route in question (Karar, et al., 2023). Because of the low span loss, an EDFA can cover up to 100 *km* on newly installed fibre.

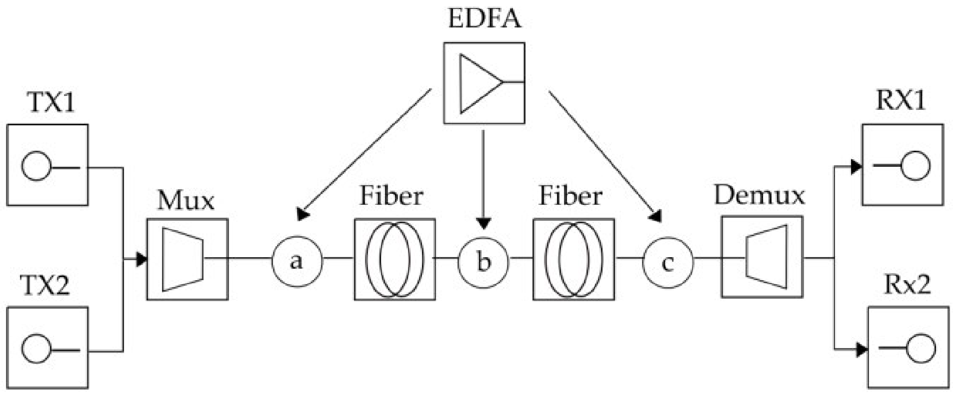


**Figure 2.6:** Different Optical Amplifier Placements **(Zdravecký, et al., 2022)**

For distances that are longer than EDFA coverage, Raman optical amplifiers (ROA) are used. ROAs are currently very popular and, along with EDFA, are used for long-distance transmissions in DWDM systems. Its advantage over EDFA is that the pump source allows for greater flexibility in wavelength selection. One significant advantage is the ease with which it can be integrated into existing infrastructure (Zdravecký, et al., 2022). A ROA can cover a distance of up to 100-150 *km*; again, the quality of the fibre-optic cable determines the span loss on the route.

### 2.3.2. Evolution of Optical Add-Drop Multiplexers (OADMs)

An OADM forms part of the core components of DWDM technology. It is responsible for adding or dropping optical signals of a specific wavelength (Irving, 2021). An incoming composite signal is split into two components: drop and pass-through. OADMs are classified into two types: fixed optical add-drop multiplexer (FOADM) and reconfigurable optical add-drop multiplexer (ROADM). A FOADM is a conventional OADM that can only input or output one wavelength via the fixed port. FOADMs have pre-assigned wavelength channels in static nodes. A FOADM allows for the removal and reuse of one wavelength locally, as well as the addition of the same wavelength to be transported in the opposite direction (Sousa & Drummond, 2022).



C2 General

As traffic demands became more dynamic, a ROADM capable of modifying designated wavelength routing in the optical network was developed. A ROADM node comprises two main structures: the ROADM architecture is responsible for routing optical signals and the add/Drop stage is responsible for adding and dropping client signals into the optical network (Sequeira, et al., 2021). The important component in ROADM systems is the wavelength selective switch (WSS) module. WSS modules are responsible for dynamically routing, blocking, and attenuating all DWDM wavelengths within a network node (Singh & Marom, 2017). Table 2.2 highlights the fundamental differences between FOADMs and ROADMs. The emphasis is on the type of activities that are done manually and those that are automated depending on the OADM type. The automation component that ROADMs bring is critical in ensuring a much smoother network deployment. More importantly, certain activities can be conducted without the need for dispatching engineers to the site, which is frequently done at night, resulting in overtime claims. Furthermore, automation simplifies service configuration and maintenance tasks, which contributes significantly to the organisation's OPEX reduction.

**Table 2.2:** FOADM vs. ROADM **(Fogliata, 2019)**

| **Installation and Commissioning** | **FOADM** | **ROADM** |
|---|---|---|
| First Installation/Power up | Manual/Manual | Manual/Automated |
| Cabling | Manual | Manual |
| Configuration/Routing | Manual/Manual | Automated |
| Power Balancing | Manual | Automated |
| Testing | Manual | Automated |
| **Maintenance/Re-Configurations** | | |
| New circuit changes/Provisioning | Manual | Automated |
| Network re-configuration due to change | Manual | Automated |
| Re-engineering and re-optimization | Manual | Automated |
| Training of network staff | Medium to High | Low |

Since optical networks carry massive volumes of data, they must be dynamic, adaptable, and reconfigurable. CDC ROADM is the most recent iteration of OADM evolution; it has received widespread industry acceptance because of its flexibility, streamlined operations, and increased efficiency (Eisenach, 2021). The CDC ROADM systems can add, drop, and express any WDM signal without wavelength blocking or conflict (Sequeira, et al., 2018). Multicast switches (MCSs) are used in CDC-ROADMs, instead of the WSS modules used on conventional ROADMs. The MCS provides a



C2 General

copy of the signal; any wavelength of the input port can be switched to any output port in the CDC network (Sousa & Drummond, 2022). Table 2.3 shows all the different architectures that ROADMs support, with different levels of flexibility. The most elementary ROADM architecture employs fixed filters for the add/drop function. Other ROADM systems offer (a) flexibility in wavelength assignment; (b) flexibility in add/drop direction; (c) the ability to route wavelengths in any direction without wavelength collision/channel blocking; (d) finally, flexible-grid WSS that supports Flex-Grid technology (Nance-Hall, et al., 2021). The optical network operator chooses among the ROADM architectures shown in Table 2.3, based on the level of flexibility necessary as well as affordability (Infinera, 2021).

**Table 2.3:** ROADM architectures with differing degrees of flexibility **(Infinera, 2021)**

| ROADM Type | Colourless | Directionless | Contentionless | Flex-Grid |
|---|---|---|---|---|
| Coloured-Directional (or Fixed) | x | x | x | x |
| Colourless-Directional | ✓ | x | x | ✓ |
| Coloured-Directionless | x | ✓ | x | ✓ |
| Colourless-Directionless (CD) | ✓ | ✓ | x | ✓ |
| Colourless-Directionless-Contentionless (CDC) | ✓ | ✓ | ✓ | ✓ |

### 2.3.3. Optical Transport Network (OTN)

The demand for technologies that improve transmission quality has increased in recent years, as telecommunications services have evolved. One of these technologies is OTN, which functions as a layer above the DWDM network to enable the most efficient use of resources (Xavier, et al., 2020). The OTN technology is a superior layer to the DWDM network, allowing for more efficient resource utilisation (Silva, et al., 2022). The OTN is the next-generation backbone transmission network that builds networks in the optical layer using wavelength division multiplexing technology (www.heyoptics.net, 2022). As defined by ITU-T G.709, OTN is a versatile method of transporting and switching various types of digital signals across an optical core via an optical data unit (ODU) and/or optical channels multiplexing. The OTN can handle transparent signal transmission, high-bandwidth multiplexing, and configuration. It also allows for end-to-end connectivity and networking (Chen, et al., 2022). Since OTN is a DWDM evolution product, it provides a wide range of services, such as customer signal encapsulation, transparent transmission, large bandwidth



C2 General

multiplexing, flexible crossover, configuration scheduling, and network survivability enhancement. Figure 2.7 illustrates a typical modern OTN network where each site has an OTN layer chassis connected to the DWDM layer chassis. The OTN chassis is responsible for terminating data types and multiplexing for transmission purposes. The DWDM chassis is responsible for terminating line fibres, amplification, and wavelength lambda restoration.

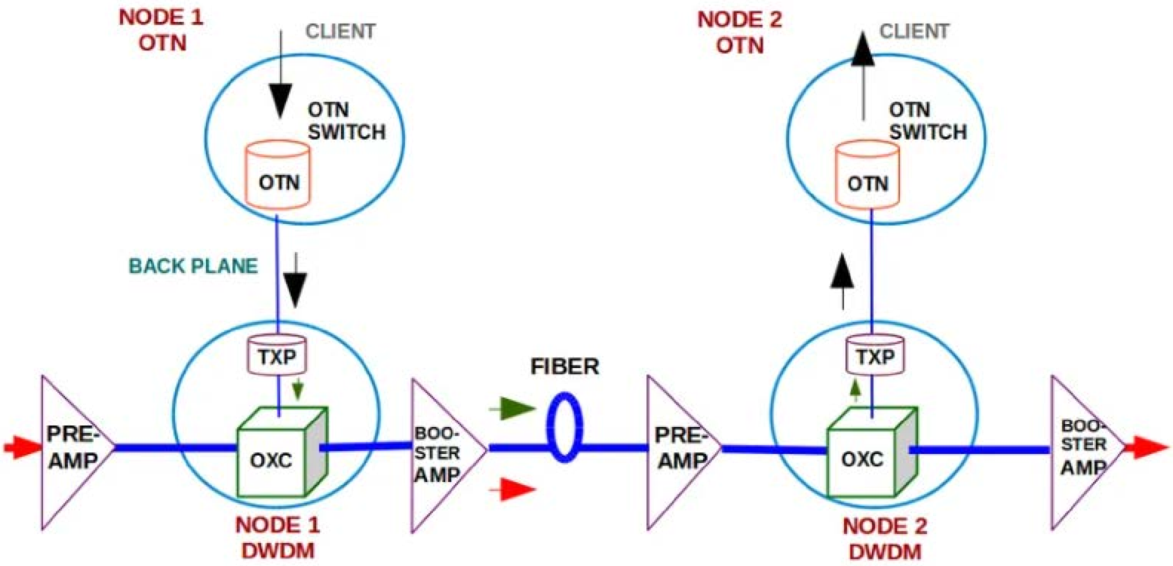


**Figure 2.7:** OTN Architecture with OTN Layer and DWDM Layer **(www.heyoptics.net, 2022)**

Figure 2.8 shows multiple layers of the OTN network from the different types of client services, multi-service transport, and wavelength switching at the wavelength lambda level. The different segments of the DWDM optical layer are also highlighted.

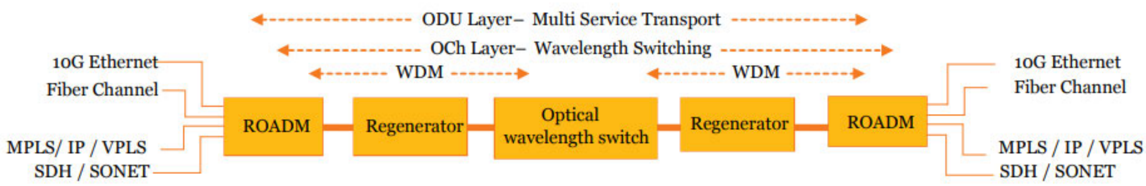


**Figure 2.8:** The Multiple Layers of the OTN Network **(Sundararajan, 2019)**

There are eight benefits of OTN networks, namely, scalability beyond 100/400 *Gbit/s* on a single wavelength, reliability, flexibility, security, cost optimisation, deterministic, infrastructure agility, and virtualised network operations (Sundararajan, 2019).



C2 General

## 2.4. Flex-Grid Technology

The growing reliance on the internet to meet daily needs at all levels of society drives MNOs to improve their bandwidth accessibility regularly (Simanjuntak, et al., 2022). 5G technology has also allowed for the growth of novel IoT solutions and cloud services, which has led to an increase in the transmission of data into and out of access networks (Karar, et al., 2023). Figure 2.9 demonstrates ITU's global mobile data traffic forecasting in exabytes per month between the years 2020 and 2030. To put this in context, an exabyte is one million terabytes, which indicates unprecedented levels of data traffic in the coming years.

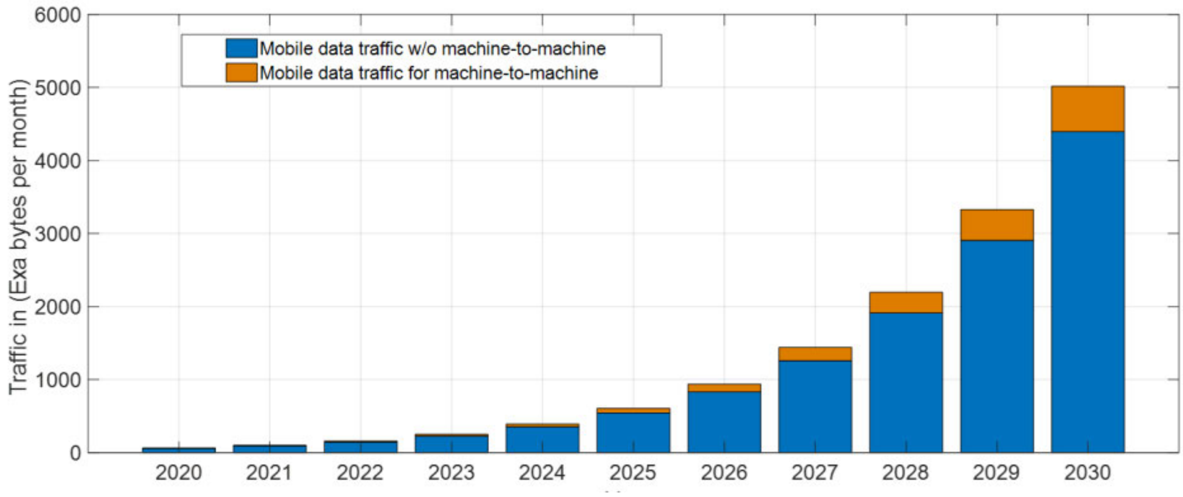


**Figure 2.9**: ITU Forecasts on Global Mobile Data Traffic from 2020 to 2030 **(Karar, et al., 2023)**

This ever-increasing demand for data transport, particularly from transparent WDM optical networks, has prompted research into a wide range of forward-thinking solutions to address this issue using existing infrastructure (D'Amico, et al., 2022). New standards and approaches have emerged to overcome existing capacity limits. Traditionally, optical transport has been using a fixed grid of 50 *GHz* channel spacing to transmit data through a fibre-optical network. This allows the transmission of a maximum of 88 wavelength channels with 50 *GHz* channel spacing in the C-band spectrum, resulting in spectrum underutilisation (Yu, et al., 2022). Given the ongoing emergence of new internet services such as data centres and high-definition services, the rigid capacity of an optical channel in Fixed-Grid WDM optical networks makes flexible service activation difficult to achieve (Zhu, et al., 2021). The rigid features of a traditional WDM backbone network make it unsuitable for emerging diverse and high



C2 General

bitrate traffic needs (Ahmed, et al., 2018). Flex-Grid technology has become increasingly common in recent years as an answer to data evolution.

Flex-Grid technology is defined in the ITU-T G.694.1 recommendation (Vyukusenge, 2020). The terms Flex-Grid technology and elastic optical networks (eons) are used interchangeably in the telecommunications sector (Nance-Hall, 2020). Nevertheless, this study opted for Flex-Grid technology as the term of choice. Figure 2.10 depicts spectrum assignments in both the fixed and flexible grids. Flex-Grid technology makes the most of available fibre spectrum resources due to its superior optical channel flexibility (Rumipamba-Zambrano, et al., 2017). On the Fixed-Grid, all wavelengths are assigned 50 *GHz* regardless of traffic size.

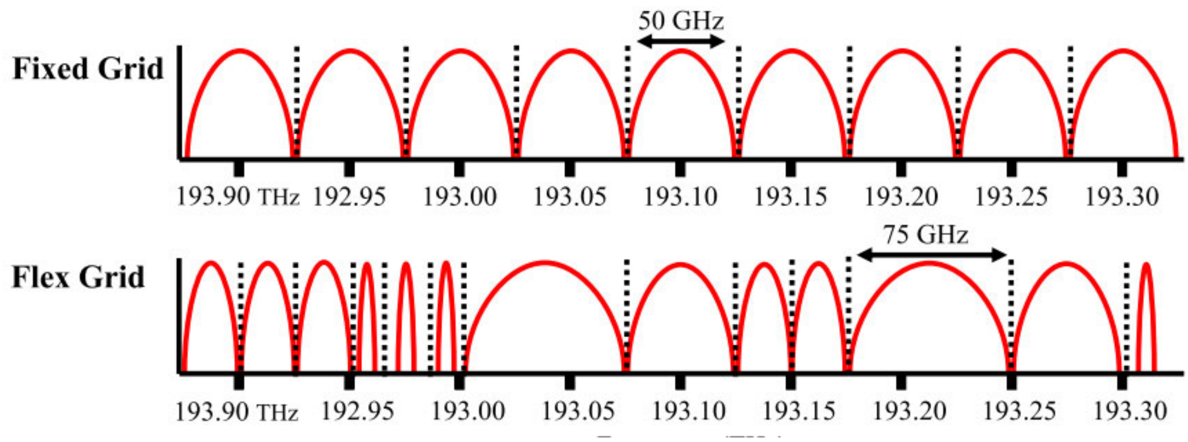


**Figure 2.10:** Fixed Grid vs. Flex-Grid Spacing **(Nance-Hall, et al., 2021)**

### 2.4.1. Single Carrier vs Multiple-Carrier

The literature has established that the spectrum is a limited resource that should be used sparingly. Figure 2.10 illustrates the differences in spectrum resource allocation between the two grids. According to (Zhu, et al., 2019), Flex-Grid enables the allocation of optical spectrum at finer granularities of a few gigahertz, such as 12.5 *GHz*, thereby enabling dynamic spectrum management. When the traffic being transmitted is minimal, a modest amount of spectrum can be assigned on the flexible grid, resulting in superior spectral efficiency. In contrast, the Fixed-Grid has a rigid channel spacing of 50 *GHz* and a maximum transmission rate of 100 *Gbit/s* per wavelength.



C2 General

Table 2.4 contrasts the channel bandwidth utilization of Flex-Grid and Fixed-Grid in various line rates and modulation schemes. Channel Bandwidth (BW) is indicated including a 10 *GHz* guard band. According to (Zhou, et al., 2022), in Flex-Grid technology, four modulation schemes are typically used, namely, Quadrature Phase Shift Keying (QPSK), 8-Quadrature Amplitude Modulation (QAM), 16-QAM, and 64-QAM. Dual polarization (DP) is used as a prefix for modulation schemes relating to optical communication.

**Table 2. 4:** Efficiency Improvement in Flex-Grid vs Fixed-Grid Spectrum **(Stapleton, et al., 2018)**

| Demand bit rate (*Gbit/s*) | Modulation Format | Channel BW (*GHz*) | Fixed Grid | Efficiency Increase in Flex-Grid |
|---|---|---|---|---|
| 40 | DP-QPSK | 25+10 | 1*50 *GHz* Channel | 35 *GHz* vs 50 *GHz* = 43% |
| 100 | DP-QPSK | 37.5+10 | 1*50 *GHz* Channel | 47.5 *GHz* vs 50 *GHz* = 5% |
| 100 | DP-16QAM | 25+10 | 1*50 *GHz* Channel | 35 *GHz* vs 50 *GHz* = 43% |
| 400 | DP-QPSK | 75+10 | 4*100 *Gbit/s* in 4*50 *GHz* Channel | 85 *GHz* vs 200 *GHz* = 135% |
| 400 | DP-16QAM | 75+10 | 2*100 *Gbit/s* in 2*50 *GHz* Channel | 85 *GHz* vs 100 *GHz* = 17% |
| 1000 | DP-QPSK | 190+10 | 10*100 *Gbit/s* in 10*50 *GHz* Channel | 200 *GHz* vs 500 *GHz* = 150% |
| 1000 | DP-16QAM | 19+10 | 5*200 *Gbit/s* in 5*50 *GHz* Channel | 200 *GHz* vs 250 *GHz* = 25% |

Table 2.4 shows that when transmitting a wavelength with a line rate of more than 100 *Gbit/s*, an additional 50 *GHz* channel spacing, including new transponders, must be provided, potentially resulting in wasted spectrum and increased power consumption. As an example, to provide 400 *Gbit/s* demand using DP-QPSK modulation, 4x carrier wavelengths of 100 *Gbit/s* must be used with a spectrum allocation of 200 *GHz*. In Flex-Grid technology, when a wavelength is transmitted at a line rate higher than 100 *Gbit/s*, an adequate amount of spectrum is allocated without the need to assign an extra wavelength or additional transponders. The same 400 *Gbit/s* demand using DP-QPSK can be achieved using a single carrier with a spectrum utilization of 85 *GHz*.
As a result, Flex-Grid technology outperforms Fixed-Grid in terms of spectrum efficiency.

### 2.4.2. High Data Rate Transmission in Flex Grid Technology

Overall, optical fibre transmission systems have developed significantly in the last 30 years (Liu, 2019). Table 2.5 shows the typical evolution of fibre-optical transmission over this period. The typical single-channel data rate of fibre-optic transmission has increased more than 100 times from 2.5 *Gbit/s* in 1980 to 400 *Gbit/s* in 2022. The



C2 General

distance over which fibre-optic transmission can be deployed has also increased throughout the years. In the year 2000, a Raman optical amplifier was released to the market. Optical spans could be made longer than the conventional 80 *km*, which is critical for long-distance national routes. The deployment of a 400 *Gbit/s* lambda over a 1000 *km* distance was accomplished in 2022. In the same year, 200 *Gbit/s* lambdas could be deployed over 2000 *km*. To make optical networks transparent and flexible, elements such as a ROADM enable flexible wavelength management (Liu, 2019).

**Table 2.5:** Fibre Optical Transmission Advances over the Last 30 Years **(Liu, 2019)**

| Year: | 1980 | 1990 | 2000 | 2010 | 2022 |
|---|---|---|---|---|---|
| Channel Rate | 2.5 *Gbit/s* | 10 *Gbit/s* | 40 *Gbit/s* | 100 *Gbit/s* | 200/400 *Gbit/s* |
| **Modulation format** (typical) | OOK (NRZ) | OOK (NRZ) | DPSK DQPSK | PDM-QPSK | PDM-nQAM, CS, PAM4, DMT |
| **System features** (newly added) | Single-span Single-channel | Multi-span with EDFAs, WDM | DWDM, Raman, ROADMs | 1: N WSS CDC-ROADMs | Flexible-Grid WDM, M: N WSS, Super-C EDFA |
| **System capacity** (typical) | 2.5 Gb/s (single-channel) | 400 Gb/s (40 WDM channel) | 1.6 Tb/s (40 WDM channel) | 8 Tb/s (80 WDM channel) | 16~32 Tb/s (Fixed-Grid or Flex-Grid channels) |
| **System reach** (typical) | 100 *km* (single-channel) | 1000 *km* | 1000 *km* @40*Gbit/s* 3000 *km* @10*Gbit/s* | 4000 *km* @100*Gbit/s* | 2000 (1000) *km* @200 (400)*Gbit/s* |
| **Enabling technologies** | Directly modulated laser | High-speed modulation, HD-FEC | Differential phase-shift-keying | Coherent detection with oDSP, SD-FEC | 100Gbaud-class OE device and advanced oDSP |

Flex-Grid technology enables ultra-high bit-rate transmissions beyond 100 *Gbit/s* by joining multiple adjacent flexible sub-channels. This flexibly enables the packing of more data into a single wavelength channel (Rumipamba-Zambrano, et al., 2017). Figure 2.11 illustrates the difference between the two types of grid, where the lanes represent the channel spacing for the various wavelengths. The Fixed-Grid allocates the same channel spacing of 50 *GHz* regardless of the size of the wavelength being transmitted. It is clear in Figure 2.11 (a) that **λ**1 has a smaller capacity that can be accommodated with a much smaller allocation but, because the grid is fixed, it gets its dedicated 50 *GHz* lane. This leads to spectrum underutilisation. Flex-Grid technology addresses this issue because its lowest channel spacing granularity is 12.5 *GHz*; therefore, small capacity wavelengths can be accommodated adequately, as shown



C2 General

in Figure 2.11 (b). What distinguishes Flex-Grid technology is its ability to combine multiple 12.5 *GHz* allocations into a single super-channel capable of carrying large data rates (Lui, 2022). In Figure 2.11 (b), **λ**1 can represent a 100 *Gbit/s* wavelength, **λ**2 a 400 *Gbit/s* wavelength, and *λ*5 a 1 *Tbit/s* wavelength, all of which coexist in the same grid.

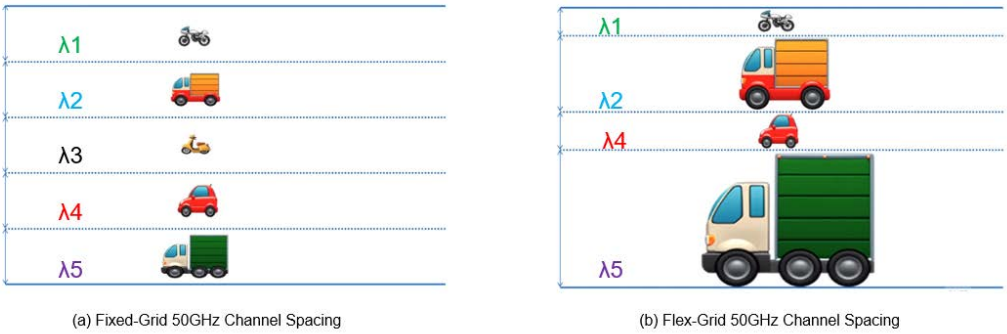


**Figure 2.11:** Fixed-Grid vs Flex-Grid Channel Spacing **(World Wide Technology, 2020)**

The implementation of Flex-Grid technology demands a change in the modulation scheme for the DWDM network to transmit large data rates. As a result, modulation is an essential component of Flex-Grid technology. The number of binary bits transmitted by a signal in one symbol is determined by the modulation scheme. A sender and a receiver agree on a symbol rate (baud), which specifies the clock speed to which the receiver is tuned when it reads a symbol from the sender (Nance-Hall, et al., 2021). On-off keying (OOK) is the most basic modulation scheme, transmitting one bit per symbol. Superior modulation schemes enable the transmission of high data rates. Flex-Grid technology allows for increased data rates by utilising advanced polarised modulation schemes (Ujjwal & Thangaraj, 2018). QPSK, 8-QAM, 16-QAM, and 64-QAM are the four common modulation methods used (Zhou, et al., 2022). QAM modulation is superior to PSK and QPSK modulation because it incorporates amplitude. As a result, both the phase and amplitude are modulated to transmit data. Table 2.6 shows various modulation schemes as well as the associated transmitted bit per symbol. The total number of constellation points for a modulation scheme is $2^n$, where “n” represents the number of transmitted bits per symbol (Dhingra, et al., 2018).



C2 General

**Table 2.6:** Modulation Schemes and Transmitted Bits per Symbol

| Modulation Scheme | Bit per Symbol |
|---|---|
| BPSK | 1 |
| QPSK | 2 |
| 8QAM | 3 |
| 16QAM | 4 |
| 32QAM | 5 |
| 64QAM | 6 |
| 256-QAM | 8 |

Figure 2.12 shows constellation diagrams of different modulation schemes. As you go up in QAM modulation schemes, the dots get denser, with fewer spaces between them, making them more susceptible to noise (Moore, 2023). This explains why high QAM modulation techniques are more successful over shorter distances than QPSK, but they compensate for this with a high data-transmission rate. QPSK modulation is considered robust and is used for lower-capacity/longer-reach transmission.

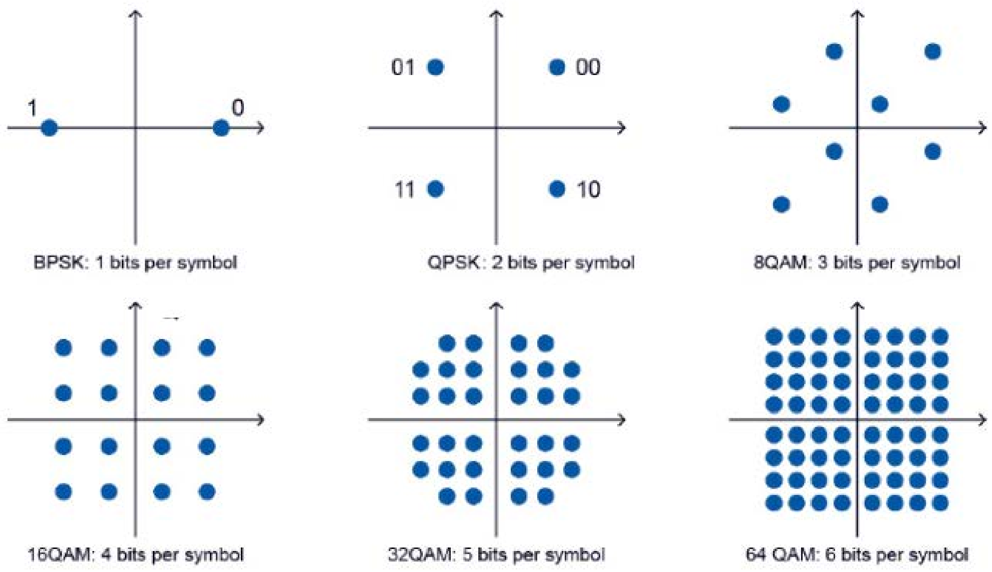


**Figure 2.12:** Constellation Diagrams for Various Modulation Schemes **(Dhingra, et al., 2018)**

Another crucial factor to consider when dealing with optical transmission is the reach. The ability to transmit large amounts of data over long distances is the key offering of DWDM technology. Transponder type, modulation scheme, baud rate, and OSNR are four key variables that determine reach when transmitting data at high line rates. OSNR is the ratio of signal power to noise power. Superior modulation schemes are more sensitive to the OSNR, which tends to decrease gradually with distance (Nance-



C2 General

Hall, 2020). The OSNR is directly related to the bit error ratio and can be used to indicate signal quality; it is a vital parameter when troubleshooting an optical link (Yu, et al., 2022). The OSNR measurement determines the best modulation technique for the link. In turn, the modulation scheme outputs a possible capacity (*Gbit/s*) for an optical channel (Nance-Hall, et al., 2021). OSNR comprises four key measurements, namely:

- Required OSNR – minimum OSNR required in decoding a signal correctly.
- Delivered OSNR – the actual OSNR measure for the specific lambda.
- OSNR Margin – the difference between the delivered and the required OSNR.
- OSNR Degradation – the percentage of the OSNR margin used by the lambda.

The bigger the OSNR margin, the better the lambda performance. In the context of optical communication, noise power is defined as any undesired signal interference. Figure 2.13 highlights the relationship between modulation/data rate and distance/noise as it relates to optical communication. High-order QAM modulation schemes are better suited for higher data rate transmission but fall short of stretching a long distance because they are more sensitive to phase noise and nonlinear effects (Li, et al., 2020). QPSK is a robust modulation system that can handle high noise and may be deployed over long distances; nevertheless, the data rate transmitted on this modulation scheme is modest. OSNR is calculated using the formula:

$$OSNR = 10 * \log\left(\frac{S}{N}\right) \quad \text{(Eq. 2.2)}$$

Where S is the signal power and N is the noise power (in Watts).



C2 General

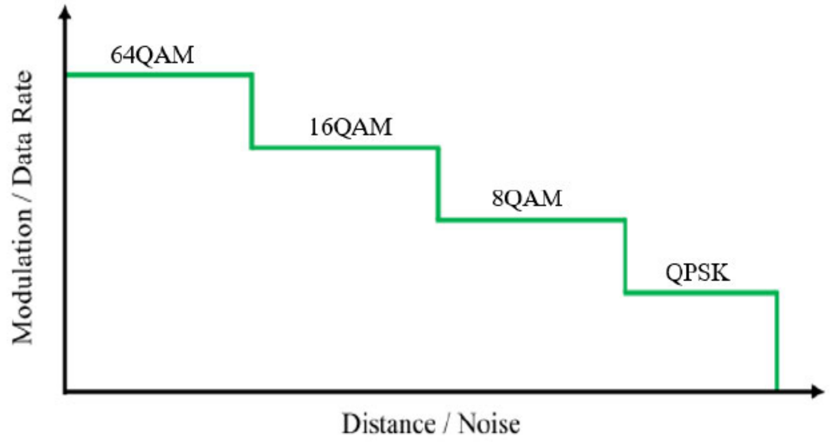


**Figure 2.13:** Modulation/Data Rate vs Distance/Noise **(Nance-Hall, et al., 2021)**

Aside from using high-order modulation schemes to increase capacity, increasing the baud rate on a transponder is another way to support higher-capacity wavelengths. While modulation is based on the number of symbols sent, the baud rate is about the rate at which those symbols are sent (Infinera, 2021). Transmitting information faster and frequently increases the number of bits transmitted in a given time frame (Moore, 2023). Both approaches are effective; it is up to the network operator to determine which is best suited to their needs. Figure 2.14 illustrates how increasing the baud rate and modulation scheme both enhance capacity.

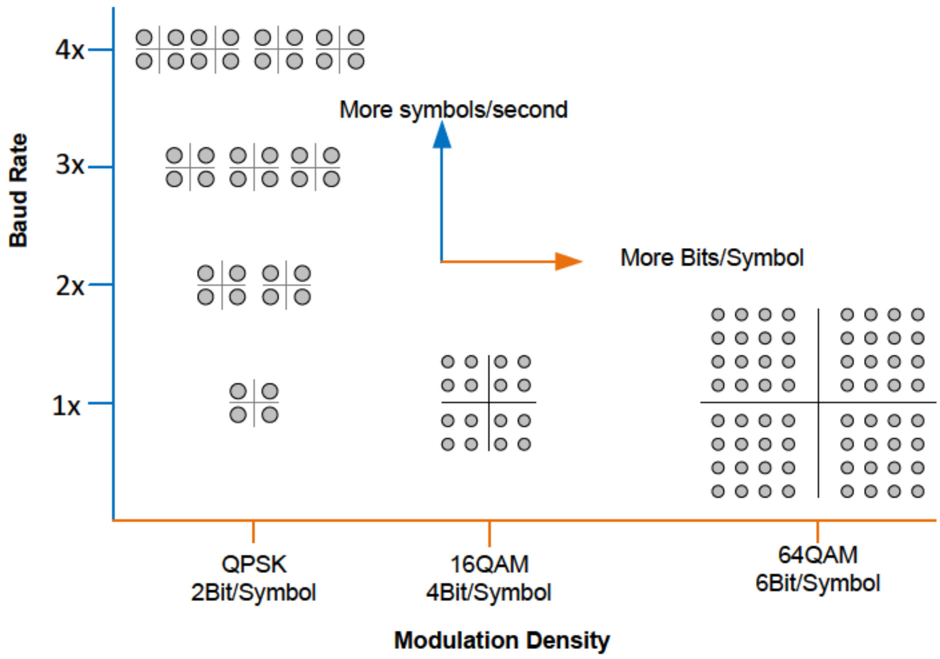


**Figure 2.14:** Baud Rate vs. Modulation Density **(Moore, 2023)**

On the modulation density plane, whenever a QPSK symbol is sent out, information for two bits is transmitted. 4xbits/symbol results in a 16QAM transmission rate with 16 polarisation states. On the extreme right is 64QAM, where 6xbits/symbol 64 different positions. As the modulation scheme advances, so does the bit rate, resulting in high volumes of data transmission per second. The baud rate axis looks at increasing transmission capacity by raising the data-transmission rate while keeping the modulation scheme unchanged. Increasing the pace at which the symbols are transmitted will result in more symbols being transmitted. Figure 2.13 shows how increasing the baud rate results in more symbols being sent per second.

### 2.4.3. Flex-Grid Transponder

Core and metro networks have undergone substantial capacity upgrades in recent years because of massive traffic growth associated with internet-based services. The surge in traffic has necessitated the development of DWDM wavelengths supporting line rates from 400 *Gbit/s* to more than 1 *Tbit/s*, which can be deployed using Flex-Grid technology (Wu, et al., 2017). Flex-Grid technology can satisfy current and future capacity requirements driven by bandwidth-intensive applications, such as video conferencing, high-definition television, and multicasting (Kumar, et al., 2020). While the flexible grid is an excellent addition to the world of DWDM optical networks, transponders that can manage the flexibility, as well as the high line rates being transmitted, are essential. One Flex-Grid transponder can support several line rates, modulation schemes, and board rates. The Flex-Grid transponder attributes allow network operators to customise the baud and line rates to optimise spectral efficiency and reach (Maenpaa, 2020). A bandwidth variable transponder (BVT) is a more advanced flexible transponder. Depending on the link or network needs, a BVT can dynamically change optical bandwidth and transmission reach by altering a range of parameters. Such parameters include the baud rate, modulation scheme, and FEC coding (Moreolo, et al., 2019). BVTs are designed with the highest transmission rate possible to meet future demands; nevertheless, deployment for low-rate traffic might result in considerable resource waste and a large amount of wasteful energy in the end (Zhu, et al., 2019). Furthermore, a BVT can deal with a single traffic demand on a single section of the optical spectrum via a specified network channel between the source and destination nodes (Moreolo, et al., 2019).



C2 General

The next iteration of the BVT is the sliceable bandwidth variable transponder (S-BVT). This next-generation transponder is composed of multiple BVTs that can serve many clients at higher data rates, from 100 *Gbit/s* to 1 *Tbit/s* (Ujjwal, 2017). S-BVTs enable many optical connections to share the capacity of a single transponder. Such innovation allows several optical channels with the same source and destination to be packed into a super-channel without guard bands (Lin & Tseng, 2023). This breakthrough in optical grooming elevates optical transmission to an entirely new level.

### 2.4.4. Transitioning from Fixed-Grid to Flex-Grid

To meet current and future bandwidth demands in DWDM optical networks, the network must transition from a fixed grid to a flexible grid (WANG, et al., 2021). The most pressing question for MNOs with DWDM networks that are now deployed on a Fixed-Grid is whether moving to Flex-Grid is feasible on the existing infrastructure. Different authors agree that the transition is feasible, but they put forward various points to consider before embarking on the journey to Flex-Grid technology. A more gradual transition to Flex-Grid technology is recommended where nodes with Flex-Grid switching capabilities coexist with Fixed-Grid nodes for some time before complete migration (Ahmed, et al., 2018). Flex-Grid deployment on top of existing Fixed-Grid networks is a more realistic and pragmatic way to transition from Fixed-Grid WDM optical networks to Flex-Grid technology (Zhu, et al., 2021).

While the deployment of Flex-Grid technology provides much-needed bandwidth in the metro and core DWDM optical networks, it is not without drawbacks. Flex-Grid technology allows for many more optical channels, which means that the optical power pumped into the amplifiers of existing Fixed-Grid infrastructure increases, causing some amplifiers to shut down completely. Given that, Flex-Grid technology is being introduced over the existing Fixed-Grid network; skilled and experienced resources are required to manage the complexity. Furthermore, transponders with 400 *Gbit/s*, 1Tbit/s, and higher capacities that use high-order spectrally efficient modulation schemes are expensive (Imran, et al., 2017). Ultimately, the decision for MNOs to transition to flexible-grid technology will be influenced by the trade-off between benefit and hardware/software cost, backward compatibility with previously deployed technologies, and network-management complexity (Shah & Prajapati, 2018).



C2 General

## 2.5. Survivability Strategies that Enhancing Network Availability

Optical networks are important for satisfying the rapidly increasing bandwidth demand created by applications such as cloud computing, the Internet of Things (IoT), bandwidth on demand, and many others (Agrawal, et al., 2017). Because optical networks transport huge amounts of data, network availability is just as critical as bandwidth demand. Network availability, often known as *network uptime*, refers to the total amount of time that subscribers can access network resources without interruption. High availability is an essential factor that must be considered throughout the network-planning phase, which means survivability strategies must be employed to improve network availability once a failure occurs (Lacerda Jr, et al., 2017). Network survivability is the ability of a network to self-heal and continue functioning correctly when a link or node fails (Krishnamurthy, et al., 2019). The survivability plan must include both proactive and reactive mechanisms (Kantor, et al., 2019). DWDM technology combines numerous wavelength channels at high line rates onto a single fibre, resulting in significant data loss if a fibre link fails. This loss is much greater than in a traditional network using copper wire or a microwave link. As a result, specific safeguarding measures must be implemented to establish a fault-tolerant optical network (Krishnamurthy, et al., 2019). The core and metro networks are critical components of mobile network infrastructure. They collect, combine, and route traffic to other network segments of varying priority, which may be subject to a variety of SLAs (Hosseini, et al., 2022). There are different mechanisms available to ensure optical network survivability during common failures. Regardless of how well optic-fibre cables are installed, certain incidents will always pose a risk to them, which is why they have been established as the most common cause of failure in optical networks. Fibre cuts are caused by vandalism, construction, natural disasters, and theft, to mention a few. Optical networks enable a wide range of communication services, including residential, enterprise, and mobile services (Liu, 2019). When an optical-fibre cable fails, lambdas provisioned on that route are affected, subsequently putting many vital services at risk. At that point, those wavelength lambdas must be restored in the shortest time possible to avoid service disruption on the upper layers.

Several attempts have been made to improve optical network survivability against single and multiple link or node failures, through protection and restoration (Agrawal, et al., 2017). Protection is a proactive strategy in which resources are pre-allocated to



C2 General

ensure connectivity in the event of a failure. Restoration is when the optical system searches for resources dynamically after the failure has occurred. Protection and restoration can be performed at both service and wavelength level, depending on the network design. DWDM network availability can be improved by deploying different combinations of the classification of survivability depicted in Figure 2.15.

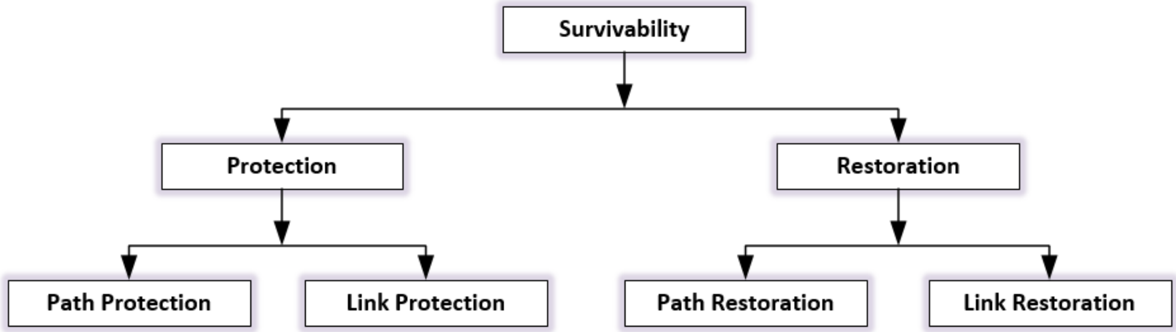


**Figure 2.15:** Classification of Survivability **(Krishnamurthy, et al., 2019)**

The protection system is selected based on traffic requirements, network topology, and economic considerations (Abduhuu & Purnawan, 2018). Restoration does not necessitate dedicated resources, but it also does not guarantee recovery (Stapleton, et al., 2018). It is up to network operators to decide on a trade-off between protection and restoration schemes based on what is required for their traffic needs. For this study, the researcher will focus on protection at the service level and restoration at a wavelength level. This combination is called protection restoration combined, PRC in short.

### 2.5.1. Protection

Optical communications provide enormous bandwidth at very high speed, making them an extremely appealing means of meeting the ever-increasing demand for broadband traffic. This is the traffic predominantly driven by internet access. Optical fibres are now the most common type of optical communication system, with capacities exceeding 1 *Tbit/s* because of DWDM technology (Elsayed, 2021). Given the large data volumes and the critical nature of the services transmitted on the DWDM network, it follows that such critical traffic needs to be protected. Protection is used to configure pre-assigned capacity to ensure survivability by setting aside spare capacity for a specific set of failure scenarios. When using the protection method, at the network



C2 General

design stage, resources are reserved for failure recovery, and these are kept inactive when there is no failure. The protection strategy can be used to protect against link failure, node failure, and network area failure (Ju, 2018). The focal point of the study is link failure protection. Table 2.7 outlines the different layers of protection available on OTN networks as specified by Recommendation ITU-T G.873.1. On the equipment side, power supply and card redundancy are important. On the optical layer, protection can be implemented at various stages of the DWDM network. The protection can be implemented on the optical route, wavelength/lambda, and service.

In a linear protection architecture, protection switching occurs at the two distinct endpoints of a protected trail. Between these two endpoints, there will be both working and protection entities (ITU-T, 2017). Electrical layer protection is deployed in the OTN; this type of protection is called ODUk SNCP Protection. SNC protection is a type of path protection that provides 1+1 protection for a specific subnetwork connection (www.vmware.com, 2022).

**Table 2.7:** DWDM Protection Types **(Khan, 2022)**

| DWDM Protection Types | |
|---|---|
| Equipment-Level Protection | Power Protection<br>Board/Card 1+1 Protection |
| Optical-Layer Protection | Optical-Line Protection<br>OTU Intra-Board 1+1 Protection<br>Client 1+1 Protection |
| Electrical-Layer Protection | ODUk SNCP Protection<br>SW SNCP Protection<br>Tributary SNCP Protection<br>ODUk SPRing Protection |

To protect ODUk services in an optical transport network, ODUk SNCP protection employs dual feeding and selective receiving functions. SNCP switching occurs when particular defects on the worker‘s transport entities within the protected domain are detected. There are three types of ODUk SNCP protection available, each with a different monitoring mode.

**SNC/I** – Inherent monitoring: the server layer’s fixed information is monitored to initiate client-layer protection switching.



C2 General

**SNC/N** – Non-intrusive monitoring: when only the listening function is used, service signals are not affected.
**SNC/S** – Sub-layer monitoring: TCM overheads are monitored to display signal quality.

For protected services, the recommended electrical switching time at the OTN layer is less than 50 *ms* (Tejas Networks, 2022). According to (Moura, 2019), protection switching time is typically sub 50 *ms*.

### 2.5.2. Restoration

Protection and restoration are the primary survival mechanisms in OTN networks. In restoration, the resources are allocated to each connection in a failure state, only after the failure occurs (Xavier, et al., 2020). Restoration does not require dedicated resources; it is dynamic. However, it does not guarantee recovery (Stapleton, 2018). Restoration can be done at either the electrical layer or the optical layers. In a DWDM system, the ROADM facilitates optical switching and, in OTN, the node matrix facilitates electrical restoration. Automatically Switched Optical Network (ASON) and Generalised Multi-Protocol Label Switching (GMPLS) standards are used for restoration.

**ASON** – is based on the ITU-T G.8081 standard (Abduhuu & Purnawan, 2018). ASON is a protection solution that can survive multiple faults by automatically restoring services on the alternative fibre route available to the DWDM node if the primary route fails. ASON facilitates both protection and restoration. The primary goal of the ASON control plane is to enable quick and efficient connection configuration within a transport layer network to support both switched and soft permanent connections in a high-capacity core optical network (Kaczmarek & Młynarczuk, 2021).

**GMPLS** – is a networking technology that enables fast and dependable traffic switching on any type of network infrastructure. GMPLS is particularly useful for fibre-optic networks. It is responsible for facilitating the separation of the control plane and the data plane, since it is concerned with the data interface rather than the data content. As a result, GMPLS is the default control method in the vast majority of wavelength-switched optical networks (Wright, 2021). The two standards can be combined to work as one in what is called ASON/GMPLS. The ASON approach



C2 General

utilising GMPLS protocols by control plane is named ASON/GMPLS (Kaczmarek & Młynarczuk, 2021). For this study, the focus is on optical restoration that occurs at the wavelength. As indicated, ROADMs are responsible for restoration on the optical layer.

A ROADM node has two main structures: the ROADM architecture, which is responsible for routing optical signals, and the add/drop stage, which is responsible for adding and dropping client signals into the optical network (Sequeira, et al., 2021). CDC-ROADM refers to ROADM with colourless, directionless, and contentionless functionalities. The CDC ROADM nodes can express, add, and drop any DWDM signal without regard for any wavelength constraints or contention. (Sequeira, et al., 2018). ROADM architectures for CDC DWDM nodes are of particular interest for next-generation optical networks because they enable access to any colour and any direction from any transponder within a network node. Colourless, directionless, and contentionless features were introduced as ROADMs evolved through time. While the three functionalities can be deployed separately, when combined, they provide the most flexibility to a DWDM node. As a result, network availability is improved. The risk of human error is reduced with CDC-ROADMs, due to fully automated provisioning (Kozdrowski, et al., 2019).

**Colourless** – allows the assignment of any wavelength channel to any port within the DWDM system. For any channel dropped at the local node, the corresponding add channel can go to any output port, regardless of which input port it comes from. Figure 2.16 depicts the colourless functionality, in which wavelength lambdas can be remotely distributed across any viable path (Kozdrowski & Sujecki, 2018). Operators should equip their networks with tuneable transponders to get the most out of C-ROADMs. It gives more flexibility to maintenance teams when doing the configurations to a remote node (Nance-Hall, 2020). Figure 2.16 captures a colourless ROADM that allows any wavelength channel to be dropped on any port. This is a significant advancement because it allows the same transponder to be configured to a different wavelength channel without the need for an engineer on-site to redo the cabling.



C2 General

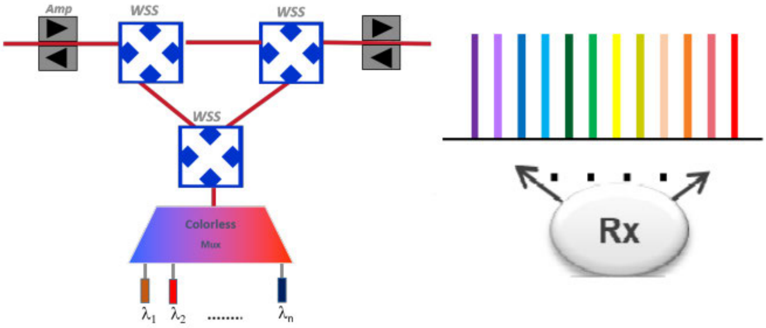


**Figure 2.16:** Colourless ROADM **(Kozdrowski, et al., 2019)**

**Directionless** – enables a DWDM system to reroute a wavelength across any degree available in the system in the event of a failure on the nominal route. This traffic flow occurs regardless of which add/drop block the lambda is connected to. Directionless functionality enables automatic reconfiguration of a lambda's direction after it has been added or dropped, increasing the flexibility of route design and implementation even further (Nishimoto, 2021). Figure 2.17 shows the directionless concept where λ1 is connected to the add/drop block on "Fibre Route 1" yet it can transit via "Fibre Route 2".

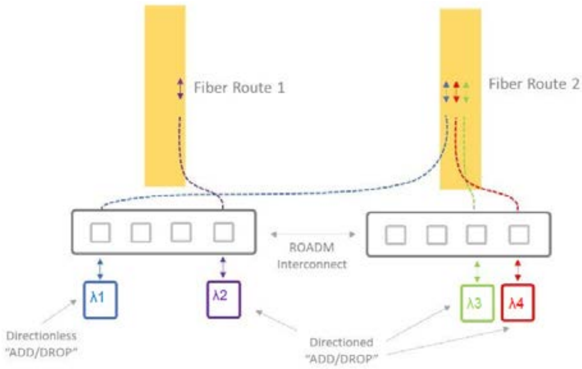


**Figure 2.17**: Directionless Add/Drop **(Nishimoto, 2021)**

**Contentionless** – On the add/drop architecture, the arrival of lambdas assigned to the same wavelength channel or colour causes wavelength contention, otherwise known as *wavelength blocking* (Kozdrowski, et al., 2019). The contentionless ROADM architecture eliminates wavelength blocking. This is a phenomenon where two or more wavelengths with the same frequency share the same add/drop. Figure 2.18 shows that three wavelengths λ1 (green colour) can be added or dropped at the same multiplexer/demultiplexer module. Furthermore, the contentionless functionality allows CDC ROADM to recolour the lambda's wavelength during restoration if it traverses a



C2 General

span with the same wavelength, which is an important advancement for DWDM Layer 0 lambda restoration.

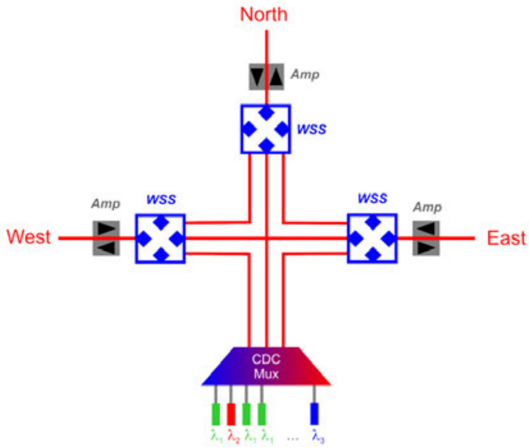


**Figure 2.18:** Contentionless Add/Drop **(Kozdrowski, et al., 2019)**

CDC-ROADMs increase overall availability and simplify network management routing algorithms. Currently, one of the primary motivators for MNOs to deploy GMPLS in their DWDM networks is failure survivability and very quick network restoration following a failure event. This significantly improves the quality of service (QoS) of optical networks from the perspective of network customers (Kozdrowski & Sujecki, 2018). While restoration is critical in improving DWDM optical network survivability, it should be noted that it does not guarantee service recovery. Restoration is initiated after the failure has occurred, and its success is dependent on the optical routes that are available at the time. The suggested approach for MNOs deploying DWDM optical networks is to include both protection and restoration functionality in their network, which is why the notion of PRC exists. Although the restoration strategy is less expensive than the protection strategy, the recovery time for restoration is longer (Xavier, et al., 2020). Both schemes are used concurrently in modern resilience-enabled OTN networks, even to provide survivability for the same client service.

### 2.5.3. Shared-Risk Link Group

Network providers must carefully evaluate the availability of their services and, if necessary, reserve protective resources and implement mechanisms for recovery to meet network availability demands (Vass, et al., 2018). A shared-risk link group (SRLG) is one such innovation; it is a mechanism where nominal and protection routes



C2 General

are configured to avoid any single point of failure. SRGL highlights the interaction between links that have a common vulnerability, such as a shared fibre cable, and have the potential to fail at the same time (Tapolcai, et al., 2020). When the SRGL routing restriction is satisfied, a single outage cannot disrupt both paths at the same time (Lu, et al., 2018).

### 2.6. Reducing OPEX cost in the DWDM Network

The survival of any business is contingent upon lowering the cost of doing business while raising the profit margin, mobile network operators are no exception. According to (SM-Optics, 2017), reducing OPEX costs is crucial to guaranteeing long-term business viability. Lowering OPEX expenses is one of the most significant difficulties that network operators face; it must be addressed to ensure consumer satisfaction and revenue generation (Imran, et al., 2017). One key consideration is the expense of fiber connectivity, whether self-built or leased. The optical fiber footprint continues to grow, but fiber lease fees have only dropped marginally; in general, the cost remains rather high. As a result, the existing fibre infrastructure must be used sensibly, with survivability mechanisms that can enable service restoration over different available fiber routes, reducing the need to acquire more fibre routes.

Power consumption is another variable that can be lowered, resulting in OPEX cost savings. According to (Iyer & Singh, 2017), a Flex-Grid network consumes less power than the conventional Fixed-Grid network, which requires more network resources. Flex-Grid transponders support high line rates and have high port density. A single transponder can have several line rates and modulation schemes. According to (www.packetlight.com, 2023), a high port density reduces OPEX by conserving space and power. Using fewer transponders is an excellent way to reduce power usage (Wu, et al., 2017). The variation in transponder numbers has a direct impact on overall power usage, as transponders contribute substantially to it (Kyriakopoulos, et al., 2019). A modern ROADM lowers OPEX through automated functionalities. The next-generation ROADM enables automated end-to-end provisioning and improves QoS. It allows flexible bandwidth allocation, eliminating technician visits to sites, and the associated human errors (Kozdrowski & Sujecki, 2018). According to (Kozdrowski, et al., 2019), touchless activation of network bandwidth and provisioning is a fundamental strategy for reducing OPEX..



C2 General

## 2.7. Similar Studies and Gaps

Previous research in the area of optical communication has identified DWDM as the most advanced transmission technology, with numerous advantages. Backbone networks using DWDM technology transport massive amounts of traffic; even a single fibre cut can result in significant traffic loss due to the disruption of several active services (Lu, et al., 2018). Much effort has been expended to improve optical network survivability in the event of single and multiple link or node failures through protection and restoration (Agrawal, et al., 2017). In the realm of optical networks, network survivability is crucial; moreover, self-healing mechanisms promote high network availability (Sairam & Singh, 2017).

Along with the importance of network availability, the studied literature indicated that bandwidth needs will continue to rise as more and more bandwidth-intensive services are produced regularly. The literature further indicated that Flex-Grid technology uplink line rates can reach 1 *Tbit/s* and beyond, making it an ideal solution for handling large bandwidth demands. A study in this area conducted by (Stapleton, 2018) investigated protection and restoration schemes in elastic optical networks. This study concluded that Flex-Grid technology has superior spectral efficiency compared to the conventional Fixed-Grid. This is a key finding considering that the spectrum is a finite resource. As a result, Fixed-Grid wavelength switched optical networks are gradually giving way to Flex-Grid elastic optical networks (Iyer & Singh, 2017).

While there is much information available about a DWDM ROADM, there is a gap in the technical details of how a CDC-ROADM improves lambda restoration and survivability in DWDM optical networks. Furthermore, Flex-Grid technology is discussed in the literature; nevertheless, the major comparison with Fixed-Grid is usually spectral efficiency, leaving out other extremely important comparative aspects such as power consumption and transponder versatility. This study seeks to provide an in-depth technical understanding of the highlighted gaps, as well as demonstrate how the CDC ROADM and Flex-Grid technology can contribute to OPEX reduction when deployed together.



C2 General

## 2.8. Chapter 2 Summary

The literature review provided a thorough understanding of optical networks in general and DWDM optical networks in particular. According to the literature, optic fibre was the best transmission medium in the telecommunications industry to date. DWDM technology was the most advanced data-transmission technology due to its capacity for transmitting huge amounts of data on a single wavelength using a single fibre. Furthermore, DWDM technology can cover short and long distances as it can be amplified along the route. There was a clear consensus among the authors reviewed that the amount of data carried by MNOs through their DWDM optical networks has increased significantly over the years. The surge in data traffic was due to technological advancement, which resulted in a variety of bandwidth-hungry applications used for entertainment, education, and business. This chapter also looked at the deployment of a single carrier using Flex-Grid technology as opposed to the several carriers required in Fixed-Grid when transmitting capacity demands exceeded 100 *Gbit/s*. Flex-Grid technology was highlighted as a solution to this bandwidth demand because it supports uplinks of more than 100 *Gbit/s*. Depending on the DWDM system used, the line rates can go as high as 1 *Tbit/s* per wavelength and beyond. The most significant discovery in this regard is that Fixed-Grid and Flex-Grid technologies can coexist in the same DWDM optical network, allowing for gradual migration. Another key topic discussed was the evolution of DWDM optical OADM from FOADM to ROADM and, more recently, CDC-ROADM. The ability to support wavelength lambda restoration via CDC ROADM was highlighted as the evolution's biggest win, as it contributed to DWDM optical network availability. This chapter also discussed various initiatives used to reduce OPEX costs in DWDM optical networks.



C2 General

# CHAPTER 3: RESEARCH METHODOLOGY

## 3.1. Introduction

This chapter describes the research methodology employed in the study, as well as the rationale behind it. Research methodology refers to the various types of activities used to systematically address the research topic, based on assumptions and the logic of the decisions taken (Wohlin & Runeson, 2021). The Research Methodology section also describes how data was obtained as well as the methodologies utilised to analyse it to address all the research questions raised by the study.

## 3.2. Research Approach

The telecommunications sector is a highly contested terrain, making primary data particularly difficult to access due to non-disclosure agreements and confidentiality. As a result, the study used a pragmatic mixed method that combined quantitative and qualitative research methods. In this regard, Figure 3.1 illustrates the strategy of conducting this study. The research delved into the existing literature on strategies for enhancing network and bandwidth availability in DWDW optical networks and then used simulation to confirm or refute the concepts emanating from the literature.

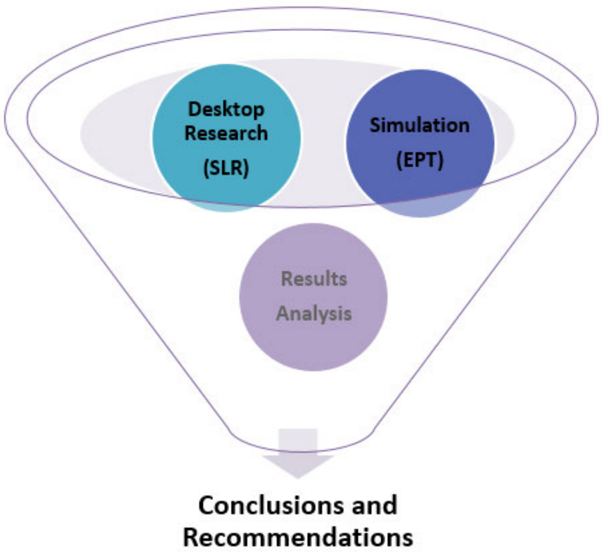


**Figure 3.1:** Framework for the Research Approach



C2 General

A desk research strategy was used for the qualitative aspect, where secondary data on DWDM optical networks was reviewed. The EPT simulation was used for the quantitative research component. Quantitative research focuses on quantity or extent, and it entails systematic experimental analyses of measurable events using statistical or mathematical processes in numerical form, such as statistics, percentages, and so on (Mishra & Alok, 2017).

### 3.3. Desk Research

Desk research involves inspecting, reviewing, and processing previously published material from official sources (Turon & Kubik, 2021). This technique is less expensive in terms of both money and time because secondary data can be gathered in a relatively short period. Researchers should be aware, however, that the results of a desk-research strategy may be skewed due to the number and quality of sources reviewed warns (Hofman & Sutherland, 2018). To counteract the effect of bias, this study examined literature from 102 different publications. The research questions described in Section 1.4 were developed in response to the study's objective. In addressing research questions, a thorough literature review was undertaken in which DWDM optical networks have been studied from their inception to their most recent advancement. Figure 3.2 outlines the different phases involved in doing desk research, from identifying the topic to research, including data collecting and analysis.

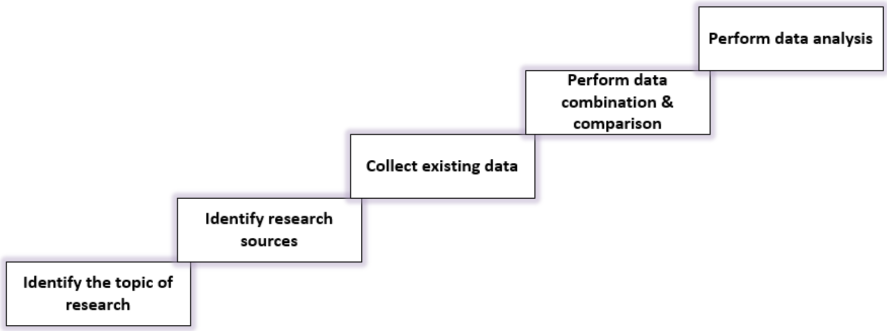


**Figure 3.2:** Desk Research Strategy Process **(Turon & Kubik, 2021)**

The systematic literature review (SLR) approach was used to conduct a thorough search of the literature on DWDM optical networks. The SLR approach gives a clear direction for finding and assessing relevant material. SLR includes identifying data sources for the search, keywords for the search, and inclusion criteria (Daniyan, et al., 2021).



C2 General

### 3.3.1. Data Collection

Secondary data for this desk research was gathered from several academic research databases, the internet, and data sheets from different DWDM vendors. Google Scholar, Springer, ResearchGate, Open Access Journals, the Institute of Electrical and Electronics Engineers (IEEE), and Science Direct are among the academic research databases used. The selection process for the material began with a review of the abstract to establish the relevance of the article to the research objectives. If the article was deemed relevant, it was added to the list of papers to be thoroughly reviewed for this study. DWDM vendors researched were Huawei, Nokia, Ciena, Infinera, and ADVA. These vendors are the major industry players in Europe, the Middle East, and Africa regions (Yu, 2021).

### 3.3.2. Keyword Search

The keyword search method is used to ensure that only relevant literature is collected and considered in this research (Daniyan, et al., 2021). Keywords used for this study include DWDM, OTN, bandwidth, restoration, network survivability, network availability, Flex-Grid, and CDC-F ROADM. The Boolean operators AND and OR were employed to govern the search.

### 3.3.3. Inclusion Criteria

- All publications had to be written in English.
- The publication period ranged between 2017 and 2023.
- Publication’s relevance to the subject matter.
- Publication’s availability to fellow academics.

Figure 3.3 shows the number of publications reviewed in years. The research included 102 full-text articles published between 2017 and 2023. Most of the publications examined were published between 2019 and 2023, indicating that the research is mostly based on recently published material.



C2 General

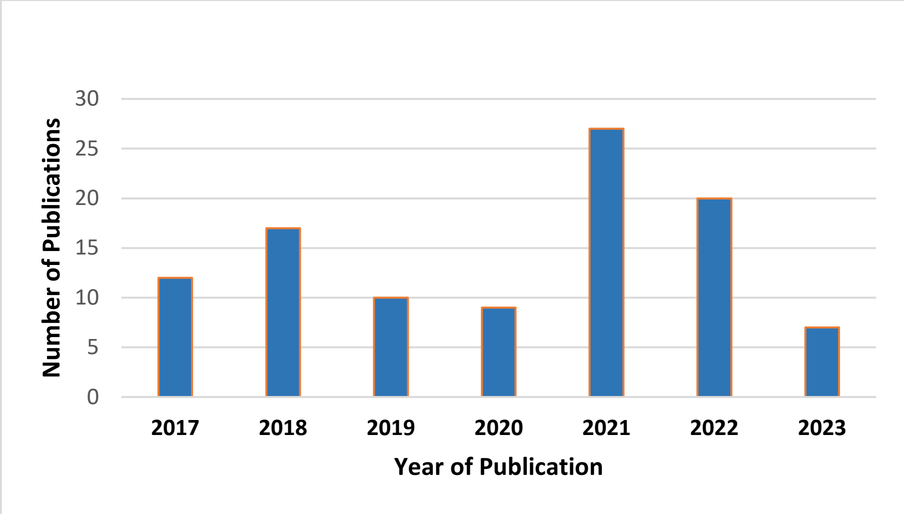


**Figure 3.3:** Articles Reviewed and Years of Publication

## 3.4. Simulation

The simulation aspect of the research was conducted using the 1830 Engineering and Planning Tool (Release: EPT-22.12.0). In this study, the tool was simply referred to as EPT for convenience.

### 3.4.1. Simulation Tool

The EPT is a Nokia proprietary tool. Nokia is one of the leading DWDM vendors in Europe, the Middle East, and Africa region, which gives credibility to its equipment and tools (Yu, 2021). The EPT was appropriate for this study since it supports the CDC-F ROADM profile, as shown in Figure 3.4. Because the EPT supports CDC DWDM features, it was suitable for demonstrating the effectiveness (or lack thereof) of these functionalities in terms of network survivability. The EPT also supports both Fixed and Flex-Grid deployment, which is useful for doing comparative analysis. Although the EPT supports spectrum bands C, L, and C+L, only the C-band was considered for this study.

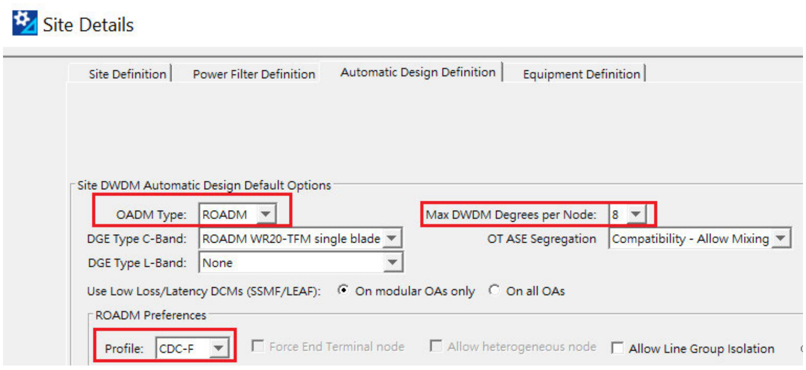


**Figure 3.4:** CDC-F ROADM Profile Supported by EPT



C2 General

### 3.4.2. Simulation Setup

The goal was to design and simulate a network that was similar to a real-world DWDM optical network with multiple spans to ensure a variety of restoration routes in the event of a route failure. The simulated network had to be mashed with varying fibre lengths and span losses connecting DWDM nodes. Figure 3.5 shows the simulated DWDM optical network designed for this research.

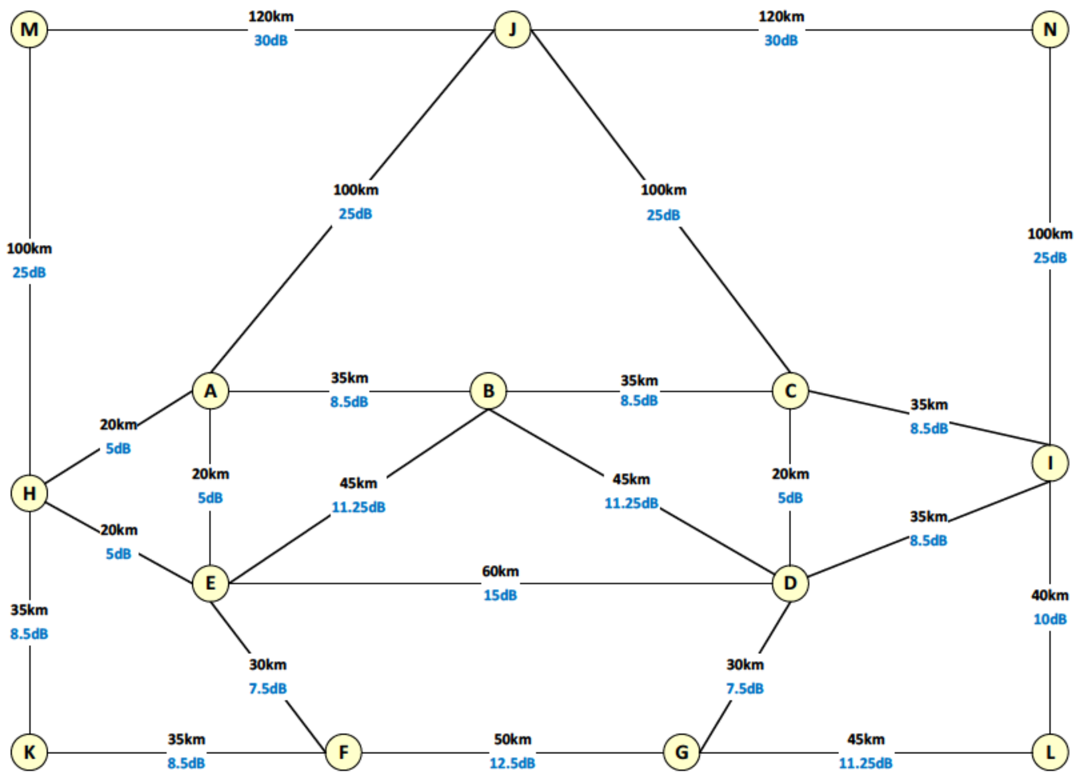


**Figure 3.5:** Simulated DWDM Optical Network

The span loss was estimated to be 0.25 *dB* per kilometre, which is the industry standard. According to (Laferrière, et al., 2018), fibre loss (dB/km) at 1550 *nm* is 0.25 in the metro, 0.22 in medium haul and 0.19 in long haul. Table 3.1 summarises the simulated network information, including the node count, span count, and number of degrees per node.



C2 General

**Table 3.1:** Simulated DWDM Optical Network Information

| Simulated Network Information | |
|---|---|
| DWDM Nodes | 14 |
| Spans/Segments | 24 |
| Span Loss per/km | 0.25 dB |
| 5 Degree Nodes | D and E |
| 4 Degree Nodes | A, B, C, H, I, and J |
| 3 Degree Nodes | F and G |
| 2 Degree Nodes | K, L, M, and N |

The optical distances and span losses shown are only for the purposes of this study. The OTN part is done by the PSS24x shelf, which holds transponders and various client modules. An 1830 PSS-32 shelf shown in Figure 3.6 was used for the simulated DWDM nodes. The shelf houses EDFAs, transponders, muxponders, and MCS modules.

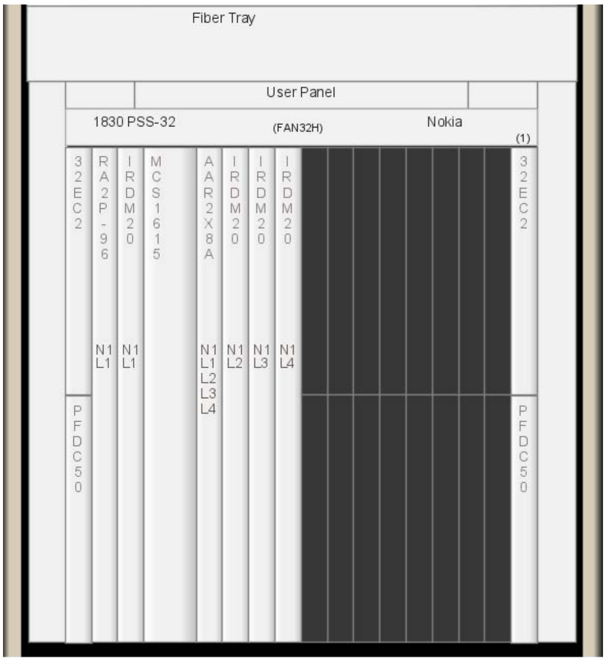


**Figure 3.6:** 1830 PSS32 Shelf

### 3.4.3. Simulation Tests

Different test scenarios were simulated using EPT, in accordance with the study objectives. This chapter details the parameters for each test case. The topics addressed were bandwidth enhancement, spectral efficiency, lambda reach, CDC functionalities, and OPEX Saving. Chapter 4 has a detailed discussion of the findings.



C2 General

#### 3.4.3.1 Bandwidth Enhancement and Spectral Efficiency Setup

In line with the first and third objectives outlined in section 1.3, bandwidth enhancement and spectral efficiency comparison between Fixed-Grid and Flex-Grid was simulated. Uplinks with capacities of 100/200/400 *Gbit/s* were compared for both grid types. A transponder used for the Fixed-Grid was 130SCUPH, the specifications of this module are detailed in Annexure 8. The Flex-Grid transponders were 4UC400, 4UC1T, and 2UC1T, the datasheets outlining the specifications of these modules are Annexure 4, Annexure 1, and Annexure 2 respectively. It should be noted that the highest line rate for a Fixed-Grid transponder is 100 *Gbit/s with 50 GHz* spectrum consumption, as detailed in section 2.4.1 of this study. To ensure a fair comparison, all lambdas are configured over the same fibre route, with the same fibre length and span loss. Table 3.2 details the setup for the 100 *Gbit/s* comparison where all the parameters for each grid type are indicated.

**Table 3. 2:** Simulated 100 Gbit/s Capacity, Fixed-Grid vs Flex-Grid

| **Lambda Parameters** | **Fixed-Grid** | **Flex-Grid** |
|---|---|---|
| Transponder Type | 130SCUPH | 4UC400 |
| Number of Transponders Required | 2 | 2 |
| Number of Uplink Ports per Transponder | 1 | 4 |
| Line Rate (*Gbit/s*) | 100 | 100 |
| Modulation Scheme | QPSK | QPSK |
| Wavelength (*nm*) | 9440 | 9448.75 |
| Total Route Length (*km*) | 45 | 45 |
| Total Span Loss (*dB*) | 11.25 | 11.25 |
| Route | B-E | B-E |

Table 3.3 shows the parameters for the 200 *Gbit/s* capacity simulation. As indicated, the maximum uplink line rate on the Fixed-Grid is 100 *Gbit/s*. Hence, two 100 *Gbit/s* lambdas were simulated using the Fixed-Grid transponder, with a total of 4x SCUPH transponders. A Flex-Grid 200 *Gbit/s* lambda was simulated using 2x 4UC1T transponders.



C2 General

**Table 3. 3:** Simulated 200 Gbit/s Capacity, Fixed-Grid vs Flex-Grid

| **Lambda Parameters** | **Fixed-Grid** | **Flex-Grid** |
|---|---|---|
| Transponder Type | 130SCUPH | 4UC1T |
| Number of Transponders Required | 4 | 2 |
| Number of Uplink Ports per Transponder | 1 | 4 |
| Line Rate (*Gbit/s*) | 100 | 200 |
| Modulation Scheme | QPSK | QPSK |
| Wavelength (*nm*) | 9450 & 9458.750 | 9464.38 |
| Total Route Length (*km*) | 45 | 45 |
| Total Span Loss (*dB*) | 11.25 | 11.25 |
| Route | B-D | B-D |

Parameters for the 400 *Gbit/s* capacity simulation are shown in Table 3.5. 4x 100 *Gbit/s* Fixed-Grid lambdas were simulated using 8x SCUPH transponders. A Flex-Grid 400 *Gbit/s* lambda was simulated using 2x 2UC1T transponders.

**Table 3. 4:** Simulated 400 Gbit/s Capacity, Fixed-Grid vs Flex-Grid

| **Lambda Parameters** | **Fixed-Grid** | **Flex-Grid** |
|---|---|---|
| Transponder Type | 130SCUPH | 4UC1T |
| Number of Transponders Required | 8 | 2 |
| Number of Uplink Ports per Transponder | 1 | 4 |
| Line Rate (Gbit/s) | 100 | 400 |
| Modulation Scheme | QPSK | 16QAM |
| Wavelength (nm) | 9400, 9405.625, 9411.250 & 9416.875 | 9432.5 |
| Total Route Length (km) | 35 | 35 |
| Total Span Loss (dB) | 8.5 | 8.5 |
| Route | A-B | A-B |

#### 3.4.3.2 Test Setup for Lambda Reach Simulation

The effect of modulation scheme type on the OSNR was compared. Three 200 Gbit/s lambdas that had different modulation schemes (QPSK, 8QAM, and 16QAM) were simulated. All the lambdas traversed the same spans (M-J and J-N) and were simulated using a 4UC1T transponder. Table 3.5 shows three simulated 200 *Gbit/s* lambdas with different modulation schemes, namely, QPSK, 8QAM, and 16QAM. All three lambdas traversed the same spans, M-J and J-N; these were two of the longest spans in the simulated network, totalling 240 *km* and a 60 *dB* accumulated span loss.



C2 General

**Table 3. 5:** OSNR Report for the 3x 200 Gbit/s Lambdas Simulated at Different Modulation Schemes

**C-Band Trail Routing Report**

**Network: MP_Mkhwanazi**

| Trail | Channel Line Rate | Feasibility: Required OSNR (dB) | Feasibility: Delivered OSNR (dB) | Feasibility: OSNR Margin (dB) | OT/OPS Type | OT/OPS Mode |
|---|---|---|---|---|---|---|
| M-J-N_9400_4UC1T_200Gbit/s_QPSK | 200G | 15.83 | 22.52 | 6.69 | 4UC1T-compatible | 2. 200G@62Gbaud - QPSK |
| OTSi | | 15.83 | 22.52 | 6.69 | 4UC1T-compatible | 2. 200G@62Gbaud - QPSK |
| SDFEC-G2 | | | | | | |
| Bidir PT-PT | | | | | | |
| M-J-N_9410_4UC1T_200Gbit/s_8QAM | 200G | 18.61 | 22.13 | 3.52 | 4UC1T-compatible | 20. 200G@45Gbaud - 8QAM |
| OTSi | | 18.61 | 22.13 | 3.52 | 4UC1T-compatible | 20. 200G@45Gbaud - 8QAM |
| SDFEC-G2 | | | | | | |
| Bidir PT-PT | | | | | | |
| M-J-N_9420_4UC1T_200Gbit/s_16QAM | 200G | 20.94 | 21.61 | 0.67 | 4UC1T-compatible | 12. 200G@33Gbaud - 16QAM |
| OTSi | | 20.94 | 21.61 | 0.67 | 4UC1T-compatible | 12. 200G@33Gbaud - 16QAM |
| SDFEC-G2 | | | | | | |
| Bidir PT-PT | | | | | | |

### 3.4.3.3 Test Setup for CDC Simulation

CDC DWDM functions play a critical part in lambda restoration, thereby enhancing network survivability. This test simulated various failure scenarios that caused lambdas to restore via alternative fibre routes and DWDM nodes in line with the second and fourth objectives outlined in section 1.3 of the study. Tables 3.6 and 3.7 provide the lambda parameters for the nominal route: *E-D_9360_2UC1T_200Gbit/s* and the protection route: *E-B-D_9370_2UC1T_200Gbit/s* that were used.

**Table 3. 6:** E-D_9360_2UC1T_200Gbit/s

| **Lambda Parameters** | |
|---|---|
| Transponder Type | 2UC1T |
| Line Rate (*Gbit/s*) | 200 |
| Modulation Scheme | QPSK |
| Wavelength (*nm*) | 9360 |
| Total Route Length (*km*) | 60 |
| Total Span Loss (*dB*) | 15 |
| Route | E-D |



C2 General

**Table 3. 7:** E-B-D_9370_2UC1T_200Gbit/s

| Lambda Parameters | |
|---|---|
| Transponder Type | 2UC1T |
| Line Rate (*Gbit/s*) | 200 |
| Modulation Scheme | QPSK |
| Wavelength (*nm*) | 9370 |
| Total Route Length (*km*) | 90 |
| Total Span Loss (*dB*) | 22.5 |
| Route | E-B-D |

The OSNR degradation analysis was performed on a 200 *Gbit/s* lambda, as it rerouted through spans with different accumulative distances and span losses. The EPT allows for the simulation of multiple failure conditions. The failure conditions can be simulated as SR failure, fibre break, node isolation, or a combination. The maximum number of concurrent failure conditions was five, resulting in a variety of possible failure scenarios. Table 3.8 shows the parameters of lambda *F-G_9440_4UC1T_200Gbit/s_8QAM* routed across a single span.

**Table 3. 8:** F-G_9440_4UC1T_200 Gbit/s_8QAM

| Lambda Parameters | |
|---|---|
| Transponder Type | 4UC1T |
| Line Rate (*Gbit/s*) | 200 |
| Modulation Scheme | 8QAM |
| Wavelength (*nm*) | 9440 |
| Total Route Length (*km*) | 50 |
| Total Span Loss (*dB*) | 12.5 |
| Route | F-G |

#### 3.4.3.4 Considerations for OPEX Cost Saving

This study explored ways to reduce OPEX costs for the simulated network in Figure 3.5, which is crucial for business profitability. This is consistent with the fifth objection in section 1.3 of the research. Reducing OPEX costs is essential for long-term business viability. The study examined OPEX savings mechanisms using datasheets from renowned DWDM vendors and South Africa's leading fibre supplier, Dark Fibre Africa. The advantages of using CDC ROADM with automatic provisioning were also examined.



C2 General

### 3.5. Chapter 3 Summary

This chapter described the methodology used in the study. The research adopted a hybrid approach that combined desk research with simulation. Using the SLR approach, the desk research accounted for the qualitative research aspect of the study. The EPT simulation addressed the quantitative research component. A DWDM optical network with 14 nodes and 24 spans was simulated. This chapter also discussed key variables that govern the simulation, such as the fibre length, span loss, DWDM nodes, and transponders used. The different tests undertaken were outlined, including the comparison of Fixed-Grid and Flex-Grid spectral efficiency, various modulation schemes and a variety of failure scenarios to interrogate the features of a CDC ROADM.



C2 General

# CHAPTER 4: RESULTS AND DISCUSSION

## 4.1. Introduction

Previous chapters detailed the chosen research topic, highlighting its significance and relevance. The literature on DWDM optical networks was thoroughly reviewed, and the methodology adopted to approach this research was also documented. This chapter details the findings, as well as the relevant discussion points, of this research. This chapter analyses and compares the literature and the results of the EPT simulation as they relate to bandwidth and network-availability enhancement.

## 4.2. Bandwidth Enhancement and Spectral Efficiency Comparison

This section compared a DWDM Fixed-Grid deployment with Fixed-Grid technology using EPT simulation. Single-wavelength lambdas were simulated at 100 *Gbit/s*, 200 *Gbit/s*, and 400 *Gbit/s* line rates.

### 4.2.1. 100 *Gbit/s* Capacity Comparison

Table 3.2 outlined the parameters for the 100 *Gbit/s* lambdas simulated. Because the simulated network used Flex-Grid technology, the channel spacing was 6.25 *GHz*, which is significantly more efficient than the fixed-grid spectrum's spacing of 50 *GHz*. Figure 4.1 shows the channel utilisation view retrieved from span B-E, where the two lambdas were simulated. *B-E_9440_130SCUPH_100Gbit/s* is the Fixed-Grid lambda and *B-E_9448.750_4UC400_100Gbit/s* is the Flex-Grid lambda. Figure 4.1 also shows the number of 6.25 *GHz* channel spacings used at the base of each lambda, as well as the wavelength channel selected. Both 100 *Gbit/s* lambdas consumed 8× 6.25 *GHz* spacing, resulting in a total spectrum utilisation of 50 *GHz* for both.

While there was no difference in spectrum consumption for both 100 *Gbit/s* lambdas, an important observation was made. The Flex-Grid transponder (4UC400) had a better port density, with four 100 *Gbit/s* uplink ports compared to the SCUPH, which only had one. This aspect was discussed in detail in sections 4.4.2 and 4.4.3.



C2 General

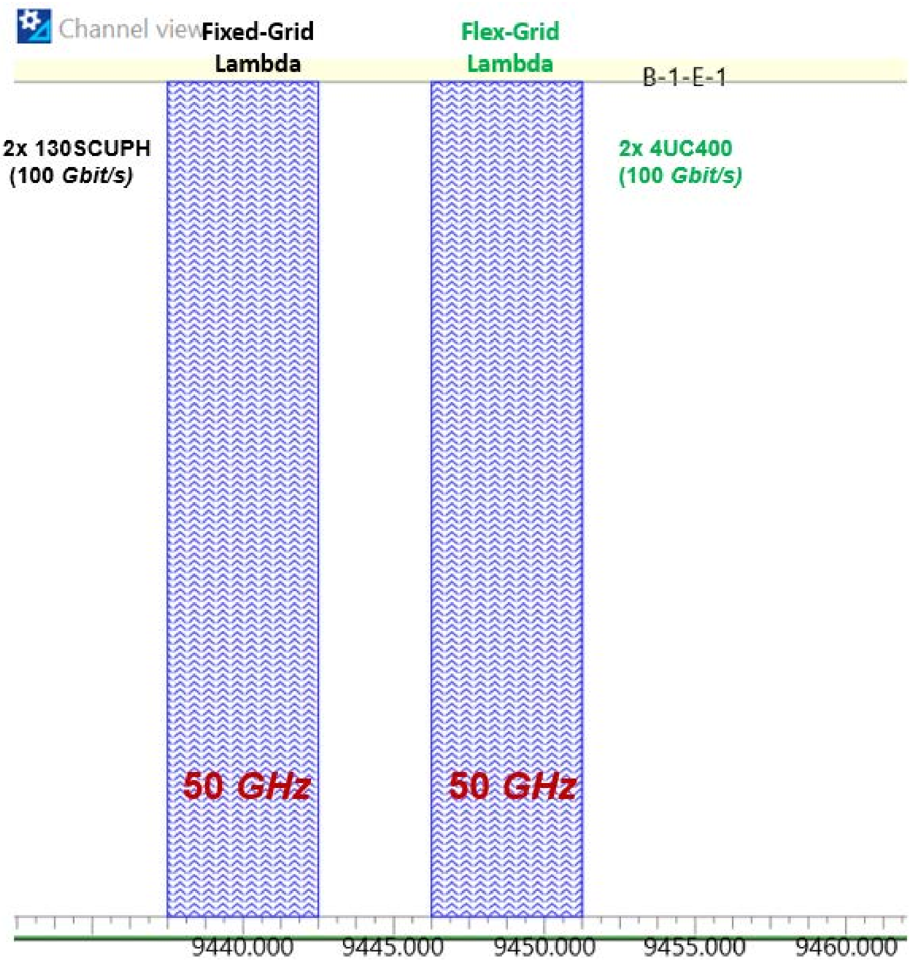


**Figure 4.1:** Simulated 100 *Gbit/s* Capacity, Fixed-Grid vs Flex-Grid

### 4.2.2. 200 *Gbit/s* Capacity Comparison

Table 3.3 showed the parameters for the 200 *Gbit/s* capacity simulation. *B-D_9450_130SCUPH_100Gbit/s_1* and B-*D_9458.750_130SCUPH_100Gbit/s_2* were the lambdas that made up the 200 *Gbit/s* Fixed-Grid capacity (2× 100 *Gbit/s*). *B-D_ 9472.500_4UC1T_200Gbit/s* was the Flex-Grid lambda. Figure 4.2 shows the channel utilisation view retrieved from span B-D, where 200 *Gbit/s* capacity was simulated. Since the Fixed-Grid required two 100 *Gbit/s* lambdas to account for 200 *Gbit/s* capacity, the total spectrum utilisation is 100 *GHz* (each lambda consumed 50 *GHz* of the spectrum resources). The Flex-Grid 200 *Gbit/s* lambda used 12× 6.25 *GHz* spacing, for a total spectrum usage of 75 *GHz*.

Some important observations were made for this 200 *Gbit/s* capacity deployment as well. Since the Fixed-Grid simulation required two 100 *Gbit/s* lambdas for the 200 *Gbit/s* capacity requirement, two wavelengths were used, as opposed to just one used



C2 General

in the Flex-Grid 200 *Gbit/s* lambda. Furthermore, the Fixed-Grid deployment required four SCUPH transponders, while the Flex-Grid 200 *Gbit/s* lambda only needed two 4UC1T transponders. A 2UC400 transponder can also be used for 200G Fixed-Grid deployment, Annexure 3 provides the specifications for this module.

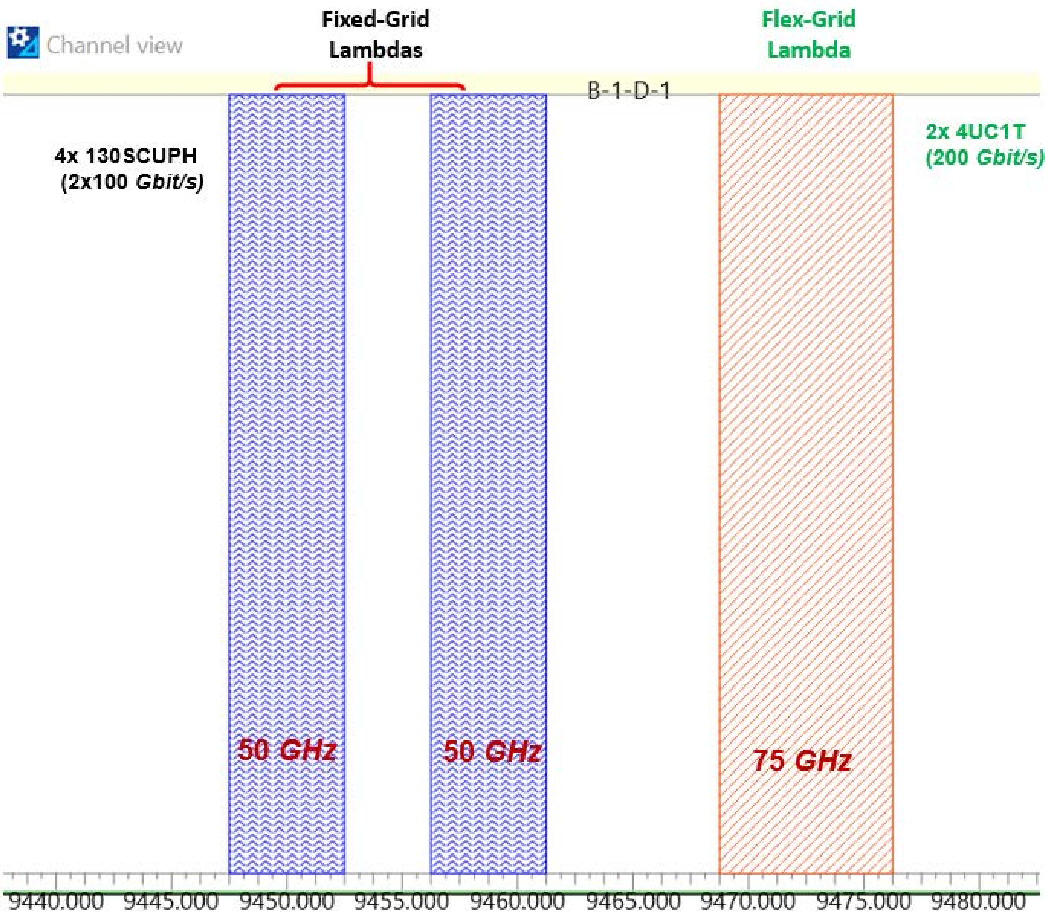


**Figure 4.2:** Simulated 200 *Gbit/s* Capacity, Fixed-Grid vs Flex-Grid

### 4.2.3. 400 *Gbit/s* Capacity Comparison

Parameters for the 400 *Gbit/s* capacity simulation were shown in Table 3.4. *A-B_9400_130SCUPH_100Gbit/s_1, A-B_9405.625_130SCUPH_100Gbit/s_2*, *A-B_9411.250_130SCUPH_100Gbit/s_3*, and *A-B_9416.875_130SCUPH_100Gbit/s_4* were simulated for the Fixed-Grid deployment. For the Fixed-Grid deployment, *A-B_9432.500_4UC1T_400Gbit/s* was simulated. The channel utilisation view retrieved from span A-B is shown in Figure 4.3. The total spectrum used on the Fixed-Grid was 200 *GHz*, with each of the four lambdas consuming 50 *GHz*. The Flex-Grid 400 *Gbit/s* lambda used 14x 6.25 *GHz* spacing, for a total spectrum usage of 87.5 *GHz*.



C2 General

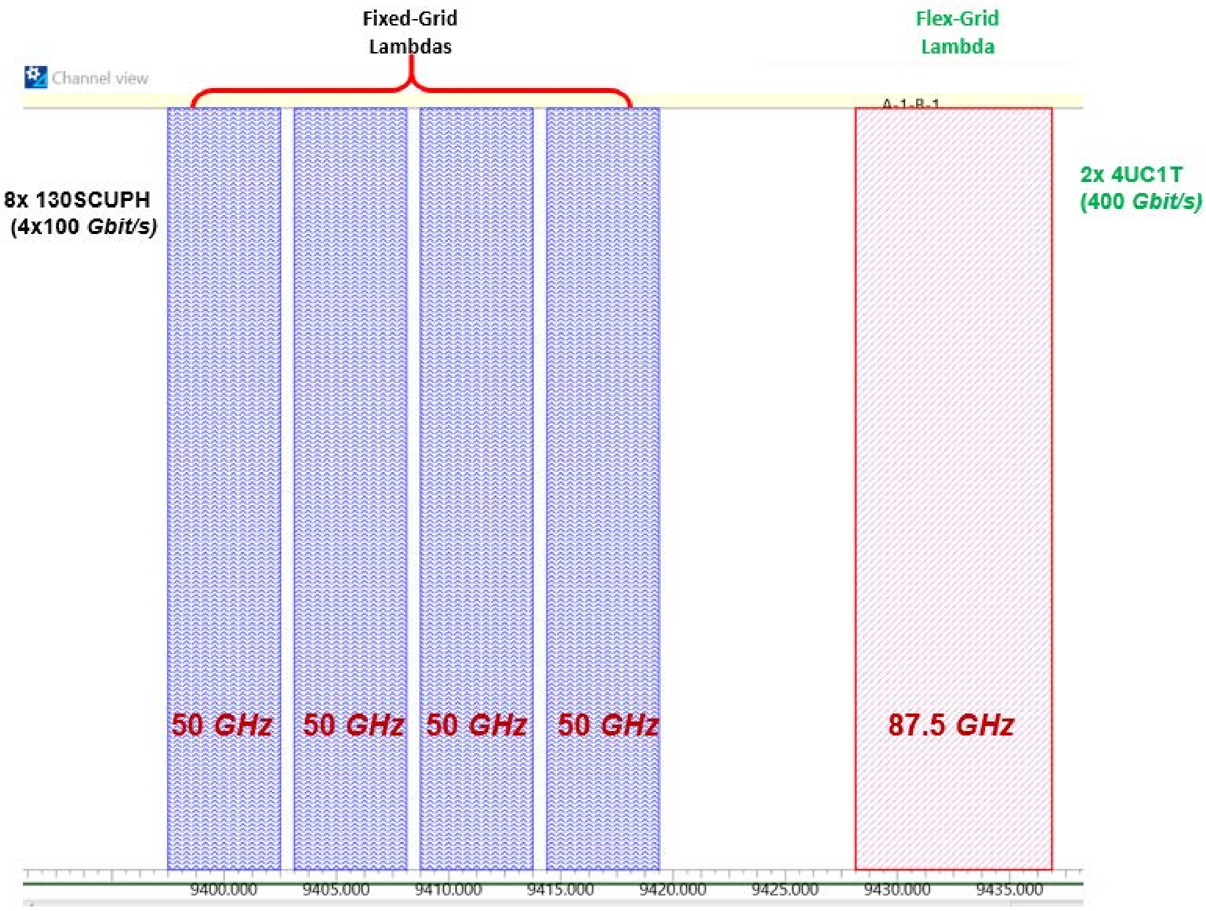


**Figure 4.3:** Simulated 400 *Gbit/s* Capacity, Fixed-Grid vs Flex-Grid

Figure 4.4 compares the spectral efficiency of Flex and Fixed-Grid for 100/200/400 *Gbit/s* capacities. Flex-Grid technology offered no advantage in terms of spectral efficiency at 100 *Gbit/s*. Both grid types required 50 *GHz* of spectrum. For the 200 *Gbit/s* deployment, Fixed-Grid utilised two 100 *Gbit/s* lambdas at 50 *GHz* spacing each, resulting in a total spectral consumption of 100 *GHz*. When compared to the Fixed-Grid deployment, the Flex-Grid 200 *Gbit/s* lambda used 75 *GHz* of the spectrum, saving 25% of the spectrum resources. The Flex-Grid lambda required 87.5 *GHz* of the spectrum for 400 *Gbit/s* capacity, significantly less than the 200 *GHz* consumed by the four 100 *Gbit/s* lambdas for the Fixed-Grid. The Flex-Grid 400 *Gbit/s* lambda consumed only 44% of the spectrum resources consumed by the Fixed-Grid deployment.



C2 General

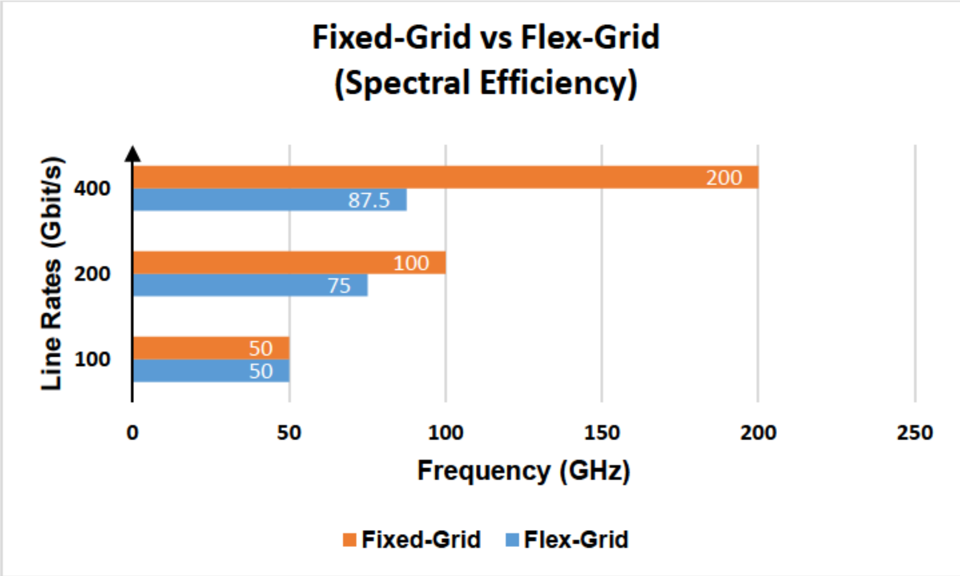


**Figure 4.4:** Fixed-Grid vs Flex-Grid Spectrum Utilisation

Figure 4.4 shows all three capacity comparisons performed on both types of grids in one plane. Flex-Grid technology was more spectrally efficient compared to Fixed-Grid. According to (Stapleton, 2018), Flex-Grid technology outperforms Fixed-Grid implementation in terms of spectrum efficiency, which is in line with the findings in Figure 4.4. (Zhu, et al., 2019) attributes Flex-Grid technology's spectral efficiency to the allocation of optical spectrum at finer granularities of a few gigahertz, such as 6.25 *GHz*, enabling flexible spectrum management.

### 4.2.4. Reach on Flex-Grid Technology

This section analysed how the transponder type, modulation technique, and OSNR affected the reach. Table 3.5 shows three simulated 200 *Gbit/s* lambdas below:

- *M-J-N_9400_4UC1T_200Gbit/s_QPSK*
- *M-J-N_9410_4UC1T_200Gbit/s_8QAM*
- *M-J-N_9420_4UC1T_200Gbit/s_16QAM*

*M-J-N_9400_4UC1T_200Gbit/s_QPSK* – this lambda had the required OSNR of 15.83 *dB*, and a delivered OSNR value of 22.52 *dB*, resulting in an OSNR margin of 6.66 *dB*. Figure 4.5 shows a lambda route map, across a 240 *km* distance with a span loss of 60 *dB*; the lambda had 21% OSNR degradation, leaving 79% in reserve. The lower the percentage of the OSNR degradation on the lambda, the better the lambda performance. The OSNR degradation percentage is inversely proportional to the



C2 General

OSNR margin. Furthermore, the OSNR degradation percentage shows the lambda's ability to be restored in the event of a failure; the lower this percentage, the higher the lambda's chances of restoration. When the OSNR degradation percentage approaches 100, the lambda is unlikely to be restored because there is less OSNR margin left.

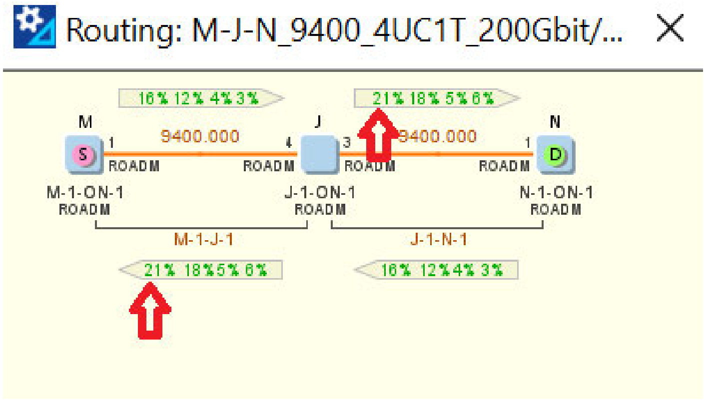


**Figure 4.5:** M-J-N_9400_4UC1T_200Gbit/s_QPSK Lambda Route Map

*M-J-N_9410_4UC1T_200Gbit/s_8QAM* – this lambda had a required OSNR of 18.61 *dB* and a delivered OSNR of 22.13 *dB*, yielding a 3.52 *dB* OSNR margin. Figure 4.6 shows a lambda route map with 44% OSNR degradation, allowing a 56% buffer. At this point, it is clear that a change in modulation has promoted the need for a bigger "required OSNR", as well as the consumption of more OSNR margin. This meant that, although using the same transponder type and covering the same distance, this lambda could travel less distance than the lambda M-J-N_9400_4UC1T_200Gbit/s_QPSK.

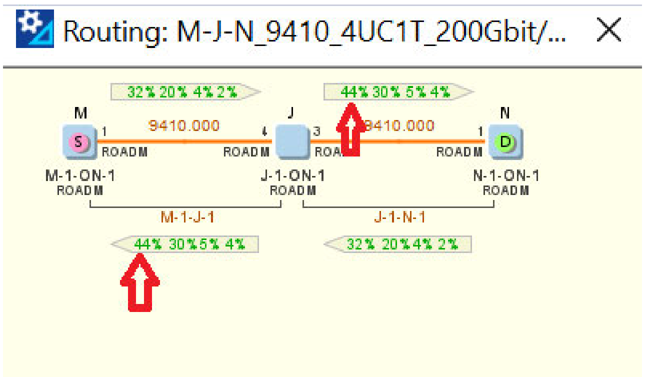


**Figure 4.6:** M-J-N_9410_4UC1T_200Gbit/s_8QAM Lambda Route Map



C2 General

*M-J-N_9420_4UC1T_200Gbit/s_16QAM* **–** had a required OSNR of 20.94 *dB* and a delivered OSNR of 21.61 *dB*, yielding a 0.67 *dB* OSNR margin. Figure 4.7 shows a lambda route map at 86% of the OSNR degradation, leaving only 14% in reserve. In comparison to QPSK and 8QAM, 16QAM was the most advanced modulation scheme. When the modulation technique changed to 16QAM over the same distance and transponder as the other two lambdas, the OSNR margin approached zero (0.67 *dB*). If the OSNR margin is equal to or lower than zero, that lambda is considered unusable. When the OSNR degradation approaches 100%, the lambda will require a 3R point. The phrase *3R* refers to the process of re-amplifying, reshaping, and retiming a signal in DWDM optical networks (Papageorgiou, 2018).

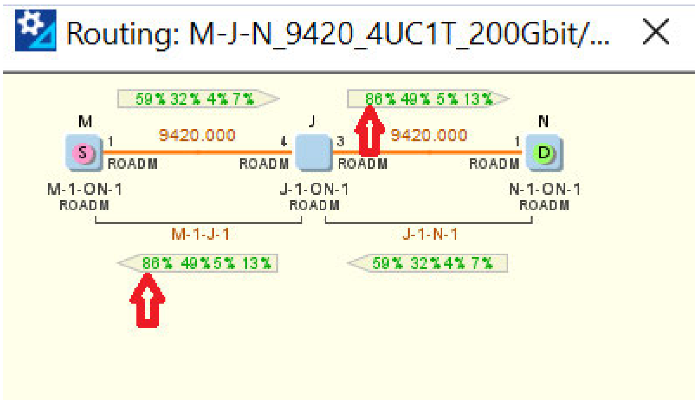


**Figure 4.7:** M-J-N_9420_4UC1T_200Gbit/s_16QAM Lambda Route Map

Figure 4.8 shows the OSNR measurements for the three 200 *Gbit/s* lambdas, with a focus on the OSNR margin and the required OSNR. The OSNR margin for QPSK lambda was 6.96 *dB*, with a required OSNR of 15.83 *dB*. The lambda configuration at 8QAM was in the middle of the other two lambdas in terms of OSNR margin (3.52 *dB*) and required OSNR (18.61 *dB*). The OSNR margin for the 16QAM lambda was 0.67, with a required OSNR of 20.94 *dB*. It is also worth mentioning that the QPSK lambda had the largest OSNR margin but the lowest OSNR degradation of 21%. This finding revealed that the bigger the OSNR margin, the lower the value of OSNR degradation after lambda configuration. Another observation was that, as the OSNR margin shrunk, the transponder required more OSNR.



C2 General

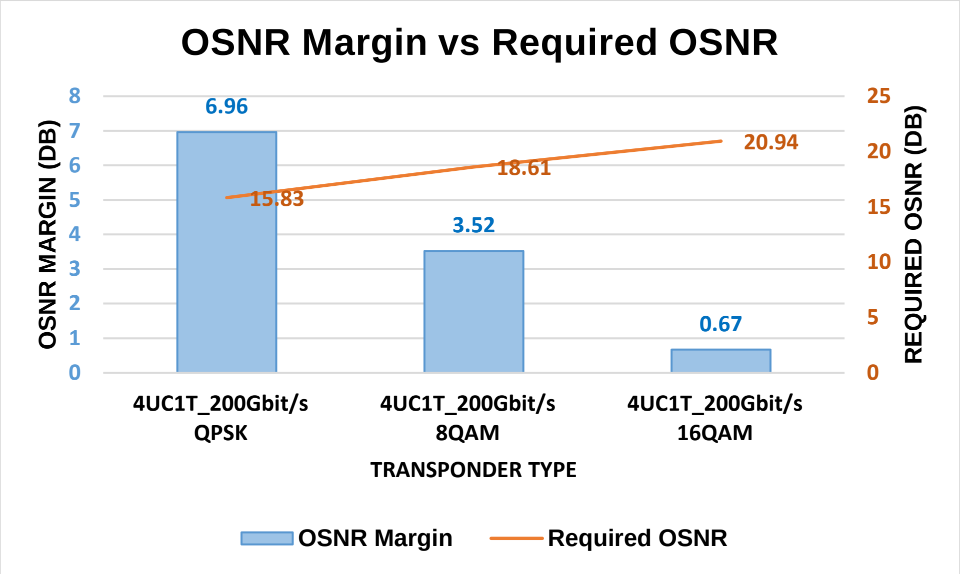


**Figure 4.8:** OSNR Margin vs Required OSNR

According to (Li, et al., 2020), high-order QAM modulation techniques are better suited for higher data rate transmission over a short distance because they are more vulnerable to phase noise and nonlinear effects, Figure 4.8 collaborates this assertion. As can be seen, *M-J-N_9420_4UC1T_200Gbit/s_16QAM* has the least OSNR margin. (Nance-Hall, 2020) made a similar observation, stating that high-order modulation techniques are more sensitive to the OSNR, which steadily decreases with distance. Figure 2.12 in the literature review depicted the relationship between modulation/Line rate and noise/distance, corroborating the findings in Figure 4.8. QPSK is the most robust modulation technique, according to the literature, making it suited for long-distance transmission. This explains why it had the highest OSNR margin and the least OSNR degradation over the 240 *km* distance when compared to 8QAM and 16QAM. During the analysis of the three simulated 200 *Gbit/s* lambdas, this study also noted that a lambda with an OSNR margin less than zero is unusable. At that moment, the 3R point can be used to improve the signal strength on that particular lambda. According to (Iyer, 2018), Flex-Grid technology's primary features also include the use of multiple modulation schemes with high spectral efficiency and transmission reach, signal regeneration, and the transmission of super-channels. Furthermore, the study observed that the route maps indicated that the OSNR degradation is inversely proportional to the OSNR margin.



C2 General

## 4.3. Network Survivability Techniques to Enhance Availability

This aspect of the EPT simulation looked at the network survivability through lambda restoration, incorporating functionalities such as directionless, colourless, contentionless, and SRG. Tables 3.6 and 3.7 provided the lambda parameters for the nominal route: *E-D_9360_2UC1T_200Gbit/s* and the protection route: *E-B-D_9370_2UC1T_200Gbit/s* that were used.

### 4.3.1. Colourless

Figure 4.9 shows lambda *E-B-D_9370_2UC1T_200Gbit/s* transponder configuration in which any C-band wavelength can be used, which demonstrates that the DWDM node's add/drop ports were colourless. The colourless feature allowed the wavelength of the transponder to be customised without the need for manual intervention. The same was true for all DWDM nodes in the simulated network; they all had colourless add/drop ports. This capability is useful for making modifications to the lambda configuration for a remote location. The changes can be implemented in the shortest amount of time possible, without incurring the costs of driving to the site and paying the labour costs of the resource responding to the change.

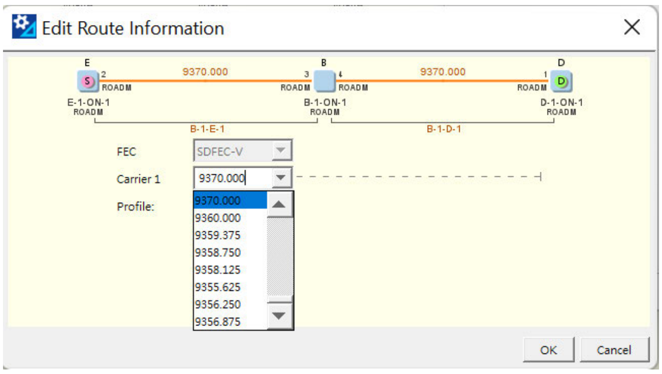


**Figure 4.9:** Add/Drop Colourless Ports Configurable to any C-Band Wavelength

### 4.3.2. Directionless

Figure 4.10 shows *E-D_9360_2UC1T_200Gbit/s* and *E-B-D_9370_2UC1T_200Gbit/s* with their route maps, *E-D_9360_2UC1T_200Gbit/s* at 8% OSNR degradation and *E-B-D_9370_2UC1T_200Gbit/s* at 9%. This indicated that each of these lambdas had a strong OSNR margin in their reserves, which came in handy when the lambdas needed to restore over longer routes.

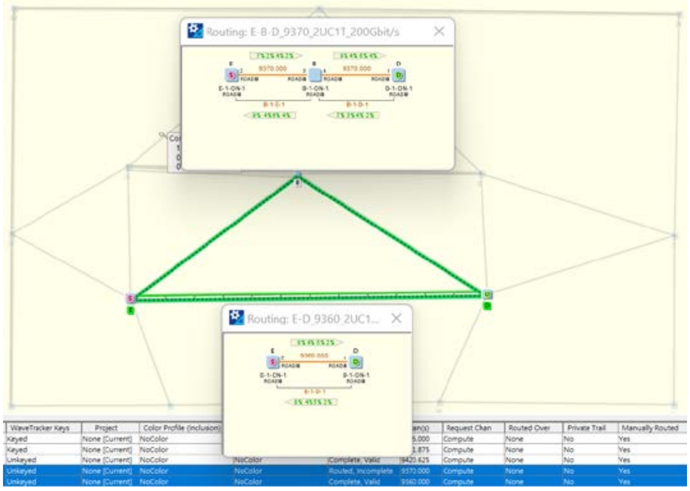

**Figure 4.10:** E-D_9360_2UC1T_200Gbit/s and E-B-D_9370_2UC1T_200Gbit/s Routing

As demonstrated in Figure 4.11, the EPT tool allowed for the simulation of several failure scenarios. These failure scenarios are customisable as SRGs, segments, nodes, or a combination. The maximum number of concurrent failure conditions was five, resulting in a variety of possible failure scenarios.

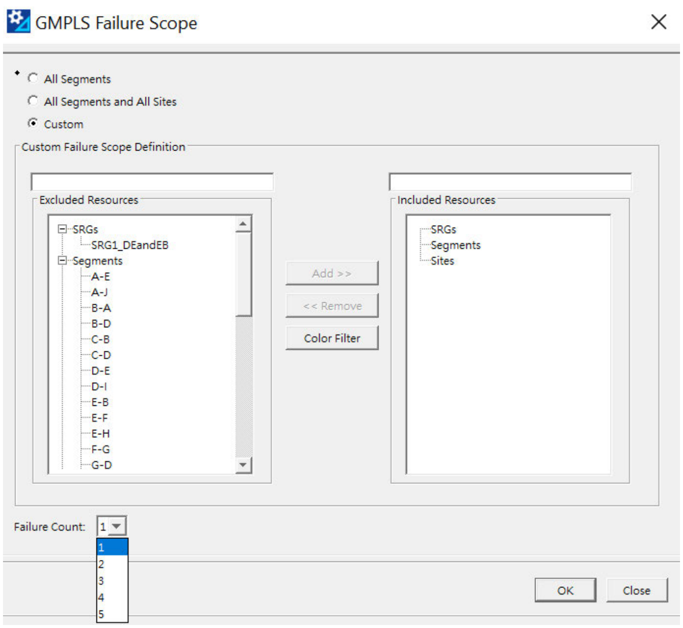


**Figure 4.11:** GMPLS Failure Scenarios

Figure 4.12 shows a simulated fibre cut on route E-B that affected *E-B-D_9370_2UC1T_200Gbit/s*, the protection lambda. The lambda rerouted to span E-D, as this was the best route; it was shorter (60 *km*) and had a low span loss (15 *dB*) compared to the original route E-B-D, which spanned 90 *km* at 22.5 *dB* span loss.



C2 General

Aside from the restoration of this lambda, another noteworthy finding was that it was restored on route E-D, which was a different degree than the nominal route, demonstrating that DWDM nodes E and D were directionless. This meant, if the nominal route failed, lambdas could be rerouted on any other route without any manual intervention. All the DWDM nodes in the simulated network were similarly directionless.

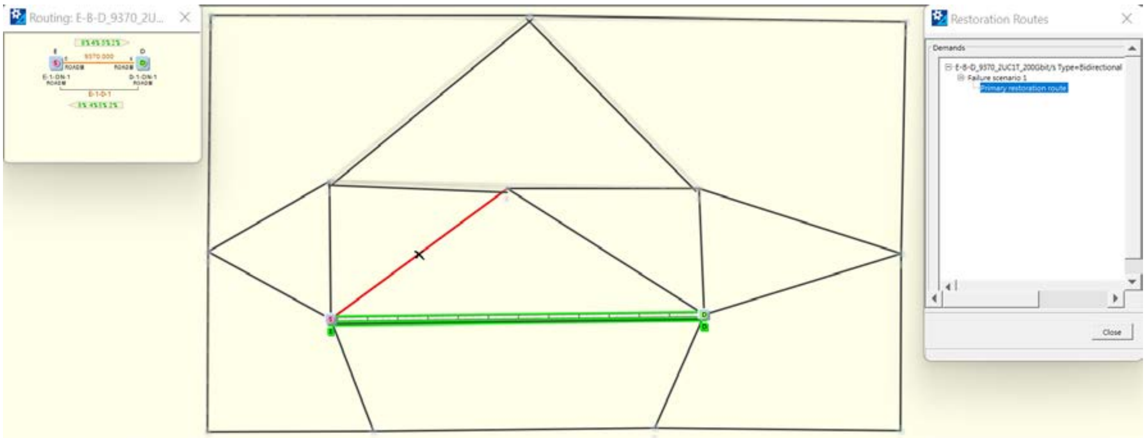


**Figure 4.12:** Fibre Cut 1_E-B

### 4.3.3. SRG Routing Restriction

Still on the restoration of *E-B-D_9370_2UC1T_200Gbit/s*, yet another observation was apparent, restoring the lambda on route E-D caused an issue because both nominal and protection lambda were on the same path, as indicated in Figure 4.12. The same happened when the E-D route was cut and the *E-D_9360_2UC1T_200Gbit/s* lambda was restored on route E-B-D. Again, both nominal and protection lambda were on the same path, as shown in Figure 4.13.



C2 General

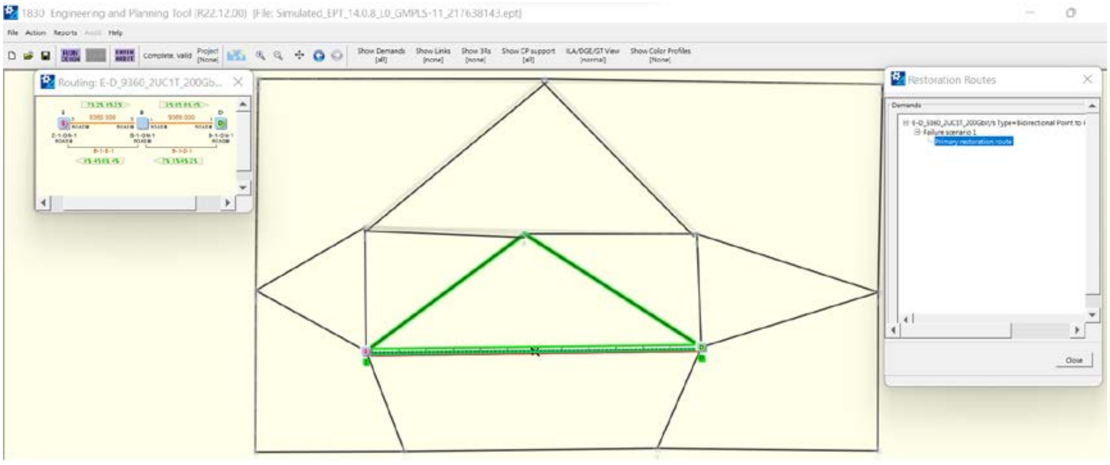

**Figure 4.13:** Fibre Cut 2_E-D

To address the issue of the nominal and protection lambdas ending up on the same route, routes D-E and E-B were configured into the shared risk group (SRG), as depicted in Figure 4.14. This was done to avoid a situation in which a single fibre cut affects both the nominal and the protection route, which was likely to result in a service interruption.

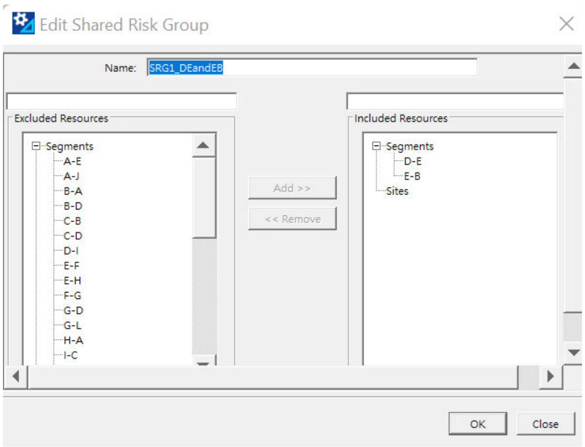


**Figure 4.14:** D-E and E-B SRG

Figure 4.15 shows the new restoration route of lambda *E-B-D_9370_2UC1T_200Gbit/s,* following the implementation of the SRG constraint and a fibre cut on route E-B. Instead of restoring the lambda through route E-D, which is the shortest available route, the restoration route was E-A-B-D.



C2 General

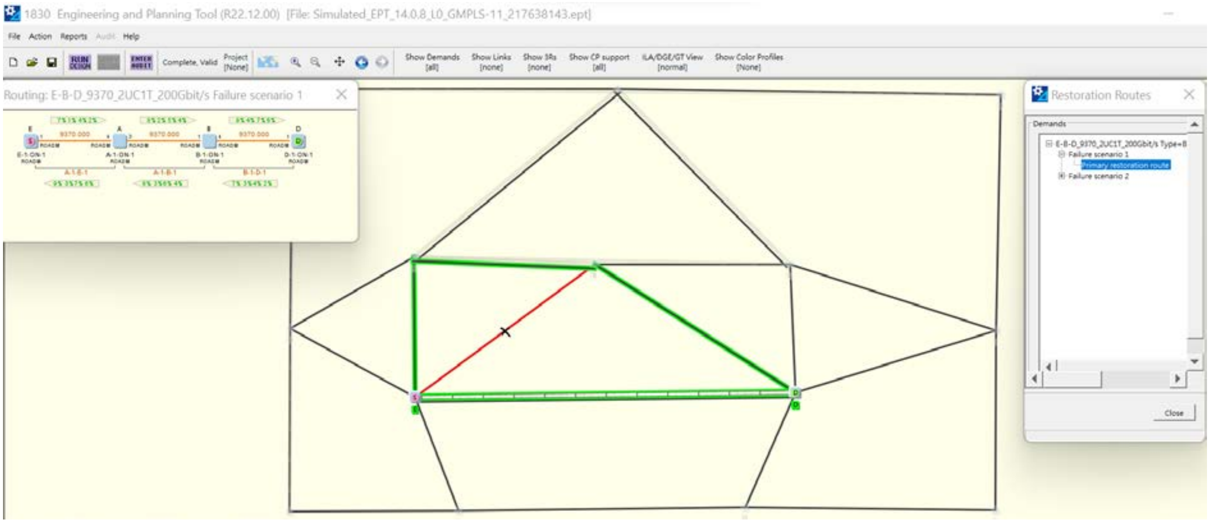

**Figure 4.15:** Restored E-B-D_9370_2UC1T_200Gbit/s after the Introduction of the SRG Restriction

### 4.3.4. Contentionless

Another difficulty with colourless and directionless ROADM networks is that wavelength-blocking events can occur when two wavelengths of the same colour arrive at the same WSS structure at the same time, resulting in wavelength contention (Kozdrowski & Sujecki, 2018). The contentionless functionality enables CDC ROADMs to recolour the lambda's wavelength during restoration if it traversed a span where the same wavelength had been used, which is a game changer for DWDM Layer 0 lambda restoration. Figure 4.16 shows two 200 *Gbit/s* lambdas configured across two spans, E-D and A-J, but with the same wavelength channel 9360.

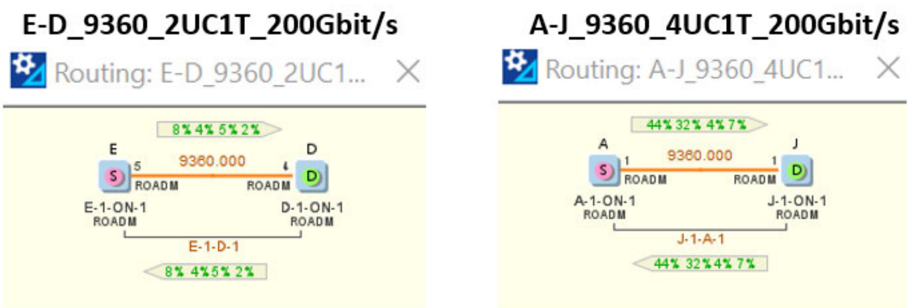


**Figure 4.16:** Two 100 *Gbit/s* Lambdas with the Same Wavelength (9360)

Figure 4.17 shows failure scenario 168 that forced *E-D_9360_2UC1T_200Gbit/s* to restore over route A-J that already had wavelength channel 9360 used. This failure scenario had five elements, 4xDWDM nodes isolated (B, H, F, and I) as well as a fibre cut on route E-D, which left E-A-J-C-D as the only possible restoration route.



C2 General

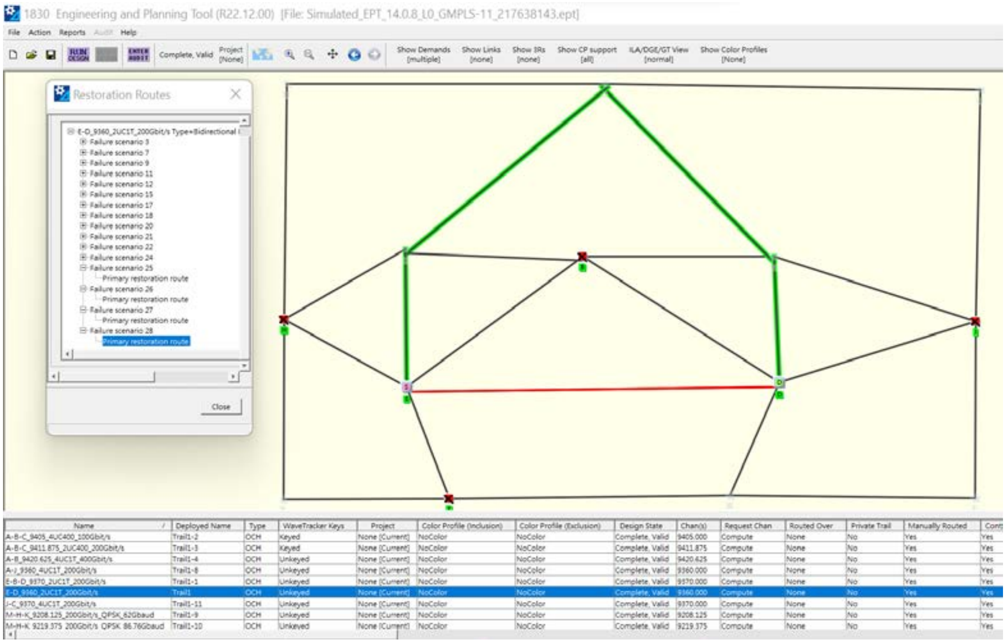


**Figure 4.17:** Scenario Including Five Distinct Failure Conditions

Because these DWDM nodes had a CDC ROADM, the restoration of *E-D_9360_2UC1T_200Gbit/s* was made possible by recolouring the wavelength channel from 9360 to **9352.500**, as shown in Figure 4.18. This lambda would have failed in a conventional ROADM system, leading to traffic loss. The results further established the CDC ROADM as a significant contributor to increased DWDM optical network survivability and subsequently network availability. After route E-D was reinstated, *E-D_9360_2UC1T_200Gbit/s* reverted to its original route and wavelength of 9360.

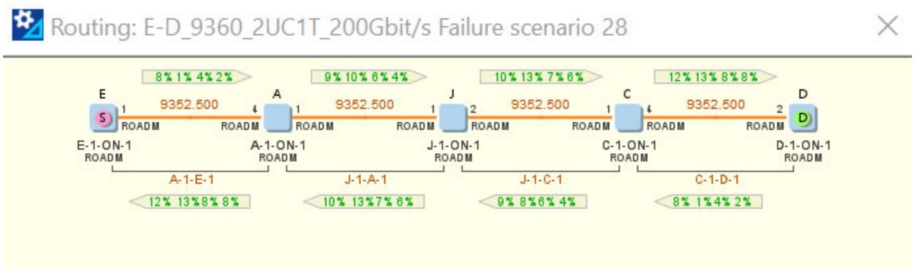


**Figure 4.18:** E-D_9360_2UC1T_200Gbit/s Restoration Route Map after Recolouring

### 4.3.5. Different Scenarios for Long Haul Lambda Restoration

Table 3.8 depicted the parameters of lambda *F-G_9440_4UC1T_200Gbit/s_8QAM* routed across a single span.



C2 General

Figure 4.19 shows the route map of *F-G_9440_4UC1T_200Gbit/s_8QAM* with OSNR degradation of only 23%. This indicated that this lambda has enough OSNR margin to survive multiple failure scenarios within the simulated network.

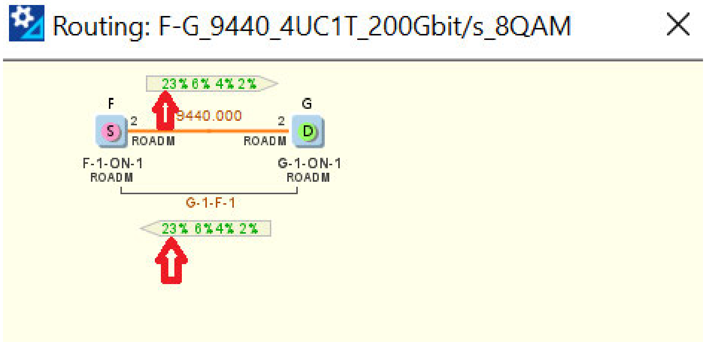


**Figure 4.19:** F-G_9440_4UC1T_200Gbit/s_8QAM

**Failure Scenario 5 -** shows one failure condition, a fibre cut on route F-G, which prompted lambda *F-G_9440_4UC1T_200Gbit/s_8QAM* to restore over the next possible route with the lowest OSNR. Figure 4.20 shows the restoration route as F-E-D-G, which was over three spans; the total distance on the restoration route was 120 *km*, with an accumulative span loss of 30 *dB*.

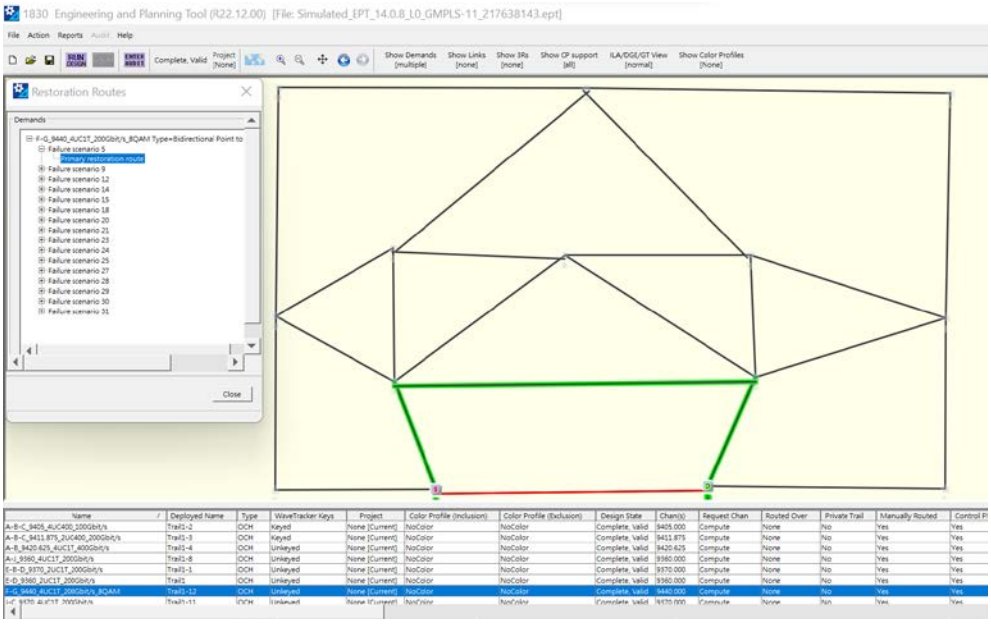

**Figure 4.20:** F-G_9440_4UC1T_200Gbit/s_8QAM Restoration after Failure Scenario 5

Figure 4.21 shows a route map of *F-G_9440_4UC1T_200Gbit/s_8QAM* after Scenario 5 with an OSNR degradation at 30%, a slight difference from the 23% measured on the nominal route.

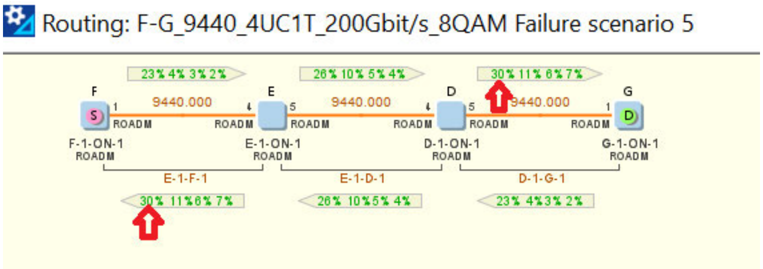


**Figure 4.21:** F-G_9440_4UC1T_200Gbit/s_8QAM Route Map after Failure Scenario 5

**Failure Scenario 14** – show the two failure conditions, a fibre cut on route F-G and a node isolation of DWDM node D. *F-G_9440_4UC1T_200Gbit/s_8QAM* restored on route F-E-B-C-I-L-G as shown in Figure 4.22. The total distance was 230 *km*, over six spans, at an accumulated span loss of 57.5 *dB*.

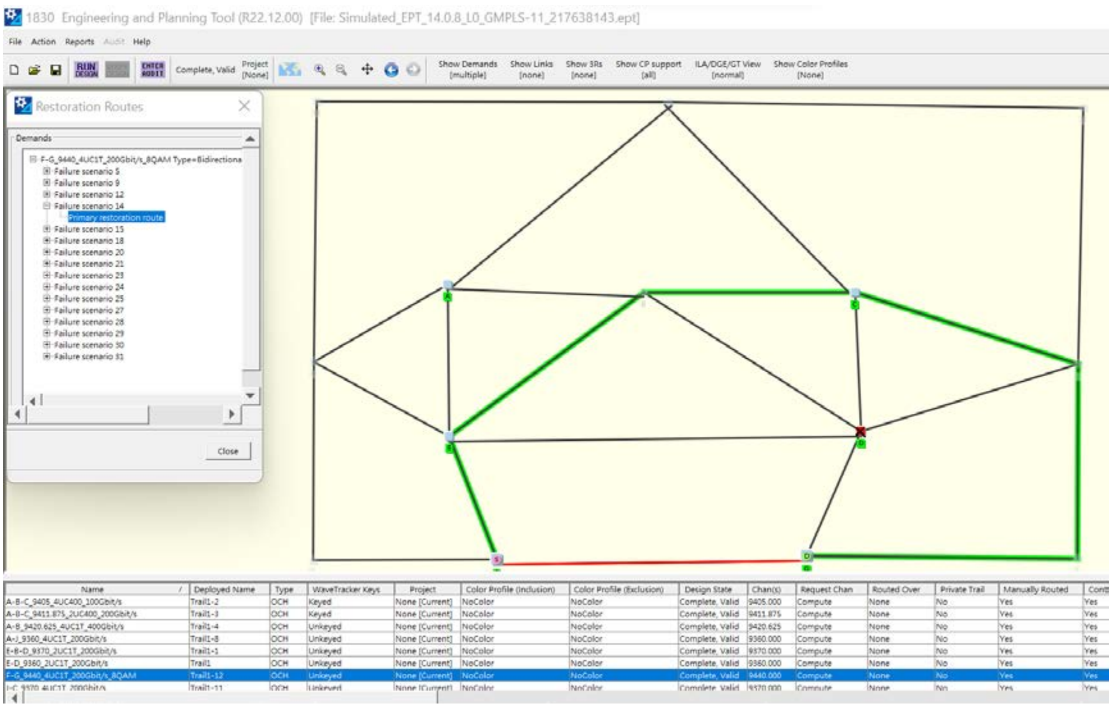


**Figure 4.22:** F-G_9440_4UC1T_200Gbit/s_8QAM Restoration after Failure Scenario 14

Figure 4.23 shows a route map of F-G_9440_4UC1T_200Gbit/s_8QAM after Scenario 14, with an OSNR degradation at 42%, highlighting that this was a much longer restoration route compared to the one in failure Scenario 5.



C2 General

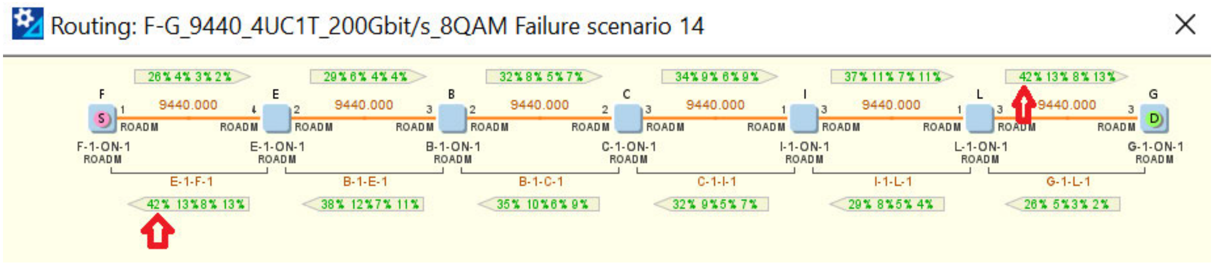


**Figure 4.23:** F-G_9440_4UC1T_200Gbit/s_8QAM Route Map after Failure Scenario 14

**Failure Scenario 31** – was the ultimate failure scenario, as it combined five different failure conditions, a fibre cut on route F-G and node isolation of 4xDWDM nodes: A, C, D, and E. Lambda *F-G_9440_4UC1T_200Gbit/s_8QAM* restored on the longest route possible for the simulated network, F-K-H-M-J-N-I-L-G as shown in Figure 4.24. The total distance was 595 *km*, over eight spans, and the accumulated span loss was 148.75 *dB*. Figure 4.25 shows a route map of *F-G_9440_4UC1T_200Gbit/s_8QAM* after Scenario 31, with an OSNR degradation at 89%, very different from the mere 23% OSNR degradation on the nominal route.

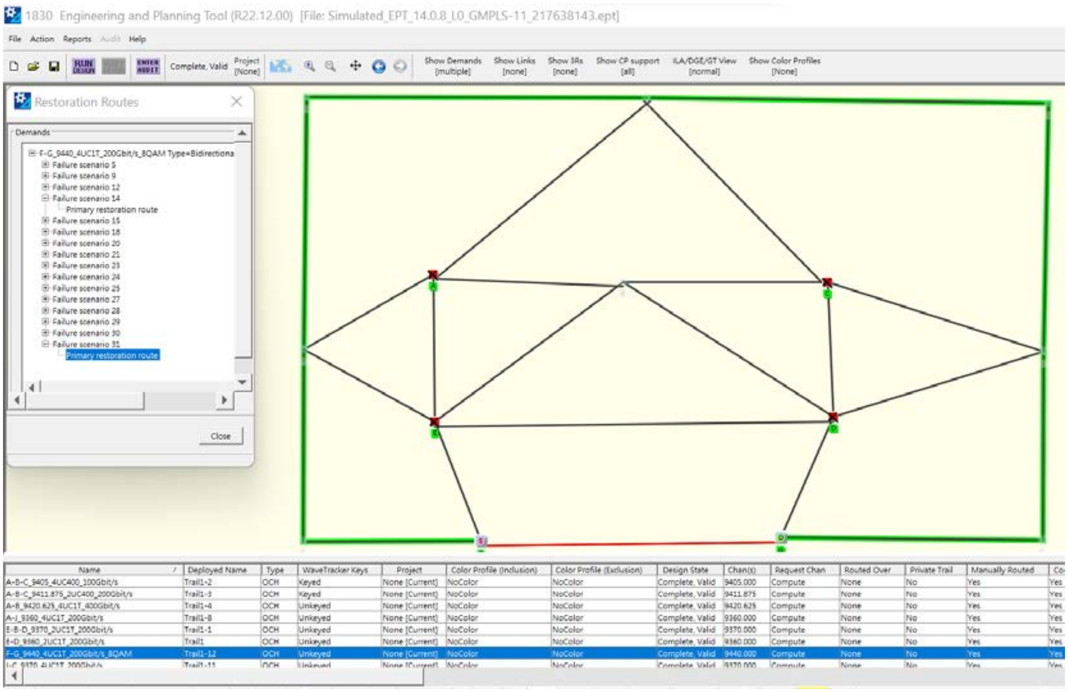


**Figure 4. 24:** F-G_9440_4UC1T_200Gbit/s_8QAM Restoration after Failure Scenario 31



C2 General

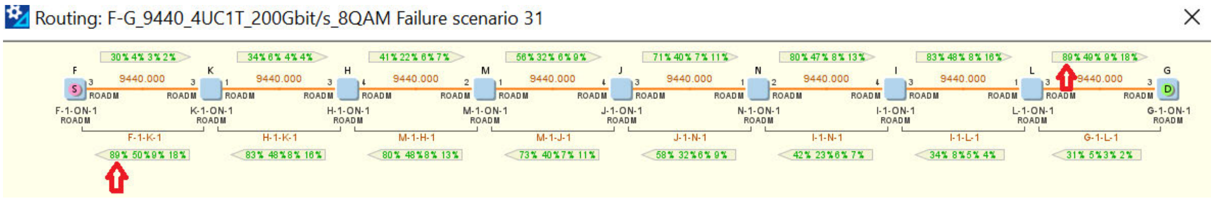


**Figure 4.25:** F-G_9440_4UC1T_200Gbit/s_8QAM Route Map after Failure Scenario 31

*F-G_9440_4UC1T_200Gbit/s_8QAM* was stretched to its limits on route F-K-H-M-J-N-I-L-G, with OSNR degradation of 89%, but the crucial thing was that it was restored, meaning there was no disruption of services. To travel further than 595 *km*, the lambda would have needed a 3R site for lambda regeneration. Another possibility would have been to change the modulation scheme to QPSK, which would have provided even greater reach. The ability to switch between modulation schemes depends on the type of transponder: the more flexible the transponder, the better for the network. Flexible transponders are slightly more expensive than normal transponders; the DWDM network operator makes the decision based on the network demands.

Figure 4.26 shows the OSNR degradation trend for lambda F-G_9440_4UC1T_200Gbit/s_8QAM over the three failure scenarios. The lambda consumed 23% of the OSNR margin when deployed on its 50 *km* nominal route F-G. When stretched in Scenario 31 and forced to traverse 595 *km* with an accumulated span loss of 148.75 *dB*, the lambda required higher OSNR to complete the distance and ended up with 89% OSNR degradation. The “OSNR degradation” concept is critical for understanding the lambda’s survivability potential, hence the need to model various failure scenarios before implementation. Furthermore, Figure 4.26 highlighted the significance of network survivability in DWDM optical networks; the lambda in question withstood five different failure conditions. Backbone networks using DWDM technology transport massive amounts of traffic; even a single fibre cut can result in significant traffic loss due to the disruption of several active services (Lu, et al., 2018). (Sairam & Singh, 2017) also stated that survivability is critical in the realm of optical networks; it represents the networks’ self-protection and restoration mechanisms.



C2 General

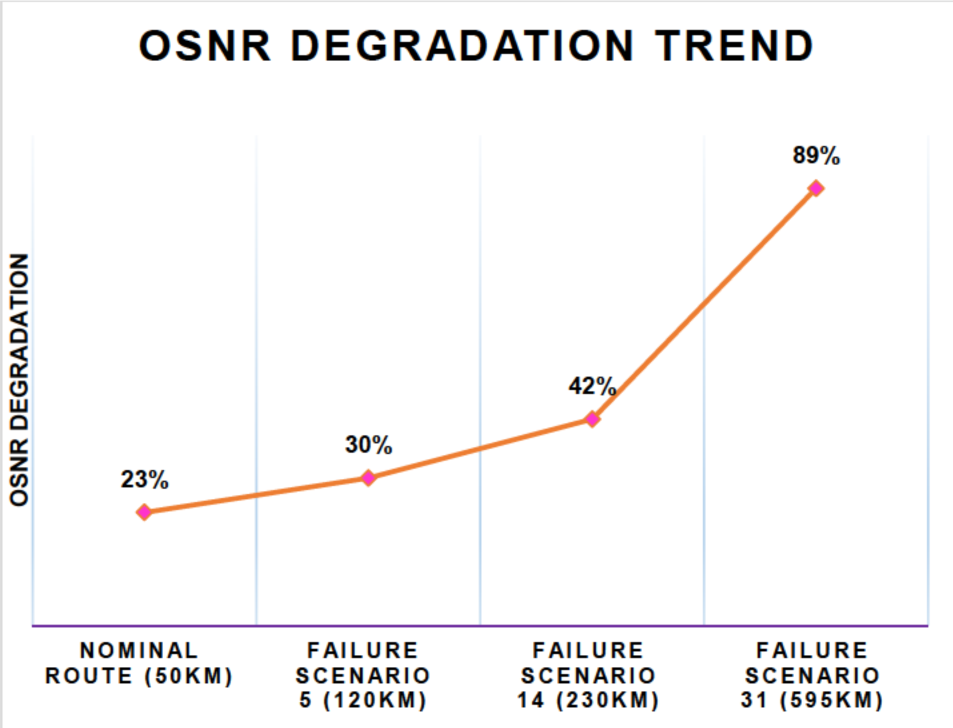


**Figure 4.26:** OSNR Degradation Trend for Lambda F-G_9440_4UC1T_200Gbit/s_8QAM

Protection and restoration mechanisms can be deployed together to achieve superior network survivability. That approach is called protection restoration combined, abbreviated as PRC. PRC is the fault-handling method used by an automatically switched optical network to enhance network availability and, by extension, network availability (Abduhuu & Purnawan, 2018).

A flowchart outlining the various processes involved in the PRC approach is shown in Figure 4.27. When a fibre cut is detected, the DWDM system establishes if it affects the nominal or protection route. When the fibre-optic cable break affects the protection route, the DWDM system raises a service-degraded alarm. This alarm indicates that the protection route is compromised but the service remains unaffected. While this situation does not disrupt services, sufficient attention must be given to resolving the issue because the next failure may be service-affecting. When the fibre cut is on the nominal route, the services are switched to the protection route; the transition is heatless for the client since the switching time is sub-50ms; this is a typical protection switching time (Tejas Networks, 2022). The only obvious difference may be a change in latency depending on the length of the protection route. The lambda(s) on the failed route, whether nominal or protection route, initiates the restoration procedure via GMPLS. Successful optical restoration is subject to whether restoration fibre routes



C2 General

are available at the time the failure occurs. If the failed lambda cannot be restored because network resources are unavailable, it is dropped and remains down until the failed fibre route is repaired. Where network resources are available, failed lambda(s) are restored using a new temporal fibre route. What is more crucial in this circumstance is that a recovered lambda provides an entirely new temporal SNC-P path for the service, increasing network survivability even more.

During the configuration process, both a service and a lambda can be configured to use revertive or non-revertive switching modes. In revertive switching, the service is switched back to the normal route when it has recovered from a failure. A switch to the protection route remains in place in non-revertive switching even after the nominal route has recovered from a failure (Nokia, 2021). The return of services and lambdas to their normal paths signifies the end of the PRC process.



C2 General

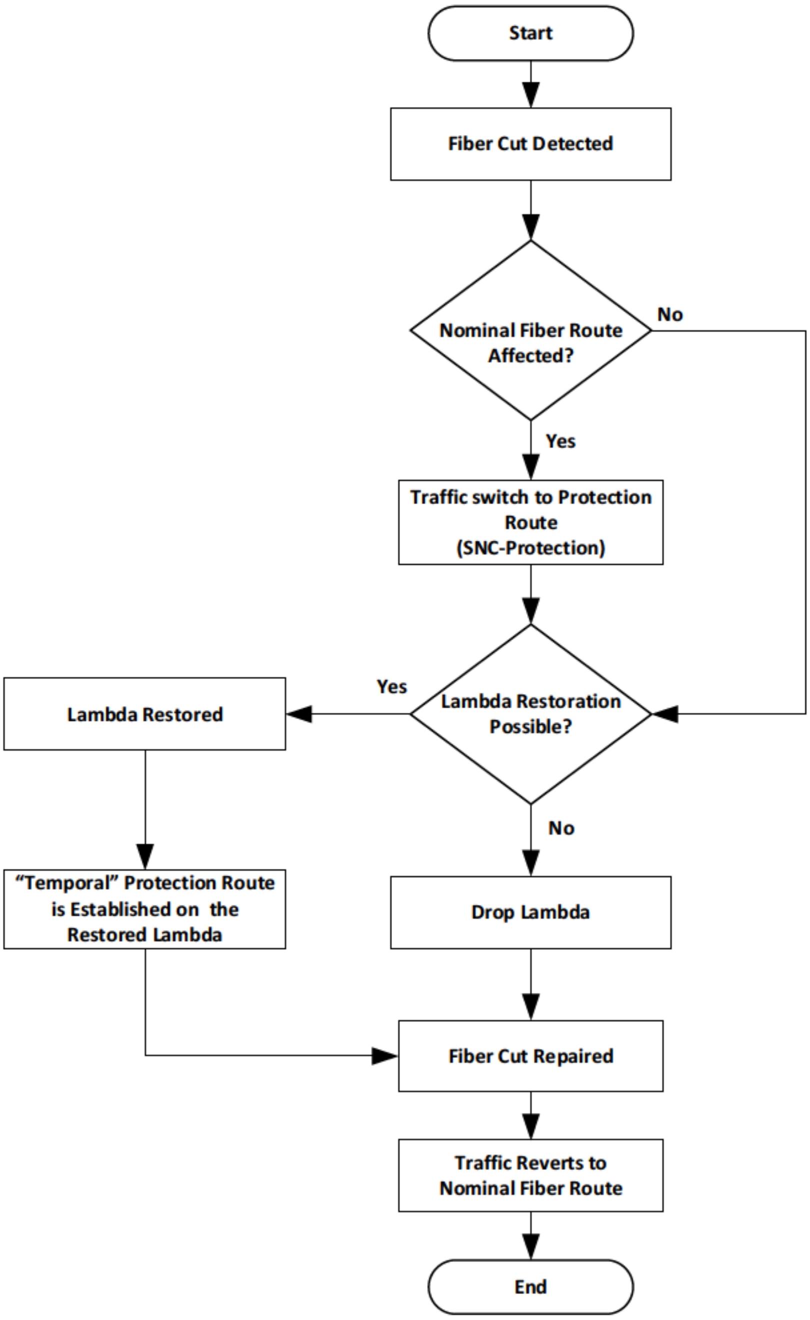


**Figure 4.27:** Flow Chart of PRC Process for a Protected Service

## 4.4. OPEX Reduction

Both the literature and the EPT simulation demonstrated that CDC ROADM with Flex-Grid technology enhances bandwidth and network survivability, thereby enhancing network availability. Furthermore, this study looked at several advantages that allow this sort of network to lower OPEX, which is critical to the profitability of any business. OPEX cost reduction is a critical element in ensuring long-term business viability (SM-Optics, 2017).



C2 General

### 4.4.1. Leased Fibre

The study used Dark Fibre Africa's (DFA) costing model for leased fibre, indicated in Annexure 5. With about 14 000 *km* of dark-fibre network built over the past 15 years, DFA is the leading provider of open-access connectivity in South Africa (dfafrica.co.za, 2023). For the purposes of this study, the simulated network shown in Figure 3.6 was used, with the following assumptions:

i. All fibre routes were leased from DFA on a monthly recurring charge for the same period.
ii. The lease agreement comprised two fibre pairs per route, the first pair was a worker and the second was the maintenance pair.

Eq. 4.1 was used to calculate the monthly recurring charge for the leased fibre routes.

$$\textbf{\textit{Monthly Recurring charge}} = \textit{Line-of-sight distance x 1.4 routing factor x R/metre} \quad \text{(Eq. 4.1)}$$

*Source:* (**dfafrica.co.za, 2023**).

Where the line-of-site distance is the optical distance between the two DWDM sites. The routing factor is the value, showing the extent the network components are utilised for generating the value of a telecommunications service/product. Table 4.1 shows three different SLAs that MNOs can choose from when leasing line-of-site dark-fibre cable. The charge depicted was expressed in the South African currency, the rand (R). The amounts reflected the typical R/metre monthly charge on a line-of-site lease in the South African market.

**Table 4. 1:** Leased Fibre SLA

| SLA Type | R/metre |
|---|---|
| SLA1_4 hours MTTR | R5.33 |
| SLA2_8 hours MTTR | R4.10 |
| SLA3_16 hours MTTR | R3.79 |

** These price estimates are the averages based on the South African fibre suppliers and may not be used for commercial purposes.*



C2 General

Figure 4.28 shows the monthly recurring charges for SLA1, SLA2, and SLA3 for all 24 routes in the simulated network. Because this was a CDC ROADM network with Flex-Grid and several restoration routes, the MNO could choose a lower SLA because services could be restored via an alternate route while the fibre break was fixed. The MNO may decide on a specific SLA for selected routes while keeping the rest of the network on another SLA.

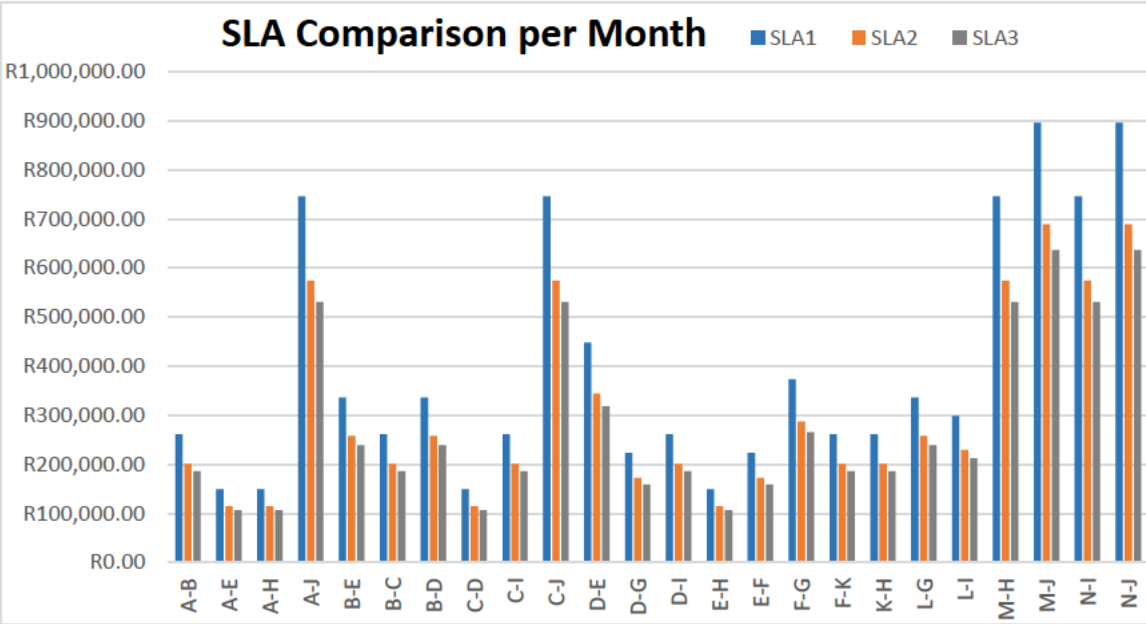


**Figure 4.28:** Simulated Network SLA Comparison per Month

Figure 4.29 shows the SLA comparison per year. Conventional DWDM networks without CDC capabilities would benefit more from SLA1 based solely on the MTTR of four hours. Considering the cost variations between the three SLAs, as well as the MTTR, SLA2 is the best SLA for the simulated network. SLA2 showed an OPEX saving of **R26 346 600** per year, which was massive. While SLA3 showed the most OPEX savings, one could argue that **R6 640 200** per year was insufficient to risk the network for an additional eight hours. Nonetheless, SLA3 remained an option for some metro routes.



C2 General

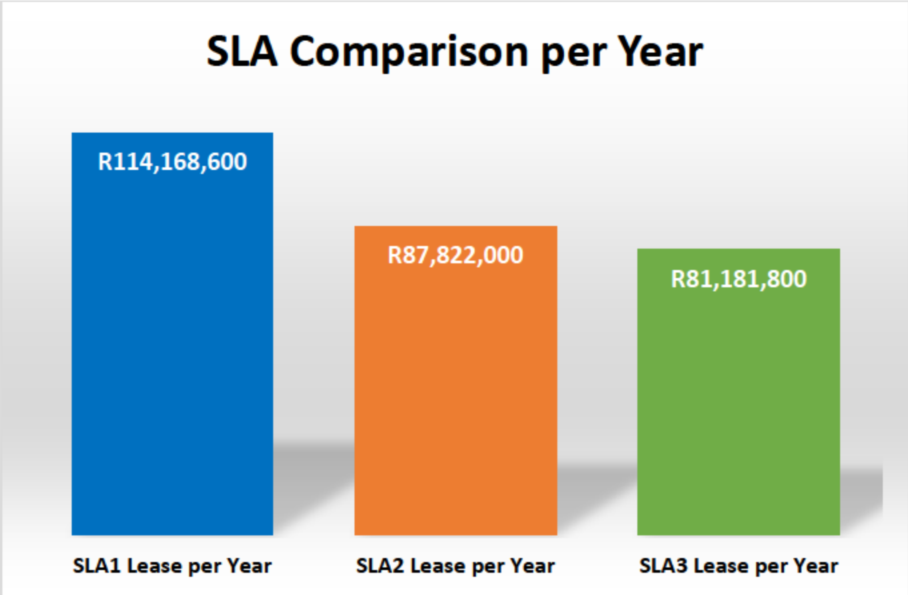


**Figure 4.29:** Simulated Network SLA Comparison per Year

### 4.4.2. Power Consumption

Another major factor in lowering OPEX is reducing the overall power consumption in the DWDM optical network. In the study, the power consumption of Fixed-Grid and Flex-Grid transponders was compared using the lambdas of the 400 *Gbit/s* capacity comparison in Section 4.2.3. Table 3.4 shows that, for the Fixed-Grid deployment, eight 130SCUPH transponders were used, whereas only two 4CU1T transponders were deployed for the Flex-Grid. As shown in Annexure 6, the power consumption of a single 130SCUPH was 160 *W*. The power consumption of a 4CU400 transponder for a single 400 *Gbit/s* lambda was 198 *W*, as indicated in Annexure 7.

Figure 4.30 shows that the power consumption of a single 130SCUPH transponder is 38 *W* less than that of a single 4UC1T transponder. The Fixed-Grid deployment had a higher installed base than the Flex-Grid deployment; as a result, its cumulative power consumption was significantly higher. The deployment of Flex-Grid 400 *Gbit/s* capacity proved to be significantly more power efficient, reducing total power usage by 69% compared to the Fixed-Grid deployment. (Papageorgiou, 2018) conducted a study on techno-economic analysis of open optical line systems, where Eq.4.2 depicted the total annual OPEX of a DWDM optical network. While there are other factors to consider, Eq. 4.2 affirms that lowering energy consumption has a direct impact on lowering OPEX.



C2 General

$$OPEX = Tot_{Cost\ (energy\ consumption)} + Tot_{Cost\ (fault\ managment)} + Tot_{Cost\ (preventative\ maintenence)} + Tot_{Cost\ (help\ desk)} \quad \text{(Eq. 4.2)}$$

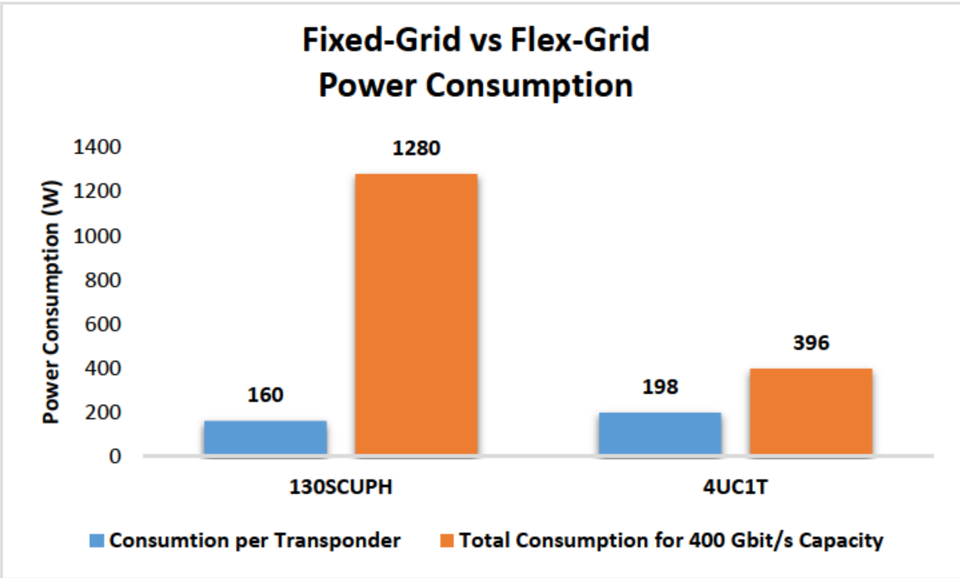


**Figure 4.30:** Fixed-Grid vs Flex-Grid Power Consumption

While lowering power consumption is an OPEX-cutting measure in DWDM optical networks, it is also significant in terms of sustainability. Although the telecommunications industry provides the infrastructure for the transmission of essential services, it also contributes significantly to carbon dioxide emissions (Kukreti & Ganguly, 2022). This has required DWDM vendors to integrate a sustainability component into their production, with one such consideration being lower power consumption on equipment manufactured. As a result, MNOs are constantly on the search for power-efficient solutions.

### 4.4.3. Flex-Grid Transponder Versatility

Continuing with the 400 *Gbit/s* capacity comparison from Section 4.2.3, there were some major differences between the two types of transponders. As shown in Annexure 8, the 130SCUPH had a single uplink port, a single wavelength, a single line rate (100 *Gbit/s*) and supported just one modulation scheme (QPSK). According to Annexure 1, the 4UC1T transponder had four uplink ports; the high port density required less



C2 General

installed base on Flex-Grid transponders because a single transponder could be used for multiple uplinks. Looking back at the 100 *Gbit/s* comparison of the Fixed-Grid and Flex-Grid deployments, both lambdas required the same spectrum resources (50 *GHz*). The 4UC400 transponder, on the other hand, had four uplink ports as opposed to the SCUPH's one port. By using a 4UC400 transponder instead of an SCUPH in the same direction, the installed base of 100 *Gbit/s* deployment would be reduced by 75%. In practice, this means less power usage and fewer maintenance spares, resulting in savings for the business.

Figure 4.31 demonstrates an even more crucial attribute of a 4UC1T, a transponder that can support a wide range of line rates, modulation schemes, and baud rates. The 4CU1T transponder had six configuration options. Not only does this reduce power consumption, as discussed in Section 4.4.2, but also significantly reduces the installed base. The MNO does not need to purchase a transponder for 200 *Gbit/s* lambda and another for 400 *Gbit/s* lambda; a 4UC1T supports both line rates, including 300 *Gbit/s* lambdas.

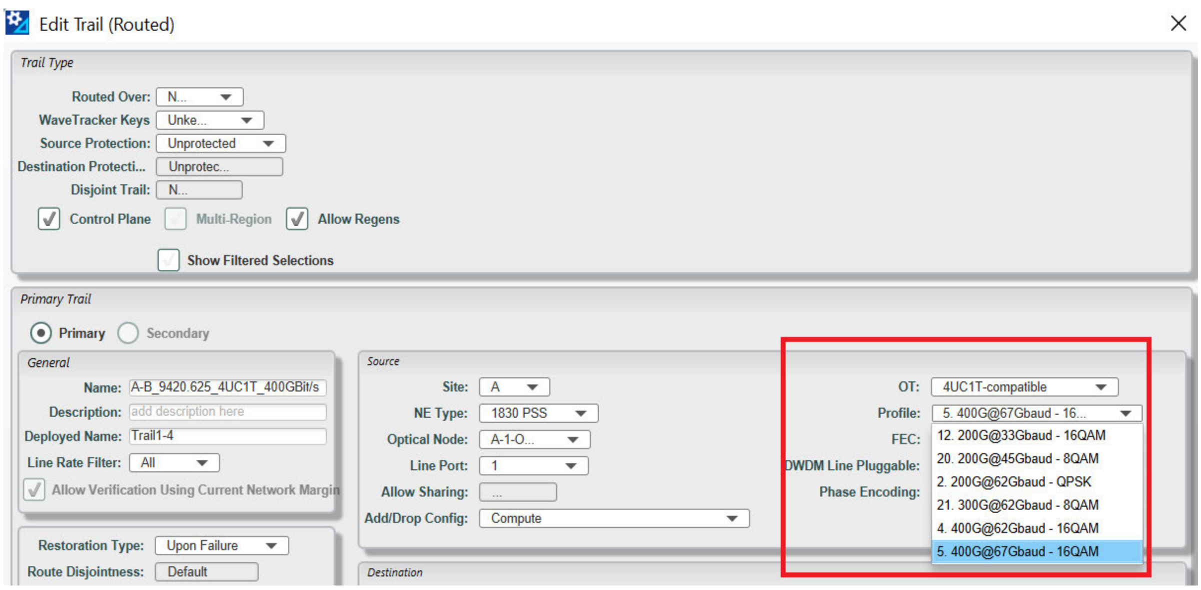


**Figure 4.31:** 4UC1T Transponder Versatility

The same adaptability is shown in Figure 4.32 for the 2UC1T transponder. This transponder may be configured in eight different ways, making it extremely versatile.



C2 General

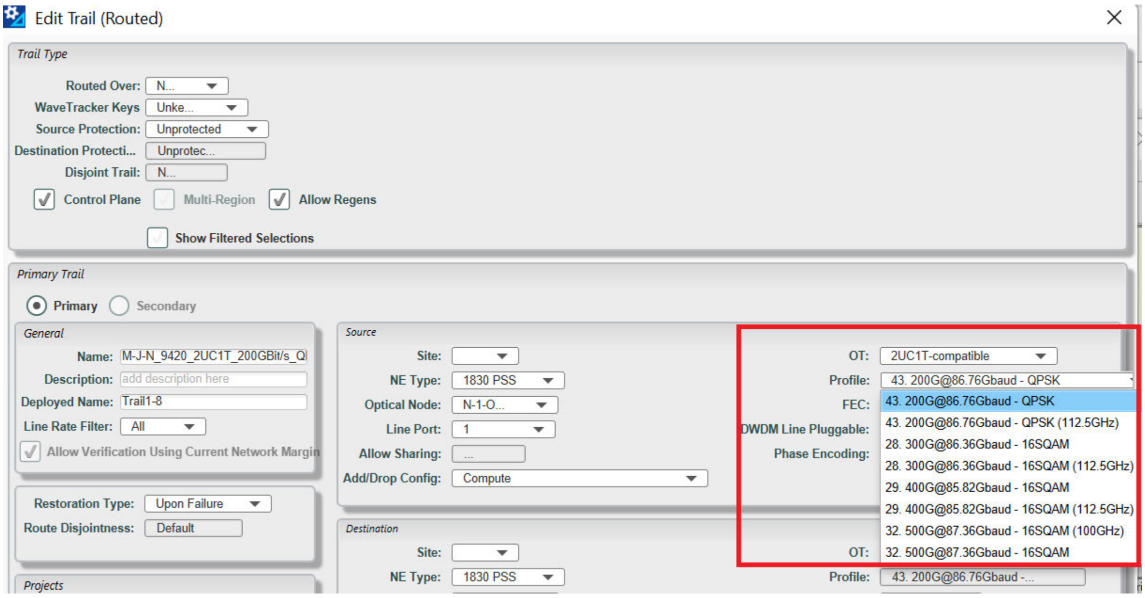


**Figure 4.32:** 2UC1T Transponder Versatility

As previously stated, the high port density and versatility of Flex-Grid transponders reduce the installed base, which in turn reduces the number of maintenance spares required in the network.

### 4.4.4. Reducing Labour Hours

Section 4.4.3 described the versatility of Flex-Grid transponders, which allowed a single transponder to be deployed at varied line rates, modulation schemes, and baud rates. This is a crucial part in decreasing labour hours, since it allows the configurator to alter transponder configurations without requiring manual intervention. CDC ROADM functionalities also contributes to this effect, if a lambda needs to be reconfigured to a different line rate, modulation, wavelength channel, and direction. In legacy DWDM optical networks, a change like that would enlist the following activities:

i. Sourcing a different transponder that supported the desired line rate from the warehouse.
ii. A technician drove from the warehouse to Site A to instal the transponder and make the necessary cabling changes.
iii. A different technician drove to Site B to instal the new transponder and make the necessary cabling changes.
iv. The resource at the central office did the configuration after the onsite changes had been completed.



C2 General

v. The technicians at both sites could not leave the site until all the configurations were completed.

Looking at the five activities mentioned above, the associated costs are labour hours, fuel costs, and time. With CDC ROADM features and Flex-Grid technology, the above activities are not necessary. One person using the NMS can make the configuration changes from the central office. Table 2.2 of the representation by (Fogliata, 2019) highlighted the automation components of a ROADM, and Table 2.3 of the whitepaper published by (Infinera, 2021) indicated the different DWDM functionalities associated with a CDC ROADM. Furthermore, since CDC ROADM are fully automated, the possibility of human mistakes is largely eradicated.

### 4.5. Chapter 4 Summary

The EPT simulation tool was used to simulate DWDM functionalities. The spectral efficiency of Fixed-Grid and Flex-Grid was compared, and Flex-Grid was shown to be superior. The chapter analysed how transponder type, modulation scheme, and baud rate affect OSNR and effectively the reach. The study indicated that low modulation schemes, such as QPSK, are suitable for long-distance transmission but have transmission-rate limitations. High-order modulation methods, on the other hand, are well suited for high data-transmission rates, but the trade-off is that they cannot cover long distances. The EPT simulation tool was also used to demonstrate CDC ROADM features and SRGs. The study established the significance of OSNR margin and OSNR degradation in relation to reach by using various simulated failure conditions. This chapter delved deeper into engineering management elements, looking at OPEX reduction measures in leased fibre, power consumption, Flex-Grid transponder adaptability, and lowering labour hours using Flex-Grid transponders and CDC ROADM.



C2 General

# CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

## 5.1. Introduction

Given the ever-increasing bandwidth demand caused by the emergency of 5G technology and the numerous data-hungry services used by subscribers, MNOs must develop strategies that enhance bandwidth and network availability. This study sought to analyse network survivability strategies as well as bandwidth-enhancing solutions for DWDM optical networks.

Data analysis played an important role in this research work since it provided insights that were fundamental in formulating the study's conclusion. The data obtained from the sources specified in the data-collecting section, 3.3.1, as well as the results from the EPT simulation, were analysed to determine whether the various mechanisms discussed improve bandwidth and availability in DWDM optical networks. For ease of comparison and making scientific conclusions, raw data was converted to a graphical representation.

Research questions outlined in Section 1.4 were used to guide and keep the research on track. The research objectives detailed in Section 1.3 were used to determine whether the findings from both the reviewed literature and the EPT simulation were consistent with the challenges the research sought to address. The results chapter noted and discussed anomalies and inconsistencies where they existed. Indicators such as line rate per wavelength channel, type of transponder, reach, OSNR, modulation technique, baud rate, and spectral efficiency were used to evaluate bandwidth enhancement. The network availability aspect was analysed using nominal routes, protection routes, restoration, SNC-P, path constraints, SRG, and wavelength colour availability.

## 5.2. Findings and Research Conclusions

The first aspect of the study was to establish if Flex-Grid technology could enhance bandwidth in DWDM optical networks. The simulation of 200 *Gbit/s* and 400 *Gbit/s* lambdas using a single wavelength per lambda confirmed that Flex-Grid technology did support uplinks with line rates higher than 100 *Gbit/s*. The study went on to



C2 General

compare the spectrum consumption of the Fixed-Grid as well as the Flex-Grid deployments using 100/200/400 *Gbit/s* lambdas. On a 100 *Gbit/s* capacity deployment, the Fixed-Grid lambda used the same spectral resources as the Flex-Grid lambda, which was 50 *GHz*.. On the 200 *Gbit/s* capacity deployment, Fixed-Grid lambdas utilised 100 *GHz* of spectrum resources while a Flex-Grid lambda consumed 75 *GHz*, resulting in a 25% decrease in spectrum resources. Fixed-Grid lambdas consumed 200 *GHz* of spectrum resources for the 400 *Gbit/s* capacity deployment, while the Flex-Grid lambda only used 87.5 *GHz*, accounting for only 44% of the spectrum resources consumed by the Fixed-Grid deployment. This research concluded that Flex-Grid technology had the ability to transmit uplink line rates greater than 100 *Gbit/s* while maintaining superior spectral efficiency when compared to the conventional Fixed-Grid. According to the reviewed literature, there are clear forecasts of rising uptake in mobile-device subscriptions globally, both now and in the future. This suggests an increase in data traffic from now to the future, and Flex-Grid technology will be essential for MNOs as they expand their backbone networks.

The literature further indicated that the OSNR and the type of modulation scheme used while deploying lambdas play a role in determining a lambda's reach. Three 200 *Gbit/s* lambdas were simulated over the same fibre routes (M-J-N) using different modulation schemes (QPSK, 8QAM, and 16QAM) to test this theory. The comparison of the performance of these three lambdas revealed that, as recommended by the literature, QPSK modulation was robust and well-suited to long-distance transmission. The QPSK lambda had the highest OSNR margin of 6.69 *dB* and a low OSNR degradation of 21%. The simulation further collaborates the literature on the assertion that, when QAM modulation schemes increase in size, the reach decreases but the line rates transmitted increase. The 16QAM lambda had the lowest OSNR margin of 0.67 *dB* and a high OSNR degradation of 86%. 8QAM lambda's performance was in the middle with 3.52 *dB* OSNR and OSNR degradation of 44%.

The study also investigated the CDC ROADM functionalities as they relate to network survivability and, ultimately, network availability. The EPT simulation demonstrated the colourless feature, which allowed the DWDM node's add/drop block to add and drop any C-band wavelength without the need for manual intervention. Directionless and contentionless functionalities were also demonstrated when different lambdas were



C2 General

able to route via any degree on the simulated network. Lambda recolouring is another vital component of contentionless functionality. During restoration, E-D_9360_2UC1T_200Gbit/s recoloured its wavelength from 9360 to 9352.500, as it was restoring over a span with wavelength 9360 already utilised. The wavelength recolouring of a CDC ROADM is a game changer for DWDM optical networks since it allows lambdas that would have failed on prior ROADM versions to be restored, directly enhancing network availability. EPT was also used to demonstrate the relationship between the OSNR and the reach during lambda restoration. Lambda *F-G_9440_4UC1T_200Gbit/s_8QAM* was configured on a single 50 *km* span with an OSNR degradation of only 23%, leaving enough room for the lambda to restore in the event of a failure. Failure scenarios 5, 14, and 31 were simulated and the OSNR degradation trend is shown in Figure 4.26. The restoration of the lambda over 120 *km* resulted in an overall OSNR degradation of 30%. When restored over 230 *km*, the OSNR degraded by 42%. The OSNR degradation was 89% when the lambda was restored over 595 *km*, nearly 12 times the original distance, and demonstrating remarkable resilience with no loss of services.

Furthermore, the study interrogated how CDC ROADM and Flex-Grid technology can help lower OPEX. The initial analysis focused on leased fibre routes. The study found that the CDC ROADM's ability to restore lambdas to any degree gave MNOs the flexibility to choose a lower SLA of eight-hour MTTR as opposed to the typical four-hour MTTR SLA. Over 12 months, the simulated network's OPEX savings on SLA2 was R26 346 600. Furthermore, CDC-ROADMs are fully automated, and the chance of human error is significantly decreased, resulting in reduced labour hours and lower OPEX. According to the reviewed literature, another key strategy for lowering OPEX is to reduce the power consumption of the DWDM system. The power consumption for 400 *Gbit/s* capacity was compared using eight SCUPH transponders for the Fixed-Grid deployment and two 4UC1T transponders for the Flex-Grid deployment. The power consumption on the Fixed Grid was 1280 *W*, and the Flex-Grid deployment consumed only 396 *W*. Overall, using Flex-Grid transponders proved to be a better 400 *Gbit/s* option, because it reduced power usage by 69%, thus lowering OPEX. A Flex-Grid transponder outperformed a Fixed-Grid transponder in terms of port density, variable line rates, variable baud rates, and flexible modulation scheme. All these factors combined to lower the installed base, maintenance spares, and labour hours



C2 General

associated with deploying a new lambda, resulting in another OPEX reduction accomplishment.

Overall, based on the literature reviewed and the simulations conducted in this research, the study was successful, as it was able to demonstrate ways to enhance bandwidth and network availability in DWDM optical networks. DWDM technology is invaluable to the telecommunications industry, particularly for MNOs, which must meet ever-increasing traffic demands, adhere to rigorous SLAs, and maintain market dominance. A CDC ROADM enhances network availability greatly by improving lambda restoration. Flex-Grid technology's capacity to transit uplinks with line rates exceeding 1 *Tbit* on a single wavelength, along with its superior spectral efficiency, establishes it as a solution to current and future bandwidth requirements. Finally, this study concluded that, while CDC ROADM features and Flex-Grid technology can be deployed separately, when deployed together, they provide the most flexibility DWDM optical network while minimising OPEX cost.

### 5.3. Recommendations

Bandwidth demands will continue to rise in the future. Therefore, DWDM optical network operators are encouraged to transition from Fixed-Grid to Flex-Grid technology. Deploying 100 *Gbit/s* lambdas over Flex-Grid technology has no spectral efficiency benefits because it consumes the same 50 *GHz* of spectrum as the Fixed-Grid deployment. MNOs ought to consider implementing uplinks of 200 *Gbit/s* or higher on Flex-Grid; this is where the true benefit is realised. Flex-Grid transponder deployment is highly recommended because they may be deployed in a variety of ways, resulting in a smaller installed base, lower power consumption, and fewer maintenance spares, all of which contribute to reduced OPEX. Above all, Flex-Grid technology enables the adoption of greater line rates, up to 1 *Tbit/s* and beyond, on a single wavelength, which is critical for present and future bandwidth demands. CDC-ROADMs are highly recommended for today's DWDM optical networks since they are fully automated, which reduces the potential for human error and speeds up maintenance and operating activities.



C2 General

## 5.4. Future Studies

The telecommunications industry continues to develop data-hungry applications regularly, which will only increase bandwidth demand in the future. Given that the spectrum is a finite resource, the DWDM C-band deployment may fall short of meeting these bandwidth demands. Extending DWDM deployment into the L-band is becoming a more popular choice for network growth (Maenpaa, 2020). The L-band spans the wavelength range of 1565 *nm* to 1625 *nm*. While C-band is preferred more than L-band due to significantly lower attenuation during data transmission, L-band is the next viable option for optical communication (Zdravecký, et al., 2022). More research on the deployment of DWDM technology in the L-band spectrum is recommended by this study. The proposed research would investigate the effectiveness of Flex-Grid technology for bandwidth enhancement in the L-band, as well as survivability techniques. Ultimately, the research will determine the long-term viability of L-band adoption.

## 5.5. Chapter 5 Summary

This chapter concluded the study by presenting the findings, research conclusions, recommendations, and a proposal for further studies. The research objectives outlined in Chapter 1 were achieved. The study found that colourless, directionless, contentionless, and Flex-Grid technology are critical components for enhancing bandwidth and availability in DWDM optical networks.



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C2 General

## Annexure 1: 4UC1T Data Sheet

### 4UC1T – 1 Terabit Programmable High-speed Uplink Card

| Unit Name | 4UC1T |
| --- | --- |
| Part # | 3KC61074AA |
| Size | Single slot |
| Chassis | 24 per PSS-24x |

- Key Features:
  - 100G to 400G Metro/LH transport for high-density applications
  - Enhanced reach, density, & power consumption enabled by the Nokia PSE-Vc
  - Modular pay-as-you-grow CFP2-DCO pluggables
  - 1Tbps per slot
  - B100G applications: OTUCn, 400GE
  - Enhanced OCH PM monitoring
  - L1, L0, MRN GMPLS support
  - OLP/OMSP 1+1 optical line side protection, OPSUM protection
  - Trail (TCM) based latency measurement
- Interfaces:
  - 4-port WDM 100G-400G programmable coherent line
    - CFP2-DCO (C2DCO4/C2DCO4O) pluggable
  - Line structure: N x OTU4, OTUCn
  - Single or dual carrier operation
  - 100G*, 200G, 250G*, 300G, 400G *(* prepared )*
  - 33 - 62 Gbaud symbol rate
  - QPSK, 8QAM, 16QAM

CFP2-DCO supp.
C2DCO4 / C2DCO4O

4UC1T

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## Annexure 2: 2UC1T Data Sheet

### 2UC1T – 1 Terabit Programmable High-speed Uplink Card

| Unit Name | 2UC1T |
| --- | --- |
| Part # | 3KC61122AA |
| Size | Single slot |
| Chassis | 24 per PSS-24x |

- Key Features:
  - 400G Anywhere - Regional/LH/ULH transport
  - Maximum optical reach / capacity
  - Improved network utilization
  - Based on PSE-V Super Coherent (PSE-Vs) silicon
  - 1Tbps per slot
  - B100G applications: OTUCn, 400GE
  - Lines fully tunable across C-Band; FlexGrid-capable
  - OLP/OMSP 1+1 optical line side protection, OPSUM protection
  - Trail (TCM) based Latency Measurement
- Interfaces:
  - 2 x flexible 200G - 500G super coherent line ports
    - BMDCO6 coherent pluggable module (part # 3KC93815AA)
  - Line structure: N x OTU4, OTUCn
  - Single or dual carrier operation
  - 33 – 90 Gbaud symbol rate
  - Probabilistic Constellation Shaping (PCS)

Pluggable module
BMDCO6

2UC1T

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## Annexure 3: 2UC400 Data Sheet

### 2UC400 – 2 Carrier Uplink Card

| | |
|---|---|
| Unit Name | 2UC400 / 2UC400E |
| Part # | 3KC59824AA, 3KC60346AA, 3KC60491AA / 3KC60522AA |
| Size | Single slot |
| Chassis | 24 per PSS-24x |

- Key Features:
  - Optimal transport wavelength capacity & distance
  - Based on PSE-2 Super Coherent (PSE-2s) silicon
  - Lines fully tunable across C-Band; FlexGrid-capable
  - Single or dual carrier operation, individually routed or superchannel
  - 200G supporting 2,000 km using unique 8-QAM
  - 100G supporting 3,000 km to 5,000+ km using unique DP-SPQPSK modulation
  - Wavelength Tracker OAM
  - GCC0, GCC1, GCC2 support
  - Part # and licensing options:
    - 3KC59824AA – restricted licensing
    - 3KC60346AA – unrestricted licensing
    - 3KC60491AA - subsea applications
    - 3KC60522AA - optional encryption ("E" version), unrestricted licensing
- Interfaces:
  - 2 x Flexible 100G / 200G Super Coherent line ports
  - Programmable modulation per carrier optimizes density to the network:
    - 100G QPSK, 100G SP-QPSK, 200G 16QAM, 200G 8QAM

2UC400

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## Annexure 4: 4UC400 Data Sheet

### 4UC400 – 4 × 100G Uplink Card

| | |
|---|---|
| Unit Name | 4UC400 |
| Part # | 3KC59925AA |
| Size | Single slot |
| Chassis | 24 per PSS-24x |

- Key Features:
  - High density 100G line support
  - Optimized for 100G applications
  - Based on PSE-2 Compact for high density and low power consumption
  - Lines fully tunable across C-Band; FlexGrid-capable
  - ODUk/ODUflex fabric interface
  - OLP, OCH (OPSflex) protection
  - Wavelength Tracker OAM
  - GCC0, GCC1, GCC2 support
- Interfaces:
  - 4 x 100G line ports
  - 100G QPSK transport wavelengths
  - CFP2 Gen2 Analog Coherent Optics pluggables
    - Pay-as-you-grow scale
    - Increased reliability
    - Application optimized CFP2 ACO versions
    - SD-FEC-G2

CFP2-ACO

4UC400

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# Annexure 5: DFA Metro Fibre Lease Data Sheet

## Peregrine Metro

Peregrine Metro is a dark-fibre link that is billed according to distance. Save costs by building your network on our reliable infrastructure.

### Data sheet

| | |
|---|---|
| **Connectivity options** | Core network and switching centres /<br>Core site to core site /<br>Core sites to a DFA aggregation node /<br>Branch site to branch site |
| **Non-recurring charge** | Connection fee<br>Distance-based capex fee |
| **Monthly recurring charge** | Minimum monthly lease /<br>Line-of-sight distance × 1.4 routing factor × R/metre |
| **Discount criteria** | Volume (total leased kilometres)<br>Lease term |
| **Lease/payment terms** | 1, 2, 3, 4, 5, 10, or 15 years<br>Fixed monthly lease payment /<br>Down payment with reduced fixed monthly lease payment |
| **Fibre pairs** | Single / Multiple |
| **Optional redundancy** | Diverse link at 50% of monthly recurring charge |
| **Service level** | 4-hour mean time to repair |
| **Monitoring** | Main route |



C2 General

# Annexure 6: 130SCUPH Power Consumption Data Sheet



**Table 12-32 Weight and power consumption 1830 PSS-36/64 I/O cards (continued)**

| Abbreviation | Description | Item (mnemonic) | Weight [kg] | Typical power consumption [W] |
|---|---|---|---|---|
| 10XANY10G | 10 × 10G ANY Port Unit | 10AN10G | 2.2 | 215.0 |
| 10XANY10GC | 10 × 10G ANY Port Unit (C) | 10AN10GC | 2.2 | 114.4 |
| 10XSTH10G | 10 × STM-64/OC-192 / XFP Port Unit | 10SD10G | 2.2 | 215.0 |
| 10XOTH10G | 10 × OTU2 / XFP Port Unit | 10OT10G | 2.2 | 215.0 |
| 10XETH10G | 10 × 10 GbE / XFP Port Unit | 10ET10G | 2.2 | 215.0 |
| 10XETH10GC | 10 × 10 GbE / XFP Port Unit (C) | 10ET10GC | 2.2 | 114.4 |
| 2XANY40G | 2 × 40G ANY Port Unit | 2AN40F1 | 2.2 | 120.0 |
| 2XANYQ40G | 2 × 40G ANY Port Unit with QSFP+ module | 2AN40G | 1.4 | 88.0 |
| 24XANYMR | 24 × Multirate ANY Port Unit | 24ANM | 2.2 | 102.0 |
| 24XANYMRB | 24 × Multirate ANY Port Unit | 24ANMB | 2.2 | 90.0 |
| 24XSTHMR | 24 × SDH/SONET / SFP Port Unit | 24SDM | 2.2 | 102.0 |
| 8XETH1G | 8 × 1 GbE / SFP Port Unit | 8ET1G | 2.2 | 64.0 |
| 8XETH1GB | 8 × 1 GbE / SFP Port Unit | 8ET1GB | 2.2 | 32.0 |
| 24XETH1G | 24 × 1 GbE / SFP Port Unit | 24ET1G | 2.2 | 102.0 |
| 24XETH1GB | 24 × 1 GbE / SFP Port Unit | 24ET1GB | 2.2 | 90.0 |
| 11QCUPC | 4 × 11G Switchponder | 11QCUPC | 2.2 | 134 |
| 43SCUP | 1 × 43G Switchponder | 43SCUP | 2.2 | 180 |
| 130SCUP | 1 × 130G Switchponder | 130SCUP | 2.2 | 260 |
| 130SCUPB | 1 × 130G Switchponder (B) | 130SCUPB | 2.2 | 200 |
| 130SCUPC | 1 × 130G Switchponder (C) | 130SCUPC | 2.2 | 200 |
| 130SCUPH | 1 × 130G Switchponder (H) | 130SCUPH | 2.2 | 160 |
| 1XANY100G | 1 × 100G ANY Port Unit | 1AN100G | 2.2 | 97 |
| 103SCEC | 1 × 100GbE Switched Port Unit (103SCEC) | 103SCEC | 2.5 | 149 |
| 11OCEC | 8 × 10GbE Switched Port Unit (11OCEC) | 11OCEC | 1.9 | 150 |
| SFC8 | Static Filter CWDM Card for eight CWDM channels | SFC8 | 1.1 | 0.2 |

# Annexure 7: 4UC400/2UC400/4UC1T/ 2UC1T Data Sheet



*Table 9-45* Weight and power consumption 1830 PSS-24x I/O cards (continued)

| Abbreviation | Description | Item (mnemonic) | Part number | Weight [kg] | Power consumption [W] | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Percent Utilization | | | Max [1] |
| | | | | | 0% | 50% | 100% [1] | |
| 10AN1T | 10 x 100G / 2 x 400G ANY Port Unit | 10AN1T | 3KC61010AB | 3.6 | 108 | 177 | 251 | 275 |
| 2UC400 | 2 × 200G Uplink Card | 2UC400 | 3KC59824AA<br>3KC60346AA | 4.2 | 272 | 291 | 305 | 384 |
| 4UC400 | 4 × 100G Uplink Card | 4UC400 | 3KC59925AA | 3.5 | 270 | 282 | 309 | 370 |
| 20UC200 | 20 × 10G Uplink Card | 20UC200 | 3KC35452AA | 2.2 | 57 | 81 | 107 | 195 |
| 4UC1T | 2 x 400G, 300G / 4 x 200G Uplink Card | 4UC1T | 3KC61074AA | 2.8 | 115 | 198 | 277 | 299 |
| 8UC1T | 8 × 100G / 5 × 200G Uplink Card | 8UC1T | 3KC61026AA | 3.6 | 175 | 290 | 410 | 445 |
| 2UC1T | 2× 200G-500G Uplink Card | 2UC1T | 3KC61122AA | 2.6 | 140 | 235 | 330 | 360 |
| 6SE300 | 3 × 100GbE Ethernet Client Card | 6SE300 | 3KC60165AA | 2.3 | 175 | 215 | 235 | 268 |
| 30SE300 | 30 × 10GbE Ethernet Client Card | 30SE300 | 3KC60153AA | 2.3 | 190 | 217 | 256 | 300 |

**Notes:**

1. The power consumption values 100% and Max include the optical modules in service on all ports.

*Table 9-46* Weight and power consumption 1830 PSS-24x miscellaneous parts

| Abbreviation | Description | Item (mnemonic) | Part number | Weight [kg] | Pwer consumption [W] | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Percent Utilization | | | Max |
| | | | | | 0% | 50% | 100% | |
| **Miscellaneous** | | | | | | | | |
| | 1830 PSS-24x rack door kit | | 3KC40952AA | 20.4 | NA | NA | NA | NA |
| IOCBLANK | IO card blank front plate | IOCBLANK | 3KC59819AC | 2 | NA | NA | NA | NA |
| | 1830 PSS-24x shelf blank (ETSI) | | 3KC50707AA | 10 | NA | NA | NA | NA |
| | 1830 PSS-24x shelf blank (ANSI) | | 3KC50699AA | 10.5 | NA | NA | NA | NA |
| | 1830 PSS-24x air filter | | 3KC60351AA | 0.4 | NA | NA | NA | NA |
| | SFP dummy plug kit (16 pieces) | KITSFP | 3AL89857AA | 0.2 | NA | NA | NA | NA |



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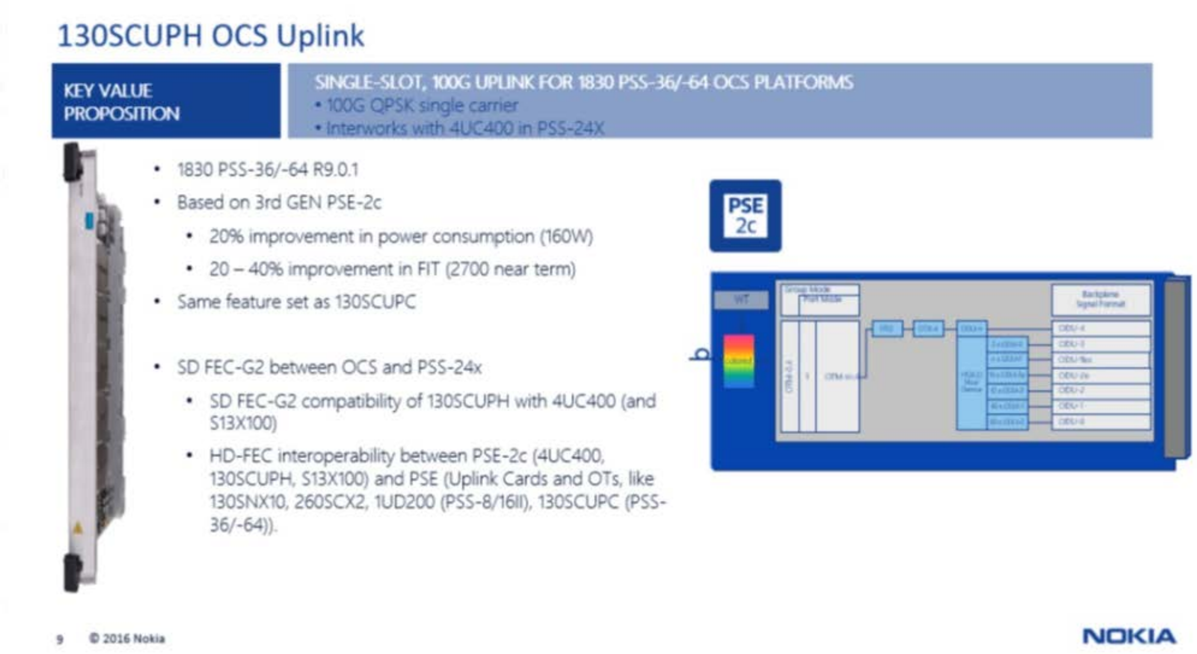
# Annexure 8: 130SCUPH Data Sheet






C2 General