A Simulation Tool To Optimize Cost, Spectrum And Reach Of Flex-Grid Metro Optical Networks

A Project as a Course requirement for

Master of Technology in

Optoelectronics and Communications

By

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CERTIFICATE

This is to certify that this Project titled "**A Simulation Tool To Optimize The Cost, Spectrum And Reach Of Flex-Grid Metro Optical Networks**" submitted by P Sai Ram Reddy, 17704, Department of Physics, Prasanthi Nilayam Campus is a bonafide record of the original work done under my supervision as a Course requirement for the Degree of Masters in Optoelectronics and Communications.

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DECLARATION

The Project report entitled "**A Simulation Tool To Optimize Cost, Spectrum And Reach Of Flex-Grid Metro Optical Networks"** is an original work by me under the supervision of **Dr. R Gowri Shankar, Department of Physics, Prasanthi Nilayam**, in partial fulfilment of the requirements for the award of the degree of Master of Technology in Optoelectronics and Communications of this Institute, and has not formed the basis for the award of any degree, diploma or any other such title by this or any other University.

……………………………..

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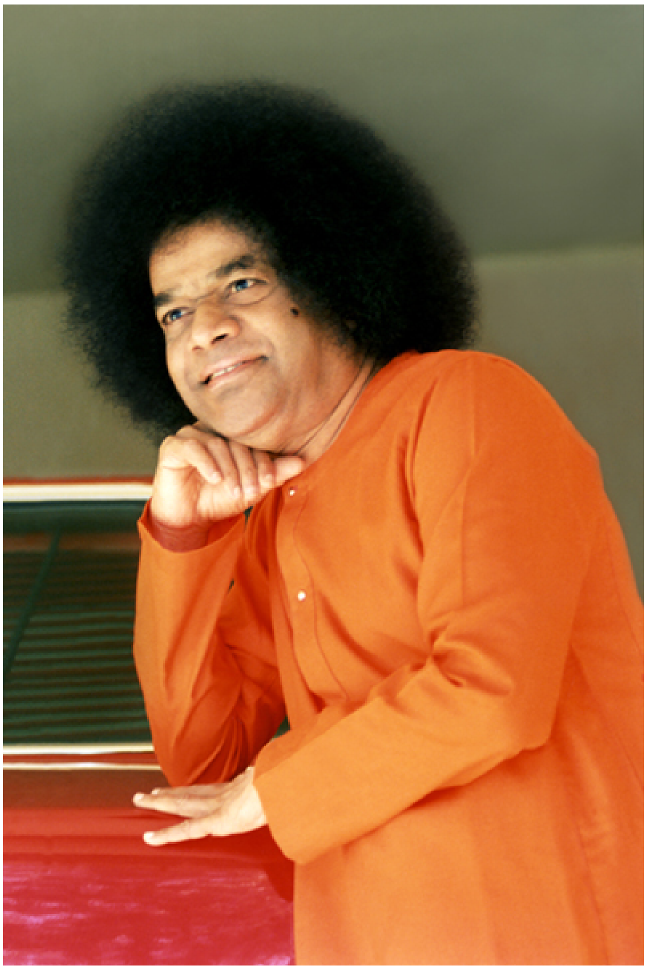
Dedicated at The Lotus Feet of my

Guru, Eternal Guide, Master and Friend.....



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Abstract

Internet traffic is growing dramatically, which means that broadband, 5G, cloud, and IOT services need a new prototype in order to draw more capacity from the existing fiber. Therefore, the traditionally fixed WDM network is moving into a new paradigm in which the network is adapted and tuned to different transmission conditions. Using high-speed electronics and modulation formats or by increasing the number of channels, higher bits rates can be achieved. The re-configuration of network equipment can satisfy dynamic traffic as customer demand changes over time. This changing paradigm clearly benefits from new network design opportunities to address a number of important issues. Flex grid networks have the ability to meet the dynamic capacity requirements of future core networks through a combination of two technologies, BVT and FS-ROADMs. On the other hand, the algorithm's role in the planning and network management of optical systems has become more flexible and complex. This helps to reduce the cost and management of the increasingly adaptable network.

We propose a cost-optimized routing and spectrum assignment (RWSA) scheme for greenfield Elastic optical networks in our work. The aim of this algorithm is to divide the customer's demand by providing an optimal solution with the formula suggested in the presented work. A proposed RWSA scheme is implemented and the algorithm's performance is compared to the proposed regeneration scheme and different case studies in our work have been reported.

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Abbreviations

EON	Elastic Optical Network
RWSA	Routing Wavelength & Spectrum Assignment
RWA	Routing Wavelength Assignment
OTT	Over the Top
Qos	Quality of Service
WDM	Wavelength Division Multiplexing
CWDM	Coarse Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
FS-ROADM	Flex Spectrum-Reconfigurable Optical Add/Drop Multiplexer
BVT	Bandwidth variable transponder
WSS	wavelegth selective switch
EDFA	Erbium Dobed Fiber Amplifier
ITU	International Telecommunication Union
PDM	Polarization division Multiplexing
MUX	Multiplexer
LCOS	Liquid crystal on silicon
MEMS	Micro-electro-mechanical switches
SMR	Single Module ROADM
QAM	Quadrature amplitude modulation
SLICE	Spectrum sliced elastic otpical network
QAM	Quadrature Amplitute Modulation
NSFNET	National science foundation Network
OSNR	Optical signal to noise ratio
LCOS	liquid crystal on silicon
MEMS	micro-electro-mechanical switches

Chapter 1

Introduction

Today's lifestyle is digitalized. We rely on digital applications on all aspects of our life that require huge bandwidth. In an environment where bandwidth requirements continue to grow as revenues decline, service providers are looking for cost-effective ways to maximize their network infrastructure. The over-provisioning of the network simply does not solve the problem of rapidly growing bandwidth, as was the case in the traffic of previous static applications. By using the entire fiber spectrum and re-configurable optical components in the network, the optical transport platform can satisfy the dynamic nature of traffic to go where it is needed and when it is needed.

In the current networking scenario, a prerequisite has been set for the system foundation to encourage ever - increasing bandwidth - hungry transmission apps and to keep pace with QoS (quality of service) standards. As discussed earlier, the possible solution to overcome bandwidth constraint is to implement the Elastic Optical Network(EON)/Flex - Grid Network. In this section, we show the capabilities of flex - grid optical systems over unbending WDM networks, in dealing with the constantly developing powerful traffic, its importance and evolution.

1.1 Flex-grid Optical networks - the need of the hour

Internet traffic is growing at a tremendous rate right from the start. The big players in the mobile and enterprise world chase each other to maintain their networks in order to support massive Internet demand, and coming shortly they will lose their esteemed customers. However, cloud migration, the popularity of the OTT content and its traffic patterns are totally dynamic in today's applications in both time and direction, with timescales of minutes to hours. These are major challenges facing future telecommunication networks, but they also provide the optical network industry with opportunities because these challenges can just be addressed by the optical communication systems technology. The fixed network cannot support new services that drive capacity growth. The rapid bandwidth uplift in the enterprise and public space will be driven by the backhaul network. Internet usage in 1 minute is shown in figure 1.1.

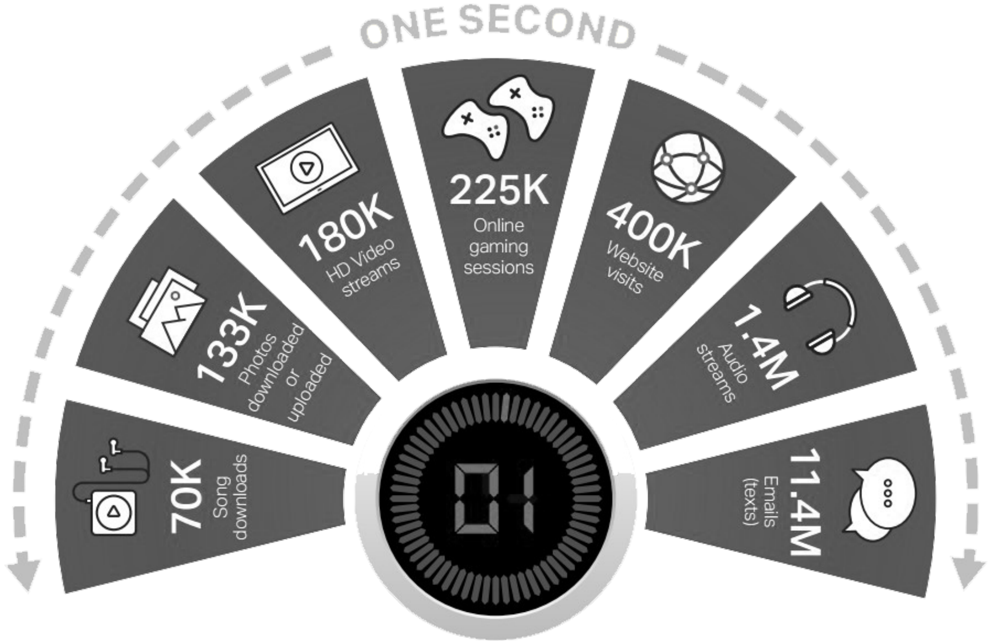


FIGURE 1.1: Whats possible in a single second with 400G speeds
Source:Primer: A guide to 400G optical networks Ciena White Paper

The future development and architectural transformation of the optical communications industry will be fueled by developments in the industry which are stated below

1.1.1 Emerging optical network services

- DC cloud interconnection service
- Ultra-bandwidth video service. **Example: Netflix, Amazon prime video**
- 5G mobile network services
- FTTH (fiber to the home)

These require low latency, high reliability, fast delivery and support for open cooperation, as well as increased bandwidth.

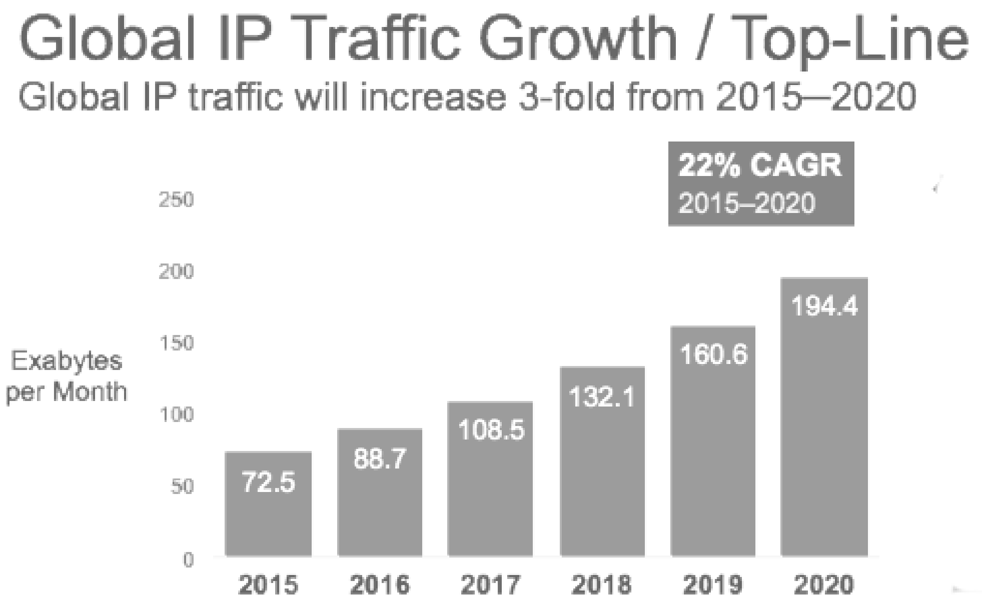


FIGURE 1.2: Cisco global IP traffic forecast report
Source: Cisco VNI Gobal IP Traffic Forecast, 2015-2020

Cisco estimates the global internet traffic will be five folds more when compared to the past 7 years and estimates that enterprise and customer traffic will increase three-fold in the upcoming years[1] as shown in figure 1.2. Due to the exponential growth of data, which presents itself as a major threat to the current networking paradigm, a robust, scalable and agile underlay infrastructure is required. Customers needs are on the verge of constantly changing, so network operators need a dynamic, flexible and protected network that changes over time. The network should become smart and intelligent enough to add new services and scale as the network grows.

1.2 Evolution of optical networks and Flex-grid networks

The fiber invention has given us an enormous bandwidth capacity with greater reach than conventional coaxial cables, which has paved the way for optical fiber communications. Cost, scalability, reliability and network capacity are some of the key benchmarks for the evolution of optical networks. The technological ability of the wavelength division multiplexing (WDM) was to multiplex many wavelengths and carry in a single fiber simultaneously. Over time, its development has evolved into two techniques. The coarse wavelength multiplex (CWDM) has a 20 nm spacing and could carry about 16 channels which later evolved into the dense multiplexing wavelength division (DWDM) which could then carry 80 to 96 channels with 0.4 nm channel spacing. The invention of erbium-doped fiber (EDFA) was the cost-effective key facilitator for the transmission of optical signals over long distances before regeneration was required. The bit rate was around 2.5 Gb / s in the 1990s, which then took a leapfrog to 10, 40 and 100. The industry is moved to achieve transportation speeds of over 100 G by coherent optical technology. For the last 15 plus years, the International Telecommunications Union (ITU) WDM grid [2] has been the preferred choice for operators with a channel spacing of 100 GHz or 50 GHz in the C band. Shifting to the denser grid spacing or improving transponder speed has served the increasing traffic growth in the fixed grid system. Much of the optical spectrum was wasted because the data rates occupied less spectrum compared to the DWDM grid spacing. The fixed grid optical equipment has fixed grid filters (ROADMS) which will notch the signals starting from 100 Gbps when passed through them.[3], [4],[5]. These signals cannot be fitted in the traditionally fixed grid channel spacing of 50 GHz. An alternative approach is to move to the 100Ghz grid, but the channel bandwidth will be underutilized by lower bandwidth transponders. The electrical bandwidth is a bottleneck problem [6] when higher bit rates are required. The data rate divided by the channel width(bandwidth) provides spectral efficiency. The data rate per channel can be increased by increasing the modulation format or the baud rate or by using multiple carriers (super channels). The evolution of cloud computing & 5G services has led to the deployment of the virtual machines, micro-services, edge computing near to the user's premises. The next generations systems producing bit rates

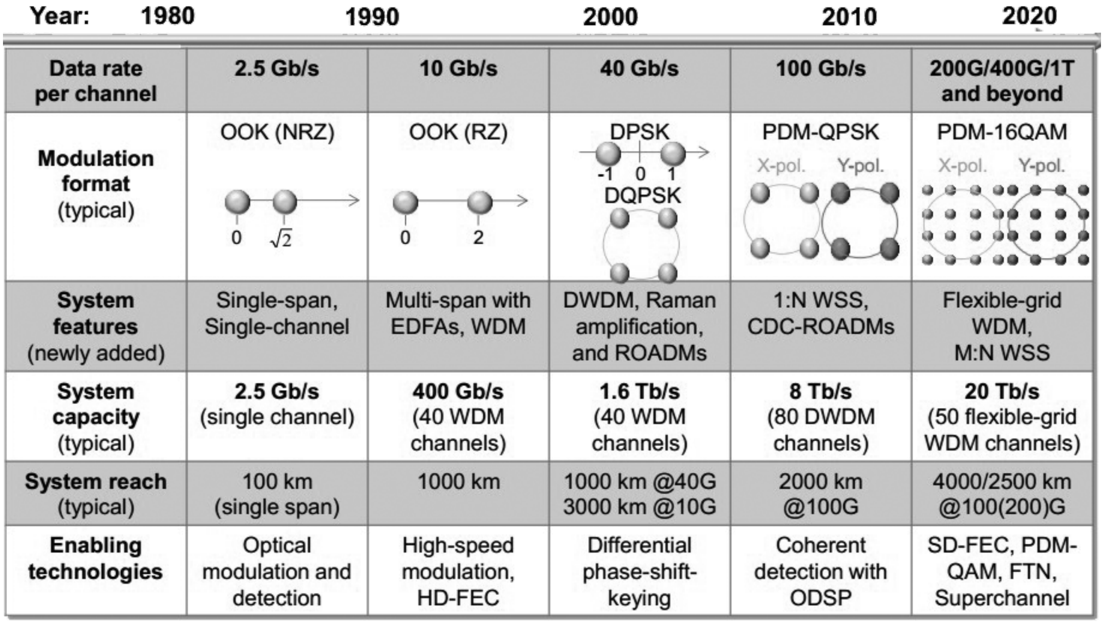


FIGURE 1.3: The Technology evolution of WDM
Source: White Paper on Technological Developments of Optical Networks HUAWEI

of 400 Gbps and 600 Gbps are already coming into commercial deployment from the research stage and if this happens, the use of mixed line rates is expected to become more popular. A fixed grid must be built at different line rates with more bitrate transponders to satisfy a mixer of bit rates that co-propagates. This can be achieved, but at a cost increase because we have not previously understood where and when traffic is growing during the design and procurement phase of the network. This unpredictability in traffic capacity requirement can be satisfied by tuning the network equipment. The development of flex spectrum-reconfigurable add/drop multiplexers (FS-ROADM's) over fixed optical add/drop multiplexers (OADM's) and the invention of bandwidth variable transponders (BVT) with backbone support from ITU - T flex grid is capable of producing different bit rates, which can now support both increased capacity demand and the dynamic nature of the traffic. Evolution of the optical networks is shown in figure 1.3. The "Flex - grid networks" or "Elastic Optical Networks" (EONs) or "Spectrum-sliced Elastic Optical Path" (SLICE) [7][8] have risen as an approach to providing an efficient way to work with optical assets [9]. The Flex-Grid has smaller chunks of slices (6.25 GHz)[10] and these smaller chunks are contiguously combined to form an arbitrary sized spectrum block as shown in figure 1.5. Flex grid passes broad bandwidth channels without filtering and densely packs channels to maximize spectrum utilization.

The transmission of terabit [11] will be accommodated in the future. "flex-grid",

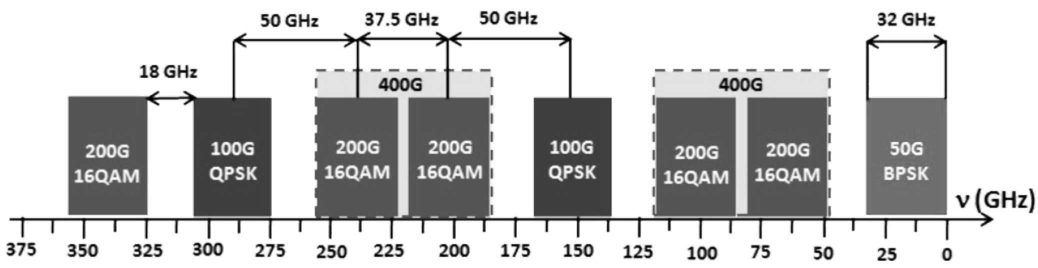


FIGURE 1.4: Flex Grid Network

FIGURE 1.5: Source: Technology Options for 400G Implementation OIF-Tech

"elastic" is often used interchangeably in the literature with "tunable" or "gridless". The term ' flexibility' refers to the system's ability to change its resources dynamically, such as the modulation format, baud rate, and bandwidth according to each connection requirement. When a new connection is requested by the client, the Routing and Wavelength Assignment (RWA)[9] algorithms assign routes and light paths. The traditional RWA algorithm has evolved into an RWSA algorithm since it is necessary to support the mixed line rates with different bandwidths. Subcarriers are used in multiplexing orthogonal frequency division (OFDM) technology where the bandwidth is divided into [11][9][12][13] fine-granular spectrum bands. A series of transmission parameters such as a format modulation, wavelength spacing between channels and bit rate otherwise fixed in the current DWDM network is adjustable for EONs. Given the need for future requirements to optimize and manage, cost-effectively and increase the transfer of high - speed optical connections, flex - grid networks are a valuable successor to DWDM - based optical networks.

1.3 Literature Survey

The Literature survey involved studying and understanding of a few papers that concretized the fact that a new solution has to be employed to get an optimized network design(planning tool).

Ref 1.

This paper "Planning and Operation of Elastic Flexgrid Optical Networks with OFDM Variable Bandwidth Capabilities" [14] has integrated design constraints and cost functions into their operation and planning of flex grid network. They have formulated a metric for the optical reach of each bit rate. The metric takes in the bit rate and spectral efficiency and gives out the estimated distance the signal can travel before a 3R is required. They have compared their results with a fixed grid and showcased that the elastic networks have superiority in terms of planning and online operation.

Ref 2.

This paper "Bottom-up framework for cost allocation to services in telecommunication networks Case study: cost allocation for flex-grid optical networks" [15] talks about the cost-efficiency in deploying a network. The transport services are investigated with the network components cost(eg: transponders). They have done the capex study on the network, but have to still extend their study on the OPEX. Their cost analysis has shown an impact on the RSA algorithm and has achieved a less cost-efficient solution when compared to the flex grid and semi-elastic RSA algorithm.

1.4 Motivation

- Continuing attempts to squeeze more out of a single optical fiber.
- International Telecommunication Union (ITU-T) has already standardized the new scalable and flexible spectrum grid in multiples of 6.25Ghz or 12.5 GHz.
- Having BVTs, FS-ROADMS at the architecture level. The underlying technologies are highly affected by the allocation of resources, route selection and adaptation of the modulation format which is software controlled.
- Our aim is to propose an agile spectrum management system to achieve more efficient spectral efficiency at optimized cost with optical feasibility.

These sources [15] [14] have worked on cost analysis in the flex - grid network. None of the works, however, took the fiber spectrum and OSNR as its internal parameters. Their cost analysis included only transponder costs. The laying of new fibers is sometimes an expensive business in some places like the metro area. Therefore, in such cases, the spectrum plays a major role. A new algorithm should, therefore, be developed that minimizes spectrum use in order to pack additional data into the fibers at an affordable price.

1.5 Thesis Outline

The Thesis is structured as follows

In Chapter 1

This chapter provided an insight into how traffic is becoming dynamic and increasing day by day exponentially. The need for a flex grid transition from a fixed grid was also indicated.

In Chapter 2

This chapter states the state of the art technology currently being deployed in the provider's network and its underlying architecture.

In Chapter 3

This chapter presents the first fit regeneration and without regeneration schemes together with the description of the network, traffic matrix and components present in the network.

In Chapter 4

The comparative study between the two aforementioned algorithms for various network scenarios is presented in this chapter.

In Chapter 5

The conclusions and future work are presented in this chapter.

Chapter 2

Cutting Edge technology and concepts

Modern internet needs a new paradigm shift which can be provided by the optical network. With the availability of Flex-spectrum Reconfigurable add drop multiplexes(ROADM), Bandwidth Variable Transponders(BVT), high speed electrical-optical modulation(transmitter), high speed optical detection(receiver), Soft-decision forward error correction(SD-FEC), polarization division multiplexing(PDM), advanced DSP (digital signal processing), advanced modulation formats and the evolution of the semiconductors are the driving forces for the future development of optical networking. Unlike the previous generation where the infrastructure has been fixed. Combining this massive advancement in technology with the flex grid opens up new horizons in introducing new scalability, flexibility and connectivity in the networks. This chapter presents this new and generation-long scalable technology.

2.1 ROADM

It is an optical network element which can add/drop and express wavelengths at an optical node. The express wavelengths can be switched, with the wavelength selective switches(WSS). Either LCOS or MEMS is the technology behind these systems. Lightpaths (λ) were transmitted on a 50Ghz fixed grid until the previous generations. Adding and dropping of wavelengths with both fixed and flex-grid bandwidths is now possible in flex-grid ROADMS [16]. Wavelengths Add /drop and routing is completely controlled by software that eliminates manual operation, reduces operating costs and reduces provisioning and recovery times. The agile DWDM innovations are as follows:

Colorless: The ports are not frequency specific. Previously due to fixed filters in MUX/DEMUX, we were not able to have this colourless option. This colourless option allows the express channel to be connected to any add/drop port of the transponder associated with that fiber.

Contentionless: The add/drop refers to the ability of an N-degree ROADM node to satisfy the wavelengths of the same frequency from an add/drop device. The contentionless architecture is shown in Figure 2.1 compared with the colourless and directionless only architectures.

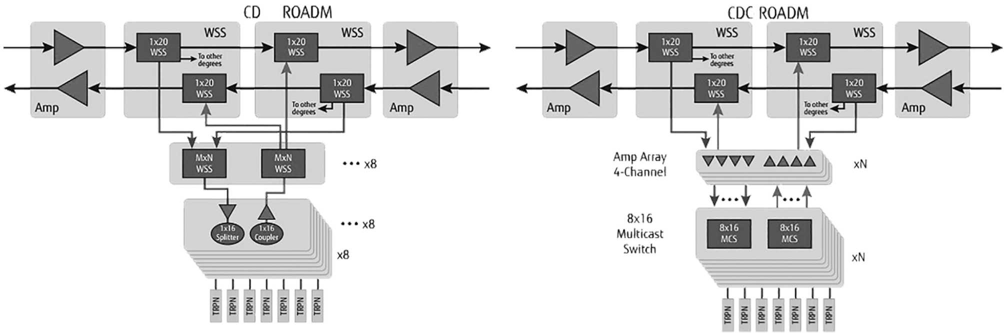


Figure 2.1: CD ROADM Vs CDC ROADM
Source: CDC ROADM Applications and Cost Comparison FUJITSU

Directionless: Wavelength reroute does not require a physical fiber move, as a single group of transponder shares the wavelength.

Flex spectrum: Multicarrier super channels or single carrier channel can be flexibly provisioned which have varying channel bandwidth exceeding 50-GHz channel spacing.

Together, colourless, contentionless, directionless, and flex spectrum functionalities help in configuring the network on the fly.

2.2 Bandwidth Variable Transponders(BVT)

Until the previous generations, the transponders have been a fixed device giving out a specific spectral bandwidth, wavelength, specific modulation format and a specific reach. Wavelength was the only tunable parameter in it. The advancements in the digital signal processing technology have been a boon to the transponder technology, after which the DSPs are incorporated into the transponder for achieving higher line rates. The bit rate and the baud rate can be changed by tuning the transponder[17]. The software comparability has become a reality with this advancement, which can be very useful in a dynamic network. This helps to carry different demands as they enter and leave the optical node. Regardless of the long - term to a single connection of the transponder, the adaptable transfer capacity of the programmable transponder enables it to be consistent with Association's diurnal changes and enhances the utilization of system capacity. Therefore, the transponder can be modified to help the lower rate of use with lower control if the association's information rate is reduced (e.g. due to daytime). Software-defined optics refers to quickly adjusting the spectral width in software by changing the baud rate or bitrate formats. The trade-off between the spectrum & reach is another advantage given by the BVT.For eq: A 200 Gbps over 500km can be achieved by using a higher modulation format PDM-16QAM, whose bandwidth is 37.5Ghz, but if we want to reach a distance of 1000 km we then use a lower order such as PDM-QPSK. The modulation format and optical reach tradeoff is shown in Figure 2.2

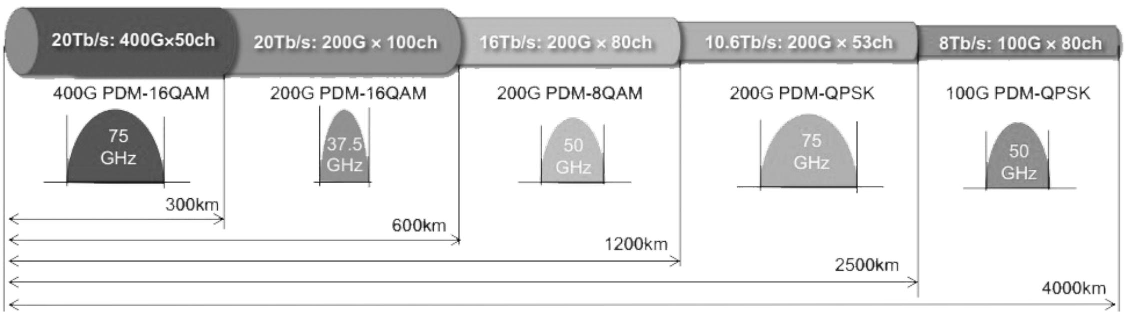


FIGURE 2.2: Bandwidth variable transponder
Source: White Paper on Technological Developments of Optical Networks HUAWEI

2.3 The Media Channel Group

The media channel acts as the continuous spectrum portion from the initial source to the final destination, which brings a single or many carriers. The set of carriers inside the media channel is called a super-channel. The allocated bandwidth and the path is taken, information will be included in the media channel(Mch). It is possible to aggregate several media channels into a Media Channel Group [18]. Its primary use case can be for super-channels(multiple wavelengths) or many single carriers which have already been deployed. These can now be grouped together, but if one fails, the other waves are not affected. This will allow us to squeeze the media channels into the smallest portion of the spectrum. The media channel group is also defined from the source to the destination as shown in fig 2.3. The media channel group is a collection of media channels that need to be transported without interruption. In addition, the bandwidth of an existent media channel group can also be extended (increasing the number of slices) to allow the transport of more media channels. This can be automated or done manually by the user. The bandwidth of the media channel group can be shrunk or expanded even after the deployment. Media Channel includes Optical BW with Slice granularity. It is routed at the optical level as a single entity. Defining parameters:

1. Source + Destination
2. Path
3. Central Freq + B.W in Ghz with a 0.1Ghz resolution or ([m,n] index as per RFC -7698)
4. Superchannel Included
5. Carrier freq. defined as absolute frequency[Ghz] with resolution 0.1Ghz or as relative offset with respect to the MCH center freq[k * 0.1Ghz] with k positive/negative interger

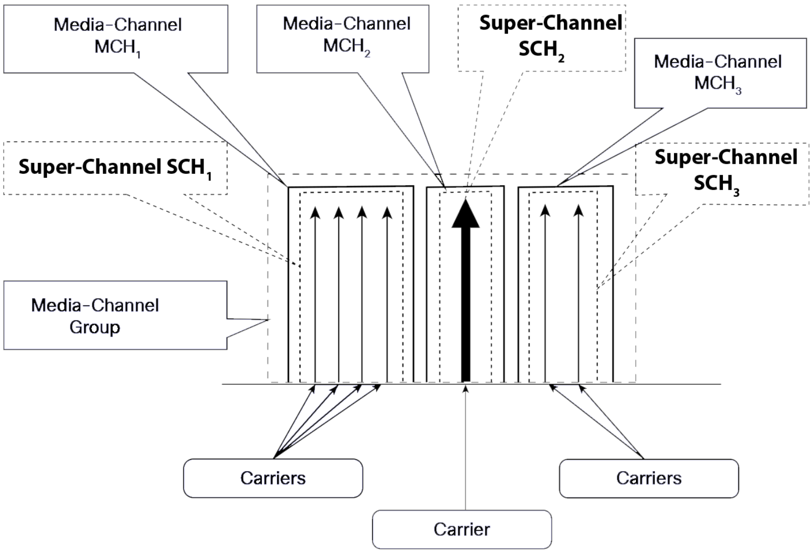


FIGURE 2.3: Media Channel Group
Source: Cisco FLOW white paper

2.4 Advanced Modulation Format

The data can be coded on to a light stream and this format is called modulation format. Till 10 Gb/s the modulation format used was simple ON/OFF keying. Its called direct detection, which means the signal is OFF if "0" is detected and the signal is ON if "1" is detected. The DQPSK(differential quadrature phase shift keying) and DPSK (differential phase shift keying) came into the picture at 40Gb/s. The DP-QPSK(dual polarisation quadrature phase shift keying) came into the picture at the speeds of 100 Gb/s. Here the data is transmitted in two polarisations one is quadrature phase and other is in-phase. The advanced modulation formats evolved to increase spectral efficiency, such as QPSK(quadrature phase shift keying). The capacity of the fiber can be increased if we go to higher modulation formats since the spectral efficiency is higher compared to the ON/OFF keying techniques which follow NRZ. By employing the Polarization multiplexing and higher modulation format the baud rate can be reduced by a fraction of 4 in QPSK, which means the electronics required is less when compared to the line rate. As we squeeze a number of bits per second we get higher modulation formats, the evolution of QAM is shown in Figure 2.4. We can increase the spectral efficiency by going to higher modulation format, but this stress the DAC/ADC in terms of their bandwidth. The effective number of bits (ENOB) stress the DAC/ADC as we go to higher order QAM. The transmission reach is reduced as we go for higher order

QAM, which required more OSNR[19] at the receiver side. It also accumulates more linear(laser) and nonlinear phase noise(fiber).

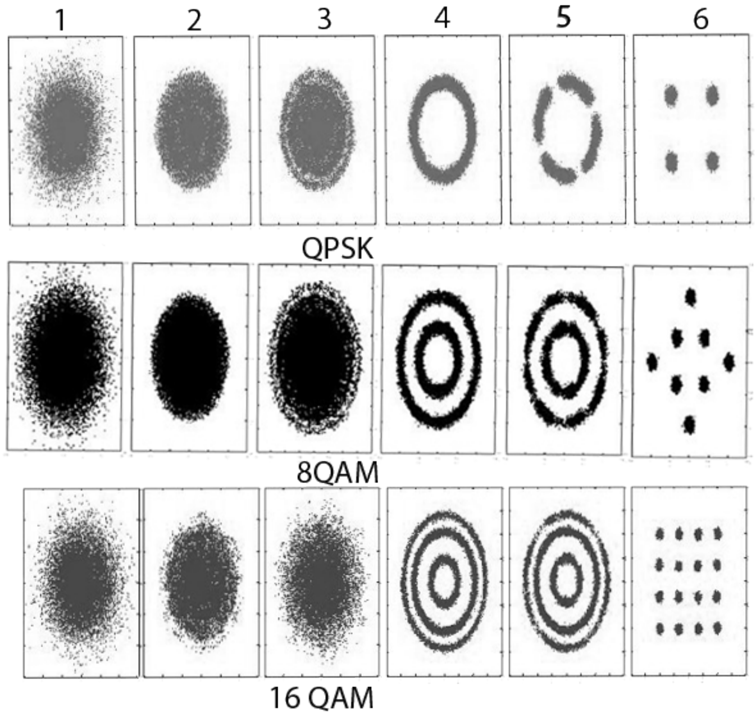


FIGURE 2.4: Evolution of advanced modulation format
Source: Technology Options for 400G Implementation OIF-Tech

2.5 Routing Wavelength and Spectrum Assignment(RSA)

Until now the Routing and wavelength assignment(RWA) algorithm assigns a wavelength to the incoming demand, but in the case of flex-grid networks, the Routing, wavelength and Spectrum Assignment (RWSA) algorithm assigns appropriate spectrum along with a light path(wavelength). Assigning each demand a lightpath is the RWA objective. The required wavelength is assigned to the route chosen by the Yens K-shortest path or Breath first search algorithm [20] [21]. An appropriate route can be found out by any famous routing algorithm and the light path can be assigned. In the absence of the wavelength converters, only a single wavelength has to assigned to all the hops in the end-to-end path of the connection. This property is popularly known as wavelength continuity constraint. The flexibility of the RWSA algorithm helps in satisfying the requested data rates, which lies truly in the architecture of the flex grid network when compared to the RWA algorithm. This is depicted in Figure 2.5 A connection of spectrum slots which are continuous is assigned in the RWSA algorithm, whereas in the fixed-grid only a wavelength(spectral resource) is assigned to the demand. The spectrum contiguity can be overcome by positioning the spectrum slots adjacent to each other [12]. If the continuously required slots are unavailable, then the demand can be divided into smaller chunks and this is called multi-path routing. These smaller chunks are then assigned a smaller number of contiguous subcarriers. The subcarriers also should satisfy the wavelength continuity constraint.

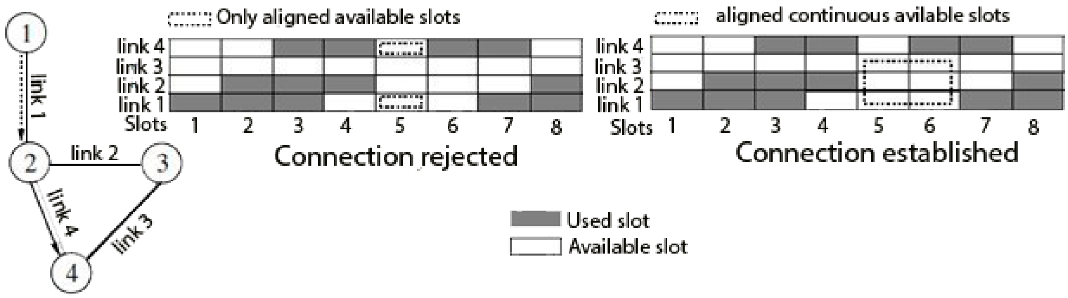


Figure 2.5: Illustration of spectrum continuity and spectrum contiguity constraints

In this chapter, the up to date technology and concepts that are currently being used in the real network were discussed. In the next chapter, algorithms are developed on these underlying technologies that give them the flexibility to be controlled by software.

Chapter 3

Problem Statement & Cost Optimized RWSA Scheme

The evolution of the the the flex grid from the fixed has paved way for the spectrum continuity and spectrum contiguity constraints limitations in RSA algorithm. It is a complete NP-hard problem. The RSA algorithm is made up of two parts: routing and spectrum assignment. Our algorithm uses the first fit scheme. Many authors presented their work in the literature on the spectrum assignment in the flex grid network. In building this process, our algorithm has taken two parameters into account: OSNR & Spectrum. This chapter deals with the network topology, traffic matrix used and the approach taken to solve the problem.

3.1 Problem Statement

Given a greenfield mesh network, where each of the nodes in the network is built using SMR 20 ROADMs with contentionless add/drop cards and all the transponders are flex mod and flex baud transponders giving rise to different bit rates. If this is the network scenario, how can a customer demand be broken down to offer a spectrum efficient, affordable and optically feasible solution? A network like this now has too many parameters to optimize for better use of resources at lower costs. Our study aims to assess the effect of selecting different modulation formats and channel bandwidths in conjunction with optical feasibility.

3.2 Network Topology and its Description

In the real world, the optimized algorithms are to be tested on a platform. Such a platform is called network topology. In our case, we have taken 3 such famous topologies which are NSF-NET(National Science Foundation network), US-NET (United states backbone network), Telefonica Spain Network. The NSF-NET is shown in Figure 3.1. It has 14 nodes and 21 links in it. The link length is measured in kilometres (km). The nodes consist of the node number and its location i.e latitude and longitude. The links consist of the first node & the next node with the distance between them. The start and end slice are taken from the specification sheet SMR 20 ROADM, i. e. 196.125 THz to 191.325 THz of 4.8 THz bandwidth. Each fiber link has 384 spectrum slots which are obtained by dividing the fiber bandwidth 4.8 THz with 12.5 GHz slice granularity. Each node is equipped with a flex spectrum ROADM [22] [23] with a pre and booster amplifier inbuilt in it. The transponders which are used at the nodes are bandwidth variable transponders (BVT). This network now replicates a real-world scenario.

Table 3.1: Network Topology

network topology	edges	nodes
NSF-NET	21	14
US-NET	42	24
Telefonica Spain Net	56	30

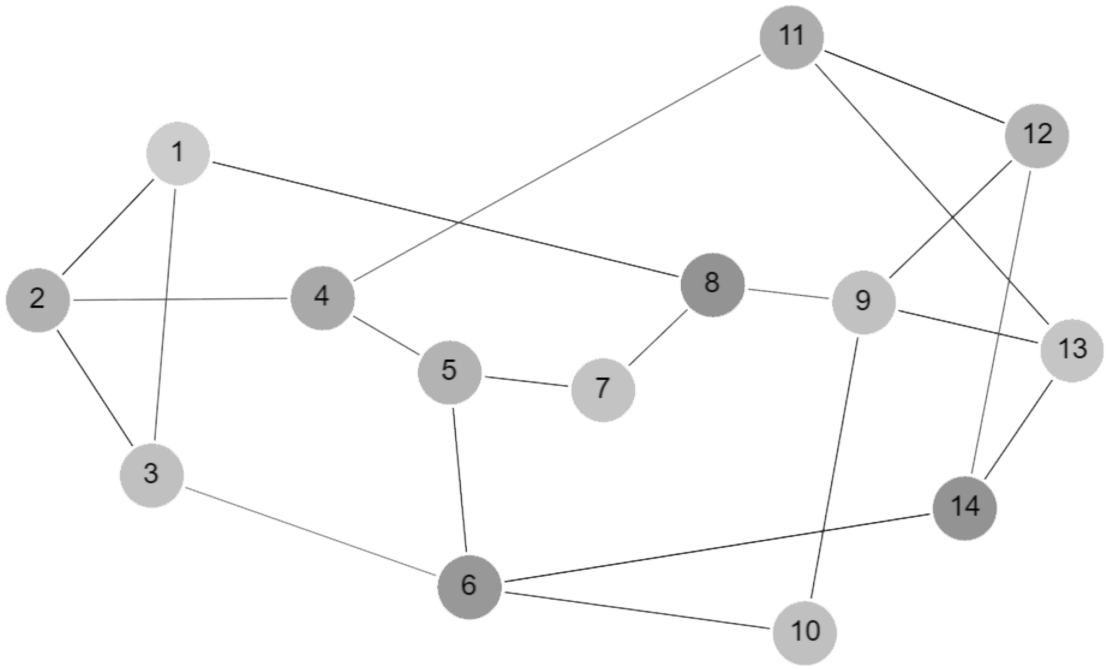


FIGURE 3.1: NSF-NET (National Science Foundation)

3.3 Depiction of Traffic Matrix

The name traffic denotes three parameters the network is trying to solve. Source, destination and its demand. The traffic scenario has been modelled to take in demands which start from 2000 Gb/s and above. The random variable is a Poisson distribution output. The available data rates that the BVT can produce are from 100 to 600 Gb/s, in multiples of 50/100 Gb/s. The services in our network are unprotected. The slot requirements for these data rates vary from 3 to 7. The baud rate, bandwidth, cost and bit-rate back to back OSNR [24] are also in Table 3.2. The cost values considered are the normalised values. The base card for the transponder is 100 Gb / s. So when demand is divided and not in the multiples of 100, we round the demand to the nearest 100. For example, a 2149 Gb/s bit rate will become 2200 Gb/s. This whole bit rate is called as the media channel group. An additional 2dB penalty is added to the OSNR bit rate. The penalty shall include all losses from linear (CD, PMD, ROADM filters) and non - linear losses (XPM, FWM), respectively.

TABLE 3.2: Bandwidth variable transponders in flex grid

Bit rate (Gbps)	Modulation Format	B.W(Ghz)	Baud rate (Gbaud)	slots	OSNR (dB)	Cost Normalised Units
100	QPSK	37.5	34.58	3	12	1
150	8 QAM	39.8	34.58	4	15	1.2
200	QPSK	75.4	69.16	7	12	1.3
200	16QAM	41.14	34.58	4	18	1.5
250	16 QAM	51.5	43.225	5	18	1.7
300	8QAM	79.5	69.16	7	15	2.2
400	16QAM	82.3	69.16	7	18	2.5
400	64QAM	59.9	46.11	5	24	2.8
500	32QAM	86.5	69.16	7	21	3.2
500	64QAM	74.9	57.63	6	24	3.5
600	64QAM	87.5	69.16	7	24	4

3.4 Finding Shortest Paths

A well - known Yen's K - shortest path algorithm built on the Dijkstra is used for calculating the shortest paths[25].It has been applied to the topology of the network. It calculates the K - shortest loopless paths for the graph(topology) matrix given to it. First, the yens path finds the shortest path either in terms of the distance between the links or in terms of hops, the metric is up to the user to decide. After finding the first shortest path, the adjacent link used for the calculation is deleted and the second shortest path is calculated if there is one. In this way, the algorithm calculates the shortest K-1 paths for a given source and destination. The user decides the ' K ' parameter, we require a maximum of 5 alternative paths for a given source-destination pair in the real scenario as shown in Table 3.3.

TABLE 3.3: Five alternative Shortest paths

S.No	Alternate Shortest paths	Hops
1	7>8>9>13	3
2	7>5>4>11>13	4
3	7>5>6>14>13	4
4	7>5>6>10>9>13	5
5	7>8>9>12>14>13	5

3.5 Amplifier Placement

Optical amplifiers are used to remove loss limitations that amplify the transmitter's optical signal directly without converting it into electric form. Optical amplifiers are used primarily for simultaneous amplification of all WDM lightwave system channels. By installing the amplifier immediately following the transmitter it can be used to increase the transmitted power. The transmission distance can also be increased by placing an amplifier just before the receiver to boost the received power. The ROADM has inbuilt pre and booster amplifier, this reduces the wiring of more fibers. The losses at the ROADM node are due to multiplexer, de-multiplexer, connector, add/drop of channels, pp mesh. It is a Switchable preamplifier that allows optimum operation across two distinct gain ranges. This card can operate over almost any fiber length, easy to deploy. The noise figure NF is calculated at each node. The output power is constant that is 0 dBm, which is in a gain controlled mode of the amplifier. The maximum and minimum gain values are shown in Table 3.4 for the pre and booster amplifier. The first, last gain and noise figure values were taken from the specification sheets. The noise figures (NF) for the corresponding gain values were extrapolated and taken into account. The SMR 20 ROADM and 16 contentionless add/drop card losses are shown in the Tables 3.5 and 3.6

Table 3.4: SMR-20 ROADM Amplifier Gain Values

S.NO	Amplifier Type	Minimum Gain	Maximum Gain
1	Pre amplifier	0 dB	35 dB
2	Booster amplifier	12 dB	24 dB

Table 3.5: SMR 20 ROADM Component Losses

S.NO	Component	Loss(dB)
1	Minimum Insertion Loss	6
2	Patch Panel mesh	2

Table 3.6: 16 Add/Drop CCOFS card

S.NO	Component	Loss(dB)
1	Upgrade path loss	6

3.6 OSNR

3.6.1 Optical signal to noise ratio calculation

The OSNR is a critical parameter that is calculated in an optical system for a given optical signal. It determines the strength of the signal with respect to the noise accumulated and also the threshold at which the amplifier should function. The OSNR is calculated at every stage in the optical network, but it's a dependent quantity as it depends on the previous stage. We can use 2 formula [26] for the calculation. The simple formulae from Equation 3.1 is used when the NF (noise figure) values are constant along with their span loses. The OSNR path values for 20 and 120 km are shown in the Table 3.7. The second formula from Equation 3.2 is used when the NF and link losses are not constant but vary with the network design. OSNR is a measurable quantity. OSNR is calculated using the following formula.

$$OSNR_{dB} = 58 + P_{in} + \lceil_{dB} - NF_{dB} - 10log(N) \tag{3.1}$$

$$OSNR_{currentstage} = \frac{1}{\frac{1}{OSNR_{previousstage}} + \frac{NF \times h \times v \times \Delta f}{P_{in}}} \tag{3.2}$$

where,

P-in= input power to the amplifier

$\lceil$ = span loss

v = optical frequency = 193 THz

h = Plancks constant = 6.634 x 10-34

Δf = optical bandwidth = 0.1nm (12.5GHz)

NF = the amplifier noise figure

The above formula calculates OSNR value of a channel in the network. The minimum OSNR is required at an amplifier which specifies a specific BER (bit error rate) at which the signal is received which can be detected without any errors.

Table 3.7: Path OSNR at 20 and 120 km

path	hops	OSNR @ 20 Km	OSNR dB @ 120Km
1>3	1	33.94 dB	20.76
1>2>3	2	30.72	17.741
2>3>6>5	3	28.89	15.97
2>1>8>7>5	4	27.60	14.725
1>8>7>5>6>3	5	26.61	13.755

3.7 Web GUI

Python is a very popular high-level programming language. It is a dynamically typed language, where you need not determine variable types and formatting in the code. Since our network contains more than 14 nodes and 21 links, python was preferred. It's easy to learn since it is written in simple English language. The lists and dictionary in python are powerful tools, which have been used extensively in designing the algorithm. A user interface tool has been developed with python as the back-end and HTML as the front end. The front-end and back-end are connected by the Flask tool. Flask is a micro web development tool that has the basic functionality of routing requests and is compatible with python. Axios is another tool used for the interaction between the server(front end) and python(back-end). HTML, CSS and java-query are used as the designing tools for the front end interface. Bootstrap in a simpler version of HTML and CSS with inbuilt custom commands. Java query scripts have been used for the projection of the topology. The data is feed in the back-end and the results are projected on the HTML page, by logging into the server IP address and port number. Example: 192.168.28.50:5100. The python packages used are numpy, pandas. The output generated is automated using pandas and is stored in excel sheets. The network topology, the free matrix of the network, the occupied matrix, the nodes, the edges and the demands are all displayed as soon as the algorithm is executed. Visual representation of the data speaks a lot and the mistakes can be easily interpreted. The web interface is shown in Figure 3.2

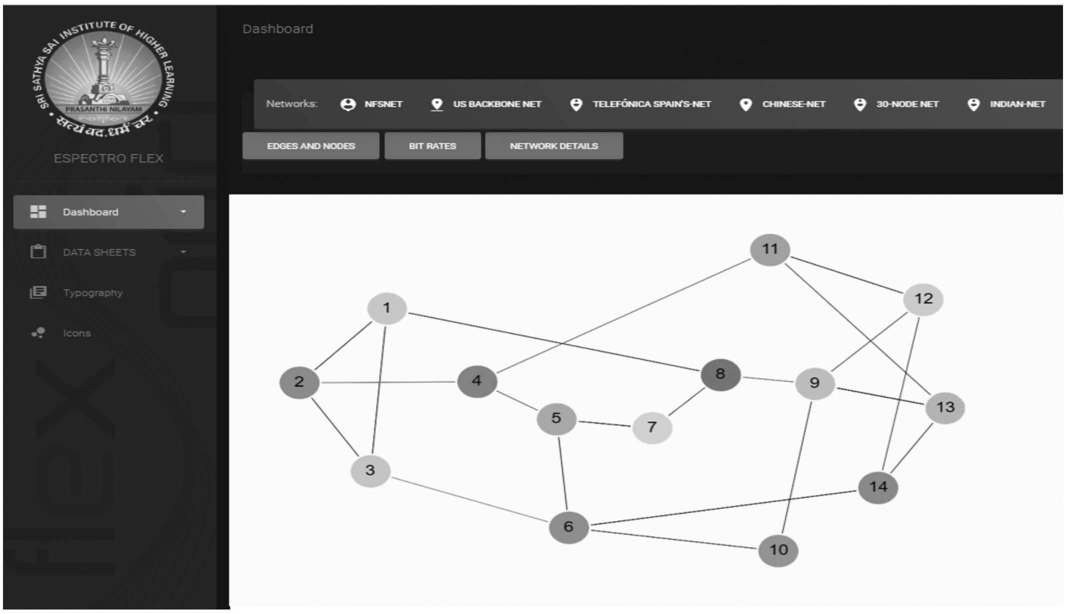


Figure 3.2: Web Interface tool

3.8 Algorithm

3.8.1 Cost optimized RSA algorithm

First, the network parameters like the number of nodes, edges and the traffic matrix are fed into the network graph. The famous network topologies like NSF-NET, US-NET, Spain-NET have been selected for testing the algorithm. The traffic is generated using the randint method from the numpy package in python. Therefore the obtained source, destination and demand follow a Poisson distribution. Then the YENS k - path algorithm runs to locate the first five k - shortest paths for each demands request, source & destination pair. All five paths are stored in a variable list. Find the OSNR (actual OSNR) of all these 5 paths using the formula stated before in eq (3.2). Then assign them in descending order, with the highest OSNR path first. Select the first path, which is optically feasible for that source, destination pair. The BVT's data sheet[24] contains the bit rates along with their required baud rate, OSNR (required OSNR) & slots required. Check the actual OSNR from the path with the required OSNR for each bit rate from the specification sheet. After comparing the OSNR, bit rates are selected which are feasible on the path, i.e all the bit rates whose OSNR is greater than the path OSNR. Now with the obtained set of bit rates for that demand, find all the possible combinations in which the demand can be divided. For eq: The

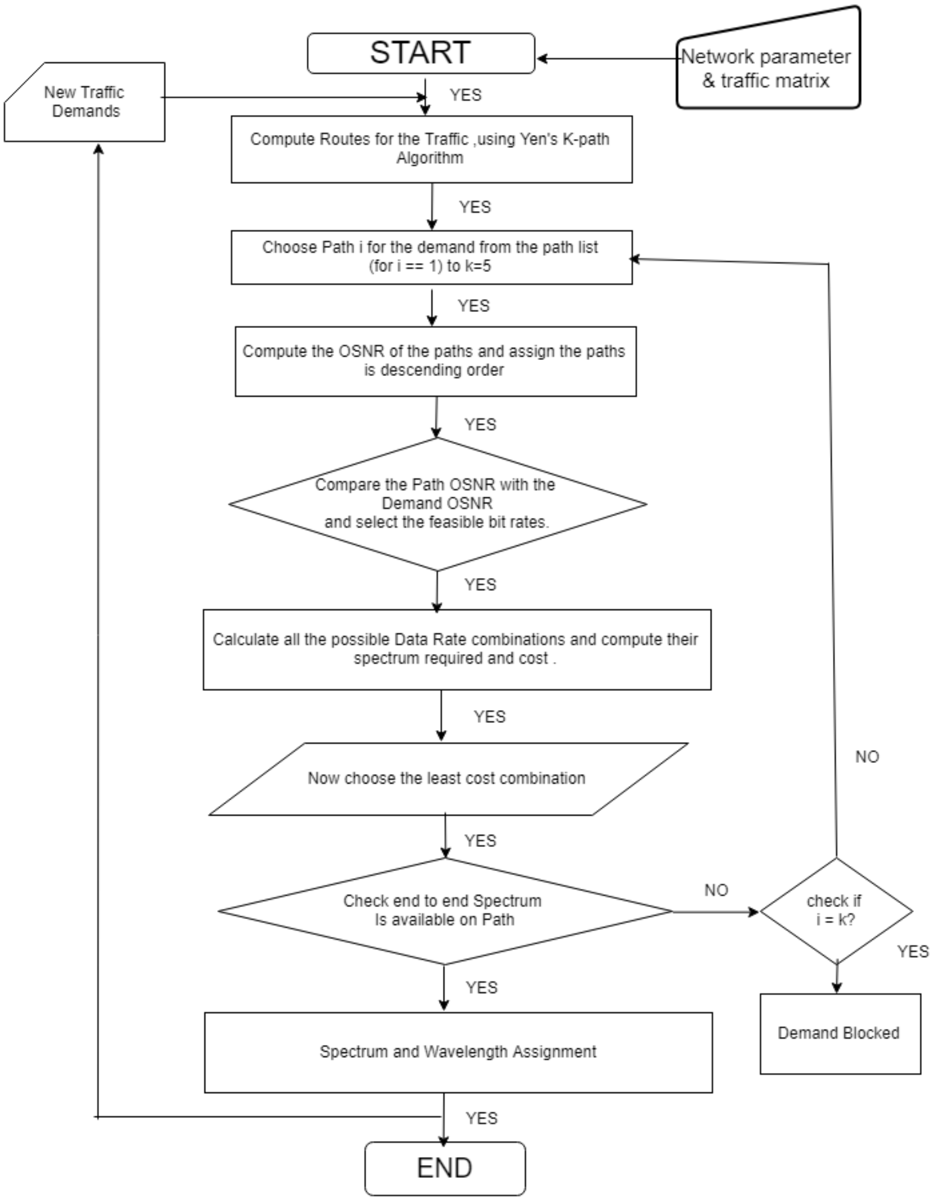


FIGURE 3.3: Proposed Cost optimized algorithm

possible combinations for a 600 Gb/s demand are shown in Table 3.8. Then calculate the overall cost & spectrum for that demand. The transponders cost are taken from Table 3.2 and the cost of the fiber is taken as 1 NCU (normalised cost unit). The cost metric used in the calculation is equation (3.3).

$$COST_{total} = cost\ of\ transponders + (cost\ of\ the\ slots * number\ of\ hops) \tag{3.3}$$

A set of all possible combinations with their cost have been obtained. Then select

TABLE 3.8: Possible division of bit rates for 600

S.NO	100	200	300
1	6	0	0
2	4	1	0
3	2	2	0
4	0	3	0
5	3	0	1
6	1	1	1
7	0	0	2

that combination which has the least cost among all the obtained values. Find the overall spectrum required by that demand, this is called the media channel group. If free slots are available on the path, then continue to Routing, spectrum & wavelength algorithm or else check for the next four paths in the list. If none of the five paths has the required free slots, then the demand is blocked, if not then proceed to the next demand. This is the flow at which the algorithm is executed as shown in Figure 3.3.

3.8.2 Cost optimized RSA algorithm with regeneration

By re-amplifying, re-shaping and re-timing the regeneration "cleans up" the optical signal. This is referred to as "3R" regeneration. Since regeneration is a costly affair, the algorithm is designed in such a way that, we have a trade-off between the choice of regenerating the signal with a higher modulation format or to use a lower modulation format with more spectrum utilization. We are not regenerating all the channels in our network at all nodes. We only regenerate when its cost is less when compared to the without regeneration case. The algorithm explanation which is stated in section 3.7.1 holds good for the regeneration case also, with one major change as shown in the Figure 3.4. Here, the actual OSNR of the path is not compared with the required OSNR. If the actual OSNR is greater than or equal to the required OSNR, then it is no regeneration. But, if it is less, then we calculate the OSNR margin as in Equation 3.4. Then calculate the number of regeneration's required for that bit rate to reach its destination as in Equation 3.5. Ceil the number of regeneration's value. This gives for each bit rate how many regenerations are required. Which implies transponders have to be placed at these regeneration points. Then this is evaluated with the hops that path has. For eq:

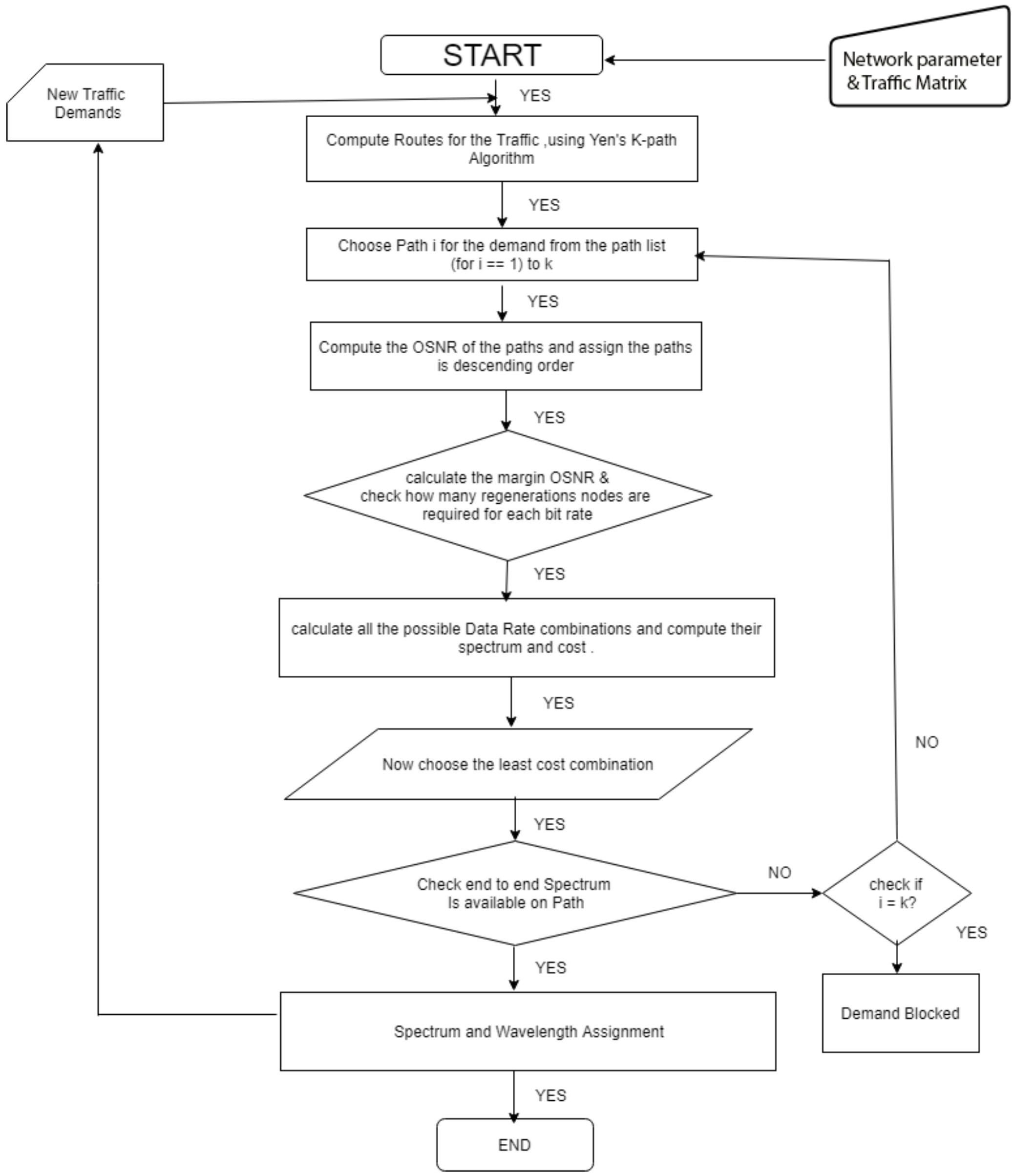


Figure 3.4: Proposed Cost optimized algorithm with regeneration

Suppose we need 3 regeneration nodes and we get 2 hops, then that bit rate cannot be taken into consideration. Then move to the next lower bit rate, like this store all the possible bit rates that can be regenerated. Then find all the possible combinations that can be possible with those selected bit rates for that demand. Suppose none of the bit rates is feasible then we shall block that demand and move to the next one. The rest of the algorithm follows as discussed above i.e routing and spectrum assignment.

$$OSNR_{margin} = (actual_{OSNR} - required_{OSNR}) \tag{3.4}$$

$$Number\ of\ regenerations = \frac{OSNR_{margin}}{3} \tag{3.5}$$

3.8.3 RSWA algorithm

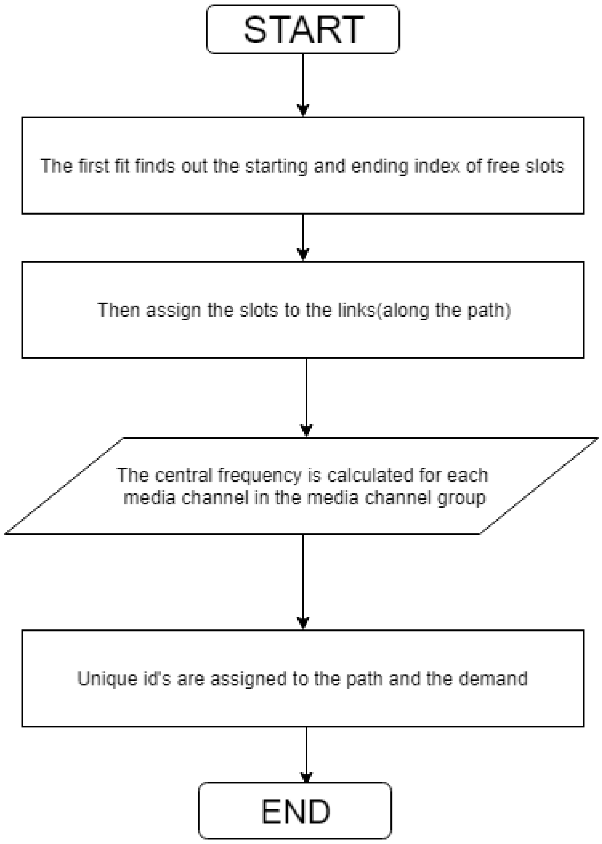


FIGURE 3.5: Routing wavelength and spectrum algorithm

This is the core part of the algorithm. Here spectrum and wavelength are assigned to each individual media channels contained in a media channel group. The first fit method is employed. The first fit method goes to each link in the path and finds out all the free slots available [27]. First, we have tried with an array. But it became computationally challenging since each fiber in the network should contain an array of 384 ”0”s which are changed to ”1”s when occupied. So using lists in python reduced the complexity in maintaining such huge data. The free slots are represented as a list, with the first number representing the starting index and the second number representing the last index. This implies that the subtraction of the first and the last index gives us the number of slots free. For Eg: [1-11], this implies that 10 slots are free. Then compare the required slots with available slots, if the available slots are equal or greater than required slots, we shall store that value in a variable. Then start assigning the spectrum

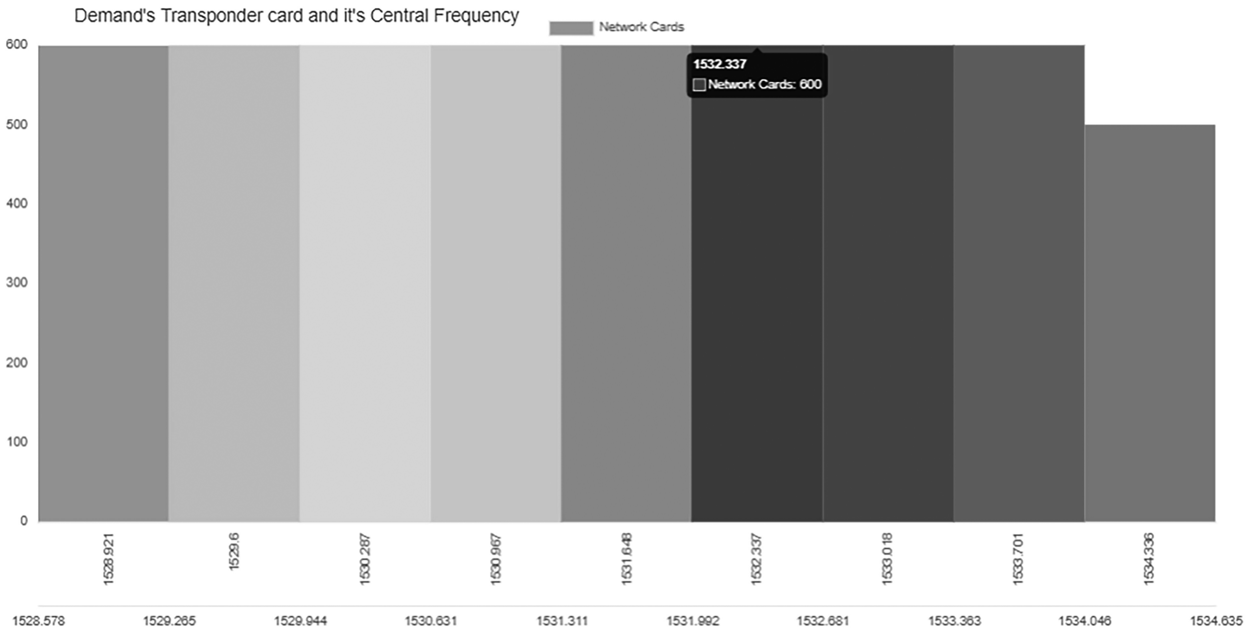


FIGURE 3.6: Central Wavelength assignment in media channel group

to each media channel. Start assigning the central wavelength to each media channel inside the media channel group as shown in Figure 3.6. Then each demand is assigned a unique path & demand id. The RSWA algorithm flow is shown in Figure 3.5. In the next chapter, we present our results.

Chapter 4

Results

In this chapter, a comparative analysis between the two schemes namely regeneration and without regeneration is presented. The study was conducted in two different scenarios, namely a positive scenario and a negative scenario. Blocking probability is given by the percentage of total slots for all blocked network demands divided by total slots for all requested network demands. Few more case studies have been carried out to reduce the chance of blockage by changing different parameters in the negative scenario. The algorithm always tries to optimize the spectrum and optical reach at a lower cost. Their performance is presented and evaluated with graphs, plots and explanations.

4.1 First fit comparative analysis between regeneration and without regeneration case

These are the different scenarios for which the algorithm has been tested: Theoretically, as distance increases, the higher bit rates would no longer be optically feasible. All test cases were conducted in steps of 20 for different distances ranging from 20 to 120 km. This was considered to observe how increasing distances will result in a change in the solution. These distances are selected because they are within the gain range of the SMR 20 ROADM amplifier.

- **Positive Scenario**
  In this scenario, the traffic matrix was taken in such a way that the network was not over-provisioned. Compared to the network's actual capacity, the traffic matrix taken was much lower. It doesn't let the probability of blocking come into the picture. This was done for regeneration and without regeneration case. The same traffic matrix was provided to both of them throughout the process.

- **Negative Scenario**
  In this scenario the traffic matrix was taken in such a way that it leads to blocking probability. Which means provisioning of more capacity into the network. This applies both to the case of regeneration and without regeneration. The blocking probability was calculated for the scenarios below

  - traffic being generated Randomly
  - traffic being generated in source destination pairwise
  - traffic with sorted spectrum
  - traffic with multi-path routing

The comparative study flow chart was shown in Figure 4.1. Two scenarios were taken for our simulations and each scenario has two cases, namely regeneration and without regeneration. The algorithm flow for these scenarios was discussed in Chapter 4. The results obtained were compared with the schemes mentioned above.

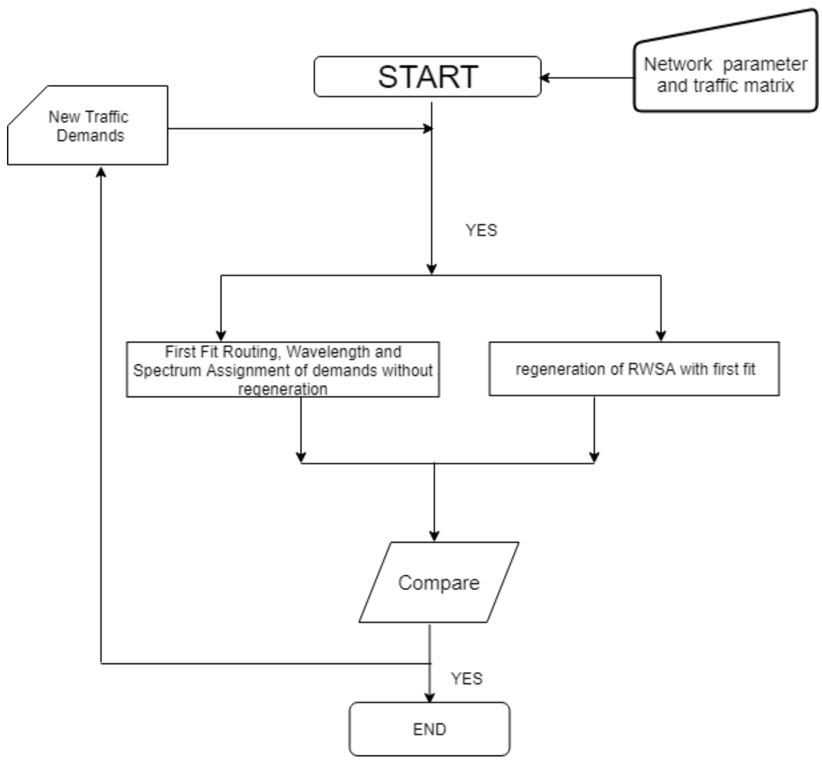


FIGURE 4.1: Comparison of Regeneration and without regeneration scheme

4.2 NSF-NET

4.2.1 Positive Scenario

4.2.1.1 Without Regeneration

This figure 4.2 shows how traffic was divided between different bit rates. Higher bit rates with higher modulation formats i.e. 600 Gb/s (64QAM), 500 Gb/s (64 QAM) and 400 Gb/s (64 QAM) were selected for the first three distances of 20, 40 & 60. But the lower bit rates with lower modulation format come into the picture as distance increases. The number of 600 (64QAM) has been drastically reduced and more of 500 (32 QAM), 400(16QAM) and 200 (16 QAM) have emerged for a distance of 80 km. Which means at higher distances, lower modulation formats with lower bitrates are selected due to OSNR infeasibility. This is the optimal solution that we have achieved.

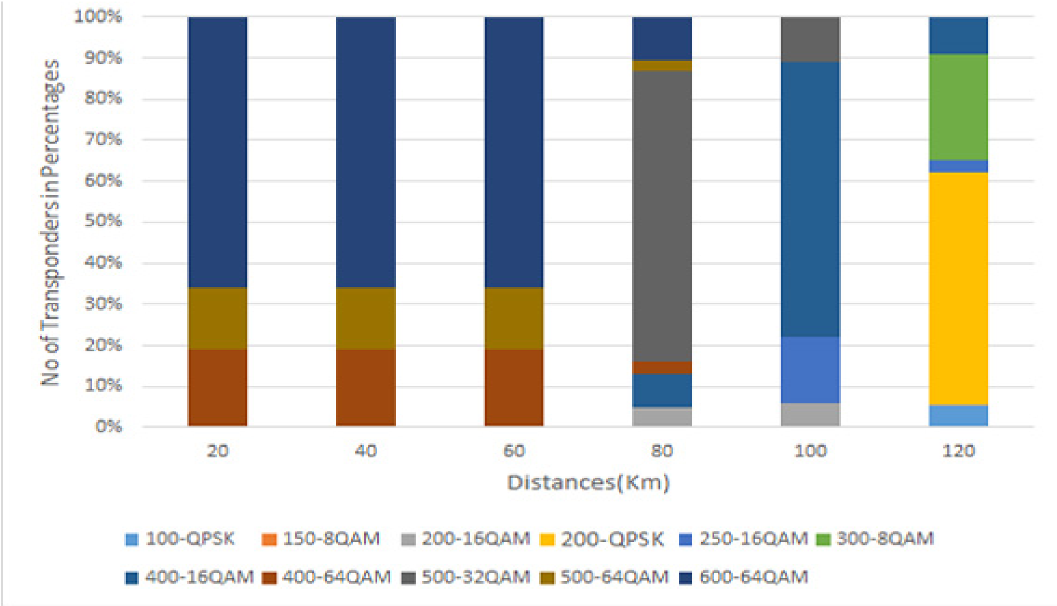


FIGURE 4.2: Distribution of transponder cards in "without regeneration" case in NSF-NET

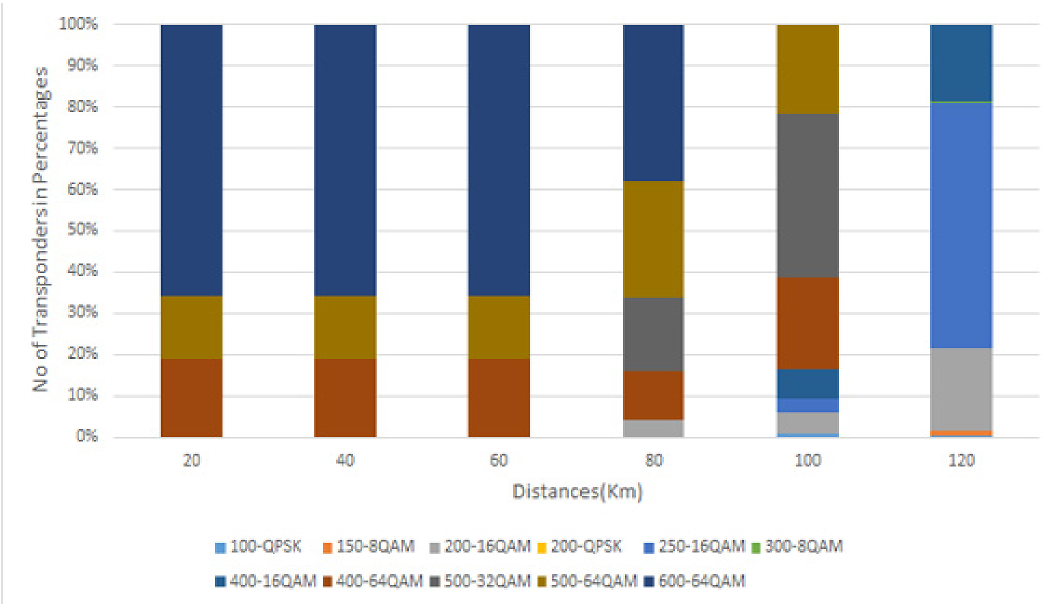


FIGURE 4.3: Distribution of transponder cards in "with regeneration" case

4.2.1.2 With Regeneration

Regeneration means that the same signal is generated again with enough sufficient power for reaching the destination. As discussed earlier in the without regeneration case, the lower modulation formats were selected at higher distances. This has occupied a higher spectrum, as they have a larger bandwidth. The OSNR decreases as the distance increases which is verified by the OSNR formula. In Figure 4.3 the first three distances plots are similar to those of without regeneration case. The ratio of optical signal to noise at these three distances was sufficient to carry all the higher bit rates. But the OSNR trail was much smaller than the back to back OSNR of higher bit rates from 80 km onwards and therefore a regeneration was necessary. This will squeeze more traffic in a lesser spectrum. We now have more permutations, because we now have more data rates on the same path. Every regeneration adds 2-3 dB to the path OSNR. Therefore, higher or medium - bit rates can be observed at the 80, 100 and 120 km distances. The optimum solution will divide the traffic matrix in such a way that more of the middle or higher bit rates that are optically feasible for the end to end OSNR are selected. The chart 4.3 shows which bit rates were chosen at each increase in distance.

4.2.1.3 Cost & Spectrum Analysis

In this case, the first 3 distances have the same cost and spectrum as shown in the figures 4.4, 4.5. The interesting part begins here. Cost and spectrum utilization were less for the case of regeneration. The cost formula described in the previous chapter includes the transponder cost, the spectrum cost, and the number of hops that the demand traversed. We can observe that the cost of the spectrum plays a major role. When regeneration is done we choose a higher bit rate which occupies a lesser spectrum. Regeneration was chosen to get a higher optimal solution. The optical signal loses its OSNR (signal strength) when we move on higher distances. When we regenerate this traffic, higher bit rates are chosen. Since the spectrum utilized for each demand was less, therefore the cost of that demand was also less compared to its counterpart. More number of permutations were possible in this case. In both cases, the best solution is selected. The total cost and spectrum of the network are calculated by calculating the optimum cost and spectrum of each traffic and summing up all those calculations. For different bit rates and hops, the regeneration vs without regeneration is shown in Table 4.1.

TABLE 4.1: Tradeoff between Bitrates, Modulation format and Hops

traffic matrix	bitrates with regeneration	bitrates without regenerations	hops
2448	10 - 250 (16QAM)	1- 100(QPSK), 12 - 200 (QPSK)	3
2195	11- 200 (16QAM)	1- 100(QPSK), 7- 300(8-QAM)	2
2374	6-400(64QAM)	6-400(64QAM)	1

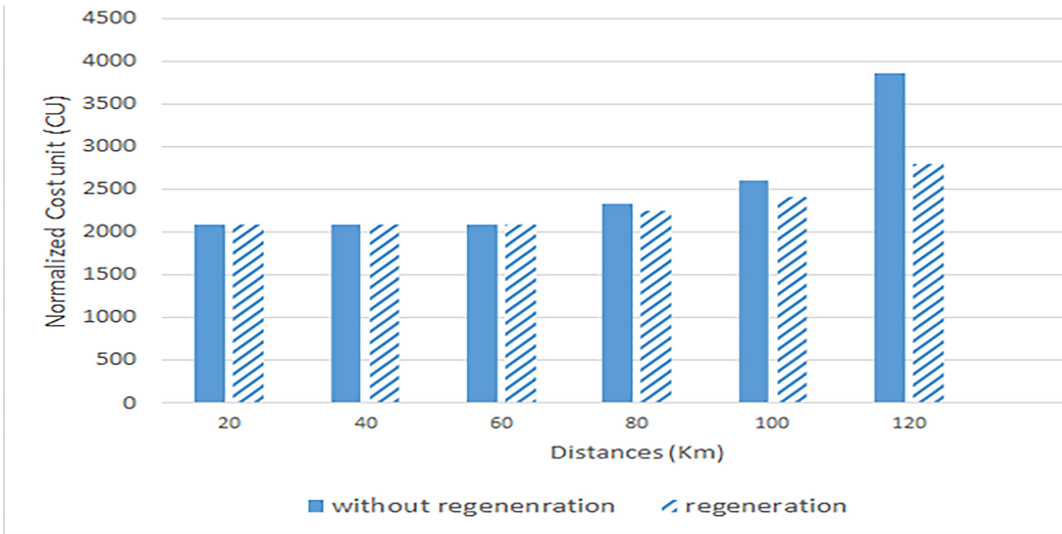


FIGURE 4.4: Cost of the NSF-network

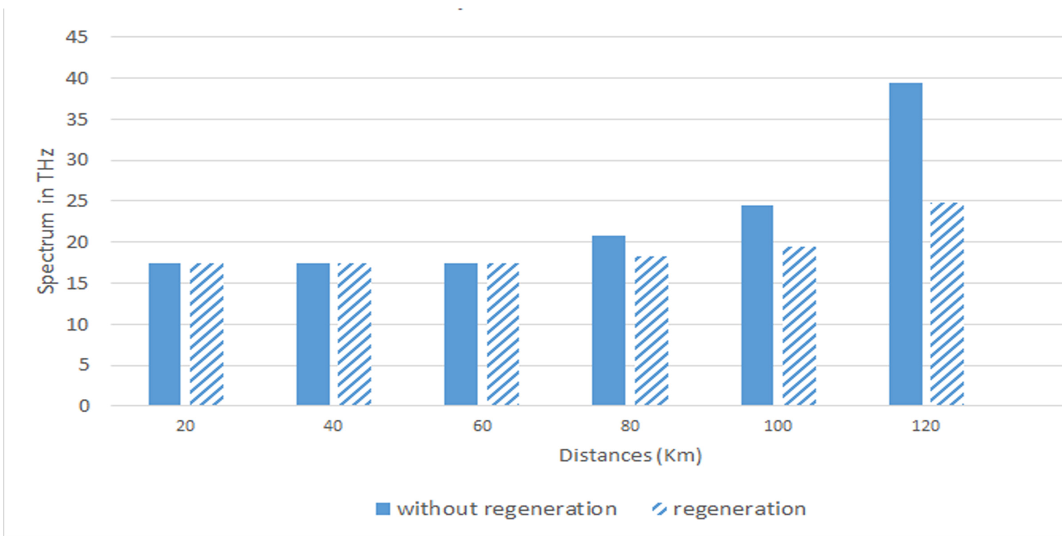


FIGURE 4.5: Spectrum Utilized in the NSF-network

Therefore, the regeneration plot's spectrum and cost are less compared to the plot of without regeneration. The regeneration algorithm has provided a better cost-optimized solution. For example: from the table 4.1, the traffic 2448 is rounded to 2500 and then divided into ten 250 Gb/s in the case of regeneration and one 100 Gb/s and twelve 200 Gb/s in the case without regeneration.

4.2.2 Negative Scenario

The network is over-provisioned with more traffic so that blocking probability occurs. Higher bit rates require less bandwidth, which implies less use of spectrum. The algorithm tries to determine the bit rates that can be regenerated with increased optical reach. As shown in figure 4.6, at 120 km we can see a big difference. The difference in B.P is 16.67 , i.e. almost a difference of 4.8 Tb/s of extra data provisioned to the network when compared to without regeneration case.

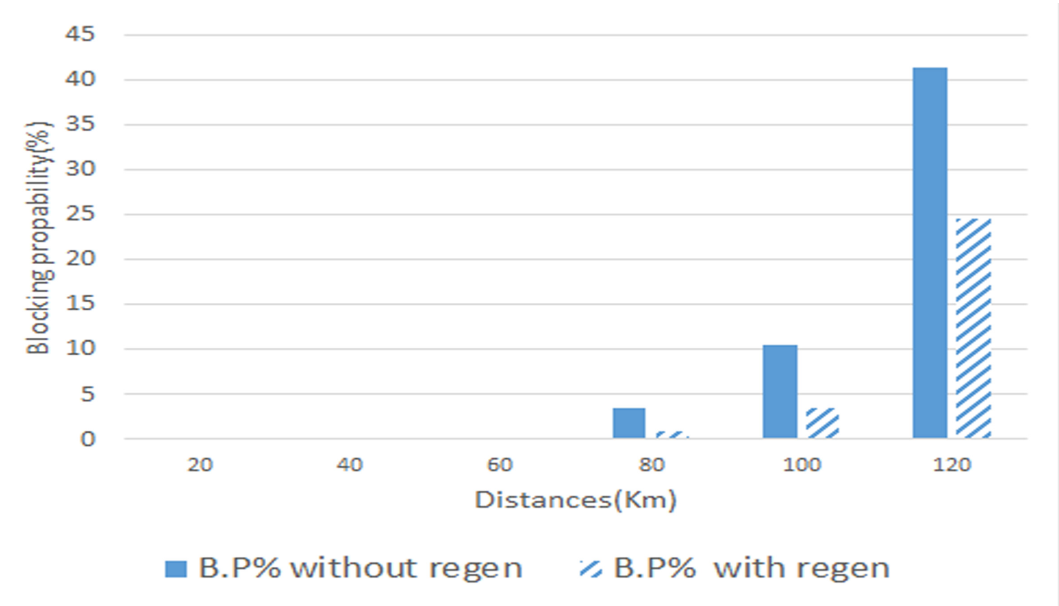


FIGURE 4.6: Blocking probability in the network

4.2.2.1 Blocking probability for different scenarios

Different scenarios as shown in Figure 4.7 have been simulated to reduce the blocking probability. By twisting the way traffic is supplied in the network has led to these results.

Random traffic: Traffic was generated and supplied to the network randomly.

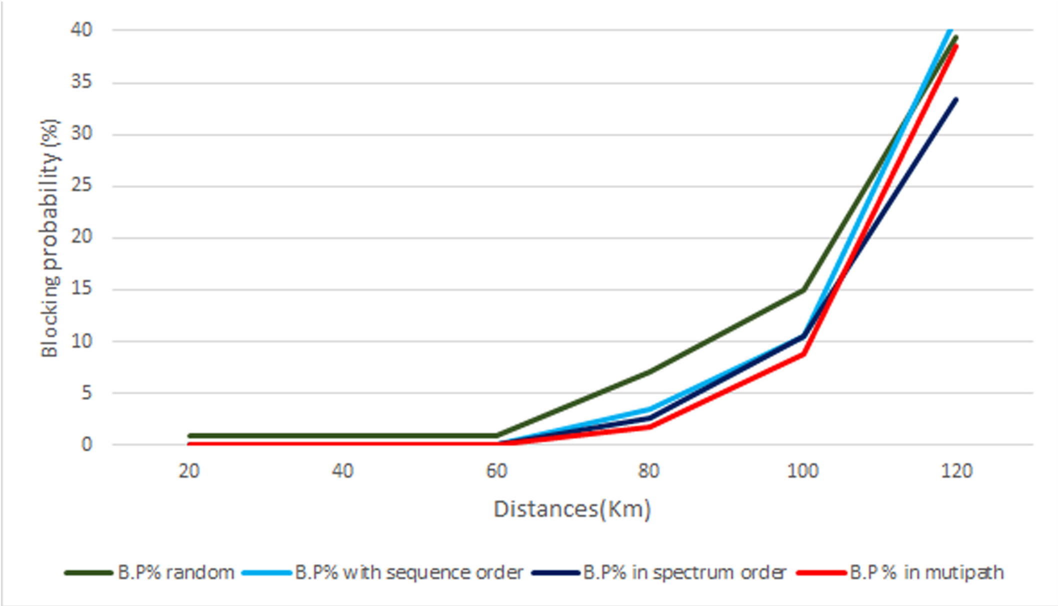


FIGURE 4.7: Blocking probability in different scenarios

Source/Destination pairwise: The traffic was generated as a source destination pair. This helps to meet all the requirements of one S / D pair and then move to the other pair. This further reduced the B.P % compared to the random case.

Sorted spectrum: The traffic was sorted in terms of spectrum. All the demands on a single link are taken and sorted in descending order with regard to the spectrum. This is by far the best case scenario where we were able to further reduce the B.P% at 80,100 and 120 Km.

Multi-path Routing: Generally, if demand does not have the exact number of slots required in the first path, demand is shifted to the second alternative path. Although some slots are available on the first path, we are under-using the spectrum. Therefore, we will divide the traffic into smaller demands in multi-path routing and try to provide some of the demand on the first path and the rest on the second path. This has helped to some extent to reduce B.P% compared to the random scenario and S/D scenario.

4.3 Other Network Scenarios

The algorithm is tested on two other networks, namely US - NET and Spain's Telefonica. Similar conclusions were obtained for these two networks.

4.4 Telefonica Spain Net

The Network was loaded with 30 nodes and 56 links, with maximum node degree 5.

4.4.1 Positive Scenario

Without Regeneration Scheme

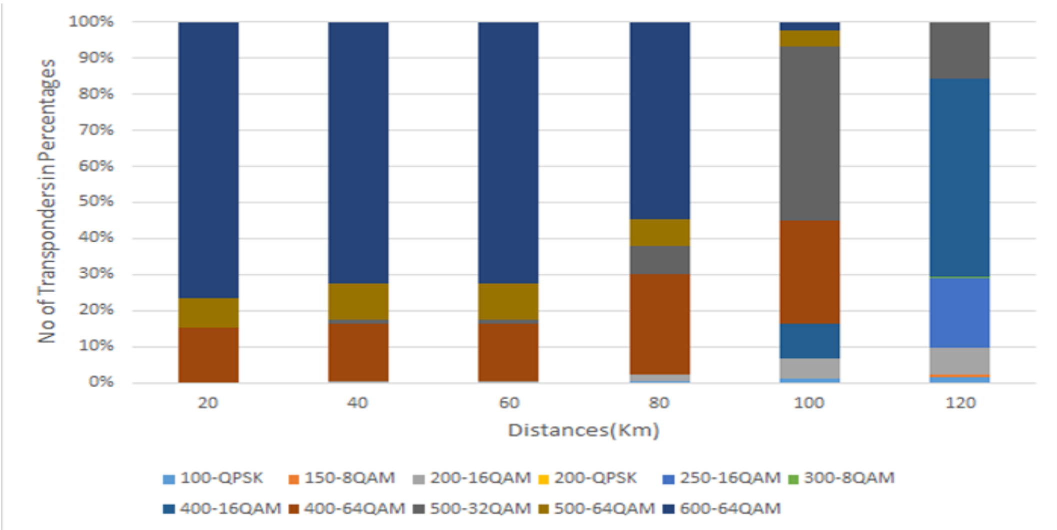


FIGURE 4.8: Distribution of transponder cards in without regeneration case in Spain Network

Regeneration Scheme

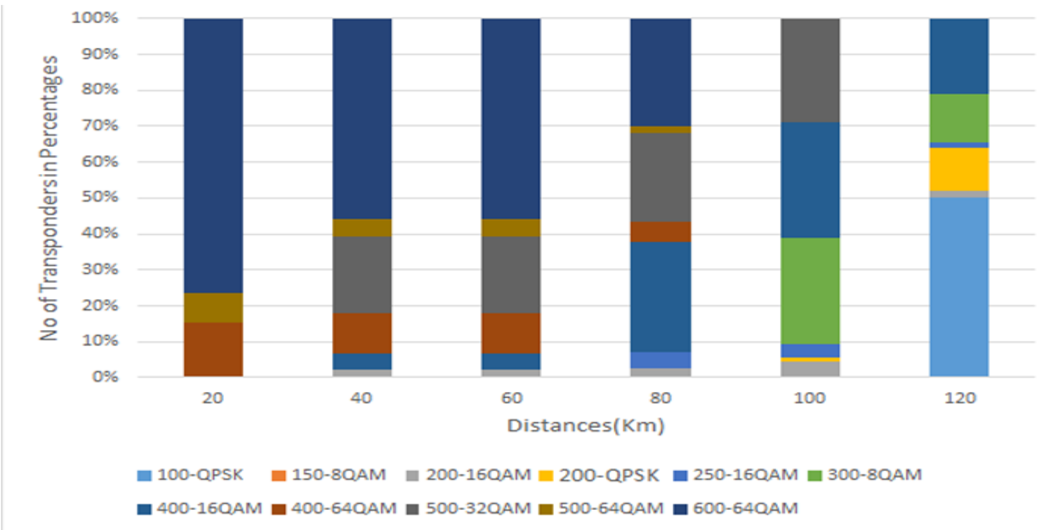


FIGURE 4.9: Distribution of transponder cards in regeneration case

Cost & Spectrum Analysis

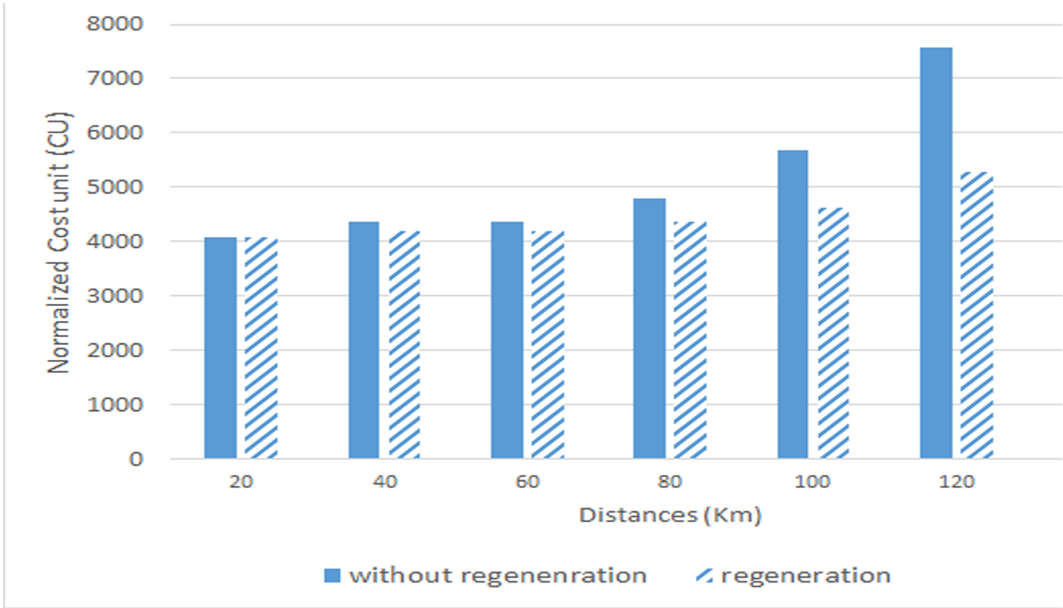


FIGURE 4.10: Cost of the Spain network

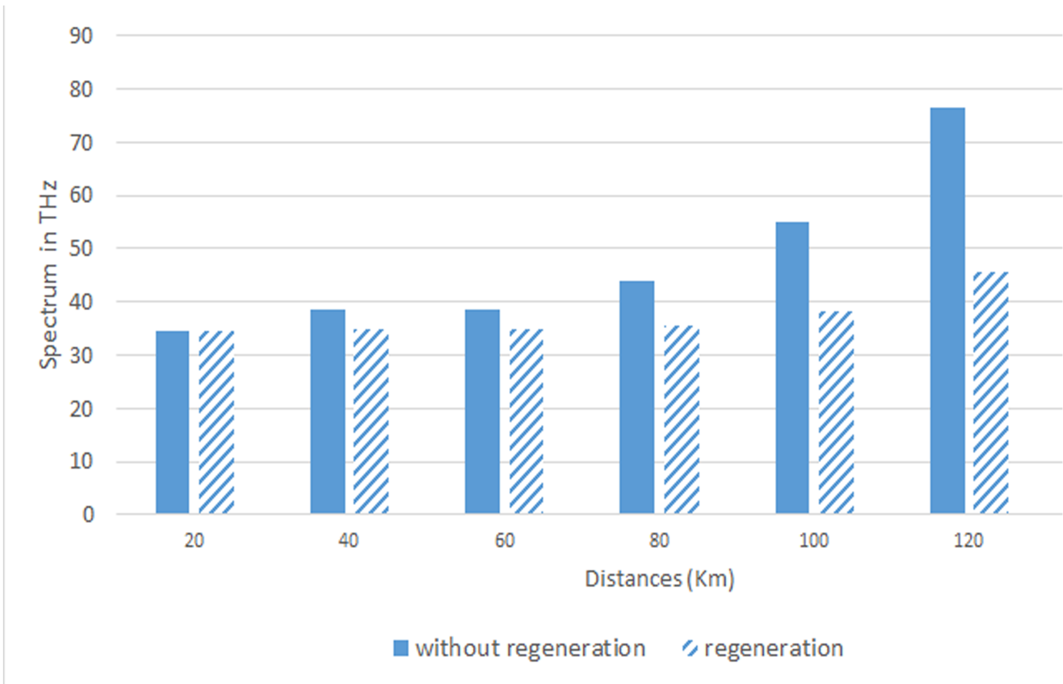


FIGURE 4.11: Spectrum Utilization

4.4.2 Negative Scenario

B.P%

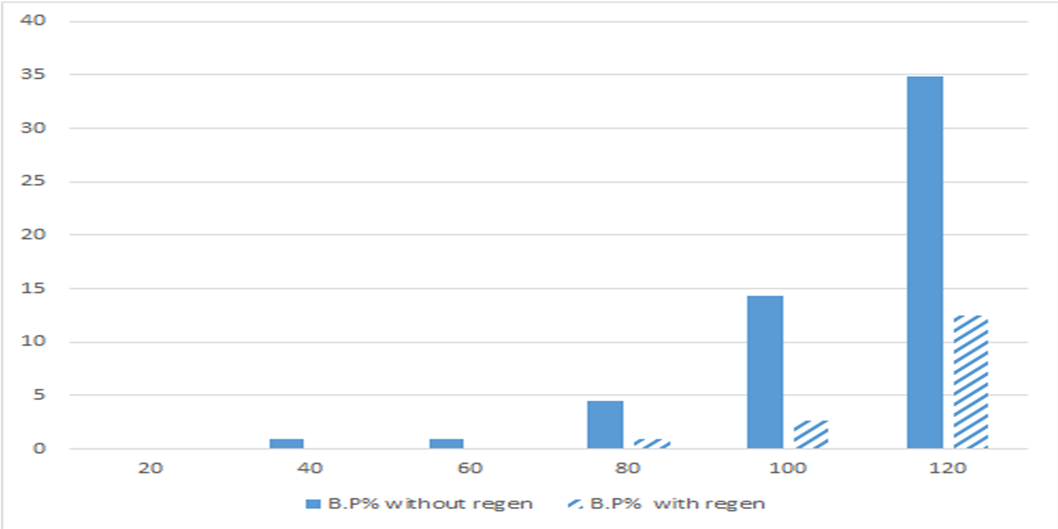


FIGURE 4.12: Blocking probability in Spain network

B.P% in different scenarios

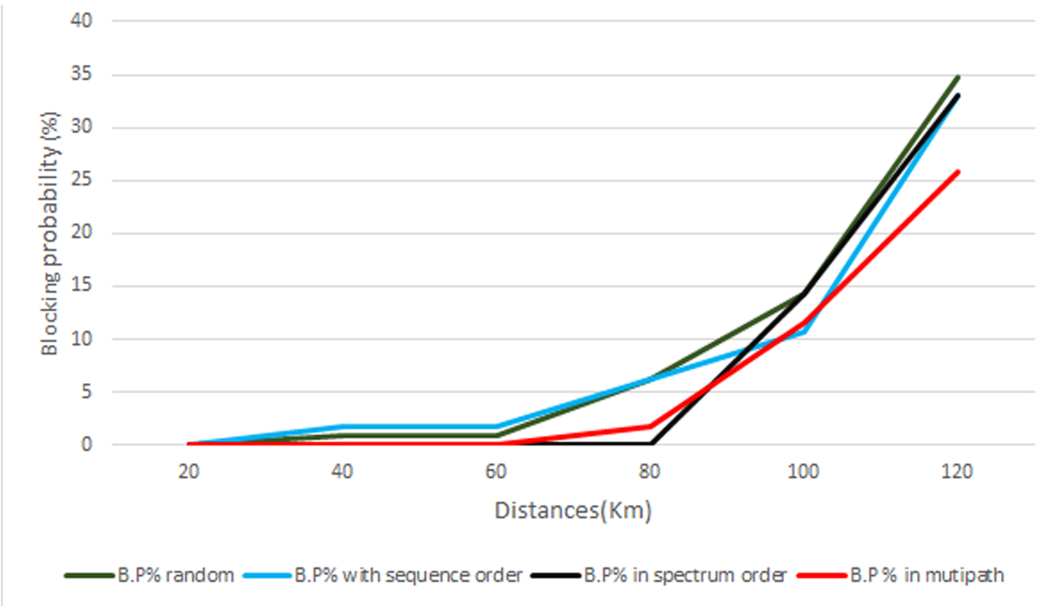


FIGURE 4.13: Blocking probability in different scenarios

4.5 US-Net

The network is loaded with 24 nodes and 42 links, with a maximum node degree of 5

4.5.1 Positive Scenario

Without Regeneration Scheme

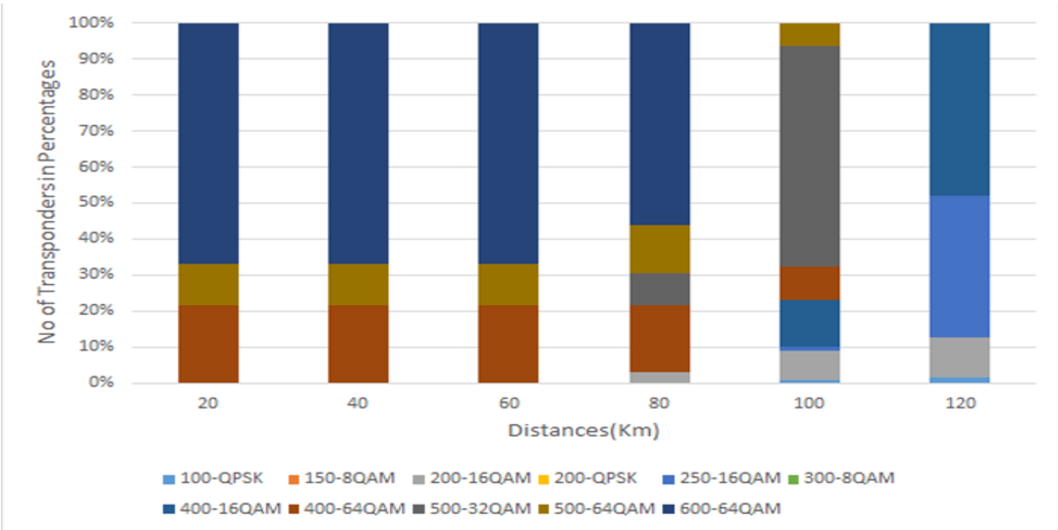


FIGURE 4.14: Distribution of transponder cards in without regeneration case in US-Net

Regeneration Scheme

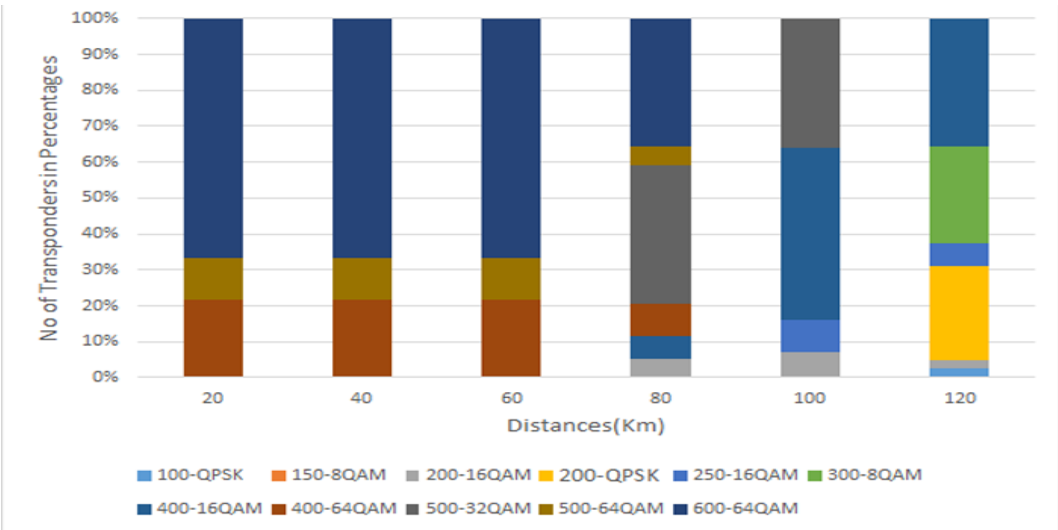


FIGURE 4.15: Distribution of transponder cards in regeneration case

Cost & Spectrum Analysis

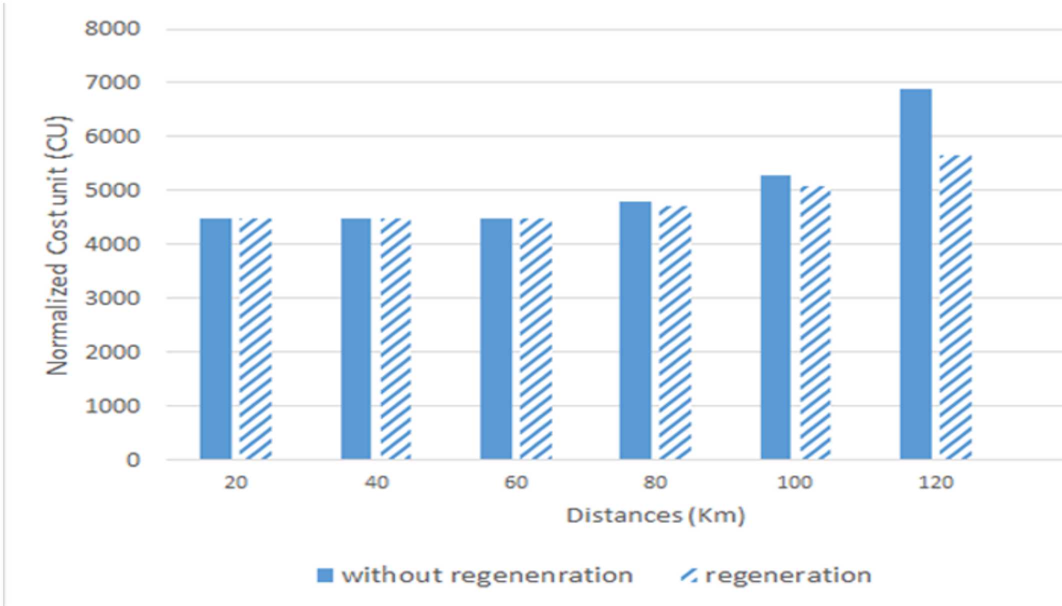


FIGURE 4.16: Cost of the US-network

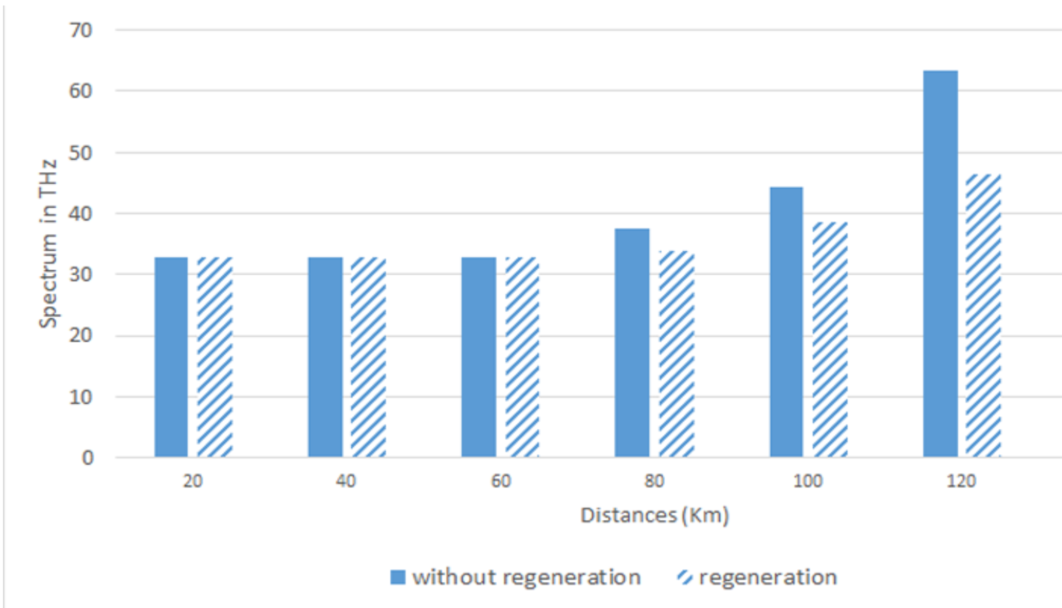


FIGURE 4.17: Spectrum utilization

4.5.2 Negative Scenario

B.P%

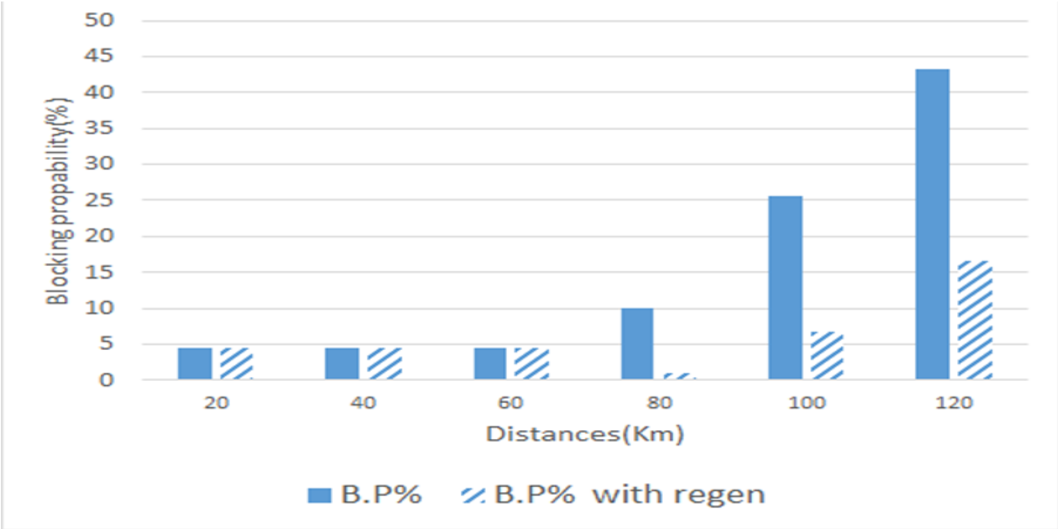


FIGURE 4.18: Blocking probability in the US-network

B.P% in different scenarios in US-NET

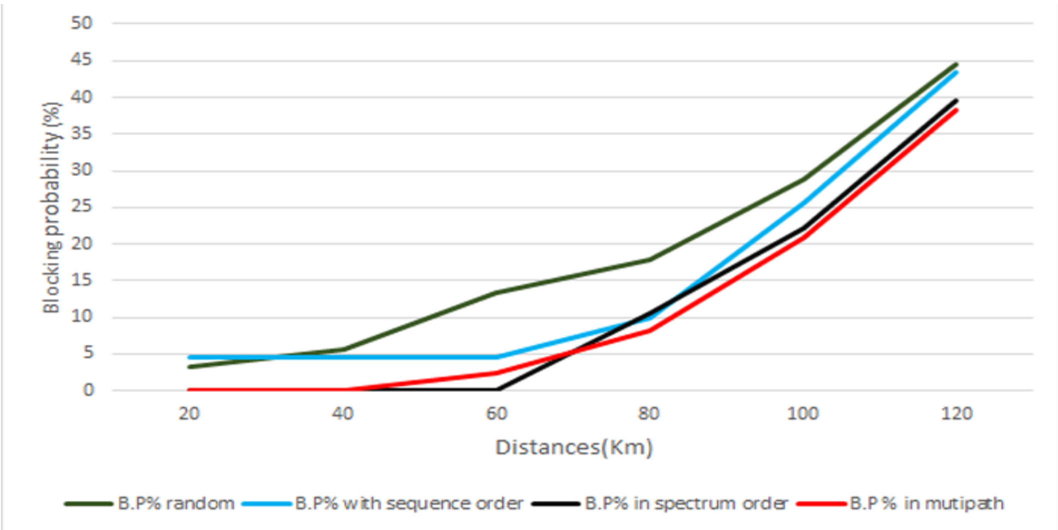


FIGURE 4.19: Blocking probability in different scenarios

The findings of the proposed schemes were presented in this chapter. It provided an outlook on how to divide customer traffic and achieve efficient spectrum and optical reach. Next chapter deals with the conclusion and future work.

Chapter 5

Conclusion and future work

5.1 Conclusion

The project's goal was to develop a customer-specific algorithm that could divide the bandwidth into specific DWDM channels to optimize the overall network in terms of optical feasibility, spectrum efficiency and affordability. The proposed regeneration and without regeneration provides cost-effective, efficient and reliable use of spectrum resources in flex grid optical networks after the inevitable need to use the limited optical transmission spectrum efficiently. Chapter 3 provided a clear flowchart for the operation of the algorithm. However, the methodology shows that in both cases the proposed scheme was adaptive in different network scenarios. The three parameters were evaluated for two scenarios, namely positive and negative. The without regeneration case has given us an optimal solution in which demand can be divided with higher bit rates. The results thus provided clearly indicate the regeneration performance outperforms the without regeneration case. By regenerating demands with higher bit rates, lower costs and lower utilization of the spectrum have been achieved. From the evaluation of the algorithm, the network operator can choose whether or not to regenerate a signal. In the negative case, we have achieved less blocking probability by segregating demands with respect to spectrum and multi-path routing. The results showed how to manage the optical spectrum and its optical reach, as our project aimed at achieving the lowest possible cost.

5.2 Future work

The work presented in this master's thesis has led to abundant opportunities for future work:

- The provision of network protection schemes using varied protection strategies such as 1+1, 1:1, M: N is of great interest. This could be implemented by disjoint path algorithm, together with the Yen's K, to provide a disjointed set of paths
- To implement a brownfield scenario and begin to solve the defragmentation problem that occurs due to network fragmentation with dynamic demands.
- The physical layer impairments are a serious threat to the design and implementation of optical networks. Model the linear and non-linear effects into the algorithm. This improves the simulation model.
- The web interface tool can be made more interactive by providing data from the web itself. To integrate a dashboard of tools such as real - time results.

Bibliography

[1] Cisco visual networking index: Forecast and trends, 20172022 white paper, Feb 2019. URL www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-741490.html.

[2] Farhad Arpanaei, Nahid Ardalani, Hamzeh Beyranvand, and S Ali Alavian. Three-dimensional resource allocation in space division multiplexing elastic optical networks. volume 10, pages 959–974. Optical Society of America, 2018.

[3] H Takara M Jinno and B Kozicki. Dynamic optical mesh networks: drivers, challenges and solutions for the future. In *35th European Conference on. IEEE*, 2009.

[4] Xiaojun Cao Yang Wang and Yi Pan. A study of the routing and spectrum allocation in spectrum-sliced elastic optical path networks. In *in INFOCOM, 2011 Proceedings IEEE*, pages 1503–1511, 2011.

[5] Ioannis Tomkos Kostas Christodoulopoulos and Emmanouel A Varvarigos. Routing and spectrum allocation in ofdm-based optical networks with elastic bandwidth allocation. In *Global Telecommunications Conference (GLOBECOM),IEEE*, pages 1–6, 2010.

[6] Chava Vijaya Saradhi and Suresh Subramaniam. Physical layer impairment aware routing (pliar) in wdm optical networks: issues and challenges. *IEEE Communications Surveys & Tutorials*, 11(4):109–130, 2009.

[7] Bartlomiej Kozicki Yukio Tsukishima Yoshiaki Sone Masahiko Jinno, Hidehiko Takara and Shinji Matsuoka. Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies. In *IEEE communications magazine, vol. 47, no. 11*, 2009.

[8] Andrew Lord Ori Gerstel, Masahiko Jinno and SJ Ben Yoo. Elastic optical networking: A new dawn for the optical layer? In *IEEE Communications Magazine, vol. 50, no. 2*, pages 3431–3440, 2012.

[9] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka. Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies. *IEEE Communications Magazine*, 47(11):6673, 2009. doi: 10.1109/mcom.2009.5307468.

[10] Tsbmail. URL https://www.itu.int/rec/T-REC-G.694.1-201202-I/en.

[11] H. Takara M. Jinno and B.Kozicki. Dynamic traffic grooming. *Optical Networks Traffic Grooming in Optical WDM Mesh Networks*, page 7192. doi: 10.1007/0-387-27098-1_4.

[12] Yang Wang, Xiaojun Cao, and Yi Pan. A study of the routing and spectrum allocation in spectrum-sliced elastic optical path networks. In *2011 Proceedings Ieee Infocom*, pages 1503–1511. IEEE, 2011.

[13] Kostas Christodoulopoulos, Ioannis Tomkos, and Emmanouel A Varvarigos. Routing and spectrum allocation in ofdm-based optical networks with elastic bandwidth allocation. In *2010 IEEE Global Telecommunications Conference GLOBECOM 2010*, pages 1–6. IEEE, 2010.

[14] Christina Politi, Chris Matrakidis, Theofanis Orphanoudakis, Vassilios Anagnostopoulos, and Alexandros Stavdas. Planning and operation of elastic flex-grid optical networks with ofdm variable bandwidth capabilities. In *2013 15th International Conference on Transparent Optical Networks (ICTON)*, pages 1–4. IEEE, 2013.

[15] Ronald Romero Reyes and Thomas Bauschert. Bottom-up framework for cost allocation to services in telecommunication networks. volume 18, pages 81–105. Springer, 2017.

[16] Inwoong Kim, Paparao Palacharla, Xi Wang, Daniel Bihon, Mark D Feuer, and Sheryl L Woodward. Performance of colorless, non-directional roadms with modular client-side fiber cross-connects. In *National Fiber Optic Engineers Conference*, pages NM3F–7. Optical Society of America, 2012.

[17] Axel Klekamp, Olivier Rival, Annalisa Morea, Roman Dischler, and Fred Buchali. Transparent wdm network with bitrate tunable optical ofdm transponders. In *2010 Conference on Optical Fiber Communication (OFC/NFOEC), collocated National Fiber Optic Engineers Conference*, pages 1–3. IEEE, 2010.

[18] Flexible light orchestration of wavelengths, white paper, 2018. URL https://www.cisco.com/c/dam/en/us/solutions/collateral/service-provider/optical-network-solutions/white-paper-c11-739696.pdf.

[19] Master 400g poster. URL https://connectlp.keysight.com/EMO_Master400GDigitalPoster.

[20] Biswanath Mukherjee. In *Optical WDM networks, Springer Science & Business Media*, 2006.

[21] Ram Murthy C Siva and G Mohan. In *Wdm optical networks: concepts, design and algorithms,*, 2003.

[22] Cisco ncs 2000 flex spectrum single module roadm line cards data sheet, May 2017. URL https://www.cisco.com/c/en/us/products/collateral/optical-networking\/network-convergence-system-2000-series/datasheet-c78-734544.html.

[23] Cisco contentionless add/drop, Mar 2018. URL https://www.cisco.com/c/en/us/products/collateral/optical-networking/network-convergence-system-2000-series/datasheet-c78-734914.html.

[24] On-demand library. URL https://ciscolive.cisco.com/on-demand-library/?search.technology=scpsTechnology_optical&search=flow#/video/1533846600831002DXZr.

[25] Jin Y Yen. Finding the k shortest loopless paths in a network. *management Science*, 17(11):712–716, 1971.

[26] Ashwin Gumaste and Tony Antony. Dwdm network designs and engineering solutions. cisco press,. 2003.

[27] Miroslaw Klinkowski and Krzysztof Walkowiak. Routing and spectrum assignment in spectrum sliced elastic optical path network. *IEEE Communications Letters*, 15 (8):884–886, 2011.

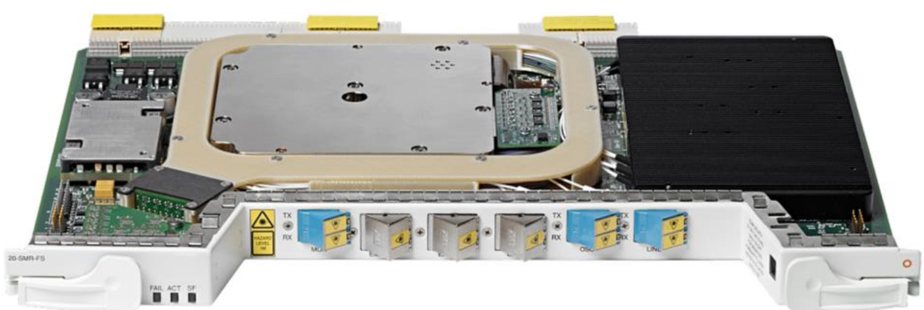
Appendix

Data Sheet

Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Cards

Operators face the challenge of deploying a scalable and agile optical network while reducing footprint and cost. The Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Cards integrate the programmability and scale of Cisco nLight ROADM with flexible amplification in an exceptionally compact single-slot form factor.

Figure 1. 20-Port Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Card

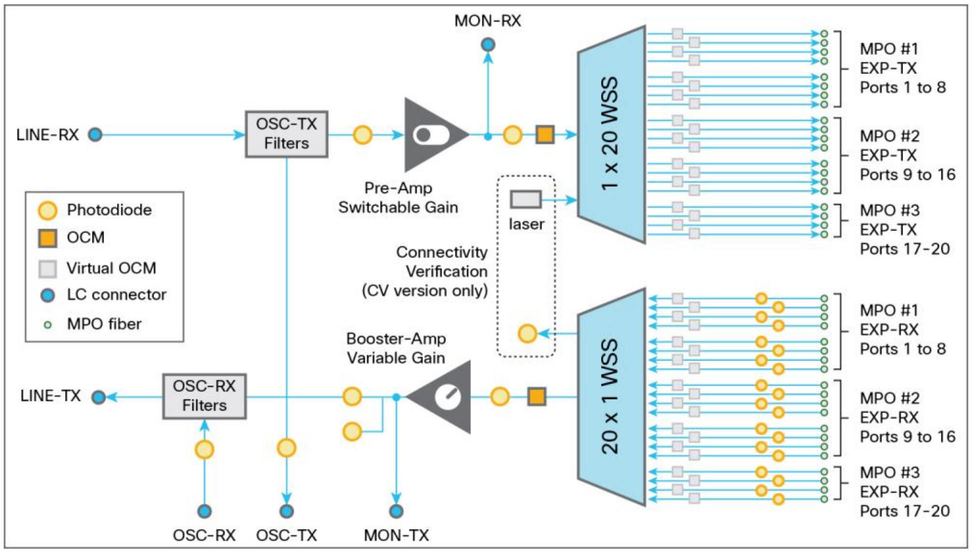


Product Overview

Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Cards combine twin wavelength selective switches (WSS) with pre- and booster amplifiers in a single-slot line card.

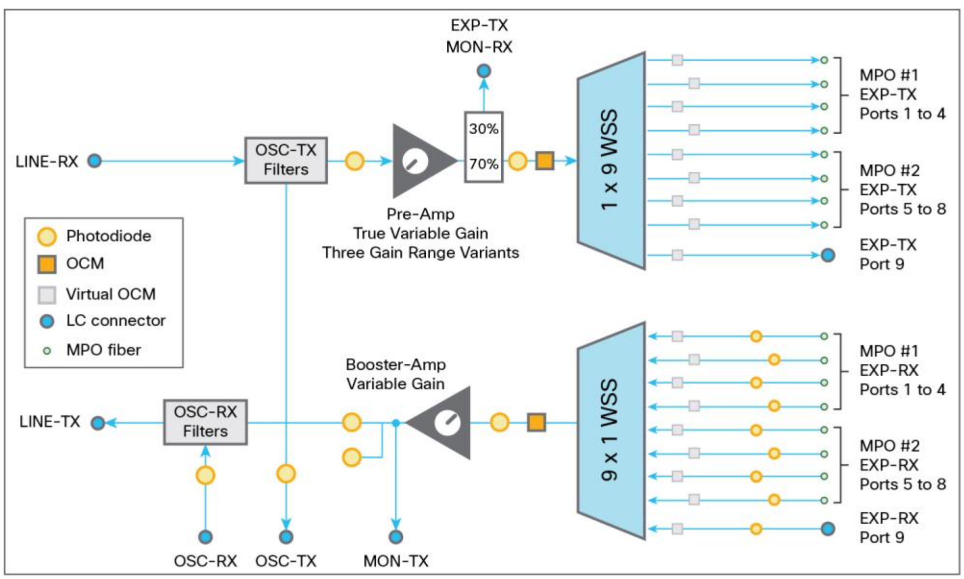
20-port and 9-port versions of the card are available to meet varying scalability requirements. The 20-port line card (Figure 1) features a switchable gain pre-amplifier, allowing optimal operation across two different gain ranges. One card can therefore operate across fiber spans of nearly any length, simplifying ordering, sparing, and deployment. A second variant of the 20-port line card provides connectivity verification of attached add/drop and express patch-panel components, helping ensure error-free node turn-up. The 20-port line card functional diagram is shown in Figure 2.

Figure 2. 20-Port Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Card Functional Diagram



The 9-port version of the line card is offered in three variants corresponding to three different pre-amplifier gain ranges. It also offers an optimized two-degree configuration by including a broadcast express port (TX) and a high isolation select (RX) port (Figure 3). This design reduces loss and filtering penalties.

Figure 3. 9-Port Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Card Functional Diagram



Both the 20-port and 9-port line cards support the cascading of multiple cards to increase port count.

Features and Benefits

Programmability and Agility

Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Cards create an agile DWDM layer forming the foundation for converged transport architectures, delivering features that allow programmability and agility in provisioning and recovery operations. Wavelength add/drop and routing are entirely software-driven, which eliminates manual operations, helps decrease operating expenses (OpEx), and reduces provisioning and recovery times.

The following agile DWDM innovations are supported by the Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Cards:

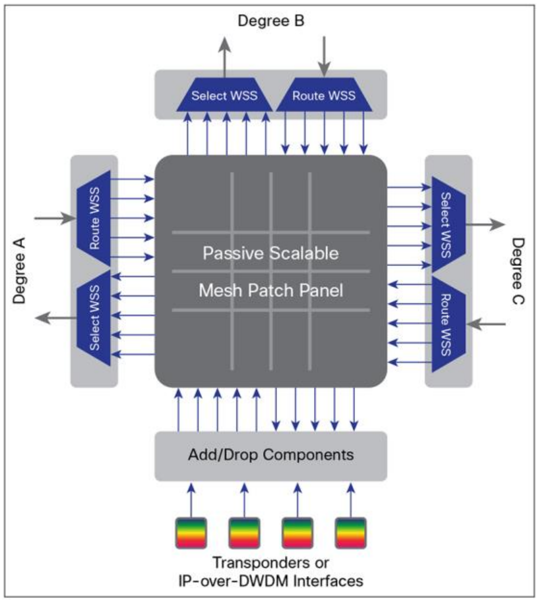
- Colorless: Colorless ROADM ports are not frequency-specific. This simplifies provisioning and allows dynamic restoration, because the frequency of an ingress channel can be retuned by software without requiring its fiber to be relocated.
- Contentionless: Contentionless add/drop refers to the ability of an N-degree ROADM node to accommodate N wavelengths of the same frequency from a single add/drop device.
- Omnidirectional: Omnidirectional ROADM ports are not associated to specific ROADM degree, therefore a wavelength reroute does not require a physical fiber move, and can thus be executed entirely by software.
- Flex spectrum: The amount of spectrum allocated to a wavelength can be flexibly provisioned to allow for multicarrier superchannels or single wavelengths exceeding today's 50-GHz channel spacing.

Together, colorless, contentionless, omnidirectional, and flex spectrum (CCOFS) functionalities bring programmability to the optical layer, allowing direct and complete control by packet-layer devices and centralized network orchestrators.

Scale and Flexibility

The large numbers of ports on the Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Cards are made possible by the twin-WSS route and select architecture featured by Cisco nLight ROADMs (Figure 4). Channels are isolated by both the ingress and egress WSS, improving performance. By routing, instead of broadcasting, express channels, insertion loss is reduced, preserving optical signal-to-noise ratio (OSNR). The Cisco nLight architecture therefore allows multi-degree ROADM nodes, plus CCOFS add/drop, at large scale.

Figure 4. Cisco nLight ROADM Architecture



Cisco nLight ROADM ports can be used for any combination of the following:

- Express connections to other degrees in a multi-degree ROADM node
- Add/drop connections to Cisco NCS 2000 Passive Auxiliary Modules
- Add/drop connections to Cisco NCS 2000 Contentionless Add/Drop Line Cards
- Direct add/drop of individual wavelengths

Nodes with a modest number of degrees can still benefit from a large quantity of ROADM ports. Increasing add/drop channel count by using multiple ROADM ports reduces the fan-out requirements of the add/drop layer. This lowers cost, reduces loss, and improves performance.

Table 1 summarizes the features and benefits of Cisco NCS 2000 Single Module ROADM Line Cards. Specific feature support is hardware and software dependent.

Table 1. Features and Benefits

Feature	Benefit
Colorless, contentionless, and omnidirectional add/drop	Delivers a fully programmability DWDM layer, allowing automated provisioning and orchestrated multilayer restoration, reducing operating and capital expenses.
Flexible spectrum allocation	Improves spectral efficiency by allowing the creation and switching of multicarrier superchannels. Prepares networks for future modulation formats exceeding 50 GHz.
Single-slot form factor for combined ROADM and amplification	Reduces footprint and simplifies cabling of multidegree ROADM network elements.
Support for up to 20 ports	Allows highly scalable mesh nodes, while offering flexibility in allocating ROADM ports to either degree interconnection or add/drop.
Switchable gain pre-amplifier (20-port line card only)	Simplifies planning and deployment by allowing a single ROADM line card to accommodate fiber spans of nearly any length.
Pay-as-you-grow licensing	Allows operators to deploy highly scalable hardware while minimizing upfront cost.
Integrated optical spectrum analysis	Provides valuable insight into the spectral characteristics of system channels, facilitating planning and troubleshooting.
Connectivity verification (20-port CV line card only)	Aids in the installation of high-degree-count mesh nodes by verifying that components have been properly fibered and are functioning within specified insertion losses.

Licensing

The Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Cards are available with optional pay-as-you-grow licensing. This allows network operators to deploy highly scalable hardware while reducing upfront costs. Licensed variants of the 20-port and 9-port line cards are available with four and three ports activated, respectively. Available ports can be used for express or add/drop connectivity, and they support ninety-six 50 GHz-spaced channels. Port expansion licenses are available in increments of two or four ports, and another license activates flex spectrum capability.

Product Specifications

Tables 2 lists the optical specifications for the Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Cards. Table 3 lists the pre-amplifier specifications, and Table 4 provides the booster amplifier specifications.

Table 2. Optical Specifications for the Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Cards

Parameter	All Cards
Channel grid	97 channels, 50 GHz-spaced ITU grid
Center wavelength - Channel 0	191.300 GHz (1567.13 nm, for Connectivity Verification only)
Center wavelength - Channel 1	191.350 GHz (1566.72 nm)
Center wavelength - Channel 96	196.100 GHz (1528.77 nm)
Flex spectrum "slice" width	12.5 GHz
Minimum settable channel bandwidth	25 GHz, 2 slices
Maximum settable "super-channel" bandwidth	4850 GHz, 388 slices
Total number of slices	388 slices, 4850 GHz
f_start of first slice	191.325 GHz
f_stop of last slice	196.125 GHz
Optical port isolation	Typical 28 dB (for 0-15 dB attenuation) Typical 25 dB (for 15-25 dB attenuation) Typical 30 dB (0-15 dB attenuation, EXP-RX Port #9 of 9-port line card only)
Minimum insertion loss (0 dB VOA setting)	Typical 6 dB
Variable optical attenuator (VOA) dynamic range	15 dB (operative) 25 dB (during channel start-up)
VOA attenuation setting accuracy	±0.5 dB (0-5 dB attenuation) ±1.0 dB (5-15 dB attenuation)
Per-channel maximum input power	15 dB
Maximum polarization dependent loss (PDL)	0.5 dB

Table 3. Pre-Amplifier Specifications for the Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Cards

Pre-Amplifier Specifications	20-Port Line Card		9-Port Line Card		
	Low Gain Range	High Gain Range	17 dB Gain	24 dB Gain	34 dB Gain
Input power range - total	-25 to 21 dBm	-40 to 9 dBm	-25 to 21 dBm	-32 to 9 dBm	-45 to 1 dBm
Input power range - per channel (with 1 dBm per channel output power)	-16 to 1 dBm	-23 to -11 dBm	-16 to 1 dBm	-23 to -11 dBm	-33 to -19 dBm
Output power (POUT maximum)	21.2 dBm	21 dBm	21 dBm	21 dBm	21 dBm
Standard gain range	0 - 17 dB	12 - 35 dB	0 - 17 dB	12 - 24 dB	20 - 34 dB
Extended gain range	17 - 20 dB	24 - 35 dB	17 - 20 dB	24 - 27 dB	34 - 40 dB

Pre-Amplifier Specifications	20-Port Line Card		9-Port Line Card		
	Low Gain Range	High Gain Range	17 dB Gain	24 dB Gain	34 dB Gain
Noise figure at nominal gain	5.5 dB (17 dB gain)	5.5 dB (24 dB gain)	5.5 dB (17 dB gain)	5.5 dB (24 dB gain)	5.5 dB (34 dB gain)
Noise figure at minimum gain	-	11.7 dB (12 dB gain)	-	11.7 dB (12 dB gain)	7.1 dB (20 dB gain)

Table 4. Booster Amplifier Specifications for the Cisco NCS 2000 Flex Spectrum Single Module ROADM Line Cards

Booster-Amplifier Specifications	All Cards
Input power range - total	-29 to 9 dBm
Input power range - per channel	-20 to -11 dBm (with 1 dBm per channel output power)
Output power (POUT maximum)	21.2 dBm
Standard gain range	12-21 dB
Extended gain range	21-24 dB
Noise figure at nominal gain	5.5 dB (at 21 dB gain)
Noise figure at minimum gain	9.6 dB (at 12 dB gain)

Table 5. Physical Specifications for the Flex Spectrum Single Module ROADM Line Cards (All Variants)

Parameter	Value
Power	Typical 60W Maximum 84W
Size	1 slot
Management	
Card LEDs • Failure (FAIL) • Active/standby (ACT/STBY) • Signal fail (SF)	 Red Green/yellow Yellow
Operating Environment	
Temperature	23 to 131°F (-5 to 55°C)
Relative humidity	5 to 95%

Regulatory Compliance

Table 6 summarizes regulatory standard compliance and agency approvals.

Table 6. Regulatory Compliance

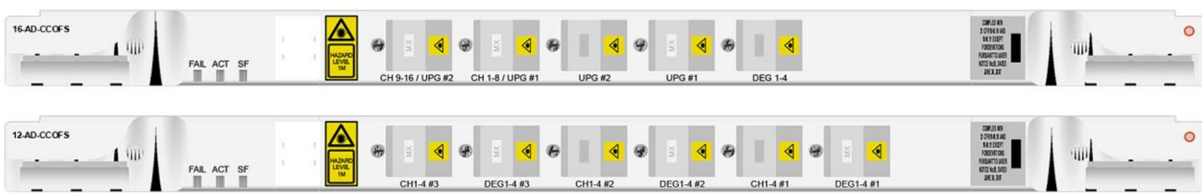
ANSI System	ETSI System
Countries and Regions Supported	
• Canada • United States • Korea • Japan • European Union	• European Union • Africa • CSI • Australia • New Zealand • China • Korea • India • Saudi Arabia • South America

Data Sheet

Cisco NCS 2000 Contentionless Add/Drop Line Cards

Optical network agility is a cornerstone of programmable network architectures. The Cisco® Network Convergence System 2000 Series (NCS 2000 Series) Contentionless Add/Drop Line Cards combine nonblocking scale and touchless reconfigurability in an easy-to-use form factor. They allow network operators to add a fully programmable optical layer to their Cisco nLight™ reconfigurable optical add-drop multiplexer (ROADM) infrastructures.

Figure 1. 16-Port (Top) and 12-Port (Bottom) Cisco NCS 2000 Contentionless Add/Drop Line Cards

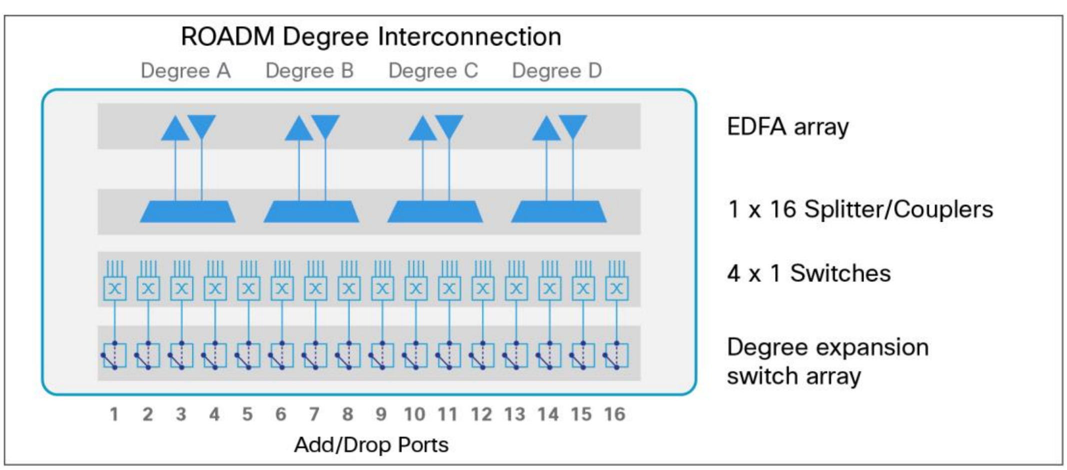


Product Overview

The NCS 2000 Contentionless Add/Drop Line Cards provide colorless, contentionless, omnidirectional, and flex spectrum add/drop functionality to the Cisco nLight ROADM architecture. The cards are available in 16-port and 12-port versions to meet varying scalability requirements.

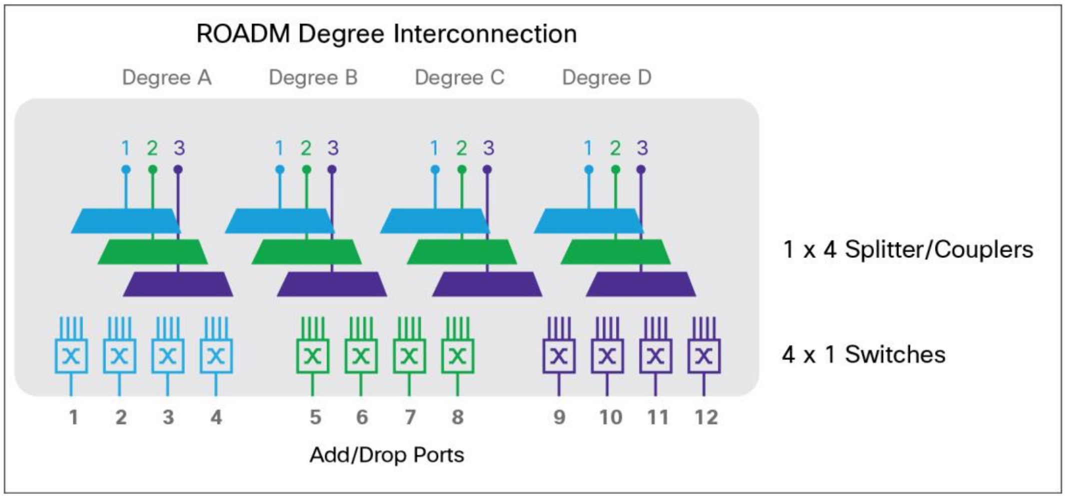
The 16-port line card adds and drops up to 16 channels across four ROADM degrees, and is expandable to 16 degrees with additional cards. An integrated 4 x 16 multicast switch and erbium-doped fiber amplifier (EDFA) array maximizes channel scalability by requiring only one ROADM port per degree. The 16-port line card functional diagram is shown in Figure 2.

Figure 2. 16-Port NCS 2000 Contentionless Add/Drop Line Card Functional Diagram



The 12-port line card adds and drops up to 12 channels across four ROADM degrees. Combining three 4 x 4 multicast switches into one line card, it uses three ROADM ports per degree. The 12-port line card functional diagram is shown in Figure 3.

Figure 3. 12-Port NCS 2000 Contentionless Add/Drop Line Card Functional Diagram



Features and Benefits

The NCS 2000 Contentionless Add/Drop Line Cards operate in tandem with Cisco NCS 2000 Single Module ROADM Line Cards to create an agile dense wavelength-division multiplexing (DWDM) layer, supporting the following agile DWDM innovations:

- Contentionless: Contentionless add/drop refers to the ability of an N-degree ROADM node to accommodate N wavelengths of the same frequency from a single add/drop device.
- Colorless: Colorless ROADM ports are not frequency-specific. This characteristic simplifies provisioning and allows dynamic restoration, because the frequency of an ingress channel can be retuned by software without requiring its fiber to be relocated.
- Omnidirectional: Omnidirectional ROADM ports are not associated with a specific ROADM degree. Therefore, a wavelength reroute does not require a physical fiber move, and it can be executed entirely by software.
- Flex spectrum: The amount of spectrum allocated to a wavelength can be flexibly provisioned to allow for multicarrier superchannels or single wavelengths exceeding today's 50-GHz channel spacing.

The Cisco nLight ROADM architecture (Figure 4) combines, colorless, contentionless, omnidirectional, and flex spectrum (CCOFS) functionalities, which together bring full programmability to the optical layer.

Figure 4. Cisco nLight ROADM Architecture

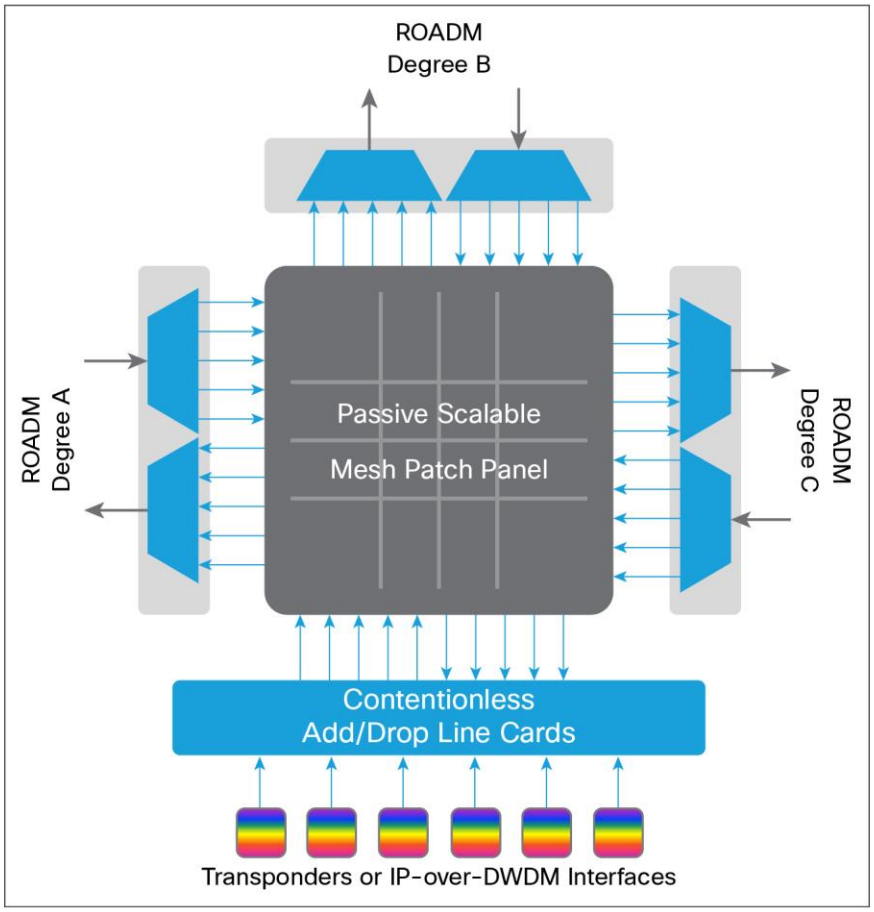


Table 1 summarizes the features and benefits of NCS 2000 Contentionless Add/Drop Line Cards. Specific feature support is hardware and software dependent.

Table 1. Features and Benefits

Feature	Benefit
Colorless, contentionless, and omnidirectional add/drop	Delivers a fully programmability DWDM layer, allowing automated provisioning and orchestrated multilayer restoration, which reduce operating and capital expenses
Flexible spectrum allocation	Improves spectral efficiency by allowing the creation and switching of multicarrier superchannels Prepares networks for future modulation formats exceeding 50 GHz
Single-slot form factor	Reduces footprint and simplifies cabling for the add/drop stage of a ROADM node
Support for up to 16 degrees	Allows highly scalable mesh nodes, with no blocking of add/drop wavelengths within the add/drop structure.
Pay-As-You-Grow Architecture	Two line card variants allow a trade-off between scalability and cost. Multiple line cards can be added to scale channel add/drop count in-service.

Product Specifications

Tables 2 and 3 list the optical specifications for NCS 2000 Contentionless Add/Drop Line Cards. Table 4 lists the physical specifications for the cards.

Table 2. Optical Specifications for NCS 2000 12-port Contentionless Add/Drop Line Cards

Description	Specification
Multicast Switch	
Optical port isolation (minimum)	40 dB
Add and drop section isolation (minimum)	60 dB
Polarization dependent loss (maximum)	0.5 dB
Multicast switch insertion loss (typical)	8 dB

Table 3. Optical Specifications for NCS 2000 16-port Contentionless Add/Drop Line Cards

Description	Minimum	Typical	Maximum
Multicast Switch			
Insertion loss		16.5 dB	
Optical port isolation	40 dB		
Add and drop section isolation	60 dB		
Polarization dependent loss			0.5 dB
Upgrade path loss		1.75 dB	
Add Path EDFA Array			
Per-channel input power range (at CH-RX port)	-4 dBm	0 dBm	4 dBm
Maximum UPG loss (from TP-E to TP-F)			2.5 dBm
Total per-channel input power range (at CH-RX port)	-9 dBm	-5 dBm	4 dBm
Total input power range	-9 dBm		16 dBm
Maximum total output power			17.2 dBm
Signal output power range - Full channel load			14 dBm
Signal output power range - Single channel load	-11 dBm	-2 dBm	
Nominal gain		-2 dB	
Gain range	-5 dB	-2 dB	7 dB
Noise figure at nominal gain			20.5 dB
Drop Path EDFA Array			
Per-channel input power range (at DIR-RX port)	-14 dBm	-10 dBm	-6 dBm
Max UPG loss (from TP-C to TP-D)			2.5 dB
Targeted per-channel output power (at CH-TX port)		-16 dBm	
Total input power range	-14 dBm		6 dBm
Maximum total output power			17.2 dBm
Signal output power range - Full channel load			5 dBm

Description	Minimum	Typical	Maximum
Signal output power range - Single channel load	-15 dBm	-11 dBm	
Nominal gain		-1 dB	
Gain range	-4 dB	-1 dB	3 dB
Noise figure at nominal gain			5 dB

Table 4. Physical Specifications for NCS 2000 Contentionless Add/Drop Line Cards

Description	Specification
Power consumption • **16-port - 4- to 12-degree - Contentionless Add/Drop Unit (Product number: NCS2K-16-AD-CCOFS)** • **12-port - 4-degree - Contentionless Add/Drop Unit (Product number: NCS2K-12-AD-CCOFS)**	Typical 40W, maximum 50W Typical 20W, maximum 30W
Size	1 slot
Management	
Card LEDs • **Failure (FAIL)** • **Active/standby (ACT/STBY)** • **Signal fail (SF)**	Red Green/yellow Yellow
Operating Environment	
Temperature	23 to 131°F (-5 to 55°C)
Relative humidity	5 to 95%

Regulatory Compliance

Table 5 summarizes regulatory standard compliance and agency approvals for NCS 2000 Series Contentionless Add/Drop Line Cards.

Table 5. Regulatory Compliance

ANSI System	ETSI System
Countries and Regions Supported	
• Canada • United States • Korea • Japan • European Union	• European Union • Africa • CSI • Australia • New Zealand • China • Korea • India • Saudi Arabia • South America
EMC (Class A)	
• ICES-003, 2004 • GR-1089-CORE Issue 4, NEBS EMC and Safety, June 2006 • FCC 47CFR15, 2007	• ETSI EN 300 386 V1.4.1 (2008-04) Telecommunication network equipment EMC requirements (**Note:** EMC-1) • CISPR22:2008 and EN55022:2006/A1:2007 Information Technology Equipment (Emissions) (EMC-2) • CISPR24: 1997/ A1:2001/A2:2002 and EN55024:1998/A1:2001/A2:2003: Information Technology Equipment - Immunity characteristics - Limits and Methods of Measurement (test levels)