Routing and Spectrum Allocation Method to Avoid the Generation of Crosstalk and the Blocking of Lightpath Establishment in Multi-Core Fiber Networks

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***Abstract*—This paper proposes a dynamic routing and spectrum allocation method that avoids the generation of crosstalk and the blocking of lightpath establishment in elastic optical networks with multi-core fibers. In the elastic optical networks with multi-core fibers, crosstalk occurs when the same frequency band is used for signals of adjacent cores. The proposed method provides a routing and spectrum allocation strategy, which suppresses the generation of crosstalk by avoiding using the same frequency band in adjacent cores and blocking of lightpath establishment by selecting appropriate routes. Through simulation experiments, we show the effectiveness of the proposed method.**

Keywords–Elastic optical network; multi-core fiber; crosstalk; routing and spectrum allocation.

I. Introduction

Recently, elastic optical networks have attracted much attention because they can accommodate rapidly increasing network traffic by utilizing network resources flexibly [1][2]. In the elastic optical networks, frequency spectrum is divided into small pieces named frequency slots and data are transmitted on lightpaths, which are routes allocated frequency slots. Furthermore, the elastic optical networks use multilevel modulation such as Quadrature Phase Sift Keying (QPSK) and Quadrature Amplitude Modulation (QAM) according to the transmission distance, instead of using on-off pulses in conventional Wavelength Division Multiplexing (WDM) optical networks. By doing so, the elastic optical networks further enhance the utilization efficiency of frequency resources.

In order to design elastic optical networks, we should consider a Routing and Spectrum Allocation (RSA) problem [3] [4][5], which is one of most important technical issues. The RSA problem determines a route and frequency slots for a lightpath to transmit data. The RSA problem is categorized into two problems: static and dynamic. The static RSA problem assumes that traffic demands of all sender and receiver pairs (i.e., traffic matrix) in a network are known in advance. Routes and frequency slots for established lightpaths are determined by solving optimization methods such as mathematical programming and meta-heuristic, based on the traffic matrix. On the other hand, the traffic matrix is not available for the dynamic RSA problem. In the dynamic RSA problem, lightpath-setup requests are stochastically generated with the time elapsed and the lightpaths are dynamically established accordingly. After the holding time of the lightpaths, they are released. This paper focuses on the dynamic RSA problem.

Generally, the performance metric of the dynamic RSA problem is the blocking probability of lightpath establishment. A lightpath must use successive frequency slots. Moreover, the lightpath must use common frequency slots in all links along its route. Lightpaths are established by RSA under these constraints. When there are no available frequency slots that meet these constraints on candidate routes for a lightpath to be established, the lightpath establishment is blocked. Therefore, the performance of elastic optical networks strongly depends on RSA.

In order to enhance the performance of elastic optical networks, multi-core fibers have been developed in the past [6][7]. The multi-core fibers have multiple cores and different optical signals can be simultaneously transmitted through the cores. By using multi-core fibers in elastic optical networks, we can reduce the blocking probability of lightpath establishment because multi-core fibers can relax the above-mentioned constraints. Specifically, multiple lightpaths can simultaneously use the same frequency slots in the same fiber when they pass through different cores. However, when the same frequency slots are used in neighboring cores, crosstalk occurs between them. The crosstalk generates noise in the neighboring cores and thus degrades the quality of the optical signals. Therefore, in order to design high-quality multi-core fiber networks, we need to consider the crosstalk in addition to the blocking of lightpath establishment.

In this paper, we propose a dynamic RSA method that aims at avoiding the blocking of lightpath establishment and the generation of crosstalk in elastic optical networks with multi-core fibers. The proposed method balances the usage of frequency slots by selecting a route and frequency slots for a newly established lightpath according to available frequency slots. By doing so, the proposed method avoids the blocking of lightpath establishment. Furthermore, the proposed method selects frequency slots and cores in such a way that the same frequency slots are not used in neighboring cores, which avoids the generation of crosstalk. Through simulation experiments, we show the effectiveness of the proposed method.

The rest of this paper is organized as follows. In Section II, we explain elastic optical networks with multi-core fibers. Section III discusses our proposed method. In Section IV, the performance of the proposed method is discussed with the results of the simulation experiments. Finally, we conclude the paper in Section V.

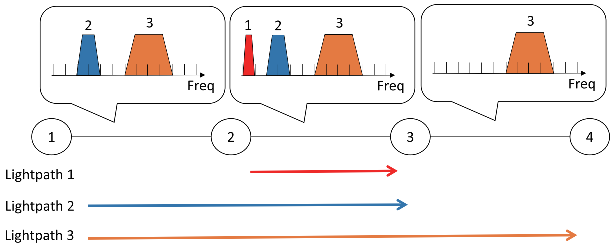


Figure 1. Elastic optical network.

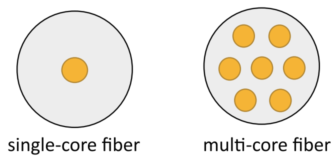


Figure 2. Single-core and multi-core fibers.

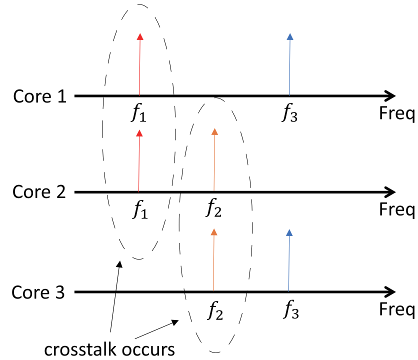


Figure 3. Crosstalk in a multi-core fiber.

II. Elastic optical networks with multi-core fibers

In elastic optical networks, the unit of frequency slots is 12.5 [GHz] or less, which is smaller than that in conventional WDM networks. Lightpaths are established with multiple frequency slots and the number of frequency slots used for the lightpaths can be changed according to their traffic demands as shown in Figure 1. Thus, frequency resources are efficiently utilized. Furthermore, by using multilevel modulation according to the length of the lightpaths, the elastic optical networks enhance the utilization efficiency of frequency resources. For example, when the length of a lightpath is short, we can use modulation schemes such as 16-QAM and 64-QAM, whose frequency utilization efficiency is high, because of high Optical Signal-to-Noise Ratio (OSNR). On the other hand, for a lightpath whose length is large, modulation schemes with low frequency utilization efficiency, such as Binary Phase Sift Keying (BPSK) and QPSK are used because OSNR is low.

In order to communicate in elastic optical networks, lightpaths are established between senders and receivers by selecting routes and frequency slots. When we establish a lightpath, we should consider two constraints about frequency slots. The first constraint is that successive frequency slots must be assigned to the lightpath as shown in Figure 1. Frequency slots that are not adjacent to each other cannot be used for the lightpath. The second constraint is that common frequency slots must be assigned to all links used in the lightpath. We cannot use different frequency slots for different links through which the lightpath passes. We need to consider a RSA method to meet these constraints.

For multi-core environments, we should further consider the generation of crosstalk. In the multi-core fiber networks, a fiber consists of multiple cores as shown in Figure 2. Different lightpaths can be established in different cores in the same fiber, and thus the transmission capacity of elastic optical networks is enhanced according to the number of cores. However, crosstalk occurs when the same frequency slots are used in different cores in the same fiber as shown in Figure 3. The crosstalk degrades the quality of optical signals. The effect of the crosstalk exponentially decreases with the increase in the distance between cores. Therefore, the effect of the crosstalk becomes the strongest when the same frequency slots are used in adjacent cores. For simplicity, in this paper, we assume that the crosstalk occurs only when the same frequency slots are used in adjacent cores. We also assume that the impact of the crosstalk is the same for each frequency slot.

In the past, several RSA methods that aim at suppressing the generation of crosstalk and/or the blocking of lightpath establishment have been proposed. In [8], the authors proposed a RSA method that considers immediate reservation and advance reservation of network resources for elastic optical networks. This method allocates frequency slots to lightpaths according to the required number of frequency slots of the lightpaths, so that blocking probability of lightpath establishment is reduced. Furthermore, in [9] the authors have proposed a spectrum and core/mode assignment method that aims at reducing the blocking probability of lightpath establishment. This method prioritizes frequency slots and lightpaths are allocated to the frequency slots according to the number of frequency slots required by them. In [9], [10], the authors have proposed a dynamic spectrum allocation method that considers both the blocking of lightpath establishment and crosstalk. This method prioritizes cores in such a way that non-adjacent cores are preferentially used to avoid the generation of crosstalk. Furthermore, lightpaths are allocated to the cores according to the number of frequency slots required by them to avoid the blocking of lightpath establishment. Specifically, lightpaths with different number of frequency slots use different cores. By doing so, this method reduces the blocking probability of lightpath establishment and the number of crosstalk occurrences. However, this method cannot flexibly accommodate fluctuating traffic demand because it needs to determine cores to which lightpaths are allocated according to the required number of frequency slots in advance. Furthermore, this method does not consider routing. On the other hand, our proposed method adaptively selects routes, frequency slots, and cores for established lightpaths based on current network status, and thus it is expected to flexibly accommodate fluctuating traffic demand.

III. Proposed RSA method

In this section, we first explain the overview of our proposed method in Section III-A, and then we detail the procedure in Section III-B.

A. Overview

Our proposed RSA method provides a route, frequency slot, and core selection strategy that considers not only the blocking of the lightpath establishment owing to the depletion of the frequency resources but also the generation of crosstalk due to multi-core fiber environments. In the proposed method, a route, frequency slots, and cores of each fiber along the route for a newly established lightpath is selected based on two policies. Note that the proposed method selects a route from the pre-defined candidate routes constructed by the K-shortest path algorithm because multilevel modulation schemes used for the lightpath are determined according to the length of the routes. The two policies a) and b) are described as follows:

a) In order to avoid the blocking of lightpath establishment, we should balance the usage of frequency slots in each link. A bottleneck link is generated when traffic concentrates in a certain link and there are no available frequency slots in all the cores of the link. In this case, new lightpaths cannot be established further in the link. In order to distribute the load and avoid the generation of bottleneck links, the proposed method selects a route, frequency slots, and cores according to the number of available frequency slots in each core of each link along candidate routes.

b) In order to avoid the generation of crosstalk, we should not use the same frequency slots in adjacent cores. The crosstalk decays the communication quality of lightpaths. The crosstalk generated in each link accumulates along a lightpath as noise at a receiver node. When the effect of crosstalk is large, it is highly possible that data transmission fails even if the lightpath is correctly established. In order to avoid this situation, the proposed method also selects a route, frequency slots, and cores according to the usage of frequency slots in adjacent cores.

B. Procedure of the proposed method

In what follows, we describe the detailed procedure of the proposed method. Note that we assume that the usage of frequency slots, which is needed for lightpath establishment, is known in advance by periodically collecting it.

1) Construction of candidate routes: The proposed method selects a route from a set of candidate routes. In this paper, we use the K-shortest path algorithm to make the set $\mathcal{P}_{i,j} = \{p_1^{[i,j]}, p_2^{[i,j]}, \ldots, p_K^{[i,j]}\}$ of candidate routes for each sender i and receiver j pair. Let $G = (\mathcal{V}, \mathcal{E})$ denote a directed graph, where $\mathcal{V}$ and $\mathcal{E}$ denote sets of nodes and links, respectively. The K-shortest path algorithm first finds the shortest path from $i \in \mathcal{V}$ to $j \in \mathcal{V}$ on G, where the cost of each link is set to be 1, using a general shortest path algorithm such as Dijkstra's algorithm. It then adopts the path as a candidate route and doubles the cost of each link along the route. We find the new shortest path on the resulting graph and the path is adopted as a new candidate route. The procedure is repeated until K candidate routes are found. Modulation schemes used for lightpath along routes are determined according to the length of the routes.

2) Lightpath establishment: Let $\mathcal{F} = \{1, 2, \ldots, |\mathcal{F}|\}$ denote a set of frequency slots supported by each fiber. In order to establish a lightpath for a pair of sender i and receiver j, we use the cost $C_{p,f}$ of each frequency slot $f \in \mathcal{F}$ along each route $p \in \mathcal{P}_{i,j}$, based on the current usage of frequency slots on each link l on the route. The cost $C_{p,f}$ is defined by

$$C_{p,f} = \sum_{l \in p} \left\{ \min_{m \in \mathcal{M}_l} \sum_{f'=f}^{f+B_p-1} U_{l,m,f'} \right\}, \quad (1)$$

where $\mathcal{M}_l$ denotes a set of cores in link l's fiber, $U_{l,m,f}$ denotes the cost of the frequency slot f of core m in link l, and B_p denotes the required number of frequency slots to establish the lightpath along the route. Note that $\sum_{f'=f}^{f+B_p-1} U_{l,m,f'}$ indicates the total cost when the frequency slots from f to $f + B_p - 1$ are used for the lightpath. Specifically, the starting frequency slot is f and the number of frequency slots for the lightpath is B_p, the value of which is determined according to modulation schemes and traffic demands. The proposed method uses the smallest $\sum_{f'=f}^{f+B_p-1} U_{l,m,f'}$ among cores in order to calculate $C_{p,f}$.

Let $u_{l,m,f}$ be 1 if frequency slot f of core m in link l is already used; otherwise, 0. If the frequency slot f of core m in link l is available (i.e., $u_{l,m,f} = 0$), the cost $U_{l,m,f}$ of frequency slot f of core m in link l is given by

$$U_{l,m,f} = \sum_{f' \in \mathcal{F}: f \neq f'} u_{l,m,f'} + \beta \sum_{m' \in \mathcal{M}_l: m \neq m'} a_{m,m'} u_{l,m',f}; \quad (2)$$

otherwise (i.e., $u_{l,m,f} = 1$),

$$U_{l,m,f} = \infty, \quad (3)$$

where β is a parameter ($\beta > 0$). $a_{m,m'}$ is a variable that is equal to 1 if core m is adjacent to core m'; otherwise, 0. In (2), the first term derives from policy a) described in Section III-A. Specifically, the cost $U_{l,m,f}$ increases as the number of used frequency slots in the same core increases. Also, the second term derives from policy b) and the cost $U_{l,m,f}$ increases with the number of frequency slots used in adjacent cores. We can adjust the impact of policies a) and b) with the parameter β. (3) means that the lightpath cannot be established with the frequency slot of the core in the link.

Whenever a new lightpath-setup request arrives, the proposed method calculates the cost $C_{p,f}$ with (1) for each frequency slot f along each route p. Then, the proposed method selects a combination of a route and frequency slots with the smallest cost $C_{p,f}$. If the cost $C_{p,f}$ is infinity for all the combinations, the lightpath-setup request is blocked. If there are two or more combinations with the minimum cost, the proposed method selects the combination with smaller number of hops. Furthermore, the proposed method selects one randomly if the numbers of hops among them are the same. After selecting a route and frequency slots, the proposed method selects a core in each link along the selected route. Specifically, the proposed method uses core m given by

$$\arg\min_{m \in \mathcal{M}_l} \sum_{f'=f}^{f+B_p-1} U_{l,m,f'},$$

the cost of which is used for $C_{p,f}$ in (1).

Figure 4 shows an example of the proposed method. In this figure, we assume that node 1 is a sender and node 3 is a receiver and there are two links 1 and 2 along a route between them. Each link consists of 3 cores and each core supports 6 frequency slots. Core 2 is adjacent to both core 1 and core 3.

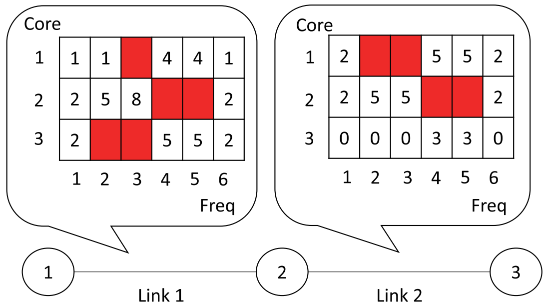
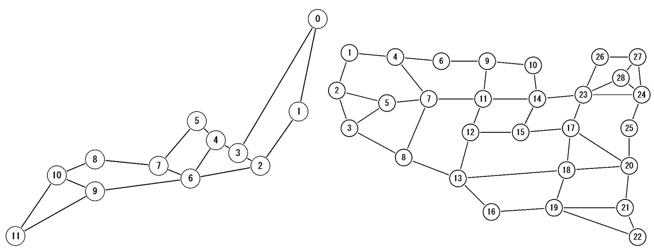
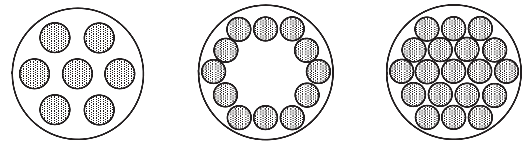


Figure 4. Example of the proposed method.



(a) JPN network (b) USA network

Figure 5. Network model.



(a) Core 7 (b) Core 12 (c) Core 19

Figure 6. Three types of multi-core fibers

TABLE I. REQUIRED NUMBER OF FREQUENCY SLOTS (JPN NETWORK)

# of hops	required # of frequency slots
1 - 4	1
5 - 9	2
10 -	3

Core 1 and core 3 are not adjacent to each other. Red cells (e.g., frequency slot 2 of core 3 in link 1) indicate that the cells are already used by other lightpaths. The number in each cell indicates the value of $U_{l,m,f}$, where β is set to be 3. For instance, the value for frequency slot 2 of core 2 of link 1 is 5 because two frequency slots 4 and 5 are already used in core 2 and frequency slot 2 of adjacent core 3 is already used (i.e., $U_{1,2,2} = 2 + 3 \times 1 = 5$). In this case, we calculate $C_{p,f}$ as follows, where $B_p = 2$. For frequency slot 1 in link 1, $\sum_{f'=1}^{2} U_{1,1,f'} = 2$, $\sum_{f'=1}^{2} U_{1,2,f'} = 7$, and $\sum_{f'=1}^{2} U_{1,3,f'} = \infty$, and thus $\min\{2, 7, \infty\} = 2$. Similarly, for frequency slot 1 in link 2, $\sum_{f'=1}^{2} U_{2,1,f'} = \infty$, $\sum_{f'=1}^{2} U_{2,2,f'} = 7$, and $\sum_{f'=1}^{2} U_{2,3,f'} = 0$, and thus $\min\{\infty, 7, 0\} = 0$. Therefore, the cost $C_{p,1}$ is $2 + 0 = 2$. We can also calculate $C_{p,f}$ for other frequency slots and other routes. After calculating $C_{p,f}$ for all the combinations, the proposed method selects a route and frequency slots with the smallest $C_{p,f}$.

IV. Performance evaluation

We first describe the simulation model in Section IV-A, and then we show the results of the simulation experiments in Section IV-B.

A. Model

To evaluate the performance of the proposed method, we conduct simulation experiments with two network models: JPN network and USA network shown in Figures 5(a) and (b), respectively. In the networks, each link consists of a multi-core fiber. We assume that each node fills the role of an intermediate switch, a sender node, and a receiver node. We use three types of multi-core fibers that has 7, 12, and 19 cores shown in Figures 6(a), (b), and (c), respectively. The number $|\mathcal{F}|$ of frequency slots supported by each fiber is equal to 320.

Lightpath-setup requests are generated according to a Poisson Process with rate λ [1/sec] at each node and the destination of each request is independently chosen equally likely among all the possible nodes. The holding time of each lightpath follows an exponential distribution with mean H [sec]. After the holding time, the lightpath is released. The parameter β in (2) is set to be 200. The number K of candidate routes constructed by the K-shortest path algorithm described in Section III-B1 is set to be 3. For simplicity, we assume that the length of each link is identical and the traffic demand of each lightpath-setup request is also identical. Therefore, the required number of frequency slots for each lightpath establishment is determined based on the number of hops of the lightpath as shown in Tables I and II. This means that the required number of frequency slots becomes small when a high-level modulation scheme is used for the established lightpath. We define ρ as the offered load per frequency slot in a core:

$$\rho = \frac{\lambda H}{|\mathcal{F}||\mathcal{M}|},$$

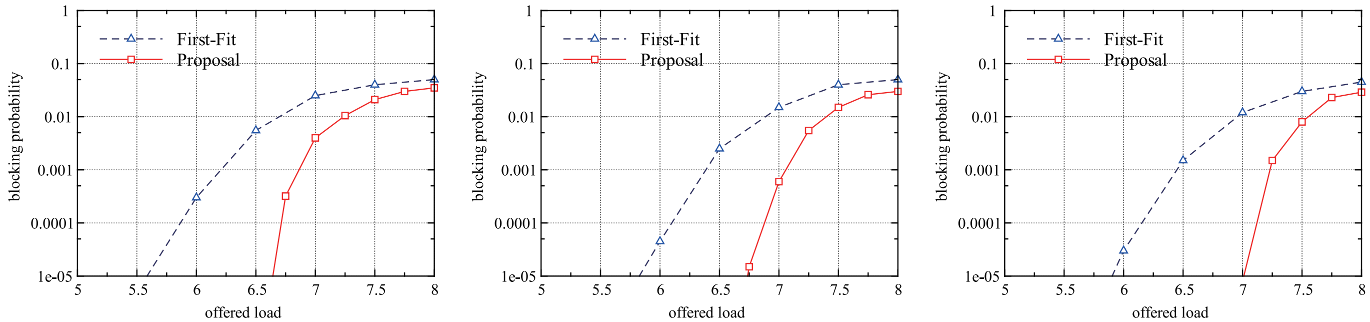
where $|\mathcal{M}|$ denotes the number of cores in each fiber. We obtain an average of 10 independent samples from each simulation experiment.

For the sake of comparison, we use a first-fit method. The first-fit method prepares K candidate routes as well as the proposed method. It preferentially selects the shortest path in terms of the number of hops from among the candidate routes with available frequency slots whenever a new lightpath-setup request arrives. Then, the first-fit method looks for available frequency slots on the selected route in a first-fit manner. If there are no available frequency slots meeting the requirement of the lightpath in the route, then the first-fit method looks for available frequency slots on the next route. If there are no available frequency slots on all the routes, the lightpath-setup request is blocked.

B. Results

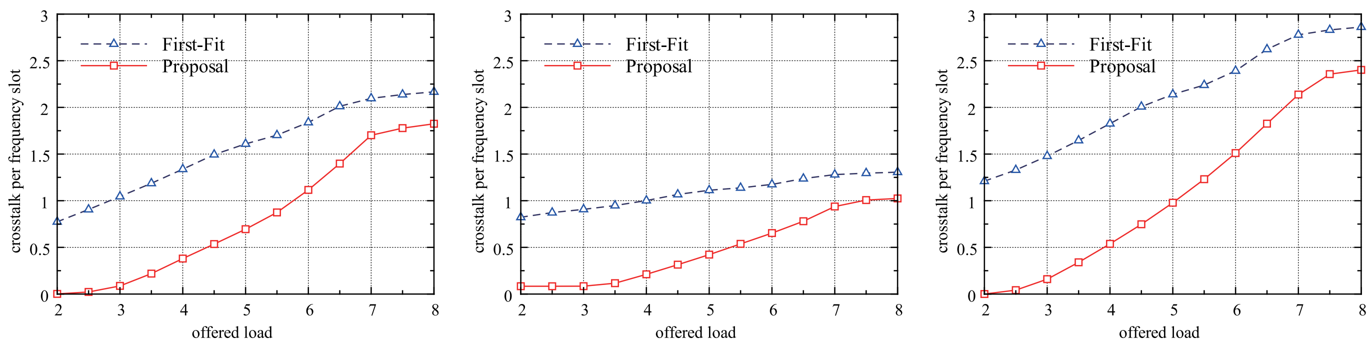
Figure 7(a) shows the blocking probability of lightpath establishment as a function of the offered load ρ in the JPN network, where the number $|\mathcal{M}|$ of cores in each fiber is 7. We define the blocking probability of lightpath establishment

 ISBN: 978-1-61208-650-7



(a) $|\mathcal{M}| = 7$ (b) $|\mathcal{M}| = 12$ (c) $|\mathcal{M}| = 19$

Figure 7. Blocking probability of lightpath establishment in the JPN network.



(a) $|\mathcal{M}| = 7$ (b) $|\mathcal{M}| = 12$ (c) $|\mathcal{M}| = 19$

Figure 8. Average number of crosstalk occurrences in the JPN network.

TABLE II. REQUIRED NUMBER OF FREQUENCY SLOTS (USA NETWORK)

#of hops	required # of frequency slots
1, 2	1
3 - 5	2
6 - 9	3
10 -	4

as follows:

$$\text{blocking probability of lightpath establishment} = \frac{\text{number of blocked lightpath-setup requests}}{\text{total number of lightpath-setup requests}}.$$

As we can see from Figure 7(a), the blocking probability of lightpath establishment in the first-fit method is very high. This is because the usage of frequency slots in each link is uneven in the first-fit method and bottleneck links are often generated. By contrast, our proposed method efficiently reduces the blocking probability of lightpath establishment because the proposed method considers wavelength availability in each link.

Figures 7(b) and (c) show the blocking probability of lightpath establishment as a function of the offered load ρ in the JPN network, where $|\mathcal{M}| = 12$ and 19, respectively. As we can see from these figures, the blocking probability of the proposed method is smaller than that of the first-fit method, similar to the result of $|\mathcal{M}| = 7$. From these figures, we also observe that the blocking probability of lightpath establishment decreases with the increase in the number $|\mathcal{M}|$ of cores because of the large-scale effect.

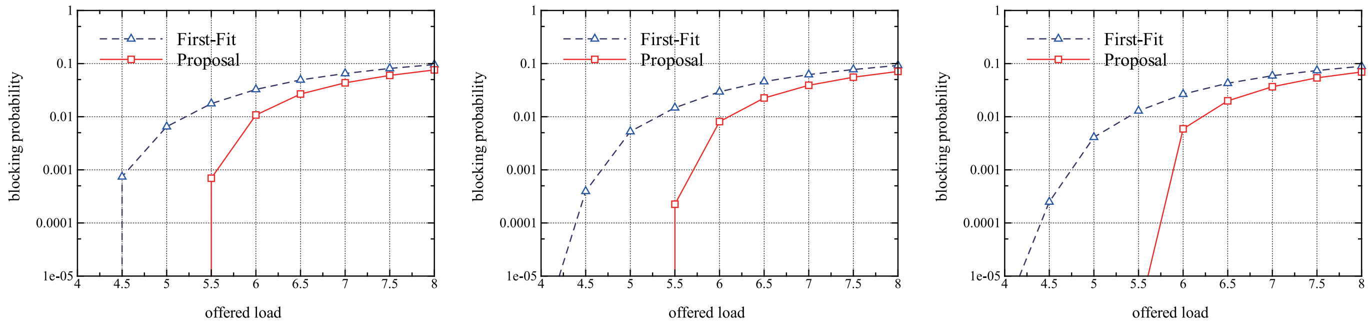
Figure 8(a) shows the average number of crosstalk occurrences per frequency slot as a function of the offered load ρ in the JPN network, where $|\mathcal{M}| = 7$. We count the number of crosstalk occurrences every time a new lightpath is established and the average number of crosstalk occurrences is defined by

$$\text{average number of crosstalk occurrences} = \frac{\text{total number of crosstalk occurrences}}{\text{number of established lightpaths}}.$$

As we can see from this figure, the proposed method greatly reduces the crosstalk effect in lightly loaded situations while the first-fit method is severely affected by crosstalk. The average number of crosstalk occurrences increases with the offered load ρ because it is highly possible that there are no available frequency slots that are not used in adjacent cores in heavily loaded situations.

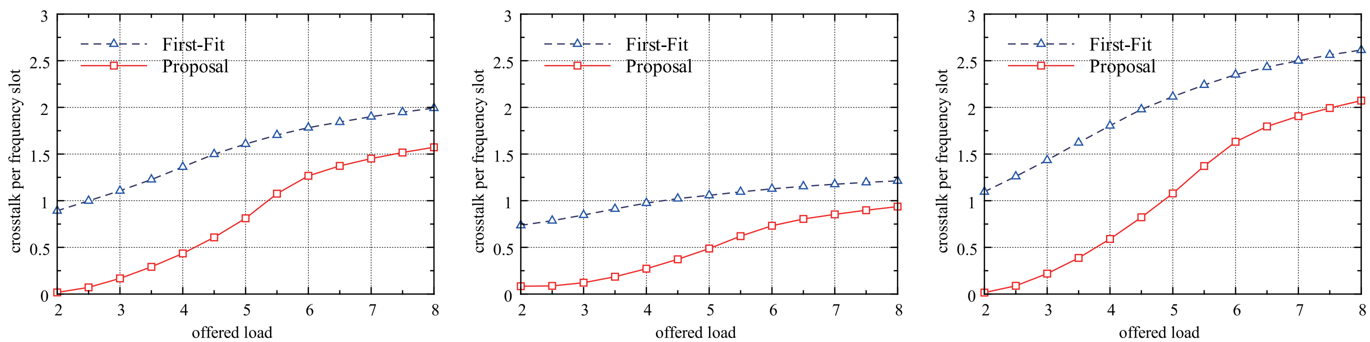
Figures 8(b) and (c) show the average number of crosstalk occurrences per frequency slot as a function of the offered load ρ in the JPN network, where $|\mathcal{M}| = 12$ and 19. From these figures, we observe that the proposed method efficiently reduces the average number of crosstalk occurrences as well as the case of $|\mathcal{M}| = 7$. Note that values of the average number of crosstalk occurrences depend on the placement of cores shown in Figure 6, so that the average number of crosstalk occurrences in the case of $|\mathcal{M}| = 12$ is smaller than those in the other cases.

Figures 9(a)-(c) show the blocking probability of lightpath establishment as a function of the offered load ρ in the USA network, where $|\mathcal{M}| = 7$, 12, and 19, respectively. Also, Figures 10(a)-(c) show the average number of crosstalk



(a) $|\mathcal{M}| = 7$ (b) $|\mathcal{M}| = 12$ (c) $|\mathcal{M}| = 19$

Figure 9. Blocking probability of lightpath establishment in the USA network.



(a) $|\mathcal{M}| = 7$ (b) $|\mathcal{M}| = 12$ (c) $|\mathcal{M}| = 19$

Figure 10. Average number of crosstalk occurrences in the USA network.

occurrences per frequency slot as a function of the offered load ρ in the USA network, where $|\mathcal{M}| = 7$, 12, and 19, respectively. As we can see from these figures, the proposed method dramatically reduces both the blocking probability of lightpath establishment and the average number of crosstalk occurrences, regardless of the number $|\mathcal{M}|$ of cores in each fiber, similar to the results in the JPN network.

V. Conclusion

This paper proposed a dynamic RSA method that avoids the generation of crosstalk and the blocking of lightpath establishment in elastic optical networks with multi-core fibers. The proposed method provides a routing and spectrum allocation strategy, which suppresses both the generation of crosstalk and blocking of lightpath establishment. Through simulation experiments, we showed the effectiveness of the proposed method.

Acknowledgment

This work was partially supported by Grant-in-Aid for Scientific Research (C) of the Japan Society for the Promotion of Science under Grant No. 18K11282.

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