Heuristic Algorithms for Routing and Spectrum Allocation in Elastic Optical Network

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Approval

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Abstract

The rapid change in optical networking is the result of progressive growth in IP traffic volume, its diversity and bandwidth hungry applications. In this connection, Elastic Optical Network (EON) is emerging as a promising solution, due to its adaptable characteristics and adjustable data rate accommodation to support heterogeneity of traffic demands. Routing and Spectrum Allocation (RSA) is a spectrum management problem in EON and NP hard. Clearly the efficient utilization of network resources, mainly bank on the applied ordering strategy. In this thesis, we propose a novel heuristic algorithm Minimum Hops with Least Slot Spectrum (MHLS) to accommodate maximum traffic requests with better spectrum utilization. The objective of the proposed algorithm is to minimize the total number of Blocked Requests (BR), Blocked Bit-rates (BB) in Gb/s and Slots Used (SU) in the network. The performance is evaluated on random optical network of 20 nodes along with two different real size optical networks such as PAN_EU and USA network. Network performances are evaluated in terms of BR, BB and SU through simulation. Results depict that propose technique is effective in minimizing the number of rejected traffic demands, bit-rates (Gb/s) and considerable spectrum savings can be achieved as compared to other considered benchmark techniques.

Dedication

I dedicate this thesis to my parents and friends.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST RCMS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST RCMS or elsewhere, is explicitly acknowledged in the thesis.

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Acknowledgment

I would like to thank my advisor, my parents and my friends.

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Chapter 1

Introduction

In the last few years optical networking has experienced some significant changes, due to the tremendous increase in IP traffic volume globally, fueled by intensive spectrum hungry application such as ubiquitous cloud computing, online games, various advance emerging applications, IPTV and HDTV. Which keep on increasing with a projected annual growth of 16% from 2012 to 2017 [1]. An optical network has the potential to keep up the pace with such continues increasing demands of communication bandwidth. Currently deployed optical network systems, based on high capacity Dense Wavelength Division Multiplexing (DWDM) transmission technology [2]. DWDM system has inefficient scaling performance for those spectrum hungry emerging applications, due to some limitations such as its fix frequency grid, electrical bandwidth bottleneck and physical impairment [3] [4]. Therefore a need for system is emerging that can support such huge traffic volume in more efficient and cost effective manner. Which can also tackle with unpredictable nature of traffic. To achieve this purpose, a lot of the research work is being done to design a system, which features higher data rates per fiber, flexible in nature and more scalable with lower cost which in turn, will help Service Providers (SPs) to address the increasing need of network capacity.

This emergence of high traffic demands gives birth to a new system named as Elastic Optical Network (EON) [5], which have diverse granularity, adaptable characteristics and adjustable data rate accommodation, which can support dynamicity of traffic demands in core networks. As compared to traditional DWDM optical network, which operates in fixed 50 GHz frequency grid, EONs offers 25Ghz, 12.5GHz and 6.25GHz of fine granularity. Thus enabling flexible spectrum characteristic and allocating just enough spectrum according to the actual traffic demands [6] [7].

A vital problem in the design and operation phase of EONs, is Routing and Spectrum Allocation (RSA) problem. RSA is considered as key parameter, due to its characteristic of using spectrum resources efficiently. RSA is an NP (Non-deterministic Polynomial time) hard problem [8] [9]. To exploit the benefits of EONs, besides the importance of its components i.e Bandwidth-variable Cross-connects (BV-WXCs) and Bandwidth Variable Transponder (BVT), RSA plays a key role as it is used as an input for these components to enhance spectrum efficacy. In this thesis, we have proposed a novel heuristic algorithm "MHLS" to address the RSA problem in EONs.

1.1 Motivation

In the last decades we have witnessed a significant increase in the utilization of web primarily based applications along with streaming, sharing and downloading of multimedia contents, on line gaming and ubiquitous cloud Computing. This sudden increase of bandwidth demanding application, creates some serious challenges for DWDM-based network architecture.

Currently, deployed backbone optical network is DWDM-based and which follows fixed 50GHz frequency grid International Telecommunication Union standard (ITU) and also known as fixed-grid system. In which optical spectrum (15301565 nm) is divided into fixed 50 GHz spectrum slots and supports high date rates including (10 Gb/s, 40 Gb/s and 100 Gb/s) capacity per wavelength [5]. Globally, users cellular devices and network connections grew to 7 billion in 2013, up from 6.5 billion in 2012. Soon the Internet of Things(IoT) will be in the market. TeleGeography has predicted increases in the spectrum demands to 606.6Tb/s by 2018, and 1103.3Tb/s by 2020 [10]. It is expected that in near future upcoming client demands will require more and more spectrum, ranging from several Gb/s up to Tb/s level [11]. Due to this rapid increase in IP traffic, service providers (SPs) reach to a point where, 40 Gb/s technology has reached maturity, SPs are now considering to install higher transmission bit rates beyond 100 Gb/s [5]. However, traditional optical transmission technology (DWDM) is unable to cater such huge traffic demands, due to some limitation such as electronic bandwidth bottleneck and as the transmission speed increases physical impairment becomes more serious issue [4]. Besides the increasing growth of IP traffic volume, the unpredictable and dynamic nature of traffic demands across the networks, creates some serious challenges for DWDM transmission technology. Due to its fix-grid system, it creates a mismatch between small and large spectrum demands applications.

In order to address these limitations in the traditional optical network (DWDM), new system have been proposed, which is Elastic optical network (EON) [6]. To facilities the traffic demands beyond 100Gb/s, we need a network that can be more flexible and scalable according to actual traffic demands. EONs are capable of accommodating such huge traffic, due to their adaptability and flexible characteristics. Lightpaths in EON are capable of being contracted or expanded according to the required traffic demand, which in turn increase the spectrum efficacy unlike in DWDM where 50GHz fixed grid is used. EONs follows a flex grid (25Ghz ,12.5GHz, 6.25GHz) International Telecommunication Union (ITU) and also known as flex-grid system. In which spectrum is divided into fine frequency slots of (25Ghz ,12.5GHz, 6.25GHz) and helps the network to adopt flexible characteristic and increases spectrum efficiency [12].

An important issue arises in designing and operational stage of EONs is Routing and Spectrum Allocation (RSA). RSA define as: for any given traffic demand, first select the appropriate route between source and destination, second is to allocate just enough number of frequency slots spectrum along that route, in a away, that spectrum is utilize efficiently. In order to take full advantage of EONs technology, we need to address the RSA problem. The better RSA algorithm will produce better spectrum utilization which in turn results in better use of EONs. A lot of research work has been done on RSA problem. As it is NP-complete problem, thus we need some heuristic algorithm to solve this problem for large scale network. In this thesis, we addresses the RSA issue and try to solve it efficiently by proposing a novel heuristic algorithm (MHLS), which is discussed in details in next chapters.

1.2 Organization of the Thesis

Describing the basic introduction in Chapter 1, the rest of the chapters of this thesis are organized as follows:

Chapter 2 covers the primarily evolution and development of optical communication along with evolution of transmission networks, enabling technologies, fixed and flexible-grid network system. Finally a brief review of RSA problem.

Chapter 3 covers the major literature review portion. This chapters review the different routing strategies and spectrum allocation techniques used in EONs. Finally, a brief review of previous proposed heuristic algorithm for RSA problem is also presented.

Chapter 4 explains the model and design of Elastic Optical Network

Chapter 5 explains the proposed algorithm (MHLS) to solve Routing and Spectrum Allocation in EON, along with the benchmark algorithms.

In Chapter 6, simulation results of proposed heuristic algorithm MHLS and benchmark algorithm on various network scenarios are describe in details. A proper comparison of different algorithms on real network topologies are also covered while consideration of objective function i.e. minimize the total number of Blocked Requests (BR), Blocked Bit-rates (BB) in Gb/s and Slots Used (SU) in the network. Finally, the thesis conclusion is also presented in this chapter

Chapter 2

Elastic Optical Network: A New Dawn

This chapter explains the historical journey of evolutions of networks and their enabling transmission technologies. The main reason for the evolution of networks is the rapid increase in global communication, due to vast acceptance of the Internet, which significantly changed our way of life. These factors leads towards the massive increase in communication bandwidth every year. Optical network has tremendous capability to support this continuous increase demands for communication bandwidth.

In the 1960s The Godfather of Broadband, Dr. Charles Cao (Nobel prized holder) proposed the material ”silica” for long distance optical communication. Which is the basis of the revolution in the optical world, started from the mid 1970s up till now. With approximately, over 50 years of the time period, fiber communication that was started from just few megabits of traffic per second, now serving multi-gigabytes of traffic per second. Optical fiber not only enables the core network to facilitate the huge amount of traffic, but also reduces the cost of a transmission bit per kilometer over the years as compared to other technologies [13]. Today the traditional optical backbone network is based on Dense wavelength Division Multiplexing (DWDM) technology, which is migrating towards the new era of optical domain network known as ”Elastic Optical Network” [5]. These technologies are explained in details in the next sections.

2.1 Evolution of Transmission Networks

In early 1980s, transmission network revolution began with line-rate of 45 megabits per sec. The networks that support basic telephone services through local telephone operators are now supporting and transmitting thousands of gigabits of information per second. Throughout this revolution, telecommunication networks have evolved in three defined stages.

- Asynchronous Network.
- Synchronous Network.
- Optical Network.

2.1.1 Asynchronous Network

Asynchronous network was the first digital network. In mid 1980s PDH (Plesiochronous Digital Hierarchy) transmission mood is used as for data multiplexing, which support 2048 Kbps data rates. Limitation in Asynchronous network was its timing variation (synchronization) problem which often results in bit-error. In each network element there is internal clock which timed its transmission signal that cause large variation problems in arriving and transmitting timing. Beside with PDH, it adds cost and complexity to the network. More importantly, when deployment of optical fiber increases, there was no standard outlines are defined for optical signals. Thus making it difficult for service provider to interconnect equipment from different vendors.

2.1.2 Asynchronous Network

Limitations in Asynchronous network and standard format needed for optical signal give birth to SONET (Synchronous Optical Network) / SDH (Synchronous Digital Hierarchy) technology. SONET and SDH are standardized protocols that synchronously transmit multiple bit rate over fiber using laser or LEDs and eliminates the synchronization issue. SONET/SDH specification standardized bit-rate, frame-format, coding-schemes, line-rate, operation and maintenance functionality and multiplication and synchronization technique as well as defined the optical interfaces. SONET enables the ability to use equipments from different vendors in a one system which is known as the Mid-Span Meet. SONET provides much more bandwidth to carry data and voice traffic than PDH. The basic building block in SONET is frame structure and defined bit-rate. Normally transmits data at speed between 155 megabits per second and 2.5 gigabits per second and supports ring topology network [14]. Scalability is the only factor that helps SONET to survive. Limitation in SONET is its requirement of strict synchronization scheme and complex and costly equipment required as compared to cheaper Ethernet and also some physical limitation in Laser sources and optical fiber due to no upper limit for the bit-rate.

2.1.3 Optical Network

To accommodate the continuous increasing demand for high bandwidth and data rates, needs revolution in existing network. Therefore a system is needed that can fulfill the all high demanding capacity and data rates traffic of customers. Thus, optical network provides such platform in which, it offers high bandwidth to facilities huge traffic. The basic building block in optical network is the wavelength. Transmission technology that helps the optical network to enable such characteristic is WDM (Wavelength Division Multiplexing). Fiber optic network began with WDM, which allows additional capacity on fiber. The network elements and components in optical network is defined while considering the aspect that how wavelength is implemented, transmitted and groomed. In order to define the network, functionality, it is divided into different virtual and physical layered. First layer known as services layer, SONET is the next layer, which monitors performances, provisioning and restoration. Third layer is optical layer, it supports the same functionality as SONET but operating totally in the optical domain.

2.2 Enabling Technologies

The continuous growth in the communication globally, is mainly due to rapid acceptance of Internet, which demands high data rates capacity network. Therefore, need of maximum transmission capacity, becomes the major issue in the optical network domain. Three methods exists to increase the capcity of netwrok: i) Install more cables. ii) Increase system bit rates to multiplex more signals. iii) WDM (Wavelength Division Multiplexing). First two methods is not cost effective as compare to third one. So, researchers came up with a new technology WDM as solution to increase the capacity of network by handling more wavelength per fiber.

In 1994, WDM (Wavelength Division Multiplexing) scheme was first used, which combine signals on one same fiber and supporting 5Gbps on one fiber. This scheme is known as Broadband WDM. In 1995, WDM was first time commercially been deployed and in the next year, 1996 undersea cable was deployed with WDM system. Figure 2.1 represents the basic function of WDM system.

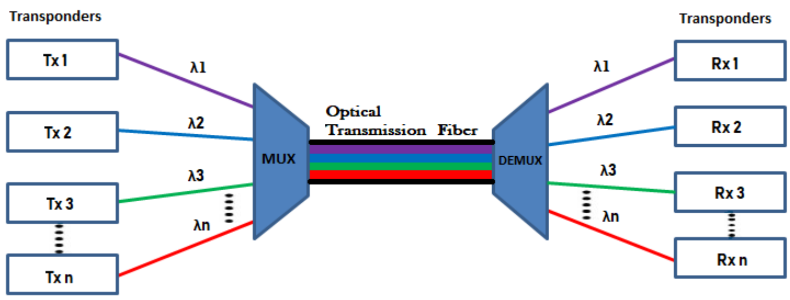

Figure 2.1: WDM

WDM is simple multiplexing technique, thats work in pure wavelength domain. In WDM system, the optical spectrum is divided into several non-overlapping bands of wavelength onto a single fiber strand, where each single band representing a single communication channel. Now each single fiber is able to carry multiple wavelengths which increase the overall traffic per fiber results in increasing the transmission capacity of the network. WDM system is very popular among different telecommunication companies due its ability to expand the capacity of network without laying more fiber.

In optical network, wavelength is used for communication which operates in certain wavelength bands, where optical fibers have low attenuation as shown in figure 2.2.The wavelength band range from 1260 nm to 1675 nm, which is divided into the six optical wavelength bands named O(original band), E (Extented), S (Short), C (Conventional band), L (long) and U (Ultra) bands. The range of their wavelength is shown in figure 2.3. Among these bands, the O-band was the first band used to optical communication because of the small pulse broadening (small dispersion). The most commonly used band now a days is C-band (1530-1565 nm) because optical fiber shows lowest loss in this region. C-band is used for metro, long-haul, ultra-long-haul, and submarine optical transmission systems. Second lowest loss wavelength band is L-band.

	Optical band	Wavelengths
O	(Original)-Band	1260 nm – 1360 nm
E	(Extended)-Band	1360 nm – 1460 nm
S	(Short)-Band	1460 nm – 1530 nm
C	(Conventional)-Band	1530 nm – 1565 nm
L	(Long)-Band	1565 nm – 1625 nm
U	(Ultralong)-Band	1625 nm – 1675 nm

Figure 2.2: Transmission loss of silica fiber and optical communication wavelength bands

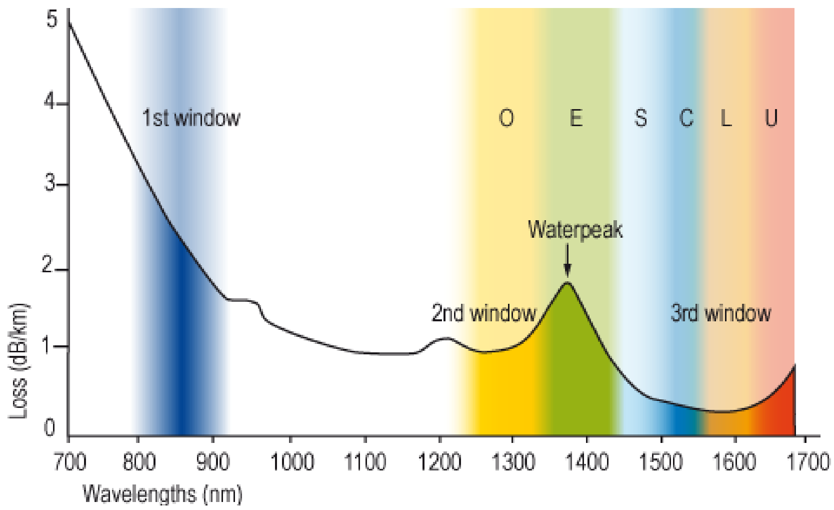

Figure 2.3: optical communication wavelength bands

WDM system is classified into three different types. The basic principle is same as a WDM system, but differs in a number of channels, channel spacing and ability to amplify the Mux signal in optical domain.

- Normal WDM
- Coarse WDM
- Dense WDM

2.2.1 Normal WDM

Normal WDM is also known as broadband WDM. Normal WDM uses dual wavelength 1320 nm and 1550 and spacing between channels is several hundred nm and supports, 2 to 8 channels. Simple function of NWDM is show in figure 2.4.

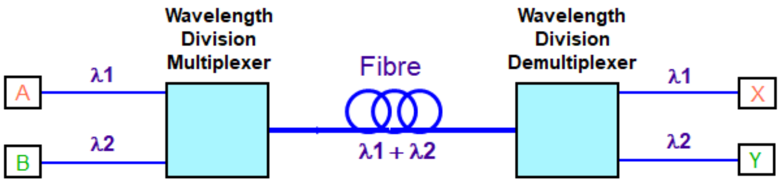

Figure 2.4: NWDM

2.2.2 Coarse WDM

Limitations in Normal WDM are addressed by Coarse Wavelength multiplexing (CWDM). It is an economical WDM solution. In 2002 International Telecommunication Union ITU-T G.694.2 standardized spacing between channels for CWDM is 20nm and its wavelength range is between 1270nm and 1610nm [15]. It can support 18 wavelengths on a single fiber and its total fiber span for 60km is 2.5Gbps signals. Thus, this scheme is suited for short haul applications, mainly for metropolitan networks. The drawback of CWDM is that it cant be used for long-haul communication because channel spacing is not appropriate, it does not support amplification by EDF. Therefore, we need a system which can transmit data over long distance. DWDM system is the solution for this problem. The basic function of CWDM system is shown in figure 2.5

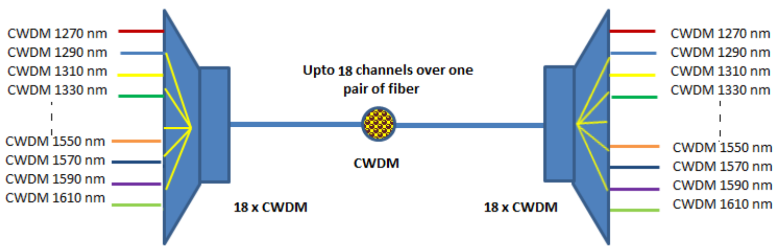

Figure 2.5: CWDM

2.2.3 Dense WDM

ITU-T recommendation for DWDM is G.692 with spacing between channels is 50GHz, 100GHz and 200GHz, equivalent to wavelength spacing of 0.4nm,0.8nm and 1,6nm. This unique characteristic enables the system to increase its network capacity, which in turn helps system to accommodate maximum traffic. DWDM system can support 40 channels at 100 GHz and 80 channels with 50 GHz. DWDM basically refers to optical channels that multiplexed within range lies between 1530.3nm to 1567.1 nm (C-band) and 1570 nm to 1620 nm (L-band), this enables DWDM system to use the capability of EDFAs (erbium doped fiber amplifier) because EDFAs is only useful for wavelengths lies between 1525-1565nm (C-band) and 1570-1610nm(L-band). Erbium doped fiber amplifier was developed for a purpose to replace SONET/SDH optical-electrical-optical (OEO) re-generators, which they have made practically obsolete. With the use of optical amplifiers, DWDM system becomes more powerful as it can transmit data up to 3000km. Optical amplifiers provide an economical edge over re-generators and it quickly became one of the most fundamental components in optical networks. Using WDM and optical amplifiers, network can accommodate many generations of upgrading technology in their optical infrastructure without the need to renovate the backbone network. Figure 2.6 represents a basic principle of DWDM system.

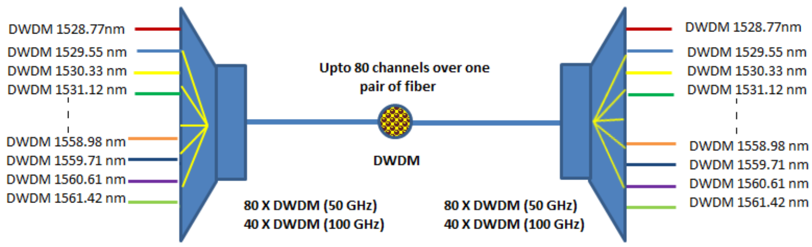

Figure 2.6: DWDM

In the beginning of the twentieth century, DWDM systems with 10 Gb/s capacity were available and efforts are being made to upgrade it to 40 Gb/s DWDM systems. In 2007, it can support 40Gb/s capacity per wavelength. But with the passage of the time, due to continuous increases in the growth of IP globally, causes some serious problem in DWDM systems, even 40Gb/s DWDM based optical systems almost reaches to its maturity level. Here again need for new technology is emerged to deal with such high traffic demands. Drawback in DWDM is its rigid frequency spacing between channels, which is 100GHz or 50GHz and it is relatively large. If channel required low bandwidth then no traffic will be carried in large unused frequency gap, results in wasting of large portion of spectrum, which is clearly shown in figure 2.7. Therefore the desperate need for a new system is required, that can be more flexible, adaptable and more scalable, in terms of spectrum allocations. That need paved the way towards a new dawn in optical network that is Elastic optical network (EON).

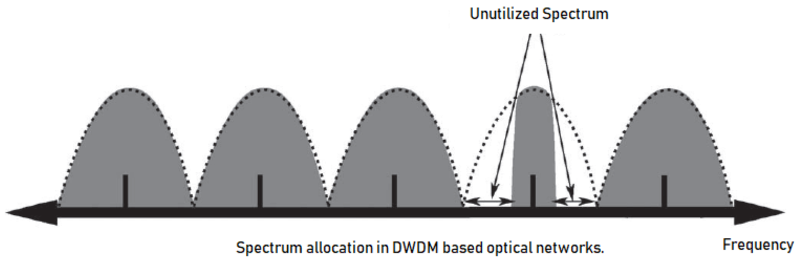

Figure 2.7: Limitation in DWDM

2.3 New Dawn: EON

Two major factors that drive the optical network towards the new era and dimension. These factors are : i) Phenomenal growth in IP traffic globally, and ii) Unpredictability in the nature of IP traffic.

In the last decades, we have witnessed the tremendous growth in IP traffic volume as earlier mentioned in chapter 1. The multimedia and voice connecting devices grew up to 7 billion in 2013, were 6.5 billion in 2012. This is predicated to be 10 billion in 2020. Due to this continues growth, high data rate 40Gb/s and 100Gb/s are already installed and are gradually getting saturated.Service providers (SPs) are now considering transmission data rate beyond 100 Gb/s and 400 Gb/s [5]. Beyond 100 GB/s traffic demand cant be fit into fixed size window spectrum scheme (DWDM) of 50 GHz and 100 GHz, because spectrum width possessed by 400 Gb/s at standard modulation format is too wide to be fit in fixed 50 GHz ITU grid as it is likely to overlap at 50 GHz grid boundary. Second factor is the heterogeneity and dynamicity in traffic demands. Here the word factor heterogeneity means that every traffic demand differs from another in terms of bit-rates required, required spectrum, modulation format and having different physical and optical length. Well, currently deployed network can't differentiate between them due to its non-flexible nature. As it is clearly shown in figure 2.7 that in fix grid based system network, it assigned full wavelength capacity, even to those requests which demands pretty low spectrum. This functionality of fix-grid leads to the inefficient use of spectrum.

Therefore an essential need to redesign the current network is required. Which helps the core and metropolitan telecommunication network to keep the pace with such exponential growth of IP traffic. To address this issue, a network be should design with flexible transceivers and other network elements that can be flexible according to the dynamic of requested traffic. These combinations enables a new dawn named as Elastic optical network (EON).

2.3.1 Basic Concept of EON

In 2008, first time the concept of Elasticity was introduced in spectrum allocation by M. Jinno. In which spectrum is divided into a fine narrow size frequency slots which enables the characteristics of elasticity, scalability and adaptability according to the actual traffic demands on the network. Due to the characteristics of elasticity, it is called Elastic Optical Network (EON) and sometimes also called flex grid network. The main objective of EON is to address the problems in the current deployed optical network by providing efficient and flexible spectrum allocation services to 100Gb/s and beyond 100Gb/s traffic, across the network [5]. In 2012 International Telecommunication Union (IT-U) defines the standards for flex grid network, that is frequency spectrum slot size of 6.25GHz, 12.5GHz, 25GHz. In EON transmission parameters such as data rate, modulation format and spacing between wavelength, which are fixed in the DWDM, will be flexible. Figure 2.8 represents the main difference between flex and fix grid network. Considerable spectrum saving can achieve by using the flex grid network. As it can be seen from the figure 2.8, that in flex grid, optical path can be expand or contract according to actually required capacity of the demand. Which in return save the considerable amount of spectrum for future traffic demands. The performance superiority of EON over DWDM has been demonstrated in [6] [7].

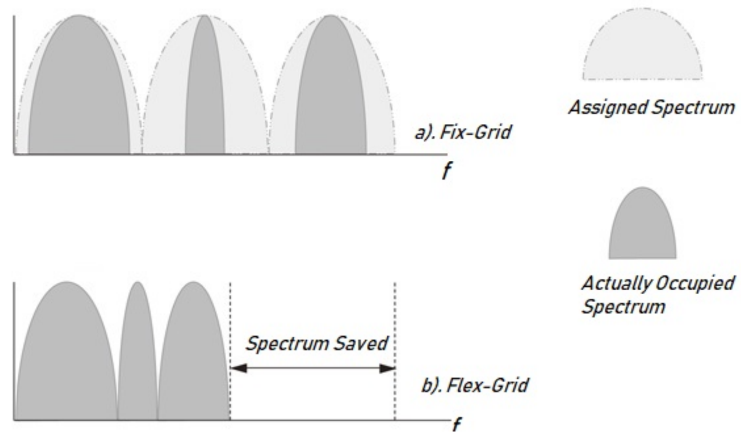

Figure 2.8: Elastic Optical Network (EON)

2.3.2 Fundamental Components in EON

EON concept is accepted widely as next generation high speed Optical Transport Network (OTN). Now researcher is focusing on its design, architecture, spectrum allocation technique and future perspective. As the concept of optical network migrated from fix to flex grid, network elements and components also have to shift from fix to flexible. The main component of EON consists of BVTs (Bandwidth variable transponders) and BV-WXC (Bandwidth variable cross connector).

2.3.3 BVTs

The main purpose of using BVTs, is to tune the spectrum according to the required transmission data rate and modulation format. BVT enables the high speed transmission by using highly efficient spectrum modulation format (16 QAM, 64 QAM) for short distance ligthpaths while for long distance less efficient modulation format (BPSK, QPSK) is used. So there is a trade-off between optical reach and spectrum efficiency. Table **??** represents the modulation format vs Transmission rate vs Optical reach. Draw back in high speed BVT is, when it is operating at lower than its maximum rate due to optical reach or any impairment on the route, then some part of BVT capacity is wasted. In order to address this issue, researcher comes out with SBVT (Sliceable Bandwidth Variable Transponder) to improve the flexibility. SBVT has ability to slice its capacity into multiple optical flows according to traffic requirement and transmit it to one or more destination.

SBVT architecture basically designed to enable the feature of adaptability in a network in a way to support multiple modulation format and multiple data rate. Figure 2.9 shows the basic functions of BVT and SBVT.

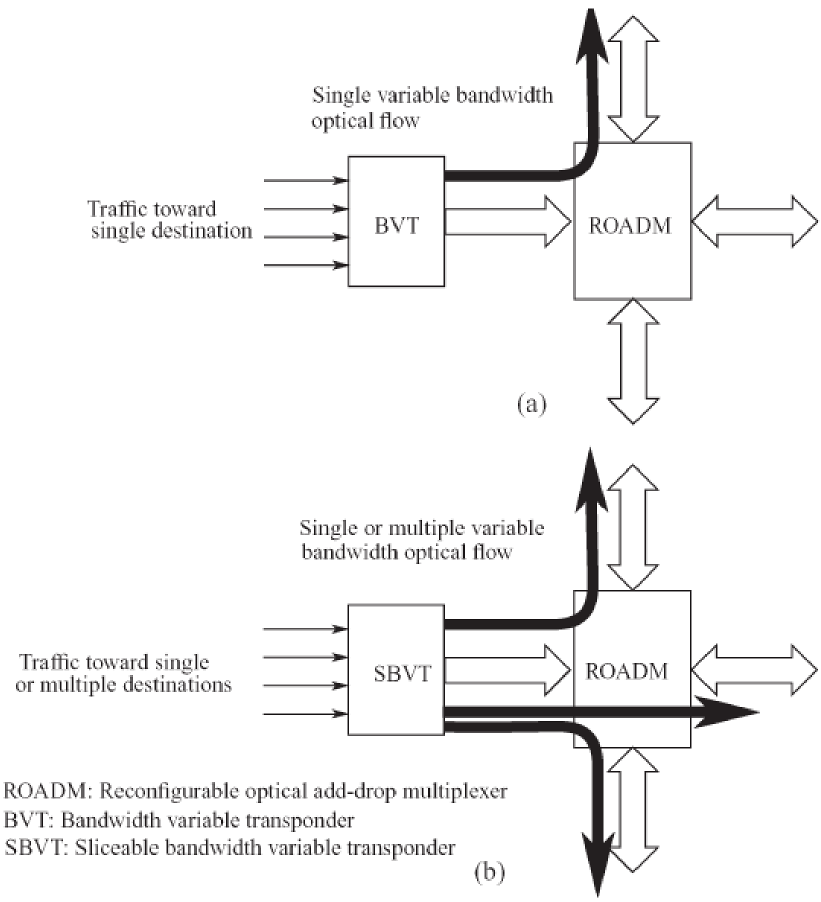

Figure 2.9: BVT and SBVT

2.3.4 BV-WXC

The basic function of WXC (cross connects) is to route the transmitted optical signal towards the destination. In order to support the elastic characteristic in lightpath, WXC need be flexible. So the function of BV-WXC (Bandwidth Variable cross connectors) is to establish the appropriate size optical route, with corresponding frequency slots according to traffic requirement. In BV-WXC the switching window needs to be flexible according to the width of the allocated frequency slots of optical signal. Liquid crystal based wavelength selective switches (WSS) can be used as BV-WXC. The basic function of the BV-WXC is shown in figure 2.10.

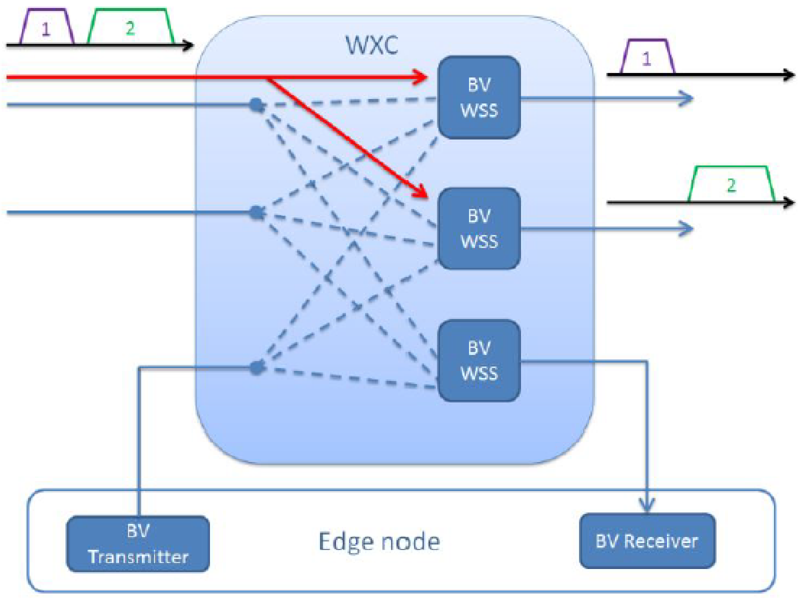

Figure 2.10: BV-WXC

2.3.5 Challenges for EON in Design and Management

There are many issues and challenges in the Elastic optical network, that attracted a lot of attention of researchers. In figure 2.11 illustrates the different areas of research which required attention.

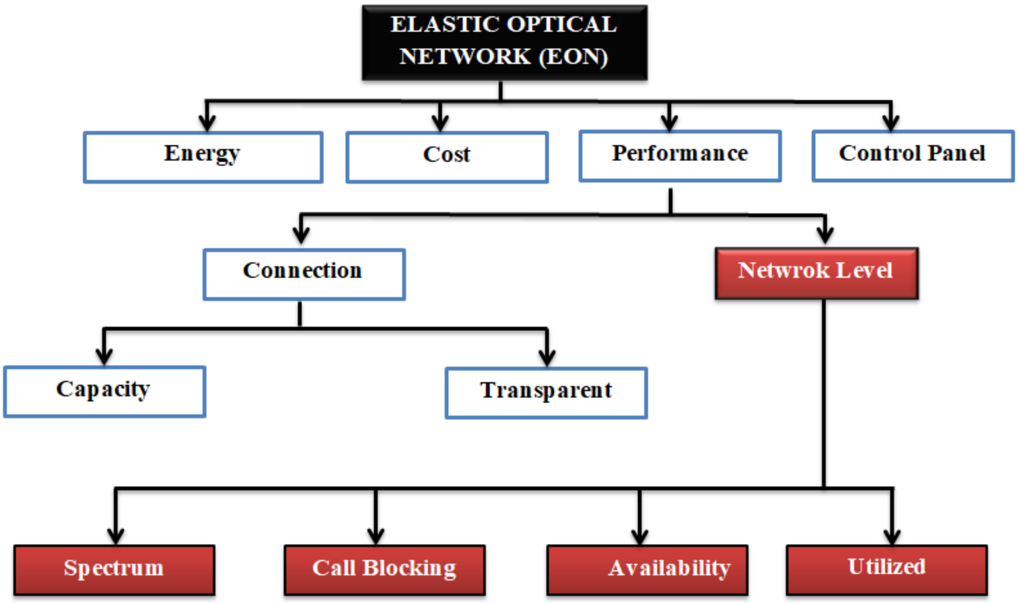

Figure 2.11: Challenges in the Elastic Optical Network (EON)

In this thesis, we are addressing the issues in the network level of the EON, which is RSA (Routing and Spectrum Allocation). In network designing and operation phase RSA plays a vital role, especially when it comes to the performance of the network, in terms of spectrum efficiency. As we move from fix to flex, the algorithms used to address the issues in the conventional DWDM network, is not applicable in EON. So we need to develop any efficient algorithm to address the routing and spectrum allocation problem. To exploit the advantages of EON, an efficient RSA algorithm is a must. In the recent past RSA attracted a lot of attention of researchers and variety of RSA heuristic algorithms, ILP(Integer Linear Programming) model and meta heuristic has been proposed, which is discussed in details in Chapter 3.

2.3.6 RSA

RSA plays a significant role in order to achieve the flexibility, adaptability and scalability characteristics of EON. RSA is pre-requisite to BVT and BV-WXC. An Effective RSA algorithm plays efficient spectrum allocation which will help with accommodation of maximum traffic demands and saving precious limited spectrum.

The basic concept of RSA is to select the most appropriate optical path and assign the appropriate number of frequency slots along that route to respective destinations. RSA work as : When traffic request arrives to network, RSA will first examine the all available condition and will select the most optimum and shortest path from respective source to destination, then will look for required number of free consecutive and contiguous frequency spectrum slots on spectrum and will establish a lightpath from source to destination. Figure 2.12 shows the diagrammatic view of RSA.

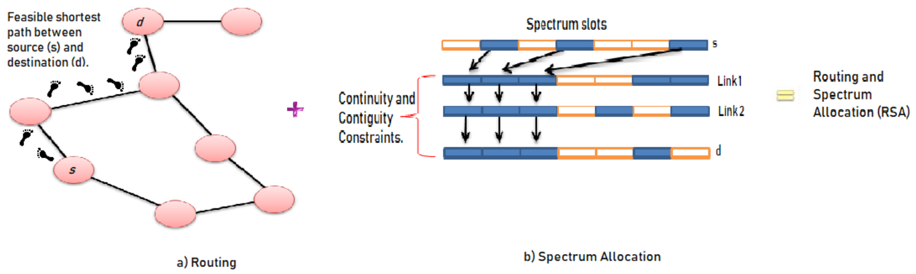

Figure 2.12: Routing and Spectrum Allocation in Elastic Optical Network.

2.3.7 Constraint in RSA

There are two constraints on spectrum assignment. These constraints must be considered while allocating the frequency slots along the route. These constraints are continuity and contiguity.

- Continuity Constraint.

  During spectrum assignment phase, while allocating frequency slots, continuity factor must be considered. The term continuity means frequency slots must be assigned in a consecutive manner in the spectrum allocation phase.

- Contiguity Constraint.

  Another compulsion in the allocation of spectrum is Contiguity constraint. Here the contiguity means the same number of frequency slots must be allocated in all links of the lightpath. Contiguity increases the complexity of spectrum assignment, but contiguity and continuity constraint must be assured in RSA.

2.3.8 Types of RSA

There are two types of RSA in EONs. Classified on the basis of the traffic requests. Online RSA and Offline RSA.

- Online RSA.

  Online RSA is also known as Dynamic RSA, in which traffic requests arrive in real time on the network.

- Offline RSA.

  In Offline RSA the traffic requests known in advance (traffic matrix, network topology). It is also known as Static RSA.

In this thesis we are addressing Offline-RSA problem in the EON.

2.4 Summary

In this chapter, Evolution of optical network over the years is explored in detail. Discussed different transmission technologies, how they evolved and their pro and cons. Different Enabling technologies such as WDM, CWDM, DWDM, which takes the optical transport network to new heights and towards the new directions. In the last section New dawn in optical world Elastic optical network is described in detail. Advantages, their concepts, etc. Finally the One of the important Challenge that faces by the spectrum management team in the Elastic optical network is RSA (Routing and Spectrum Allocation) which is explain in details.

Chapter 3

Literature Review

The rapid increase of IP traffic globally in the core network, demands more spectrum as explained earlier in Chapter 01. As a result of this, optical transport network quickly approaching to its maximum limits [16] and demanding to drive the core network from the current transmission capacity of 10Gb/s, 40Gb/s to 100Gb/s in the next few years and to 1Tb/s by 2020.

Currently deployed backbone optical network (DWDM) reaches to its bottleneck and a need of new technology is needed, that can use the limited resources in a more efficient manner. New Technology Elastic optical network has emerged as a solution, after the evolution of multiple stages. Due to its flex characteristics, EONs are a favorable candidate for future optical network, can accommodate traffic beyond 100Gb/s [17] [6]. The term flexibility means the ability of network to adjust its resources (spectrum, modulation format, data rate) dynamically in an elastic and efficient way according to given traffic demands. EONs following flex International Telecommunication Union (ITU) fine spectrum frequency slots (e.g. 12.5GHz, 6.25GHz Vs 50GHz or 100GHz) [18].

There are a variety of different research areas in flexible optical network. The areas consist performance, cost, energy efficiency and control panel requirement. The main area of interest is a performance analysis on a network level (spectrum utilization, blocking probability). This thesis relates to that area, in which network optimization is taken as consideration. In designing and operational phase of EONs, an important issue is RSA. Routing and spectrum allocation is an essential issue which needed to address in an efficient manner, in order to improve the spectrum efficiency in EONs. Due to its importance in spectrum efficiency, RSA seeks a lot of attention of researcher and producing a number of algorithms. Different ILP (Integer Linear Program) models, meta-heuristic and heuristics are proposed to solve this issue efficiently. The main thrust of all research is to use the network resources efficiently and to accommodate maximum traffic requests. The literature review is done by first describing the conventional algorithms for RSA problem that being marked as benchmark algorithms in maximum research papers. Followed by different related literature work based on RSA problem in EON is being described.

3.1 Conventional algorithms for RSA

Although Routing and Spectrum Allocation (RSA) in EONs is NP-hard problem, in order to simplified it RSA is divided into two sub-problems. As shown in follow.

- Routing sub-problem.
- Spectrum allocation sub-problem.

Routing sub-problem

This section mainly focuses on the routing algorithms used to solve the routing sub-problem in EONs. Figure 3.1 illustrates the routing sub-problem in EONs.

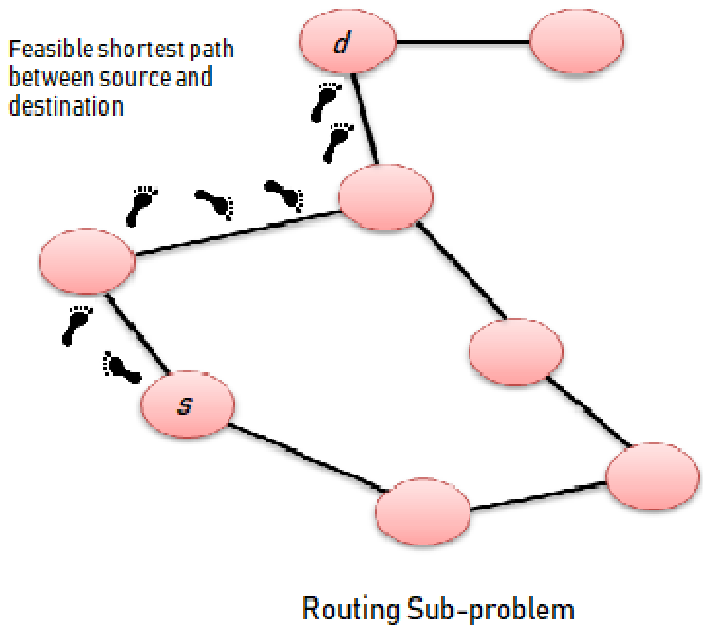

Figure 3.1: Routing sub-problem in RSA

These algorithm are:

- Fixed Routing (FR).
- Fixed Alternate Routing (FAR).
- Least Congested Routing (LCR).
- Adaptive Routing (AR)

In most of the RSA algorithms, Network graph plays an critical role. These algorithm have to find set of feasible possible routes between source and destination and then look for free frequency spectrum slots in the spectrum in order to allocate the spectrum solution. To compute the feasible routing path, Dijkstras algorithm is used which the simplest approach that can be applied within the network. In our work we use Dijkstras algorithm in order to find the shortest feasible path between source and destination. This algorithm is designed to compute the shortest between source and destination, also find all the alternate routing path until no feasible path is available. In some research work, Yens algorithm is used in order to compute the path between source and destination [19].

In FR algorithm [20] [3], first it will compute the shortest single fixed path, for each source and destination pair with the help of Dijkstras algorithm. When request arrives in the network, FR algorithms try to establish lightpath between source and destination along the precomputed fixed path. It will check if on predetermined route, is there enough free slots available to accommodate the given traffic request, if yes then predetermined route will be selected otherwise another route will be compute using Dijkstras algorithm. Establishment of the lightpath is the critical part in the network operation. To transmit data between source and destination in optical network, it is required to establish lightpath connection between nodes it is just like circuit switched networks which is the electronic domain. This operation determines the route between nodes and then assign available slots to that link. lightpath is basically node to node logical connection. FAR algorithm is advance version of FR algorithm. In FAR algorithm [20] [3], each node in the network contains table in which there is number of list of fixed routing paths. when the request will arrive in the network, respective node will try to establish a lightpath through each path in the routing table, until required number of free slots along the path is found. If no available path is found with required number of slots then the respective request will be blocked, otherwise connection will be establish successfully. In LCR algorithm [3], just like in FAR algorithm, number of fixed routes is computed for each node in the network. The least-congested path is selected among the number of predetermined routes. Congestion is calculated with respect to number of free available slots in the link.In AR algorithm [21] [20], path between given source and destination is selected on the basis of link-state information in the network. Link state is define by the number of connection that is currently active in the network. AR works for dynamic RSA.

Spectrum allocation sub-problem

The another key parameter in RSA, is allocation of the frequency slots on given spectrum for traffic demands. There are various algorithms for the allocation of frequency slots on spectrum in the network. While during allocation of slots two important constraint are to considered, that is Continuity and contiguity constraint. Figure 3.2 demonstrates the spectrum allocation sub-problem in RSA.

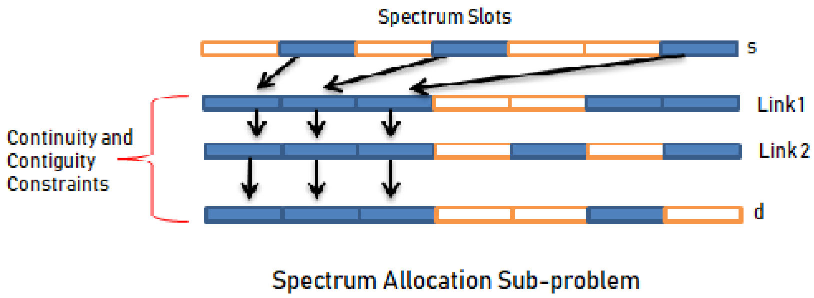

Figure 3.2: Spectrum Allocation sub-problem in RSA

Following are the some conventional algorithms used to address the spectrum allocation problem in RSA and some of them are used as benchmark algorithm in most of the research papers.

- First Fit (FF).
- Random Fit (RF).
- Least Used (LU).
- Most Used (MU).
- Longest Path First(LPF).

FF algorithm, is most simple and commonly used algorithm. when the traffic request arrives in the network, FF search for number of required free slots on the given spectrum and allocate the traffic. FF doesn't check any special condition, it just serves the traffic that arrives first in the network [3] [18]. FF considered to be the least complex and best spectrum allocation policy, as it has very low Blocking Probability (BP) with respect to the traffic request. In RF algorithm, as the name suggests it works on the random policy. It keep the record of number of free available slots and used slots in the network. As the traffic request arrives in the network, RF randomly selects the slots from available free slots on the spectrum and then assigns it to given traffic request [3]. In LU algorithm, when the traffic requests is arrived, it will check the lightpath that has used fewest link in the network, will allocate the spectrum slots to that lightpath [3]. In simple word, the request that required least number of slots, will be served first in the network. MU algorithm is inverse to LU, in MU the request that required maximum number of slots to fulfill their request will be served first in the network. By doing this, we get better spectrum reuse in the newtork [18]. In LPF, it keep record of the optical reach (length of the fiber between source and destination) for all nodes in the network. Request with longest optical reach will be serve first in the network [18]. These are the some conventional algorithm that is used as benchmark algorithm in most of the research paper.

3.2 Related literature work

Different ILP (Integer Linear Programming) models, meta-heuristic and heuristic have been proposed to solve RSA problems. The main thrust of all research work is to use the network resources efficiently and to accommodate maximum traffic requests.

The concept of RSA was first introduced by Jinno et.al 2010 [22], in which spectrum resources are allocated on the basis of distances. Christodoulopoulos et.al [18] (2010) formulated an ILP (Integer Linear Programming) model to minimize the spectrum usage in elastic optical networks and proposed a method to solve RSA. The method decomposes the RSA-problem into two parts: first part is Routing problem (R); second part is Spectrum Allocation (SA) problem and solves them in sequence. Two conventional ordering polices MSF (Most Subcarrier First) and LPF (Longest Path First) along with meta-heuristic simulated annealing (SA) is used in to order provide better spectrum allocation. Results are obtained on random optical network of 6-nodes and on real optical network topology DT-network (14-nodes, 46-links). The objective is to minimize the number of sub-carries used in a network.

In 2011 Christodulopoulos et.al [8] extended the RSA problem as Routing(R) + Modulation level (ML) and then spectrum allocation (SA). The author first shows that RSA is NP-complete problem and develops an ILP model to minimize the spectrum used to accommodate the given traffic demands for small size network. For a large size network, however, it decomposes the RSA problem into sub-problem as first R+ML and then SA, solves them in a sequential manner. Performance is evaluated on small network of 6-nodes and Generic DT-network (14-nodes, 46-links) network topology on the basis of utilized spectrum and algorithm runtime. In the same year Yoshiaki Sone et.al [23] proposed Maximize Common Large Segment (MCLS) RSA algorithm and results show that in terms of provisionable path capacity, MCLS is more efficient as compared to other referenced algorithm. For comparison purpose FF (First Fit) and MSF are used. Yang Wang et.al [9] (2011) proved the NP-hardness of RSA and formulated an ILP model. Two RSA heuristic algorithms; Shortest path with Maximum Spectrum Reuse(SPSR) algorithm and Balanced Load Spectrum Allocation (BLSA) algorithm is also proposed. The performance analysis for ILP is done on small size random optical network of 6-nodes while for heuristic algorithm real network (14-node NSF) is used. Goal is to reduce the maximum number of sub-carrier used on fiber link in SLICE network.

Mirosaw Klinkowski et.al [24](2012) presented an ILP model as DPP-ILP (Dedicated Path Protection) for optimal solution. Heuristic algorithm Adaptive frequency assignment with Dedicated Path Protection is also proposed to obtain sub-optimal results for large scale optical network. For comparison purposes FF, LSF and MSF are used on different real size networks i.e. SIMPLE (6-nodes, 16 links), NSF15 and UBN24 (24 nodes, 86links). In the same year Song Yang et.al [25] referred RSA problem as IARSA (Impairment-Aware Routing and Spectrum Allocation) and proved that respective problem is NP-hard. Proposed algorithm is designed for dynamic traffic demands. Aim is to find shortest viable route, where its viability is determined by three factors; i) Availability of free sub-carriers along the route. ii) Impairment level and iii) Use of regenerators. The performance parameter is BP (Blocking Probability) and USA network topology of 24 nodes is used for analysis purpose. In paper [26] authors comprehensively describe the Dynamic RSA in flex grid optical network while considering traditional routing algorithms such as FR (Fixed Routing), FAR (Fixed Alternate Routing) and AR (Alternate Routing). In later part, brief description of their concepts, advantages and disadvantages are discussed. Comparison is done on the basis of BP and computational time as performance parameters. R.J. Duran et.al [27] (2012) also addresses the Dynamic RSA scenario, in which author considered four well known heuristic algorithms in RWA problem and used them to solve RSA problem and proposed two heuristic algorithms known as Least Unusable Spectrum First (LUSF) and Adaptive Unconstrained Routing Exhaustive Spectrum Search (AUR-ESS). Comparison is conducted on the basis of BP and 14-node NSFNet is used as physical network topology.

Shahrzad Shirazi pourazad et.al [28] (2013) also proved that RSA is NP-complete problem even in the simple case of chain or a ring network topology. A Heuristic algorithm known as DPH (Disjoint Path Algorithm) is proposed. Main point is to find disjoint route for routing purpose, in order to increase the reuse of sub-carrier. Traffic is first sorted in descending order. Results demonstrate the efficacy of heuristic DPH against (i) ILP solution and (ii) results of the two heuristics algorithms in paper12. Physical network topology used for this purpose is NSFnet. G Zhang et.al [29] (2013) presents a detail survey based on OFDM modulation technology in EONs. Authors explained the fundamentals of OFDM its advantages and disadvantages in details. Different authors used different meta-heuristic techniques to tackle NP-hard RSA problem in EON. Such as R. C. Almeida Jr. et.al [30] (2013) proposed an intelligence search algorithm known as Evolutionary Algorithm (EA) for spectrum assignment. This is not the conventional EA in fact it is combination of two strategies genetic and evolutionary algorithm. The theme of the paper is to use intelligence computational search in order to minimize the request BP. Joao H. L. Capucho et.al [31] (2013) uses Genetic Algorithm (GA) to optimize the static RSA problem in EONs and also proposed ILP formulation. Tabu Search (TS) algorithm used by Roza Goscien et.al [32] (2013) to address the optimization problem in EONs and compare it with the results obtained by CPLEX solver and with reference algorithms (FF, MSF ,LPF and AFA). Three different network topologies: NSF15 (15 nodes, 46 links), Euro16 (16 nodes, 48 links) and US26 (26 nodes, 84 links) are considered for performance evaluation. Y. Wang et.al [33] (2013) addresses the dynamic RSA with the help of Ant Colony Optimization (ACO) in order to minimize the BP in optical network, while, in the same year Hamzeh Beyranvand et.al [34] presented RSA as Quality of transmission (QoT) aware dynamic routing , modulation level and spectrum assignment (QoT-aware RSA) problem. It consists of three stages; i) path computation on the basis of QoT-aware modulation level ii) path selection on the basis of OSNR (Optical Signal- to- Noise Ratio) and iii) spectrum assignment.

In 2014 Lu Raun et.al [35] studied the dynamic Survivable Multipath (SM) routing and spectrum allocation in EONs. The author developed the ILP model and also presented the heuristic algorithm for SM-RSA. In SM-RSA algorithm, link disjoint path is calculated by using Bhandaris link-disjoint paths algorithm. Simulations are conducted on USA 24 nodes network to analyze the advantages of MPP (Multi-Path Provisioning) over SPP (Single-Path Provisioning) for dynamic traffic demands while considering BP as performance parameter. J Scrates-Dantas et.al [36] (2014) presented a Fragmentation-Aware RSA algorithm for online traffic demands and tested it on German network topology with 17 nodes and 26 links. Kadu et.al [37] (2014) proposed modulation-aware multipath routing and spectrum allocation algorithm and results are compared with single and multi-path RSA algorithm in terms of minimum BP.

In 2015 Bijoy Chand Chatterjee et.al [3] [38] presented two papers, on

RSA-problem in EONs. In the article [3], a comprehensive tutorial on routing and spectrum allocation in EONs is done. Different routing algorithms, spectrum allocation algorithm, their pros and cons are explained in details. Various other aspect such as fragmentation, energy saving, traffic grooming linked with RSA are also discussed. In paper [38], complete performance comparison of well-known spectrum allocation ordering strategies (FF, RF, FLF, LU, MU and EF) on the basis of time complexity and BP is presented. Mirosaw Klinkowski et.al [39] (2015) formulated MLP (Mixed Integer Program) model to address the RSA problem. Proposed branch and price algorithm to tackle the RSA issue in EONs. Fernando Lezama1 et.al [40] (2015) uses Differential Evolution (DE) optimization technique to solve the RSA problem. Results are compared with FF, MSF and LPF in terms of minimum spectrum utilization and average length path. Real optical networks, such as the NSFnet and the European optical network, USA and Japan networks are used for evaluation purpose.

Recently in 2017 Bee Colony Optimization (BCO) meta-heuristic algorithm is used to solve the RSA problem [41]. In which Paper [40] is used as benchmark paper and FF, MSF and LPF as referenced algorithms. Performance parameters used in this article are total number of Slots Used (SU) and average path length (APL). Experiments are performed on Two European network and USA network topology. Results show that BCO outperforms DE optimization technique and referenced algorithms. In the same year two novel heuristic algorithm [42], [43] is also proposed to tackle the RSA problem. Afsharlar et al [42] propose Delayed Spectrum Allocation (DSA) technique in scheduled requests. Results show that DSA-RSA minimizes the blocking percentage for scheduled traffic request light paths. Sahar Talebi [43] represents RSA problem as a multiprocessor problem and proposed Distance Adaptive (DA) technique in spectrum allocation phase. The aim is to minimize the total SU on determined path. NSFnet, GEANT2 and 60-nodes network topologies are used for performance evaluation.

In this thesis, we propose a novel heuristic algorithm MHLS to solve the RSA problem efficiently, in order to increase the number of served traffic requests and minimize the number of slots used in network. Performance analyses are done on random network topology of 20-nodes and on practical network of PAN_EU of 37 nodes and USA of 40 nodes. For comparison purposes traditional algorithms FF, MSF and LPF are used. Results depict that performance of our proposed algorithm superior than all referred algorithms.

3.3 Summary

In this chapter we review the previous work done on RSA problem in EONs. In which Different ILP models, MLP model, meta-heuristics and heuristic algorithms proposed for Online and offline RSA problem are discussed. Also discuss some conventional algorithm used to address this issue. Finally, a brief review of our proposed algorithm MHLS is illustrated.

Chapter 4

Network Design and Proposed Methodology

The nonstop increase in IP traffic volume globally, drives the service providers for high data rate, more efficient and scalable network design. In this effort, optical network is shifted from fix to flexible; towards Elastic Optical Network (EON). Which is more flexible in terms of accommodating high data rate and efficient in utilization of the spectrum as compare to the conventional backbone optical network (DWDM). In this chapter we will present our elastic optical network model and design along with proposed algorithm Minimum Hops with Least Slot Spectrum (MHLS) . In our network design we added an additional feature that is traffic grooming. Performance of our proposed algorithm MHLS and benchmark algorithm (FF, MSF, and LPF) will be tested on our design network.

4.1 Elastic Optical Network Model

In this work, we are considering the Internet protocol over an elastic optical network. A connected graph G = (V, E) represents the physical topology, where V represents nodes (different locations) and E represents the physical links between the nodes in the network. Nodes are equipped with IP routers and BV-WXC (bandwidth variable cross connectors). Each E from s to d is represented by physical length L_{sd} denoted in Km and is bi-directional i.e. L_{sd}=L_{sd} respectively.

Each traffic requests from s to d is accommodated by using lightpaths. lightpath is the optical logical path and mapped onto E which can extent over multiple E, depends on the path availability. If a single traffic request spanned over multiple hops then the optical lightpath is switched at intermediate nodes using BV-WXC. Traffic request may need one or more consecutive lightpaths to reach the respective destination. In such case, with the help IP routers that switch the request between multiple consecutive lightpaths, the whole set of lightpaths formed is by L_T (Lightpath Topology), in which lightpaths are initiates at source node (V_{sd}) and ends at destination node (V_{sd}) by BVT (Bandwidth Variable Transponder). The algorithm used to establish L_T is described in the next section. The maximum transmission capacity of BVT is X_{max}=400 Gb/s and the maximum capacity of spectrum link (C-band) is SL_{max}=4THz. Optical Spectrum in the network is divided into narrow slots of size12.5 GHz and each link is of 320 slots. We assumed one empty S as guard band. Lightpaths are related with modulation format (M) and S. Where M is defined by the optical reach (OR) and given traffic request (t) from V_{sd} toV_{sd}. Table 4.1 represents the details of modulation format studied in this work. Lightpaths are created for a long distance running on low data-rates or for short distance operating with high data rate; it all depends on selection of modulation level. Number of S that is linked with lightpath is associated with given traffic request (t) and transmission data rate (Z).

Table 4.1: Details of available modulation formats

Modulation Level	**BPSK**	**QPSK**	**8QAM**	**16QAM**	**32QAM**	**64QAM**
Transmission Rate [Gb/s]	12.5	25	37.5	50	62.5	75
Optical Reach [Km]	4000	2000	1000	500	250	125

Our network model consists of set of lightpaths, which satisfy the given traffic requests in the network. For given traffic request, lightpath is established by selecting most suitable M and appropriate numbers of S according to distance in km and amount of required bit rate in Gb/s. Finally, to each lightpath slots assignment is done, while considering all constraints (continuity, contiguity and guard band). Performance analysis of our proposed algorithm MHLS along with benchmark algorithms are conducted on this network model while considering different network topologies and traffic scenarios.

4.2 Elastic Optical Network Design

Our network design consists of two heuristic algorithms; first is the Direct Lightpath Establishment (DLE) and second is the Traffic Grooming Algorithm (TGA), which helps to use the capacity of already existing lightpaths thus, resulting in optimization of network design.

The output (Ψ) of our proposed MHLS heuristic algorithm and benchmark algorithms (FF, MSF, LPF) is used as an input parameter to our network design algorithms (DLE, TGA). Dijkstra shortest-path algorithm is used to compute all the shortest physical paths. A set γ_{sd} containing all the shortest paths from s to d. The traffic request that needed to be fulfilled is arranged according toΨ. If size of the given traffic request (Gb/s) is greater than the $\mathrm{X_{max}}$ than it will splits it into traffic request size of ($\mathrm{T_{sd}}$ / $\mathrm{X_{max}}$). The output of the design network is ζ, which represents total number of Blocked Requests (BR), Blocked Bit-rates (BB) and Slots Used (SU) in the network.

4.2.1 Direct Lightpath Establishment (DLE)

The DLE process is illustrated in algorithm 4.1 and flowchart 4.1. Traffic requests that needed to be fulfilled are arranged in set Ψ according to algorithms used (MHLS, FF, MSF, FF). For each traffic request in set Ψ same steps will be repeated. Selects the shortest route from s to d from the set γ_{sd}. while until feasible route between s and d exists (feasible route means that its length is less than max OR of transmitter) and traffic request is not fulfilled, algorithm try to build a lightpath. In order to establish a lightpath, DLE chooses the most appropriate M considering the distance of selected feasible route. Modulation format plays a vital role in achieving the optimum spectrum utilization. Keeping this in mind, selection of M is done in such a way that entire traffic request can be assigned to lightpath using just enough frequency slots. Then number of S required to accommodate the traffic request is calculated and its availability is checked on determined route. If enough slots are available, establish a lightpath and allocate traffic requests to lightpath, else repeat the same steps for next route in set γ_{sd}. If request is still not fulfilled and route exists but is not feasible then divide the given route into several Intermediate Routes (IR) in such a way that their distance is less than maximum OR. Check if each IR can support lightpath by considering M, S and their availability. If true, then establish a lightpath and allocate the given traffic request to lightpath else select another route from set γ_{sd}.

After checking all feasible and non-feasible routes, if traffic request is still not fulfilled then respective traffic will be blocked and no feasible solution would be found. Next traffic request is selected and same process is repeated for all traffic requests. When the entire traffic request is being served then to each lightpath, frequency slots are assigned. During slot assignment, while considering the constraints (continuity, contiguity and guard band) in the network if slot allocation is possible then slot is assigned successfully, otherwise, respective slot will be rejected and given traffic will be blocked. FF heuristic algorithm is used for frequency slots assignment. The output (ζ) we get is number of successfully assigned slots (slots used), number of traffic request blocked and number of bit-rates (Gb/s) blocked.

4.2.2 Traffic Grooming Heuristic (TGH)

To exploit the features of EON, traffic grooming heuristic is used which helps in utilizing the spectrum more efficiently, by using capacity of already existing lightpaths in network. The main function performed by TGH is shown in Algorithm 4.2, as well as in flow chart 4.2. For each traffic request in set Ψ TGH checks the capacity of lightpath, whether it has enough capacity to accommodate the given traffic, if yes, traffic is allocated and moves to new traffic request. If no lightpath available or it has not enough capacity then TGH will check for all optical paths availability (O_P) that is to find sequence of previously existing lightpath with respective s and d.
If no O_P exists then the traffic request will be served by D_L(Direct Lightpath), same procedure as in DLE is repeated for given traffic requests (Algorithm 1). If D_L is also not true then respective traffic will be blocked and no feasible solution is found. In case O_P exists then TGH will check whether it is possible to use this optical path to serve the given traffic request. For each available optical path TGH, will first check its capacity, if it has enough capacity to accommodate the given request. If yes then allocate the traffic request. If there is not enough space to accommodate the given traffic request in all the available optical paths, then same steps will be repeated and given traffic request will be served by DLE algorithm. After serving all given traffic requests, assignment of frequency slots are performed. Assignment is performed under the constraints (continuity, contiguity and guard band) in the network. If frequency slot assignment is possible then slots are assigned successfully otherwise is will be rejected and blocked.

Algorithm 4.1 The Direct Lightpath Establishment

```
Input Ψ_sd ∀(s, d)ϵV, Ψ
Output ζ
for all Ψ_sd ϵ Ψ do
  traffic_request_fulfilled = false;
  P= shortest_route(γ_sd );
  while P is true and traffic_request_fulfilled is false do
    M=find_modulation_level(Ψ_sd, P );
    slots_calculation = findnumberrequiredslots(Ψ_sd,M);
    if slots_calculation ≤ available-slots(P) then
      establish_lightpath(Ψ_sd,M,P);
      traffic_request_fulfilled = true;
    else
      P= next_ shortest_route(γ_sd );
    end if
  end while
  if traffic_request_fulfilled is false then
    while traffic_request_fulfilled is false and P is truebut not feasible
    route do
      IR = divide_route(P);
      intermediate_routes =check_intermediate_routes (Ψ_sd ,IR);
      if intermediate_routes is true then
        establish_alternate_lightpaths(Ψ_sd, IR);
        traffic_ request_fulfilled = true;
      else
        P=next_shortest_route(γ_sd);
      end if
    end while
  end if
  if traffic_request_fulfilled is false then
    traffic_request = blocked;
    return No feasible solution found;
  end if
end for
Assign_frequency_slots = assign appropriate number of slots to each light-
paths while considering constraint;
if Assign_frequency_slots is true then
  Assign_frequency_slots = successfully;
  return ζ;
else
  traffic_request = blocked;
  return No feasible solution found;
end if
```

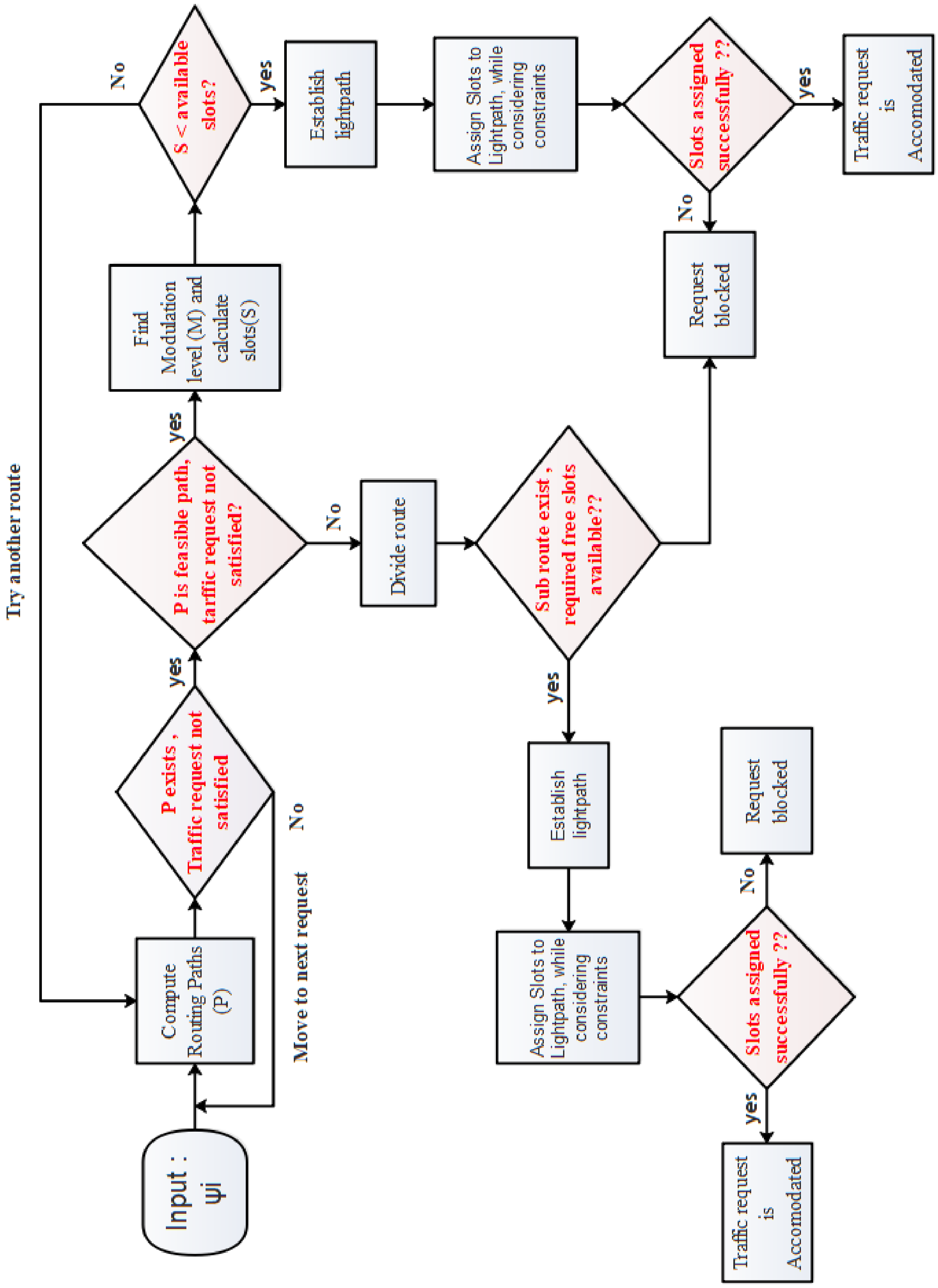

Figure 4.1: Flow Chart of Direct Lightpath Establishment (DLE)

Algorithm 4.2 Traffic Grooming Heuristic

```
Input Ψsd ∀(s, d) ϵ V, Ψ
Output ζ
for all Ψsd ϵ Ψ do
   if Ψsd ≤ capacity (Lsd) then
      allocate_traffic(Ψsd) ;
   else
      O_P= compute_O_P(s, d);
      if O_P is false then
         D_L=D_L_E (Ψsd);
         if  D_L is false then
            traffic_request = blocked;
            return  No feasible solution found;
         end if
      else
         if Ψsd ≤ capacity(O_P) then
            allocate_traffic (Ψsd ,O_P);
         else
            D_L=D_L_E (Ψsd );
            if  Direct_lightpath is false then
               traffic_request = blocked;
               return  No feasible solution found;
            end if
         end if
      end if
   end if
end for
Assign_frequency_slots = assign appropriate number of slots to each light-
paths while considering constraint;
if Assign_frequency_slots is true then
   Assign_frequency_slots = successfully;
   return  ζ;
else
   traffic_request = blocked;
   return  No feasible solution found;
end if
```

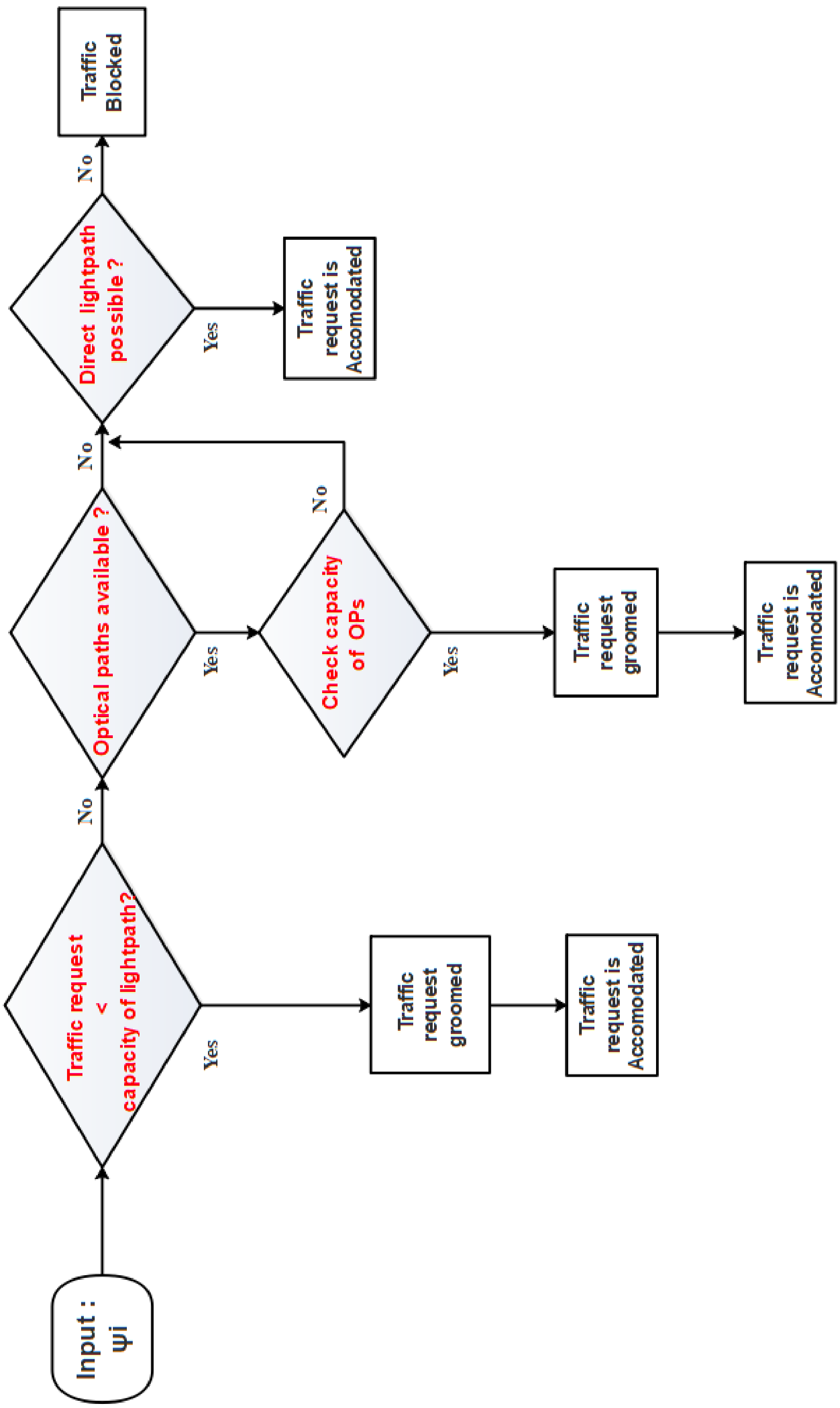

Figure 4.2: Flow Chart of Traffic Grooming Heuristic (TGH)

4.3 Proposed Method to Solve RSA

Heuristic Algorithm is used to achieve sub-optimum and particle solution for large size network problems in well reasonable time. In this section, we will explain our proposed heuristic algorithm Minimum Hops with Least Slots comprehensively. For performance evaluation purpose, we are considering some traditional algorithm naming them as benchmark algorithm. These algorithms are FF (First Fit), MSF (Most Sub-carrier First) and LPF (Longest Path First). These algorithms are simulated on the same network and traffic scenarios.

4.3.1 Minimum Hops with Least Slots

The MHLS heuristic algorithm is designed while considering two general key points. The first point is total number of Hops (H) and second is total number of frequency slots (S) for each traffic requests in the network. In algorithm MHLS, input parameter is D, which represents the set of offline traffic demands that needed to be fulfilled. For each demand from respective source to destination and required traffic bit-rates in Gb/s is known. The main function of the MHLS, is for each request (s, d, t), first calculate the Optical Reach (OR) for the respective s and d. Then its number of Hops (H) is calculated. Dijkstra shortest path algorithm is used to compute H and OR for give traffic request. MHLS will find an appropriate modulation level for the given traffic request with the help of OR and required bit-rates (Gb/s). A suitable selection of the Modulation level (M) plays a vital role in order to achieve an efficient use of the spectrum resources. Transmission Data rate (Z) is calculated, after selection of M. After the calculation of OR, H, M and Z, slots calculation is performed. For a given s and d, slots are calculated with the help of equation 5.1. After calculating all these parameters, a new parameter is being introduced N_P, which is product of two parameters S and H as shown in equation 5.2. Which helps us in finding the total number of slots required by given s and d in the network. Same steps will be repeated for entire traffic matrix D. After that, Sorting is done in the ascending order of the N_P and save as output in matrix Ψ. Thus, the proposed algorithm MHLS as shown in Algorithm 4.3, which combines two parameters H and S, then sort it down in ascending order and served to our design network in a sequentially manner. Results reflects that (MHLS) algorithm minimize BB,BR and SU the in network as compared to other algorithms. Algorithm MHLS also illustrated in flow chart 4.3.

Algorithm 4.3 Minimum Hops with Least Slot Spectrum

Input $D_{sdt} \forall (s, d, t) \epsilon V$
Output Ψ
for all $D_{sdt} \epsilon D$ **do**
  OR_{sd} = calculate_optical_reach;
  H_{sd} =calculate_hops(OR_{sd});
  M_{sd}= find_modulation_level (OR_{sd});
  Z_{sd}= find_data_rate(M_{sd});
  S_{sd}= Slot_calcualtion(Z_{sd});
  N_P= $Z_s d$ * H_{sd};
end for
Sort the N_P in the ascending order; Ψ = sorted N_P;
return Ψ;

$$S_{sd} = \frac{T_{sd}}{Z_{sd}} \tag{4.1}$$

$$N_P = S_{sd} \times H_{sd} \tag{4.2}$$

4.4 Benchmark Algorithms

For the sake of comparing, the quality and efficiency of MHLS, conventional algorithms such as FF, MSF and LPF are used as referenced algorithm in our proposed work.

In FF (First Fit) algorithm, the traffic request (s, d, t) is first sort in descending order of traffic bit-rates (Gb/s), then served sequentially. In MSF algorithm, first for each traffic request, frequency slots (S) are calculated then they are arranged from maximum to minimum order according to number frequency slots required. The traffic request that required maximum S will be served first in order. In LPF algorithm, for each traffic requests, first we calculate the Optical Reach(OR) with the help of Dijkstra algorithm and then sort it as descending order with respect to their OR. Each Algorithm generates an output as a set of off-line traffic matrixΨ, which is served as input parameter to our design network. Despite these reference algorithms (FF, MSF, LPF) are simple to implement but it is very much clear that only better ordering policy plays a vital role in efficient utilization of spectrum.

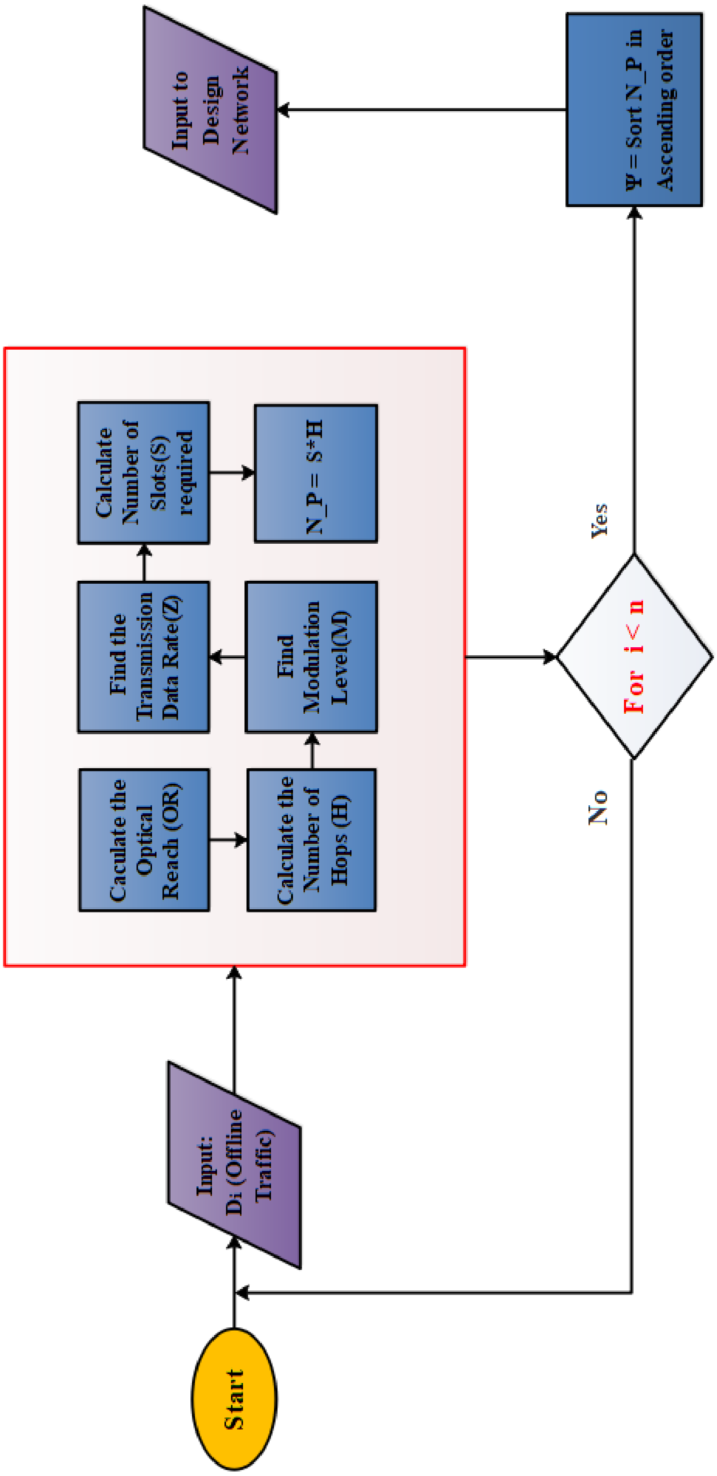

Figure 4.3: Flow Chart of Minimum Hops with Least Slot Spectrum (MHLS)

4.5 Summary

In this chapter, we illustrated the Elastic optical network model and design. In the design phase, we use two heuristic algorithms DLE and TGH which comprehensively explained along with the algorithm pseudo code. Different parameters used in the network are also described. In later part proposed heuristic algorithm Minimum Hops with Least slot is explained in detail along with benchmark algorithms (FF, MSF and LPF). Performance analysis and results will be explained in the next chapter.

Chapter 5

Performance Analysis and Conclusions

In this section, comparison of simulation results in proposed algorithm MHLS and benchmark algorithm (FF, MSF and LPF). Performance is analyzed for different real size network topologies (USA, PAN_EU) and 20 nodes of random network topology. In our test, we assume C-band with 320 frequency slots per link, 4THz as maximum capacity of spectrum, 400Gb/s as maximum transmission capacity of BVT and one empty S for guard band. However, the simulation is performed on static network scenario. All the functions are performed by running programming code in C/C++ language that is implemented in Microsoft visual studio. In the simulator, we have created certain libraries that work as the optical network simulator.

5.1 Network Scenarios

The algorithms are analyzed under varying number of nodes (topologies), nodal degree, optical reach and the nature of traffic (heterogeneous traffic and homogeneous traffic). This permits us to understand which algorithm performs better in terms of minimum BR, BB and SU in the network.

Different physical networks topologies considered in this work are shown in Figures 5.1 , 5.2 and 5.3. These figures illustrate Random topology, PAN_EU and USA. Their specifications are: random network with 20 nodes, 2.5 nodal degree and average length is 1000km, PAN_EU network with 37 nodes, 114 bidirectional physical links and nodal degree 3.05 and USA network with 40 nodes, 116 physical links and 2.9 nodal degrees as shown in table 5.1.

Table 5.1: Pan-EU, USA & Random Topologies

Parameter	**Pan-Eu**			**USA**			**Random**		
	mean	**min**	**max**	**mean**	**min**	**max**	**mean**	**min**	**max**
Fiber Distance (km)	648	218	1977	702	52	2133	485	71	1865
Node Degree	3.08	2	5	2.9	2	6	2.5	2	4

For each considered network, different homogeneous and heterogeneous traffic is used. In heterogeneous case traffic is randomly distributed on link. While in homogeneous, traffic is uniformly distributed on the network link. We are considering 50 Gb/s, 100 Gb/s and 150 Gb/s of homogeneous traffic per node and 1000 Gb/s, 1500 Gb/s, 2000 Gb/s and 2500 Gb/s of heterogeneous traffic average per node.

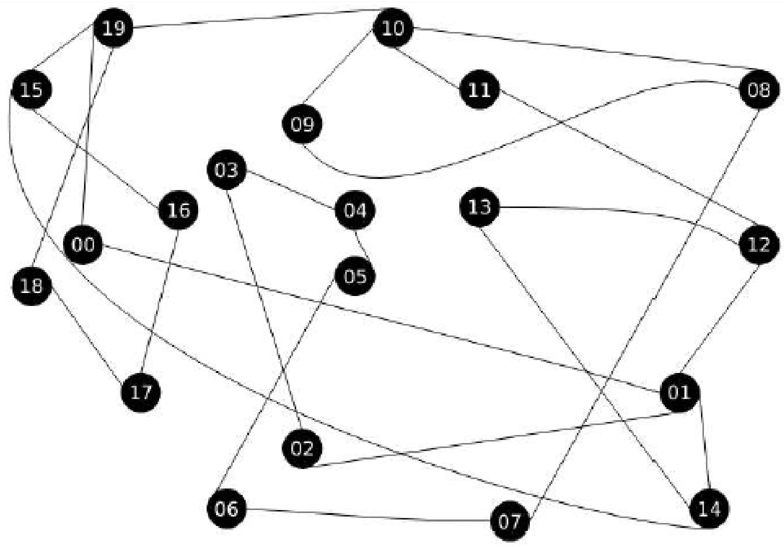

Figure 5.1: Random network topology

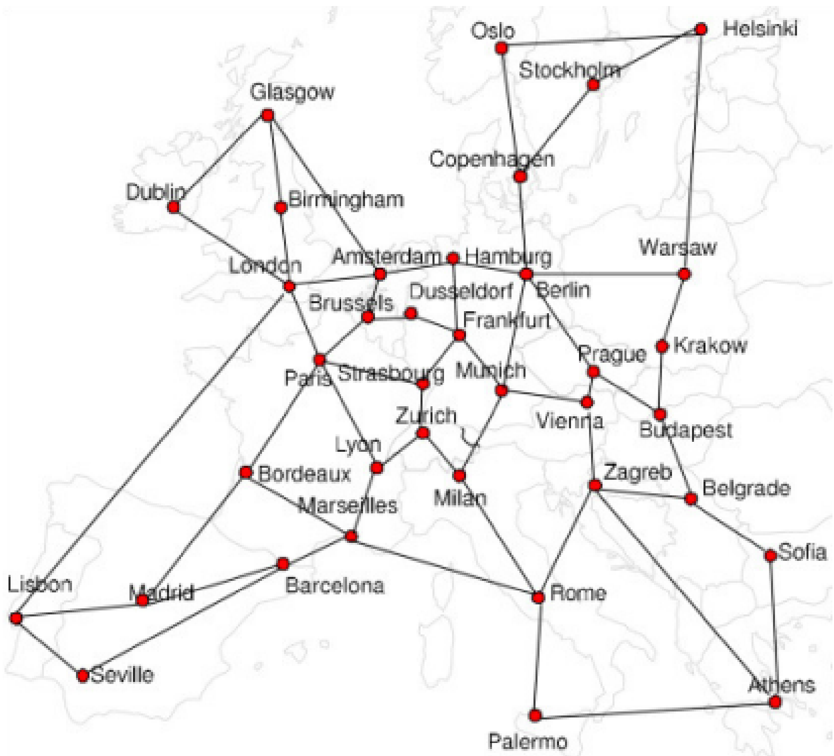

Figure 5.2: PAN_EU network topology

Figure 5.3: USA network topology

5.2 Comparison of Algorithms

For each network topology and traffic scenario different algorithms are evaluated in terms of their performance parameters.

Performance parameters considered in this work are i) Total number of Blocked Bequests (BR) ii) Total number of Bit-rates (Gb/s) Blocked (BB) and iii) Total number of Slots Used in the network (SU). Performance parameters are plotted along X-axis and Y-axis represent values in percentage. With the help of equation 6.1, 6.2 and 6.3 objective parameters are defined.

$$\lambda = \frac{\theta \times 100}{\iota} \tag{5.1}$$

$$\beta = \frac{\mu \times 100}{\tau} \tag{5.2}$$

$$\S = \frac{\omega \times 100}{\sigma} \tag{5.3}$$

where
λ represents: Total number of Blocked Request (BB) in the network.
θ represents: Number of blocked request in the network.
ι represents: Total number of traffic requests in the network.
β represents: Total number of Blocked Bit-rates (Gb/s) (BR) in the network.
μ represents: Number of block bit-rates in the network.
τ represents: Total traffic volume (Gb/s) in the network.
§ represents: Total number of Slots Used (SU) in the network.
ω represents : Number of slots used in the network.
σ represents: Total spectrum in the network.

5.2.1 Random Network Topology

Random network topology is defined with 20 nodes and the average distance between the nodes is 1000km. Two types of traffic scenarios, i.e. homogeneous and heterogeneous are considered.

Homogeneous Traffic

Detailed comparison of different algorithms results for homogeneous traffic scenarios of 50 Gb/s, 100 Gb/s and 150 Gb/s is illustrated in figure 5.4, 5.5

and 5.6. Results show that performance of MHLS is much better as compared to other algorithms. At first, for 50 Gb/s traffic performance for algorithm MHLS: 5.7% is BB, BR and 27.1%SU, for FF: its BB, BR is 6.3% and SU is 28.9% while for MSF: its BB, BR is 9.20% and its SU is 32.30% and for LPF: its BB and BR is 9.40% and its SU is 33.20% as shown in figure 1 (a). Lesser the value of BB, BR, SU, better the performance of algorithm in turn will result in efficient utilization of network resources. As input traffic rate increases to 100 Gb/s and 150 Gb/s, performance of MHLS enhances with approx. 23%, 25% less BB ,BR and with 12%, 14% less SU as compared to FF, MSF and LPF as shown in figure 5.5 and 5.6.

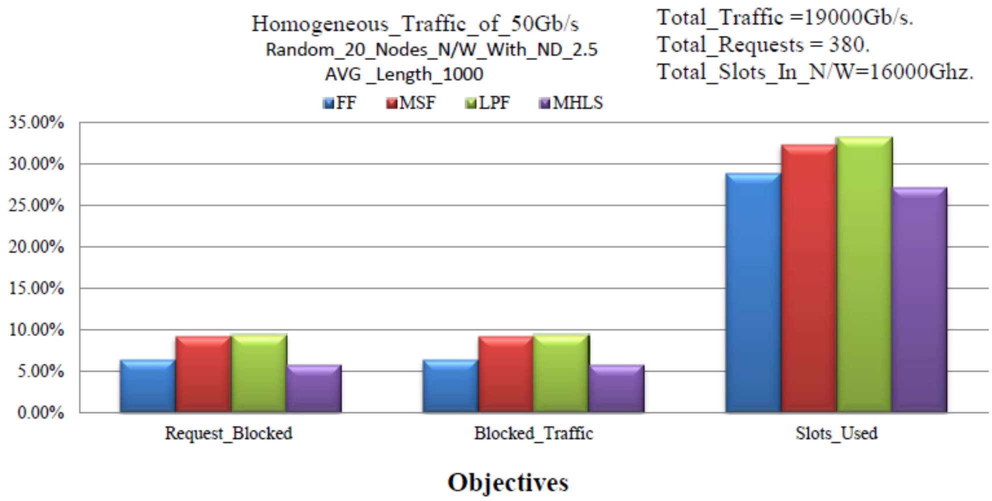

Figure 5.4: Comparison of MHLS,MSF,FF and LPF at 50Gb/s

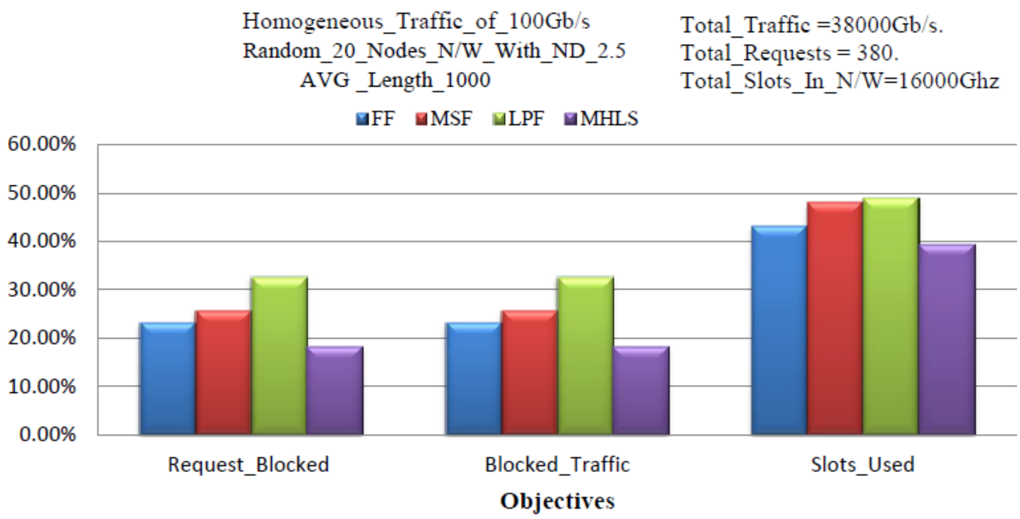

Figure 5.5: Comparison of MHLS,MSF,FF and LPF at 100Gb/s

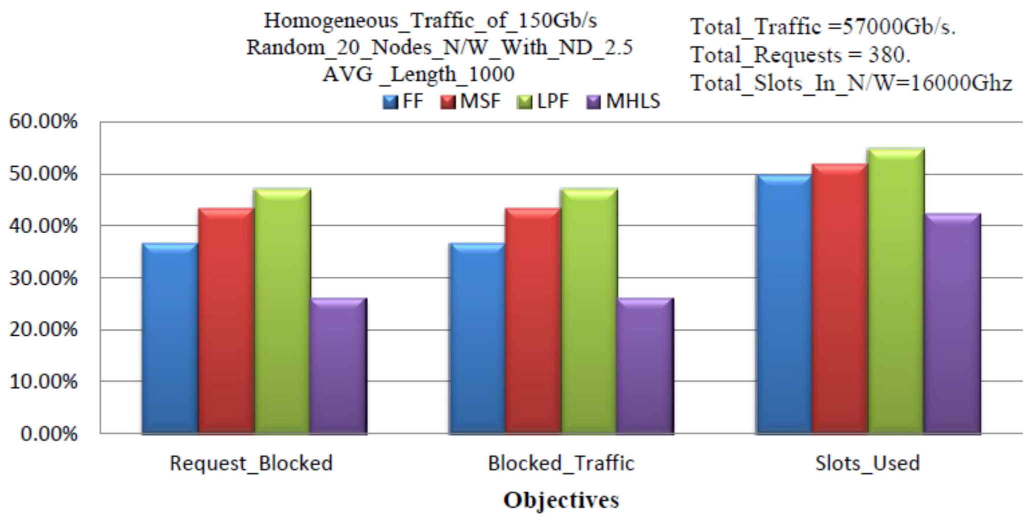

Figure 5.6: Comparison of MHLS,MSF,FF and LPF at 150Gb/s

Heterogeneous Traffic

Figure 5.7, 5.8, 5.9 and 5.10 represents the simulation results of different algorithms for heterogeneous traffic scenarios of 1000 Gb/s, 1500 Gb/s, 2000 Gb/s and 2500 Gb/s. At first, for traffic of 1000 Gb/s, MHLS accommodates approx. 10, 8 and 6% more traffic requests and saving 3, 4, and 6% spectrum as compare to FF, MSF and LPF as shown in figure 5.7. As the traffic rate increases to 1500 Gb/s, 2000 Gb/s and 2500 Gb/s, performance of MHLS improves up to approx. 19, 20 and 18% less BR, 16, 12 and 11% less BB with 9, 10 and 11% less SU as observed in FF,MSF and LPF clearly shown in figure 5.8, 5.9 and 5.10.

It is concluded that for small network topology of 20 nodes if input traffic request is arranged according to ascending order of minimum hops with least slots requirement, it will not only reduce the number of blocked requests but also considerable spectrum will be saved for future accommodation of traffic request. The reason is that MHLS offers better traffic grooming in the constraint environment of continuity and contiguity as compared to others.

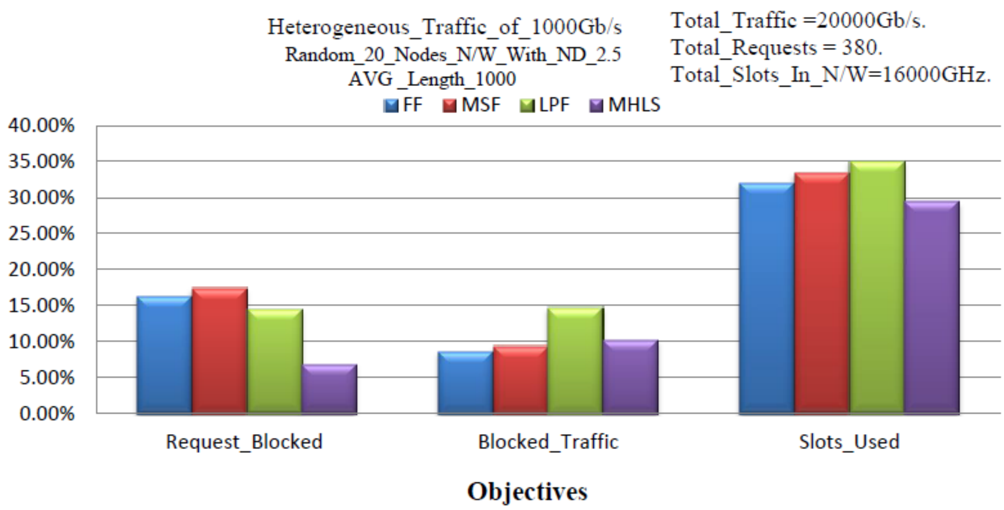

Figure 5.7: Comparison of MHLS,MSF,FF and LPF at 1000Gb/s

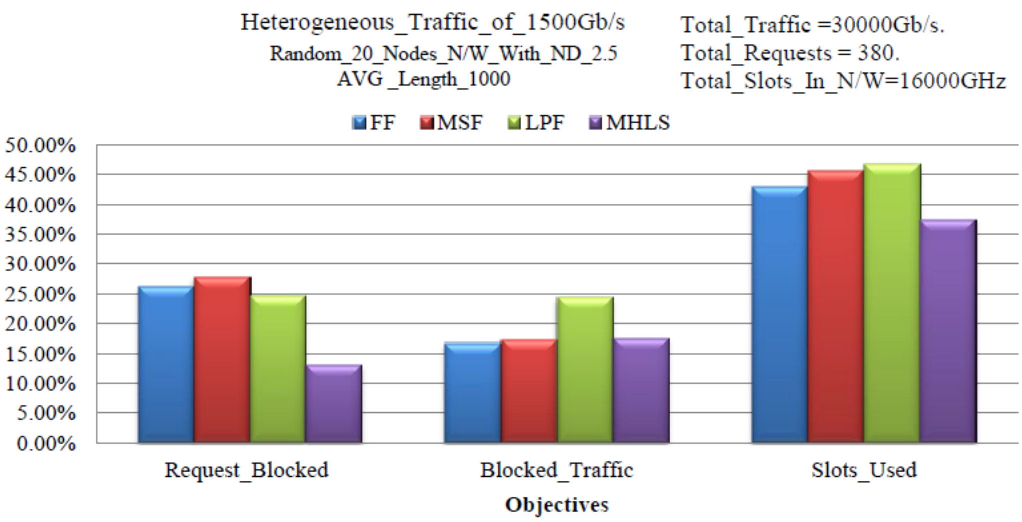

Figure 5.8: Comparison of MHLS,MSF,FF and LPF at 1500Gb/s

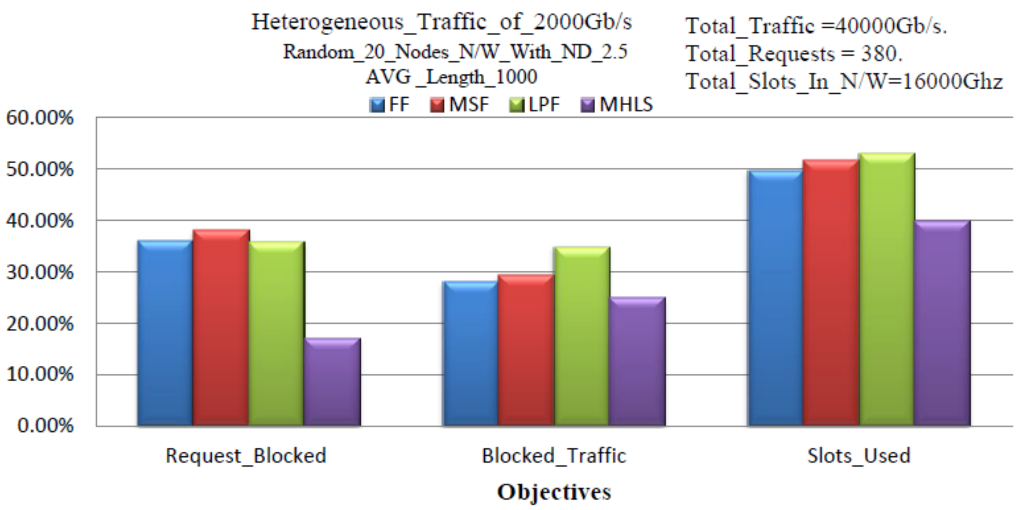

Figure 5.9: Comparison of MHLS,MSF,FF and LPF at 2000Gb/s

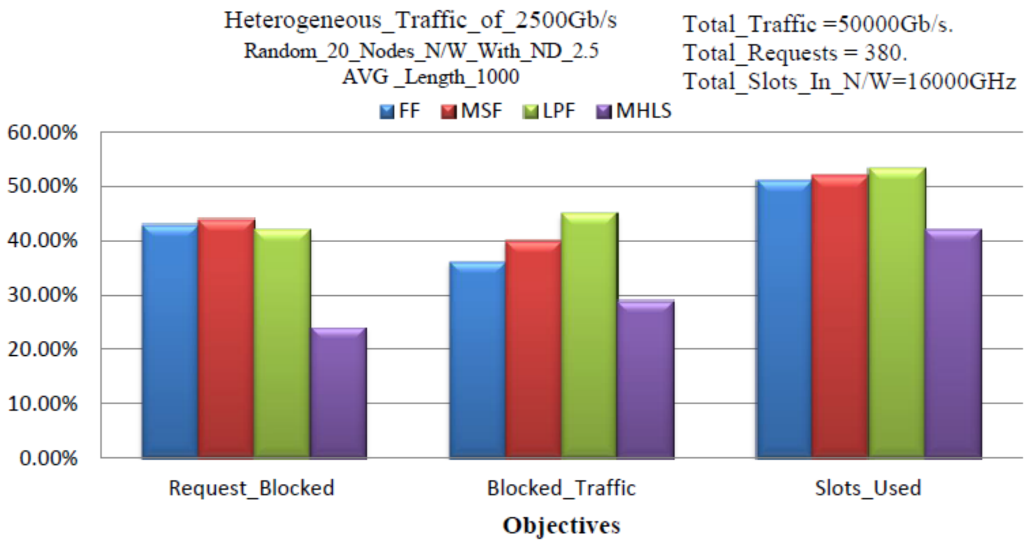

Figure 5.10: Comparison of MHLS,MSF,FF and LPF at 2500Gb/s

5.2.2 PAN_EU Network Topology

Here the real network topology is considered with 37 nodes, distance between the nodes is from 218km to 1977km and 3.08 nodal degree. This permits us to understand which algorithm is superior in real and large network scenarios. Two types of traffic is been considered i.e. homogeneous and heterogeneous.

Homogeneous Traffic

Detailed comparison of different algorithms is represented in figure 3 (a), (b) and (c) for homogeneous traffic of 50 Gb/s, 100 Gb/s and 150 Gb/s. First, for 50Gb/s traffic performance of different algorithm is observed: when the ordering policy is MHLS 8.7% is BB,BR and 45% is its SU, and for FF: BB, BR is 11.9% and 48% SU while for MSF: BB, BR is 22% and SU is 52%, for LPF: BB ,BR is 23.4% with 51% SU, which is clearly shown in figure 5.12. So, in this case, MHLS saves approx. 6% of spectrum and accommodate approx. 15% more traffic requests as compared to other algorithms. For 100 Gb/s and 150 Gb/s traffic, a fair amount of improvement in the simulation results for MHLS can be seen in figure 5.12 and 5.13. Up to 10% less SU and 29% less BB, BR is achieved as compared to benchmark algorithms.

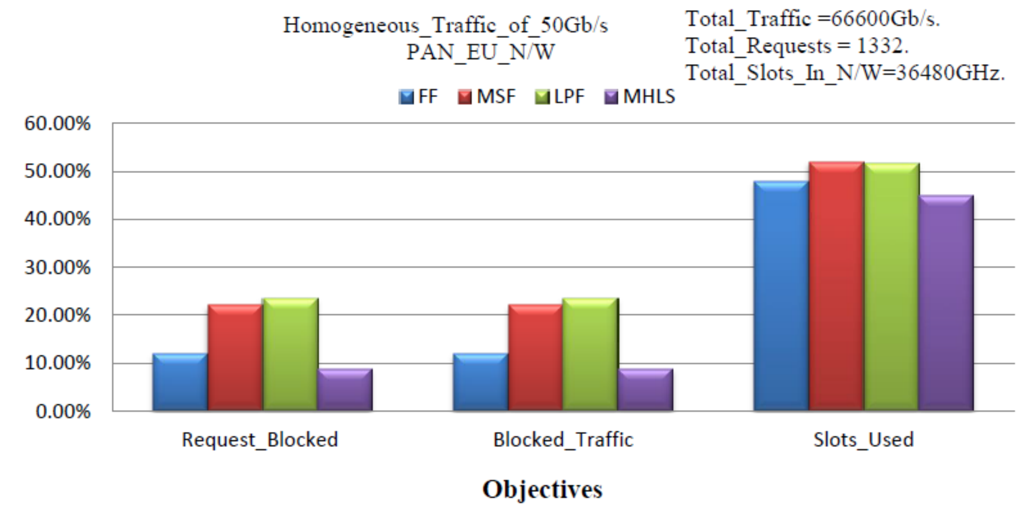

Figure 5.11: Comparison of MHLS,MSF,FF and LPF at 50Gb/s

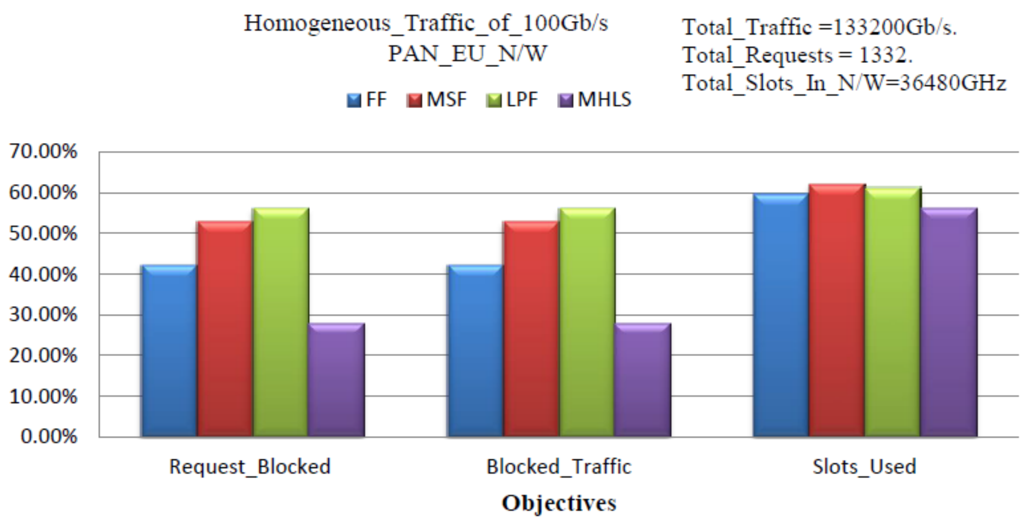

Figure 5.12: Comparison of MHLS,MSF,FF and LPF at 100Gb/s

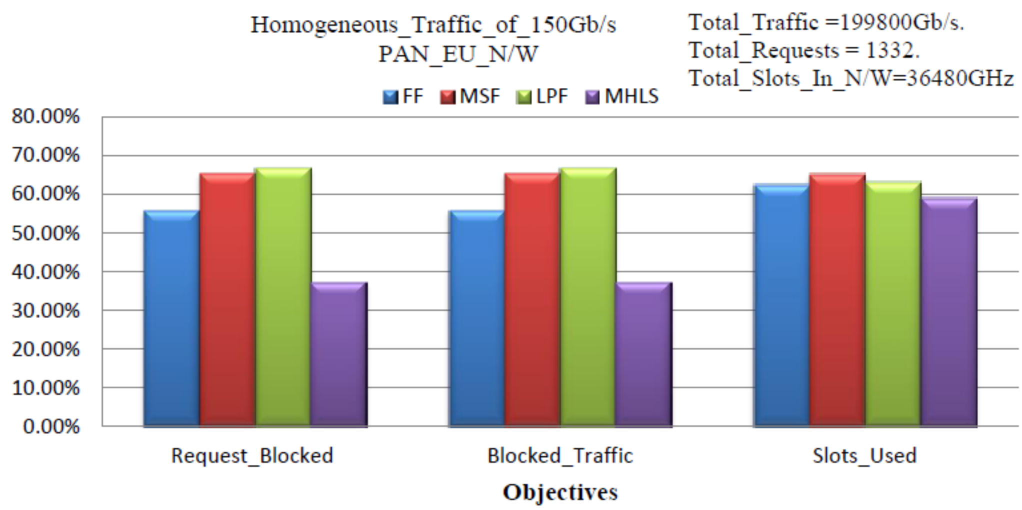

Figure 5.13: Comparison of MHLS,MSF,FF and LPF at 150Gb/s

Heterogeneous Traffic

For heterogeneous traffic of 1000 Gb/s, 1500 Gb/s, 2000 Gb/s and 2500 Gb/s , detailed comparison of results obtained from different algorithms is shown in figure 5.14, 5.15, 5.16 and 5.17. Similar trend is observed as seen in homogeneous traffic scenario. MHLS accommodates approx. up to 21, 25 and 23% more traffic request, 15, 9 and 21% more bit-rates (Gb/s) with 10, 12 and 10% less number of total used slots in the network as compared to FF, MSF and LPF. It is concluded that MHLS outperform all other algorithms in all considered objective parameters.

As traffic rate increases, demands for spectrum increase which in turn demands efficient ordering policies. Due to continuity and contiguity constraints and poor traffic grooming in traditional algorithm FF, MSF and LPF is unable to deliver efficiently as compared to MHLS. MHLS offers better traffic grooming with better ordering policy which enables to accommodate more traffic request and save more spectrum as compared to others algorithm even for large size real optical network.

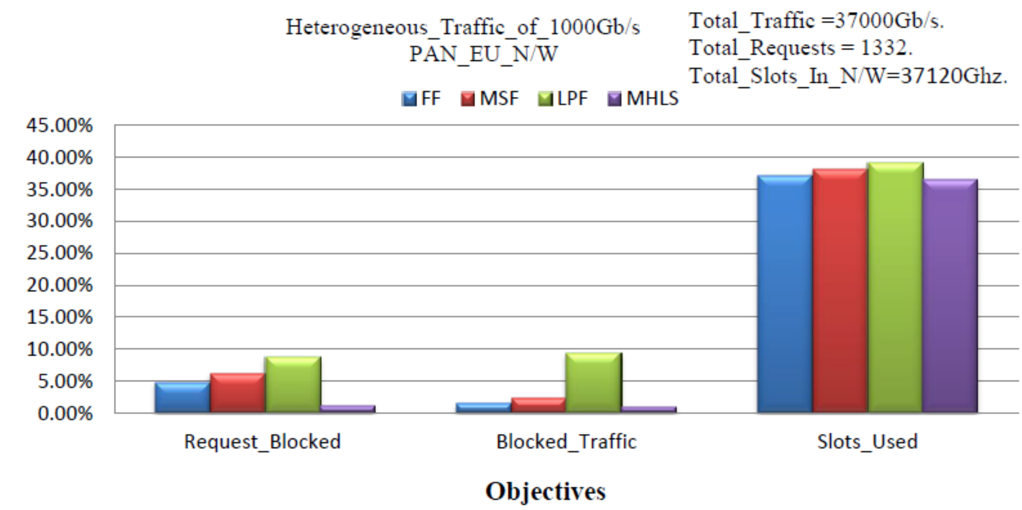

Figure 5.14: Comparison of MHLS,MSF,FF and LPF at 1000Gb/s

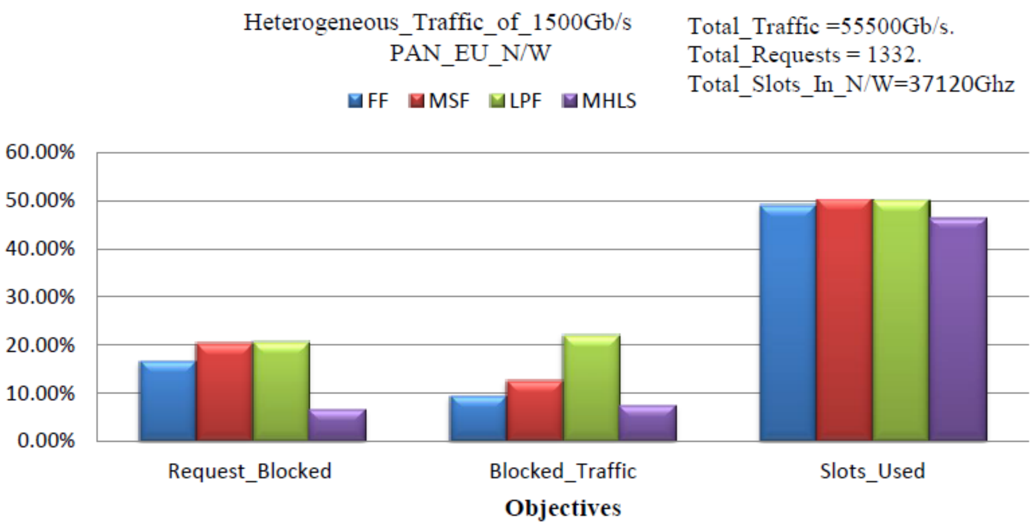

Figure 5.15: Comparison of MHLS,MSF,FF and LPF at 1500Gb/s

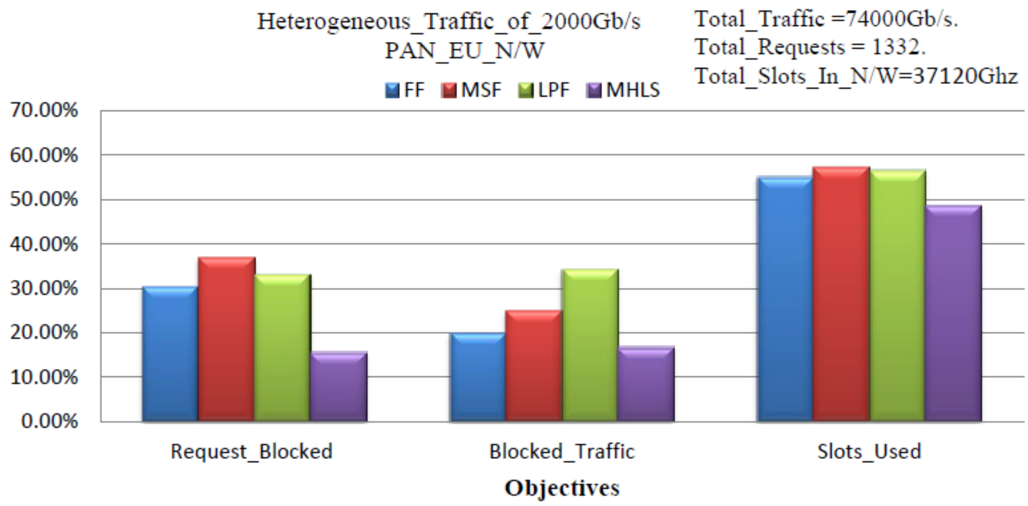

Figure 5.16: Comparison of MHLS,MSF,FF and LPF at 2000Gb/s

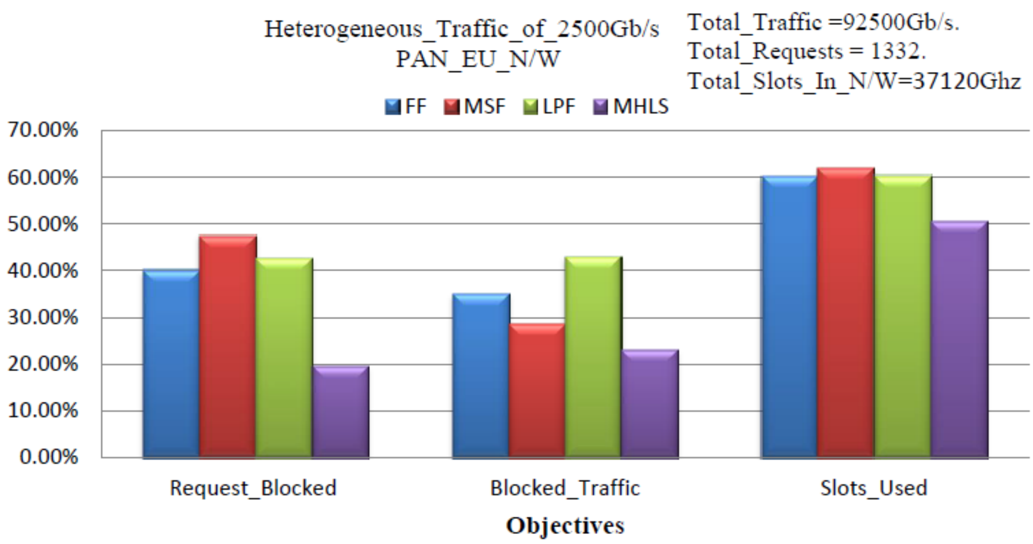

Figure 5.17: Comparison of MHLS,MSF,FF and LPF at 2500Gb/s

5.2.3 USA Network Topology

To get more explicit results of MLHS-RSA algorithm, we are considering USA topology for 40 nodes with distance between nodes ranging from 52km to 2133km and with 2.9 nodal connectivity. Two types of traffic cases; homogeneous and heterogeneous are taken into consideration.

Homogeneous Traffic

Comparison of different algorithm for homogeneous traffic of 50 Gb/s, 100 Gb/s and 150 Gb/s is illustrated in figure 5.18, 5.19 and 5.20. It is observed that similar kind of outcome is obtained as in the previous network topologies. Even for large size network with larger distance between nodes, MHLS still offers fine traffic grooming and prove to be the best ordering policy as compared to others. For traffic of 150Gb/s, MHLS facilities 12.7, 20 and 26 % more traffic requests with 7, 9.3 and 12.3% less spectrum used as compared to FF, MSF and LPF as shown in figure 5 (c). MHLS performs better to all other algorithm.

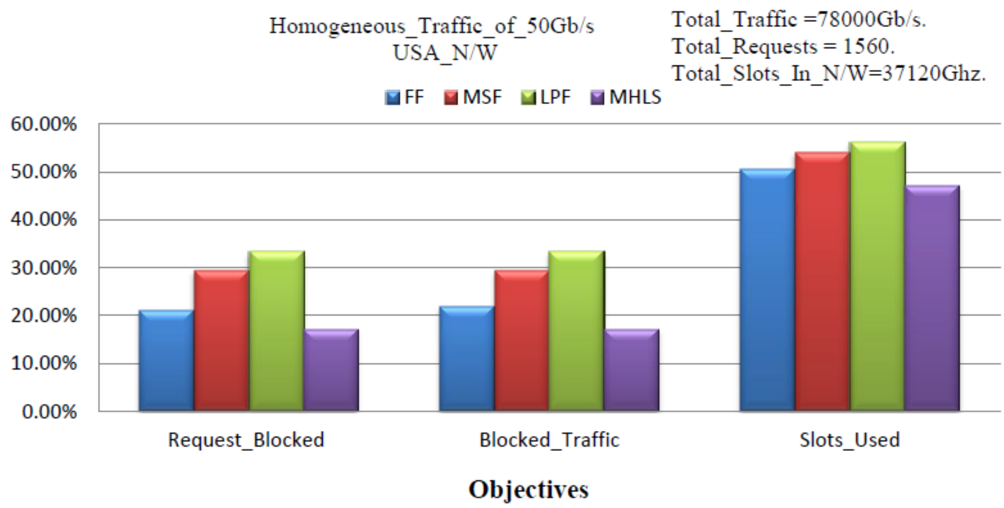

Figure 5.18: Comparison of MHLS,MSF,FF and LPF at 50Gb/s

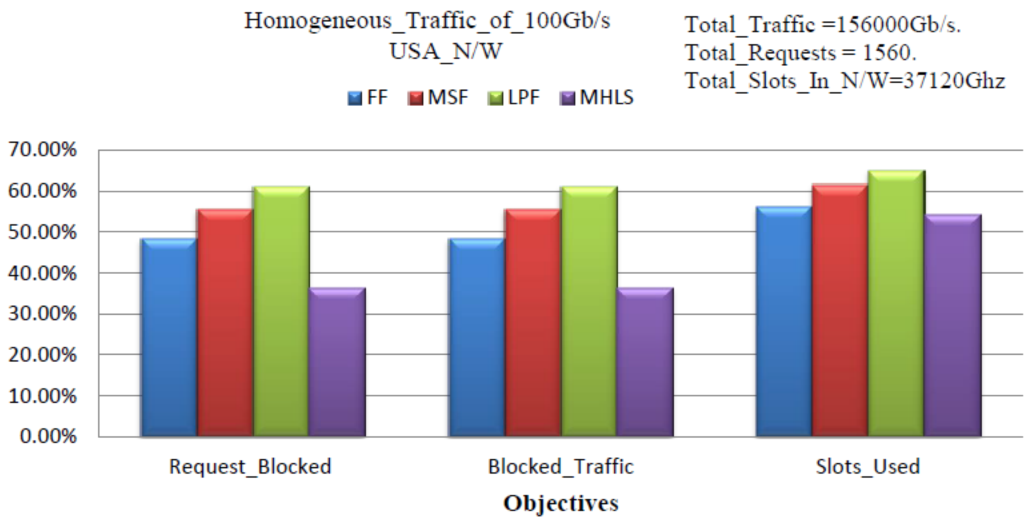

Figure 5.19: Comparison of MHLS,MSF,FF and LPF at 100Gb/s

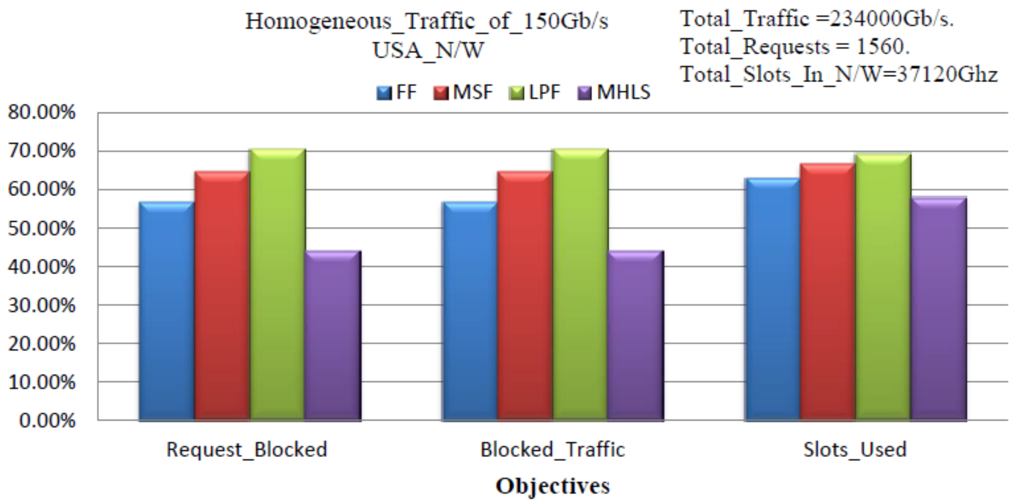

Figure 5.20: Comparison of MHLS,MSF,FF and LPF at 150Gb/s

Heterogeneous Traffic

Different heterogeneous traffic of 1000 Gb/s, 1500 Gb/s, 2000 Gb/s and 2500 Gb/s are considered to examine algorithm performance as shown in figure 5.21,5.22,5.23 and 5.24. It is observed that the algorithm MHLS can accommodate approx. 24, 27 and 25 % more number traffic request 6, 8 and 10 % more number of bit-rates with saving 10, 11.1 and 11.5 % spectrum as compared to others approaches (FF,MSF, LPF).

This proves the superiority of MHLS among all other approaches. Arranging the traffic request in accordance with MLHS algorithm proves to be more efficient even in more complex network and traffic scenarios i.e. network with greater number of requested frequency slots having large number of nodes and links.

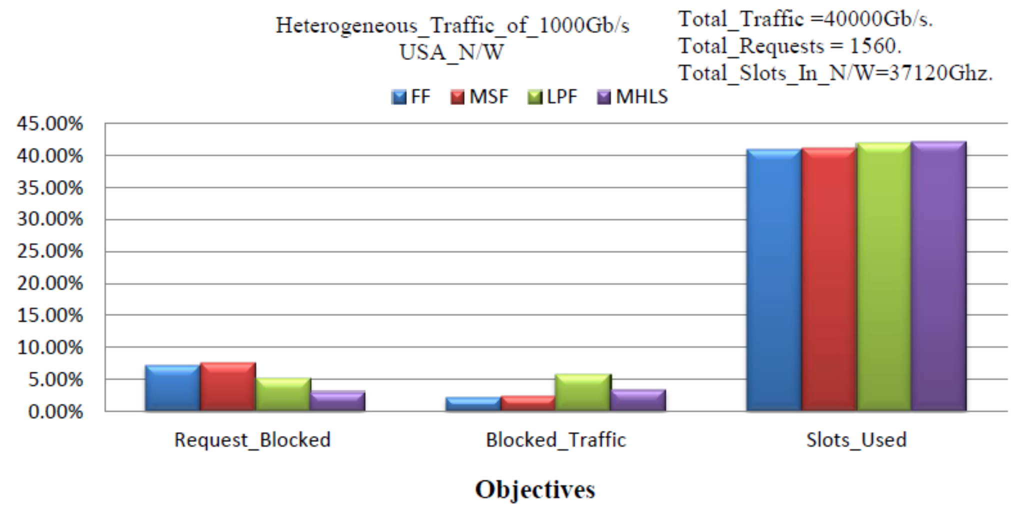

Figure 5.21: Comparison of MHLS,MSF,FF and LPF at 1000Gb/s

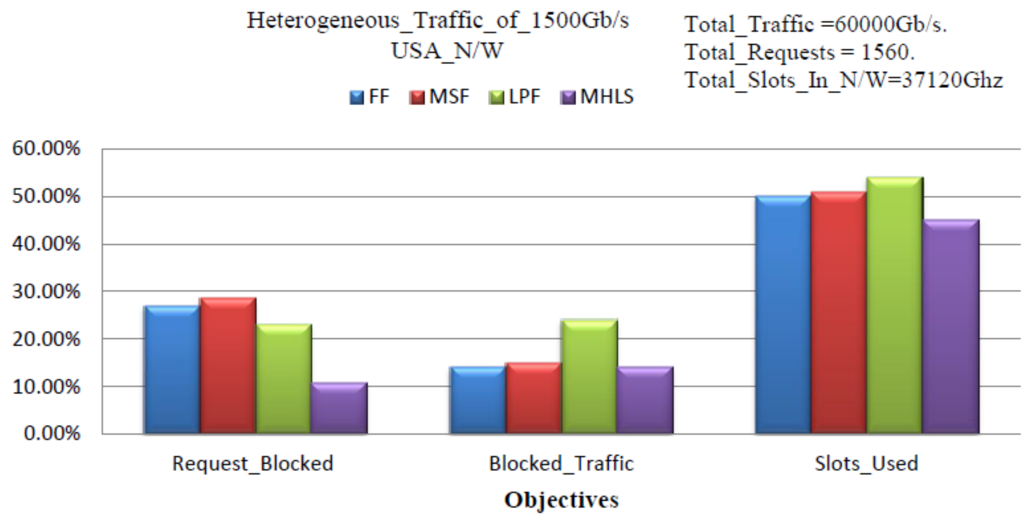

Figure 5.22: Comparison of MHLS,MSF,FF and LPF at 1500Gb/s

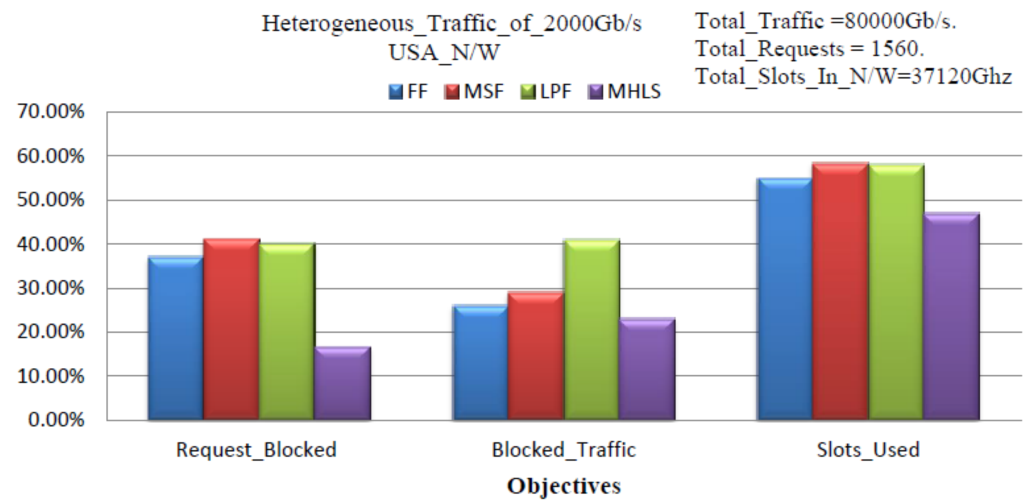

Figure 5.23: Comparison of MHLS,MSF,FF and LPF at 2000Gb/s

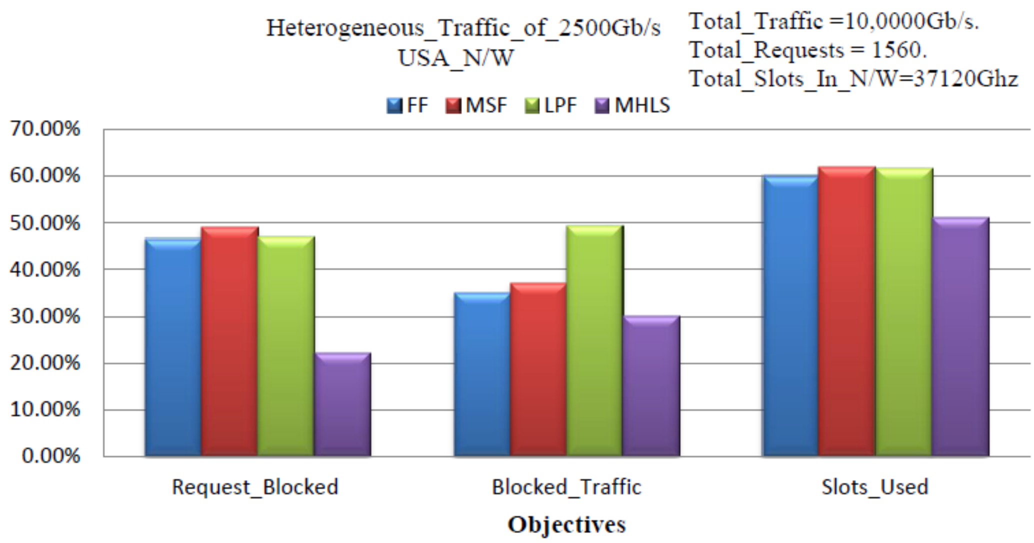

Figure 5.24: Comparison of MHLS,MSF,FF and LPF at 2500Gb/s

5.3 Discussion

Simulation results demonstrate that proposed algorithm MHLS outperformed the benchmark algorithms FF, MSF and LPF in all considered objective parameters (BB, BR and SU).

In MHLS two key parameters are considered that is the minimum number of hops and least number of spectrum slots. Hops and spectrum slots have direct impact on the network resources especially on spectrum. Traffic request with greater number of hops, will have to travel from the greater number of nodes toward to its destination, which eventually add additional hardware cost in the network. Here additional cost means different devices associated with nodes, e.g. transponders, optical cross connectors, routers. Beside this, it also occupies a large portion of spectrum for example, assume that a request required 02 slots to fulfill its demand with a number of hops 04, will occupy total 08 frequency slots on the spectrum. Similar request with 02 numbers of hops will occupy total 04 frequency slots in the network, thus minimum hops save the spectrum. Another advantage of the MHLS is that it reuses the spectrum, it offers better traffic grooming as compare to others. As one ligtpath can accommodate more than one traffic request, which in turn increases the number of served traffic requests and save the spectrum for the future traffic request.

FF algorithm works without any ordering or any specific parameter. It works in a random manner. Its just like first in first serve, the request that arrives first in the network will be serve first. In MSF, one parameter is considered that is a maximum frequency spectrum slot. The request with maximum number required frequency slots are served first in the network, which maximize the spectrum slot usage and the block traffic with respect to the number of requests. While in LPF, distance is used as a parameter. The request with longest path is allocated the spectrum first in the network. Which adapts the smallest modulation format and transmission data rates that results in maximum number of required frequency slots on the spectrum, which eventually needs a large portion of the spectrum to fulfill its request. Occupying a large portion of the spectrum first, has the drawback that is, it increases the blocked traffic requests due to the constraints in the optical network that is continuity and contiguity.

5.4 Conclusion

SPs facing continuous growth in IP traffic volume globally, due to which currently deployed OTN suffer from serious limitation [16] [44]. EON appeared as capable candidate for future deployment option to tackle the diversity and spectrum demanding traffic requests. An important issue arises in designing and operational phase for EON is RSA. In order to exploit the advantages of

EON, an efficient RSA algorithm is required. In this thesis, novel heuristic algorithm MHLS is presented. Goal is to accommodate the maximum number of Traffic Request (BR), minimize the total number of Block Bit-rates (BB) and frequency Slot Usage (SU). To evaluate the performance of MHLS, simulations are conducted for two real (USA, PAN_EU) and one random network topology with varying traffic scenarios. For analysis purpose some traditional algorithms (FF, MSF, and LPF) are used. Results show that MHLS outperforms all referenced algorithms in terms of BR, BB and SU. MHLS algorithm not only maximizes the accommodation of traffic requests but also save some significant amount of spectrum.

In this thesis, we have considered Offline (static) RSA, this work can be extended for Online(dynamic) RSA as well. In future, for the formulation of ILP model and to design meta-heuristic for RSA, MHLS algorithm can be used as a fitness function. It can also be used in cost comparison analysis.

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