修 士 論 文 の 和 文 要 旨

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論 文 題 目	Spectrum Allocation Suppressing Fragmentation Proactively in Elastic Optical Networks (エラスティック光ネットワークにおけるスペクトル分断を抑制するスペクトル割り当て)		

要　　旨

エラスティック光ネットワーク(EON: Elastic Optical Network) において，帯域フラグメンテーションは，サブキャリアスロットのセットにおける未使用である未整列・非連続のサブキャリアの存在によって生じる。コネクションが使用する波長は，連続したサブキャリアスロットに割り当てられなければならないので，これらの未整列・非連続サブキャリアスロットは，帯域ブロッキングの原因となる。本論文はエラスティック光ネットワークにおけるスペクトル分断を抑制するスペクトル割り当てを提案する。２つ方式、サブキャリアスロット分割方式と first-last-exact fit 割り当てポリシー、が提示された。１つ目の方式には、1 つの同一のリンクを共有していないコネクションは同じパティションに割り当てられて、同一のリンクを使用するコネクションは別のパティションに割り当てられた。こうしてより多くの整列サブキャリアスロットを生成し。また、奇数インデックスのパティションは first fit 波長割り当てポリシーを採用して、偶数インデックスのパティションは last-fit 波長割り当てポリシーを採用した。こうしてより多くの連続したサブキャリアスロットを生成し。２つ目の方式には、1 つの同一のリンクを共有していないコネクションは first-exact fit 波長割り当てポリシーを採用して、同一のリンクを使用するコネクションは last-exact fit 波長割り当てポリシーを採用した。こうしてもより多くの整列・連続したサブキャリアスロットを生成し。提案方式は，より多くの整列・連続したサブキャリアスロットを生成し，帯域ブロッキングを削減する。シミュレーション結果により従来方式と比べ，帯域ブロッキングを削減することが定量的に示されている。

Spectrum Allocation Suppressing Fragmentation Proactively in Elastic Optical Networks

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Abstract

Optical network based on wavelength division multiplexing (WDM) has been considered inefficient to overcome the exponential growth of bandwidth demand in telecommunication networks. Elastic optical networks with optical-orthogonal frequency division multiplexing (OFDM) has been researched for its efficient bandwidth utilization. However, bandwidth fragmentation problem arise in the elastic optical networks. Bandwidth fragmentation refers to the existence of non-aligned and non-contiguous available (unused) subcarrier slots. Since spectrum for a connection must be allocated to contiguous slots and aligned along the routing path, non-contiguous and non-aligned available slots could cause blocking of connections. In this direction, some researches have been conducted to overcome the bandwidth fragmentation problem. However, most of the researches perform traffic rerouting, that may creates traffic disruption. Moreover, the effect of contiguous and aligned available slots for reducing the blocking probability in the network has not been thoroughly considered.

This thesis introduces a spectrum allocation suppressing fragmentation proactively in elastic optical networks. To avoid traffic rerouting, the spectrum allocation suppress fragmentation proactively. It increases the number of contiguous aligned available slots, and hence the blocking probability in the network is reduced. Two schemes are presented throughout this thesis. The first scheme is called subcarrier-slot partition scheme with first-last fit spectrum allocation. The partition approach creates more aligned available slots by separating the spectrum allocation of the non-disjoint connections. The first-last fit allocation policy creates more contiguous aligned available slots between two partitions. To avoid the effect of partitioning to the blocking probability, the second scheme creates more aligned available slots without partitions. It is called spectrum allocation scheme based on first-last-exact fit policy. This scheme allocates connections according to their types of path, namely, (i) disjoint and (ii) non-disjoint paths. Connections with disjoint paths are allocated using the first-exact fit allocation policy, whereas we use the last-exact fit spectrum allocation policy for non-disjoint connections. Simulation results show that the presented schemes outperforms the conventional scheme in terms of blocking probability.

Acknowledgement

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Special thanks to my friends Nova, who paved the way for me, Maureen and her words of wisdom every lunch break, Arisa Chan, Asri Suciati, Fiyu, Icha, Zia, Hage, Mas Hendro, Radian, Roffi, Mas Hendy, Rifan, Mas Mamat, Fadlil, Sre, Tami, Steffi, Seisei, Kadri, Edgar, and others who support me throughout my living in Japan.

I would like to dedicate this thesis to my parents, Ayah and Bunda, and my brother Yusuf for their love and support. Your words of encouragement have made my accomplishments possible.

Contents

Chapter 1

Introduction

1.1 Background

The rapid growth in world-wide communications and proliferating use of Internet has significantly modified the ways of life. This revolution has led to vast growth of communication bandwidth. In this context, traditional optical network has been proven to be quite inefficient to exploit the potential capacity of the emerging next-generation optical networks. Elastic optical networks with optical-orthogonal frequency division multiplexing (OFDM) has the potential to fulfill the ever-increasing vast communication bandwidth for the emerging next-generation networks. OFDM technology [2] uses overlapped subcarrier slots in the optical spectrum, which results in high bandwidth efficiency. The OFDM transponder [9, 3, 20] allocates an appropriate number of contiguous subcarrier slots, based on the required bandwidth demand of an optical connection request. In this way, flexible granularity can be achieved in the optical layer that enables elastic optical networks.

1.2 Problem statement

Elastic optical networks allocates spectrum for connections on contiguous slots in the subcarrier slots of a fiber link. The bandwidth of the contiguous slots is elastic, it can be a few GHz or even narrower. Dynamically setting up and tearing down connections generate bandwidth fragmentation [3, 11] problems. The bandwidth fragmentation problem occurs when the available slots are isolated from each other due to either they are non-aligned along the routing path or they are non-contiguous in the spectrum domain [15]. Non-aligned available slots occurs when one or more available slots of different links on a connection route are not aligned. Non-contiguous available slots occurs when one or more available slots of a link are not adjacent to each other. The non-aligned and non-contiguous available slots may be more difficult to be utilized for upcoming connection requests. When any available slot cannot fulfill the required bandwidth demand of a connection request, the connection request is considered to be rejected or blocked. This is called call/connection blocking. The call blocking in the network is measured in terms of blocking probability, which is defined as a ratio of total number of blocked connection requests to the total number of connection requests in the network.

1.3 Objective

Our objective in this master thesis is to prevent bandwidth fragmentation by reducing the number of non-aligned and non-contiguous available slots without rerouting of connections.

1.4 Research works

To achieve the objective, we introduce a spectrum allocation suppressing fragmentation proactively. It is presented into two schemes, namely, subcarrier-slot partition scheme with first-last fit spectrum allocation and spectrum allocation scheme based on first-last-exact fit allocation policy.

The subcarrier-slot partition scheme with first-last fit spectrum allocation separates the spectrum allocation of connections that use different routes and share some link(s). We define a connection group as a set of connections whose routes are exactly the same. We use the term of disjoint connections for connections that do not share any links. The term of non-disjoint connections refers to connections that share some link(s). When the spectrum for non-disjoint connections are allocated on adjacent slots, non-aligned available slots are created. By separating the spectrum allocation of non-disjoint connections, non-aligned available slots can be avoided. To separate it, the subcarrier slots of each fiber link are divided into partitions. The spectrum for disjoint connections is allocated in the same partition, while the spectrum for non-disjoint connections is allocated in different partitions. The first-last fit allocation policy applied in the partition approach in order to put the aligned available slots together between two partitions. This would lead to contiguous aligned available slots.

The spectrum allocation scheme based on first-last fit allocation policy separates the disjoint and non-disjoint connections by choosing a suitable spectrum allocation policy for each connection request. We introduce a first-exact fit allocation policy for disjoint connections, and a last-exact fit allocation policy for non-disjoint connections. The first-exact fit allocation policy attempts to choose the lowest indexed available slot that has the number of available contiguous slots exactly the same with the number of slots of a connection request. If the exact available contiguous slots are not available, this policy allocates spectrum from the lowest indexed available slots, similar to the conventional first fit allocation policy. The last-exact fit allocation policy attempts to choose the highest indexed available slots that have the number of available contiguous slots exactly the same with the number of slots of a connection request. If the exact available contiguous slots are not available, this policy allocates spectrum from the highest indexed available slots. We use the term of first-last-exact fit allocation policy for the combination of these two policies, which attempts to use the exact number of contiguous available slots. This policy prevents small contiguous available slots.

1.5 Structure of the thesis

The thesis is organized as follows. Chapter 1 introduces the background, problem statement, objective, method, and structure of the thesis. Chapter 2 presents related works and the contribution of this thesis. Chapter 3 describes the subcarrier-slot partition scheme with first-last fit spectrum allocation. The spectrum allocation scheme based on first-last-exact fit policy is described in chapter 4. Finally, chapter 5 concludes this thesis.

Chapter 2

Related works

2.1 Introduction

This chapter describes the related works. The chapter is organized as follows. Section 2.2 describes the study of bandwidth fragmentation. Section 2.3 presents the main contribution of the thesis. Section 2.4 concludes this chapter.

2.2 Study of bandwidth fragmentation

Routing and spectrum allocation approaches [3, 8, 18, 16, 22] have been presented to minimize the call blocking. However, these mentioned approaches perform the bandwidth defragmentation after the bandwidth fragmentation occurs. This means that the traffic is disrupted due to the rerouting of the connection, as the bandwidth defragmentation is performed. To overcome this problem, Kadohata et al. [10] and Zhang et al. [21] have developed bandwidth defragmentation schemes which reduce the traffic disruption. However they assume the green field scenario (100% rerouting all the time) to solve the bandwidth fragmentation problem, which increases the traffic delay and system complexity. Therefore, a suitable spectrum allocation scheme is required in order to prevent the bandwidth fragmentation before its occurrence in the network without rerouting of connections.

In this direction, R. Wang and B. Mukherjee [17] have presented a scheme that prevents the bandwidth fragmentation without performing any rerouting of connections. Typically, when the connection requests with lower-bandwidth and higher-bandwidth are not separated during spectrum allocation, it may lead to a situation where the higher-bandwidth connection requests may be blocked. In order to circumvent this drawback, they explore an admission control mechanism that captures the unique challenges posed by heterogeneous bandwidths. They adopt a preventive admission control based on spectrum partitioning to achieve higher provisioning efficiency. As a result, it prevents the blocking of connections due to the unfairness of bandwidth issues. However, this approach does not consider the effect of non-aligned and non-contiguous available slots, which may create bandwidth fragmentation.

2.3 Thesis main contribution

This thesis introduces a spectrum allocation suppressing fragmentation proactively in elastic optical networks. It prevents the bandwidth fragmentation problem proactively by creating more contiguous aligned available slots. It is presented into two schemes, namely a subcarrier-slot partition scheme with first-last fit spectrum allocation and spectrum allocation scheme based on first-last-exact fit allocation policy.

The first scheme is a subcarrier-slot partition scheme with first-last fit spectrum allocation. This scheme provides more contiguous aligned available slots by partitioning and by the first-last fit spectrum allocation. Part of this work has been published on IEEE HPSR 2014 [6] and IEICE JPN Design Contest 2014 [5].

The second scheme is spectrum allocation scheme based on first-last-exact fit allocation policy. This scheme provides more contiguous aligned available slots by separating disjoint and non-disjoint connections using first-last-exact fit allocation policy.

2.4 Conclusion

This chapter presented the study of bandwidth fragmentation and the thesis main contribution. The bandwidth fragmentation is a problem caused by lack of contiguous aligned available slots. The thesis main contribution is a spectrum allocation suppressing fragmentation provides more contiguous aligned available slots proactively.

Chapter 3

Subcarrier-slot partition scheme with first-last fit spectrum allocation

3.1 Introduction

This described one of the scheme that suppressed fragmentation proactively in elastic optical networks, namely a subcarrier-slot partition scheme with first-last fit spectrum allocation.

The chapter is organized as follows. Section 3.2 describes the aligned available slots created by partitioning. Section 3.3 presents the model and assumptions used throughout this chapter. Section 3.4 describes the subcarrier-slot partition scheme with first-last fit spectrum allocation. The performance evaluation is presented in section 3.5. Finally, section 3.6 concludes this chapter.

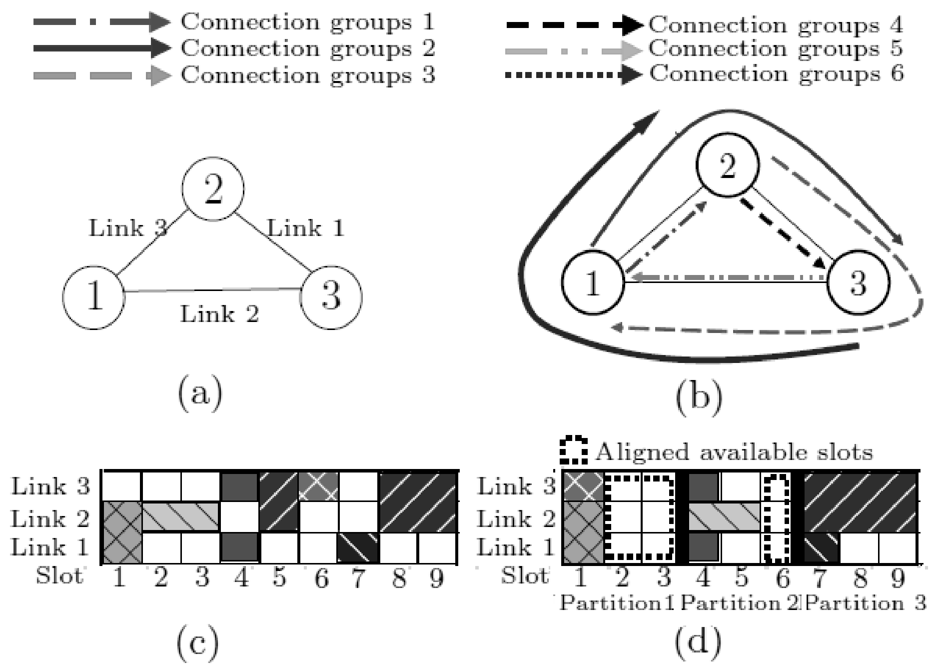


Figure 3.1: (a) Physical topology of sample network, (b) Virtual topology of sample network, (c) Spectrum allocation without partitions in elastic optical networks, and (d) Spectrum allocation with partitions in elastic optical networks

3.2 Aligned available slots created by partitioning

Partitioning the subcarrier slot of each fiber link can create more aligned available slots. This is because the partitioning enables the spectrum allocation to be organized by separating the spectrum allocation of connections that use different routes and share some link(s).

Figure 3.1 shows that partitioning can create more aligned available slots in elastic optical networks. Figs. 3.1(a) and 3.1(b) show the physical and virtual topology of the sample network. When partitioning is not applied in Fig. 3.1(c), the available slots are isolated thus create non-aligned available slots. When we apply partitioning in Fig. 3.1(d), the spectrum allocation is organized. Thus it creates more aligned available slots.

However, partitioning also negatively impacts the blocking probability due to the lack of statistical multiplexing gain [12]. In general, as the maximum number of acceptable connections, or channels, is increased, the blocking probability is decreased. For an example, we calculate the blocking probability using Erlang B loss formula [13] under a simple traffic model with a Poisson arrival process and an exponential distribution of the connection holding time. If the number of channels is 100 and the offered traffic is 100 Erlang, the blocking probability is 0.0757. Dividing the same channel resources among four partitions and splitting the traffic among the partitions (i.e, 25 channels with offered traffic volume of 25 Erlang), the blocking probability for each partition becomes 0.1438, which is higher than that of non-partitioning case. Because partitioning the subcarrier slots of each fiber link decreases the number of channels in each partition, the blocking probability may be increased.

Therefore, to improve the performance of partition approach in terms of blocking probability, the number of partitions must be minimized. Furthermore, to create more contiguous available slots, the partition approach adopts the first-last fit spectrum allocation policy, which is discussed in detail in section 3.4.

3.3 Model and assumption

We model the optical network as a connected graph $G(N, L)$, where the set of nodes is denoted as N, and the set of bi-directional optical fiber links connecting two nodes in N is denoted as L. Each fiber link has an order set $B=\{b_1, b_2, \cdots, b_{|B|}\}$ of slots. The following assumptions are considered in our model.

- Each fiber link can carry an equal number of subcarrier slots and the lightpaths are established in the network under spectrum contiguity and continuity constraint.
- The route, slot demand and traffic volume are known for each connection group.

For the remainder of this paper, the notations used are summarized in Table 3.1.

Table 3.1: Used symbol list

Symbol	Definition of Symbol
G	Graph representation of the optical network
N	Set of nodes; where $N = \{n_1, n_2, \cdots, n_{\vert N\vert}\}$
L	Set of links; where $L = \{l_1, l_2, \cdots, l_{\vert L\vert}\}$
B	Total set of subcarrier slots of each fiber link; where $B = \{b_1, b_2, \cdots, b_{\vert B\vert}\}$
V	Set of vertices in the graph coloring problem; where $V = \{v_1, v_2, \cdots, v_{\vert V\vert}\}$
E	Set of edges in the graph coloring problem; where $E = \{e_1, e_2, \cdots, e_{\vert E\vert}\}$
O	Set of colors in the graph coloring problem; where $O = \{o_1, o_2, \cdots, o_{\vert O\vert}\}$
n	Number of required partitions for subcarrier slots of each fiber link
P	Set of partitions on subcarrier slots of each fiber link; where $P = \{p_1, p_2, \cdots, p_{\vert P\vert}\}$
C	Set of connection groups; where $C = \{c_1, c_2, \cdots, c_{\vert C\vert}\}$
Z	Set of connection requests; where $Z = \{z_1, z_2, \cdots, z_{\vert Z\vert}\}$
ψ	Contiguous aligned available slot ratio in the network
ψ_c	Contiguous aligned available slot ratio of connection group c
γ_c	Maximum contiguous aligned available slots of connection group c

3.4 Subcarrier-slot partition scheme with first-last fit spectrum allocation

This section presents the subcarrier-slot partition scheme with first-last fit spectrum allocation. This scheme separates the spectrum allocation of non-disjoint connections into different partitions to create more aligned available slots. This scheme also adopts first-last fit allocation policy to put the aligned available slots together between two partitions. This would lead to more contiguous aligned available slots.

The partition scheme is decoupled into two subproblems, namely, (i) partition assignment and (ii) first-last fit spectrum allocation.

3.4.1 Partition assignment

This subsection determines the number of required partitions of subcarrier slots for each fiber link. Determining the number of required partitions in the partition allocation problem can be expressed as a graph coloring problem [14].

3.4.1.1 Graph coloring problem

Our objective in partition allocation is to determine the minimum number of required partitions that accommodate all connection groups in the network with the constraint that connections assigned in the same partition must be disjoint.

We transform the partition assignment problem into a graph coloring problem by creating a graph, which we name a *connection group graph*. The connection group graph is a graph that indicates the relationship among the connection groups in the network.

The connection group transformation partition is described as follows. The route of each connection group is assumed to be given. A vertex of the connection group graph corresponds to a connection group per unit slot demand. For an example, a connection

Algorithm 1 Connection group graph transformation

Step 1 Initialize the set of vertices $V = \{\emptyset\}$ and the set of edges $E = \{\emptyset\}$.

Step 2 Vertex generation.

Step 2.1 Generate vertex v that corresponds to each connection group per unit slot demand, where $v = 1, 2, \cdots, |V|$ for $|V|$ paths, and then add v to V.

Step 3 Edge establishment.

Step 3.1 Establish edge (v,u) between $v \in V$ and $u \in V$ if the two connection groups corresponding to vertices v and u share at least one link, add (v,u) to E.

group that has two unit slot demands, yields two vertices. If two connection groups share a common link or more links, an edge is established between the two vertices. By default, vertices that correspond to the same connection group are connected by edge(s). Algorithm 1 shows the procedure used to create the connection group graph.

The graph coloring problem assigns a color to each vertex while satisfying the constraint that the same color is not assigned to adjacent vertices. Each color corresponds to each partition unit. A partition unit is a measurement unit indicating partition size. The minimum number of colors means the minimum number of partition units. After the minimum number of partition units is obtained, partition units that belong to the same connection group are put in adjacent order and merged into one partition. Hence, the connection group that contains larger slot demand is assigned to more partition units, and thus has a larger size partition.

3.4.1.2 Graph coloring problem as an ILP model

The graph coloring problem is formulated as an ILP. The objective function is defined as below.

$$\textbf{min} \quad n = \sum_{o \in O} y_o \tag{3.1a}$$

$$\textbf{s.t.} \quad \sum_{o \in O} x_v^o = 1 \quad \forall v \in V \tag{3.1b}$$

$$x_v^o + x_{v'}^o \leq y_o \quad \forall (v, v') \in E \ \forall o \in O \tag{3.1c}$$

$$y_{o_i} \geq y_{o_{i+1}} (i = 1, 2, \cdots, |O| - 1) \tag{3.1d}$$

$$y_o = \{0, 1\} \quad \forall o \in O \tag{3.1e}$$

$$x_v^o = \{0, 1\} \quad \forall v \in V, \quad \forall o \in O \tag{3.1f}$$

In Eqs. (3.1a)-(3.1f), n, V and E are the number of required partitions, a set of vertices and a set of edges, respectively. O represents a set of colors, where $O = \{o_1, o_2, \cdots, o_{|O|}\}$. Let x_v^o and y_o be binary variables. If vertex v is assigned with color o, the value of x_v^o is 1. Otherwise its value is 0. If o is used at least one time, the value of y_o is 1. Otherwise the value of y_o is 0.

Eq. (3.1a) expresses the objective function that minimizes the number of required partitions. It shows that the number of required partitions is equal to the total number of colors. Eq. (3.1b) indicates that each vertex is assigned only one color. Eq. (3.1c) ensures that two adjacent vertices must receive different colors. In other words, this constraint prevents two connection groups whose routes share the same link(s) from being assigned to the same partition. In addition, Eq. (3.1c) indicates that x_v^o must not exceed y_o for all $v \in V$. This means that if $v \in V$ such as $x_v^o = 1$ exists, y_o must be set to 1. Eq. (3.1d) states that partitions are used in an ascending order of the partition index $i \in O$. Finally, the last two constraints express that x_v^o and y_o are binary variables.

3.4.1.3 Heuristic partitioning algorithm

From the literature [7], it had been revealed that when the number of connection groups and/or size of the traffic volume becomes large, the computational complexity of the ILP (in section 3.4.1.2) increases and it becomes difficult to solve it within a practical time. Therefore, the largest degree first (LDF) algorithm [7] can be applied to solve the graph coloring problem. LDF attempts to color the vertices in a descending order of degree. LDF is a sequential coloring heuristic that attempts to color vertices on the basis of a specified order by using the minimum indexed color that is not used by adjacent vertices. In sequential ordering, if a vertex receives a particular color once, its color remains unchanged thereafter. The details of the largest degree first (LDF) algorithm are presented in Algorithm 2.

Algorithm 2 Largest degree first (LDF)

Step 1: Select the uncolored vertex with the largest degree.

Step 2: Choose the minimum indexed color from the colors that are not used by adjacent vertices.

Step 3: Color the selected vertex using the color described in step 2.

Step 4: If all the vertices are colored, LDF stops. Otherwise, LDF returns to step 1.

3.4.2 First-last fit spectrum allocation in partition scheme

This subsection describes the first-last fit spectrum allocation that is adopted in the partition scheme.

The first-last fit spectrum allocation policy always attempts to choose the lowest indexed slots in the odd number partition from the list of available slots. For the

Algorithm 3 First-Last Fit Allocation

Step 1: Check the arriving connection requests and search appropriate connections group(s) for them.

Step 2: Check the slot demand.

Step 3: Choose the partition(s) assigned for connection group(s). If the index number of the chosen partition is even number, go to step 5. Otherwise go to step 4.

Step 4: Search the required available slots from the smallest indexed slot in the chosen partition. If contiguous available slots larger than the slot demand are found, go to step 6. Otherwise go to step 7.

Step 5: Search the required available slots from the highest indexed slot in the chosen partition. If contiguous available slots larger than the slot demand are found, go to step 6. Otherwise go to step 7.

Step 6: Allocate the contiguous available slots. Return to step 1.

Step 7: Reject the connection request. Return to step 1.

even number partition, it attempts to choose the highest indexed slots from the list of available slots. The details of the first-last fit spectrum allocation policy are given in the Algorithm 3.

The first-last fit allocation policy adopted in the partition scheme is expected to provides more contiguous aligned available slots. To show this, we illustrate the comparison between the first-last fit allocation policy and other allocation policies, namely first fit and random fit, in Fig. 3.2. It shows that the first-last fit allocation policy put the aligned available slots together between two partitions. This would lead to contiguous aligned available slots.

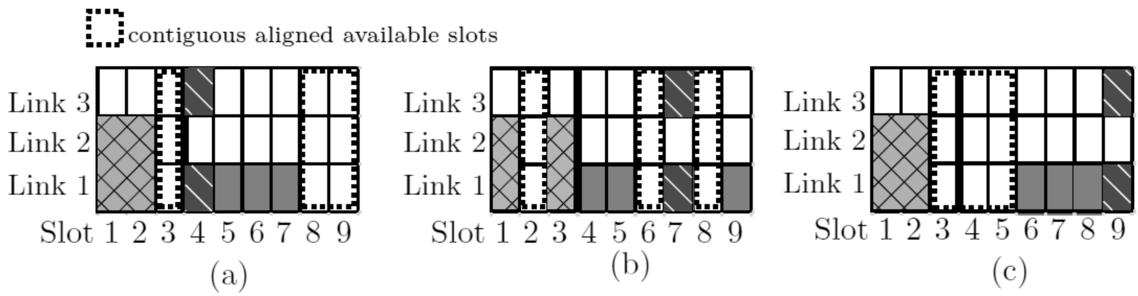
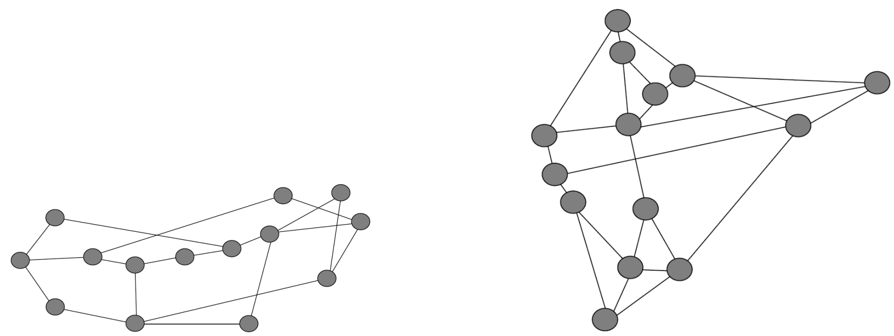


Figure 3.2: Comparison of the spectrum allocation policy (a) first-fit, (b)random-fit, and (c) first-last-fit

3.5 Performance evaluation

This section presents simulation results in two experimental setups to show that the partition scheme with first-last fit allocation policy reduces the blocking probability in the network. Our experimental setup consists of 14 nodes with 21 bi-directional physical links of NSFNET and 24 bi-directional physical links of the Indian network as shown in Fig. 3.3. We determine the number of required partitions for both NSFNET and the Indian network using Gnu Linear Programming Kit (GLPK) solver [14]. The number of required partitions in NSFNET and the Indian network are 14 and 24, respectively. The following assumptions have been made for the purpose of simulations.

- The distances between adjacent cities are used as the link cost for configuring the example networks - NSFNET and the Indian network.
- The channel spacing and the total number of subcarrier slots per channel are considered as 12.5 GHz and 400, respectively, according to [15].
- The connection requests are generated randomly based on a Poisson process and the holding time of connection requests follows an exponential distribution.
- The routes between source-destination pairs are estimated using shortest path routing.



(a) NSFNET (b) Indian network

Figure 3.3: Networks of the performance evaluation.

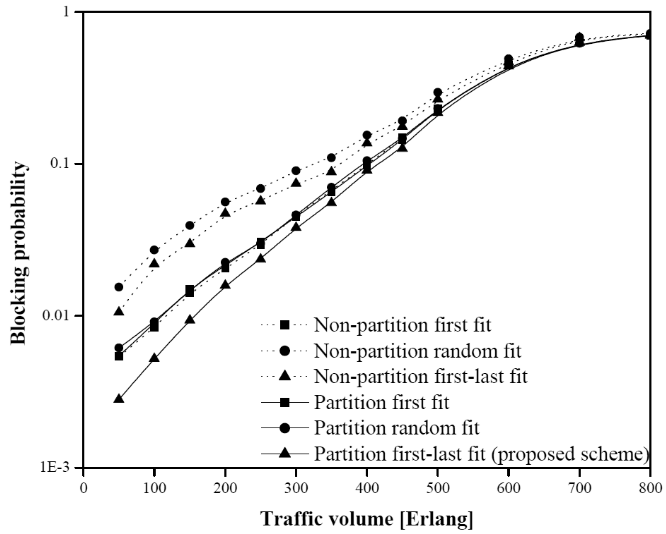
- The slot demand for each connection is distributed using a random-generated traffic matrix.

We compare the performance of the partition scheme different spectrum allocation policies, namely, first fit and random fit. We have performed the simulation study with the number of connection requests 10000, distributed randomly among all the possible source-destination pairs.

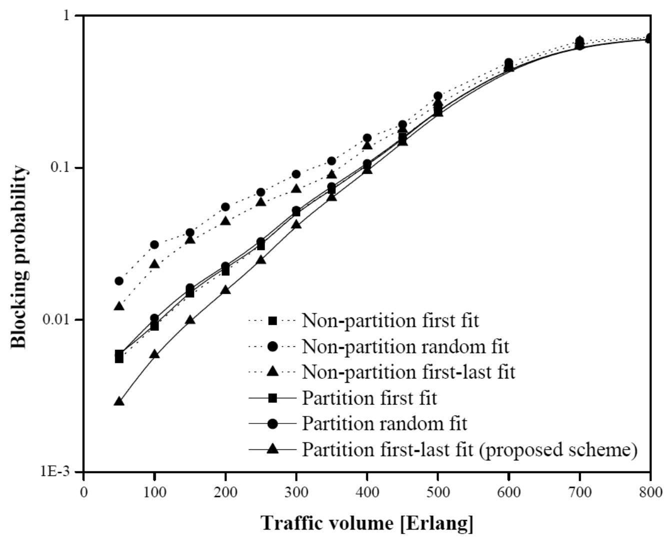
3.5.1 Evaluation of blocking probability

We evaluate the performance of the partition scheme in terms of the call blocking in the network.

Figures 3.4a and 3.4b show the blocking probability of the partition and non-partition approach with different spectrum allocation policies, namely, first fit, random fit, and first-last fit, for NSFNET and the Indian network, respectively. It is evident from both figures that the partition approach with first-last fit spectrum allocation policy provides the lowest blocking probability. This is possibly due to the partitioning approach and the first-last fit spectrum allocation policy. The partitioning approach provides more aligned available slots and the first-last fit spectrum allocation policy gives more contiguous available slots. As a result, the maximum number of connections



(a) NSFNET



(b) Indian network

Figure 3.4: Blocking probability versus traffic volume.

is established compared to other schemes.

We can also observe that the partition approach with first fit spectrum allocation policy provides higher blocking probability compared to the non-partition approach with first fit spectrum allocation policy. This is because the first fit spectrum allocation policy provides more contiguous available slots without the partitioning approach.

The non-partition approach with first fit spectrum allocation policy also has more contiguous available slots than the non-partition approach with first-last fit spectrum allocation policy. This is because in the non-partition approach with first-last fit spectrum allocation policy, the contiguous available slots are smaller than in the non-partition approach with first fit spectrum allocation policy since these slots are squeezed in the middle of the subcarrier slots. Therefore, the blocking probability using the non-partition approach with first-last fit spectrum allocation policy is lower than that of using the non-partition approach with first fit spectrum allocation policy.

The random fit spectrum allocation policy provides the worst performance in terms of the blocking probability compared to the other spectrum allocation policies. This is because the random fit policy allocates slots randomly, and thus the number of contiguous available slots is reduced.

The partition approach with random fit spectrum allocation policy allocates the slots randomly inside each partition and results in more aligned available slots compared to the non-partition approach with random fit spectrum allocation policy. This in turn leads to lower blocking probability compared to the non-partition approach with random fit spectrum allocation policy.

Let us observe how much traffic volume is admissible to guarantee the blocking probability less than a specified value, which is determined by the network designer. We assume that a value of blocking probability, which is 0.01. We can observe from Fig. 3.4a that the the partition scheme with first-last fit allocation policy provides blocking probability lower than 0.01 until the traffic volume reaches 200 Erlang. On the other hand, the non-partition approach with the first fit allocation policy reaches blocking probability 0.01, while there are 150 Erlang traffic volume. Figure 3.4b also observes the same effectiveness as that Fig. 3.4a. The above discussion suggests that the partition scheme with first-last fit allocation policy increases the amount of admissible traffic volume.

From the above simulation study, it is shown that the partition scheme with first-last fit allocation policy with outperforms in terms of blocking probability. This is possibly due to the partitioning approach, which provides more aligned available slots, and the first-last fit spectrum allocation policy, which gives more contiguous available slots. Therefore, we evaluate the effect of both partitioning and non-partitioning approach using different spectrum allocation policies in terms of contiguous aligned available slot ratio in the next subsection.

3.5.2 Evaluation of the available slot ratio

The performance of the partition scheme in terms of contiguous aligned available slot ratio in the network is evaluated. We use the metric of contiguous aligned available slot ratio (ψ) to evaluate the contiguous aligned available slots based on their paths. We use the paths of each connection group to represent the contiguous aligned available slot ratio in the network. Thus, the contiguous aligned available slot ratio (ψ) for all the connection group is estimated by using Eq. (3.2).

$$\psi = \frac{\sum_{c \in C} (\psi_c)}{|C|}, \tag{3.2}$$

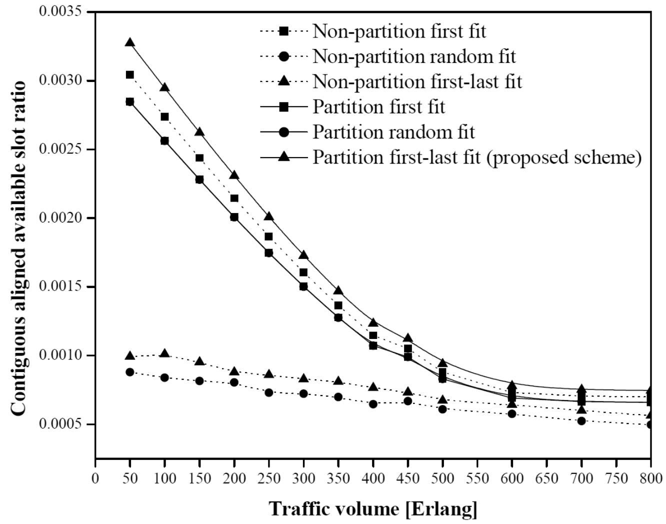
where

$$\psi_c = \frac{\gamma_c}{B}$$

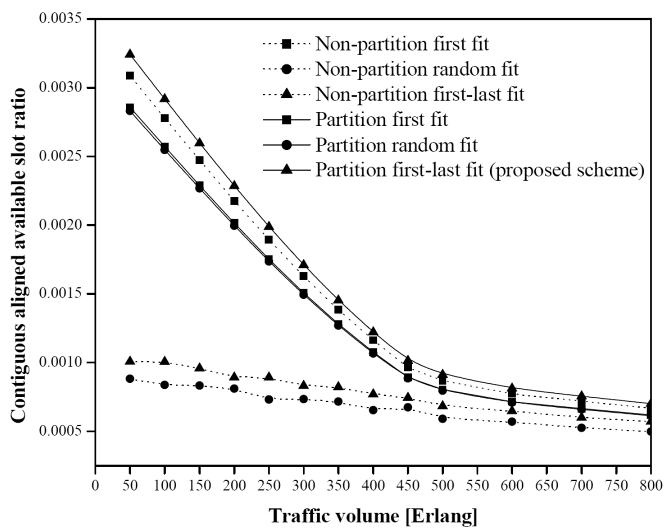
In Eq. (3.2), C represents the set of all the connection groups. γ_c presents the maximum number of contiguous aligned available slots for the connection group c. B refers to the total number of subcarrier slots.

To evaluate the performance of the combination of both partitioning approach and first-last fit spectrum allocation policy in the partition scheme, we estimate the contiguous aligned available slot ratio as per Eq. (3.2).

Figures 3.5a and 3.5b show the contiguous aligned available slot ratio versus traffic volume of the partition and non-partition approach with different spectrum allocation policies for NSFNET and the Indian network, respectively. We can observe from both



(a) NSFNET



(b) Indian network

Figure 3.5: Contiguous aligned available slot ratio versus traffic volume.

figures that the partition scheme with first-last fit policy provides more contiguous aligned available slots. This is due to the combination of the partitioning approach that provides more aligned available slots, and the first-last fit spectrum allocation policy which makes the aligned available slots to be more contiguous.

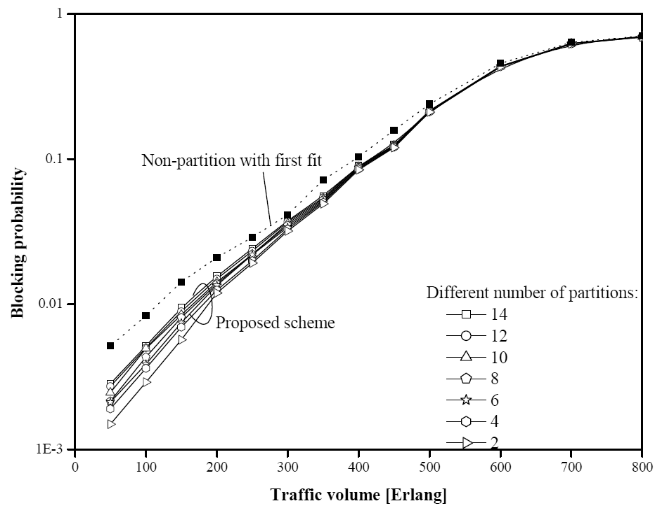
The analysis of this section indicates that the partition scheme with first-last fit policy provides more contiguous aligned available slots compared to the others, and hence the blocking probability in the network is the lowest.

3.5.3 Reducing the number of partitions

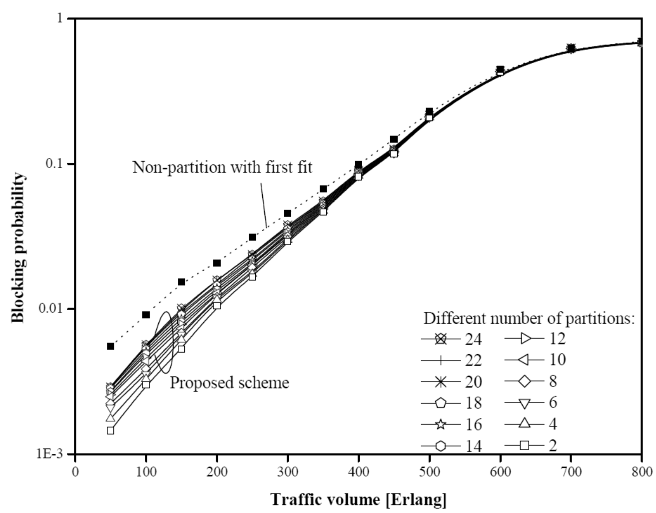
As we already mentioned in section 3.2, partitioning would be beneficial for reducing the blocking probability in elastic optical networks, provided the number of partitions is minimized. Therefore, this section evaluates the performance of our partition scheme with first-last fit policy in terms of the blocking probability as the number of partitions is reduced. Here, we further reduce the number of partitions in the partition scheme with the consequence that not all connection groups assigned in the same partition are disjoint.

We compare the partition scheme with first-last fit allocation policy to the non-partition approach with first fit spectrum allocation policy, as the performance of the non-partition approach with first fit policy is better compared to the non-partition approach with other spectrum allocation policies.

Figures 3.6a and 3.6b show the blocking probability of the partition scheme with first-last fit allocation policy under a different number of partitions and the non-partition approach with first fit spectrum allocation policy for NSFNET and the Indian network, respectively. We observe that when the number of partitions is two, the blocking probability is the lowest among other number of partitions. Therefore, we deduce that the reduction of the number of partitions could reduce the blocking probability. We analyze that too much partitioning can increase the blocking probability. This is because, partitioning reduce the size of contiguous available slots. Therefore, the minimum number of partitions must be maintained in the partition scheme.



(a) NSFNET



(b) Indian network

Figure 3.6: Blocking probability versus traffic volume under different number of partitions using partition scheme with first-last fit spectrum allocation for (a) NSFNET and (b) Indian network.

3.6 Conclusion

In this chapter, we presented a subcarrier-slot partition scheme with first-last fit spectrum allocation for elastic optical networks to increase the number of contiguous aligned available slots, and hence the blocking probability in the network is reduced. This scheme separates the subcarrier slots into several partitions, and spectrums are allocated to each partition based on the links utilized by particular connections.

The effectiveness of the partition scheme is investigated through performance evaluation in two examined optical networks. The simulation results have observed that the partition scheme with first-last fit allocation policy reduces the blocking probability by creating more contiguous aligned available slots. This scheme accommodate 33.33% more of the admissible traffic volume compared to the conventional first fit allocation policy when the blocking probability of 0.01 is expected.

Furthermore, it is indicated that the performance of the partition scheme improves in terms of blocking probability as the number of partitions is reduced. We analyze that too much partitioning can increase the blocking probability, because the size of contiguous available slots is reduced. To overcome this problem, next chapter will introduce a scheme that do not perform partitioning while maintaining the separation between the disjoint and non-disjoint connections.

Chapter 4

Spectrum allocation scheme based on first-last-exact fit policy

4.1 Introduction

This chapter described one of the scheme that suppressed fragmentation proactively in elastic optical networks, namely a spectrum allocation scheme based on first-last-exact fit policy. This scheme separates the disjoint and non-disjoint connections without using partitioning. By omitting partitions, this scheme is expected to provides more contiguous available slots compare to the partition scheme presented in the chapter 3.

The chapter is organized as follows. Section 4.3 describes the subcarrier-slot partition scheme with first-last fit spectrum allocation. The performance evaluation is presented in section 4.4. Finally, section 4.5 concludes this chapter.

4.2 Model and assumption

We model the optical network as a connected graph $G(N, L)$, where the set of nodes is denoted as N, and the set of bi-directional optical fiber links connecting two nodes in N is denoted as L. Each fiber link has an order set B=$\{b_1,\ b_2,\ \cdots,\ b_{|B|}\}$ of slots.

The following assumptions are considered in our model.

- Each fiber link can carry an equal number of subcarrier slots and the lightpaths are established in the network under spectrum contiguity and continuity constraint.
- The route, slot demand and traffic volume are known for each connection group.

For the remainder of this paper, the notations used are summarized in Table 4.1.

4.3 Spectrum allocation scheme based on first-last-exact fit policy

This section presents the spectrum allocation scheme based on first-last-exact fit policy. Similar with the partition scheme described in chapter 3, the spectrum allocation scheme based on first-last-exact fit separates the disjoint from the non-disjoint connections. However, to reduce the effect of partitions to the blocking probability, the first-last-exact fit scheme does not use partitioning. Instead, it uses spectrum allocation policy to separate the disjoint from the non-disjoint connections. We introduce a first-exact fit allocation policy for disjoint connections, and a last-exact fit allocation policy for non-disjoint connections. We use the term of first-last-exact fit allocation policy for the combination of these two policies, which attempts to use the exact number of contiguous available slots. This policy prevents small contiguous available slots.

The scheme is decoupled into two subproblems, namely, (i) creating disjoint connection group and (ii) first-last-exact fit spectrum allocation policy.

4.3.1 Creating disjoint connection group

This section presents the basis of our spectrum allocation scheme based on first-last-exact fit allocation policy. We categorize connection requests into two distinct groups,

Table 4.1: Used symbol list

Symbol	Definition of Symbol
G	Graph representation of the optical network
N	Set of nodes; where $N = \{n_1, n_2, \cdots, n_{\|N\|}\}$
L	Set of links; where $L = \{l_1, l_2, \cdots, l_{\|L\|}\}$
B	Total set of subcarrier slots of each fiber link; where $B = \{b_1, b_2, \cdots, b_{\|B\|}\}$
V	Set of vertices in the graph coloring problem; where $V = \{v_1, v_2, \cdots, v_{\|V\|}\}$
E	Set of edges in the path graph transformation problem; where $E = \{e_1, e_2, \cdots, e_{\|E\|}\}$
O	Set of colors in the path graph transformation problem; where $O = \{o_1, o_2, \cdots, o_{\|O\|}\}$
P	Set of source and destination pairs; where $P = \{p_1, p_2, \cdots, p_{\|P\|}\}$
w^p	Traffic demand between source and destination pair p
C	Set of connection groups; where $C = \{c_1, c_2, \cdots, c_{\|C\|}\}$
Z	Set of connection requests; where $Z = \{z_1, z_2, \cdots, z_{\|Z\|}\}$
ψ	Contiguous aligned available slot ratio in the network
ψ_p	Contiguous aligned available slot ratio of source and destination pair p
γ_p	Maximum contiguous aligned available slots of source and destination pair p

namely (i) disjoint connection group and (ii) non-disjoint connection group. The disjoint connection group is the set of connections whose end-to-end paths are disjoint to each other. We determine the disjoint connection group at the initial stage. The non-disjoint connection group contains the remaining connections whose end-to-end paths do not belong to the disjoint connection group.

The first-last-exact scheme uses different spectrum allocation policies based on types of connection groups. Connections belonging to the disjoint connection group adopt first-exact fit allocation policy, whereas connections belonging to the non-disjoint connection group adopt the last-exact fit allocation policy. The routing policy for a connection that belong to the disjoint connection group is determined by considering all the possible paths, whereas for non-disjoint connections use shortest path routing.

The first-last-exact scheme is decoupled into two subproblems, namely, (i) creating a disjoint connection group and (ii) spectrum allocation. The details of two steps of the first-last-exact fit scheme are presented in the following sections.

4.3.1.1 Optimum problem formulation

We model the network as a directed graph $G(N, L)$, where the set of nodes is denoted as N, and the set of links connecting two nodes in N is denoted as L. A link from node $i \in N$ to node $j \in N$ is denoted as $(i, j) \in L$. P is the set of all possible source-destination pairs in the network. $p = (s, d) \in P$ represents a source-destination pair. w^p represents the traffic demand between the source-destination pair p.

The spectrum allocation for disjoint connections leads to creating aligned available slots, as they do not share any common link. It is desirable that the disjoint connection group accommodates as large number of connections as possible. Therefore, the objective of creating a disjoint connection group is to maximize the total traffic demands of the connections whose paths are disjoint. This optimization problem is formulated as an integer linear programming (ILP) model as below.

$$\textbf{max} \quad \sum_{p \in P} g_p w_p \tag{4.1a}$$

$$\textbf{s.t.} \quad \sum_{(i,j) \in L} x_{ij}^p - \sum_{(j,i) \in L} x_{ji}^p = 1$$

$$\forall p = (s, d) \in P, i = s \tag{4.1b}$$

$$\sum_{(i,j)\in L} x_{ij}^p - \sum_{(j,i)\in L} x_{ji}^p = 0$$
$$\forall p = (s,d) \in P, i \neq s, d \tag{4.1c}$$
$$\sum_{p\in P} z_{ij}^p \leq 1 \quad \forall (i,j) \in L \tag{4.1d}$$
$$z_{ij}^p \leq x_{ij}^p \quad \forall (i,j) \in L, p \in P \tag{4.1e}$$
$$z_{ij}^p \leq g_p \quad \forall (i,j) \in L, p \in P \tag{4.1f}$$
$$z_{ij}^p \leq x_{ij}^p + g_p - 1 \quad \forall (i,j) \in L, p \in P \tag{4.1g}$$
$$z_{ij}^p = \{0,1\} \quad \forall (i,j) \in L, p \in P \tag{4.1h}$$
$$g_p = \{0,1\} \quad \forall p \in P \tag{4.1i}$$
$$x_{ij}^p = \{0,1\} \quad \forall (i,j) \in L, p \in P \tag{4.1j}$$

In Eqs. (4.1a)-(4.1j), g_p, x_{ij}^p, and z_{ij}^p are binary decision variables. If a path between source-destination pair p belongs to the disjoint connection group, g_p is 1, otherwise its value is 0. If $(i,j) \in L$ is used for source-destination pair p, x_{ij}^p is 1, otherwise 0. Lastly, if the link (i,j) is used for the source-destination pair p and is put into the disjoint connection group, z_{ij}^p is 1, otherwise 0.

Eq. (4.1a) expresses the objective function that maximizes the total traffic demands of the disjoint connection group. Eqs. (4.1b) and (4.1c) represent the flow constraints. Eq. (4.1d) ensures that the disjointness of paths in the disjoint connection group. It also describes that a path between a source-destination pair is not split. Eqs. (4.1e)-(4.1g) show the relationship between variables g_p, x_{ij}^p, and z_{ij}^p. It indicates that z_{ij}^p must be equal to 1, if both g_p and x_{ij}^p are 1. Finally, the last three constraints in Eqs. (4.1h)-(4.1j) are used to express the binary variables.

4.3.1.2 Heuristic approach

The ILP model presented in section 4.3.1.1 considers all the possible paths for all source-destination pairs in the network as decision variables. As the network size becomes large, the computational complexity of the ILP model increases and it becomes difficult to solve it within a practical time. Therefore, we introduce a heuristic approach that consists of two algorithms for transforming the problem into a graph, and creating the disjoint connection group in order to maximize the traffic demand.

In the Algorithm 4, multiple paths for all the source-destination pairs are determined in an advance. We can adapt any routing policy to determine the multiple paths, such as k shortest paths [4]. We assume that the traffic demand of each source-destination pair is known in advance, and one of multiple paths belonging to the same source-destination pair is used with the given traffic demand.

Transformation to Path Graph

After obtaining the set of paths for all source-destination pairs, we transform these paths into a graph, which we name a *path graph*. The path graph is a graph that indicates the relationship among the multiple paths of all the source-destination pairs.

The details of the path graph transformation is presented in Algorithm 4. Step 1 initializes the graph, whereas step 2 generates vertices of the graph. A vertex corresponds to a path. Each vertex is assigned with a value that corresponds to the traffic demand of the path. Step 3 generates the edges of the graph. It establishes an edge between two vertices that belong to the multiple paths of the same source-destination pairs. This guarantees that the multiple paths of the same source-destination pairs are not be assigned in the disjoint connection group together. It also establishes an edge between two vertices that belong to non-disjoint paths. This ensures that all the members of the disjoint connection group have disjoint paths.

Largest Value First

After transforming all the paths into the path graph, we maximize the total traffic demands in the disjoint connection group. We introduce a largest value first algorithm to select the appropriate member of the disjoint connection group.

The largest value first algorithm is presented in Algorithm 5. This algorithm assigns

Algorithm 4 Path Graph Transformation

Step 1: Initialize the set of vertices $V = \{\emptyset\}$ and the set of edges $E = \{\emptyset\}$.

Step 2: Vertex generation.

2.1: Generate vertex v that corresponds to each path, where $v = 1, 2, \cdots, |V|$ for $|V|$ paths, and then add v to V.

2.2: Generate vertex value w_v, which corresponds to each traffic demand of the path associated with vertex v.

Step 3: Edge establishment.

3.1: Establish edge (v,u) between $v \in V$ and $u \in V$ if the two paths corresponding to vertices v and u are multiple paths of the same source-destination pairs, add (v,u) to E.

3.2: Establish edge (v,u) between $v \in V$ and $u \in V$ if the two paths corresponding to vertices v and u share at least one link, add (v,u) to E.

Algorithm 5 Largest Value First

Step 1: Select the unmarked vertex with the largest value, mark the selected vertex.

Step 2: If no adjacent vertex with the selected vertex belongs to the disjoint connection group, go to step 3. Otherwise go to step 4.

Step 3: Put the selected vertex into the disjoint connection group.

Step 4: If all the vertices are marked, the algorithm stops. Otherwise, go to step 1.

the member of the disjoint connection group in descending order of vertex value, where each vertex value represents a traffic demand. In the initial stage, all the vertices are set to be unmarked vertices. This algorithm selects an unmarked vertex with the largest value, and mark this vertex. If no adjacent vertex with the selected vertex belongs to the disjoint connection group, the selected one is put into the disjoint connection group. This algorithm repeats the same procedure until all the vertices are marked.

4.3.2 First-last-exact fit spectrum allocation policy

This section presents the spectrum allocation of the connection request. We introduce a first-last-exact fit allocation policy to separate the disjoint and non-disjoint connections. The first-last-exact allocation policy is a combination of two allocation policies, namely, (i) first-exact fit and (ii) last-exact fit. The first-exact fit allocation policy is performed on connections whose end-to-end paths belong to the disjoint connection group. Last-exact fit allocation policy is performed on connections whose end-to-end paths belong to the non-disjoint connection group. These two allocation policies are expected to prevent small contiguous available slots that might be difficult to use for future connection requests. Each of the allocation policy is explained in the following subsections.

4.3.2.1 First-Exact Fit Allocation Policy

The first-exact fit allocation policy chooses the lowest indexed slot from the list of available slots that have the number of available contiguous slots exactly the same with the number of slot demand. If there is no exact available contiguous slots, this policy allocates spectrum slots from the lowest indexed available slots. This approach is similar to the conventional first fit allocation policy [19] except that it attempts to search the exact available contiguous slots at first. The details of the first-exact fit allocation policy are given in Algorithm 6.

Algorithm 6 First-Exact Fit Allocation

Step 1: Check the slot demand.

Step 2: Search the required available slots from the smallest indexed slot. If contiguous available slots equal to the slot demand are found, go to step 4. Otherwise go to step 3.

Step 3: Search the required available slots from the smallest indexed slot. If contiguous available slots larger than the slot demand are found, go to step 4. Otherwise go to step 5.

Step 4: Allocate the contiguous available slots. Return to step 1.

Step 5: Reject the connection request. Return to step 1.

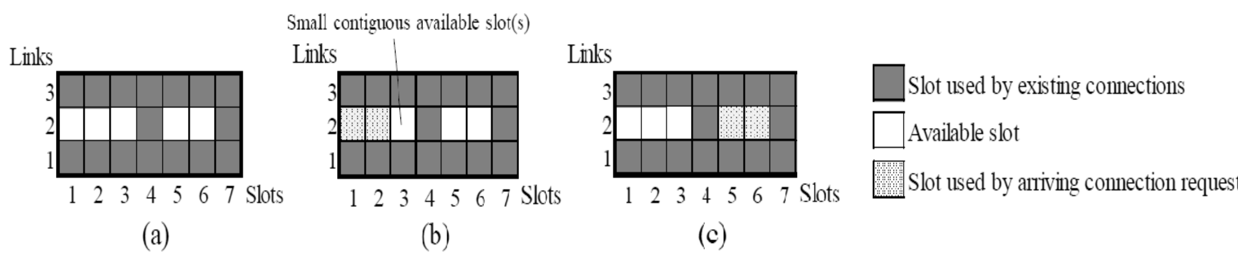


Figure 4.1: (a) Network subcarrier slot initial condition, and spectrum allocation using (b) first fit and (c) first-exact fit policies.

4.3.2.2 Last-Exact Fit Allocation Policy

The last-exact fit allocation policy chooses the highest indexed slot from the list of available slots that have the number of available contiguous slots exactly the same with the number of slot demand. If there is no exact contiguous available slots, this policy allocates spectrum slots from the highest indexed slot from the list of available slots. The details of the last-exact fit allocation policy are given in Algorithm 7.

Algorithm 7 Last-Exact Fit Allocation

Step 1: Check the slot demand.

Step 2: Search the required available slots from the highest indexed slot. If contiguous available slots equal to the slot demand are found, go to step 4. Otherwise go to step 3.

Step 3: Search the required available slots from the highest indexed slot. If contiguous available slots larger than the slot demand are found, go to step 4. Otherwise go to step 5.

Step 4: Allocate the contiguous available slots. Return to step 1.

Step 5: Reject the connection request. Return to step 1.

Figure 4.1 explains an example of the advantage of *exact* fit, which can be applied to both first-exact and last-exact fit policies. Figure 4.1(a) shows a condition of the subcarrier slots, where slots 1, 2, 3, 5, and 6 are available in link 2. When a connection (using link 2) with two slot demands arrives, its slots are allocated differently depending on the allocation policy. If we use the first fit allocation policy, slots 1 and 2 are allocated, as shown as shown in Fig. 4.1(b). In this case, if any future connection request arrives with three slots demand, it can not be established due to the lack of contiguous available slots. However, if we use the first-exact fit policy, as shown in Fig. 4.1(c), the future connection request with three slot demands can be established.

4.4 Performance evaluation

This section presents simulation results in two experimental setups to show that the first-last-exact fit scheme reduces the blocking probability in the network. Our experimental setup consists of 14 nodes with 21 bi-directional physical links of NSFNET and 24 bi-directional physical links of the Indian network as shown in Fig. 3.3. We determine the number of required partitions for both NSFNET and the Indian network using Gnu Linear Programming Kit (GLPK) solver [14]. The number of required partitions in NSFNET and the Indian network are 14 and 24, respectively. The following assumptions have been made for the purpose of simulations.

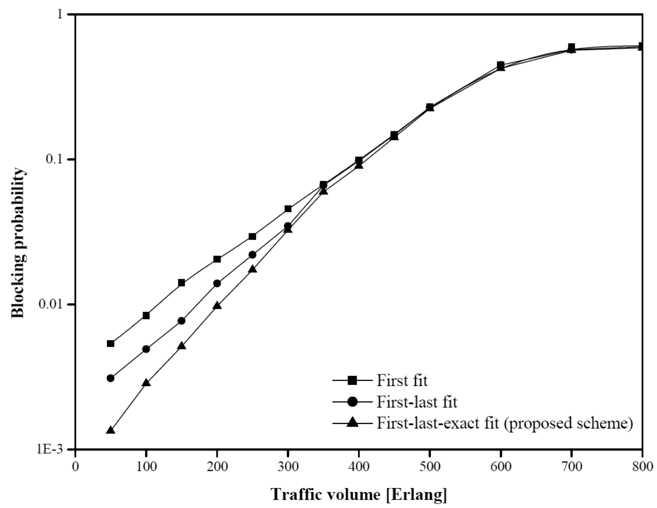
- The distances between adjacent cities are used as the link cost for configuring the example networks - NSFNET and the Indian network.
- The channel spacing and the total number of subcarrier slots per channel are considered as 12.5 GHz and 400, respectively, according to [15].
- The connection requests are generated randomly based on a Poisson process and the holding time of connection requests follows an exponential distribution.
- The slot demand for each connection is distributed using a random-generated traffic matrix.

We compare the performance of the first-last-exact fit scheme with the partition approach using different spectrum allocation policies, namely, first fit and random fit. We have performed the simulation study of the first-last-exact fit scheme with the number of connection requests 10000, distributed randomly among all the possible source-destination pairs.

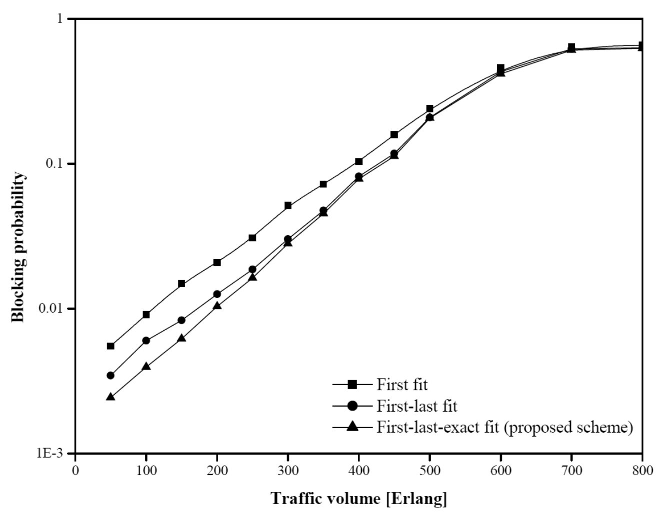
In the first-last-exact fit scheme, we create the disjoint connection group using the ILP model presented in 4.3.1.1. The ILP model is solved by the IBM ILOG CPLEX optimization solver [1].

4.4.1 Evaluation of blocking probability

We evaluate the performance of the first-last-exact fit scheme in terms of the call blocking in the network.



(a) NSFNET



(b) Indian network

Figure 4.2: Blocking probability versus traffic volume.

Figures 4.2a and 4.2b show the blocking probability versus traffic volume of the the conventional first fit spectrum allocation policy, the first-last fit spectrum allocation policy, and the first-last-exact fit scheme for NSFNET and the Indian network, respectively. It is evident that the first-last-exact fit scheme lower blocking probability compared to the conventional first fit allocation policy. Furthermore, we observe that the first-last-exact fit scheme has lower blocking probability than the first-last fit allocation policy. This is because the first-last-exact fit allocation policy prevents small contiguous available slots. Thus, it accommodates more future connection requests, and reduces the blocking probability in the network.

Let us observe how much traffic volume is admissible to guarantee the blocking probability less than a specified value, which is determined by the network designer. We assume that a value of blocking probability, which is 0.01. We can observe from Fig. 4.2a that the the first-last-exact fit scheme provides blocking probability lower than 0.01 until the traffic volume reaches 250 Erlang. On the other hand, the first fit allocation policy reaches blocking probability 0.01, while there are 150 Erlang traffic volume. Figure 4.2b also observes the same effectiveness as that Fig. 3.4a. The above discussion suggests that the first-last-exact fit scheme increases the amount of admissible traffic volume.

From the above simulation study, it is shown that the first-last-exact fit scheme with outperforms in terms of blocking probability. This is due to the separation of the disjoint and non-disjoint connections in the first-last-exact fit scheme. This separation provides more aligned available slots thereby reducing the blocking probability in the network. Furthermore, the exact fit allocation policy provides more contiguous aligned available slots. Therefore, we evaluate the effect first-last-exact fit allocation policy in terms of contiguous aligned available slot ratio in the next subsection.

4.4.2 Evaluation of the available slot ratio

The performance of the first-last-exact fit scheme in terms of contiguous aligned available slot ratio in the network is evaluated. We use the metric of contiguous aligned available slot ratio (ψ) to evaluate the aligned available slots based on their paths. We use the paths of source-destination pairs in the disjoint connection group to represent the contiguous aligned available slot ratio in the network. Thus, the contiguous aligned available slot ratio (ψ) for all source-destination pairs in the disjoint connection group is estimated by using Eq. (4.2).

$$\psi = \frac{\sum_{p \in P^{disjoint}} (\psi_p)}{|P^{disjoint}|}, \tag{4.2}$$

where

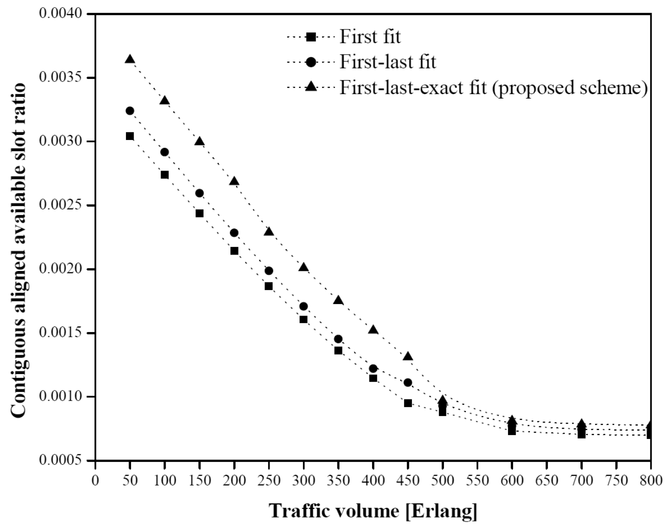
$$\psi_p = \frac{\gamma_p}{B}$$

In Eq. (4.2), $P^{disjoint}$ represents the set of all the source-destination pairs in the disjoint connection group. γ_p presents the maximum number of contiguous aligned available slots for the end-to-end path of the source-destination pair p. B refers to the total number of subcarrier slots.

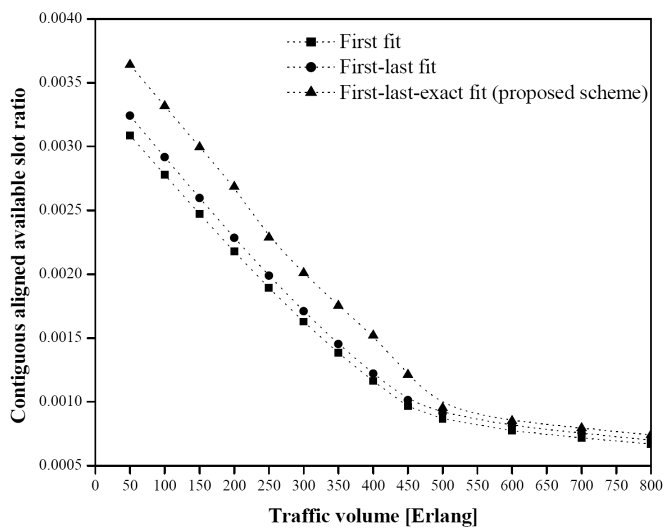
Figures 4.3a and 4.3b show the contiguous aligned available slot ratio versus traffic volume of the the conventional first fit spectrum allocation policy, the first-last fit spectrum allocation policy, and the first-last-exact fit scheme for NSFNET and the Indian network, respectively. We can observe from the figures that the first-last-exact fit scheme has a higher contiguous aligned available slot ratio than the conventional scheme. This is because the first-last-exact fit scheme separates the disjoint and non-disjoint connections thereby providing more aligned available slots. The first-last-exact fit scheme eliminates small contiguous available slots and thus provides a higher number of contiguous aligned available slots.

4.4.3 Evaluation of the heuristic approach

Our introduced ILP model is used to create the disjoint connection group in the first-last-exact fit scheme when the network size is reasonable. However, if the network size increases, the ILP model is unable to solve it within a practical time. In that situation, our introduced heuristic approach is required to solve it. Therefore, this section compares the performance of the heuristic approach and ILP model. In the heuristic approach, a set of multiple paths for each source-destination pair is determined by using the k shortest path routing algorithm when creating the disjoint connection group.



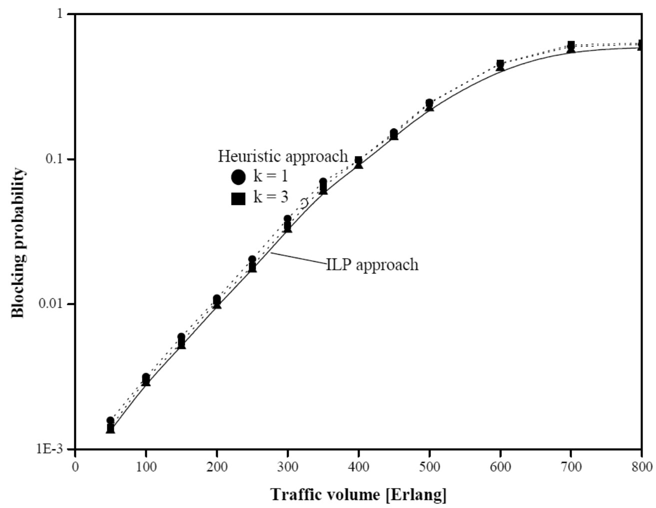
(a) NSFNET



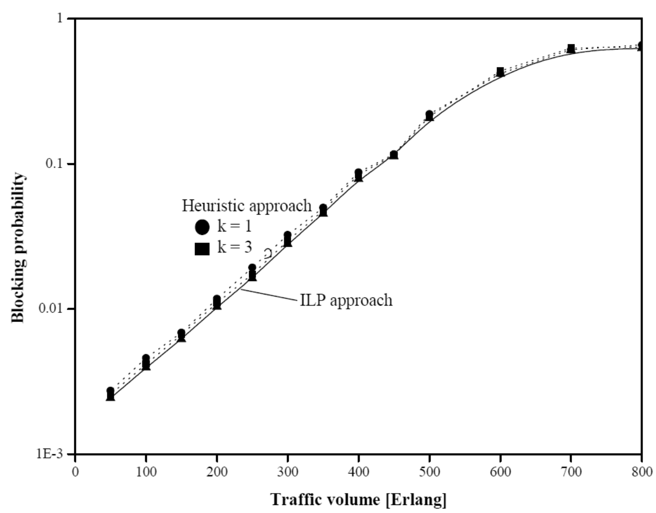
(b) Indian network

Figure 4.3: Contiguous aligned available slot ratio versus traffic volume.

Figures 4.3a and 4.3b show the blocking probability between the first-last-exact fit scheme with ILP model and with heuristic approach for NSFNET and the Indian network, respectively. We observe that the blocking probability decreases as the the value of k, which is the allowable number of multiple paths of a source-destination pair, increases. This is because a larger number of possible multiple path candidates



(a) NSFNET



(b) Indian network

Figure 4.4: Blocking probability versus traffic volume obtained by using heuristic approach and ILP model.

give more flexibility in creating the disjoint connection group. Furthermore, the results indicate that the performance of the heuristic approach with $k = 3$ provides similar results with the ILP model. This is because in the heuristic approach with $k = 3$, the set of multiple paths already covers the paths chosen in the ILP model.

The above simulation results indicate that the heuristic approach provides comparable results to the ILP model. Therefore, for a large network where ILP model does not provide solution within a practical time, our introduced heuristic approach should be adopted.

4.5 Conclusion

This chapter presented a spectrum allocation scheme based on first-last-exact fit allocation policy for elastic optical networks in order to increase the number of aligned available slots and avoids small contiguous available slots. The simulation results have shown that the first-last-exact fit policy provides a higher number of contiguous aligned available slots, and hence the blocking probability in the network is reduced. We have observed that the first-last-exact fit policy accommodates 50% more of the admissible traffic volume compared to the conventional first fit allocation policy when the satisfied blocking probability is considered 0.01. Furthermore, it is indicated that the heuristic approach provides similar results with the ILP approach given that the number of k of the k shortest path increased.

Chapter 5

Conclusion

This thesis has introduced a spectrum allocation suppressing fragmentation proactively in elastic optical networks. It prevents bandwidth fragmentation proactively by increasing the number of aligned and contiguous available slots without rerouting of connections. The spectrum allocation is presented into two schemes, namely, subcarrier-slot partition scheme with first-last fit spectrum allocation and spectrum allocation scheme based on first-last-exact fit allocation policy. Both of the schemes increase the number of contiguous aligned available slots. The performance evaluation showed that our schemes outperforms the conventional first fit allocation policy in terms of blocking probability. The results suggest that our presented schemes can be implemented by elastic optical networks operator to prevent the bandwidth fragmentation thus reducing the blocking probability.

Publications and Patent

Conference Publications

[1] Fadini, W. and Oki, E. ‘A Subcarrier-slot Partition Scheme for Wavelength Assignment in Elastic Optical Networks,’ IEEE 15th International Conference on High Performance Switching and Routing (HPSR 2014), pp: 7-12, Jul. 2014 (runner up best paper award).
[2] Fadini, W., Chatterjee, B. C., and Oki, E. ‘Performance Evaluation of Partition Scheme for Elastic Spectrum Allocation in Japan Photonic Network,’ IEICE Japan Photonic Network Design Contest (JPN 2014), pp:1-4, Nov. 2014.

Patent

[1] Patent application number 2014-12582 on June 2014, Japan

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