SUDAN UNIVERSITY OF SCIENCE &TECHNOLOGY

College of Graduate Studies

Performance Evaluation of Fixed Grid and Flex Grid in Dense Wavelength Division Multiplexing

تقييم اداء الشبكة الثابتة والشبكة المرنة في مضاعفات كثافة الطول الموجئ المقسم

A thesis Submitted in Partial Fulfillment for the Degree of M.Sc in Electronics Engineering Communication Engineering

Prepared by:

Yassir Mohammed Osman Elsheikh

Supervised by:

Dr.Ashraf Gasim Elsid Abd Allah

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DEDICATION

I dedicate this research to my family and beloved parents, who have been my source of inspiration and who continually provide their moral, spiritual and emotional
To my brothers, sisters, friends and all knowledge seekers May you benefit from it.

ACKNOWLEDGEMENTS

This dissertation would not have been possible without the guidance and the help of several individuals, who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study. Firstly and foremost, I would like to thank my supervisor Dr. Ashraf for given me the opportunity to realize my Master research at Sudan University of science and Technology. I am deeply grateful for the advice and support that I have received from him over the six months. My most sincere thanks goes to Ali Masud, who supported me throughout this thesis and contributed greatly to my simulation on Flex Grid networks. Working with you was an opportunity to learn a lot, and acquire precious knowledge on optical communication and DWDM. It was a great pleasure to work with a person like you, who is active, full of energy and ideas. I would especially like to thank Zhang, Mansoor and Ahsan, who provided their expertise to enable this thesis to work well and for their support. The many discussions we have had, has helped me a lot. I am very grateful for their feedback on this work. I would like to express my deep gratitude and sincere thanks to Mr. Mutasim and Mr. Salah for their support and help during the preparation and the completion of this thesis. I am very grateful to my family, especially my parents for their patience, motivation and support during this research. Finally, the deepest gratitude and heartiest thanks goes to my wife for her continuous help and moral support.

Abstract

Since the Internet services (video conferencing, cloud services and video streaming) and consequently traffic demands are increasing continually, leading to huge traffic growth in the core optical network. There is a need for network operators to increase their optical network capacity to follow this traffic growth

The aim of this thesis to Perform Evaluation of Fixed Grid and Flex Grid in Dense Wavelength Division Multiplexing and analyze the effect of using Flex Grid on the proposed network, different levels of Bandwidth were taken to observe the utilization .It has been observed that at flex can save BW by reducing the space between channels .

المستخلص

نظرًا لأن خدمات الإنترنت تتزايد (مؤتمرات الفيديو والخدمات السحابية وتدفق الفيديو) وبالتالي تتزايد طلبات المرور باستمرار ، مما يؤدي إلى نمو هائل في حركة المرور في الشبكة البصرية الأساسية. هناك حاجة لمشغلي الشبكات لزيادة سعة الشبكة البصرية لمتابعة نمو حركة المرور

الهدف من هذه الأطروحة هو إجراء تقييم للشبكة الثابتة والشبكة المرنة في مضاعفة تقسيم الطول الموجي الكثيف وتحليل تأثير استخدام على الشبكة المقترحة ، وقد اتخذت مستويات مختلفة من عرض النطاق الترددي لمراقبة الاستخدام . ويمكن حفظه عن طريق تقليل المسافة بين القنوات فى الشبكة المرنة .

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Abbreviations

Abbreviation	**Description**
ADM	Add and Drop Multiplexer
AGC	Automatic Gain Control
ALC	Automatic Level Control
ALS	Automatic Laser Shutdown
APD	Avalanche Photo Diode
APR	Automatic Power Reduction
ASE	Amplified Spontaneous Emission
AWG	Arrayed Waveguide Grating
BA	Booster Amplifier
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CapEx	Capital Expenditure
CATV	Community Access television
CD	Chromatic Dispersion
CLNS	Connectionless Network Layer Service
CMI	Coded Mark Inversion
CRC	Cyclical Redundancy Check
CSES	Continuous Severely Errored Second
CWDM	Coarse Wavelength Division Multiplex
DCM	Dispersion Compensation Module
DCC	Data Communication Channel
DCF	Dispersion Compensation Fibre
DCN	Data Communication Network
DDN	Digital Data Network
DFB	Distributed Feedback

Abbreviation	**Description**
DSP	Digital Signal Processor
DWDM	Dense Wave Division Multiplexing
ECC	Embedded Control Channel
EDC	Electronic Dispersion Compensation
EDFA	Erbium-Doped Fiber Amplifier
ETSI	European Telecommunication Standards Institute
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FIFO	First In First Out
FSO	Free space networks
FTTX	Fiber to the X
FTTH	Fiber to the Home
GE	Gigabit Ethernet
GUI	Graphic User Interface
IEEE	Institute of Electrical and Electronic Engineers
ICT	Information Communication Technology
InP	Indium Phosphide
ITU	International Telecommunication Union
λ	Lambda, or one optical wave
LA	Line Amplifier
LAN	Local Area Network
LCN	Local Communication Network
LCoS	Liquid Crystal on Silicon
LCT	Local Craft Terminal
LD	Laser Diode
MCF	Message Communication Function
MD	Mediation Device

Abbreviation	Description
MEMS	Micro-Electrical-Mechanical Systems
MPI-R	Main Path Interface at the Receiver
OA	Optical Amplifier
OADM	Optical Add and Drop Multiplexer
OD	Optical Demultiplexing
ODF	Optical Distribution Frame
ODU0	OTN Optical channel Data Unit 0 (~1.25 Gb/s)
OEO	Optical-Electrical-Optical
OFDM	Optical and Frequency Division Multiplex
OLA	Optical Line Amplifier
OM	Optical Multiplexing
OOK	On-Off Keying
OpEx	Operational Expenditure
OSC	Optical Supervisory Channel
OSI	Open Systems Interconnection
OSNR	Optical Signal to Noise Ratio
OTM	Optical Terminal Multiplexer
OTN	Optical Transport Network
OTU	Optical Transponder Unit
PA	Pre-amplifier
PDH	Plesiochronous Digital Hierarchy
PIC	Photonic Integrated Circuit
PIN	Positive Intrinsic Negative
PMD	Polarization Mode Dispersion
PM-QPSK	Polarization Multiplexed QPSK
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation

Abbreviation	**Description**
QPSK	Quadrature Phase Shift Keying
ROADM	Reconfigurable Optical Add/Drop Multiplexer
ROF	Radio over fiber
RX	Receive
SCC	System Control & Communication
SDH	Synchronous Digital Hierarchy
SDM	Space Division Multiplexing
SNCP	Subnetwork Connection Protection
SONET	Synchronous optical networking
STM	Synchronous Transport Module
TCP/IP	Transport Control Protocol/Internet Protocol
TDM	Time Division Multiplexing
TMN	Telecommunication Management Network
TTL	Transistor-Transistor Logic
TX	Transmit
WDM	Wavelength Division Multiplexing

Chapter One

Introduction

1 Introduction

1.1 Preface

Flex grid is likely to be used in the future for Wavelength Division Multiplexing (WDM) networks, providing operators with additional flexibility when assigning spectrum compared to traditional WDM networks using the 50GHz ITU grid. Flex grid breaks the spectrum up into small, typically 12.5GHz slots, but its key feature is that contiguous slots can be joined together to form arbitrary sized blocks of spectrum.

This additional flexibility will allow faster transponder that utilize high spectral efficiency modulation techniques, but no longer fit within a 50GHz slot due to their larger spectral width requirements, to be carried by the optical network. From the use of these new spectrum efficient modulation formats and finer control over spectrum allocations, a key benefit that Flexgrid offers network operators is that their WDM networks can carry more traffic.

This research will look at the capacity improvements by reducing the space between channels to add higher capacity channels using the same number or wavelength, which can be realized on a WDM network that is using Flex grid over those that are using a traditional fixed grid.

In this research, shows the Flexgrid can provide high efficiency utilization of optical network resource and capacity improvements, which can be made in a WDM network by reducing the space between channels instead of a traditional fixed grid network.

1.2 Problem statement

Traffic demands are increasing continually, leading to huge traffic growth in the core optical network and network traffic increases sharply. and are expecting to see ever increasing traffic demands over the coming years .

. The transmission rate increases to 400 Gbit/s or even 1 Tbit/s, broadening the spectrum of optical signals.

Continued internet-based exponential traffic growth has resulted that DWDM Spectrum to start to fill. The current Technology with fixed frequency spacing of 50 GHz is wasting space between channels due to high Guard band, Moreover; the deployment of new optical fibers is still very expensive.

1.3 Proposed Solution

Compare between Fixed Grid and Flex grid to see the difference in Bandwidth Expected traffic volumes for short and medium term (few Tb/s of total traffic) are not enough to justify immediate flex-grid deployment across entire network. Some links grow more quickly than others and become congested, acting as bottle necks to future network growth.

It is in those links where flex-grid can be first deployed to extend network lifetime.

1.4 Objectives

The aim of this thesis is to show how the use of Flex Grid technology will reduce the space between channels to provide high efficiency utilization of existing DWDM network resource. And how the capacity will be improved compare to traditional fixed grid network.

1.5 Methodology

Simulating a different cases and how this improvement in capacity by using the same resource and same frequency range.

Compare between Fixed Grid and Flex grid By Simulation of 80 channels in 4 scenarios.

Two scenarios 80 channels divided in 30 Channels 10G, 30 Channels 100G and 20 channels 400 G Fixed Grid and Flex grid

Another two scenarios for 80 channels full 400G, Fixed grid and Flex grid. to see the difference in Bandwidth when using Fixed Grid and Flex grid.

1.6 Thesis outlines

The details of the chapter, as follows:-

Chapter two:

Background about DWDM and the benefit of use, flex grid in state of fixed grid in WDM (Wavelength Division Multiplexing) to reduce the space between channels and carry more channels to increase the traffic capacity

Chapter three:

Simulation setup, Show the simulation of design and implementation of 80 channels in four scenarios.

Chapter Four:

Result and compare between Fixed Grid and Flex grid in all cases and proof that Flex grid can provide high efficiency utilization of optical network resource and capacity improvements.

Chapter Five: Discuss the conclusion and recommendation.

Chapter Two

Theoretical background and related studies

2 Theoretical background and related studies

2.1 Background

The continuous demand for additional optical transport bandwidth is driving new technology at a Very fast pace to increase spectral efficiency and bandwidth utilization, all while lowering the overall transport cost per bit. Multi-carrier super-channels (which operate on a flexible grid channel plan that supports variable bandwidth channels) increasing spectral capacity by eliminating passive protection bands associated with fixed network channel plans and by enabling scalable modulation formats, which allow operators to configure their networks for optimum spectral capacity versus access. 16QAM modulation can deliver up to 24 Tb/s of capacity per fiber, but at the expense of much shorter reach compared to QPSK.

Ideally, multi-carrier super-channels will support independent tuning of each wave in the super-channel, which will allow super-channel carriers to be configured as independent waves, using independent modulation techniques, or in combinations that support one or more super-channels of varying size, up to the full bandwidth of the super-channel. One likely configuration for future super-channels is a 12x100G multi-carrier channel, which will transport three 400G Ethernet services in a 1.2 Tb/s super-channel, configured either as one 1.2 Tb/s channel or as three 400 GB/s channels. Multi-carrier super-channels offer the promise of significantly increasing transport capacity per fiber while providing greatly enhanced flexibility, both of which result in increased network efficiency.

To support multi-carrier super-channels, a flexible grid line system is required, which allows channel and switching bandwidth to be assigned as needed to each individual variable bandwidth super-channel. The flexible grid architecture supports bandwidth assignments in the C-band in 12.5 GHz increments, allowing efficient use of the C-band for both fixed and flexible grid channels. To achieve maximum transport efficiency with super-channels, which have much higher bandwidth than 100G fixed grid waves, a multi-layer switching architecture with integrated optical and digital layer switching is required. This architecture optimizes super-channel bandwidth utilization by allowing sub-lambda OTN digital grooming within and between super channels, and optimizes super-channel routing between destinations with flexible grid optical.

2.2 WDM Technology

2.2.1 DWDM Principle

The optical communication system can be classified according to different modes. If it is categorized according to signal multiplexing mode, it can be categorized into Frequency Division Multiplexing (FDM) figure 2.1, Time Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM) and Space Division Multiplexing (SDM). All refer to optical communication systems classified according to the frequency, time, wavelength and space. It can be said that frequency is closely connected with the wavelength. Frequency division is wave division. But in optical communication system, WDM system adopts optical spectral component that is different from filter adopted in the common communication.

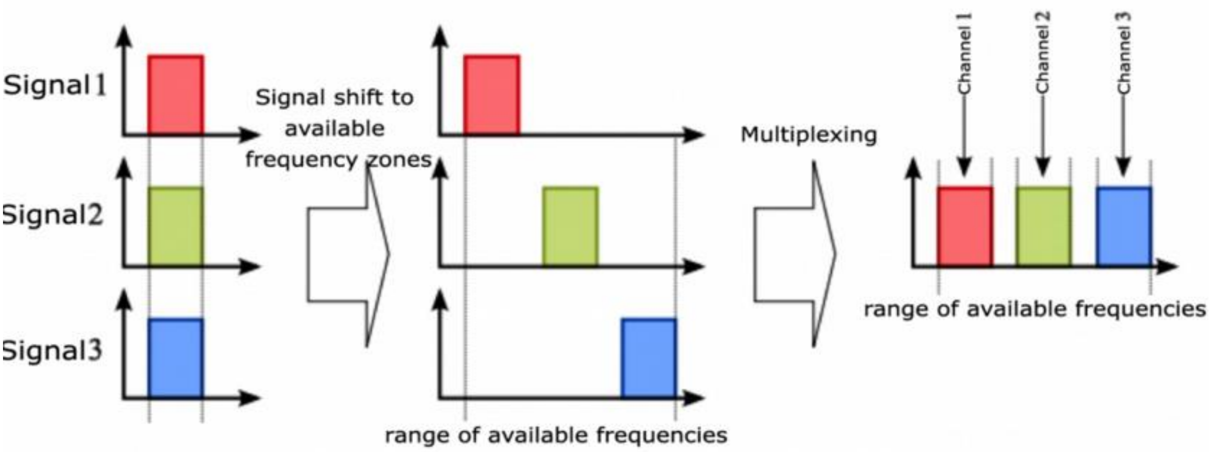


Figure 2.1 Frequency Division Multiplexing

It still classify into two different systems. WDM is a kind of transmission technology of fiber communication. Depending on the fact that a fiber can transmit several optical carrier of different wavelengths at the same time, it divides wavelength possibly used by fiber into several bands.

As an independent channel, each band transmits a kind of optical signal with a preset wavelength. Optical and wavelength division multiplex is in fact the optical and frequency division multiplex on fiber (OFDM), but optical wave usually use wavelength instead of frequency, to describe, supervise and control. Along with the development of the electric-optical technology, the wavelength density in the same fiber will become very high. Compared with Dense Wavelength Division Multiplexing (DWDM) there are still WDM with low densities that are called Coarse Wave Division Multiplexing (CWDM).

A fiber can be regarded as a road with several driveways here. The traditional TDM system just uses one of driveways. To increase bit rate is to increase the driving speed in the driveway in order to increase the transportation burden in unit time. To use DWDM technology is similar to using the driveway not yet used, so as to obtain the large transportation capacity to be developed in fiber.

2.2.2 WDM Background

WDM is a technology which multiplexes a number of optical carrier signals into a single optical fiber by using different wavelengths of laser light. This technique enables bidirectional communications over one strand of fiber, as well as multiplication of capacity.

With the rapid development of science and technology, information transmission in communication area expands with accelerated speed. Information Age requires Transmission network with larger and larger capacity. In recent years, companies and manufacturers worldwide have paid more and more attention to WDM technology, and been more worried about it.

There are many methods to increase the capacity and flexibility of fiber network, and increase the transmission speed and expand capacity. The compare of the different expansion methods in the following.

2.2.2.1 Space Division Multiplexing (SDM)

The SDM method increases the transmission capacity linearly by adding the number of optical fibers, and the transmission equipment will be increased linearly as well. At present, optical cable manufacturing technology has matured greatly, the multi-core band optical cables are widely used, the advanced optical fiber connection technology makes the construction easier, but the increase in the number of optical fibers will inevitably complicate the cable layout and maintenance. If there are not enough optical fibers in the existing optical cable tunnel, it require to lay down additional cables to expand the capacity, and this method will multiply the engineering cost.

This means doesn’t make full use of transmission bandwidth of fibers as well and results in the waste of fiber bandwidth resources. As the construction of communication networks, it is impossible to expand capacity by laying down new fibers all the time. In fact, it is very hard to estimate the increasing business demand and the number of fibers that should be laid down at the beginning of the project. Therefore, the method to expand capacity in SDM is very limited.

2.2.2.2 Time Division Multiplexing (TDM)

TDM is also a commonly used method for capacity expansion, e.g. multiplexing of the primary group to the fourth group of the traditional PDH, and STM-1, STM-4, STM-16 and STM-64 of current SDH. TDM technology can enhance the capacity of optical transmission information in duplication and greatly reduce the circuit cost in equipment and line. Moreover, it is easy to extract specific digital signals from the data stream via this multiplexing method. It is especially suitable for networks requiring the protection strategy of self-healing rings. However, TDM method has two disadvantages. Firstly, Upgrading affects services. An overall upgrade to higher rate levels required to replace the network interfaces and equipment completely. Thus the equipment in operation must be interrupted during the upgrade process. Secondly, rate upgrade is not more flexible.

Let's take SDH as an example, when a system with a line rate of 155Mbit/s is required to provide two 155Mbit/s channels, the only way is to upgrade the system to 622Mbit/s even though two 155Mbit/s are idle. Presently, TDM equipment of higher rate costs much more, and the 40Gbit/s TDM equipment has reached the rate limit of the electronic component. Even for the rate of 10Gbit/s, its non-linear effect in different types of optical fibers will make different limitations on the transmission.

Currently, the TDM technology is widely used for the capacity expansion since it can expand the capacity by constantly upgrading the system rate. But when the rate reaches a certain level, the limitation due to the component and line features will drive to look for other solutions.

All the basic transmission networks, whether using SDM or TDM to expand the capacity, adopt traditional PDH or SDH technology, i.e. utilizing optical signals on a single wavelength for transmission. This transmission method is a great waste of optical capacity because the bandwidth of optical fiber is almost infinite when compared to the single wavelength channel currently use. And worrying about the jam of networks, on the other hand huge network resources are being wasted.

2.2.2.3 Wavelength Division Multiplexing (WDM)

WDM utilizes the large bandwidth of low loss band section in single-mode fibers to transmit by mixing optical signals with various rates (wavelengths). The digital signals carried by optical signals with different wavelengths can be either the format of the same rate and protocol or the format of different rates and protocol. Also can determine the network capacity according to requirement of the users by adding new features of wavelength figure 2.2. For the WDM the current technology can completely overcome the limitation due to the fiber dispersion and fiber non-linear effect. It can satisfy various requirements for transmission capacity and transmission distance. The disadvantage of WDM is that it needs many fiber components and increases the failure probability.

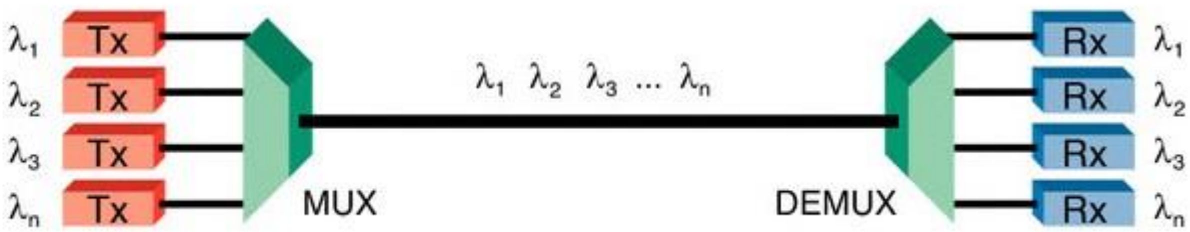


Figure 2.2 Wavelength Division Multiplexing

2.2.2.4 Technology combination of TDM and WDM

It is the application direction to make use of the technology advantages of TDM and WDM for network capacity expansion. Also can choose the highest transmission rate of TDM according to fibers of different types. On this basis, moreover can choose the number of WDM optical channels according to the transmission capacity and use the maximum optical carriers under the possible condition. Undoubtedly the transmission capacity of multi-channel is forever bigger than that of single channel and is more economical.

2.3 Overview OF DWDM Principle

Based on such features as bandwidth and low loss of the single mode optical fiber, the DWDM technology uses multiple wavelengths as carriers and allows the signals to be transmitted simultaneously over the carrier channels in the optical fiber.

Compared with the general single channel system, the dense WDM (DWDM) not only drastically increases the communication capacity of the network system and fully uses the bandwidth of the optical fiber, but also has many advantages, such as simple expansion and reliable performance especially it can directly access multiple services, so it enjoys bright prospects.

In analog carrier communication systems, the frequency division multiplexing (FDM) method is often adopted to make full use of the bandwidth resources of cables and enhance the transmission capacity of the system. That is, to transmit several signals of different frequencies simultaneously in the same cable and, at the receiver end, to utilize band-pass filters to filter the signal on each channel according to the frequency differences among the carriers. In the same way, in optical fiber communication systems, optical frequency division multiplexing method can also be used to enhance the transmission capacity of the systems. In fact, this multiplexing method is very effective in optical communication systems.

Unlike the frequency division multiplexing in analog carrier communication systems, optical fiber communication systems utilize optical wavelengths as signal carriers, divide the low attenuation window of optical fibers into several channels according to the frequency (or wavelength) difference of each wavelength channel and implement multiplexing transmission of multi-channel optical signals in a single fiber. Since some optical components (such as narrow-bandwidth optical filters and Coherence light source) are currently very immature, it is difficult to implement the Ultra-dense optical frequency division multiplexing (coherence optical communication Technology) of optical channels. However, alternate-optical-channel frequency division multiplexing can be implemented based on the current component technical level.

Usually, multiplexing with a larger channel spacing (even in different windows of optical fibers) is called optical wavelength division multiplexing (WDM), and DWDM in the same window with smaller channel spacing is called dense wavelength division multiplexing (DWDM) , Figure 2.3. With the progresses of sciences & technologies, the multiplexing of the nanometer level wavelength spacing can be implemented by using modern technologies. Even the multiplexing of sub-nanometer level wavelength spacing can be implemented, only need stricter component technical requirements. Hence, multiplexing of 16, 40, 80 or more wavelengths with smaller wavelength spaces is called DWDM. The frequency grid defined by ITU-T G.694.1 supports a variety of channel spacing ranging from 12.5 GHz to 100 GHz and wider (integer multiples of 100 GHz). Uneven channel spacing are also allowed.

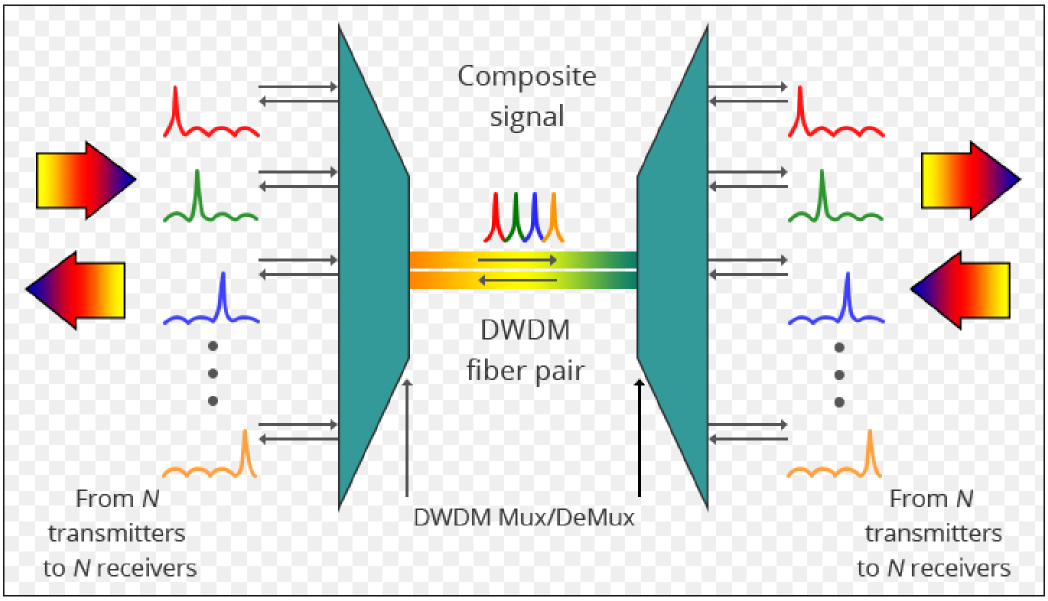


Figure 2.3 Dense Wavelength Division Multiplexing

2.3.1 Advantages of DWDM

The capacity of optical fiber is huge. However, traditional optical fiber communication systems, with one optical signal transmitted in a single fiber, only exploited a little part of the abundant bandwidth of optical fiber. To fully use the huge bandwidth resources of optical fiber and increase its transmission capacity, a new generation optical fiber communication technology based on the dense WDM (DWDM) has emerged. The DWDM technology has the following features:

2.3.1.1 Super-large capacity

The transmittable bandwidth of the current widely used conventional fiber is very wide, but the utilization ratio is still low. By using DWDM technology, the transmission capacity of a single optical fiber is increased by several, tens of or even hundreds of times when compared to the transmission capacity of single wavelength systems. The current highest commercial transmission capacity is 1.6 T bit/s.

2.3.1.2 Data transparency transmission

DWDM systems conduct multiplexing and de-multiplexing in terms of optical wavelength differences and are independent of signal rates and modulation modes, which is transparent to the data. A WDM system service can carry “service” signal of many formats, such as ATM, IP or signals that may appear in the future. WDM implements the transparent transmission. For signal at the “service” layer, each optical wavelength channel in the WDM system is like the “virtual” optical fiber.

2.3.1.3 Protection of the existing investment during system upgrade

In expanding and developing the network, it is not necessary to make changes to the optical cable lines, instead, just change the optical transmitter and receiver, so this is an ideal expansion method and also a convenient way to introduce the broadband services (such as CATV, HDTV and B-ISDN etc.). With an additional wavelength, and can add any new service or new capacity required.

2.3.1.4 High networking flexibility, economy and reliability

When compared to the traditional networks using electrical TDM networks, new communication networks based on the WDM technology are greatly simplified in architecture and have clear network layers. Dispatching of various services can be implemented simply by adjusting the corresponding wavelengths of the optical signals. Because of the simple network architecture, clear layers and convenient service grooming, the flexibility, economy and reliability of networking are obvious.

2.3.1.5 Compatible with all optical switching

It is expected that, in the all optical networks realizable in the future, processing of telecommunication services adding/dropping and cross connections is implemented by changing and adjusting the optical signal wavelengths. So WDM technology is one of the key technologies to implement all optical networks. Moreover, WDM systems can be compatible with future all optical networks. It is possible to implement transparent and highly survivable all optical networks based on the existing WDM system.

2.3.2 Flexgrid Compared to Inverse Multiplexing

Inverse multiplexing is one technique to enable higher bitrate services to continue to use a fixed grid. In this approach, multiple lower bitrate channels are multiplexed together to form a higher aggregated bitrate. For example, a 400Gbit/s signal could be transmitted using 4 x 100Gbit/s sub-signals each of which could continue to fit within a 50GHz channel. This approach does have the drawback that more spectrum is utilized than is absolutely necessary:
using 4 x 100Gbit/s channels uses 200GHz of optical spectrum compared to just 75GHz for transferring a native 400Gbit/s signal. The use of simpler modulation formats in inverse multiplexing does however mean that signals should be able to propagate over longer distances.
For the Flexgrid scenario, a small amount of spectrum (12.5GHz) needs to be placed between signals to form a guard band.

2.3.3 Modulation Formats and Coherent Detection

Most 100G optical transport systems today use PM-QPSK modulation with coherent detection. Coherent detection is commonly used because it provides superior OSNR (Optical Signal to Noise Ratio) performance (and hence better reach) when compared to non-coherent detection. Coherent detection is typically implemented in a DSP (Digital Signal Processor), which lends itself well to providing additional signal processing functions such as electronic dispersion compensation (EDC).

EDC eliminates the need for external Dispersion Compensation Modules (DCMs) and typically provides a much wider range of compensation for both CD and PMD. Of course, there is usually a tradeoff to achieve increased performance, and in this case, coherent Detection is more complex to implement than non-coherent detection and requires more power As well. However, the benefits of coherent detection and enhanced EDC generally make the tradeoffs worthwhile.PM-QPSK provides a good tradeoff between spectral efficiency and reach, especially since a100 Gb/s wave using PM-QPSK efficiently utilizes a 50 GHz channel in the fixed ITU-T grid.

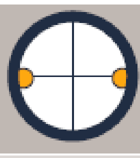
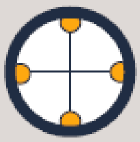
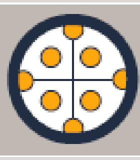
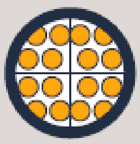
Modulation Format	Bits / Symbol	Constellation
OOK / BPSK	1	
QPSK	2	
8 QAM	3	
16 QAM	4	

Figure 2.4 Encoded Bits / Symbol and Data Constellations for Common Modulation Formats

However, other modulation formats can be used as well, including lower order modulation (e.g., BPSK, or Binary Phase Shift Keying) or higher order modulation (e.g., 16QAM, or Quadrature Amplitude Modulation). Figure 2.4, previous page, shows the encoded bits per symbol and typical constellation diagrams for four common modulation formats. For a given data rate, there are performance tradeoffs depending on the modulation format used. Higher order modulation formats, which have reduced spacing between symbol states when compared to lower order formats, are more susceptible to noise and will have a higher BER (Bit Error Rate), all else being equal. Decreased noise immunity translates to reduced transport reach for equivalent BER performance. So while higher order modulation is more spectrally efficient, its reach is shorter. For example, 16QAM with four bits encoded per symbol is spectrally twice as efficient as QPSK with two bits encoded per symbol, but its reach is about a quarter of that of QPSK.

Modern optical transport systems are capable of supporting multiple modulation formats, which can be provisioned per wave in software, and for the first time this allows cable operators to optimize their transport networks for reach versus spectral efficiency, which results in lower costs. Since the modulation format in these systems is available, this implies variable bandwidth waves, with the final bandwidth determined by the modulation format selected by the operator.

For fixed-channel ITU-T grid plans, where the channel widths and assignments are fixed, this means any improvement in spectral efficiency per wave (assuming the data rate per wave remains constant) does not translate into more capacity per fiber. It does, however, provide backwards compatibility with fixed grid systems, which work efficiently for waves up to 100 GB/s.

Achieving increased fiber capacity with scalable modulation requires a flex-grid system that supports variable bandwidth channels where bandwidth can be allocated in 12.5 GHz increments per wave and each wave's center frequency can be assigned as needed.

2.3.4 Flexible Grid Architectures

In traditional WDM networks, it depends on the fixed ITU-T grid and the spacing specified in it, however the coarse divisions of this network result in poor spectrum utilization. To reduce spectrum loss due to guard bands in the fixed grid channel plan and to support high capacity super-channels to meet evolving bandwidth demands, ITU-T has defined a flexible grid in the latest WDM grid specification, G.694.1.

The new flexible grid defines WDM channels having a frequency slot width Subdivisions of 12.5 GHz with 6.25GHz central frequency Subdivisions in contrast to the coarser 50 GHz width in the fixed grid. The flexible grid gives the ability to define an aggregate super-channel spectral width of N × 12.5 GHz to accommodate any combination of optical carriers, modulation formats, and data rates.

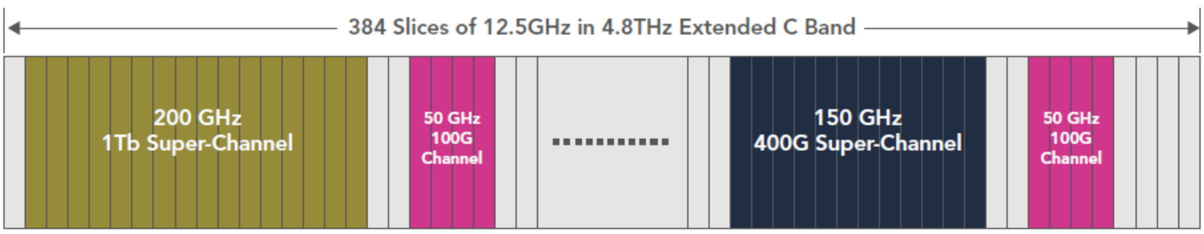


Figure 2.5 ITU-T G.694.1 Flexible Grid Architecture

This supports scalable modulation formats, which allow operators to balance their requirements for increased spectral efficiency versus extended reach of the optical signals. In addition, the flexible grid provides the capability to flexible allocate frequency slots on demand and/or modify the modulation format of optical channels according to traffic demands. This allows resources to be used efficiently in response to traffic variations. Figure 2.5, above, shows an example of a flexible grid spectrum allocated to 400G and 1Tb super-channels along with today's 50 GHz 100G channels.

The main motivation for deploying flexible grid technology is to make the network future proof by creating an optical line system that can be used for future transmission formats that may require more than 50 GHz channel spacing. Over the past two decades the bit rates and modulation formats of optical transmission systems have evolved dramatically, from 2.5 Gb/s to 100 Gb/s PM-QPSK. As this progression to increased bit-rate per channel has continued, it has become increasingly difficult to increase the bit rate while maintaining spectral efficiency and reach.

To space 100 GB/s channels 50GHz apart has required the adoption of dual polarization QPSK transmission. But to support even higher data rate super-channels, which will require spectrum to be allocated in multiples of 12.5GHz depending upon the reach and capacity requirement for that link, a flexible grid line system is ideal, and will allow operators to install line systems today that will be able to accommodate virtually any type of super-channel tomorrow.

2.4 Migration to Flexible Grid

For Green field applications, depending on the operator's requirements, it makes sense to install a flexible grid architecture throughout the network. While a flexible grid network provides several benefits, it is unlikely in brownfield applications that the entire network needs to be upgraded to flexible grid on day one. Starting from a network with enough capacity for growth, the most likely scenario is that some links in the network will grow more quickly than others and become congested, acting as bottle necks to future network growth. It is in these links where flexible grid will likely be first deployed to extend network capacity, and thereby delay the need for lighting up a second fiber pair.

A migration strategy is thus required so that new technology can be introduced where it has the most benefit, but without having to start with a new network build. Unfortunately, such a migration has been infeasible in the past, mainly due to the lack of interoperability between old and new line systems. There are, however, some synergies between the fixed flexible grids, mostly due to the capabilities of flexible grid. Fortunately, flexible grid ROADMS are capable of supporting fixed grid channels simultaneously with flexible grid channels, which can allow existing fixed grid waves to co-reside on a flexible grid line system with multi-carrier super channels.

A full description of all the steps necessary to engineer and migrate a line system from fixed to flexible grid is beyond the scope of this research. Figure 2.6 shows the Evolution of ROADM with Fixed Grid Bandwidth Management 50 GHz to Nx12.5Ghz Flexible Grid Bandwidth Management, which require traffic to be temporarily migrated off the span to be upgraded and the new flexible grid line system components to be installed.

The original fixed grid traffic may then be moved back on to the original span, and any new super-channels may then be turned up. It may be necessary or desirable as the original fixed grid channels are being moved back to their original span to allocate these to new channels in the grid to maximize available bandwidth for super-channels and to minimize any engineering constraints for optical layer performance.

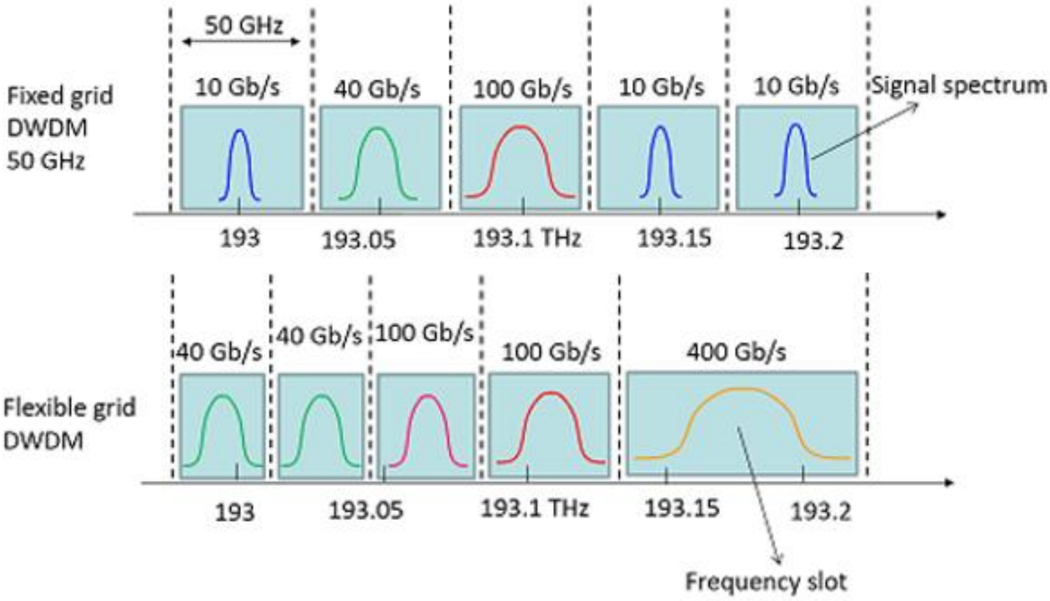


Figure 2.6 Flexible grid vs fixed grid

2.4.1 Limitations of fixed grid

- In fixed grid (channel spacing) network, constant spectral resource is allocated to every channel with different bitrates, resulting relatively low resource unitization efficiency.
- High Speed Signals beyond 100 GB/s are not expected to adapt such narrow channel spacing like 50 GHz.

2.4.2 Solutions in flex grid

- ✓ High capacity and high efficiency utilization of optical network resource is required. Flexible grid technique is a candidate to accomplish this requirement.
- ✓ High resource utilization efficiency for mixed bitrates systems.
- ✓ Adaptive to transmission distance and optical impairments.
- ✓ Support ultra-high speed modulation format like OFDM.

2.5 Identifying the Problem:

- ➢ Until recently, the large available spectrum provided by optical fiber has been significantly more than required.

- ➢ Adding more data to a fiber was a simple matter of adding additional wavelengths, making use of the fact that at low enough power levels, multiple waves can be supported on the same fibre without interaction. Recently, continued internet-based exponential traffic growth has resulted in this spectrum to start to fill.

- ➢ This has focused attention on two related areas—how to more effectively manage the spectrum and how to fill the spectrum up as much as possible with light signals.

2.6 Solution: Flex-Grid Network

- ➢ ITU-T proposed a finer grid associating a variable frequency slot to an optical connection, called flexible frequency grid, or more commonly flex-grid.

- Flex-grid allows the allocation of a variable number (n) of fixed-sized slots to an optical channel as per demand. A slot measures 12.5 GHz, allowing the transmission of 100 Gb/s channels in 37.5 GHz (n = 3), rather than 50 GHz in the fixed grid case. Figure 2.7.

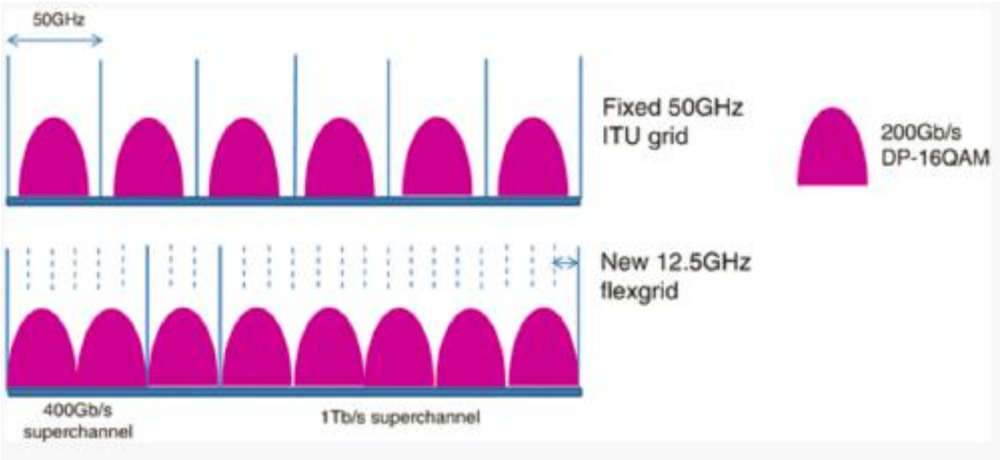


Figure 2.7 flex Grid

12.5 GHz resolution for flex-grid allow closer packing of channels. Sequencing allows creation of 1 400 GB/s and 1 Tb/s super-channel

2.7 Shift to flex-grid

Capacity exhaustion is not the only motivation behind migration.

- In short term, the use of higher bit rates and advanced modulation formats for specific connections will allow cost-effective 400 GB/s (and beyond) signals.

- In medium term, Sliceable Bit Rate Variable Transponders (SBVT) will be helpful to increase the reach of flex-grid areas to those parts where, although spectrum will not be exhausted yet, the capability of splitting multiple flows will be beneficial.

- In the long term (>2022), capacity exhaustion as a result of dealing with expected traffic volumes of hundreds Tb/s or even some Pb/s will require deploying flex grid. Legacy fixed-grid equipment would then be completely upgraded to flex grid in the core.

2.8 Approach

2.8.1 The Research Question, Hypotheses and the Specific Objectives of Research

The ITU WDM grid has now been in use for the past 20 years offering network operators the choice of either 50GHz or 100GHz fixed spaced channels. These fixed grids have allowed operators to serve this traffic growth well by either simply increasing the speed of the transponders on each channel or by moving to the denser grid spacing as the traffic levels have increased. During this time, transponders have increased in speed from 2.5Gbit/s up to today's 100Gbit/s Transponders with improvements in technology allowing them to keep within a 50GHz channel as shown in Figure 2.8.

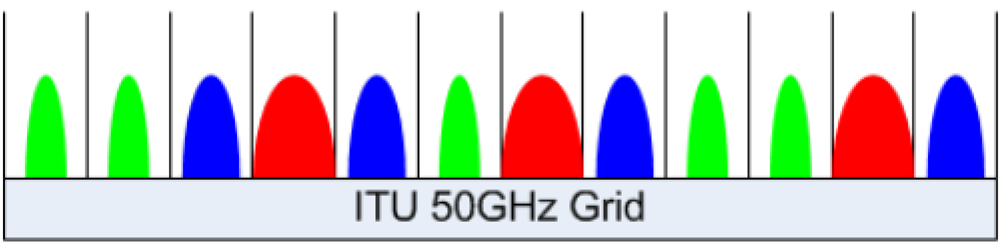


Figure 2.8 ITU-T 50 GHz

For the next generation of systems, research into producing a 400Gbit/s transponder using standard modulation formats so that the signal can still be carried over useful distances has shown that it is difficult to keep the spectral width below 50GHz. Trying to pass such a wide signal through a 50GHz filter results in the signal becoming notched as shown in Figure 2.9.

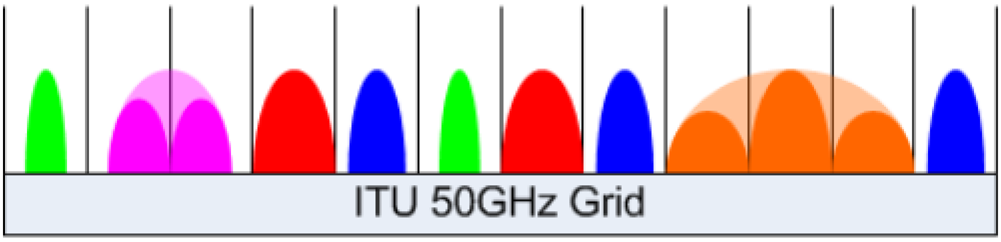


Figure 2.9 when using 400G

This would therefore mean that the 50GHz grid would no longer be able to support future traffic growth. One option would be to move to the 100GHz grid, but this would be wasteful of spectrum for services that use lower bandwidth transponders. Another possibility would be to have a fixed grid with different sized slots for different speed transponders, but that would require a prior understanding of where and when traffic growth will occur at the network design and procurement stage. What is required is a less rigid and fixed approach to wavelength allocation brought about by Flexgrid. The network capacity advantages this can bring to a network operator are covered in the rest of this research.

2.9 Related Works

ANALYSIS AND COMPARISON OF FLEX GRID AND FIX GRID NETWORK SYSTEM

Core networks offer high capacities, thanks mainly to the optical technologies they utilize, but they consume a non-negligible amount of energy. The traffic volume in metro and core networks is forecast to grow at very high rates, exceeding 30% per year for the next five years, and if the corresponding energy requirements grow analogously, they will sooner rather than later form a bottleneck for network communications. Thus, energy efficiency in optical networks is mandatory for the sustainability of the future Internet.

The objectives of the current work are to identify the main causes of energy consumption for current fixed grid wavelength division multiplexing and future flex-grid optical networks, and to propose and compare techniques for improving their energy efficiency. Wavelength Division Multiplexing (WDM) networks of the future are likely to use Flexgrid, providing operators with additional flexibility when assigning spectrum compared to traditional WDM networks using the 50GHz ITU grid. Flex grid breaks the spectrum up into small (typically 12.5GHz) slots, but its key feature is that contiguous slots can be joined together to form arbitrary sized blocks of spectrum. This additional flexibility will allow faster transponders that utilize high spectral efficiency modulation techniques, but no longer fit within a50GHz slot due to their larger spectral width requirements, to be carried by the optical network. From the use of these new spectrum efficient modulation formats and finer control over spectrum allocations, a key benefit that Flex grid offers network operators is that their WDM networks can carry more traffic.

2.9.1 What they do

Analysis and compare between flex grid and fix grid network system, and explain that due to the increasing pressure on network operators to provide higher bandwidth with more efficient resource utilization it required new solution

2.9.2 How

Example given for fixed grid to flex grid network in practice, a likely scenario is that traffic load son some nodes/links are significantly higher than others, so they become bottlenecks. For example, a common scenario concerns nodes associated with data centers, which tend to generate a large amount of traffic and can benefit from high-bandwidth super-channels interconnecting them. In these situations, the equipment causing the bottleneck could be replaced with flexible-grid equipment.

Fixed-Grid and Flex-Grid Optical Networks

The current optical transport networks are based on wavelength division multiplexing (WDM) technology to concurrently transport information on different wave-lengths. In the past decades, research has focused on in-creasing network capacity by increasing the individual wavelength's capacity.

Hence, WDM-based networks have evolved from 1 to 2.5 to 10 to 40 GB/s, while 100 GB/s transceivers are just reaching the market. The next step is 400 GB/s systems and then even higher rates. However, such transmissions would not fit in the 50 GHz wavelength grid of current WDM systems (initial designs of 400 GB/s transceivers are for 75 GHz).

Going back to the 100 GHz grid that was used in WDM systems in the past is not a viable solution. Moreover, WDM systems present an inefficiency problem due to the coarse granularity of the light-paths (as optical connections are typically referred to), which are allocated a whole wavelength.

Traffic manipulation at lower capacity levels is performed at the electronic Aggregation switches at the edges of the optical network and is, in most cases, done independently of and on different timescales than light path provisioning of the optical WDM network. Therefore, to support future optical trans-missions and improve efficiency, a more flexible optical network with finer granularity is needed.

Recent research efforts on optical networks have focused on architectures that support variable spectrum connections as a way to increase spectral efficiency, support future transmission rates, and reduce capital costs. Flex-grid (elastic or flexible are also terms used in the literature and will be used in this paper interchangeably) optical net-works appear to be a promising technology for meeting the requirements of next-generation networks that will span across both the core and the metro segments.

A flex-grid network migrates from the fixed 50 GHz grid that traditional WDM networks utilize, and has granularity of 12.5 GHz, as standardized by the International Telecommunication Union (ITU-T). Moreover, flex-grid can also combine spectrum units, referred to as slots, to create wider channels on an as-needed basis (Figure 2.10).

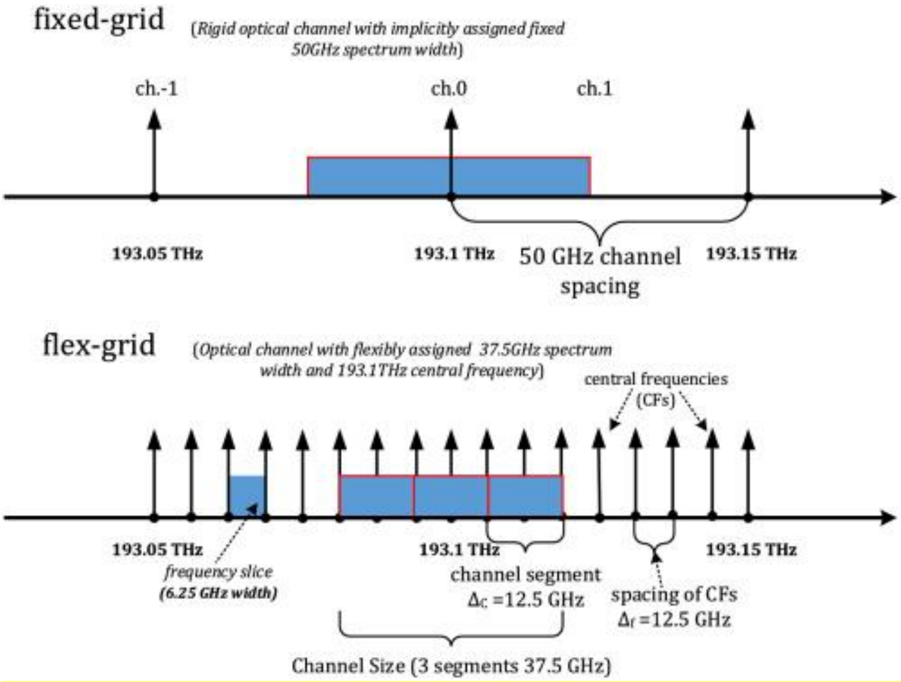


Figure 2.10 Fixed WDM grid 50 GHz and flexible grid 12.5 GHz

This technology enables a fine-granular, cost and power efficient network able to carry traffic that may vary in time, direction, and magnitude. Flex-grid networks are built using bandwidth variable switches that are configured to create appropriately sized end-to-end optical paths of sufficient spectrum slots. Bandwidth variable switches operate in a transparent manner for transit (by passing) traffic that is switched while remaining in the optical domain.

2.9.3 Achieved result

Flex grid are able to provide more live connections using flex grid method. Parameters for Load on network are some as Inter-arrival time, Holding time, live connections & other random parameters that comes with a use of grid network. Comparison shows us that Flex grid better utilizes provided frequency slots.

2.9.4 Limitations

The flexibility of Flex-grid offers a great benefit but it may have some disadvantages. If channel assignment is not properly planned, it can lead to stranded spectrum within the optical band.

An operator should be careful in ensuring that they are not leaving unassigned spectrum components between wavelengths that are not at least 50 GHz.

The appearance of unusable stranded spectrum can actually occur over time. Optical circuits are dynamically created and deleted and this dynamic nature can unintentionally create spectrum fragmentation.

Chapter Three

Simulation setup

3 Simulation setup

3.1 Methodology

In the case of optical data communication, there are different frequency bands, which are suitable for the transmission of signals, providing a large number of different channels in the wavelength range from 1260nm to 1675nm. In this case, a distinction is made between Original (O-band 1260-1360nm), Extended (E-band 1360-1460nm), Short Wavelength (S-band 1460-1530nm), Conventional (C-band 1530-1565nm), Long Wavelength (L-Band 1565-1625nm) and Ultra long Wavelength (U-band 1625-1675nm) Figure 3.1.

Typical DWDM systems use 40 channels with a channel spacing of 100 GHz from channel to channel or 80 channels with a channel spacing of 50 GHz from channel to channel. The latter is used in all newer DWDM applications, since the dual number of channels is available. In both ways, primarily the bands of the C- or L-band are used, which are listed in the following table with a distance of 100GHz:

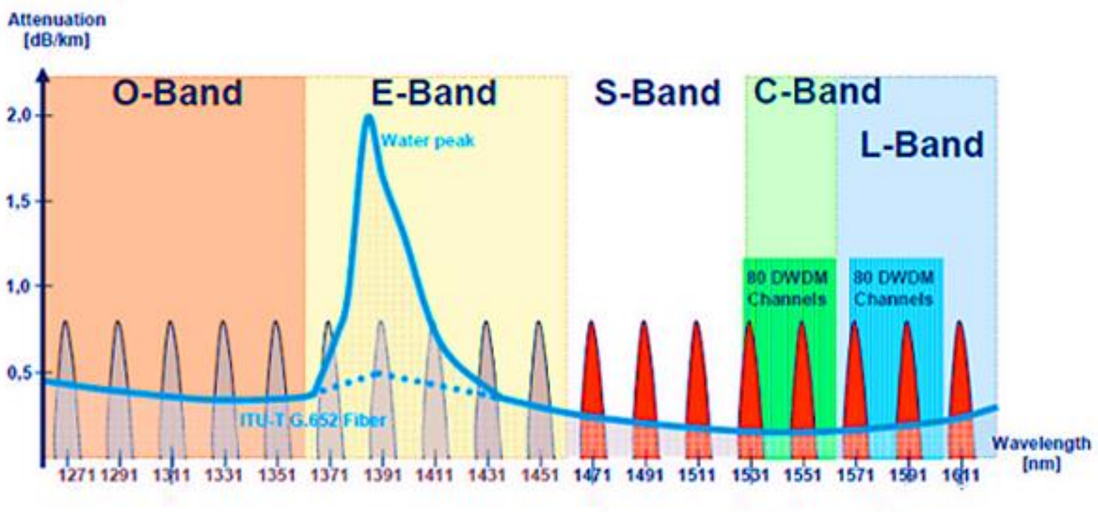


Figure 3.11 C band used

3.2 Frequency used for this simulation

In this research to see the differences between Fixed Grid and Flex Grid, The simulation will be for 80 channels frequency range between 192.100 to 196.050. This is the mainstream frequency ban used in the industry for commercial networks which lies in lowest attenuation /wavelength graph in the C- Band frequency range.

In this simulation design four scenario has been implemented:

- Scenario 1
  80 channels Fixed Grid using first 30 channels from CH1- CH30 for 10G rate ,30 channels CH31-CH60 for 100G rate and last 20 channels CH61 to CH80 for 400G rate.

- Scenario 2
  80 channels Flex Grid using first 30 channels from CH1- CH30 for 10G rate , 30 channels CH31-CH60 for 100G rate and last 20 channels CH61 to CH80 for 400G rate.

- Scenario 3
  80 channels Fixed Grid using channels from CH1- CH80 for 400G rate.

- Scenario 4
  80 channels Flex Grid using channels from CH1- CH80 for 400G rate.

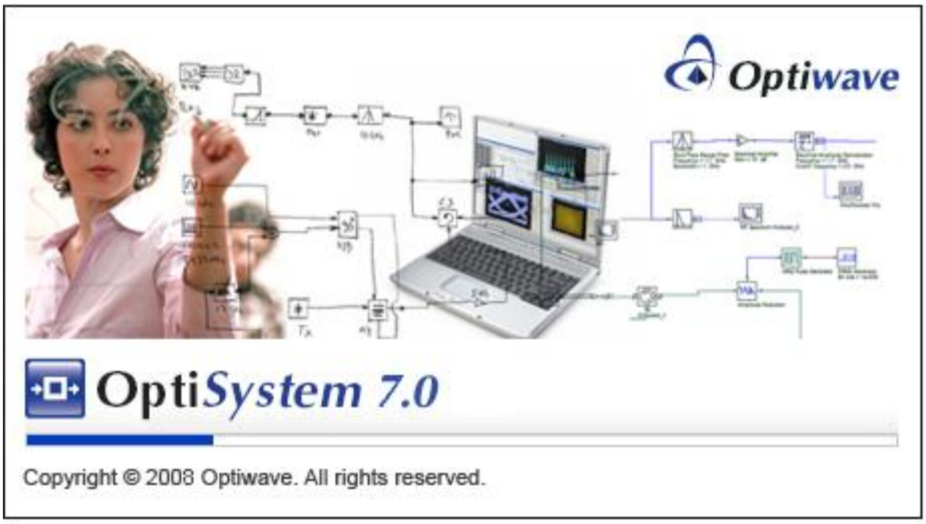
3.3 The OptiSystem Tool used for this simulation

OptiSystem is an innovative optical communication system simulation package that designs, tests, and optimizes virtually any type of optical link in the physical layer of a broad spectrum of optical networks, from analog video broadcasting systems to intercontinental backbones.

Optical communication systems are increasing in complexity on an almost daily basis. The design and analysis of these systems, which normally include nonlinear devices and non-Gaussian noise sources, are highly complex and extremely time-intensive. As a result, these tasks can now only be performed efficiently and effectively with the help of advanced new software tools.

OptiSystem is a stand-alone product that does not rely on other simulation frameworks. It is a system level simulator based on the realistic modeling of fiber-optic communication systems. It possesses a powerful new simulation environment and a hierarchical definition of components and systems. Its capabilities can be extended easily with the addition of user components, and can be seamlessly interfaced to a wide range of tools.

A comprehensive Graphical User Interface (GUI) controls the optical component layout and netlist, component models, and presentation graphics (see Figure 10)



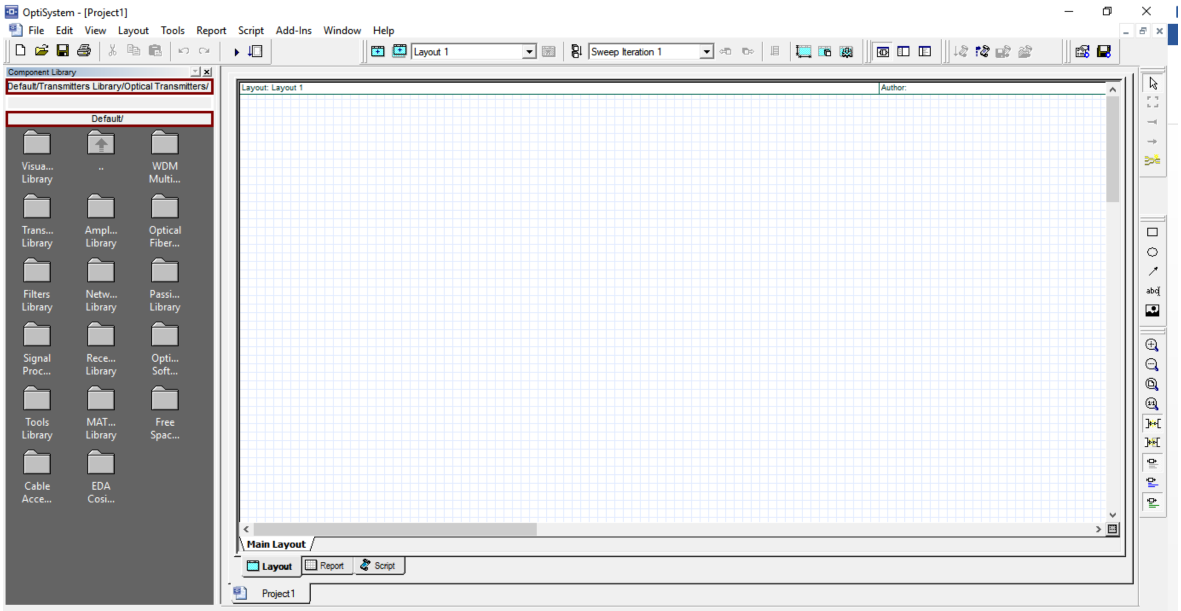


Figure 3.12 OptiSystem main page

The extensive library of active and passive components includes realistic, wavelength-dependent parameters. Parameter sweeps allow to investigate the effect of particular device specifications on system performance.

Created to address the needs of research scientists, optical telecom engineers, system integrators, students, and a wide variety of other users; OptiSystem satisfies the demand of the booming photonics market for a powerful and easy-to-use optical system design tool.

3.3.1 Benefits of OptiSystem

- Rapid, low-cost prototyping
- Global insight into system performance
- Straightforward access to extensive sets of system characterization data
- Automatic parameter scanning and optimization
- Assessment of parameter sensitivities aiding design tolerance specifications
- Dramatic reduction of investment risk and time-to-market
- Visual representation of design options and scenarios to present to prospective customers

3.3.2 Applications can be support by OptiSystem

OptiSystem allows for the design automation of virtually any type of optical link in the physical layer, and the analysis of a broad spectrum of optical networks, from long-haul systems to MANs and LANs.

OptiSystem's wide range of applications include:

- Optical communication system design from component to system level at the physical layer
- CATV or TDM/WDM network design
- Passive optical networks (PON) based FTTX
- Free space optic (FSO) systems
- Radio over fiber (ROF) systems
- SONET/SDH ring design
- Transmitter, channel, amplifier, and receiver design
- Dispersion map design
- Estimation of BER and system penalties with different receiver models
- Amplified system BER and link budget calculations

3.3.3 Main features

The main features of the OptiSystem interface include

3.3.3.1 Component Library

To be fully effective, component modules must be able to reproduce the actual behavior of the real device and specified effects according to the selected accuracy and efficiency. The OptiSystem Component Library includes hundreds of components, all of which have been carefully validated in order to deliver results that are comparable with real life applications.

3.3.3.2 Measured components

The OptiSystem Component Library allows user to enter parameters that can be measured from real devices. It integrates with test and measurement equipment from different vendors.

3.3.3.3 Integration with Optiwave Software Tools

OptiSystem allows user to employ specific Optiwave software tools for integrated and fiber optics at the component level: OptiAmplifier, OptiBPM, OptiGrating, WDM_Phasar, OptiFiber & OptiSPICE.

3.3.3.4 Mixed signal representation

OptiSystem handles mixed signal formats for optical and electrical signals in the Component Library. OptiSystem calculates the signals using the appropriate algorithms related to the required simulation accuracy and efficiency.

3.3.3.5 Quality and performance algorithms

In order to predict the system performance, OptiSystem calculates parameters such as BER and Q-Factor using numerical analysis or semi-analytical techniques for systems limited by inter symbol interference and noise.

3.3.3.6 Advanced visualization tools

Advanced visualization tools produce OSA Spectra, signal chirp, eye diagrams, polarization state, constellation diagrams and much more. Also included are WDM analysis tools listing signal power, gain, noise figure, and OSNR per channel.

3.3.3.7 Data monitors

user can select component ports to save the data and attach monitors after the simulation ends. This allows user to process data after the simulation without recalculating. user can attach an arbitrary number of visualizers to the monitor at the same port.

3.3.3.8 Hierarchical simulation with subsystems

To make a simulation tool flexible and efficient, it is essential to provide models at different abstraction levels, including the system, subsystem, and component levels. OptiSystem features a truly hierarchical definition of components and systems, enabling user to employ specific software tools for integrated and fiber optics at the component level, and allowing the simulation to be as detailed as the desired accuracy dictates.

3.3.3.9 User-defined components

user can incorporate new components based on subsystems and user-defined libraries, or use co-simulation with a third party tool such as MATLAB or Simulink.

By using Optisystem tools, creating DWDM node consist of three transmitter, first one 30-channels 10G frequency start from 192.100 and end is 193.550 with frequency spacing 50GHz, second transmitter 30-channels 100G frequency start from 193.600 and end with 195.05 with frequency spacing 50GHz, third transmitter 20 channels 400GHz with frequency spacing 100GHz frequency start from 195.10 and end with 197.00.

For this simulation C-band range is (192.1 till 196.05). Moreover multiple frequency space have been used to show the difference between Fixed and Flex Grid with different scenarios.

The simulation consist of:

One multiplexer 80 channels, one optical power meter and optical spectrum analyzer, Optical fiber 80KM, one demultiplexer 80 channels, optical receiver and BER Analyzer.

3.4 Design and implementation 80 CHannel Fixed

Below table showing the 80 channel Fixed Grid divided to **30 Channel 10G, 30 Channel 100G and 20 Channel 400G ,** frequency range (192.100 to 196.050). all channels highlights with yellow can't be used because not in frequency range

Frequency range between 192.100 to 196.050, 70 channels out of 80 channels

Table 3.1 80 channels Fixed Grid multi rat

30 Channel 10G			30 Channel 100G			20 Channel 400G		
Ch-No	**10G**	**frequency spacing**	**Ch-NO**	**100G**	**frequency spacing**	**Ch-No**	**400G**	**frequency spacing**
1	192.1	50 GHz	31	193.6	50 GHz	61	195.1	100 GHz
2	192.15	50 GHz	32	193.65	50 GHz	62	195.2	100 GHz
3	192.2	50 GHz	33	193.7	50 GHz	63	195.3	100 GHz
4	192.25	50 GHz	34	193.75	50 GHz	64	195.4	100 GHz
5	192.3	50 GHz	35	193.8	50 GHz	65	195.5	100 GHz
6	192.35	50 GHz	36	193.85	50 GHz	66	195.6	100 GHz
7	192.4	50 GHz	37	193.9	50 GHz	67	195.7	100 GHz
8	192.45	50 GHz	38	193.95	50 GHz	68	195.8	100 GHz
9	192.5	50 GHz	39	194	50 GHz	69	195.9	100 GHz
10	192.55	50 GHz	40	194.05	50 GHz	70	196	100 GHz
11	192.6	50 GHz	41	194.1	50 GHz	71	196.1	100 GHz
12	192.65	50 GHz	42	194.15	50 GHz	72	196.2	100 GHz
13	192.7	50 GHz	43	194.2	50 GHz	73	196.3	100 GHz
14	192.75	50 GHz	44	194.25	50 GHz	74	196.4	100 GHz
15	192.8	50 GHz	45	194.3	50 GHz	75	196.5	100 GHz
16	192.85	50 GHz	46	194.35	50 GHz	76	196.6	100 GHz
17	192.9	50 GHz	47	194.4	50 GHz	77	196.7	100 GHz
18	192.95	50 GHz	48	194.45	50 GHz	78	196.8	100 GHz
19	193	50 GHz	49	194.5	50 GHz	79	196.9	100 GHz
20	193.05	50 GHz	50	194.55	50 GHz	80	197	100 GHz
21	193.1	50 GHz	51	194.6	50 GHz	In 80 channels fixed Grid 30*10G,30*100 and 20*400G ,only 10*400G can be used ,frequency range between 192.100 to 196.050 ,70 channels out of 80 channels		
22	193.15	50 GHz	52	194.65	50 GHz			
23	193.2	50 GHz	53	194.7	50 GHz			
24	193.25	50 GHz	54	194.75	50 GHz			
25	193.3	50 GHz	55	194.8	50 GHz			
26	193.35	50 GHz	56	194.85	50 GHz			
27	193.4	50 GHz	57	194.9	50 GHz			
28	193.45	50 GHz	58	194.95	50 GHz			
29	193.5	50 GHz	59	195	50 GHz			
30	193.55	50 GHz	60	195.05	50 GHz			

Below simulation in DWDM node consist of three transmitter, first one 30-channels 10G frequency start from 192.100 and end is 193.55 with frequency spacing 50 GHz**,** second transmitter 30-channels 100G frequency start from 193.6 and end with 195.05 with frequency spacing 50 GHz, third transmitter 20 channels 400GHz with frequency spacing 100GHz frequency start from 195.10 and end with 197.00 and due to frequency limitation till 196.00 can be used.

One multiplexer 80 channels, one optical power meter and optical spectrum analyzer, Optical fiber 80KM, one demultiplexer 80 channels, optical receiver and BER Analyzer

- 80 channels Fixed Grid using first 30 channels from CH1- CH30 for 10G rate and 30 channels CH31-CH60 for 100G rate and last 20 channels CH61 to CH80 for 400G rate.

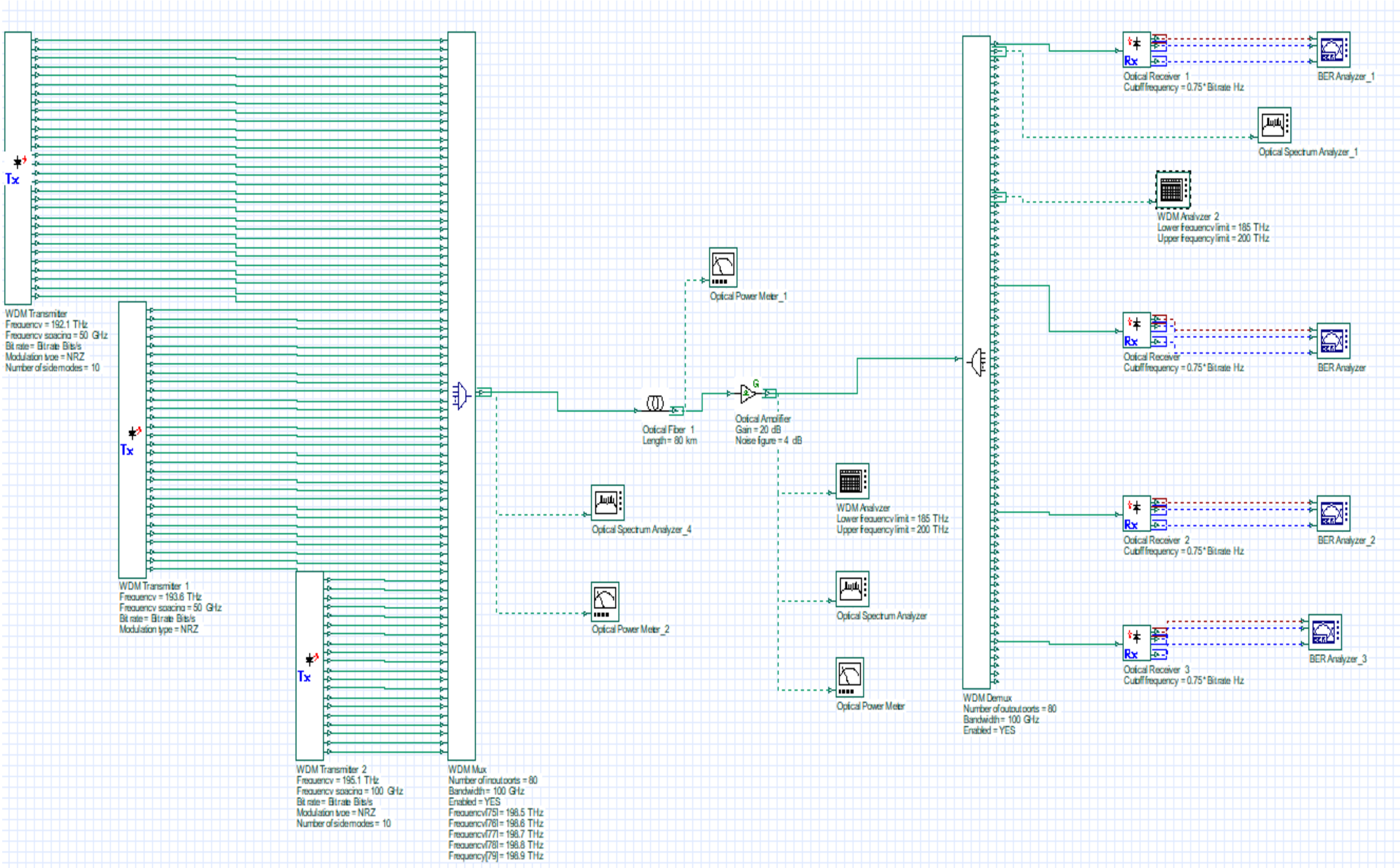


Figure 3.13 simulation design for fixed grid multiple rat

3.4.1 30 Channel 10G frequency spacing 50 GHz in fixed grid

To simulate set WDM transmitter frequency as shown below start from 192.1 THz, and define 30 channels, then set frequency space to 50GHz for Fixed Grid

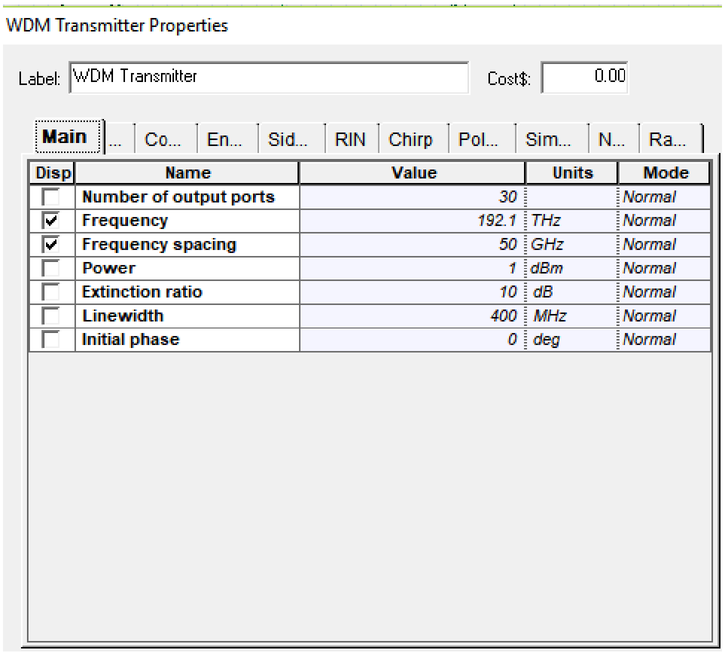


Figure 14 .WDM Transmitter 30 Channels 10G fixed grid

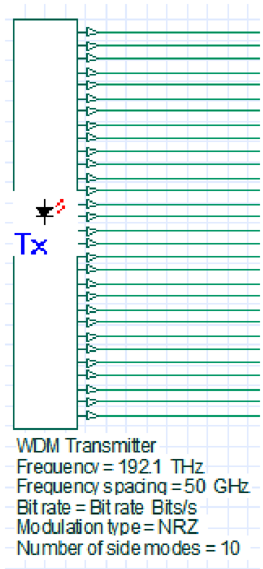


Figure 15.Transmitter 30 channels

3.4.2 30 Channel 100G frequency spacing 50 GHz in fixed grid

To simulate set WDM transmitter frequency as shown below start from 193.6 THz, and number of channels equal 30, then set frequency space to 50GHz for Fixed Grid.

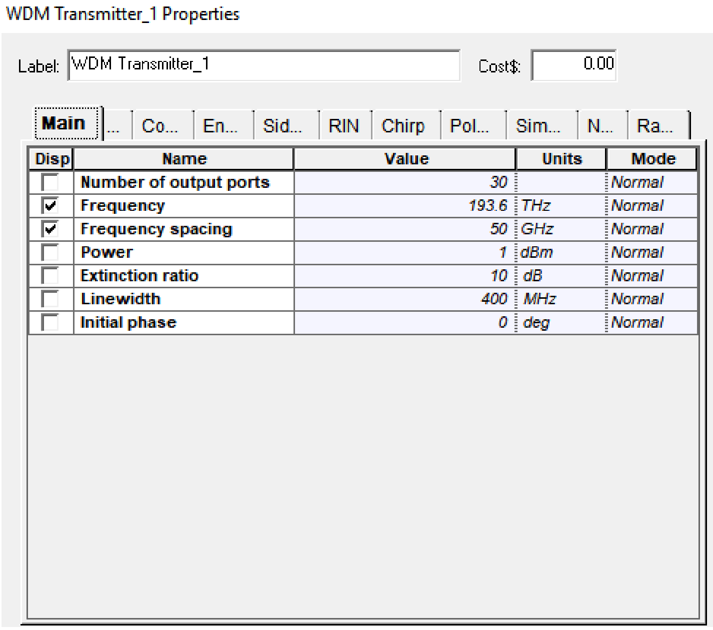


Figure 16. WDM Transmitter 30 Channels 100G fixed grid

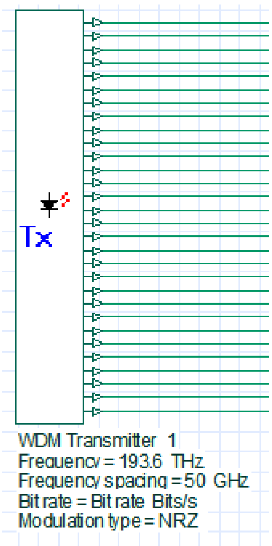


Figure 17.Tansmitter 30 channels

3.4.3 20 Channel 400G frequency spacing 100 GHz in fixed grid

To simulate set WDM transmitter frequency as shown below start from 195.1 THz, and number of channels equal 20, then set frequency space to100GHz for Fixed Grid

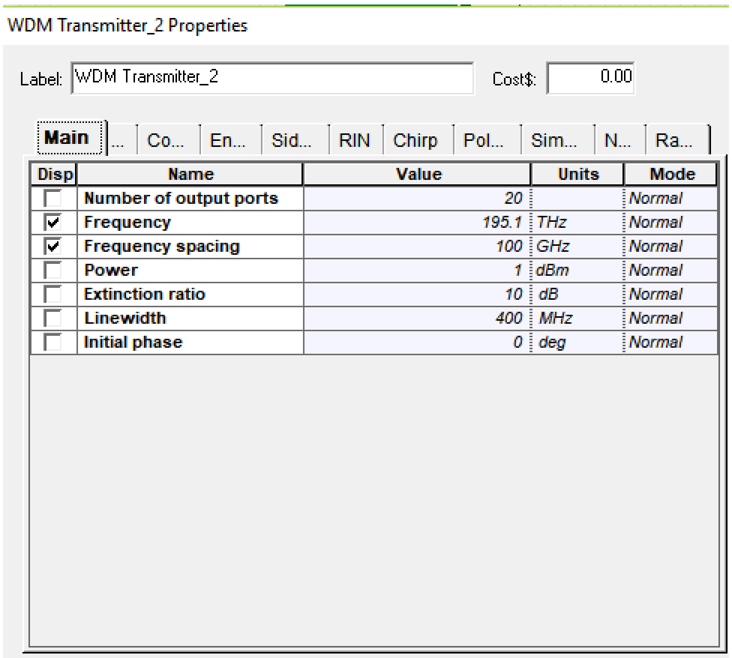


Figure 18. WDM Transmitter 20 Channels 400G fixed grid

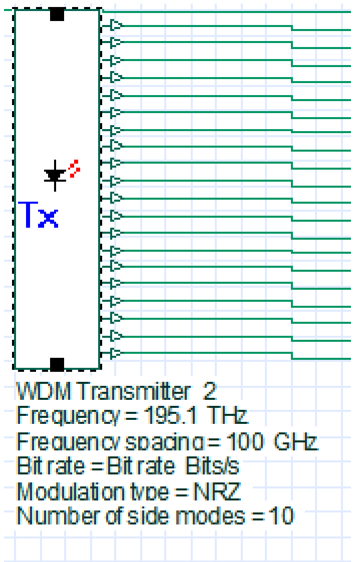


Figure 19.Transmitter 20 channels

3.5 Design and implementation 80 channel flex grid

Below table showing the 80 channel Flex Grid divided to **30 Channel 10G, 30 Channel 100G and 20 Channel 400G ,** frequency range (192.100 to 196.050). All channels highlights with green still in frequency range but can't be used due to channel limitation

Table 3.2 80 channels Flex Grid multi rate

30 Channel 10G			30 Channel 100G			20 Channel 400G		
Ch-No	10G	frequency spacing	Ch-NO	100G	frequency spacing	Ch-No	400G	frequency spacing
1	192.1	12.5 GHz	31	192.475	37.5 GHz	61	193.6	75 GHz
2	192.1125	12.5 GHz	32	192.5125	37.5 GHz	62	193.675	75 GHz
3	192.125	12.5 GHz	33	192.55	37.5 GHz	63	193.75	75 GHz
4	192.1375	12.5 GHz	34	192.5875	37.5 GHz	64	193.825	75 GHz
5	192.15	12.5 GHz	35	192.625	37.5 GHz	65	193.9	75 GHz
6	192.1625	12.5 GHz	36	192.6625	37.5 GHz	66	193.975	75 GHz
7	192.175	12.5 GHz	37	192.7	37.5 GHz	67	194.05	75 GHz
8	192.1875	12.5 GHz	38	192.7375	37.5 GHz	68	194.125	75 GHz
9	192.2	12.5 GHz	39	192.775	37.5 GHz	69	194.2	75 GHz
10	192.2125	12.5 GHz	40	192.8125	37.5 GHz	70	194.275	75 GHz
11	192.225	12.5 GHz	41	192.85	37.5 GHz	71	194.35	75 GHz
12	192.2375	12.5 GHz	42	192.8875	37.5 GHz	72	194.425	75 GHz
13	192.25	12.5 GHz	43	192.925	37.5 GHz	73	194.5	75 GHz
14	192.2625	12.5 GHz	44	192.9625	37.5 GHz	74	194.575	75 GHz
15	192.275	12.5 GHz	45	193	37.5 GHz	75	194.65	75 GHz
16	192.2875	12.5 GHz	46	193.0375	37.5 GHz	76	194.725	75 GHz
17	192.3	12.5 GHz	47	193.075	37.5 GHz	77	194.8	75 GHz
18	192.3125	12.5 GHz	48	193.1125	37.5 GHz	78	194.875	75 GHz
19	192.325	12.5 GHz	49	193.15	37.5 GHz	79	194.95	75 GHz
20	192.3375	12.5 GHz	50	193.1875	37.5 GHz	80	195.025	75 GHz
21	192.35	12.5 GHz	51	193.225	37.5 GHz	81	195.1	75 GHz
22	192.3625	12.5 GHz	52	193.2625	37.5 GHz	82	195.175	75 GHz
23	192.375	12.5 GHz	53	193.3	37.5 GHz	83	195.25	75 GHz
24	192.3875	12.5 GHz	54	193.3375	37.5 GHz	84	195.325	75 GHz
25	192.4	12.5 GHz	55	193.375	37.5 GHz	85	195.4	75 GHz
26	192.4125	12.5 GHz	56	193.4125	37.5 GHz	86	195.475	75 GHz
27	192.425	12.5 GHz	57	193.45	37.5 GHz	87	195.55	75 GHz
28	192.4375	12.5 GHz	58	193.4875	37.5 GHz	88	195.625	75 GHz
29	192.45	12.5 GHz	59	193.525	37.5 GHz	89	195.7	75 GHz
30	192.4625	12.5 GHz	60	193.5625	37.5 GHz	90	195.775	75 GHz
						91	195.85	75 GHz

In 80 channels flex grid when using 30*10G,30*100 and 20*400G ,frequency range between 192.100 to 196.050 channels number 80 is using frequency 195.0250 ,13 more frequency not used but no channel available .	92	195.925	75 GHz
	93	196	75 GHz

Below simulation in DWDM node consist of three transmitter, first one 30-channels 10G frequency start from 192.100THz and end is 192.4625 THz with frequency spacing 12.5GHz**,** second transmitter 30-channels 100G frequency start from 192.475 THz and end with 193.5625 THz with frequency spacing 37.5GHz, third transmitter 20 channels 400GHz with frequency spacing 75GHz frequency start from 193.6 THz and end with 195.025 THz

One multiplexer 80 channels, one optical power meter and optical spectrum analyzer, Optical fiber 80KM, one demultiplexer 80 channels, optical receiver and BER Analyzer

- 80 channels Flex Grid using first 30 channels from CH1- CH30 for 10G rate and 30 channels CH31-CH60 for 100G rate and last 20 channels CH61 to CH80 for 400G rate.

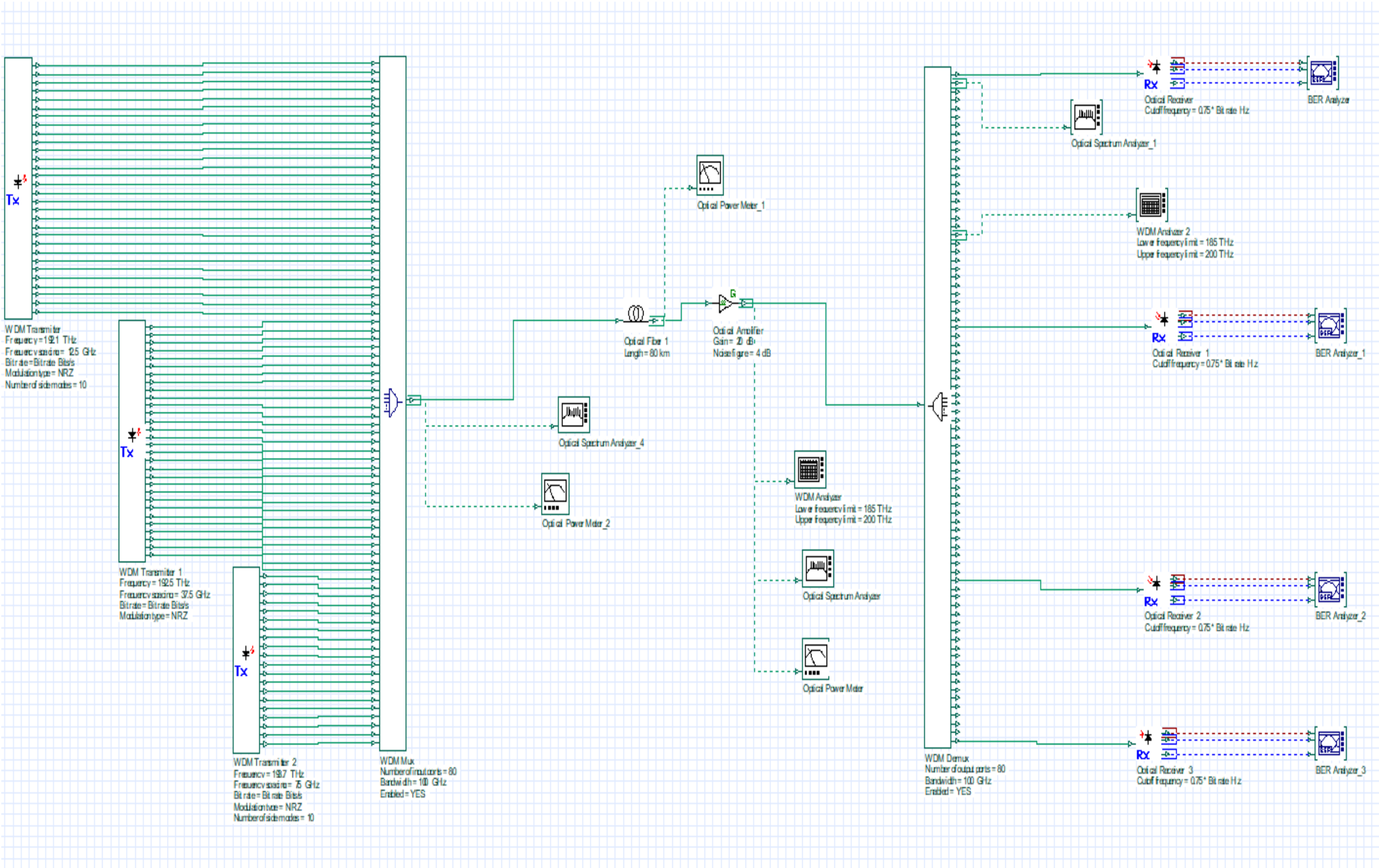


Figure 20. Simulation design for flex grid multiple rate

3.5.1 30 Channel 10G frequency spacing 12.5 in flex grid

To simulate set WDM transmitter frequency as shown below start from 192.1 THz, and number of channels equal 30, then set frequency space to 12.5GHz for Flex Grid .

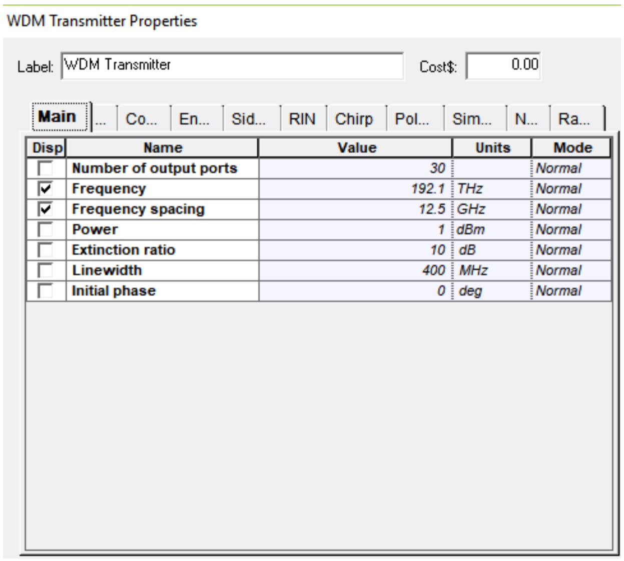


Figure 21. WDM Transmitter 30 Channels 10G flex grid

3.5.2 30 Channel 100G frequency spacing 37.5 in flex grid

To simulate set WDM transmitter frequency as shown below start from 192.475 THz, and define 30 channels, then set frequency space to 37.5GHz for Flex Grid.

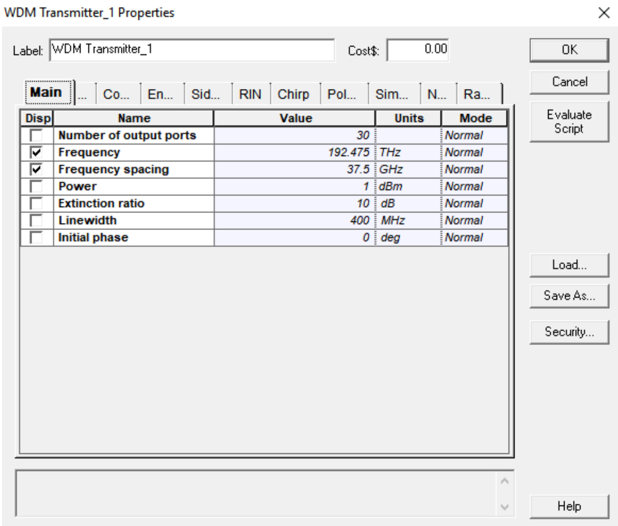


Figure 22. WDM Transmitter 30 Channels 100G flex grid

3.5.3 20 Channel 400G frequency spacing 75 in flex grid

To simulate set WDM transmitter frequency as shown below start from 193.6 THz, and number of channels equal 20, then set frequency space to 75GHz for Flex Grid .

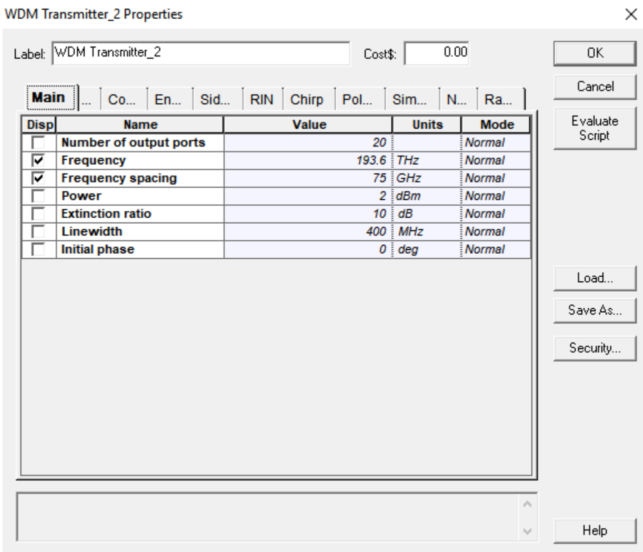


Figure 23. WDM Transmitter 20 Channels 400G flex grid

3.6 Design and implementation 80 channel 400g fixed grid

Below table showing the 80 channel Fixed Grid

Table 3.3 Fixed Grid 80 Channel 400G

80 Channel 400G-used 2*50GHz space								
Ch-No	**400G**	**frequency spacing**	**Ch-NO**	**400G**	**frequency spacing**	**Ch-No**	**400G**	**frequency spacing**
1	192.1	100 GHz	31	195.1	100 GHz	61	100 GHz	198.1
2	192.2	100 GHz	32	195.2	100 GHz	62	100 GHz	198.2
3	192.3	100 GHz	33	195.3	100 GHz	63	100 GHz	198.3
4	192.4	100 GHz	34	195.4	100 GHz	64	100 GHz	198.4
5	192.5	100 GHz	35	195.5	100 GHz	65	100 GHz	198.5
6	192.6	100 GHz	36	195.6	100 GHz	66	100 GHz	198.6
7	192.7	100 GHz	37	195.7	100 GHz	67	100 GHz	198.7
8	192.8	100 GHz	38	195.8	100 GHz	68	100 GHz	198.8
9	192.9	100 GHz	39	195.9	100 GHz	69	100 GHz	198.9
10	193	100 GHz	40	196	100 GHz	70	100 GHz	199
11	193.1	100 GHz	41	196.1	100 GHz	71	100 GHz	199.1
12	193.2	100 GHz	42	196.2	100 GHz	72	100 GHz	199.2
13	193.3	100 GHz	43	196.3	100 GHz	73	100 GHz	199.3
14	193.4	100 GHz	44	196.4	100 GHz	74	100 GHz	199.4
15	193.5	100 GHz	45	196.5	100 GHz	75	100 GHz	199.5
16	193.6	100 GHz	46	196.6	100 GHz	76	100 GHz	199.6
17	193.7	100 GHz	47	196.7	100 GHz	77	100 GHz	199.7
18	193.8	100 GHz	48	196.8	100 GHz	78	100 GHz	199.8
19	193.9	100 GHz	49	196.9	100 GHz	79	100 GHz	199.9
20	194	100 GHz	50	197	100 GHz	80	100 GHz	200
21	194.1	100 GHz	51	197.1	100 GHz	In 80 channels Fixed Grid 400G for each channel and frequency range between 192.100 to 196.050, around 40 channels can be used.		
22	194.2	100 GHz	52	197.2	100 GHz			
23	194.3	100 GHz	53	197.3	100 GHz			
24	194.4	100 GHz	54	197.4	100 GHz			
25	194.5	100 GHz	55	197.5	100 GHz			
26	194.6	100 GHz	56	197.6	100 GHz			
27	194.7	100 GHz	57	197.7	100 GHz			
28	194.8	100 GHz	58	197.8	100 GHz			
29	194.9	100 GHz	59	197.9	100 GHz			
30	195	100 GHz	60	198	100 GHz			

Below simulation in DWDM node consist of one transmitter, 80-channels 400G frequency start from 192.100 THz and end is 200.00 THz with frequency spacing 100GHz**,** and due to frequency limitation till 196.00 can be used.

One multiplexer 80 channels, one optical power meter and optical spectrum analyzer, Optical fiber 80KM, one demultiplexer 80 channels, optical receiver and BER Analyzer

➢ 80 channels Fixed Grid using channels from CH1- CH80 for 400G rate.

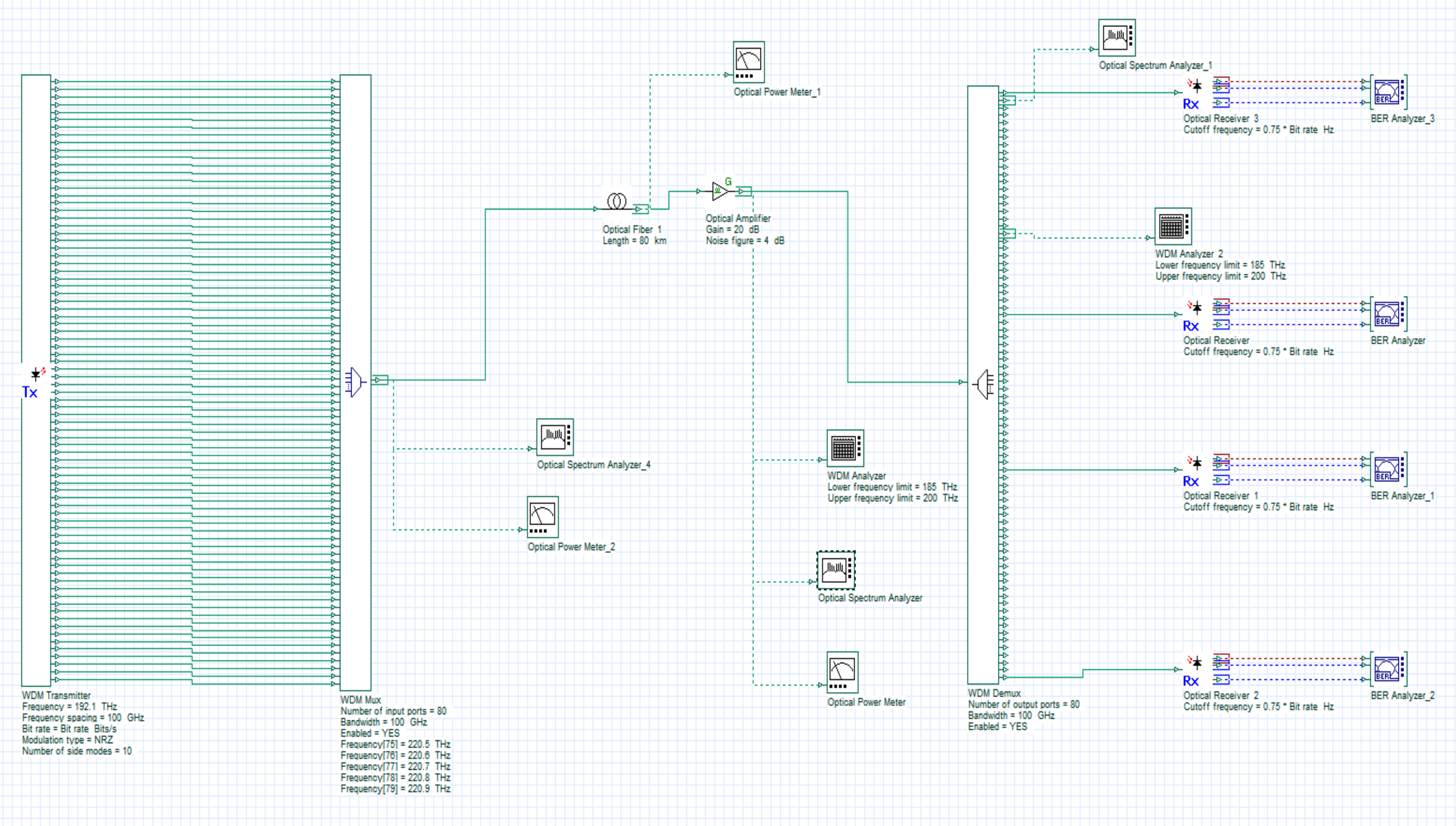


Figure 24 simulation design for fixed grid 400G rate

3.6.1 80 Channel 400G frequency spacing 100GHz in fixed grid

To simulate set WDM transmitter frequency as shown below start from 192.1 THz, and number of channels equal 80, then set frequency space to 100GHz for Fixed Grid.

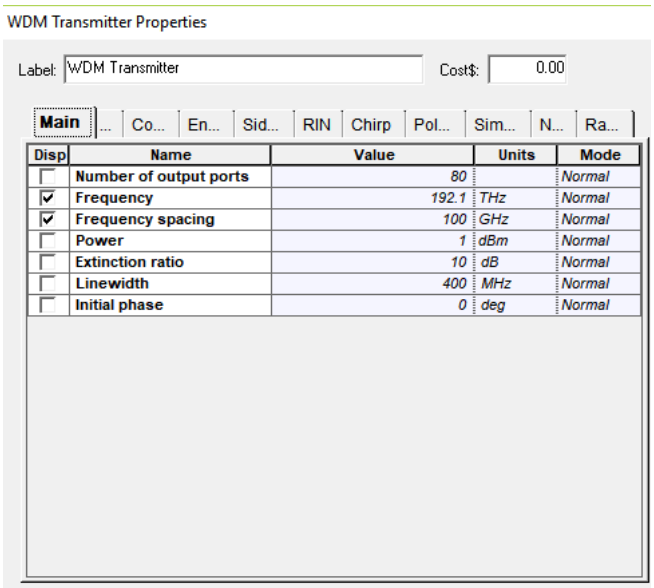


Figure 25. 80 channels fixed grid 400G with resolution BW

3.7 Design and implementation 80 channel 400g flex grid

Below table showing the 80 channel Flex Grid

Table 3.4 Flex Grid 80 Channel 400G

80 Channel 400G-used 75GH channel-Flex Grid								
Ch-No	**400G**	**frequency spacing**	**Ch-NO**	**400G**	**frequency spacing**	**Ch-No**	**400G**	**frequency spacing**
1	192.1	75 GHz	31	194.35	75 GHz	61	196.6	75 GHz
2	192.175	75 GHz	32	194.425	75 GHz	62	196.675	75 GHz
3	192.25	75 GHz	33	194.5	75 GHz	63	196.75	75 GHz
4	192.325	75 GHz	34	194.575	75 GHz	64	196.825	75 GHz
5	192.4	75 GHz	35	194.65	75 GHz	65	196.9	75 GHz
6	192.475	75 GHz	36	194.725	75 GHz	66	196.975	75 GHz
7	192.55	75 GHz	37	194.8	75 GHz	67	197.05	75 GHz
8	192.625	75 GHz	38	194.875	75 GHz	68	197.125	75 GHz
9	192.7	75 GHz	39	194.95	75 GHz	69	197.2	75 GHz
10	192.775	75 GHz	40	195.025	75 GHz	70	197.275	75 GHz
11	192.85	75 GHz	41	195.1	75 GHz	71	197.35	75 GHz
12	192.925	75 GHz	42	195.175	75 GHz	72	197.425	75 GHz
13	193	75 GHz	43	195.25	75 GHz	73	197.5	75 GHz
14	193.075	75 GHz	44	195.325	75 GHz	74	197.575	75 GHz
15	193.15	75 GHz	45	195.4	75 GHz	75	197.65	75 GHz
16	193.225	75 GHz	46	195.475	75 GHz	76	197.725	75 GHz
17	193.3	75 GHz	47	195.55	75 GHz	77	197.8	75 GHz
18	193.375	75 GHz	48	195.625	75 GHz	78	197.875	75 GHz
19	193.45	75 GHz	49	195.7	75 GHz	79	197.95	75 GHz
20	193.525	75 GHz	50	195.775	75 GHz	80	198.025	75 GHz
21	193.6	75 GHz	51	195.85	75 GHz	In 80 channels Flex Grid 400G for each channel, frequency range between 192.100 to 196.050, around 53 channels can be used.		
22	193.675	75 GHz	52	195.925	75 GHz			
23	193.75	75 GHz	53	196	75 GHz			
24	193.825	75 GHz	54	196.075	75 GHz			
25	193.9	75 GHz	55	196.15	75 GHz			
26	193.975	75 GHz	56	196.225	75 GHz			
27	194.05	75 GHz	57	196.3	75 GHz			
28	194.125	75 GHz	58	196.375	75 GHz			
29	194.2	75 GHz	59	196.45	75 GHz			
30	194.275	75 GHz	60	196.525	75 GHz			

Below simulation in DWDM node consist of one transmitter, 80-channels 400G frequency start from 192.100 THz and end is 198.025 THz with frequency spacing 75 GHz**,** and due to frequency limitation till 196.00 THz can be used.

One multiplexer 80 channels, one optical power meter and optical spectrum analyzer, Optical fiber 80KM, one demultiplexer 80 channels, optical receiver and BER Analyzer

- 80 channels Flex Grid using channels from CH1- CH80 for 400G rate.

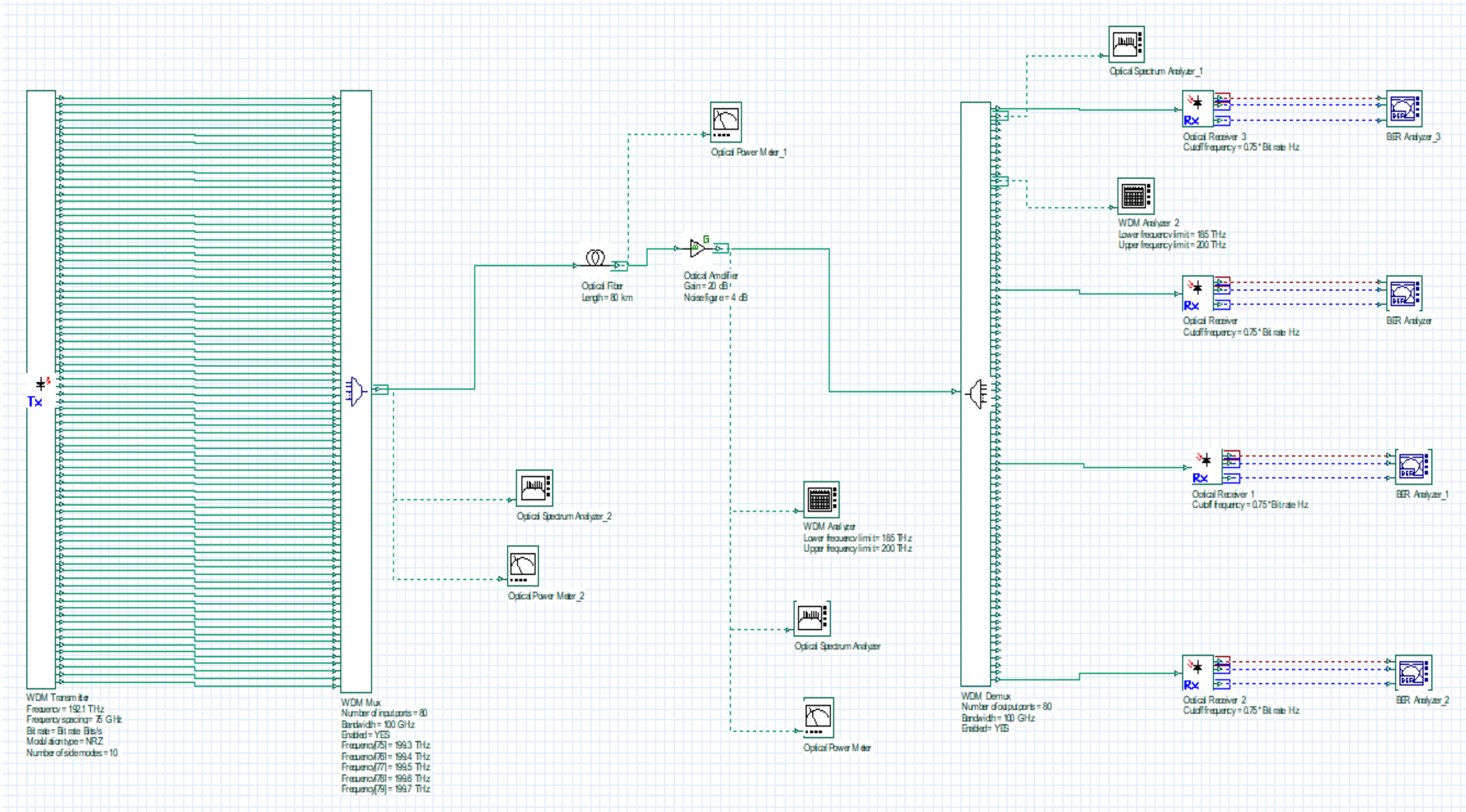


Figure 26. Simulation design for flex grid 400G rate

3.7.1 80 Channel 400G frequency spacing 75 GHz in flex grid

To simulate set WDM transmitter frequency as shown below start from 192.1 THz, and number of channels equal 80, then set frequency space to 75GHz for Flex Grid.

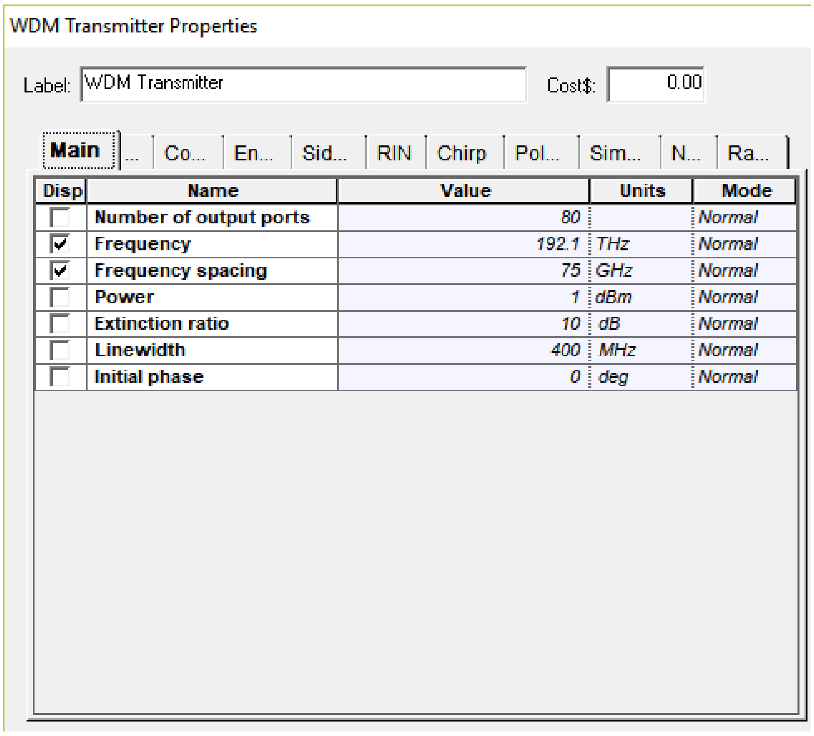


Figure 27.Transmitter 80 channels flex grid

3.8 Performance metrics

The performance metrics we used for the comparisons are the maximum spectrum used (measured in GHz), the cost of transponders, the cost of routers (measured in IDEALIST Cost Units – ICU) and the total cost of network computed as the sum of transponders and routers cost (in ICU). For the case of the flexible network, we assumed that each link has available 320 spectrum slots with 12,5

GHz width each one. Also, we assumed the use of a single type of tunable transponder that supports transmissions up to 50 GHz and modulates up to 64 QAM, so as to transmit up to 400 Gb/s. The transmission tuples (reach, rate, spectrum, guard-band, cost)

3.8.1 BW utilization

In the Fixed Grid mode, bandwidths cannot be adjusted flexibly fixed center frequency and fixed wavelength spacing of 50 GHz or 100 GHz.

In flex grid mode can divides spectrums into slices with smaller widths, such as 6.25 GHz slices or 12.5 GHz slices. A high-speed signal can occupy multiple spectrum slices, implementing flexible bandwidth adjustment and improving network-wide spectrum usage.

3.8.2 Capacity

It divides spectrums into slices with smaller widths, such as 6.25 GHz slices or 12.5 GHz slices. A high-speed signal can occupy multiple spectrum slices, implementing flexible bandwidth adjustment and improving network-wide spectrum usage.

Spectrum slices can be selected for signals randomly so that the signals can occupy different bandwidths, and the center frequency of wavelengths can be flexibly adjusted.

Transmission of multi-rate signals on a network reduces the spacing between bands, improves bandwidth usage, and satisfies requirements for large-capacity bandwidths.

3.8.3 BER

BER (Bit Error Rate) – defines the number of detected corrupted bits relative to the total number of detected bits. The lower the BER, the better the transmission quality.

Chapter four

Results and Discussion

4 Results and Discussion

4.1 80 Channel Fixed Grid

Below table showing the 80 channel Flex Grid divided to **30 Channel 10G, 30 Channel 100G and 20 Channel 400G ,** frequency range (192.100 to 196.050) THz. all channels highlights with yellow can't be used because not in frequency range

Table 4.15 80 channels Fixed Grid multi rate

30 Channel 10G			30 Channel 100G			20 Channel 400G		
Ch-No	**10G**	**frequency spacing**	**Ch-NO**	**100G**	**frequency spacing**	**Ch-No**	**400G**	**frequency spacing**
1	192.1	50 GHz	31	193.6	50 GHz	61	195.1	100 GHz
2	192.15	50 GHz	32	193.65	50 GHz	62	195.2	100 GHz
3	192.2	50 GHz	33	193.7	50 GHz	63	195.3	100 GHz
4	192.25	50 GHz	34	193.75	50 GHz	64	195.4	100 GHz
5	192.3	50 GHz	35	193.8	50 GHz	65	195.5	100 GHz
6	192.35	50 GHz	36	193.85	50 GHz	66	195.6	100 GHz
7	192.4	50 GHz	37	193.9	50 GHz	67	195.7	100 GHz
8	192.45	50 GHz	38	193.95	50 GHz	68	195.8	100 GHz
9	192.5	50 GHz	39	194	50 GHz	69	195.9	100 GHz
10	192.55	50 GHz	40	194.05	50 GHz	70	196	100 GHz
11	192.6	50 GHz	41	194.1	50 GHz	71	196.1	100 GHz
12	192.65	50 GHz	42	194.15	50 GHz	72	196.2	100 GHz
13	192.7	50 GHz	43	194.2	50 GHz	73	196.3	100 GHz
14	192.75	50 GHz	44	194.25	50 GHz	74	196.4	100 GHz
15	192.8	50 GHz	45	194.3	50 GHz	75	196.5	100 GHz
16	192.85	50 GHz	46	194.35	50 GHz	76	196.6	100 GHz
17	192.9	50 GHz	47	194.4	50 GHz	77	196.7	100 GHz
18	192.95	50 GHz	48	194.45	50 GHz	78	196.8	100 GHz
19	193	50 GHz	49	194.5	50 GHz	79	196.9	100 GHz
20	193.05	50 GHz	50	194.55	50 GHz	80	197	100 GHz
21	193.1	50 GHz	51	194.6	50 GHz			
22	193.15	50 GHz	52	194.65	50 GHz			

23	193.2	50 GHz	53	194.7	50 GHz			
24	193.25	50 GHz	54	194.75	50 GHz			
25	193.3	50 GHz	55	194.8	50 GHz			
26	193.35	50 GHz	56	194.85	50 GHz			
27	193.4	50 GHz	57	194.9	50 GHz			
28	193.45	50 GHz	58	194.95	50 GHz			
29	193.5	50 GHz	59	195	50 GHz			
30	193.55	50 GHz	60	195.05	50 GHz			

- 80 channels Fixed Grid using first 30 channels from CH1- CH30 for 10G rate and 30 channels CH31-CH60 for 100G rate and last 20 channels CH61 to CH80 for 400G rate.

4.1.1 30 Channel 10G frequency spacing 50 GHz in fixed grid

from simulation with WDM transmitter frequency start from 192.1 THz, and defined the number of channels-30 ,frequency space set 50GHz as per Fixed Grid ,the result is 30 channels with frequency space 50 GHz as showing in Figure 26 (first 30 channels)

4.1.2 30 Channel 100G frequency spacing 50 GHz in fixed grid

from simulation with WDM transmitter frequency start from 193.6 THz, and defined the number of channels-30 ,frequency space set 50GHz as per Fixed Grid. the result is 30 channels with frequency space 50 GHz as showing in Figure 26 (channels from 31-60)

4.1.3 20 Channel 400G frequency spacing 100 GHz in fixed grid

from simulation with WDM transmitter frequency start from 195.1 THz, and defined the number of channels-20 ,frequency space set 100GHz as per Fixed Grid, the result is 20 channels with frequency space 100 GHz as showing in Figure 26 (channels from 61-70)

The result of simulation of 80 channels Fixed Grid 30*10G, 30*100G and 15*400G as showing in Figure 26 and Figure 27 , showing 70 channel can be used out of 80 channels due to C-band frequency limitation , frequency range between (192.100 to 196.050) THz.

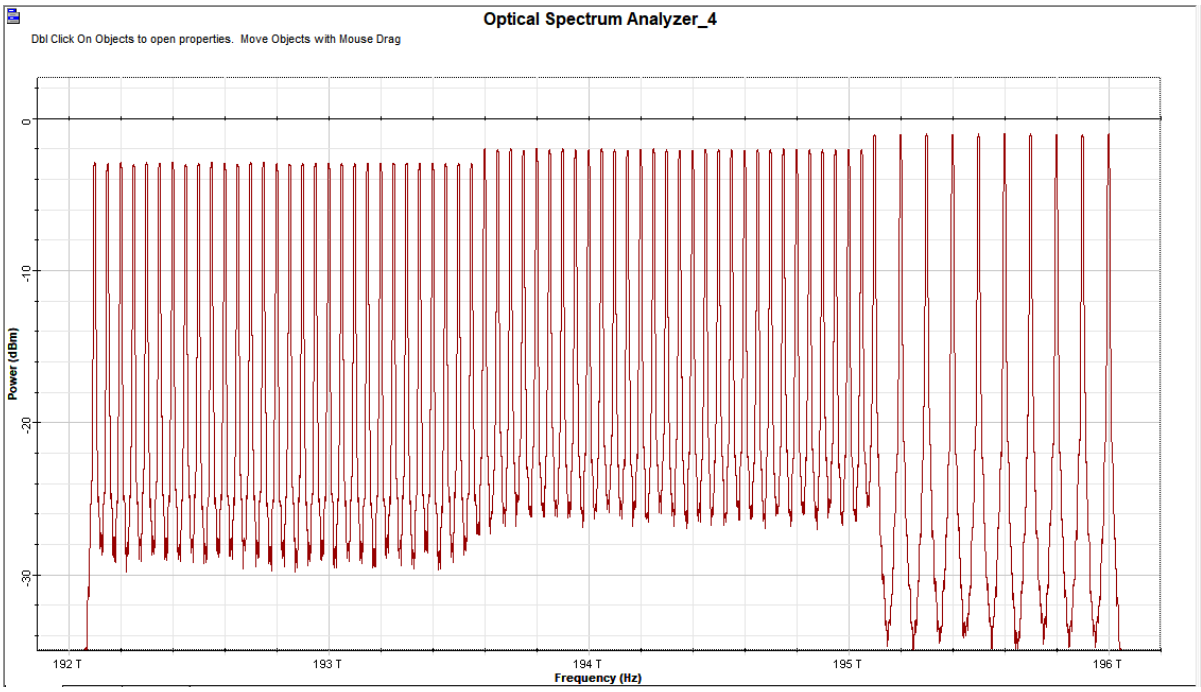


Figure 28.80 channels fixed grid multiple rate 10/100/400 G

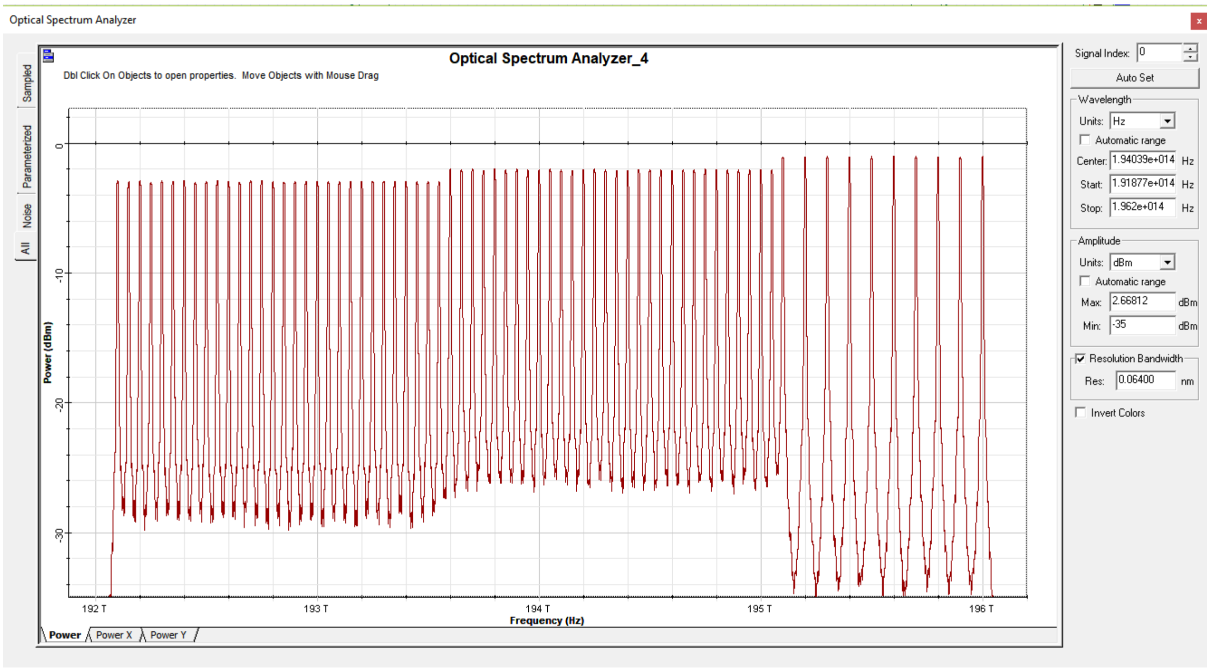


Figure 29. 80 channels fixed grid multiple rate 10/100/400 G with resolution BW

4.2 80 channel Flex Grid

Below table showing the 80 channel Flex Grid divided to **30 Channel 10G, 30 Channel 100G and 20 Channel 400G ,** frequency range (192.100 to 196.050) THz. All channels highlights with green still in frequency range but can't be used due to channel limitation

30 Channel 10G			30 Channel 100G			20 Channel 400G		
Ch-No	**10G**	**frequency spacing**	**Ch-NO**	**100G**	**frequency spacing**	**Ch-No**	**400G**	**frequency spacing**
1	192.1	12.5 GHz	31	192.475	37.5 GHz	61	193.6	75 GHz
2	192.1125	12.5 GHz	32	192.5125	37.5 GHz	62	193.675	75 GHz
3	192.125	12.5 GHz	33	192.55	37.5 GHz	63	193.75	75 GHz
4	192.1375	12.5 GHz	34	192.5875	37.5 GHz	64	193.825	75 GHz
5	192.15	12.5 GHz	35	192.625	37.5 GHz	65	193.9	75 GHz
6	192.1625	12.5 GHz	36	192.6625	37.5 GHz	66	193.975	75 GHz
7	192.175	12.5 GHz	37	192.7	37.5 GHz	67	194.05	75 GHz
8	192.1875	12.5 GHz	38	192.7375	37.5 GHz	68	194.125	75 GHz
9	192.2	12.5 GHz	39	192.775	37.5 GHz	69	194.2	75 GHz
10	192.2125	12.5 GHz	40	192.8125	37.5 GHz	70	194.275	75 GHz
11	192.225	12.5 GHz	41	192.85	37.5 GHz	71	194.35	75 GHz
12	192.2375	12.5 GHz	42	192.8875	37.5 GHz	72	194.425	75 GHz
13	192.25	12.5 GHz	43	192.925	37.5 GHz	73	194.5	75 GHz
14	192.2625	12.5 GHz	44	192.9625	37.5 GHz	74	194.575	75 GHz
15	192.275	12.5 GHz	45	193	37.5 GHz	75	194.65	75 GHz
16	192.2875	12.5 GHz	46	193.0375	37.5 GHz	76	194.725	75 GHz
17	192.3	12.5 GHz	47	193.075	37.5 GHz	77	194.8	75 GHz
18	192.3125	12.5 GHz	48	193.1125	37.5 GHz	78	194.875	75 GHz
19	192.325	12.5 GHz	49	193.15	37.5 GHz	79	194.95	75 GHz
20	192.3375	12.5 GHz	50	193.1875	37.5 GHz	80	195.025	75 GHz
21	192.35	12.5 GHz	51	193.225	37.5 GHz	81	195.1	75 GHz
22	192.3625	12.5 GHz	52	193.2625	37.5 GHz	82	195.175	75 GHz
23	192.375	12.5 GHz	53	193.3	37.5 GHz	83	195.25	75 GHz
24	192.3875	12.5 GHz	54	193.3375	37.5 GHz	84	195.325	75 GHz
25	192.4	12.5 GHz	55	193.375	37.5 GHz	85	195.4	75 GHz
26	192.4125	12.5 GHz	56	193.4125	37.5 GHz	86	195.475	75 GHz
27	192.425	12.5 GHz	57	193.45	37.5 GHz	87	195.55	75 GHz
28	192.4375	12.5 GHz	58	193.4875	37.5 GHz	88	195.625	75 GHz
29	192.45	12.5 GHz	59	193.525	37.5 GHz	89	195.7	75 GHz

30	192.4625	12.5 GHz	60	193.5625	37.5 GHz	90	195.775	75 GHz
						91	195.85	75 GHz
						92	195.925	75 GHz
						93	196	75 GHz

Table 6 80 channels Flex Grid multi rate

- 80 channels Flex Grid using first 30 channels from CH1- CH30 for 10G rate and 30 channels CH31-CH60 for 100G rate and last 20 channels CH61 to CH80 for 400G rate.

4.2.1 30 Channel 10G frequency spacing 12.5 in flex grid

from simulation with WDM transmitter frequency start from 192.1 THz,and defined the number of channels-30 ,frequency space set 12.5GHz as per Flex Grid, the result is 30 channels with frequency space 12.5 GHz as showing in Figure 28 (channels from 1-30)

4.2.2 30 Channel 100G frequency spacing 37.5 in flex grid

from simulation with WDM transmitter frequency start from 192.5 THz,and defined the number of channels-30 ,frequency space set 37.5GHz as per Flex Grid , the result is 30 channels with frequency space 37.5 GHz as showing in Figure 28 (channels from 31-60)

4.2.3 30 Channel 400G frequency spacing 75 in flex grid

from simulation with WDM transmitter frequency start from 193.7 THz,and defined the number of channels-20 ,frequency space set 75GHz as per Flex Grid , the result is 20 channels with frequency space 75.5 GHz as showing in Figure 28 (channels from 61-80)

Below Graph showing Flex Grid 80 channels

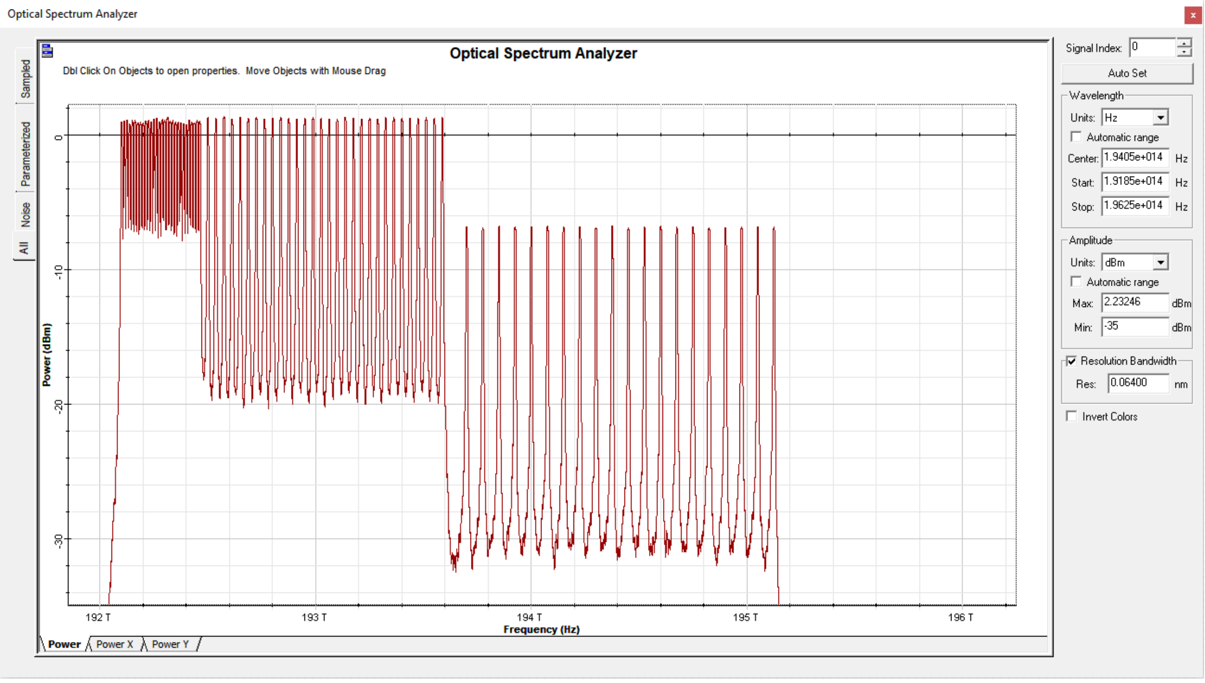


Figure 30. 80 channels fixed grid multiple rate with resolution BW

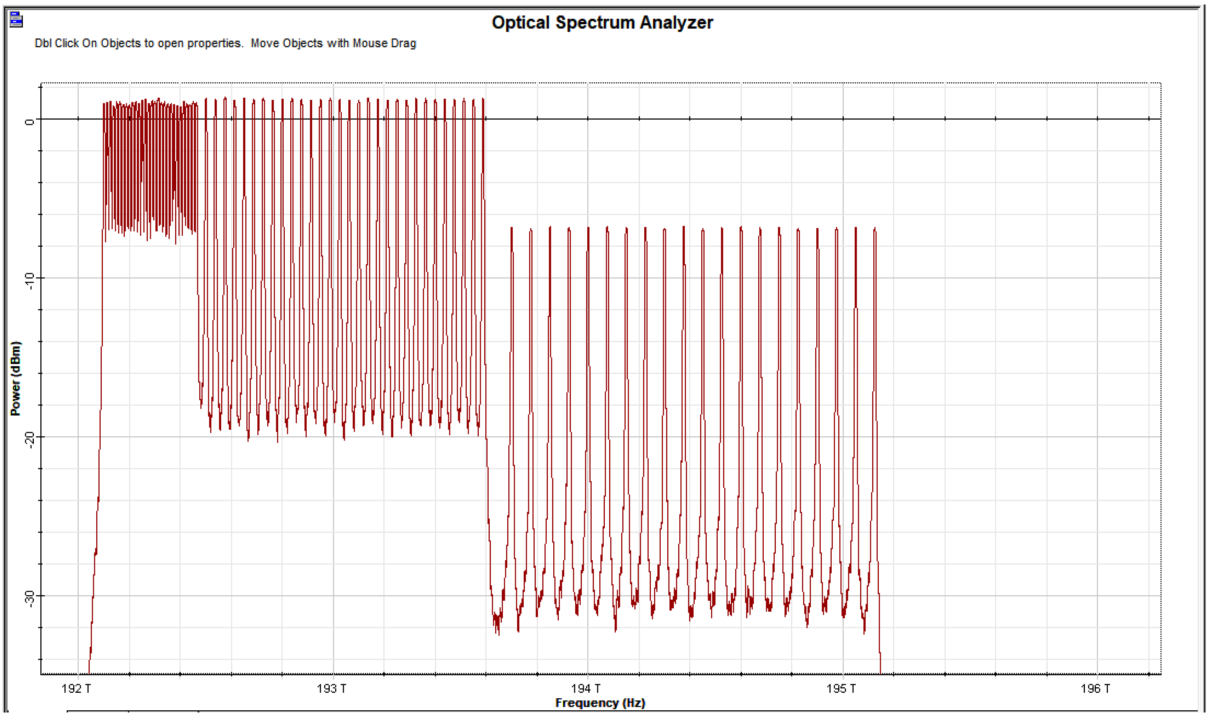


Figure 31. 80 channels fixed grid multiple rate

4.3 80 Channel 400G Fixed Grid

80 Channel 400G-used 2*50GHz space								
Ch-No	400G	frequency spacing	Ch-NO	400G	frequency spacing	Ch-No	400G	frequency spacing
1	192.1	100 GHz	31	195.1	100 GHz	61	100 GHz	198.1
2	192.2	100 GHz	32	195.2	100 GHz	62	100 GHz	198.2
3	192.3	100 GHz	33	195.3	100 GHz	63	100 GHz	198.3
4	192.4	100 GHz	34	195.4	100 GHz	64	100 GHz	198.4
5	192.5	100 GHz	35	195.5	100 GHz	65	100 GHz	198.5
6	192.6	100 GHz	36	195.6	100 GHz	66	100 GHz	198.6
7	192.7	100 GHz	37	195.7	100 GHz	67	100 GHz	198.7
8	192.8	100 GHz	38	195.8	100 GHz	68	100 GHz	198.8
9	192.9	100 GHz	39	195.9	100 GHz	69	100 GHz	198.9
10	193	100 GHz	40	196	100 GHz	70	100 GHz	199
11	193.1	100 GHz	41	196.1	100 GHz	71	100 GHz	199.1
12	193.2	100 GHz	42	196.2	100 GHz	72	100 GHz	199.2
13	193.3	100 GHz	43	196.3	100 GHz	73	100 GHz	199.3
14	193.4	100 GHz	44	196.4	100 GHz	74	100 GHz	199.4
15	193.5	100 GHz	45	196.5	100 GHz	75	100 GHz	199.5
16	193.6	100 GHz	46	196.6	100 GHz	76	100 GHz	199.6
17	193.7	100 GHz	47	196.7	100 GHz	77	100 GHz	199.7
18	193.8	100 GHz	48	196.8	100 GHz	78	100 GHz	199.8
19	193.9	100 GHz	49	196.9	100 GHz	79	100 GHz	199.9
20	194	100 GHz	50	197	100 GHz	80	100 GHz	200
21	194.1	100 GHz	51	197.1	100 GHz			
22	194.2	100 GHz	52	197.2	100 GHz			
23	194.3	100 GHz	53	197.3	100 GHz			
24	194.4	100 GHz	54	197.4	100 GHz			
25	194.5	100 GHz	55	197.5	100 GHz			
26	194.6	100 GHz	56	197.6	100 GHz			
27	194.7	100 GHz	57	197.7	100 GHz			
28	194.8	100 GHz	58	197.8	100 GHz			
29	194.9	100 GHz	59	197.9	100 GHz			
30	195	100 GHz	60	198	100 GHz			

Table 7 Fixed Grid 80 Channel 400G

4.3.1 80 Channel 400G frequency spacing 100GHz in fixed grid

- 80 channels Fixed Grid using channels from CH1- CH80 for 400G rate.

from simulation with WDM transmitter frequency start from 192.1 THz,and defined the number of channels-80 ,frequency space set 100GHz as per Flex Grid , the result is 80 channels with frequency space 100 GHz as showing in Figure 30 (channels from 1-40).

In fixed Grid Only 40 channel 400G can be pass in C band (192.1 to 196.05) THz with frequency space 100 GHz

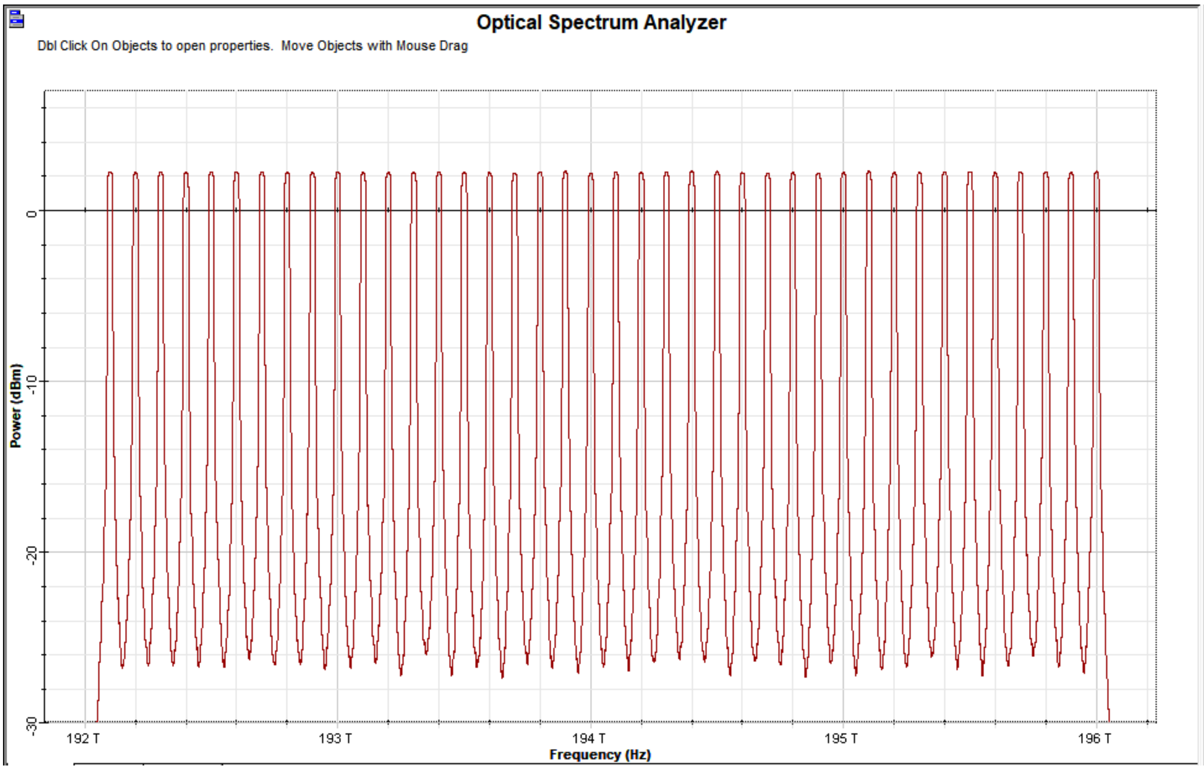


Figure 32. 80 channels fixed grid 400G

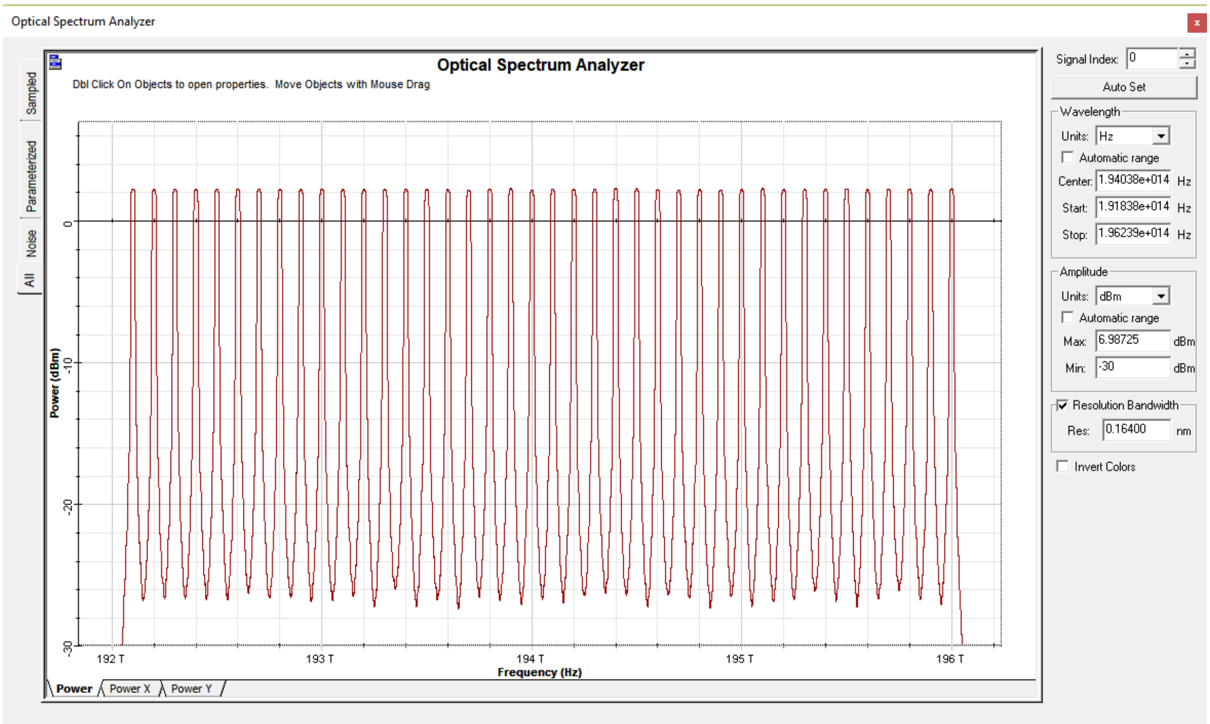


Figure 33. 80 channels fixed grid 400G with resolution BW

4.4 80 Channel 400G Flex Grid

80 Channel 400G-used 75GH channel-Flex Grid								
Ch-No	**400G**	**frequency spacing**	**Ch-NO**	**400G**	**frequency spacing**	**Ch-No**	**400G**	**frequency spacing**
1	192.1	75 GHz	31	194.35	75 GHz	61	196.6	75 GHz
2	192.175	75 GHz	32	194.425	75 GHz	62	196.675	75 GHz
3	192.25	75 GHz	33	194.5	75 GHz	63	196.75	75 GHz
4	192.325	75 GHz	34	194.575	75 GHz	64	196.825	75 GHz
5	192.4	75 GHz	35	194.65	75 GHz	65	196.9	75 GHz
6	192.475	75 GHz	36	194.725	75 GHz	66	196.975	75 GHz
7	192.55	75 GHz	37	194.8	75 GHz	67	197.05	75 GHz
8	192.625	75 GHz	38	194.875	75 GHz	68	197.125	75 GHz
9	192.7	75 GHz	39	194.95	75 GHz	69	197.2	75 GHz
10	192.775	75 GHz	40	195.025	75 GHz	70	197.275	75 GHz
11	192.85	75 GHz	41	195.1	75 GHz	71	197.35	75 GHz
12	192.925	75 GHz	42	195.175	75 GHz	72	197.425	75 GHz
13	193	75 GHz	43	195.25	75 GHz	73	197.5	75 GHz

14	193.075	75 GHz	44	195.325	75 GHz	74	197.575	75 GHz
15	193.15	75 GHz	45	195.4	75 GHz	75	197.65	75 GHz
16	193.225	75 GHz	46	195.475	75 GHz	76	197.725	75 GHz
17	193.3	75 GHz	47	195.55	75 GHz	77	197.8	75 GHz
18	193.375	75 GHz	48	195.625	75 GHz	78	197.875	75 GHz
19	193.45	75 GHz	49	195.7	75 GHz	79	197.95	75 GHz
20	193.525	75 GHz	50	195.775	75 GHz	80	198.025	75 GHz
21	193.6	75 GHz	51	195.85	75 GHz	80	198.025	76 GHz
22	193.675	75 GHz	52	195.925	75 GHz	80	198.025	77 GHz
23	193.75	75 GHz	53	196	75 GHz	80	198.025	78 GHz
24	193.825	75 GHz	54	196.075	75 GHz	80	198.025	79 GHz
25	193.9	75 GHz	55	196.15	75 GHz	80	198.025	80 GHz
26	193.975	75 GHz	56	196.225	75 GHz	80	198.025	81 GHz
27	194.05	75 GHz	57	196.3	75 GHz	80	198.025	82 GHz
28	194.125	75 GHz	58	196.375	75 GHz	80	198.025	83 GHz
29	194.2	75 GHz	59	196.45	75 GHz	80	198.025	84 GHz
30	194.275	75 GHz	60	196.525	75 GHz	80	198.025	85 GHz

Table 8 Flex Grid 80 Channel 400G

4.4.1 80 Channel 400G frequency spacing 75 GHz in flex grid

- 80 channels Flex Grid using channels from CH1- CH80 for 400G rate.

from simulation with WDM transmitter frequency start from 192.1 THz,and defined the number of channels-80 ,frequency space set 75GHz as per Flex Grid . the result is 80 channels with frequency space 75 GHz as showing in Figure 32 (channels from 1-60)

60 channel can be pass in C band (192.1 to 196.05) THz with frequency space 75GHz

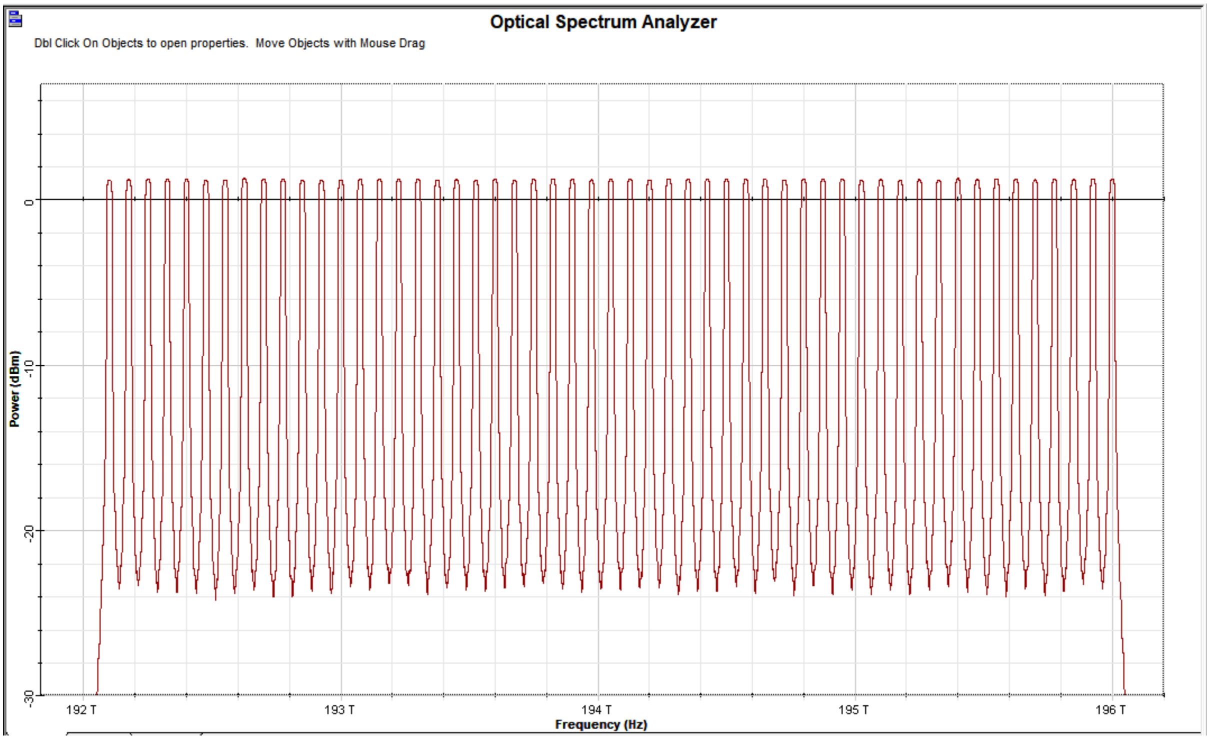


Figure 34. 80 channels flex grid 400G with resolution BW

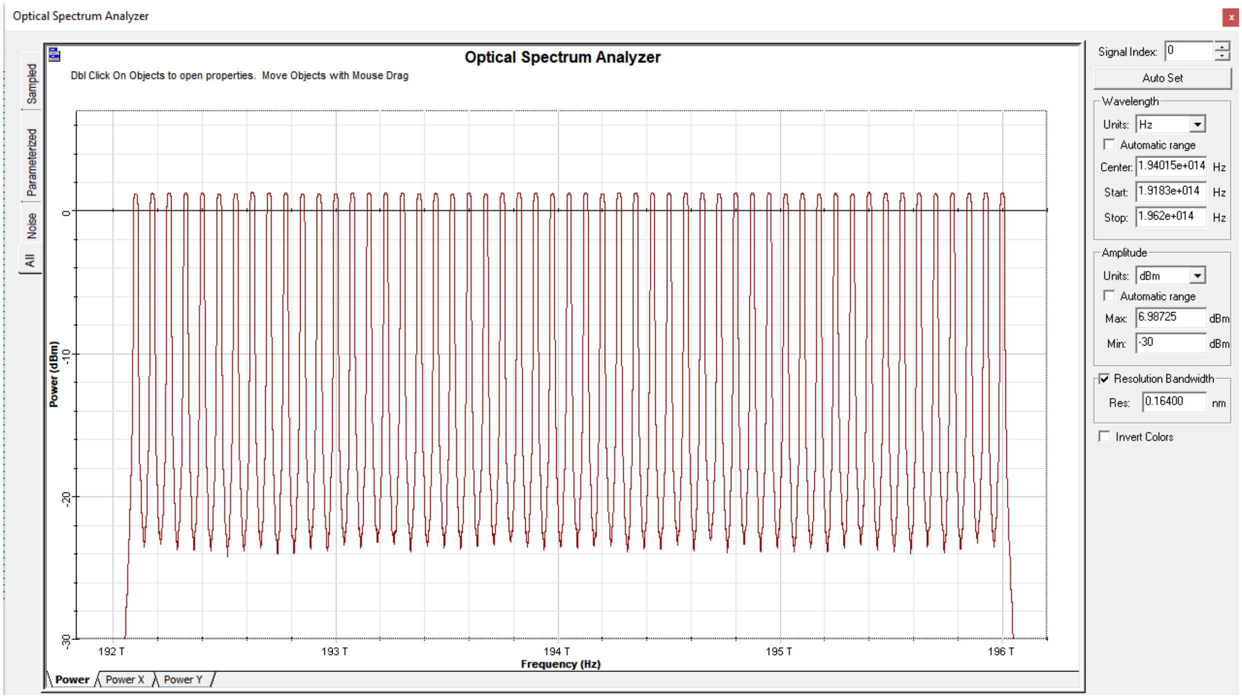


Figure 35. 80 channels flex grid 400G with resolution BW Zoom in

Compare between 400G Fixed Grid and Flex Grid

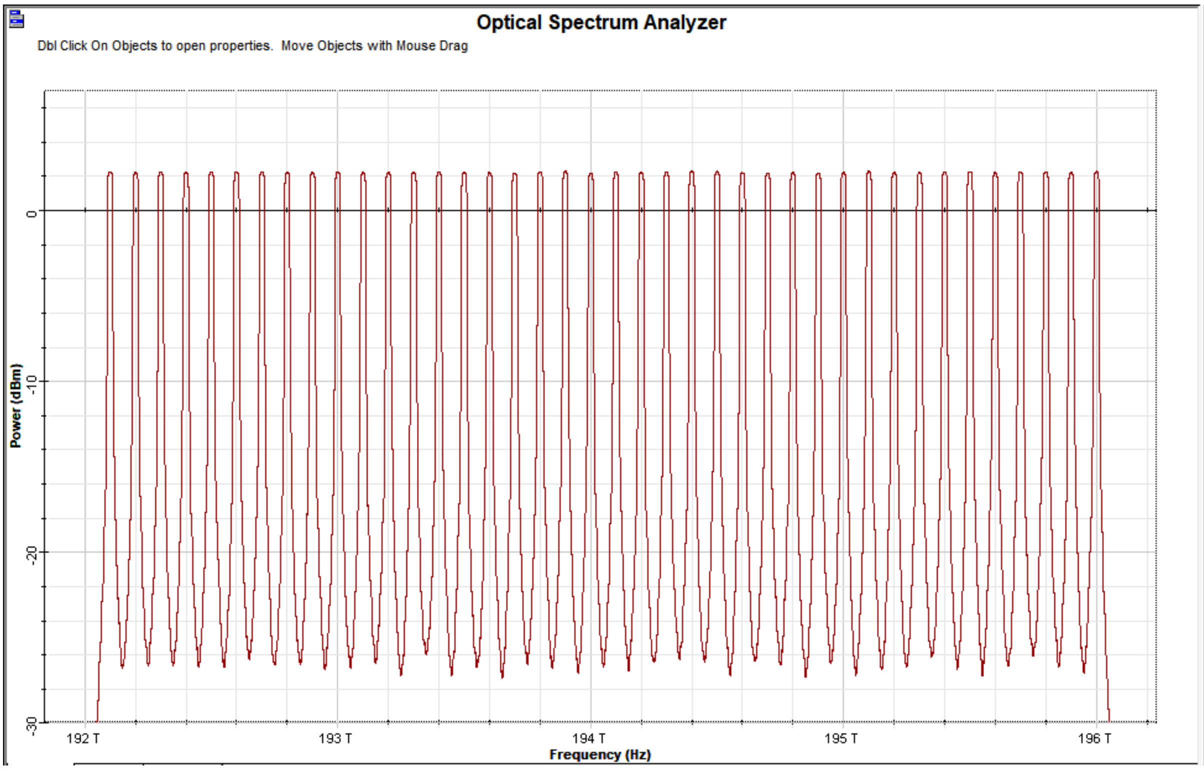


Figure 36. 40-400G in fixed grid

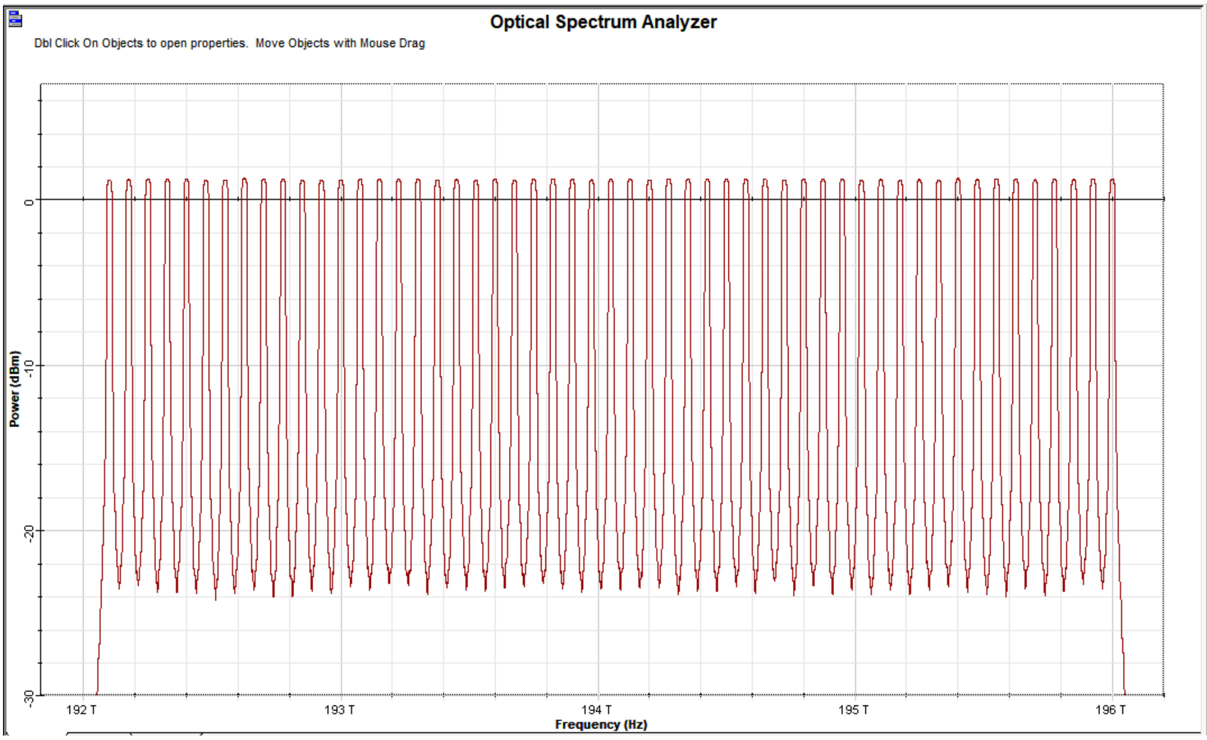


Figure 37. 60-400G in flex grid

From above Figures, the result of the four scenarios if compare between Fixed Grid and Flex Grid.

Flex grid can provide high efficiency utilization of optical network resource and capacity improvements, which can be made in a WDM network by reducing the space between channels instead of a traditional fixed grid network.

It is observed from scenario 1 when fixed Grid (30*10G, 30*100G and 20*400G) is used with fixed channel spacing of 50 GHz for 10 G / 100 G and 100GHz for 400G, the simulation result shows that only 10*400G can be used instead of the plan 20*400G. This is because the working frequency range between 192.100 THz to 196.050 THz in this simulation , this results in that only 70 channels out of 80 channels can be used with total bandwidth of 7, 3 TB.

In scenario 2 when using flex Grid (30*10G, 30*100 and 20*400G) with flexible channel spacing ,12.5 GHz for the first 30 channels 10G ,37.5Ghz for the second 30 channels 100G and 75GHz for the last 20 channels 400G , It was observed that channels number 80 is using frequency 195.0250 THz ,

And still more 13 channel can be used in case of have different Mux channel but in this simulation the frequency range limited between 192.100 THz to 196.050 THz, the simulation result shows that total 80 channels can be used with total bandwidth of 15, 3 TB.

Conclusion from scenario 1&2: after reducing the space between channels there is improvement of 8 TB showing when compare between fixed Grid and flex grid. More over another 13 frequency channels with channel space 75GHz from are saved in frequency 195.1 THz to 196.00 THz in Flex Grid, which can be utilized if required.

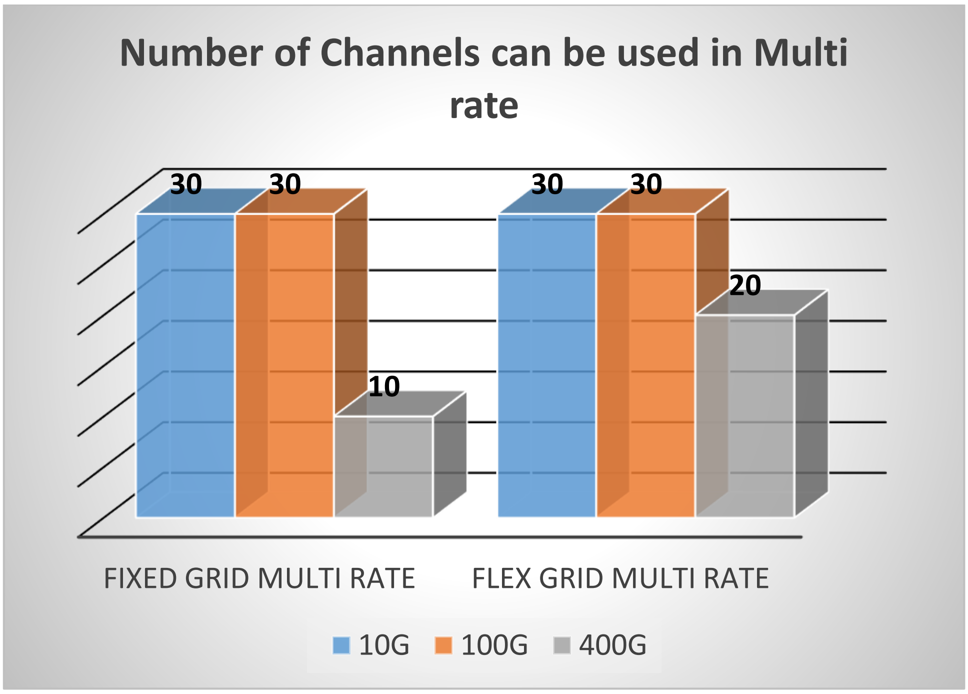
From scenario, 3 when using 80 channels Fixed Grid 400G for each channel, and frequency range between 192.100 THz to 196.050 THz with frequency space 100 GHz, around 40 channels can be used. With total bandwidth of 16TB.

In scenario 4 when using Flex Grid 80 channels 400G for each channel, frequency range between 192.100 THz to 196.050 THz and frequency spacing 75 GHz, around 53 channels can be used. With total bandwidth of 21.2TB.

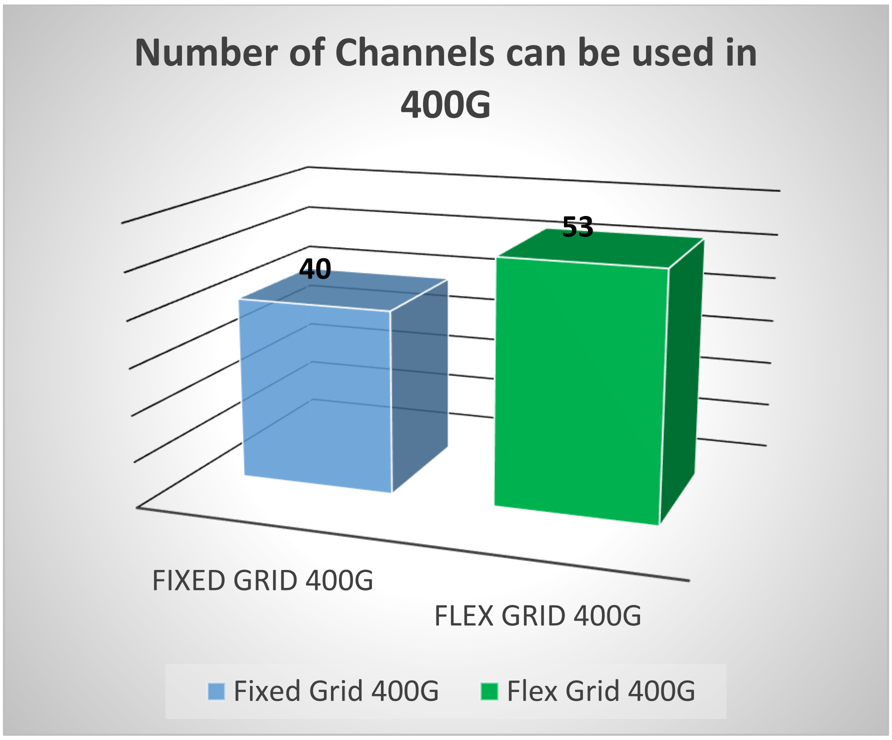
Conclusion from scenario 3&4: after reducing the space between channels there is improvement of 5.2TB between fixed Grid and flex grid for 400G.

4.5 Comparison Fixed Grid and Flex Grid results in Graph

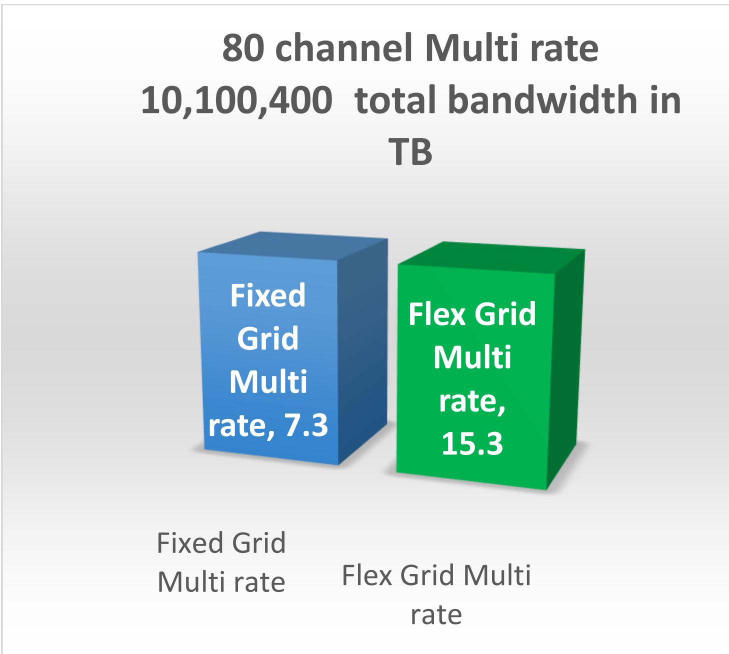
4.5.1 Number of Channels can be used in Multi rate



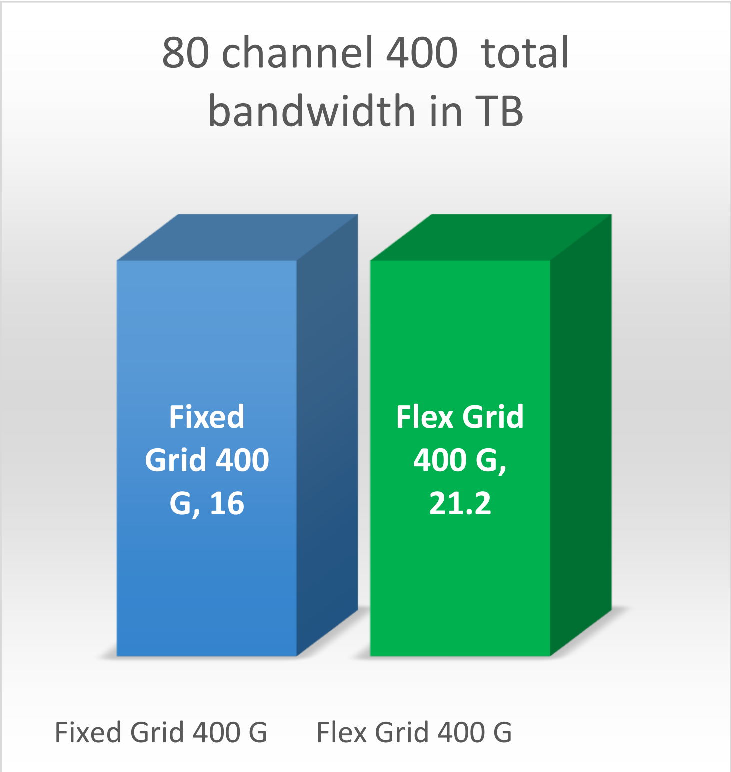
4.5.2 Number of Channels can be used in 400G



4.5.3 80 channel Multi rate 10,100,400 total bandwidth in TB



4.5.4 80 channel 400 total bandwidth in TB



Chapter five

Conclusions and recommendation

5 Chapter five Conclusions and recommendation

5.1 Conclusions

In Conclusion shows how Flex grid can provide high efficiency utilization of optical network resource and capacity improvements which can be made in a WDM network by reducing the space between channels instead of a traditional fixed grid network.

Since the Internet services (video conferencing, cloud services and video streaming) and consequently traffic demands are increasing continually, leading to huge traffic growth in the core optical network. There is a need for network operators to increase their optical network capacity to follow this traffic growth.

Since the deployment of new optical fibers is still very expensive, network operators are pushing to exploit the totality of their network capacity by optimizing their optical resources, and thus postponing the deployment of new infrastructures. This exploitation requires new technologies and flexible equipment that are able to handle different types of optical channels, from small to extremely high data rates.

Fixed-Grid technology is no longer qualified to handle the increasing data rates of optical channels. At the same time, the 50 GHz ITU grid, due to its fixed-spectrum spacing, produces losses of spectrum resources when the bandwidth occupancy of the established demands is smaller than (or is not an exact multiple of) the size of the allocated spectrum slots .

The main aim of the dissertation work was to implement and optimize Multichannel, Multi Gigabits per second DWDM ring. Optisystem 7.0, simulation software is used to implement Flex Grid technology in DWDM, Multi Gigabits per second DWDM chain. The proposed DWDM node consists of one Transmitter, Multiplexer (80 channels), Fiber, Optical power Meter, Optical Amplifier, Optical Spectrum Analyzer and Demultiplexer (80 Channels), network operates at 80 channels.

To analyze the effect of using Flex Grid on the proposed network, different levels of Bandwidth were taken to observe the utilization .It has been observed that at flex can save BW by reducing the space between channels,

To sum-up:

When Flex Grid ($30 \times 10G$,$30 \times 100G$ and 20×400G), only 10×400G can be used instead of 20×400G due to C- Band limitation. Thus 70 channels out of 80 channels can be used.

In Flex Grid (with proposed $30 \times 10G$,$30 \times 100G$ and 20×400G) all channels can be used due reduction of space between channels and the last C-Band Frequency will 195.0250. As a result 13 more channels will be available.

When using Fixed Grid 400G for each channel, only 40 channels can be used due to limitation of C-Band last frequency can be use is 196.05.

When using Flex Grid 400G for each channel, around 53 channels can be used.

When compare between Grids, Flex Grid better than Fixed Grid, around 13*400G more channels can be utilize in Flex Grid.

5.2 Recommendation

The ITU recommendation G.694.1 for a Flex-Grid optical network has defined a new flexible spectral grid standard for wavelength division multiplexing (WDM) applications. This flexible spectral grid has a smaller slot granularity of 12.5 GHz, with nominal central frequency on a grid of 6.25 GHz spacing compared to the currently 50 GHz Fixed-Grid.

This recommendation has made the Flex-Grid a promising technology that is capable of following traffic growth and various traffic demands. Flex-Grid efficiently uses available spectrum resources, especially when associated with novel coherent transmission technologies and advanced modulation formats.

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