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A Subcarrier-Slot Partition Scheme for Wavelength Assignment in Elastic Optical Networks

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***Abstract*—In elastic optical networks (EONs), bandwidth fragmentation refers to the existence of non-aligned and non-contiguous subcarrier slots (unused) in the set of all subcarrier slots. Since wavelengths for a connection must be allocated on contiguous subcarrier slots, these non-aligned and non-contiguous available subcarrier slots could cause bandwidth blocking. This paper proposes a subcarrier-slot partition scheme for wavelength assignment in EONs that can yield more contiguous aligned available subcarrier slots, which reduces the bandwidth blocking probability. On this scheme, the total set of subcarrier slots is separated into several partitions and wavelengths are assigned to each partition based on the links utilized by particular connections. Numerical results from a simulation show that the proposed scheme with a suitable wavelength assignment policy outperforms the conventional scheme in terms of bandwidth blocking. We investigate the effect of different wavelength assignment policies in the proposed scheme. The results show that the first-last fit assignment policy gives lower bandwidth blocking probability than the first fit assignment policy.**

***Index Terms*—Elastic Optical Networks (EONs), wavelength assignment, bandwidth blocking probability.**

I. Introduction

Recent applications such as video-on-demand and teleconferencing require high bandwidth. Elastic Optical Networks (EONs) based on optical-orthogonal frequency division multiplexing (OFDM) have been considered as being able to accommodate such high bandwidth demand applications [1] [2]. The OFDM technology [3] uses overlapped subcarrier slots in the optical spectrum which results in high bandwidth efficiency. The OFDM transponder can assign an appropriate number of contiguous subcarrier slots based on the required bandwidth of a connection request. In this way, flexible granularity can be achieved in the optical layer which enables elastic optical networks.

The EONs allocate spectrum on contiguous subcarrier slots. A block of contiguous subcarrier slots is called a slot block. Since slot block size is elastic, it can be a few GHz or even narrower, dynamically setting up and tearing down connections can generate bandwidth fragmentation [4]. Bandwidth fragmentation is the condition in which available slot blocks are neither aligned along the routing path nor contiguous in the spectrum domain. Since the available slot blocks are non-aligned and non-contiguous, they are isolated from each other making it difficult to utilize them for future connection requests. When the available slot blocks can not fulfill the required bandwidth of a connection request, the connection request will be rejected/blocked. This is called bandwidth blocking. Bandwidth blocking probability is considered to be the ratio of the number of blocked connection requests caused by insufficient available slot blocks to the total number of connection requests.

To this end, researchers have developed routing and spectrum assignment (RSA) algorithms for bandwidth resource allocation in EONs [4], [5], [6], [7]. Kadohata et al. developed a bandwidth defragmentation scheme assuming the greenfield scenario (100% rerouting all the time) to solve bandwidth fragmentation [8]. To reduce the traffic disruption, Zhang et al. presented a defragmentation scheme that minimizes the required number of rerouting events [9].

The two conditions that cause bandwidth blocking, which are non-contiguous available slot blocks and non-aligned available slot blocks, are explained as follows [10]. The former occurs when one or more available slot blocks are not adjacent to each other; the number of adjacent blocks is insufficient. The latter occurs when one or more available slot blocks on different links on the same route are not aligned. Here, we assume that wavelength conversion is not performed at any transit node. Both of these conditions yield isolated slot blocks which increases the bandwidth blocking probability. It is clear that both conditions must be tackled to reduce the bandwidth blocking probability.

This paper proposes a subcarrier-slot partition scheme for wavelength assignment in EONs that reduces the number of non-aligned available slot blocks. We also introduce a wavelength assignment policy in the proposed scheme to reduce the number of non-contiguous available slot blocks. When wavelengths of two connections that use different routes, but share some link(s), are assigned on adjacent slot blocks, some available slot blocks might be non-aligned from each other. When another connection whose route needs these available slot blocks arrives, it is rejected because the non-aligned slot blocks are isolated. The proposed scheme separates the wavelength assignment of connections that use different routes which share the same one or more links. The total set of subcarrier slots is divided into several partitions. Disjoint connections whose routes do not share any links are assigned to the same partition, while non-disjoint connections are assigned to different partitions. The effect of the partitioning to the

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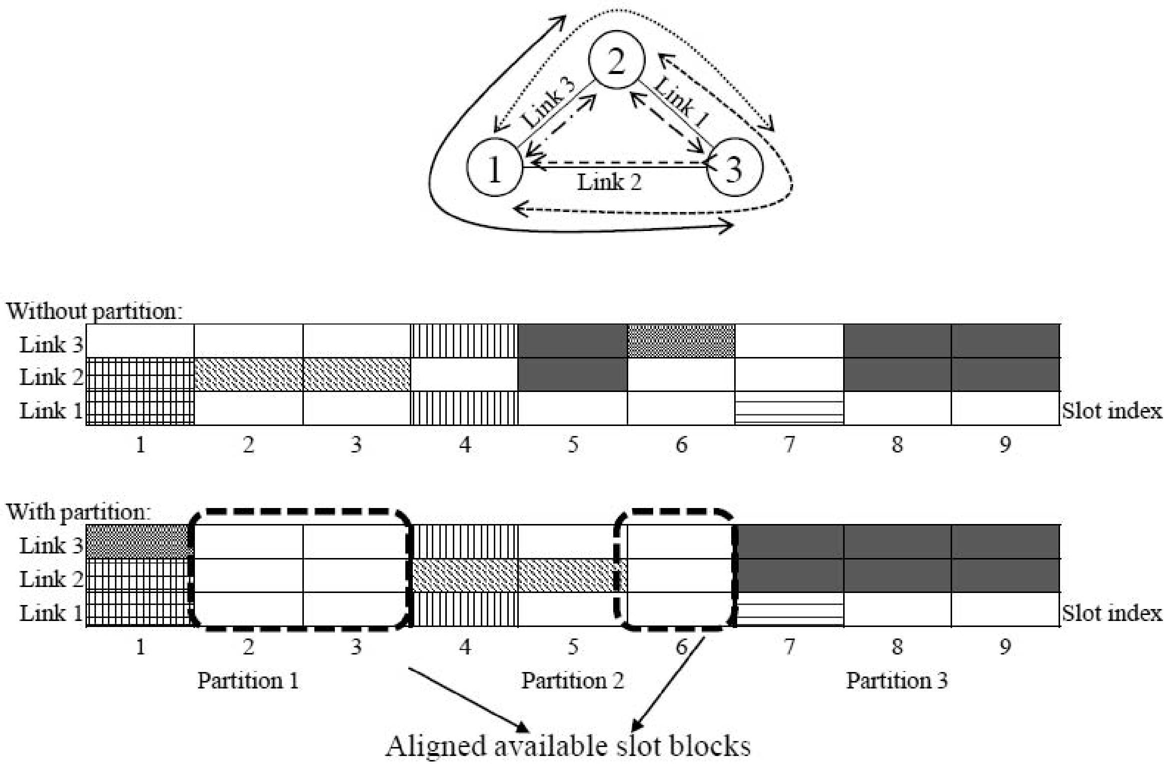

Fig. 1. Partition in EONs gives more aligned contiguous available slot blocks

blocking probability and characteristics of EONs that make partitions beneficial for reducing the blocking probability are presented. To gain more contiguous aligned available slot blocks, a first-last fit wavelength assignment policy is introduced and compared to the first fit assignment policy. We investigate the effect of these different wavelength assignment policies on the performance of the proposed scheme. Simulation results indicate that the proposed scheme with the first-last fit wavelength assignment policy reduces the bandwidth blocking probability effectively compared to the conventional non-partition scheme.

The rest of the paper is organized as follows. Section II discusses the effect of partitioning in EONs. Section III presents our proposed subcarrier-slot partition scheme. Section IV shows the performance evaluations. Finally, Section V summarizes the key points.

II. Partitioning in EONs

This section describes our interest in partitioning as a way to reduce the bandwidth blocking probability in EONs.

In EONs, wavelengths are assigned in a contiguous manner. Accordingly, assigning resources to short duration connections can increase the number of non-aligned available slot blocks if the assignment is not well organized. These non-aligned available slot blocks can be reduced by partitioning the total set of subcarrier slots.

However, partitioning also negatively impacts the blocking probability due to the lack of statistical multiplexing gain [11]. In general, as the maximum number of acceptable connections, or channels, is increased, the blocking probability is decreased. Therefore, following the same argument, partitioning the total set of subcarrier slots decreases the number of channels in each partition. This may increase the blocking probability. For example, we calculate the blocking probability using Erlang B loss formula under a simple traffic model with a Poisson arrival process and an exponential distribution of the connection holding time [12]; if the number of channels is 100 and offered traffic is 100 [erl], the blocking probability is 0.0757. Dividing the same channel resources among four partitions and splitting the traffic among the partitions (25 channels with offered traffic volume of 25 [erl]), the blocking probability for each partition becomes 0.1438, which is higher than the case without partitioning.

Therefore, based on the above discussion, partitioning might be beneficial for reducing the bandwidth blocking probability in EONs provided the number of partitions is minimized.

III. Proposed Sub-carrier Slot Partition Scheme

The section presents our proposed subcarrier-slot partition scheme. The subcarrier-slot partition scheme is divided into two steps: partition assignment and wavelength assignment.

A. Partition Assignment

Algorithm 1 Create graph coloring problem

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

Step 2: Vertex generation
Generate vertex v_{xy}, which corresponds to each connection group where $x = 1, \cdots, n$ and $y = 1, \cdots, m$ for n connection groups and m traffic demand units for each connection group, and then add v_{xy} to V. This procedure is applied to all connection groups.

Step 3: Edge establishment
Establish edge (v,w) between $v \in V$ and $w \in V$ if the two connection groups corresponding to vertices v and w share one or more links.

1) Graph Coloring Problem: Determining the minimum number of required partitions in the partition assignment problem can be expressed as a graph coloring problem [13]. We define a connection group as a set of connections whose routes are exactly the same, where the same link(s) are used. Two connection groups are considered disjoint if their routes do not share any link. Our objective in partition assignment is to determine partitions with the minimum number of required partitions that can hold all the connection groups in the network with the constraint that connection groups assigned in the same partition must be disjoint.

The partition assignment problem is transformed into a graph coloring problem as follows. The route of each connection is assumed to be given. A vertex corresponds to a connection group per unit traffic demand. For example, a connection group that has two unit traffic demands yields two vertices. If two connection groups share the same one 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). When two vertices are connected by an edge, they are adjacent. 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. Algorithm 1 shows the procedure used to create the graph coloring problem.

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 traffic demand is assigned to more partition units and thus will have a larger size partition.

2) Graph Coloring Problem as ILP problem: To formulate the graph coloring problem as an integer linear programming (ILP) problem, the following terminologies are defined. Let P be a set of partition units, where $P = \{p_1, p_2, \cdots, p_{|P|}\}$. Let x_v^p and y_p be binary variables. If a connection group per unit traffic demand corresponding to v is assigned in partition p, x_v^p = 1; otherwise x_v^p = 0. If p is used at least one time, y_p = 1; otherwise y_p = 0.

The graph coloring problem is formulated as an ILP problem as follows:

$$\textbf{min} \quad \sum_{p \in P} y_p \tag{1a}$$

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

$$x_v^p + x_{v'}^p \leq y_p \quad \forall (v, v') \in E \quad \forall p \in P \tag{1c}$$

$$y_{p_i} \geq y_{p_{i+1}} (i = 1, 2, \cdots, |P| - 1) \tag{1d}$$

$$y_p = \{0, 1\} \quad \forall p \in P \tag{1e}$$

$$x_v^p = \{0, 1\} \quad \forall v \in V, \quad \forall p \in P. \tag{1f}$$

Eq. (1a) expresses the objective function that minimizes the required number of partition units. Eq. (1b) indicates that each vertex is assigned only one partition unit. Eq. (1c) ensures that two adjacent vertices must receive different colors. In other words, this constraint prevents two connections whose routes share the same link(s) from being assigned to the same partition unit. In addition, Eq. (1c) also indicates that x_v^p must not exceed y_p for all $v \in V$. This means that if $v \in V$ such as x_v^p = 1 exists, y_p must be set to 1. Eq. (1d) states that partition units are used in ascending order of partition unit index $i \in P$. The last two constraints express binary constraints on variables x_v^p and y_p.

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) Heuristic partitioning algorithm: When the number of connection groups and/or size of the traffic demand becomes large, the complexity of the ILP computations in Section III-A2 increases and it becomes difficult to solve it in practical time. The largest degree first (LDF) algorithm [14] can be applied to solve the graph coloring problem.

LDF attempts to color the vertices in descending order of degree, where degree is the number of edges connected to the node. This algorithm is shown in Algorithm 2. 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.

B. Wavelength Assignment

After the number of required partitions is minimized and each connection group is assigned to the corresponding partition, the wavelength for each requesting connection can be assigned on the slot blocks in each corresponding partition. We introduce two types of wavelength assignment policies: first fit wavelength assignment and first-last fit wavelength assignment for odd-even partitions. The first-last fit wavelength assignment policy is expected to give more contiguous aligned available slot blocks than the first fit wavelength assignment policy. Figure 2 illustrates the first-last fit wavelength assignment policy.

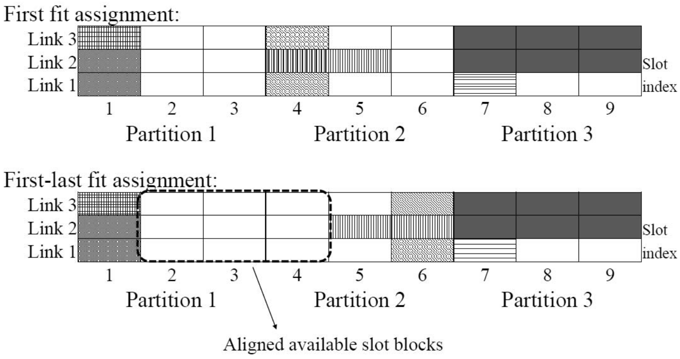

Fig. 2. First-last fit assignment gives more contiguous aligned available slot blocks

Algorithm 3 First fit wavelength assignment policy

W refers to connection request size;
S_p refers to contiguous aligned available slot blocks in each partition;
S_t refers to contiguous aligned available slot blocks in the total set of subcarrier slots;

Step 1: Check the arriving connection group;
Step 2: Assign the connection request to its group's partition;
if $S_p \geq W$ **then**
  Assign the connection request to the smallest index of the contiguous aligned available slot block in the partition;
  Finish
else
  if $S_t \geq W$ **then**
    Assign the connection request to the smallest index of the contiguous aligned available slot block in the total set of subcarrier slots;
    Finish
  else
    Reject the connection request;
    Finish
  end if
end if

The first fit wavelength assignment policy assigns wavelengths from the available lowest index number slot on each partition, see Algorithm 3. The first-last fit wavelength assignment policy assigns wavelengths from the available lowest index number slot on partition with an odd index number and assigns wavelengths from the available highest index number slot on partition with an even index number, see Algorithm 4.

Algorithm 4 First-last fit wavelength assignment policy

W refers to connection request size;
S_p refers to contiguous aligned available slot blocks in each partition;
S_t refers to contiguous aligned available slot blocks in the total set of subcarrier slots;

Step 1: Check the arriving connection group;
Step 2: Assign the connection request to its group's partition;
if $S_p \geq W$ **then**
  if the index of the partition is an odd number **then**
    Assign the connection request to the smallest index of the contiguous aligned available slot block in the partition;
    Finish
  else
    Assign the connection request to the largest index of the contiguous aligned available slot block in the partition;
    Finish
  end if
else
  if $S_t \geq W$ **then**
    Assign the connection request to the smallest index of the contiguous aligned available slot block in the total set of subcarrier slots;
    Finish
  else
    Reject the connection request;
    Finish
  end if
end if

IV. Performance Evaluation

A. *Overview of Evaluation*

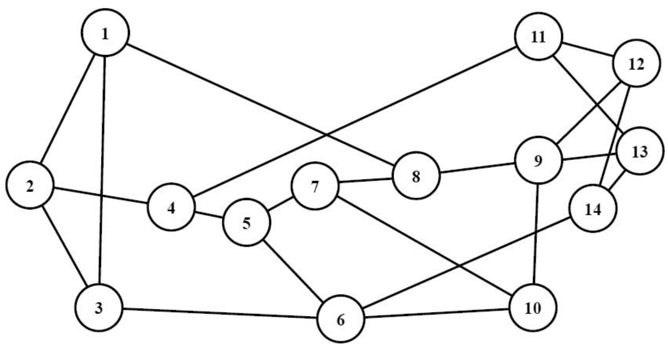

Fig. 3. Network topology

The performance of the proposed subcarrier-slot partition scheme is compared to that of the conventional non-partition scheme in terms of the bandwidth blocking probability and the number of aligned available slot blocks. Each scheme uses the two wavelength assignment policies, i.e. first fit and first-last fit.

We use the metric of aligned available slot blocks ratio (AASR) to investigate the effectiveness of the proposed scheme in terms of creating more aligned available slot blocks and the effect of this on the bandwidth blocking probability. We define AASR for connection group $c \in C$, where C denotes the set of connection groups, as follows:

$$\psi_c = \frac{A_c}{B}, \tag{2a}$$

where B refers to the total number of subcarrier slots and A_c returns the maximum number of contiguous available aligned slot-blocks for connection group $c \in C$. Thus, the average of AASR ψ for all connection groups is defined as:

$$\psi = \frac{\sum_{c \in C}(\psi_c)}{|C|} \tag{3a}$$

where $|C|$ refers to the total number of connection groups.

We perform simulations with the 14-node NSFNET topology shown in Figure 3. We use the same assumptions as used in [15]. Here the bandwidth of a subcarrier slot is set as 12.5 GHz and the total number of subcarrier slots are 300. The dynamic connection request arrivals are generated using a Poisson distribution and the holding time follows an exponential distribution. To focus on the partitioning effect, shortest path routing is adopted to simplify the discussion. The traffic demand for each connection is distributed using a random-generated traffic matrix. Based on the connection group and the traffic matrix, the minimum number of required partition units is 4. The number of slots in each partition unit is 75. On this simulation, each partition group has one partition unit, hence the number of required partitions is also 4.

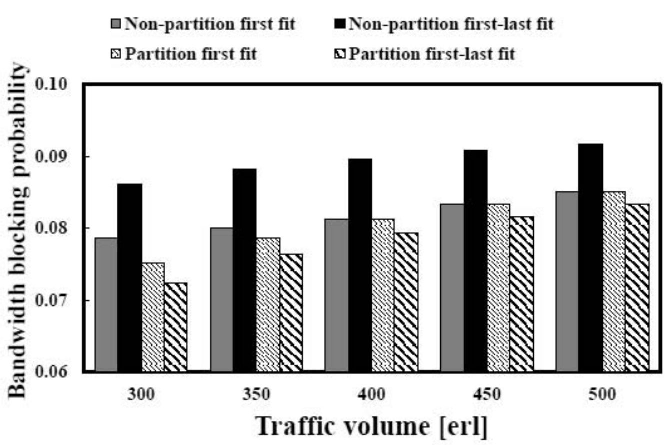

Fig. 4. Bandwidth blocking probability

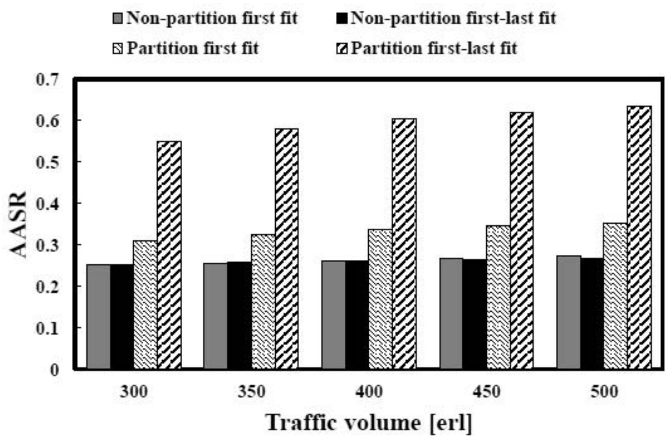

Fig. 5. Aligned available slot block ratio

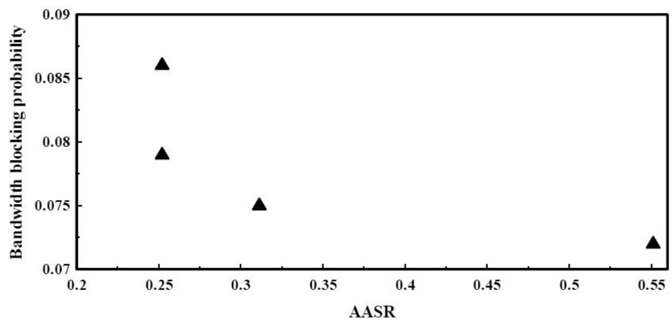

Fig. 6. Relationship between AASR and bandwidth blocking probability

B. *Comparison of Bandwidth Blocking Probability*

We compare the bandwidth blocking probabilities of the proposed subcarrier-slot partition scheme and the conventional non-partition scheme; the first fit wavelength assignment and first-last fit wavelength assignment policies are employed in each scheme. AASR is also compared.

Figure 4 shows the bandwidth blocking probability results. It shows that the proposed subcarrier-slot partition scheme with the first-last fit wavelength assignment policy gives the lowest bandwidth blocking probability.

Figure 4 also shows that the partition scheme with first fit wavelength assignment gives higher bandwidth blocking probability than the non-partition scheme with the first fit wavelength assignment policy. This is related to the condition of contiguous aligned available slot blocks. In the non-partition scheme with the first fit wavelength assignment policy, the available slot blocks are collected on the higher-index side of the total set of subcarrier slots. Whereas in the partition scheme with the first fit assignment policy, although it gives more aligned available slot blocks on each partition, the first fit assignment isolates these blocks from each other, and thus reduces the number of contiguous aligned available slot blocks.

Therefore, as the offered traffic volume increases, the contiguous available slot blocks gathered on the higher-index side of the total set of subcarrier slots in the non-partition scheme with the first fit wavelength assignment policy yields lower bandwidth blocking probability.

For the non-partition scheme with the first-last fit assignment policy, the contiguous available slot blocks are squeezed in the middle of the total set of subcarrier slots yielding fewer contiguous available slot blocks than the non-partition scheme with the first fit assignment policy. It also has fewer number of aligned available slot blocks than the partition scheme. Therefore, the non-partition scheme with first-last fit assignment creates the highest bandwidth blocking probability.

Figure 5 shows the AASR of the two schemes, each with the two wavelength assignment policies. The results show that the proposed subcarrier-slot partition scheme with first-last fit wavelength assignment gives more contiguous aligned available slot blocks.

Figure 6 shows the relationship between bandwidth blocking probability and AASR. We observe that high AASR gives low bandwidth blocking probability. This means that a higher number of contiguous aligned available slot blocks would result in lower bandwidth blocking probability.

V. Conclusions

We have proposed a subcarrier-slot partition scheme for wavelength assignment in EONs to reduce the bandwidth blocking probability, by yielding more contiguous aligned available subcarrier slots. This scheme separates the total set of subcarrier slots into several partitions and uses the partitions in assigning the wavelength resources to arriving connections. A simulation showed that the proposed scheme gives more aligned available slot blocks than the conventional non-partition scheme. Our investigation of wavelength assignment showed that the first-last fit wavelength assignment policy gives more contiguous aligned available slot blocks in the proposed scheme. By obtaining more contiguous aligned available slot blocks, the proposed scheme reduces the bandwidth blocking probability compared to the conventional scheme.

VI. Acknowledgment

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