Dynamic Lightpath Establishment Method Based on Maximum Spectrum Utilization for Elastic Optical Path Networks

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***Abstract*—In this paper, we propose a dynamic lightpath establish method for elastic optical path networks (EONs). EONs provide flexible frequency slot allocation and signal modulation. In EONs, a routing, modulation level, and spectrum allocation (RMLSA) problem is one of the most important technical issues. If routes, modulation formats, and frequency slots are appropriately determined for lightpaths, the spectrum efficiency is enhanced and the blocking probability of connection requests are reduced. To solve the RMLSA problem quickly and effectively, our proposed method focuses on the maximum spectrum utilization. The proposed method aims at smoothing the spectrum utilization of each link and alleviating the fragmentation of frequency slots by selecting routes, modulation formats, and frequency slots for new connections based on the maximum spectrum utilization. Through simulation experiments, we show that the proposed method effectively reduces the blocking probability of connection requests under the dynamic situations where connection requests dynamically are generated and released.**

Keywords–Dynamic Lightpath Establishment; Spectrum Allocation Method; Elastic Optical Path Networks.

I. INTRODUCTION

Recently, the traffic demands on the Internet have increased rapidly. To cope with this increase in traffic demands, optical path networks using wavelength division multiplexing (WDM) [1] have been implemented. In optical path networks, there is no bottleneck in the communication paths because optical signals are transmitted without optical-electrical-optical (OEO) conversion. Moreover, using WDM, many signals of different wavelengths are transmitted through a signal fiber in parallel. To realize optical path networks, a variety of technologies, such as device development, routing methods, and wavelength assignment methods have been studied [1].

Currently, optical path networks are implemented with *frequency grid* WDM systems that have discrete wavelength channels with bandwidth of 50 or 100 GHz. When a connection request arrives, the corresponding lightpath is established by allocating a wavelength channel to a path of the lightpath. The requested data is transmitted over the lightpath. In the optical path networks, even if the amount of bandwidth of a requested connection is small, a wavelength channel is allocated to the connection because of the coarse spectrum allocation granularity. This coarse spectrum allocation causes low spectrum efficiency. To improve the spectrum efficiency, the elastic optical path networks (EONs) have been actively studied [2][3].

EONs provide flexible frequency spectrum allocation and signal modulation. The frequency spectrum is divided into narrow-band frequency grids called *frequency slots* (12.25 GHz or less) as shown in Figure 1. Furthermore, flexible modulation formats (e.g., BPSK, QPSK, and QAM) are used [4][5], unlike the traditional optical path networks that only use intensity modulation with a low transmission rate. Because of these flexible attributes, EONs are a promising technology for enhancing the use efficiency of the frequency spectrum.

We should consider a routing, modulation level, and spectrum allocation (RMLSA) problem to efficiently utilize the resources of EONs. A lightpath is established by an RMLSA algorithm that selects a route, a modulation format, and frequency slots for the lightpath. In general, RMLSA is categorized as static RMLSA [5][6][7] and dynamic RMLSA [8][9][10][11]. In static RMLSA, a traffic matrix that indicates the traffic volume between each sender and receiver pair is known in advance. Accordingly, routes, modulation formats, and frequency slots of lightpaths are determined by solving optimization problems or applying heuristic algorithms. On the other hand, in dynamic RMLSA, a traffic matrix is not available. Connection requests are stochastically generated and the lightpaths are dynamically established accordingly. The performance metric in EONs using dynamic RMLSA is typically the blocking probability of connection requests. When there are no spectrum resources along a requested connection, the connection request is blocked. This paper deals with dynamic RMLSA for designing EONs with low blocking probability.

In EONs, it is preferred that the frequency slots of each link is evenly used. If the frequency slots of a certain link is intensively used, the link becomes a bottleneck link. In this case, lightpaths cannot be established further through the link. Furthermore, the fragmentation of frequency slots degrades the performance of EONs because connection requests using many frequency slots are often blocked. To overcome this difficulty, in this paper, we propose an RMLSA method that focuses on the maximum spectrum utilization. The proposed method selects routes, modulation formats, and frequency slots for new connections based on the maximum spectrum utilization. By doing so, the proposed method aims at smoothing the spectrum utilization of each link and alleviating the fragmentation of frequency slots. The proposed method is expected to reduce the blocking probability of connection requests.

 ISBN: 978-1-61208-562-3

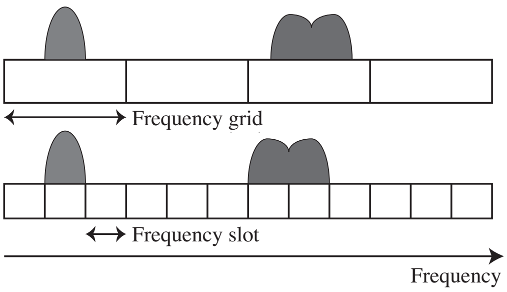

Figure 1. Frequency grids and slots.

The rest of this paper is organized as follows. In Section II, we explain EONs. Section III describes the proposed method. In Section IV, the performance of the proposed method is discussed with the results of the simulation experiments. Finally, we conclude this paper in Section V.

II. RMLSA IN ELASTIC OPTICAL PATH NETWORKS

Table I summarizes the symbols used in this paper. Graph $G = (V, E)$ represents an elastic optical network consisting of the set $\mathcal{V}$ of switching nodes and the set $\mathcal{E}$ of fiber links. Each link $e \in \mathcal{E}$ has N_{FS} frequency slots, which are labeled 1 to N_{FS} in ascending order from low frequency side, as shown in Figure 2. Mask $\boldsymbol{b}_e$ denotes the N_{FS}-bit bit-mask, and the ith element $\boldsymbol{b}_e[i]$ represents the utilization of the ith frequency slot on the link e. If $\boldsymbol{b}_e[i] = 1$, the ith frequency slot is currently used; otherwise, it is available for a new connection. As for the link A–B in the Figure 2, $\boldsymbol{b}_e = [0011111111100]$ immediately after the new connection uses the frequency slots. Guard bands are allocated to both ends of the frequency slots, and thus each connection needs the frequency slots used by guard bands.

Whenever a connection request arrives, the lightpath is established by an RMLSA method. In general, an RMLSA problem is divided to an RML problem and an SA problem. In the RML problem, a route (path) of the new connection is determined by a routing algorithm. An example of a routing algorithm is the K-shortest path algorithm [12], in which the first K shortest paths are maintained for each source-destination pair and the paths are selected in the order of the length. The modulation format of the connection is determined according to the transmission distance along the path selected by the routing algorithm. When the transmission distance is short, a multivalue modulation format (e.g., 8QAM or 16QAM) is adopted. In contrast, for long transmission distance, a low-value modulation format (e.g., BPSK or QPSK) is adopted to cope with the deterioration of communication quality.

In the SA problem, frequency slots are allocated to a path selected by an routing algorithm. When we allocate frequency slots, we should consider three constraints: spectrum continuity constraint, spectrum non-overlapping constraint, and spectrum contiguity constraint [11]. Let $\boldsymbol{a}$ denote the candidate spectrum allocation of a new connection along the path. Spectrum allocation $\boldsymbol{a}$ is represented by an N_{FS}-bit bit-mask, and the ith element $a[i] \in \{0, 1\}$ is a binary valuable. If $a[i] = 1$, the ith frequency slot is allocated to the path, otherwise, the ith frequency slot is not used for the path of the new connection. The SA problem determines the spectrum allocation $\boldsymbol{a}$ while satisfying the following three constraints.

TABLE I. SYMBOLS.

Symbol	Meaning
$\boldsymbol{a}$	N_{FS}-bit bit-mask. The spectrum allocation If the ith element $\boldsymbol{a}[i] = 1$, ith frequency slot on the link e is used, otherwise it is available.
$\boldsymbol{b}_e$	N_{FS}-bit bit-mask. If the ith element $\boldsymbol{b}_e[i] = 1$, ith frequency slot on the link e is used, otherwise it is available.
B_p	Number of frequency slots used by a connection along route p
C	Capacity of a frequency slot in case of 1-bit transmission per symbol
$\mathcal{E}$	Set of fiber links
G	Directed graph
K	Number of candidate routes
N_{FS}	Maximum number of frequency slots in each link
$\mathcal{V}$	Set of switching nodes
$\mathcal{P}_{s,d}$	Set of candidate routes between sender node s and receiver node d
R_p	Modulation format level on the route p
Z	Number of guard band slots
Λ	Volume of the traffic demand requested by a connection

- Spectrum continuity constraint – This constraint means that common frequency slots should be used all the links on the path, because this paper assumes that there is no spectrum converter in the network. Note that $a[i] = 1$ indicates that the ith frequency slots on all links along the path are allocated to the new connection.
- Spectrum non-overlapping constraint – The new connection should use available frequency slots that other connections do not use:
$$\sum_{i=1}^{N_{\mathrm{FS}}} a[i] \cdot b_e[i] = 0, \qquad \forall e \in p. \tag{1}$$
- Spectrum contiguity constraint – The frequency slots of the new connection should be successive.
$$\sum_{i=1}^{N_{\mathrm{FS}}} a[i] \cdot \mathrm{CRS}(\boldsymbol{a})[i] = \begin{cases} B_p - 1 & (B_p \in [1, N_{\mathrm{FS}} - 1]) \\ N_{\mathrm{FS}} & (B_p = N_{\mathrm{FS}}) \end{cases}, \tag{2}$$
where $\mathrm{CRS}(\boldsymbol{a})$ indicates a N_{FS}-bit bit-mask that is the circular-right-shift of $\boldsymbol{a}$ by one bit.

If there exist no spectrum allocation satisfying with these constraints, the connection request is blocked.

The First-Fit method [9][10] is one of the simplest spectrum allocation methods. In the First-Fit method, the shortest path is first selected from candidate paths. If there exists a spectrum allocation satisfying with the constraints, the connection uses the frequency slots of the spectrum allocation along the path. When there are several spectrum allocations, the frequency slots with smallest indices are chosen. Otherwise, we select the second shortest path among the candidate paths, and then check whether feasible spectrum allocations satisfying the constraints exist. This procedure is repeated until a spectrum allocation is found or all the candidate paths have been checked.

We explain the spectrum allocation of the First-Fit method using an example where the frequency slots on a path are allocated as shown in Figure 3. When a connection that needs

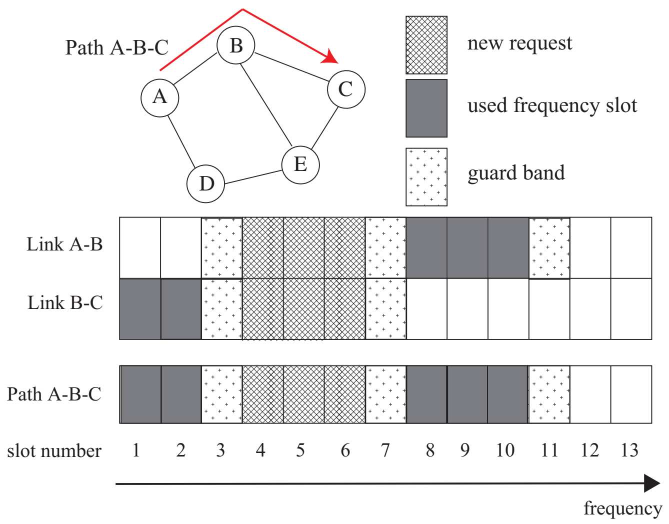

Figure 2. Frequency slots ($N_{\mathrm{FS}} = 13$).

two frequency slots arrives, there are two feasible spectrum allocations, i.e., $\boldsymbol{a}_1$ and $\boldsymbol{a}_2$. The First-Fit method selects $\boldsymbol{a}_1$ because $\boldsymbol{a}_1$ includes frequency slots with smaller indices than $\boldsymbol{a}_2$. In the First-Fit method, the spectrum fragmentation frequently occurs, and thus the frequency slots can not be used efficiently.

III. Proposed Lightpath Establishment Method

The proposed method aims at reducing the blocking probability of the connection requests by efficiently using spectrum resources. In EONs, if the frequency slots of a certain link is intensively used, the link becomes a bottleneck link. In this case, lightpaths cannot be established further through the link. Furthermore, the fragmentation of frequency slots degrades the performance of EONs because connection requests using many frequency slots is often blocked. Therefore, in order to reduce the blocking probability of connection requests, the proposed method selects a route, a modulation format, and frequency slots for each connection while smoothing the spectrum utilization of each link and suppressing the generation of the fragmentation of frequency slots.

When a new connection request arrives, the proposed method selects a combination of a path, a modulation format, and frequency slots. The proposed method prepares K candidate paths $\mathcal{P}_{s,d}$ for each sender node s and receiver node d pair in advance. The path p of the connection is selected from among candidate paths $\mathcal{P}_{s,d}$ with feasible frequency slots. The modulation format is then determined based on the transmission distance of the path p. Finally, the frequency slots are allocated to the path p.

A. Candidate paths and modulation formats

In this paper, we prepare K candidate routes using a K-shortest path algorithm. For each sender and receiver pair (s, d), the procedure of K-shortest path algorithm is as follows. First, we calculate the shortest path p_1 between sender node s and receiver node d using Dijkstra's algorithm in the topology G, where the cost of each link is one. We adopt the path as a candidate path. $\mathcal{P}_{s,d} := \{p_1\}$. We then doubles the cost of the links $e \in p_1$. We find the shortest path p_2 on the resulting graph, and the path is adopted as a new candidate path. That is, $\mathcal{P}_{s,d}$ is updated as $\mathcal{P}_{s,d} := \mathcal{P}_{s,d} \cup \{p_2\}$. Next, we double the cost of the links $e \in p_2$. This procedure is repeated until K candidate routes are chosen and $\mathcal{P}_{s,d} = \{p_1, p_2, \ldots, p_K\}$ is constructed. Figure 4 shows an example of the K-shortest path algorithm ($K = 2$) on a toy topology. In the example, the candidate routes between sender node A and receiver node C $\mathcal{P}_{A,C}$ is obtained $\mathcal{P}_{A,C} = \{p_1, p_2\}$.

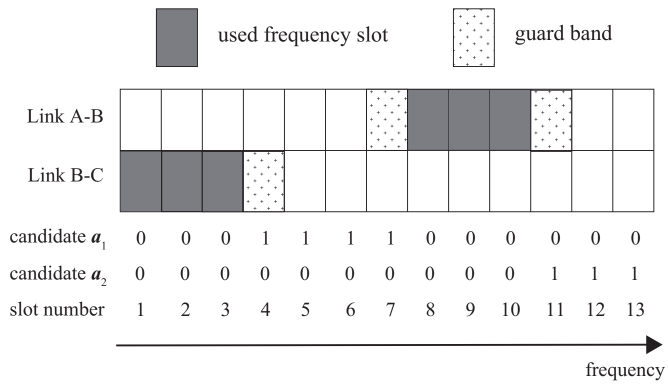

Figure 3. An example of spectrum allocations.

The modulation format of a new connection along each path is determined based on the transmission distance. Accordingly, the number of frequency slots used by the connection is given as follows. Let R_p denote the modulation format level on the route p, i.e., the capacity of the sub-carrier using a single bit per symbol (1 for BPSK, 2 for QPSK, and 3 for 8QAM). Moreover, C denotes the communication capacity of per frequency slot in the case of 1-bit transmission per symbol. We describe the calculation of the number of frequency slots when a connection requests traffic volume Λ. Let B_p denote the number of frequency slots used by a connection along path p. The value of B_p is given by:

$$B_p = \left\lceil \frac{\Lambda}{C R_p} \right\rceil + Z, \tag{3}$$

where Z indicates the number of frequency slots for a guard band.

B. Spectrum allocation

To avoid the fragmentation of frequency slots and smooth the spectrum utilization, our proposed method focuses on the maximum spectrum utilization. Let $f(p, \boldsymbol{a})$ denote the maximum spectrum utilization along path p when the spectrum allocation $\boldsymbol{a}$ is adopted on path p in a first-fit manner. Formally, $f(p, \boldsymbol{a})$ is given by:

$$f(p, \boldsymbol{a}) = \max_{i \in [1, N_{\mathrm{FS}}]} \left\{ i \mid \sum_{e \in p} b_e[i] + a[i] \geq 1 \right\}. \tag{4}$$

Note that different paths have $\boldsymbol{a}$ of different sizes because the number B_p of frequency slots used by the paths is given by (3).

First, our proposed method calculates the maximum spectrum utilization $f(p, \boldsymbol{a})$ for each candidate route $p \in \mathcal{P}_{s,d}$, and then selects the path p and the frequency allocation $\boldsymbol{a}$ with

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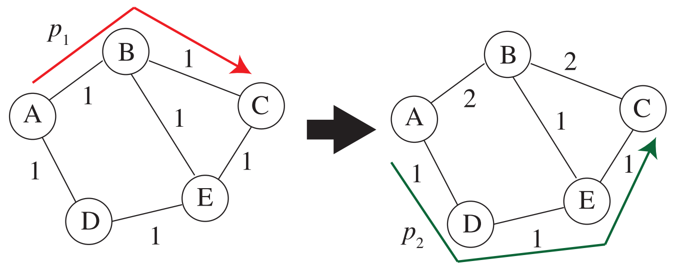


Figure 4. K-shortest path algorithm.

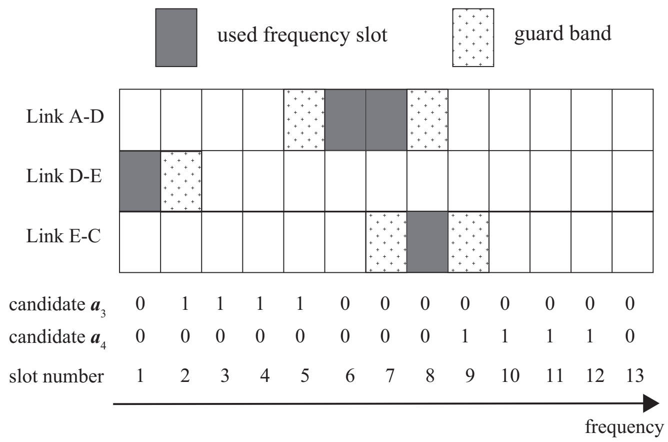


Figure 5. Path p_2 and its candidate spectrum allocations.

the minimum $f(p, \boldsymbol{a})$. In the proposed method, the frequency slots with large indices are reserved for future connections as much as possible, and thus the frequency slots used by established connections are squeezed into frequency slots with small indices, which helps to alleviate the fragmentation and smooth the frequency utilization.

C. Spectrum allocation example

We explain the spectrum allocation of our proposed method using an example where frequency slots on shortest path p_1 and second shortest path p_2 are used by the connections shown in Figs. 3 and 5, respectively. When a new connection that needs two frequency slots arrives, there are four feasible spectrum allocations $\boldsymbol{a}_1, \boldsymbol{a}_2, \boldsymbol{a}_3$, and $\boldsymbol{a}_4$. Our proposed method calculates the maximum index of used slots: $f(p_1, \boldsymbol{a}_1) = 11, f(p_1, \boldsymbol{a}_2) = 13, f(p_2, \boldsymbol{a}_3) = 9, f(p_2, \boldsymbol{a}_4) = 12$. $f(p_2, \boldsymbol{a}_3)$ is minimum, and thus our proposed method selects route p_2 and spectrum allocation $\boldsymbol{a}_3$.

IV. Performance Evaluation

A. Simulation Model

To evaluate the performance of the proposed method, we conduct simulation experiments with the network topology (24 nodes and 43 links) shown in Figure 6. For simplicity, we assume that the length of each link is the same, and thus the modulation format is determined in accordance with the hops between sender and receiver pairs. We adopt 8QAM for less than three hops, QPSK for three and four hops, and BPSK for more than four hops are adopted. Communication capacity C is set to be 2.5 Gbps, and Table II shows the transmission

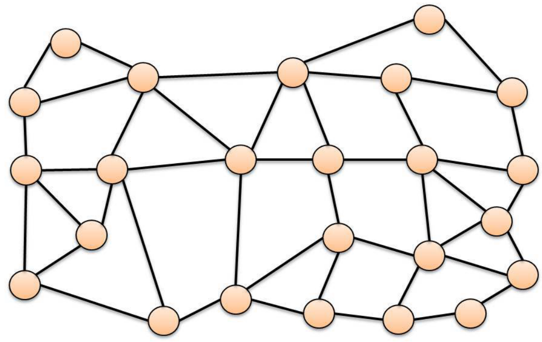


Figure 6. Network model.

TABLE II. Transmission capacity per slot.

Hops	Modulation Format	Capacity [Gbps/slot]
1, 2	8QAM	7.5
3, 4	QPSK	5.0
More than 4	BPSK	2.5

capacity per frequency slot. The number N_{FS} of frequency slots on each link is set to be 100, the guard-band width is one, and the number of candidate routes K is three.

The arrival of connection requests follows a Poisson process with the rate λ. The lifetime t_L of each connection request follows an exponential distribution with parameter μ or a log-normal distribution. The probability density function g of the log-normal distribution is given by:

$$g(t_L) = \frac{1}{\sqrt{2\pi}\sigma t_L} \exp\left(-\frac{(\log t_L - \xi)^2}{2\sigma^2}\right), \tag{5}$$

where σ and ξ are parameters satisfying $\mathrm{E}[t_L] = e^{\xi + \frac{\sigma^2}{2}}$. In the following, scenarios adopting the exponential distribution and the log-normal distribution are called the *exponential lifetime scenario* and the *log-normal lifetime scenario*, respectively. In the exponential lifetime scenario, $\mu = 10^{-4}$, and in the log-normal lifetime scenario, $\xi = 3.09$, $\sigma = 3.5$. By this setting, the mean lifetime of connections $\mathrm{E}[t_L]$ is same ($\mathrm{E}[t_L] = 10^4$) in both scenarios. Moreover, sender node and receiver node are randomly chosen from among the nodes in $\mathcal{V}$. The bandwidth requirement volume Λ of each connection is uniformly distributed between 1 and 10 Gbps.

We use two performance metrics: the blocking probability and the network utilization. The blocking probability of the connection requests is defined as follows:

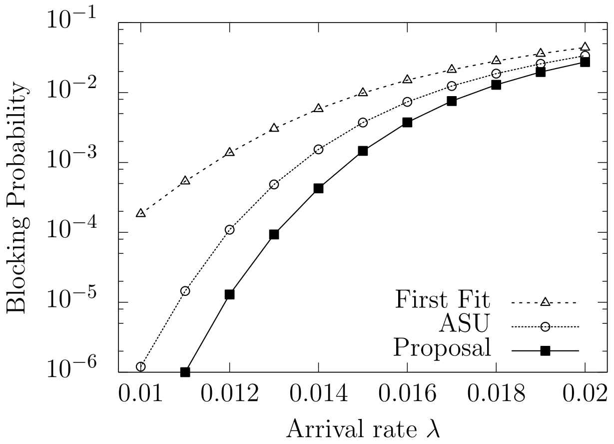
$$\frac{\text{number of blocked connection requests}}{\text{total number of connection requests}}. \tag{6}$$

The network utilization is defined as follows:

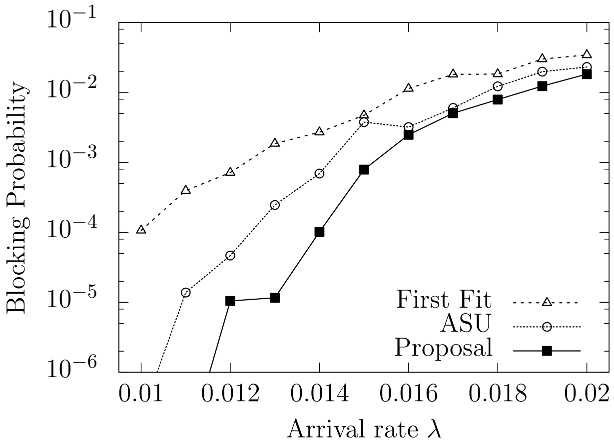
$$\frac{\text{sum of spectrum utilization } \sum_{e \in \mathcal{E}} \mathrm{E}[u_e]}{\text{number of links } |\mathcal{E}|}, \tag{7}$$

where u_e indicates the spectrum utilization of link e, i.e., the number of used frequency slots divided by N_{FS}, and $\mathrm{E}[u_e]$ denotes the time average of the spectrum utilization of link e. For each setting, we collect 1,500,000 samples for calculating these performance metrics.

 ISBN: 978-1-61208-562-3

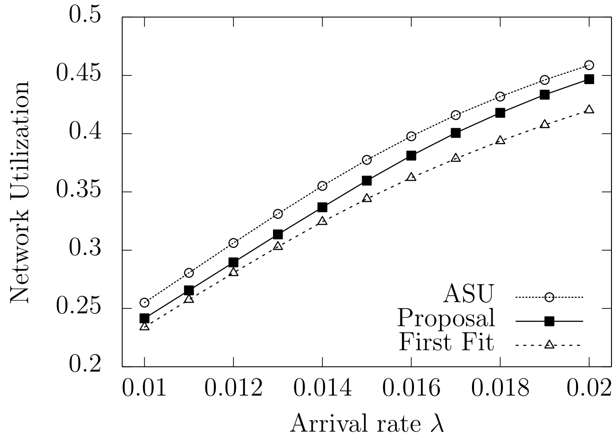


(a) the exponential lifetime scenario

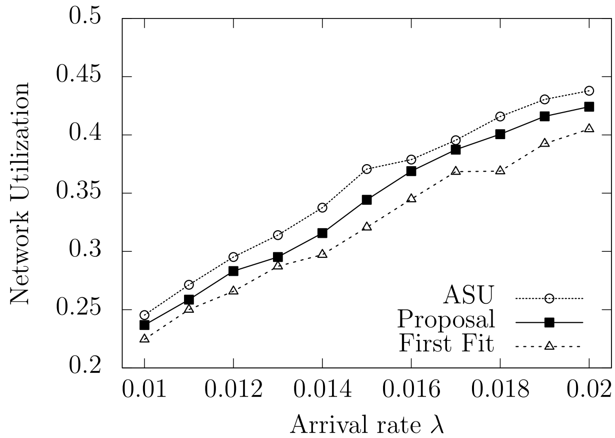


(b) the log-normal lifetime scenario

Figure 7. Blocking probability



(a) the exponential lifetime scenario



(b) the log-normal lifetime scenario

Figure 8. Network utilization

For the performance comparison, we show the results of the First-Fit and the average spectrum-utilization (ASU) methods. When a new connection request arrives, the ASU method calculates the average spectrum-utilization for each candidate route p, which is defined as the sum of the spectrum utilization among p ($\sum_{e \in p} u_e$) divided by the number of hops of route p ($|p|$). Next, the path with the minimum spectrum-utilization is selected, and if the feasible spectrum allocation exists along the path, the connection is assigned to the spectrum allocation. When there are some feasible spectrum allocations, the spectrum allocation with smalles indices is selected. When there is no feasible spectrum allocation along the path, the ASU method selects the second-minimum spectrum utilization path, and then checks whether a feasible spectrum allocation exists. This procedure is repeated until a feasible spectrum allocation is found. For the example in Figs. 3 and 5, the ASU method calculates the average spectrum-utilization for the candidate routes, which are 4/13 = 0.30 for path p_1 and $\{(4+2+3)/13\}/3$ = 0.23 for path p_2. Therefore, the route p_2 and feasible spectrum allocation $\boldsymbol{a}_3$ on the route p_2 are selected.

B. Results

Figure 7 shows the blocking probability as a function of the arrival rate λ. We observe that the blocking probability of our proposed method is smallest for any arrival rate λ. This result indicates that the maximum spectrum utilization is useful for alleviating the spectrum fragmentation. Moreover, in the log-normal lifetime scenario, connections with large lifetime occasionally arrive, which highly degrades the performance of the First-Fit method and the ASU method. In contrast, the proposed method works well even if those connections arrive.

Figure 8 shows the network utilization as a function of the arrival rate λ. The network utilization of the proposed scheme is larger than that of the First-Fit method. This result indicates that the free frequency slots are large and the frequency fragmentation frequently occurs in the First-Fit method. Moreover, the network utilization of the proposed method is smaller than that of the ASU method. Therefore, the ASU method wastes the frequency resources by allocating paths with large hops. Based on these results, we conclude that the proposed method effectively uses the frequency resources.

V. CONCLUSION

In this paper, we proposed a dynamic lightpath establishment method for EONs. Our proposed method focuses on the maximum spectrum utilization. By doing so, the proposed method aims at smoothing the spectrum utilization of each link and alleviating the fragmentation of frequency slots. Through simulation experiments, we showed that the proposed method effectively reduces the blocking probability of connection requests under the dynamic situations where connection requests dynamically are generated and released.

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 ISBN: 978-1-61208-562-3