

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**MODELING AND FAIR SLOT ASSIGNMENT IN
ELASTIC OPTICAL NETWORKS UNDER DYNAMIC TRAFFIC**



M.Sc. THESIS

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Department of Computer Engineering

Computer Engineering Programme

AUGUST 2019

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**DEĞİŞKEN TRAFİKLİ ESNEK OPTİK AĞLARDA MODELLEME
VE ADİL SLOT ATAMA**

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To my spouse Armin



FOREWORD

This thesis was done at the department of Computer Engineering at Istanbul Technical University. The work was done based on a project (115E834) supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK ARDEB). I would like to thank to my advisor for providing the opportunity to work alongside her on this interesting, yet challenging project. She truly trusted and supported me during my master's program and provided guidance and patience throughout this journey. Finally, I wish to thank my parents Hossein and Roghiyeh , sister Nastaran and spouse Armin for their love and understanding throughout my life. I always knew that you believed in me and wanted the best for me.

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ABBREVIATIONS

ITU	: International Telecommunication Union
WDM	: Wavelength Division Multiplex
RSA	: Routing and Spectrum Assignment
ROADM	: Reconfigurable Optical Add-Drop Multiplexer
WSS	: Wavelength Selective Switch
RWA	: Routing and Wavelength Assignment
SONET	: Synchronous Optical Network
DP-QPSK	: Dual-Polarization Quadrature Phase Shift Keying
DP-16QAM	: dual-polarization 16 quadrature amplitude modulation
RWSA	: Routing, Wavelength and Spectrum Assignment
ILP	: Integer Linear Programming
EON	: Elastic Optical Network
MILP	: Mixed-Integer Linear Programming



SYMBOLS

P_B	: Blocking Probability
b	: Number of slots required by connection
T	: Total number of slots in the spectrum
k	: Maximum number of slots width
M	: Total number of nodes in the model





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MODELING AND FAIR SLOT ASSIGNMENT IN ELASTIC OPTICAL NETWORKS UNDER DYNAMIC TRAFFIC

SUMMARY

In elastic optical networks, the optical spectrum is divided into very narrow bands (slots) and one or more consecutive slots can be used together, instead of thicker and fixed slots defined by the ITU-grid for WDM optical networks. Having the ability to create different bandwidth connections using only the required number of consecutive slots enables more efficient use of network resources. The most fundamental problem to be solved in elastic optical networks is to establish appropriate connections for new incoming traffic requests, known as routing and spectrum assignment problems. Under dynamic traffic conditions, the flexibility to use a different number of slots brings about a new problem called spectrum fragmentation that is not available in WDM networks. In dynamic traffic, over a period of time, the optical spectrum is divided into several free and separated slot groups of different sizes. This may result in blocking of connection requests even though there are free spaces in the spectrum.

Another problem in elastic optical network is the fairness problem, which is due to high bandwidth requests are more likely to be blocked compared to low bandwidth requests.

The main aim in thesis is to examine the problem of routing and spectrum assignment in the elastic optical networks under dynamic traffic and develop new methods for solving the problem. For this purpose, a new graphical model will be developed to model the dynamic behavior of the elastic optical network for spectrum utilization. This model simplifies the visualization of the current state of the network in a graphical form and an appropriate data structure in the memory. The basic concepts of the model are first shown for a single link, then the same idea is used to generalize the model to represent the entire network topology. The use of this model in the routing and spectrum assignment is explained by the update procedures in the structure after the addition or removal of a link. This new model can reduce the time complexity of routing and spectrum assignment methods by providing a data structure that captures the current spectrum of network links.

Using this new model, we designed new effective heuristic algorithms to solve the problem of general routing and spectrum assignment, which proved to be NP-hard. The basic approach is to reduce the probability of general blocking by trying achieve desired fairness with different bandwidth. To solve the fairness problem, we proposed two methods: In Equal Opportunity Slot Assignment (EOSA), we set the slots that are determined by the number of slots needed, and the location of the slot will begin with respect to the predefined sections of whole grid. In the second approach, Nigh-Fairness Slot Assignment (NFSA), this idea has been developed using two different slot assignment methods.

In general, the complexity of the problems prevents the optimal resolution of these except for very small samples.

To evaluate the performance of the proposed methods, we compare EOSA and NFSA with First Fit slot assignment method, which has the best performance in case of blocking probability, on different backbone topologies. The result of comparison shows that our methods achieve desired fairness and improves the performance of the entire network in terms of blocking probability remarkably.



DEĞİŞKEN TRAFİKLİ ESNEK OPTİK AĞLARDA MODELLEME VE ADİL SLOT ATAMA

ÖZET

Elastik optik ağlarda, optik spektrum çok sayıda dar bantlara bölünür ve WDM optik ağlar için ITU-grid tarafından tanımlanan daha geniş ve sabit slotlar yerine bir veya daha fazla ardışık slot birlikte kullanılabilir. Sadece gerekli sayıda ardışık slot kullanarak farklı bant genişliğinde bağlantıları oluşturma becerisine sahip olmak, ağ kaynaklarının daha verimli kullanılmasını sağlar. Esnek optik ağlarda çözülecek en temel sorun, yönlendirme ve spektrum atama problemleri olarak bilinen yeni gelen trafik talepleri için uygun bağlantılar kurmaktır. Dinamik trafik koşulları altında, farklı sayıda slot kullanma esnekliği, WDM ağlarda mevcut olmayan spektrum parçalanması olarak adlandırılan yeni bir soruna neden olur. Dinamik trafik koşullarında, bir süre sonra, gelen ve sonlanan bağlantılar nedeniyle, optik spektrum giderek farklı boyutlarda serbest ve ayrık slot gruplarına bölünür. Bu, spektrumda serbest alanlar olmasına rağmen bağlantı isteklerinin engellenmesine neden olabilir.

Esnek optik ağlar (EON), daha ince spektrum ızgaraları aracılığıyla, spektral kaynakları verimli kullanmak için çok umut verici bir çözümdür. Çoklu bant genişliği servisleri aynı ağ kaynaklarını paylaştığında, uygun bant genişliği yönetimi gerekir. Ayrıca, yüksek bant genişliği isteklerinin düşük bant genişliği istekleriyle karşılaştırıldığında engellenmesi daha olasıdır ve bu da farklı istekler arasında adalet sorununa neden olur.

Bu tezde temel amaç, dinamik trafik altındaki esnek optik ağlarda yönlendirme ve spektrum ataması problemini incelemektir ve problemi çözmek için yeni yöntemler geliştirmektir. Bu amaçla, spektrum kullanımı için elastik optik ağın dinamik davranışını modellemek için yeni bir grafik model geliştirilmiştir. Bu model, ağın mevcut durumunun grafiksel bir biçimde ve bellekteki uygun bir veri yapısının görselleştirilmesini basitleştirir. Modelin temel kavramları ilk önce tek bir bağlantı için gösteriliyor, daha sonra aynı fikir modeli tüm ağ topolojisini temsil etmek için genelleştirmek için kullanılıyor.

Tek bir bağlantı için geliştirilen katmanlı model iki istek modelinde gösterildi, birinci tip $[1, k]$ arasındaki herhangi bir sayıda slot bulunan tek biçimli bir model ve ikinci tip isteklerde ise, bağlantıların bant genişliği ihtiyacı ikinin katları halinde ifade edilebilir.

Geliştirilen model hem statik hem de dinamik yönlendirme ve kanal atama durumlarında, ağdaki slotların belli bir andaki kullanım durumunu temsil etmek için kullanılabilir. Bir ağda gelen bağlantı istekleri belirli bir süre için önceden biliniyorsa, statik yönlendirme ve kanal atama yöntemleri kullanılabilir. Bu durumda ağda çok sayıda bağlantının kurulması için en uygun konfigürasyonu belirlemek için aynı anda tüm bağlantıları ele alabilen optimizasyon yöntemleri kullanılabilir. Ancak bu problem yapısı gereği NP-zor olduğu için tamsayı doğrusal programlama gibi

yöntemler yerine sezgisel algoritmaların kullanılması tercih edilir. Bu tür sezgisel yöntemler ise bağlantıları belli bir kritere göre sıraya dizerek, teker teker kurulması prensibine dayanır. Bu durumda önerilen model ağ kaynaklarının kullanımını gösterebilmesi açısından yararlı olacaktır.

Dinamik trafik durumunda ise, bağlantı isteklerinin ağa teker teker ve rastgele olarak geldiği varsayılır. Gelen bir bağlantı isteği için uygun yolun bulunması ve bu yol üzerindeki seçilen slot gruplarının rezerve edilmesi gerekmektedir. Bunu yaparken sadece ağın o anki durumuna bakılır. Bu nedenle ağ durumunu güncel tutan bir veri yapısı yönlendirme ve kanal atama algoritmalarını hızlandırabilir.

Bu yeni modeli kullanarak, NP yönlendirme zorluğu olan genel yönlendirme ve spektrum ataması problemini çözmek için yeni etkili sezgisel algoritmalar tasarladık. Temel yaklaşım, farklı bant genişlikleri ile istenen adalet sağlamaya çalışarak genel engelleme olasılığını azaltmaktır. Adalet sorununu çözmek için iki yöntem önerdik: Birinci, Equal Opportunity Slot Assignment (EOSA) yönteminde, belirli slot numaralarından başlayan slot gruplarını tahsis etmeyi amaçlamaktadır. Bu sayede slot ataması mümkün olduğu kadar düzenli yapılır. Bir isteğin başlangıç slot numarası, kaç tane slot gerektirdiği dikkate alınarak belirlenir. Bu yöntemin asıl amacı, yüksek bant genişliği isteklerine, onları spektrumda düzgün bir şekilde yerleştirerek daha iyi atama olanakları sağlamaktır. Örneğin, biri 1 slotlu bant genişliğinde diğeri 7 slotlu iki bağlantı isteği, 16 slotlu bir blokta ilk 8 slotun parçası olarak yan yana yerleştirilebilir. Benzer şekilde, 2 ve 6 yarı, 3 ve 5 yarı, ... bağlantılar ayrıca 8 yarıda toplanır. Daha yüksek bant genişliğine sahip bağlantı istekleri için 8 slot, böyle bir tamamlama gerekli değildir. Amaç, yüksek bant genişliği bağlantıları için engelleme olasılığını mümkün olduğunca azaltmaktır.

İkinci yaklaşım olan, Nigh-Fairness Slot Ataması (NFSA), burada yine tüm spektrumunu maksimum genişlikte slot gruplarına böldük. Temel fikir, her grubu iki eşit parçaya bölmektir; birinci kısım EOSA gibi davranır ve ikinci kısım seçilen herhangi bir algoritmayı izler. Simülasyonlarımızda First-Fit slot atamalarını kullanıyoruz. Bir istek geldiğinde, algoritma isteğin bant genişliğinin maksimum genişliğin yarısından daha küçük olup olmadığını kontrol eder ve bu durumda ilk uyan yöntemi kullanılır.

Önerilen yöntemlerin her ikisi de, ağa gelen bağlantı taleplerinin slot numaralarının eşit şekilde dağıtıldığı varsayımına dayanmaktadır. Aslında, slot numaralarının dağılımı biliniyorsa, başlangıç slot numaralarına bağlı olarak farklı atamalar yapılabilir.

Deneyle için farklı özelliklerde (Atamasında, ayrıt yoğunluğu) ağ topolojileri seçilmiştir. Bunlardan ikisi Kuzey Amerika topolojisi (NSFNet ve USNet), ikisi de Avrupa kıtası topolojisidir (COST239 ve COST266). Bu topolojiler, literatürde de benzeri çalışmalarda sıklıkla kullanılan fiziksel ağlardır. Deneylede ağa gelen trafiğin, yani bağlantı isteklerinin Poisson dağılımına uygun olduğu varsayılarak, farklı yoğunluklarda bağlantı istekleri rastgele olarak üretilmiştir. Bağlantıların bant genişliği istekleri slot sayısı cinsinden 1 ile 16 arasında düzgün dağılmaktadır. Ağdaki tüm düğüm çiftleri arasında bağlantı isteği gelme olasılığı da eşittir. Bu seçilen trafik parametreleri, literatürdeki çalışmalar incelenerek ve en çok kullanılan parametreler gözönüne alınarak belirlenmiştir.

Önerilen yöntemlerin performansını değerlendirmek için, EOSA ve NFSA'yı, farklı omurga topolojilerinde, karartma olasılığı durumunda en iyi performansa sahip First Fit slot atama yöntemiyle karşılaştırıyoruz. Farklı topolojiler için yapılan simülasyon

sonuları, ilk yntemimizin, yksek engelleme olasılıđı olan kısmi adalet sorununu iyileřtirdiđini, ancak ikinci yntemimizin, engelleme olasılıđını birinciden daha iyi geliřtirdiđini gstermiřtir. Genel olarak, yntemlerimizin istenen adaleti sađladıđını ve tm ađın performansını engelleme olasılıđı aısından dikkate deđer bir řekilde iyileřtirdiđini gstermektedir.





1. INTRODUCTION

Optical network infrastructure is today's fastest data communication environment used in both backbone and wide area networks and high-speed access networks. By utilizing the advantages of the fiber network, a very high speed, safety, reliability, and noise immunity characteristics that no other physical technology can provide, provides an ideal communication infrastructure for wired networks.

In wide area networks, subsoil and submarine fiber is used to establish network connections between countries / continents, and the transmission of data over the optical medium is achieved by means of optical fiber technology. Besides, nowadays, fiber propagation is gaining momentum in approaching metropolitan or access networks.

The physical infrastructure that provides the operation of the optical network consists of several components: optical switches, transponders and transducers, light splitters and connectors, ROADM and light multiplexers. With these components, it was possible to use the very high transmission capacity provided by the fiber medium. Today, a total transmission rate of ten terabits / s can be achieved on a fiber wire. The high transmission capacity provided by optical networks can be effectively used for data transmission, which is possible by the separation of this very large transmission capacity into a plurality of smaller capacities. This approach is known as WDM (wavelength division multiplexing). The optical spectrum, which is suitable for data transmission, is divided into parallel channels by using fixed grids determined by the International Telecommunication Union known as ITU-grid [1]. The ITU-grid is defined at different bandwidths of 50 GHz, 100 GHz and 200 GHz. Thus, depending on the selected frequency bands, transmission can be performed over dozens of channels, each at 10 Gb / s, 40 Gb / s or 100 Gb / s. Hard ITU-grid and WDM technology have been under investigation for many years.

The ever-increasing speed requirements, applications that require high speed on the Internet, encourage a single channel speed to increase further. The telecom industry

now takes into account speeds of 400 Gb / s or even 1 Tb / s. However, it is not possible for a speed of 400 Gb / s to comply with 50 GHz ITU grid in standard modulation types. On the other hand, achieving this by using different modulations also significantly shortens the optical reach due to the channel noise to occur [2].

1.1 Flexible Optical Networks

With OFDM (optical frequency division multiplexing) technology, which has been developed in recent years, the spectrum can be divided into bands of different widths at the same time [3-5]. This is called the flexible-grid optical network [2]. In flexible optical networks, instead of the fixed broadband ranges determined by the ITU-grid, one or more successive convergence of much narrower bands called slots is used, so that transmission paths at different speeds can be created at different speeds on the carrier bands at the same time. In flexible networks, the unit slot width may be smaller than conventional WDM networks, for example 12.5 GHz or 6.25 GHz [6]. In this way, a wide range of data from low data rates (e.g. 10 Gb / s) to high data rates (e.g., 1 Tb / s) can be used to communicate at speeds as much as required by incoming traffic requests. (Figure 1.1).

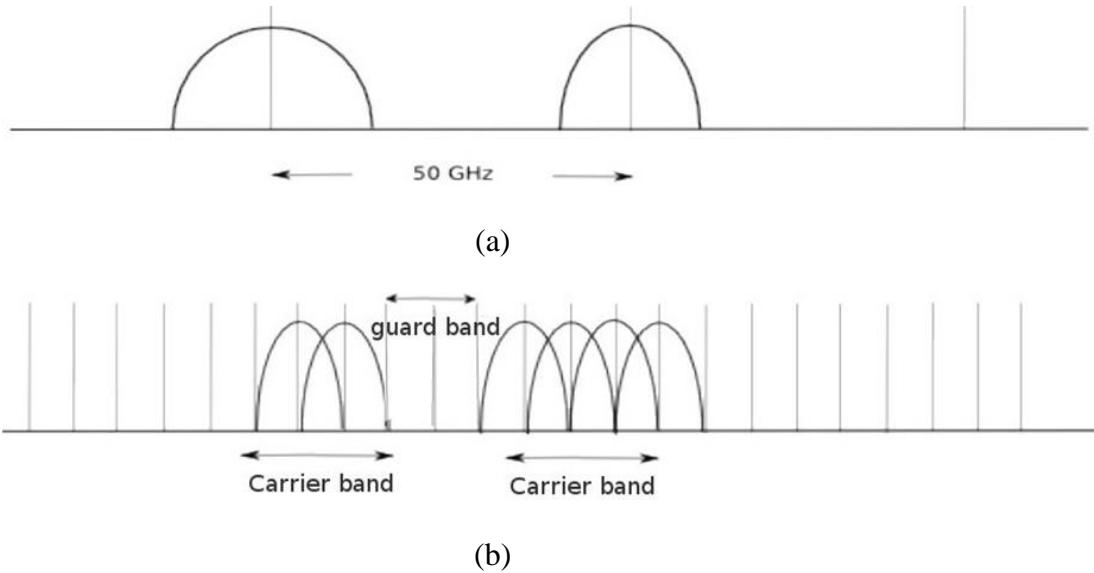


Figure 1. 1 (a)Fixed-grid spectrum allocation (50GHz ITU-T grid). (b) Flexible grid spectrum allocation.

There are some elements that are in the key position in the implementation of the flexible optical network. The first is optical transponders. Optical transmitters enable an electronic sign to be transmitted to the optical signal, that is to say the light at the desired wavelength, so that it can be transmitted along the optical path. Optical receivers detect the light from the optical medium and convert it back into electronic sign. Optical transceiver pairs have long been used in optical networks, but the development of bandwidth-changing transceivers has enabled flexible optical networks. The second important physical component is the switching elements. ROADM (reconfigurable optical add / drop multiplexer) and bandwidth-variable wavelength selective switch (WSS) are required for optical connections to be routed from one fiber to another in intermediate nodes.

The most important feature of the flexible optical network, combining multiple neighboring slots with narrowband, allows the network to be used more efficiently at different speeds, but at the same time it brings important new challenges to the operation and control mechanism of these networks [7]. The most fundamental problem to be solved in flexible optical networks is the establishment of suitable transmission paths for incoming connection requests. To do this, there must be a suitable path between the source and destination nodes on the network topology, and a range of spectrum must be assigned to this path in accordance with the speed of the connection request. For WDM networks, this problem is known as routing and wavelength assignment (RWA). In the case of flexible optical networks, the same problem becomes the problem of routing and spectrum assignment (RSA). The presence of a suitable path for a traffic request and the assignment of a spectrum to suit this path appear to be two sub-problems. However, these sub-problems are not independent of each other; therefore, they must be solved together to find the best solution and by looking at the use of the network's current resources. The RSA problem has been proven to be NP-hard [8]. The RSA problem can be examined under two broad categories.

- A static RSA problem in which all traffic requests are known in advance, and no change is to be assumed for a long time after the optical paths have been established;

- A dynamic RSA problem that the traffic requests come one by one and the path should be set up within a short time after the arrival and the path should be removed at the end of the life time.

As both categories correspond to the scenarios that may be different but valid in the operation of the network, various studies and solutions are proposed in the literature for both of them. This study assumes that the traffic in the network is dynamic, that is traffic requests are not known before and in time, new connection requests come one by one and end after a certain period of time. In such an operating condition, each request must be evaluated separately and the connection should be established in the most appropriate way according to the current situation of the network. Therefore, for every request that comes to the network in dynamic traffic conditions, it is necessary to perform the routing and spectrum assignment by considering an algorithm's operation and the current conditions of the network. If the current state of the network does not allow the incoming request to be met, for example, no path can be found between the source and the destination at the desired speed, or if the slot groups that can provide the desired speed on the path are not continuous between the successive fiber links of the path, the request will be blocked. Therefore, in dynamic traffic conditions, the blocking rate of requests constitutes a key performance criterion. While flexible optical networks allow connections at different speeds using a different number of slots, it is a very important feature that improves network performance, but also leads to a striking problem in dynamic traffic conditions that is not present in traditional WDM networks. this problem is called spectrum fragmentation. Fragmentation occurs when the consecutive slots are dynamically assigned to randomly received links and subsequently released. This is in some respect similar to the problem of fragmentation caused by disk creation and deletion over time. However, the spectrum fragmentation that occurs here is more complex than it causes the use of different spectrum ranges in the different fiber links of the network. Which slots on a fiber are used and which are free may be different from other fiber. Therefore, when attempting to find a path for a connection, it is also necessary that the same spectrum range on this path, ie the slot group, will be idle, because of that the spectrum fragmentation affects the overall performance.

Depending on the structure of the spectrum fragmentation, there may be a problem that a connection cannot be established, even though there is sufficient resources in

the network. Two types of fragmentation are described in the literature. In horizontal fragmentation, although each fiber along the connecting path has a free spectrum of sufficient width in each fiber, the same spectrum part may not be released from the source to destination. For example, if the spectrum slots are numbered from 0 to N-1, and a new connection request requires sequential 8 slots to be separated, 8 slots are free on a fiber starting from the slice 15 and 8 slots on the next fiber starting from the slice 27 may be free. This connection will be blocked as the same slots must be used along the path in the flexible optical network. The problem is that, although there is a spectrum range of sufficient width, this range does not show continuity along the path.

Another type of fragmentation is vertical fragmentation. In this case on a fiber, in total there are enough free slots, but these slots are located in non-adjacent parts. For example, when a connection request that needs to be separated is 8 slots, only one of the fibers on the path is located in 5.-7. slots and 17.-21. get slots free. Although there are eight slots in total, the connection request will be blocked because they are not in successive order.

In flexible optical networks, it is recommended that RSA algorithms should be designed to prevent fragmentation as much as possible, or run defragmentation algorithms at regular intervals, for example after a certain number of connection requests are received. The methods proposed in the literature summary section are examined in detail.

1.2 Traffic Grooming and Flexible Optical Networks

In conventional WDM networks, an optical connection is established for each traffic request. These connections are called light path. The light paths have constant speeds (such as 100 Gb / s) because the optical spectrum is divided into equal bandwidths by the ITU-grid. If the incoming traffic requests are at lower speeds (such as 10 Gb / s, 40 Gb / s), part of the capacity of the light path cannot be used. In cases where there are traffic requests with different speeds on the network, traffic grooming method is proposed in order to make more efficient use of network resources. Traffic grooming can be applied if nodes in the network have grooming switches. Its logic is based on the fact that traffic requests at different speeds in the network are groomed

together on light paths with greater speed. This problem is addressed together with the problem of routing and wavelength assignment and is a difficult optimization problem.

The problem of traffic grooming in WDM networks was first proposed in metropolitan public networks and is one of the features of the SONET network. However, the concept of grooming was then applied to wide area networks with general topology [9]. For a long time, research is being done on this subject and an important literature has been formed. Some of the questions aimed at how traffic grooming will be done, which links will be assigned together, finding ways and which nodes will be capable of traffic grooming.

In flexible optical networks, potentially, an optical connection can be established for each traffic request with the capacity corresponding to the speed of the request. In this case, you may be asked why traffic grooming is needed. However, in detail, in flexible optical networks there is no linear increase relation between the speed of a connection and the width it occupies on the spectrum (Table 1.1). For spectrum use, for example, while a spectrum interval of 35 GHz, including a guard band, is required to establish a connection at a speed of 40 Gb / s, a spectrum interval of 85 GHz is sufficient for a connection at a speed of 400 Gb / s [2, 10].

Table with single row and centered columns.

Table 1.1 The speed of sample traffic requests and the required bandwidths.

Speed of traffic request (Gb / s)	Modulation mode	Bandwidth (GHz)
40	DP-QPSK	35
100	DP-QPSK	47.5
100	DP-16QAM	35
400	DP-QPSK	85
	or DP-16QAM	
1000	DP-QPSK	200
	or DP-16QAM	

The magnitude of the spectrum interval to be used here also affects the modulation format to be used for data transmission and the length of the connection. Considering these factors, it can be summarized with two points why traffic grooming will increase the spectrum utilization efficiency

- The grooming of multiple traffic requests on a high-speed single optical path will enable the use of a lesser range of spectrum than the individual optical link for each request.
- For each optical path, a guard band must be held between the adjacent connections on the spectrum. Reduction of the number of connections reduces the number of guard bands, thus reducing the spectrum rate that cannot be used for data transmission.

When the traffic grooming problem is added to the routing and spectrum assignment problem in flexible optical networks, the optimization becomes an even more difficult problem, regardless of whether the traffic is static or dynamic. There are few studies on traffic grooming for flexible optical networks. In this thesis, proposed linear integer programming (ILP - integer linear programming) and heuristic methods are summarized in the literature summary section and new approaches to the solution to be introduced in this thesis are explained in the method section.

1.3 Purpose of Thesis

The aim of this thesis is to examine the problems of routing and spectrum assignment in flexible optical networks under dynamic traffic conditions and to develop new methods to solve the problem. The purpose of this study is to develop a graphical structure which effectively models the dynamics of the flexible optical network and uses effective heuristic algorithms to solve the general routing and spectrum assignment problem, which has been proven to be NP-completed using this new model. In addition, the problem of fragmentation in the network over time is examined. In order to evaluate how the performance can be increased in case of spectrum assignment and traffic grooming problems, observations were made to shed light on future studies The Rest of this thesis is as below:

In the rest of the current chapter, studies in the literature about routing and spectrum assignment, fragmentation and fairness in elastic optical network are discussed in detail.

Section 2 is about modeling of flexible slot assignment, a new spectrum usage model has been created. This model reduces the complexity of the system and provides a dynamic data structure to represent the spectrum. It has been shown that the model

will introduce significant acceleration in routing and spectrum assignment algorithms.

Section 3, Studies on methods to reduce fragmentation on spectrum and increase fairness for different requests are discussed. In this thesis, new spectrum assignment methods proposed.

In Section 4, Simulation of the model and implementation of the methods are explained. An important part of the thesis is the preparation and testing of a simulation code using the model.

In Section 5, different routing and wavelength assignment algorithms were tested on the simulation and the differences in the rate of blocking between different bandwidth connections are presented and methods to reduce this difference are discussed.

Finally, in Section 6, the thesis is concluded and possible future work are discussed.

1.4 Literature Review

Initial work on flexible optical networks was published in 2009 [3]. In these studies, how the technological components required for the implementation of the flexible optical network will be studied, the SLICE transceiver model, the test environments and the experiments in the physical layer were examined. The flexible optical network model has been introduced using wavelength multiplexers that can change the bandwidth, and the changes that this technology will create in wide area networks are discussed [4, 11].

1.4.1 Routing and spectrum assignment

In parallel with the technological studies related to the flexible optical network [5, 12-14], studies have also begun on the algorithms to be developed for the use of the features of the flexible network [15, 16]. The development of new methods of routing and spectrum designation for the efficient use of this new technology has been the basis of the first studies to demonstrate the performance of these methods under different traffic assumptions.

Studies on the RSA problem can be divided into two basic groups: Static RSA and dynamic RSA.

1.4.1.1 Static routing and spectrum assignment

The static RSA problem takes the physical properties of the network as input, and a group of traffic requests that are already defined. The aim is to direct these traffic requests to the minimum use of resources in the network and to assign a spectrum range of sufficient width to each request. In this problem, the assumption that all traffic requests are already known may be valid if the traffic requests on the network continue to stay on the network for too long after installation. In addition, the static RSA problem model is a starting point for other problems because it is the most fundamental problem to be solved in the flexible network. Therefore, the solution of the static RSA problem is studied extensively.

Since the RSA problem is NP-problem, it is very difficult to resolve optimally except for very small samples (with a small number of nodes, eg 6 nodes). Therefore, in these studies, it was aimed to approximate the ILP formulation by using different techniques or to determine lower bounds. In addition, two intuitive methods have been proposed in these studies. SPSR (shortest path with maximum spectrum reuse) uses the first-fit spectrum assignment method. Traffic requests are handled one by one in order from the highest speed to the lowest speed. The second heuristic method is BLSA (balanced load spectrum allocation). In another study [17] is based on the assumption that the speed of traffic demands changes over time. In this kind of traffic model, it was investigated how RSA problem could be solved and various algorithms were proposed. This makes the problem more difficult by adding a different dimension to the problem. The assumption that over time links may have more or less speed requests can be used to model periodic bulk data transfers between some applications or data centers.

In another study, as another type of RSA problem, routing, wavelength and spectrum assignment (RWSA), again by using the ILP formulation [18], tried to dissolve this problem [19]. This study assumes that the network, only allows connections at certain speeds (10/40/100/400 and 1000 Gb / s). The RWSA problem was shown to be a generalization of the RWA problem and the ILP formulation was solved for a small network (6 nodes). For this reason, RWSA problem has been solved by sub-problems and it has been tried to be solved by dynamic programming and various heuristic algorithms. Examining the problem of static routing and wavelength / spectrum assignment under the assumption that the network has both fixed-grid and

flexible-grid spectrum allocation at the same time [20], and based on the assumption that there will be gradual transition from WDM networks to flexible optical networks, it aims to solve the problems in this transitional period.

Studies using routing-based ILP approach the problem, assuming there are k predetermined paths for each traffic request, in this way, the simplification of ILP is aimed [21, 22]. Similar decomposition methods were applied in these studies and the problems of routing and spectrum allocation were solved separately from each other in a sequential manner. In fact, as the subproblems are interconnected, it is very difficult to find the best solution in this way, but because simple heuristic algorithms are easier to develop, sub routing is a preferred method in many studies.

1.4.1.2 Dynamic routing and spectrum assignment

The second group of RSA studies is based on the assumption that the traffic is dynamic. According to this model, traffic connection requests come one by one, stay in the network for a certain period of time and end when the life time is over. In this case, when each connection request is received, it is necessary to set up an appropriate path and assign the spectrum interval. Thus, network resources are used dynamically and some resources are used at a certain time while others are free, resource usage status changes continuously over time.

Due to the real-time problem, the algorithms used for the solution of the dynamic RSA problem are expected to be simple and give quick results. The proposed solutions for dynamic RSA can be divided into two groups: One-step methods aimed at solving the problems of routing and spectrum assignment together and two-step methods for solving each other separately.

In two-step methods, the approach is first to determine the alternative routes between the source and destination for each possible traffic request and arrange these candidate paths in a certain order, Then start the path at the beginning of the list to determine if there is a suitable spectrum range. The first step here can be solved offline before traffic requests arrive, so that the candidate paths for each pair of nodes in the network can be determined in advance and kept in a table [23]. In this case, the number of alternative routes determined between pairs of nodes is an important parameter affecting performance. The problem of determining the range of spectrum in the second step needs to be solved online after the traffic request has

arrived. Generally, simple heuristic methods, first-fit [23] or random-fit [24] methods are used to make quick decisions. In addition to these methods, a method which aims to determine the optimum spectrum interval by using an evolutionary algorithm has been proposed and the performance of this method has been shown to be better than the first-fit spectrum assignment method [25]. [26] proposes Spectrum Continuity, a multi-purpose routing algorithm that conforms to various constraints, such as the transmission distance of the connection for the routing problem.

Different approaches can be used to the first-fit method in the spectrum assignment. One approach is to first, route the link through the shortest path then to find a suitable spectrum interval along the path by the first-fit method. Another method is finding the k shortest path (with the KSP algorithm) then search for the desired spectrum width along each path [23]. The second method increases the chance of success since all the alternative k pathways are tried until the spectrum range is found.

In single-step methods, sub-problems of routing and spectrum assignment are solved together and greedy algorithms are mostly used for this purpose. In a study using this method [27], three heuristic algorithms, Greedy-RWSA, SP-RWSA and K paths-RWAS, were proposed and complexity and performance analyzes were given. An important part of this study is to create an auxiliary graph representing the current state of the network and to make the path finding on this graph. In the study that proposes two different one-step RSA algorithms [23], a modified Dijkstra algorithm is used to check whether the spectrum in each new link to be added to the path has the desired band. The second version of the algorithm aims to find the least cost route on alternative routes. Another study using a similar modified Dijkstra algorithm is [28].

1.4.2 Fragmentation

Fragmentation-aware RSA algorithms aim at increasing performance of the blocking and spectrum usage while solving the problem of routing and spectrum assignment. The main difference is that when solving the problem, they first define criteria that can show the amount or degree of fragmentation in the network and try to find the path and spectrum interval using these criteria. One of the criteria used is the utilization entropy [29]. These criteria measures vertical fragmentation on a link by

counting and normalizing the number of neighboring slots in different use cases (in use or free). A similar criterion to measure horizontal fragmentation, is defined by following a slot along a path and counting the state transitions whether or not the neighbor is in use. Another criterion used is the "fragmentation rate" [30]. This ratio is calculated by considering the number of slots available on the links and the size of the largest number of consecutive slots in the free state.

Fragmentation-sensitive methods can be examined in two groups as fragmentation prevention and fragmentation corrector.

In case of fragmentation prevention methods [31, 32], when the connection request comes, it is attempted to assign the spectrum and route to prevent or minimize fragmentation. The main reason for fragmentation in flexible optical networks is the ability to establish connections at different bandwidths, [32] thus comparing four different spectrum assignment methods. In the full sharing method, the entire spectrum can be used by all connections according to the first-fit method. In semi-partitioning, if the bandwidth of the connection request is low, starting from one end of the spectrum and if the bandwidth of the connection request is high, the assignment is made from the other end of the spectrum. In the dedicated partitioning method, the spectrum is divided in a strict manner according to the bandwidth, and each connection request is directed through the spectrum in the section according to the bandwidth. In fact, it is intended to eliminate the fragmentation at the same velocity by grouping the links in the spectrum. Finally, in the shared partitioning method, high-speed connections are allowed to share the partition of low-speed connections. In the study, it is shown that the performance of the last two methods is better than the previous two in terms of preventing fragmentation.

In another similar study [33], it is recommended that the spectrum be divided into a number of successive slot groups and that each slot group is separated into a pair of source-arrival node. Thus, each node pair is dedicated slot groups. Any slots that not allocated for any pair of nodes can be shared between incoming requests. It has been proposed in the study, two heuristic methods [34], which make the decision of spectrum assignment according to the current fragmentation status of the network. The Maximize Common Large Segment (MCLS) algorithm proposed in the [35], finds candidate paths for a connection and examines the slots used in the links on these paths. The method basically aimed at, if the desired connection is established

on which alternative route, guarantee the existence of more slot groups on the paths and neighbors in the new state of the network, which still indicating continuity property.

In a study aimed at preventing fragmentation depending on the distribution of traffic [36], It has been proposed to assign to links in the best possible way using probability rules of spectrum sources. In this way, it is aimed to reduce the blocking probability. In this study, which uses only fixed routing algorithms, a spectrum range of a given size (called a block in the study) has been defined as the expected capacity-EC, which is used in the proposed RSA algorithms.

The purpose of the methods of eliminating fragmentation is to perform defragmentation periodically, taking into account that fragmentation is inevitable in dynamic traffic. In spectrum defragmentation, the aim is to modify the assigned spectrum of the existing connections to bring together the unused spectrum intervals in the links as much as possible, thereby increasing the number of consecutive slots in the free state. This arrangement is expected to reduce the probability of new future connection requests being rejected due to lack of resources. Spectrum defragmentation can be followed by two different strategies: periodic and connection triggered. Periodic defragmentation methods are run after a certain time or when a number of connection requests are received to the network. Since periodic defragmentation covers the entire network in general, there is the possibility that most of the connections in the network will be affected or even short-term interruption. For methods triggered by the connection, if a suitable path and spectrum are not found for a new connection request to the network, it is intended to defragmentation the relevant links. Because the editing will only be on a group of links, the overall network is not expected to be affected. As a local defragmentation is made, the positive effect will be limited.

A study reviewing the network fragmentation problem is given in the [19]. One of the recommended methods is to use the least number of slots as a result of the new arrangement when performing spectrum defragmentation. However, this method can only be implemented with an offline algorithm and it is not considered how the existing connections will be affected. In the same study, the second proposed method is to minimize the number of interrupted connections. The problem was formulated with ILP and also heuristic approaches were proposed.

In another study [28], a link-triggered method was proposed. When a new connection request is received, an RSA algorithm is executed first, if the appropriate path and spectrum range for the new connection cannot be found, the defragmentation algorithm is activated. It is aimed that the existing connections on the selected path will be affected minimum during the defragmentation. The proposed heuristic method was designed using the GRASP (greedy randomized adaptive search) technique. In another similar study [37], a heuristic algorithm has been proposed which aims at minimizing the number of connections affected by defragmentation. Another connection triggered by the connection [38] uses an auxiliary graph in the design of the decomposition algorithm. The problem is tried to be solved by reducing the problem of finding the maximal independent set on this graph.

[39] proposes a two-step spectrum defragmentation method. If the path assignment for an incoming connection request cannot be made, the spectrum range is determined in the first stage by an heuristic algorithm to cause the least conflict on the path. In the second stage, the problem of assigning the new spectrum range, to the connections to be affected by the change, is modeled as a bipartite matching problem. If perfect matching can be found, the existing links are moved to the new spectrum ranges and the new connection request is first assigned to the selected spectrum range.

It has been proposed by a study [40] that is triggered by the connection but aims to select the most appropriate spectrum defragmentation time. It is aimed to increase the usefulness of spectrum defragmentation. For this purpose, two metrics have been defined, including the spectrum integrity on the link and the spectrum integrity across the network. In another study, it is aimed to develop algorithms that can decide when, how and on which links to apply the spectrum grooming [41]. It has been shown here that only about 30% of the connections in the network can be reduced the connection blocking rate by redirecting.

A number of hitless spectrum defragmentation methods have been proposed by [42]. This study is based on the HOPS (hitless optical path shift) technique proposed by [43]. One of the recommended methods is that when a connection in the network is terminated the other connections on the links which the terminated connection is passed, move as far as possible to one side of the spectrum,

so as to leave the other side of the spectrum as empty as possible for future connection requests. In another algorithm, a simple heuristic RSA algorithm is run when a new connection request is received, and if the connection cannot be established, spectrum defragmentation is made on the path. Another hitless spectrum defragmentation method is proposed by [44]. In this study, spectrum defragmentation was shown experimentally and it was discussed how to adapt OpenFlow protocol. Another hitless defragmentation has also been proposed by [45]. In this study, two different spectrum retuning methods were compared: spectrum sweeping and spectrum hop. As a result of the simulation studies, it has been suggested that the spectra technique gives better results in terms of network performance.

1.4.3 Fairness in elastic optical network

In general, the blocking probability of a request depends on the amount of slots requested, so requests that require more slots are more likely to be blocked than low slot requests. The reason for this problem is spectrum contiguity, which makes it difficult to find a large number of idle adjacent slots compared to finding a few idle adjacent slots. The fairness problem in EON has been studied in several studies [46-48]. In [46] the authors follow an additional performance indicator to measure the level of fairness experienced by two types of demand, each requiring a different spectrum bandwidth size. the proposed method is two-rate EONs, in which the solution is to divide the slots into two groups. One group is for one slot requests, and the other is for n-slot requests. In [47] Elastic optic networks address different types of traffic services fairness and accordingly, a fairness sensitive spectrum allocation scheme was proposed. This study proposes two methods for the problem, Progressive Allocation & Dynamic Reallocation (PADR) and another algorithm that can minimize the blocking probability, Partial Sharing, Progressive Allocation & Dynamic Reallocation (PSPADR). The proposed method in [48] is routing based trunk reservation which some trunk reservation algorithms are used and added some constraints for requirement of a continuous slots. In this paper we proposed two methods for this problem, by setting start slot for requests. It is expected that by reserving slots for each request individually while increasing fairness it has significant impact in reducing the blocking probability.

1.4.4 Grooming

The first group of studies [49, 50], which aims to solve the problem of routing and spectrum assignment by taking traffic grooming, represents the problem with MILP formulation [51-53]. The objective function of optimization is to minimize the total number of slots used on a link. However, in dynamic traffic, fast-running heuristic methods should be preferred because it is necessary to address the problem online. In the first study [51], ring-structured topologies were considered and an ILP formulation was designed. In addition, two heuristic algorithms, one aiming to reduce the amount of spectrum used and the other to reduce the number of used transceivers, have also been proposed. The second group is based on heuristic methods. Such a study was conducted by [54]. In order to model the problem, a more detailed auxiliary graph was used instead of physical topology. In this diagram, each node in the network consists of different layers; the receiver / transmitter layer represents the optical-electrical signal transformation (this layer also represents the node's grooming ability), while the spectrum layer shows ready-to-use spectrum ranges. Since the auxiliary graph shows the current state of the network in terms of resource usage, when a new connection request is received, the path and spectrum range to be assigned are determined by running the shortest path algorithm on this graph. In another study [55], by defining spectrum engineering, it was shown how a node architecture might be in a network including traffic grooming and a traffic grooming algorithm was given.

In a study [56] combining traffic grooming method with multipath routing, it recommends that if the incoming request cannot be established with a single connection, it should be divided into multiple paths. Candidate paths are pre-determined with a K shortest path algorithm and kept in a list, in other words, it has been tried to simplify the solution by making the routing through fixed candidate paths.

2. FLEXIBLE SLOT ASSIGNMENT MODEL

As the problem of routing and spectrum assignment is known to be NP-complete complexity [33], the proposed approaches for solving this problem focus on finding solutions as close as possible to the optimum solution instead of the optimum solution. The proposed approaches can be divided into two groups. The first is the mathematical formulation of the problem. In these approaches, integer linear programming (ILP) method is used. Several ILP formulations have been given in the literature [22, 27, 33, 57], and various simplification approaches to the solution of these formulations have been proposed, such as splitting into two or more stages. The second group consists of heuristic approaches. Simple heuristic methods have been proposed, which are mostly fast solutions (brute force methods), but some studies have used advanced heuristic methods [25]. Since heuristic methods are the most appropriate approach to solve the problem in practice, most studies focus on this aspect. Because of the high complexity, ILP formulation and optimization are generally used for performance comparison or evaluation as it can achieve full solution in very small networks.

When the fragmentation and traffic grooming problems are added to the RSA problem, the complexity increases. Similarly, approaches can be divided into two groups as ILP-based [53] and heuristic [54].

In general terms, the performance of the proposed methods in the literature is examined by performing parametric changes in itself, but many methods are not analyzed and critically evaluated. Another observation is that there is no intensive effort to model the problems in the flexible network and that the graphical models used for representation are limited and similar.

In this thesis, it is aimed to develop various heuristic approaches to solve the problem. In these approaches, it is recommended to make grouping based on the common features of connection requests.

In the proposed problem, connection requests are sent to the network one by one in a random order. Whenever a request is received, a decision is made based on the current situation of the network and the path through which the link is established and which range of the spectrum is decided. In order for this decision to be made quickly, the complexity of the proposed algorithms should not be high. Therefore, the four different approaches proposed above have to be transformed into fast working heuristic algorithms. An important component of the thesis is to determine the most appropriate and good result among different algorithm design techniques.

Flexible optical networks allow the optical fiber to be used for channels in the desired bandwidth by dividing the usable spectrum of the optical fiber into smaller pieces, ie slots, and combining several successive slots. Thus, a more flexible and more efficient slot sharing model is available for operators. Each slot is a spectrum part of equal width (for example 12.5 GHz), and it is possible to carry approximately 300-400 slots on a single fiber. The ability to combine several slots allows the separation of only a sufficiently wide spectrum to match the bandwidth of the incoming connection requests. Thus, the available spectrum range can be avoided by wasting more than the connections needed. This basic design objective provides theoretically important gains. In practice, however, there are some obstacles to the realization of such a system.

An important challenge is the modeling problem that is so flexible that the spectrum can be used. In conventional WDM systems, each wavelength includes, for example, a 50 GHz bandwidth and the center frequencies determined by the standards known as ITU-grid. Each wavelength can be assigned to carry a single communication channel. It is not possible to combine two wavelengths side by side, so there is no interaction between the wavelengths and there is no relation between them. In this respect, each wavelength can be seen as a separate / independent layer in all the fibers in the entire network. Thus, most of the time WDM networks are represented by a multi-layered data structure representing a wavelength of each layer. Each layer has a complete topological copy of the network, and each layer is independent of the others if the network does not contain wavelength converters.

However, such a model cannot be used in the context of flexible optical networks. The main obstacle to this is the interaction between slots. A slot can be used alone or it can be used as a separate channel by combining with the left or right side. That is,

each slot cannot be an independent layer. One of the objectives of this thesis is to develop a model that can represent dependencies between these slots. In the model laid down, a structure representing the use of each slot and possible slot groups should be established (depending on a certain section of the time).

The model proposed here is a layered representation of the network structure at a given moment. If the connection requests in the network come dynamically, remain in the network for a certain period of time, and leave the network at the end of this period and release the resources, the model shows the slot groups currently being used in the network. In addition, the information of slots not currently used should be kept. Thus, it will be possible to use the model directly by the routing and spectrum assignment algorithm. An important advantage of this model is that the network status can be expressed visually.

2.1 Single Link Model

A single link model will be used to represent slots on a single fiber. Then this model will be generalized on the network.

The number of slots that can be carried on a single fiber, and the bandwidth of each slot is fixed. The recommended slot widths in the literature are mostly 12.5 GHz or 6.25 GHz. Connection requests to the network can have different bandwidths: 40 Gb / s, 100 Gb / s, 400 Gb / s. In order for these requests to be met, multiple consecutive slots must be used in groups. For example, a 35 or 37.5 GHz band is sufficient depending on the modulation format for a 100 Gb / s connection request. In this case 3 slots with 12.5 GHz or 6 slots with 6.25 GHz must be used.

When the studies in the literature are examined, it can be seen that the total number of slots that can be carried on a single fiber is accepted between 32 and 400. The existence of such a large number of ranges is due to the acceptance of different slot widths and different modulation techniques. Similarly, some assumptions are made for the bandwidths of the different connection requests to the network. The number of slots to be allocated to a connection request has been determined to be between 1 and 32 in many studies. However, the bandwidth of the requests generally shows two different patterns.

For requests of the first type, the bandwidth request of an incoming connection may fall against any number of slots between 1 and k . In this case, it is considered that the bandwidth of the incoming traffic is uniformly distributed between the slot 1 and the k slot. In this study, the number of k is 4, 10, 16 or 32.

For the second type of requests, the bandwidth requirement of the connections can be expressed in multiples of two. A new connection request can be made with 1, 2, 4, 8, ..., slots. The upper limit of the number of slots that can be used in such requests is mostly 8, 16, or 32.

The model developed in this thesis is explained in the following examples based on the traffic models described above. In fact, however, the proposed model is generally flexible to adapt to any type of traffic request and slot usage pattern. For this reason, acceptances in the given examples should not be considered as restrictive.

Another issue to be considered here is the spectrum ranges known as the guard band. In general, it is envisaged that 1 or 2 slots are left blank to prevent marking in the two adjacent communication channels. It is assumed in the literature that in some studies a fixed empty slot space is left in this way. In another group, assuming that the guard band will be included in the slot group assigned to the channel, number of slots is assigned to 1 or 2 more than enough number of slots for incoming requests. The proposed model is suitable for both types of studies.

2.1.1 Uniform requests model

First assume that a connection request can be met with a single slot, and there are T slots in a fiber. In the network which there is no connection, all the slots on a fiber can be used to establish this connection from s_0 to s_{T-1} . If the incoming connection requires 2 slot widths, then two adjacent slots should be used: For example, s_0 and s_1 can be connected together or s_1 and s_2 can be used together. The dependency between the slots used in this way starts to create additional obstacles that do not occur in a single slot for new future connection requests in the network. The use of s_0 and s_1 together for a connection will prevent the installation of another two slots on, for example, s_1 and s_2 . This dependence between the slots is mathematically opposed to a semi-lattice structure. This relationship between the slots on a link can be modeled using a semi-lattice structure, where the set of all sets of neighbor slots form a partially ordered set.

Description 1

The slots of the spectrum in a fiber are expressed as $s_0, s_1, s_2, \dots, s_{T-1}$. The maximum number of slots that can meet the maximum bandwidth of incoming connection requests is k . Use $s_{i,j}$ to represent the set of consecutive slots starting from the slot s_i and ending with the s_j . In this statement $i < j$, in this case $s_{i,j} = \{s_i, s_{i+1}, s_{i+2}, \dots, s_j\}$. According to these definitions:

$$\begin{aligned}
 L = \{ & s_0, s_1, s_2, \dots, s_{T-1}, \\
 & s_{0,1}, s_{1,2}, \dots, s_{T-2,T-1}, \\
 & s_{0,2}, s_{1,3}, \dots, s_{T-3,T-1}, \\
 & \dots \\
 & s_{0,k-1}, s_{1,k}, s_{2,k+1}, \dots, s_{T-k,T-1} \} \tag{2.1}
 \end{aligned}$$

L is a partial ordered set. In addition, the set intersection \cap , together with the cluster combination \cup , is a semi-lattice of the structure $\langle L, \cap, \cup \rangle$.

The Hasse diagram of this half-lattice can be used to show the dependencies between adjacent slots. In other words, all possible slot groups can be represented in this diagram, and the dependency between them can be visualized using this diagram and used as a data structure.

For example, a diagram consisting of only 4 slots ($T = 4$) and maximum number of slots that can be used together is 4 ($k = 4$).

Figure 2.1 shows the diagram of this example system. Here, each node (shown by the round) shows an element of the set L , ie a set of slots that can be used individually or together. A distinction between the two nodes $s_{i,j}$ and $s_{l,m}$ ($i \leq l$ and $j \leq m$) means that the spectrum interval $[i, j]$ is a sub-interval of the spectrum interval $[l, m]$. Therefore, these two spectrum ranges are interdependent. The diagram consists of k levels representing groups of 1, 2, ..., k slots. The lowest level includes single slots, the second level above it contains groups of 2 slots, so that each level contains a set of slots of that number. The lowest level includes single slots, the second level above it contains groups of 2 slots, so that each level contains a set of slots of that number.

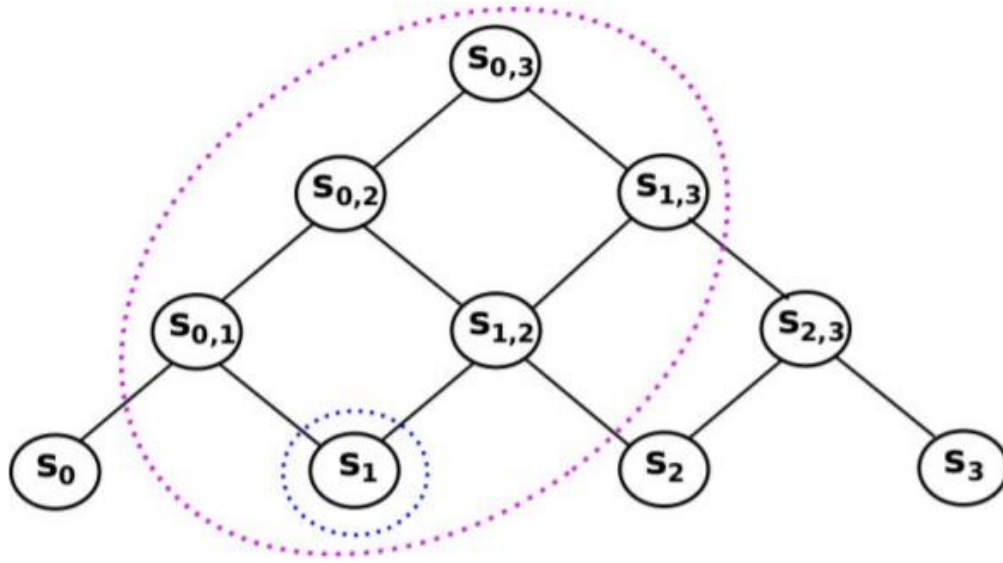


Figure 2. 1. Model for uniform requests. $T = 4$, $k = 4$

When a connection request is received, a new slot set is assigned to that connection request. It is not possible to assign that slot group to another request until this connection is terminated. This makes the single slot nodes representing the slot group in the diagram and all upper set of those nodes unusable. For example, in Figure 2.1, consider the slot s_1 assigned to a link. In this case, s_1 , $s_{0,1}$, $s_{1,2}$, $s_{0,2}$, $s_{1,3}$, and $s_{0,3}$ nodes show the slot groups that cannot be assigned to future connections in the future. To illustrate this situation in the diagram, these nodes and related details can be deleted or marked as unavailable. When these nodes are deleted, the rest of the diagram is divided into two parts, one part consists of s_0 nodes, the other part consists of nodes s_2 , s_3 and $s_{2,3}$. This effect also represents the fragmentation.

2.1.2 Power-of-two requests model

Similar to the previous one, the semi-cage structure of the slot groups can be used. In this model, the partially ordered set, is defined as the set of all possible slot groups where the number of elements is a power of two.

Definition 2

The slots of the spectrum in a fiber are expressed as $s_0, s_1, s_2, \dots, s_{T-1}$. The maximum number of slots that can meet the maximum bandwidth of incoming connection requests is 2^P . Use $s_{i,j}$ to represent the set of consecutive slots starting from the slot s_i and ending with the s_j . In this statement $i < j$, in this case $s_{i,j} = \{s_i, s_{i+1}, s_{i+2}, \dots, s_j\}$.

According to these definitions:

$$\begin{aligned}
 L = \{ & s_0, s_1, s_2, \dots, s_{T-1}, \\
 & s_{0,1}, s_{1,2}, \dots, s_{T-2,T-1}, \\
 & s_{0,3}, s_{1,4}, \dots, s_{T-4,T-1}, \\
 & \dots \\
 & s_{0,2^{P-1}}, s_{1,2^P}, s_{2,2^{P+1}}, \dots, s_{T-2^P,T-1} \} \tag{2.2}
 \end{aligned}$$

L is a partial ordered set. In addition, the set intersection \cap , together with the cluster combination \cup , is a semi-lattice of the structure $\langle L, \cap, \cup \rangle$.

The diagram consists of a exactly $p+1$ levels, one for each value of $0,1,\dots,p$. A simple example of this model is given in Figure 2.2 for a spectrum of 4 slots and a fiber where the largest bandwidth is 4 slots, ie 2^2 .

In this example, the model consists of 3 levels. $s_{0,3}$ is the slot group representing the entire spectrum. Because the maximum bandwidth request covers all of the spectrum, the set of $s_{0,3}$ can also be assigned to a connection. In a more realistic system, for example, for a spectrum of 300 slots, the top nodes will consist of groups of 2^P slots. If $P = 5$, the whole diagram will consist of a total of 6 levels.

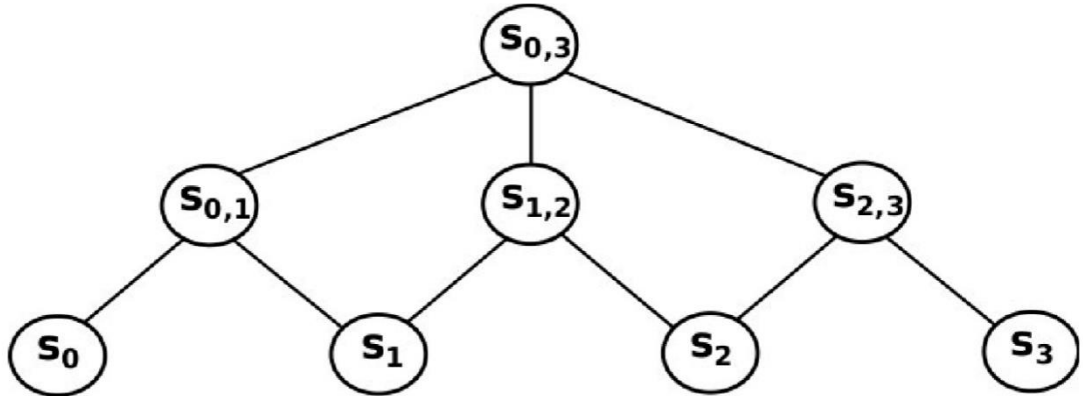


Figure 2. 2. Model for Power-of-two Requests. $T = 4, P = 2$

2.2 Generalization Model for Network

The fiber model described in the previous section can be adapted to represent an entire network. In this way, a new layered model can be formed to represent the use state of the spectrum slots of a flexible optical network and the dependencies of the

slot groups. In this model diagram, each node represents a certain group of slots in the entire network.

Assuming a simple 4 node mesh topology shown in Figure 2.3, the proposed network model is given in Figure 2.4. Diagram nodes representing the single slot are at the first level, ie at the lowest level. In general, groups of i slots are at the level i . In this example, the connection requests are assumed to be uniformly distributed between 1 and 4 slots.

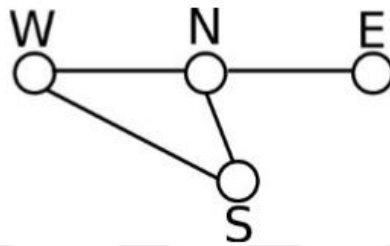


Figure 2. 3. 4-node mesh topology.

A node in the diagram contains a copy of the entire network topology. This topology knowledge can be represented by a simple neighborhood matrix structure. If the slot spacing (set) to which the node is related is in use on a fiber or is empty, the value of the corresponding matrix element is appropriately changed. As the dependencies between the slot groups are indicated by the diagram, the use of a slot group requires updating in the corresponding matrices in all the dependent groups. However, this is an easy process due to the structure of the diagram.

In Figure 2.4, for example, node $s_{1,2}$ holds information about the use of only slots s_1 and s_2 in the entire network. If W-E is connected between W-N- E using s_1 and s_2 slots, it can be specified that the W-N and N-E distances of the network in node $s_{1,2}$ are deleted / marked so that this slot group is no longer suitable for another connection.

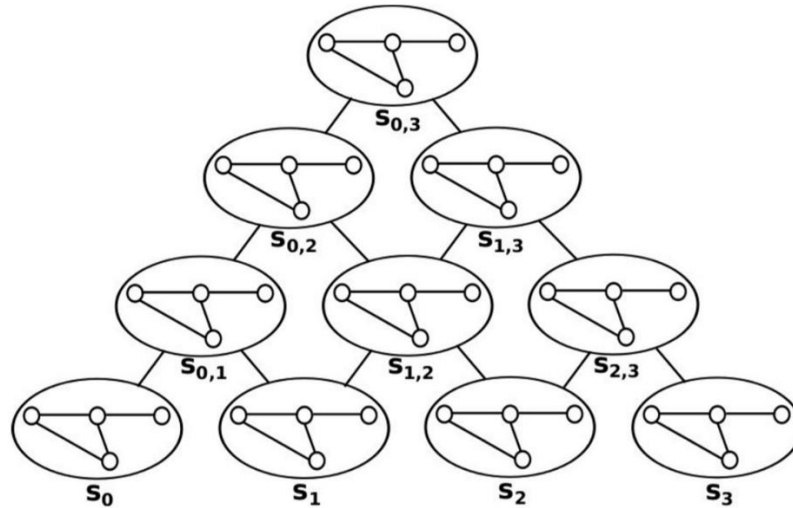


Figure 2. 4. Model representing the 4-node network in Figure 2.3.

2.3 Using the Model for Routing and Spectrum Assignment

The developed model can be used in both static and dynamic routing and spectrum assignment situations to represent the use of slots in the network at a particular time. Static routing and spectrum assignment methods can be used if incoming connection requests in a network are known in advance for a certain period of time. In this case, optimization methods that can handle all the connections at the same time can be used to determine the optimal configuration for establishing a large number of connections in the network. However, since this problem is NP-difficult, it is preferable to use heuristic algorithms instead of methods such as integer linear programming. Such heuristic methods are based on the principle of setting the connections one by one by ordering them according to a certain criterion. In this case, the proposed model will be useful to show the use of network resources.

In the case of dynamic traffic, the connection requests are assumed to come to the network one at a time and randomly. The appropriate route must be found for an incoming connection request and the selected slot groups on this path must be reserved. In doing so, only the current state of the network is checked. Therefore, a data structure that keeps the network state up to date can speed up routing and spectrum assignment algorithms.

The proposed grid structure can easily be converted into a dynamic data structure. The dependencies between the nodes in the diagram can be implemented with pointers between nodes in the data structure.

An example of how to use the data structure is given in Figure 2.5. In this example, a spectrum interval of 4 slots is assumed, and dynamic connection requests are coming on 4-nodes sample topology. Connection requests are uniform distributed, and bandwidth requests range from 1 to 4. The first-fit slot assignment is used as a method of spectrum assignment. Connection requests come in two directions.

Initially, there is no connection in the system, so all slots are empty. This is equivalent to the structure of Figure 2.4. First, there is a bandwidth request of 1 slot between the nodes W, S. As the first-fit method is used, firstly it will be checked whether there is a path using slot s_0 . If there is no path between W and S using the slot s_0 (due to the connections in the network, this slot is not empty), a path using the slot s_1 is searched. In this way, the first slot, which has a suitable path, is assigned to the connection. In the example, because the network is still empty, there is a path for the slot s_0 as a result of the path search on the topology in node s_0 in the model. This path (W-N-S) is shown in blue.

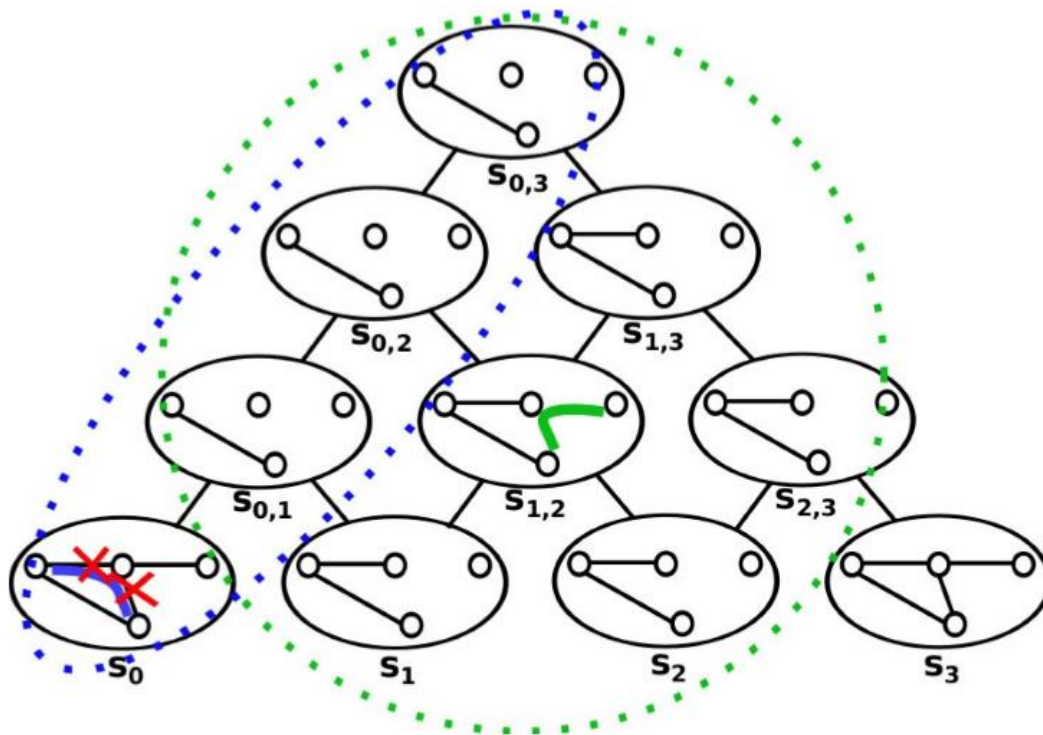


Figure 2. 5 Model for establishing two different connections.

Once the connection is established, the model needs to be updated. The two links to which the connection is passed, W-N and N-S are removed from the topology in node s_0 , this is indicated by the red 'X'. Because slot s_0 is no longer idle in these two

fibers, some slot groups are no longer available. These groups are nodes forming the upper set of node s_0 , ie $s_{0,1}$, $s_{0,2}$, and $s_{0,3}$. This upper-set is represented by dotted blue ellipses. On these nodes, the segments representing the same fibers were removed from the topology.

Assume that a second connection request (S, E) comes between the nodes, this request bandwidth requirement of two slots. Two slots bandwidth are represented at the second level in the model. Therefore, the routing algorithm will start from node $s_{0,1}$ on the leftmost. The search on the topology on this node will not find a path, because the previous connection used the slot s_0 in the corresponding fibers, and these links were deleted. Then the path $s_{1,2}$ is searched and S-N-E path is found. This path is shown by green color in node $s_{1,2}$. The second connection is established on this path using slots s_1 and s_2 .

After the second connection is established, the data structure must be updated again. For this, the links S-N and N-E used by the connection in s_1 , s_2 , and 6 nodes (dotted in green in the Figure 2.5) forming the upper set of these two nodes should be deleted from topologies. Figure 2.5 shows the situation after deletion of these links.

When a connection ends, the slots used must also be released along the path assigned to the connection. To do this, the first level nodes representing the slots used by the connection and the nodes representing all the slot groups forming the upper set of these slots must be added to topologies again. The upper set of a node is easily accessible using pointers upwards. The details of this process are given in the section Implementing the model.

An important advantage of this model is that it reduces the complexity of routing and spectrum assignment algorithms by the number of slots. In conventional models, if a connection uses a slot, there must be a path on the network topology, then a suitable slot interval must be set along the selected path. To do this, it is necessary to check that the consecutive slots are available along the path. In the proposed model, groups with the appropriate number of slots are represented by nodes at the same level. It is enough to find a route in a group, because finding a route also shows that the slot group is available on that path.

2.4 Memory Requirement

Reducing the complexity of the proposed model is actually achieved by using more space in memory. However, the space used is practically reasonable even for realistic networks. A simulation program has been prepared in C++ to implement and test the model. Each node of the structure contains a copy of the topology. This copy is represented by a matrix. Assuming that the number of nodes in the network is N , the total required field with additional information fields is $N^2 + 18$ octave per model node.

The number of nodes in the model is calculated for two different connection request types.

For uniform connection requests, assuming that the bandwidth of a connection varies between 1 and k slots, and the total number of slots in the spectrum are T , the model has a total of M nodes which is calculated based on Equation 2.3.

$$M = \left[T - \frac{k-1}{2} \right] \quad (2.3)$$

For Power-of-two connection requests, assuming that the bandwidth of a connection varies between 1 and 2^P slots, and the total number of slots in the spectrum are T , the model has a total of M nodes which is calculated based on Equation 2.4.

$$M = T(P + 1) - 2^{p+1} + p + 2 \quad (2.4)$$

To give an example, for uniform connection requests, in a 15-node network, in a case where the total number of slots is $T = 400$ and the maximum bandwidth is $k = 16$ slots, the model consists of 6280 nodes. The entire model needs approximately 1.46 MB space. For a network topology consisting of 50 nodes, for example, this amount will be approximately 15 MB.

3. ROUTING AND SPECTRUM ASSIGNMENT

The developed simulation program was used to examine the performance of various routing and spectrum assignment methods. These methods are briefly described below. All methods are based on heuristic approaches because of the difficulty of the problem. The best solution to the problem is based on the simultaneous resolution of the routing and spectrum assignment, but in the literature, these two parts of the problem in the heuristic methods are separate. The solution is reached more easily. The solutions obtained for this convenience will often not be optimal.

3.1 Routing Algorithms

When a connection between two nodes has to be established, it is generally preferred to use the shortest path. In the case of dynamic traffic conditions, that is, when the connection requests are received and installed one by one, two basic approaches are proposed: static routing and dynamic routing.

Static routing means that the shortest path between each pair of nodes is calculated and retained in a table. In this way, the same shortest path is always used between the two nodes and the current resource utilization of the network is not considered. The advantage of this method is that a routing algorithm does not run for each incoming connection request. Complexity is greatly reduced in this way. However, the fact that the static method does not consider the state of the network creates a significant problem. If the source is not available in the single selected path, ie if the desired bandwidth is not found, the connection is blocked. In this case, a new path is not searched and the connection is rejected.

In order to eliminate the disadvantage of static routing, Alternative Static Routing is proposed. In this method, instead of a single path, there are more than one shortest path. The shortest path between each of the two nodes in the network is kept in a table beforehand. When the connection request is received, the first link is looked at, if there is an appropriate bandwidth on this path, these slots are assigned to the

connection. If the appropriate number of slots is not found, the second-row path is attempted. In this way, k path is tried in order until a path can be found. If no slots are found in any path, the connection request is rejected. Alternative static routing is often a preferred method. It eliminates the additional processing load caused by dynamic routing and removes the negative impact of the single short path in static routing by offering a large number of alternatives.

The dynamic routing method runs the routing algorithm based on the current state of the network whenever a connection request arrives, with no need to find any path beforehand. With the additional workload, the dynamic method is actually much more flexible and the links are less likely to be rejected.

When the studies in the literature are examined in detail, it is seen that alternative static routing is used in most of them. In the thesis, firstly, comparisons were made about the static and dynamic routing and the number of k in the alternative static routing. For this purpose, various alternatives have been tried for K-short path (KSP) routing.

Dijkstra algorithm is used for dynamic routing. Here, when each connection request is received, the topology in the node of the corresponding slot group is searched, if the path is found in the search result in this topology, there is no need to check whether the slots are suitable. This is an important advantage of the model.

3.2 Spectrum Assignment Algorithms

3.2.1 First-Fit

The second problem in connecting is to assign a suitable slot interval. For this, the most preferred method in the literature is first-fit (FF) method. Although many wavelength assignment methods have been proposed for conventional WDM systems, the first-fit method is almost always the preferred wavelength assignment method, as it is the easiest to implement and performs as well as the others. According to the basic mode of operation, the first wavelength of the spectrum is tried to be assigned, if this wavelength is not suitable, the second is tried, so that all spectrum are tested until a suitable wavelength is found.

The first fit method can also be easily implemented for slot assignment. The difference is that for a connection using more than one slot, the slot groups are tested one by one. The difference is that the next slot interval of the slot groups is tested for a connection using more than one slot. For example, for a connection using two slots, first check if s_0 and s_1 slots are suitable. If even one of them is not available, the next slot interval, namely s_1 and s_2 slots, is tried. In the performance analysis, the first-fit slot assignment method was used as the base algorithm for comparisons.

3.2.2 Most Used Slot (MUS)

The reason for the success of the first fit method is to stack the used slots towards the left side of the spectrum as much as possible. Thus, for future connection requests, free slots are maintained towards the end of the spectrum. Another method that adopts this approach is the most used slot method. Before deciding which slot group to assign to the link, it is first necessary to keep track of how much all slot groups are used across the network.

Therefore, when each connection is established, the number of times the slots used are kept in a table. The slots are then sorted from the most used to the least used and are attempted to be assigned to the connection in this order. If the slot group that starts with the most used slot is not available along the connection path, the group starting with the second most used slot is tried.

3.2.3 Least Used Slot (LUS)

In this method, which is the exact opposite of the MUS method, the aim is to ensure that the slots assigned to the connections are used in equal amounts as possible. This method always attempts to assign the least-used slots to the link. Thus, no slot group is used more than others. The advantage of this is to ensure that there is an unused amount of resources left in each system. It is thought that equal distribution of resources will ensure that no slot group is completely blocked. Generally, the performance of this method is lower than MUS method. Nevertheless, it is used in comparisons because it is among the basic methods.

3.2.4 Equal Opportunity Slot Assignment (EOSA)

A new slot assignment method developed is a peer-to-peer slot assignment. In this method, the slots are evaluated in groups, not individually. The aim is to make the assignment at regular intervals as much as possible, minimizing the problem of fragmentation when slots are assigned. Accordingly, the starting slot number is determined by looking at how many slots the incoming connection request needs. For example, if the number of slots request is 8, the starting slot is numbers that can be fully divided into 8.

In the EOSA method, the following conditions apply when selecting the starting slot number of a connection:

```

1: for p=0 to MaxSlot do:
2:   if width < (1/2) maxwidth then
3:     if (p%maxwidth = 0)||
      (p%maxwidth = 1/2 (maxwidth) - width) then
4:       startslot = p
5:     if (width = (1/2) maxwidth)&&&
      (p%(1/2) maxwidth = 0) then
6:       startslot = p
7:     else
8:       if (p%maxwidth = 0)||
      (p%maxwidth = maxwidth - width) then
9:         startslot = p;
10: end for;
11: if no slot interval is available for the request
12: Request is blocked

```



Where width is the number of slots in which the connection request is, the startslot represents to the starting slot number. The slots are numbered from 0 to T-1. A table showing which bandwidth can start from which slots are given in Table 3.1.

In Table 3.1, each row shows the number of slots in which the connection request is made, and the columns indicate slot numbers from 0 to 15. If the spectrum of a fiber consists of, for example, 300 slots, this table shows each group of 16 slots. The X marks in the table indicate which slot is the starting slot. For example, a connection that requests 5 slots can be assigned to a group starting from 0 or 3. Similarly, slots 16, 19, 32, 35,... may also be selected as starting slot.

Table 3. 1 EOSA method: the starting slots that can be assigned according to the slot number of the connection request.

		starting slot number															
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Connection bandwidth	1	x							x								
	2	x						x									
	3	x					x										
	4	x				x											
	5	x			x												
	6	x		x													
	7	x	x														
	8	x									x						
	9	x								x							
	10	x							x								
	11	x						x									
	12	x				x											
	13	x			x												
	14	x		x													
	15	x	x														
	16	x															

This method aims to place the desired slot numbers properly on the spectrum. For example, in Figure 3.1 two connections with 1 slot and 7 slots can be placed side by side in a group of 8 slots to complement each other. Similarly, connections requested for 2 and 6 slots, 3 and 5 slots... also integrate each other into 8 slots. As a result, the spectrum is used efficiently as much as possible. Also by preventing the creation of empty slots the fragmentation problem gets minimized. For connection requests wider than 8 slots, there is no such completion. This is to reduce the blocking probability in high slot number connections as much as possible.



Figure 3. 1. Two connections with 1 slot and 7 slots integrate each other into 8 slots.

Another assumption is that the number of slots for connection requests may be any value between 1 and 16. This very general acceptance can be changed appropriately if the system parameters are different. In this case, the EOSA method should also be changed in slot assignment conditions.

3.2.5 Nigh Fair Slot Assignment (NFSA)

The main objective of this algorithm is to solve the fairness problem in different bandwidth requests without increasing the blocking in the network. The basic idea in this method is to divide each group into two equal parts, the first part acts as EOSA, and the second part follows First-Fit algorithm. When a request arrives, the algorithm decides whether the bandwidth of the incoming connection request exceeds a predetermined threshold value. For example, the threshold value is up to half of the maximum allowed bandwidth (the size specified by maxwidth in the algorithm). If the request for a connection is less than the threshold value, the slot groups are scanned starting from the first slot of the spectrum, as in the first-fit method, and the first appropriate range is assigned to the new connection. If the bandwidth is greater than the threshold value, then the slot interval is assigned as in the EOSA method.

in order to be seen more clearly, in a network where the maximum bandwidth request is 16 slots, Table 3 showing which bandwidth can start from which slots.

Table 3.2 NFSA method: the starting slots that can be assigned according to the slot number of the connection request.

		starting slot number															
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Connection bandwidth	1																
	2																
	3																
	4																
	5																
	6																
	7																
	8	x									x						
	9	x								x							
	10	x							x								
	11	x						x									
	12	x					x										
	13	x				x											
	14	x		x													
	15	x	x														
	16	x															

In Table 3.2 , each row shows the number of slots in which the connection request is made, and the columns show slot numbers from 0 to 15. If the spectrum of a fiber

consists of, for example, 300 slots, this table shows each group of 16 slots. The X marks in the table indicate which slot is the starting slot.

In this algorithm, MaxSlot is the total number of slots in the fiber, width is the number of slot request, maxwidth and startslot are the maximum possible number of slots in a request and the starting slot number to be assigned, respectively.

The NFSA Algorithm is given below.

```

1: for p=0 to MaxSlot do:
2:   if width > (1/2) maxwidth then
3:     if p%maxwidth = maxwidth - width then
4:       startslot = p;
5:   if (width = (1/2) maxwidth)&&
      (p%(1/2) maxwidth = 0) then
6:     startslot = p
7:   else
8:     Select one among them according to
9:     First-Fit algorithm
10: end for;
11: if no slot interval is available for the request
12: Request is blocked

```

The proposed EOSA and NFSA methods are designed based on the assumption that the number of slots for incoming connection to the network is uniformly distributed. In fact, if the distribution of slot numbers is known, different assignments can be made according to the starting slot numbers.



4. IMPLEMENTATION (SIMULATION STRUCTURE)

Simulation program has been developed in C ++ in order to implement and test the model. The program consists of the following components:

- Traffic generator: Generates random connection requests in desired distributions.
- Event list and event handler: Controls event-based and time-dependent operation of the simulation.
- Connection handler: Coordinates about creating and removing connection requests.
- Network class: Holds the information of the network and includes the procedures for managing them.
- Topology class: maintains physical resources information and includes procedures for management. The data structure of the model is also part of this class.

The structure of the model consists of dynamically interconnected nodes (Figure 4.1). In a typical node, the slot interval includes the number of start and end slots, a matrix representing the network topology, and four pointers: upleft, upright, downleft, and downright. The entire model is created by the combination of these nodes. The dependency slot groups are interconnected with pointers in the nodes. This makes switching between nodes easier. In particular, it is important to easily switch to the top-sets of the slots.

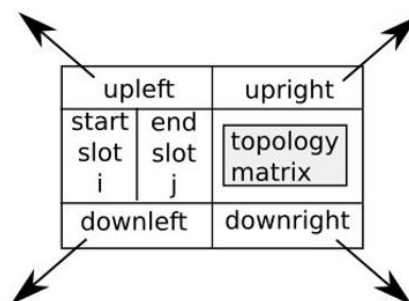


Figure 4. 1. Node of the model.

When a connection is established, the node to a slot group containing the desired number of slots is first taken. Using a routing algorithm (Dijkstra, etc.) on the topology in this node, a path is searched for between the two ends of the connection. When a path is found, this slot group must be assigned to that connection. When a path is found, this slot group must be assigned to that connection. To do this, go to the bottom, that is to the first level slot nodes, by scanning all the nodes between the first and last slots of the slot group, to erase the distances on the selected path from the topologies in each node. After the individual assignment of the slots, the same process must be done in the upper-set groups. For this, all levels are scanned from the second level. For example, if the first assigned slot number is i , the first node to go at the second level is the node that can be accessed with the upleft pointer. The remaining nodes can be scanned from left to right when going to a higher-level node. A similar method is followed when removing a link. The connection is removed from the first level nodes of the slots used by the connection ie the used links are replaced in the respective matrices. Then, the relevant nodes at the upper levels are scanned and these links are added to the matrices again.

5. EXPERIMENTAL EVALUATION

Detailed analysis of the routing and spectrum assignment methods described above has been done through the simulation program. The purpose of this study is to examine each method on the basis of connection blocking probabilities and to make sense of what can be improved.

5.1 Experimental Environment

For the experiments, network topologies with different properties (node number, edge density) were selected. Two of them are the North American topology (NSFNet and USNet), both of which are European continent topologies (COST239 and COST266). These topologies are physical networks frequently used in similar studies in the literature.

The characteristics of topologies are given in the table 5.1

Table 5. 1 Network topologies

Topology	Number of nodes	Number of edges	Average Node Degree
NSFNet	14	21	3
USNet	24	43	3.58
COST239	11	26	4.73
COST266	25	51	3.92

Assuming that the traffic coming to the network in the experiments, ie the connection requests are in accordance with the Poisson distribution, the connection requests at different densities are produced randomly. Bandwidth requests of the connections are uniformly distributed between 1 and 16 in the number of slots. The possibility of a connection request between all node pairs on the network is equal. These selected traffic parameters were determined by examining the studies in the literature and taking into consideration the most frequently used parameters.

To obtain sufficient traffic density in the network, different Erlang values have been tried and the results for the traffic generated according to these values are shown in the graphs.

There are several recommendations for the available spectrum range in a fiber, but generally ranges are from 300 to 400. Similarly, $T = 400$ was chosen for the analyzes.

The basic performance metric used in an environment with dynamic traffic is the blocking probability. In this thesis, all comparisons were made with the blocking probability and it can be calculated in two different ways. The first is the ratio of the total number of accepted requests from all connection requests to the network to the total number of connection requests. In the experiments here, the traffic-weighted blocking probability was taken. According to this:

$$P_B = \frac{\sum_i b_i A_i}{\sum_i b_i} \quad (5.1)$$

In equation 5.1, b_i is the number of slots required by connection if i is accepted connection, $A_i = 1$, otherwise $A_i = 0$. The advantage of this formula is that it also takes into account the differences in bandwidth between connection requests. Thus, a more realistic evaluation can be made.

In the drawing of the result graphs given in the rest of this section, the same value was repeated 10 times and the average was taken to obtain the value of each point. The experiment was terminated after a total of one million connections to the network for each repetition.

5.2 Performance of Routing Algorithms

Experiments were performed on all 4 topologies. Here, the conclusions taken on the USNet topology (Figure 5.1) will be discussed. The same results are not required to be shown separately because similar results are generally taken in all topologies, so it can be concluded from all experiments that the results discussed here are valid for all topologies.

In the first group experiment, it is aimed to reveal the effect of static or dynamic routing algorithms. Accordingly, alternative static routing and dynamic routing methods were compared. Both methods, were used with the first-Fit spectrum assignment algorithm. In the alternative static routing, the number of predefined paths for each pair of nodes is selected as $k = 3, 5, 7$ and 10 . (In case of $k = 1$, it is against static routing). On the other hand, in dynamic routing, a route is sought

without any restriction on the free slots of the network. The Dijkstra algorithm is used to find a path, in other words, the shortest possible path will be found.

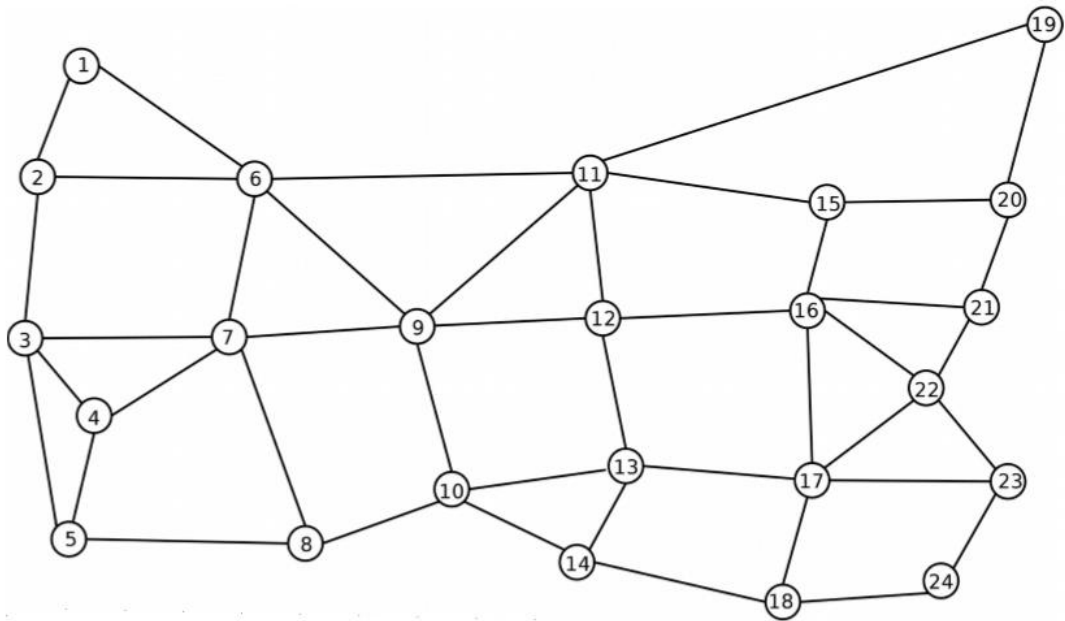


Figure 5. 1. USNet topology (24 nodes)

Figure 5.2 shows how static and dynamic routing methods for different network loads (ranging from 350 to 500) affect the blocking probability. The curve indicated by FF represents the performance in dynamic routing. The other 4 curves are the results of alternative static routing. Here the KSP (k-shortest-path) can be seen with the different shortest path numbers selected. According to these results, with the increase of the number of alternative paths as expected, the probability of blocking decreases. The worst performance occurs for the $k = 3$ condition. Increasing the number of alternate paths improves performance, but does not achieve dynamic routing performance. Even when the number of paths is 10, dynamic routing up to about 450 Erlang is more successful. Static routing appears to be more successful at high loads because, as the resources in the network are reduced, dynamic routing starts to find increasingly circulating, complicated ways, and therefore uses too many resources to avoid rejecting the current connection. As a result, network resources are consumed more quickly. If the selected paths are not available in the static alternative routing, a different path is not sought. All established connections use relatively reasonable length (hop count) paths.

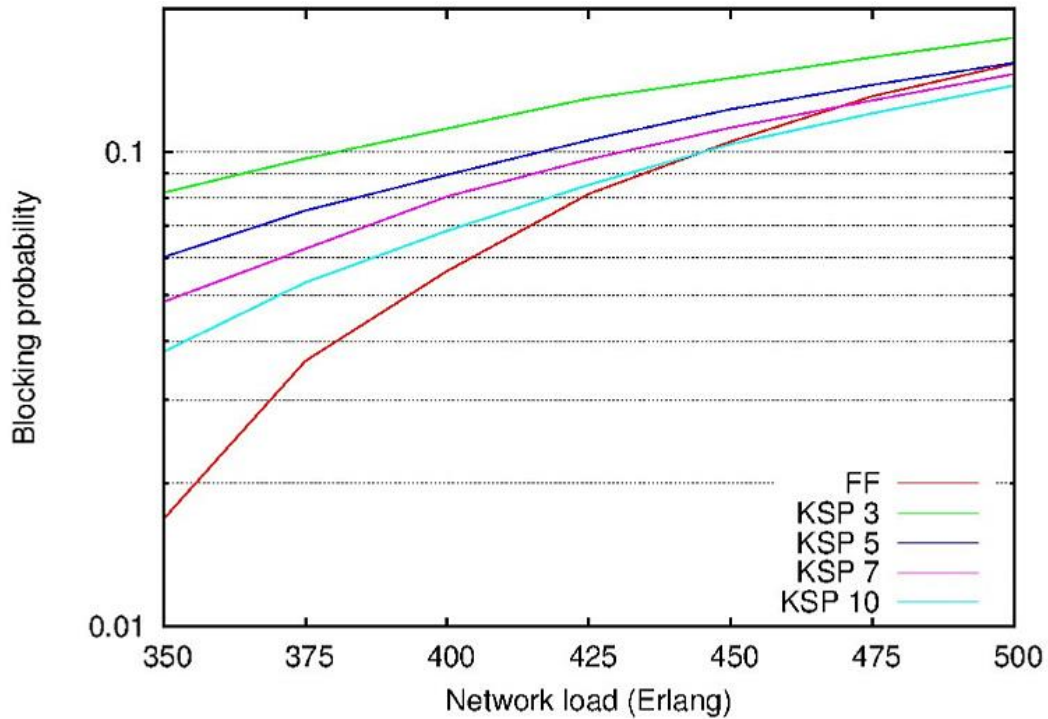


Figure 5. 2. Blocking probability of static and dynamic routing algorithms according to different network loads

This graph shows the important point. In the literature, KSP is almost used instead of dynamic routing. In these studies, the number of alternative paths is kept to a very low value of 3. However, this study shows that 3 alternative ways cannot be an alternative to dynamic direction. In order to achieve high performance in KSP, the number of paths must be at least 10.

Blocking probabilities of different bandwidths in the network are also often ignored. Although we are examining the traffic-weighted blocking probability, the probability of rejection increases as the bandwidth of the connection requests actually increases. As the network load increases the spectrum fragmentation in the system will increase, the chances of a small number of slot-using connection requests increase, and the possibility of a large number of slot-using connections decreases. This is a very important problem considering the network operator. In fact, rejection of high bandwidth connections is not desirable for the operator. On the other hand, this situation has been investigated because it may be an important indicator of the fragmentation in the spectrum.

Figure 5.3 shows the individual blocking probabilities of connections at different bandwidths when dynamic routing is used. The network load is between 350-500 Erlang. The curves are connected to 6, 7, 8, 10, 12, 14 and 16 slots. The blocking

probability of connections requesting slots 1 to 5 is not shown in the graph. For the 11, 13, 15-slot connections, the curve is not shown so that the graph does not interfere, but the blocking probabilities are the intermediate values as expected. The first observation that can be made here is that the blocking probabilities increases as the number of slots increases. This observation applies to all load conditions in the network. blocking probabilities at high band widths are well above the acceptable limits. It can be concluded that the reason for the high blocking probability is a great deal of fragmentation, especially considering that the slot widths of 1-5 are not rejected at all. Because, in fact, there is always a small number of slots in the network, but they cannot be found together to form broadband. This raises the importance of spectrum assignment methods that can eliminate fragmentation.

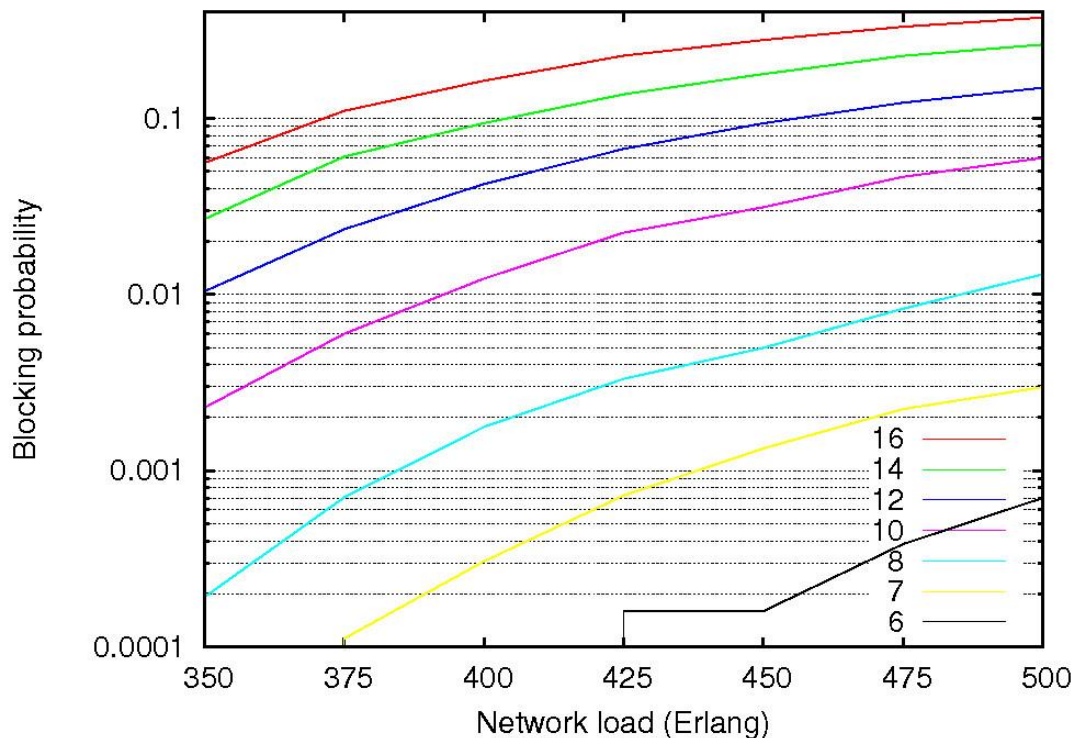


Figure 5. 3. Separate blocking probabilities for different bandwidths connection requests for dynamic routing

Figure 5.4 gives a similar result for the KSP 10 routing. The noticeable difference between the two graphs is that the blocking probabilities for different bandwidths are closer to each other. This result shows the difference between the two routing algorithms. Blocking probabilities for connection with the lower slot not shown here are not 0, but are very small, as in dynamic routing.

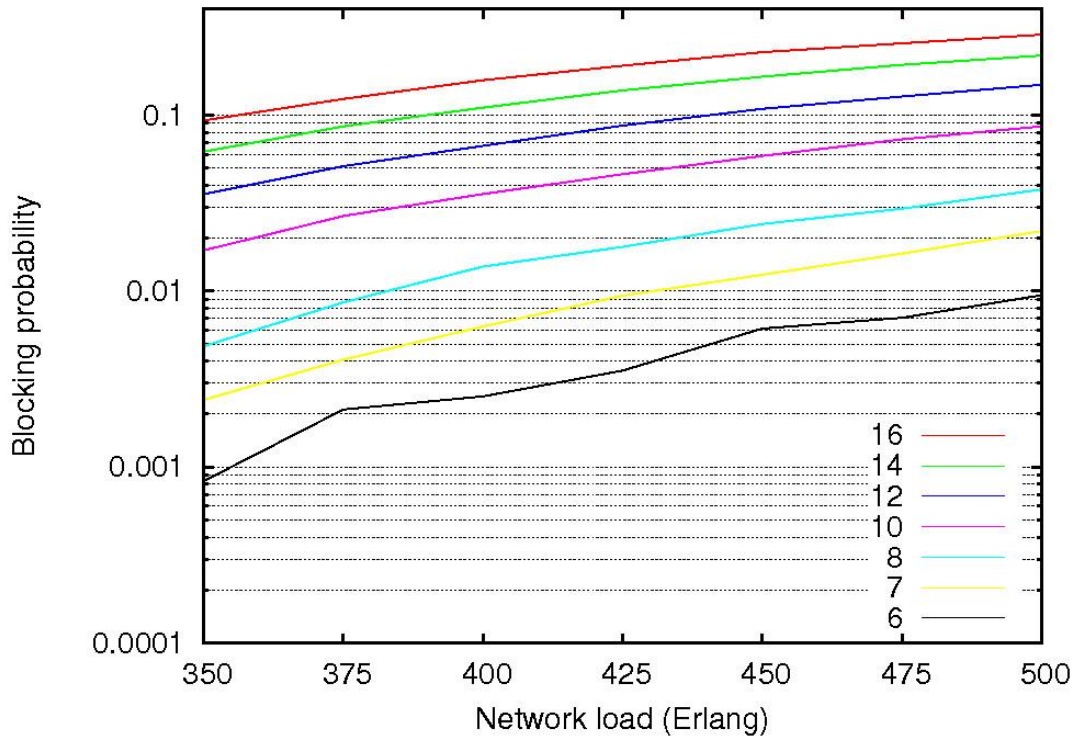


Figure 5. 4. Separate blocking probabilities for different bandwidths connection requests for KSP 10

5.3 Performance of Slot Assignment Algorithms

In this section, different slot assignment methods are compared. For all different slot assignment methods, dynamic routing is used because of its high performance. The most important reason for avoiding dynamic routing in previous studies is the complexity of the process, but the new model that we propose in this thesis addresses this complexity. Therefore, it is more meaningful to use high performance dynamic routing.

Figure 5.5 shows the results for different slot assignment methods. Here, the four curves using dynamic routing correspond to FF (First Fit), LUS (Least Used Slot), MUS (Most Used Slot), and EOSA (Equal Opportunity Slot Assignment). In addition, KSP 3, 5, 7 and 10 graphs were also included in the graph for comparison.

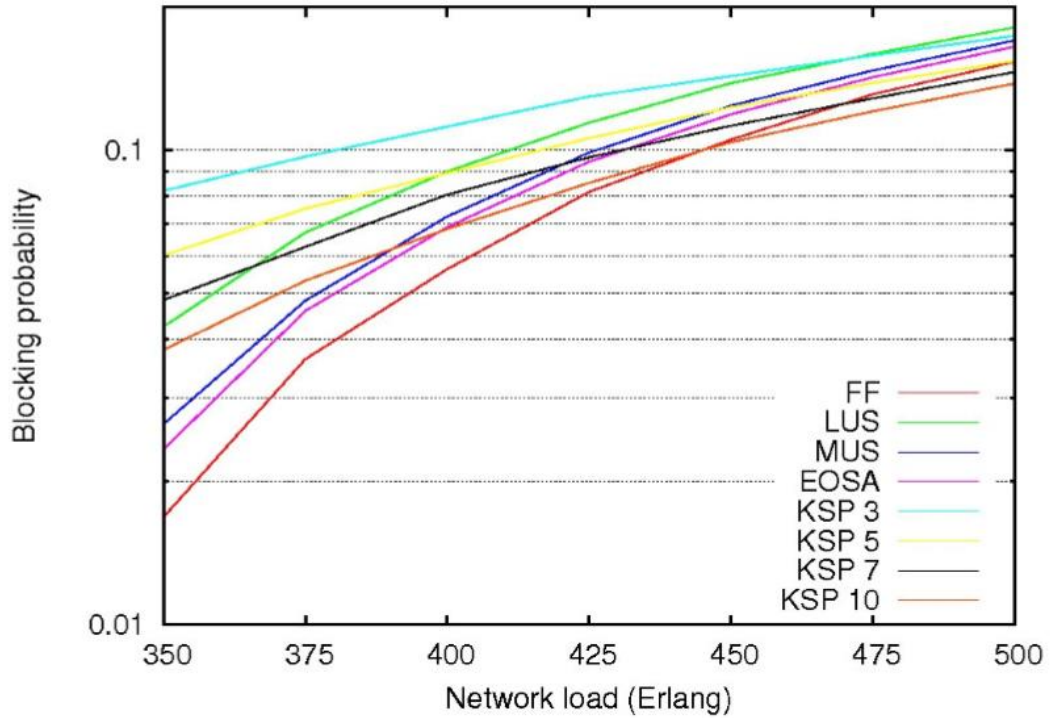


Figure 5. 5. Blocking probabilities different slot assignment methods and traffic loads

As can be seen in the graph, the first fit slot assignment method is surprisingly high performance. It is noteworthy that the LUS method has the worst performance among them, while EOSA is more successful than the others except FF. These results are an important sign for EOSA.

Figure 5.6 shows the individual blocking probabilities of requests with different slot numbers. In this way, the four best performing groups were compared. The performances of FF, MUS and EOSA using dynamic routing and static KSP-10 are shown as bars. In particular, the design objective of the EOSA method is to reduce the blocking probability of high bandwidth connections. From this point of view, EOSA shows the best performance in connections using slot 1-11. However, when the number of slots is 12 or more, it is closer to FF but worse. Naturally, it is the increase in the blocking probability in low bandwidth requests that are sacrificed for this gain. However, this is one of the objectives of the algorithm, that is, it is desirable to have an equal blocking probability of all connections in the ideal case.

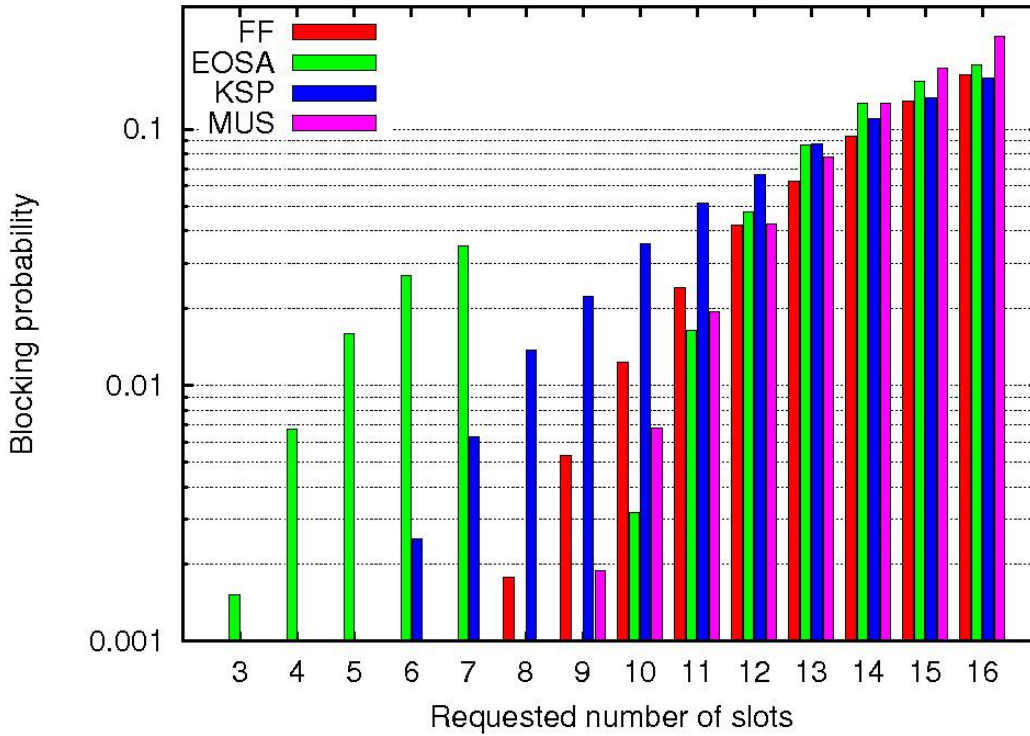


Figure 5. 6. Blocking probabilities for connection requests with different slot numbers

The results obtained in the 24-node USNet topology to evaluate the performance of the NFSA method are shown in Figures 5.7 and 5.8. Figure 5.7 shows the blocking probabilities of the First Fit (FF), EOSA and NFSA slot assignment methods for different network loads (ranging from 350 to 500). The first outstanding result is that the FF method has the lowest blocking probability. While NFSA performing is close to the FF, the EOSA performing is worst among the three methods.

In order to demonstrate how these methods are performed when considering requests with different bandwidth, the graph in Figure 5.8 is created. Here, NFSA appears to be the most successful method for the ability to respond to different bandwidth requests in terms of fairness. In general, all three methods are higher at blocked probabilities as the desired bandwidth increases. This situation is acceptable to some extent. However, even with the highest bandwidth, it seems to be an important achievement that NFSA keeps the blocking probability below a certain limit. Requests for the Bandwidth between 9 slots and 16 slots are almost the same for NFSA and the other two methods increase rapidly as the number of slots increases. In this respect, we can say that NFSA works in accordance with the design purpose.

In the case of a small increase in the overall blocking probability across the network, a more fairness distribution is seen between connection requests.

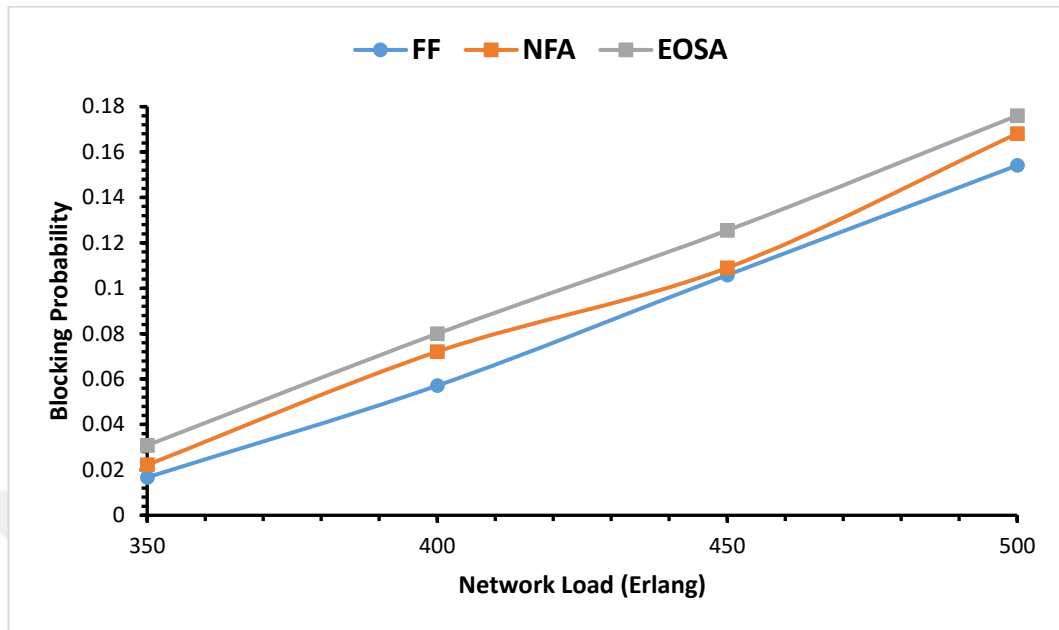


Figure 5. 7. Blocking probabilities at different network loads in the USNet topology

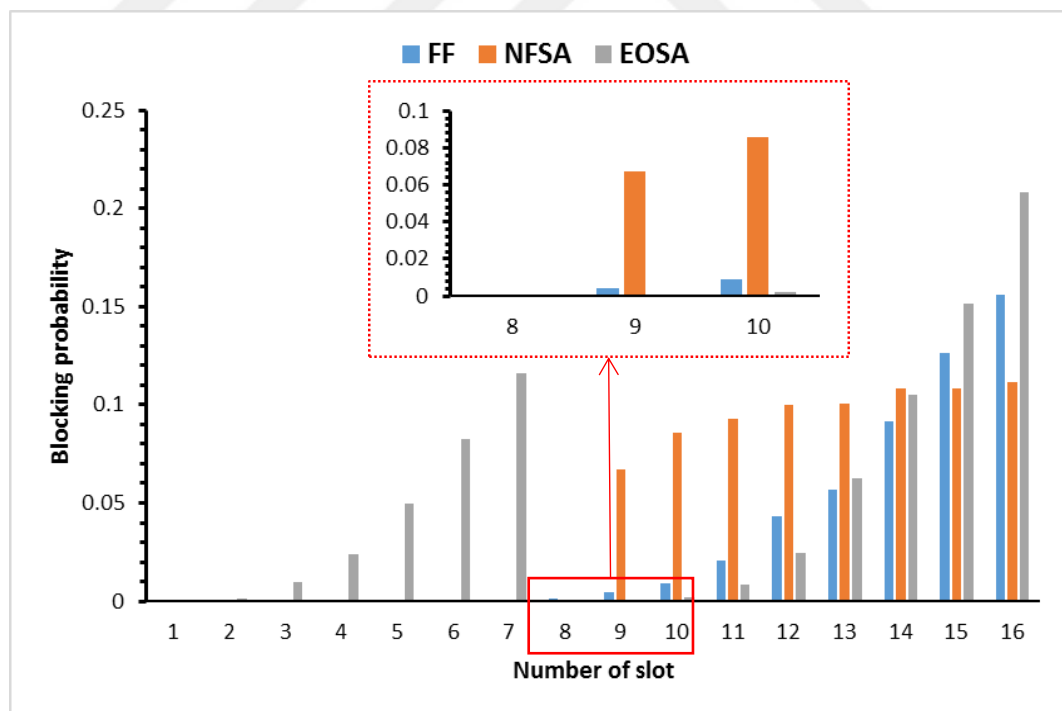


Figure 5. 8. Blocking probabilities for each slot in the USNet topology

Experiments have been repeated in three different networks to examine whether the same results apply to other topologies. Figures 5.9 and 5.10 show the results for the NSFNet network. As the number of nodes in this network is 14, the blocking rates are generally higher than those of USNet. These results provide important information to compare the performances at high loads. Although there is a different topology, a similar performance is observed for the results obtained for USNet. NSFA is located between FF and EOSA at the general blocking probability, but it is better distributed to different connection request groups.

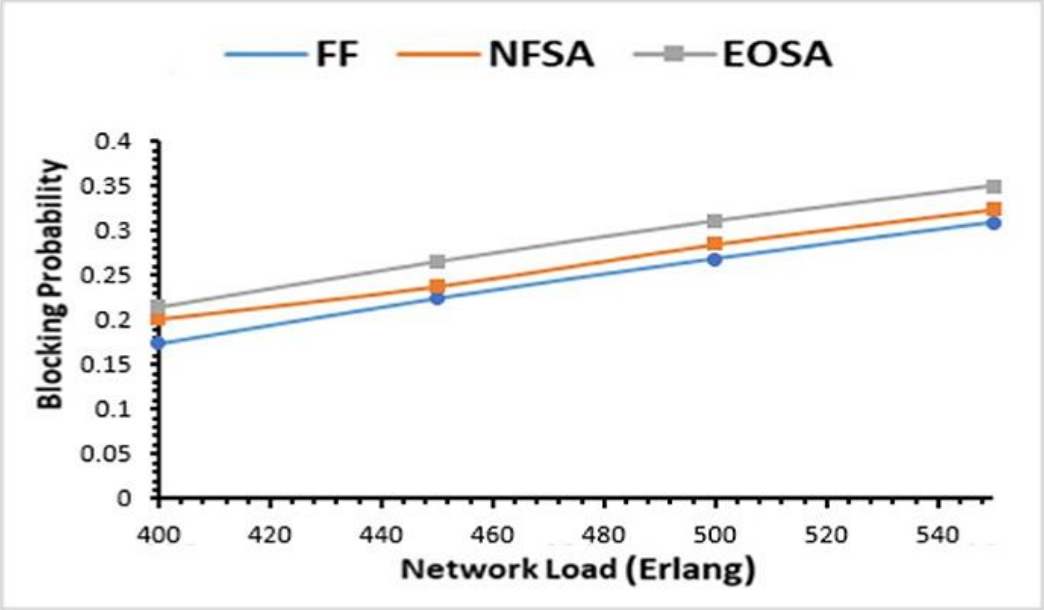


Figure 5. 9. Blocking probabilities of different bandwidth requests in NSFNet topology

The other two topologies used in the experiments are COST266 and COST239, which are commonly used in the experiments and covering the European continent.

In Figures 5.11 and 5.12, the results for COST239 topology can be seen. In COST239 results, NFSA has the highest blocking probability among the three methods. Among the four topologies used in the experiments only such a result was obtained in this topology. This topology is the smallest in number of nodes and is the topology with the highest average node degree. However, when looking at different bandwidths separately, the NFSA has the best connection distribution. Therefore, it can be said that the NFSA method has achieved its purpose.

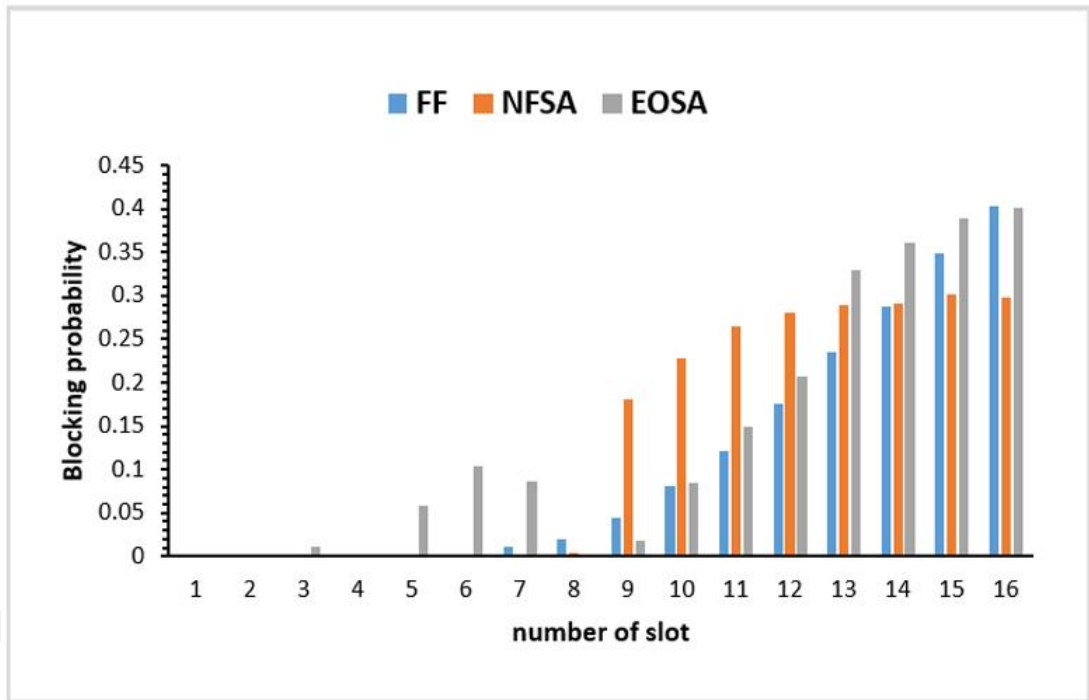


Figure 5. 10. Blocking probabilities for each slot at 400 erlang loads in NSFNet topology

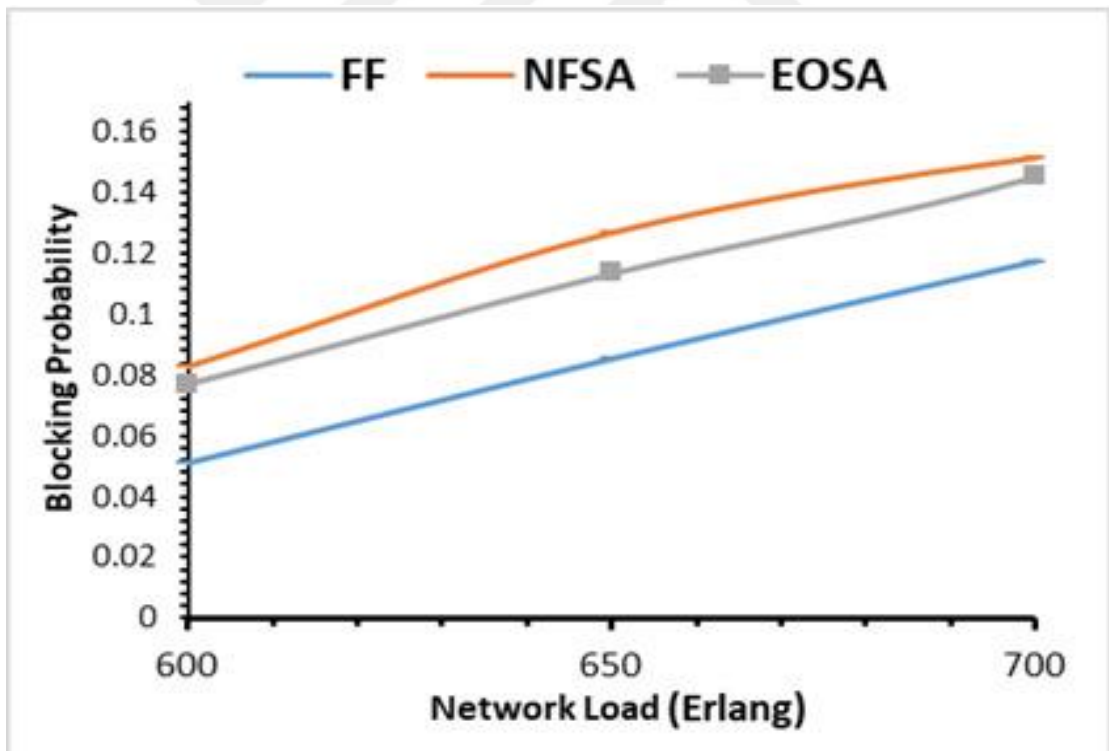


Figure 5. 11. Blocking probabilities of different bandwidth in COST239 topology

In Figures 5.13 and 5.14 the results for COST266 topology can be seen. As can be observed, for topology the blocking probability of NFSA scheme remarkably

improves and it is also below than the First-Fit results. Also, we can see the NFSA algorithm has the best result in terms of fairness. We can get the conclusion that by determining the starting slot just for high bandwidth requests, and using First-Fit for low bandwidth requests, the link utilization increases. This way, the algorithm is able decrease the overall blocking probability.

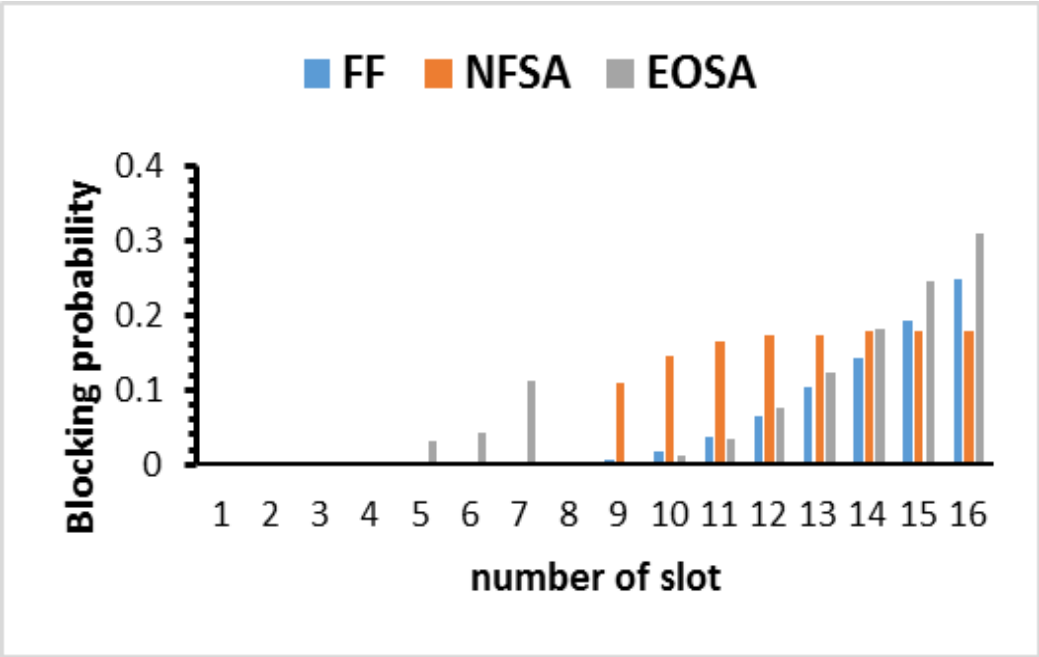


Figure 5. 12. Blocking probabilities for each slot at 650 erlang loads in COST239 topology

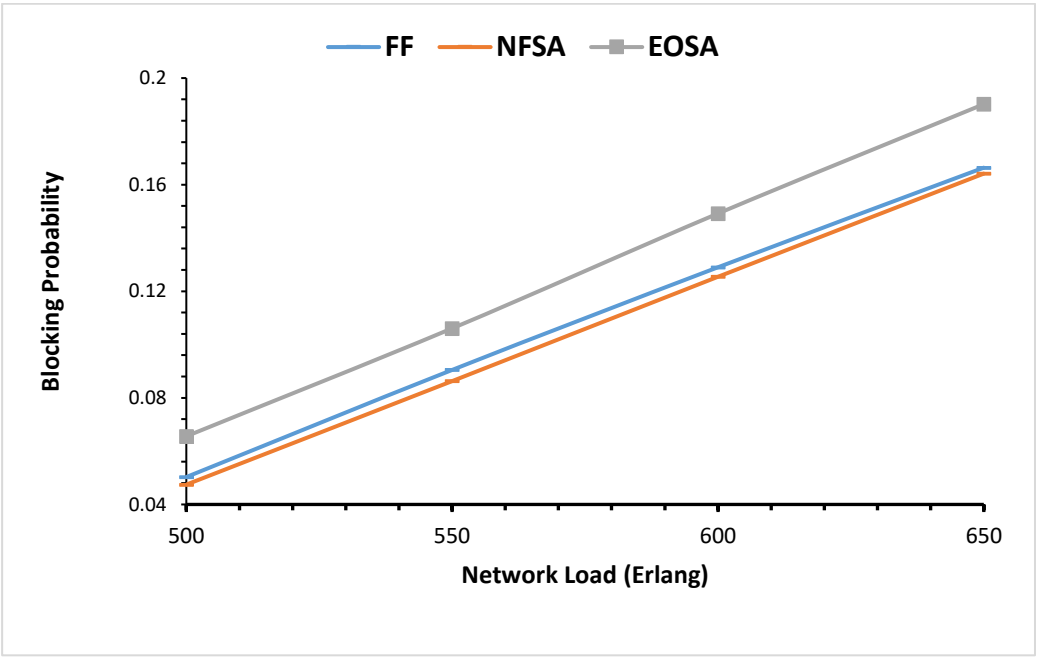


Figure 5. 13. Blocking probabilities of different bandwidth in COST266 topology.

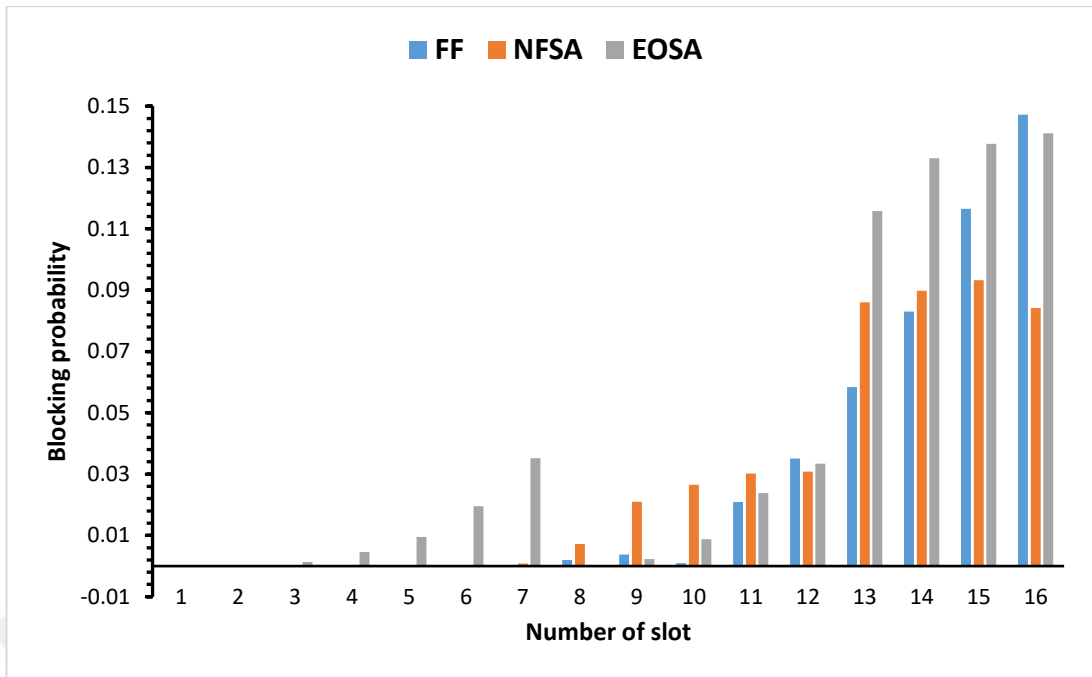


Figure 5. 14. Blocking probabilities for each slot at 500 erlang loads in COST266 topology.



6. CONCLUSION

One of the results of the project is the problem of routing and slot assignment in wide area flexible optical networks is investigated in detail. The first major contribution is the development of a model that can fully represent this new spectrum designation technology in a dynamic traffic environment. The developed model can be used for any slot assignment method and it can show the current status of all the resources of the network at a given moment.

Routing and slot assignment methods often use the K-shortest path (KSP) method. According to this, the K shortest paths between any pair of nodes are predetermined and only these paths can be used for a possible connection. With the studies in this thesis, it has been shown that dynamic routing method is better and K should be at least 7-10 in order to achieve the same performance with KSP. On the other hand, the additional time complexity, which is the main reason for not using the dynamic routing in the literature, is eliminated by the network model we recommend.

We present two new algorithms for routing and slots assignment in dynamic traffic to solve the problem of fairness among different bandwidth connections. The simulation results for different topologies showed that our first method improves a partial fairness problem with a high probability of blocking, but our second method improves the probability of blocking much better than first. We believe that these methods can inspire new methods for slot assignment, and our results indicate that solving fairness without increasing the overall block in the network is possible.

The results obtained from this thesis can be used in different ways.

New spectrum assignment methods can be developed using the proposed model. Further measurements can be made by taking into consideration the guard band which is ignored in the thesis. The effect of the guard band on the blocking rate can be examined and the effect of the traffic grooming can be observed.

Although EOSA and NFSA methods gave the best results among the methods tested in the thesis, the effect in terms of fair spectrum distribution was still limited. Studies on how to improve this can be continued.



REFERENCES

- [1] Recommendation, I. *G.694.1: Spectral grids for WDM applications: DWDM frequency grid*. 2012; Available from: <http://www.itu.int/rec/T-REC-G.694.1/>
- [2] Gerstel, O., et al., *Elastic optical networking: A new dawn for the optical layer?* IEEE Communications Magazine, 2012. **50**(2): p. s12-s20.
- [3] Jinno, M., et al., *Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies*. IEEE communications magazine, 2009. **47**(11): p. 66-73.
- [4] Jinno, M., et al., *Distance-adaptive spectrum resource allocation in spectrum-sliced elastic optical path network [topics in optical communications]*. IEEE Communications Magazine, 2010. **48**(8): p. 138-145.
- [5] Rival, O. and A. Morea. *Elastic optical networks with 25–100G format-versatile WDM transmission systems*. in *OECC 2010 Technical Digest*. 2010. IEEE.
- [6] Tornatore, M., et al. *Complexity and flexible grid networks*. in *OFC 2014*. 2014. IEEE.
- [7] Kretsis, A., et al., *Planning and operating flexible optical networks: Algorithmic issues and tools*. IEEE Communications Magazine, 2014. **52**(1): p. 61-69.
- [8] Shirazipourazad, S., et al. *On routing and spectrum allocation in spectrum-sliced optical networks*. in *2013 Proceedings IEEE INFOCOM*. 2013. IEEE.
- [9] Zhu, K. and B. Mukherjee, *Traffic grooming in an optical WDM mesh network*. IEEE Journal on selected areas in communications, 2002. **20**(1): p. 122-133.
- [10] Wright, P., A. Lord, and S. Nicholas. *Comparison of optical spectrum utilization between flexgrid and fixed grid on a real network topology*. in *OFC/NFOEC*. 2012. IEEE.
- [11] Sato, K.-i. *Recent developments in and challenges of elastic optical path networking*. in *European Conference and Exposition on Optical Communications*. 2011. Optical Society of America.
- [12] Kozicki, B., et al. *Filtering characteristics of highly-spectrum efficient spectrum-sliced elastic optical path (SLICE) network*. in *National Fiber Optic Engineers Conference*. 2009. Optical Society of America.
- [13] Klekamp, A., et al. *Transparent WDM network with bitrate tunable optical OFDM transponders*. in *2010 Conference on Optical Fiber Communication (OFC/NFOEC), collocated National Fiber Optic Engineers Conference*. 2010. IEEE.
- [14] Takara, H., et al. *Distance-adaptive super-wavelength routing in elastic optical path network (SLICE) with optical OFDM*. in *36th European Conference and Exhibition on Optical Communication*. 2010. IEEE.

- [15] Varvarigos, E.A. and K. Christodoulopoulos, *Algorithmic aspects in planning fixed and flexible optical networks with emphasis on linear optimization and heuristic techniques*. Journal of Lightwave Technology, 2014. **32**(4): p. 681-693.
- [16] Talebi, S., et al., *Spectrum management techniques for elastic optical networks: A survey*. Optical Switching and Networking, 2014. **13**: p. 34-48.
- [17] Christodoulopoulos, K., I. Tomkos, and E. Varvarigos, *Time-varying spectrum allocation policies and blocking analysis in flexible optical networks*. IEEE Journal on Selected Areas in Communications, 2013. **31**(1): p. 13-25.
- [18] Żotkiewicz, M., et al. *Optimization models for flexgrid elastic optical networks*. in *2013 15th International Conference on Transparent Optical Networks (ICTON)*. 2013. IEEE.
- [19] Patel, A.N., et al. *Survivable transparent flexible optical WDM (FWDM) networks*. in *Optical Fiber Communication Conference*. 2011. Optical Society of America.
- [20] Yu, X., et al. *Static routing and spectrum assignment in co-existing fixed/flex grid optical networks*. in *OFC 2014*. 2014. IEEE.
- [21] Christodoulopoulos, K., I. Tomkos, and E.A. Varvarigos. *Routing and spectrum allocation in OFDM-based optical networks with elastic bandwidth allocation*. in *2010 IEEE Global Telecommunications Conference GLOBECOM 2010*. 2010. IEEE.
- [22] Klinkowski, M. and K. Walkowiak, *Routing and spectrum assignment in spectrum sliced elastic optical path network*. IEEE Communications Letters, 2011. **15**(8): p. 884-886.
- [23] Wan, X., et al. *Dynamic routing and spectrum assignment in flexible optical path networks*. in *2011 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference*. 2011. IEEE.
- [24] Yu, Y., et al. *The first single-link exact model for performance analysis of flexible grid WDM networks*. in *2013 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC)*. 2013. IEEE.
- [25] Almeida, R., et al. *An evolutionary spectrum assignment algorithm for elastic optical networks*. in *2013 15th International Conference on Transparent Optical Networks (ICTON)*. 2013. IEEE.
- [26] Wang, X., et al., *Dynamic routing and spectrum allocation in elastic optical networks with mixed line rates*. Journal of Optical Communications and Networking, 2014. **6**(12): p. 1115-1127.
- [27] Patel, A.N., et al., *Routing, wavelength assignment, and spectrum allocation algorithms in transparent flexible optical WDM networks*. Optical Switching and Networking, 2012. **9**(3): p. 191-204.
- [28] Castro, A., et al., *Dynamic routing and spectrum (re) allocation in future flexgrid optical networks*. Computer Networks, 2012. **56**(12): p. 2869-2883.
- [29] Wang, X., et al. *Utilization entropy for assessing resource fragmentation in optical networks*. in *Optical Fiber Communication Conference*. 2012. Optical Society of America.

- [30] Zhu, Z., et al., *Dynamic service provisioning in elastic optical networks with hybrid single-/multi-path routing*. Journal of Lightwave Technology, 2013. **31**(1): p. 15-22.
- [31] Yin, Y., Z. Zhu, and S.B. Yoo. *Fragmentation-aware routing, modulation and spectrum assignment algorithms in elastic optical networks*. in *Optical Fiber Communication Conference*. 2013. Optical Society of America.
- [32] Wang, R. and B. Mukherjee, *Spectrum management in heterogeneous bandwidth optical networks*. Optical Switching and Networking, 2014. **11**: p. 83-91.
- [33] Christodoulopoulos, K., I. Tomkos, and E.A. Varvarigos, *Elastic bandwidth allocation in flexible OFDM-based optical networks*. Journal of Lightwave Technology, 2011. **29**(9): p. 1354-1366.
- [34] Zhang, M., et al., *Planning and provisioning of elastic O-OFDM networks with fragmentation-aware routing and spectrum assignment (RSA) algorithms*. Proc. 2012 ACP: p. 1-3.
- [35] Sone, Y., et al. *Routing and spectrum assignment algorithm maximizes spectrum utilization in optical networks*. in *2011 37th European Conference and Exhibition on Optical Communication*. 2011. IEEE.
- [36] Chen, X., et al., *A novel fragmentation-aware spectrum allocation algorithm in flexible bandwidth optical networks*. Optical Switching and Networking, 2014. **12**: p. 14-23.
- [37] Takagi, T., et al. *Disruption minimized spectrum defragmentation in elastic optical path networks that adopt distance adaptive modulation*. in *European Conference and Exposition on Optical Communications*. 2011. Optical Society of America.
- [38] Yin, Y., et al., *Dynamic on-demand defragmentation in flexible bandwidth elastic optical networks*. Optics express, 2012. **20**(2): p. 1798-1804.
- [39] Wen, K., et al. *Dynamic on-demand lightpath provisioning using spectral defragmentation in flexible bandwidth networks*. in *European Conference and Exposition on Optical Communications*. 2011. Optical Society of America.
- [40] Yu, X., et al. *Spectrum compactness based defragmentation in flexible bandwidth optical networks*. in *OFC/NFOEC*. 2012. IEEE.
- [41] Zhang, M., et al. *Bandwidth defragmentation in dynamic elastic optical networks with minimum traffic disruptions*. in *2013 IEEE International Conference on Communications (ICC)*. 2013. IEEE.
- [42] Wang, R. and B. Mukherjee, *Provisioning in elastic optical networks with non-disruptive defragmentation*. Journal of Lightwave Technology, 2013. **31**(15): p. 2491-2500.
- [43] Cugini, F., et al., *Push-pull defragmentation without traffic disruption in flexible grid optical networks*. Journal of Lightwave Technology, 2013. **31**(1): p. 125-133.
- [44] Sone, K., et al. *Effective utilization of network by spectrum defragmentation*. in *Optical Fiber Communication Conference*. 2014. Optical Society of America.
- [45] Zhang, M., et al. *Spectrum defragmentation algorithms for elastic optical networks using hitless spectrum retuning techniques*. in *Optical Fiber Communication Conference*. 2013. Optical Society of America.

- [46] Wang, X., et al. *Blocking probability and fairness in two-rate elastic optical networks*. in *2014 16th International Conference on Transparent Optical Networks (ICTON)*. 2014. IEEE.
- [47] Ma, S., et al. *A fairness-aware dynamic spectrum allocation scheme in elastic optical networks*. in *OptoElectronics and Communications Conference and Photonics in Switching*. 2013. Optical Society of America.
- [48] Callegati, F., et al., *Trunk reservation for fair utilization in flexible optical networks*. *IEEE Communications Letters*, 2014. **18**(5): p. 889-892.
- [49] Zhang, S., et al. *Evolution of traffic grooming from SDH/SONET to flexible grid*. in *39th European Conference and Exhibition on Optical Communication (ECOC 2013)*. 2013. IET.
- [50] Zhang, S., et al., *Evolving traffic grooming in multi-layer flexible-grid optical networks with software-defined elasticity*. *Journal of Lightwave Technology*, 2014. **32**(16): p. 2905-2914.
- [51] Rottondi, C., et al., *Routing, modulation level, and spectrum assignment in optical metro ring networks using elastic transceivers*. *Journal of Optical Communications and Networking*, 2013. **5**(4): p. 305-315.
- [52] Zhang, Y., et al. *Traffic grooming in spectrum-elastic optical path networks*. in *Optical Fiber Communication Conference*. 2011. Optical Society of America.
- [53] Zhang, G., M. De Leenheer, and B. Mukherjee, *Optical traffic grooming in OFDM-based elastic optical networks*. *Journal of Optical Communications and Networking*, 2012. **4**(11): p. B17-B25.
- [54] Zhang, S., C. Martel, and B. Mukherjee, *Dynamic traffic grooming in elastic optical networks*. *IEEE Journal on selected areas in communications*, 2013. **31**(1): p. 4-12.
- [55] Yu, X., Y. Zhao, and J. Zhang. *Optical grooming with spectrum engineering (og-se) in flexi-grid networks*. in *Optical Fiber Communication Conference*. 2014. Optical Society of America.
- [56] Fan, Z., Y. Qiu, and C.-K. Chan, *Dynamic multipath routing with traffic grooming in OFDM-based elastic optical path networks*. *Journal of Lightwave Technology*, 2015. **33**(1): p. 275-281.
- [57] Wang, Y., X. Cao, and Y. Pan. *A study of the routing and spectrum allocation in spectrum-sliced elastic optical path networks*. in *2011 Proceedings Ieee Infocom*. 2011. IEEE.
- [58] Pepperberg, I.M., *Alex & me: How a scientist and a parrot discovered a hidden world of animal intelligence — and formed a deep bond in the process*. 2009, Scribe Publications: New York, NY.

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