

# Priority-based RCSA method considering required frequency slot width in multi-core fiber networks

Funa Fukui\*, Yutaka Fukuchi<sup>†</sup>, and Kouji Hirata<sup>‡</sup>

\*Graduate School of Science and Engineering, Kansai University, Osaka 564-8680, Japan

<sup>†</sup>Faculty of Engineering, Tokyo University of Science, Tokyo 125-8585, Japan

<sup>‡</sup>Faculty of Engineering Science, Kansai University, Osaka 564-8680, Japan

Email: {k423171, hirata}@kansai-u.ac.jp, fukuchi@ee.kagu.tus.ac.jp

**Abstract**—In this paper, we propose a priority-based dynamic Routing, Core, and Spectrum Allocation (RCSA) method with grouping of lightpath setup requests in multi-core fiber networks. The proposed RCSA method introduces a priority-based cost function for frequency resource assignment by taking into account the required frequency slot width of lightpath setup requests. Lightpaths are assigned to prioritized cores and frequency slots based on the cost function. By doing this, we expect to mitigate the impact of spectrum fragmentation, which causes the blocking of lightpath establishment, and inter-core crosstalk, which degrades the quality of optical signals. Simulation results demonstrate that the proposed RCSA method outperforms conventional approaches in terms of both lightpath establishment success rate and inter-core crosstalk suppression performance.

## I. INTRODUCTION

The rapid growth of internet traffic demands more flexible utilization of network resources. Elastic Optical Networks (EONs) have emerged as a promising network architecture by enabling efficient resource utilization and adaptability to traffic fluctuations [1]. EONs achieves this by dividing frequency resources into finer granularity, i.e., frequency slots, and support multi-level modulation mechanism, which have not been achieved by conventional Wavelength Division Multiplexing (WDM)-based optical networks [2].

A key challenge in EON design is the Routing, Core, and Spectrum Allocation (RCSA) problem which involves selecting routing paths, cores, and frequency resources for data transmission [3], [4], [5], [6], [7]. In dynamic RCSA environments, where data traffic demands are probabilistically generated over time, lightpaths for data transmission are established based on the current network state by using an RCSA method. When a lightpath setup request generates at a sender node, the RCSA method establish a lightpath by selecting routing paths to a receiver node and cores on the selected paths, and allocating frequency slots to them. In this case, the RCSA method needs to meet two constraints. Specifically, each lightpath must use successive frequency slots, and common frequency slots along the routing path from the sender to the receiver. When these constraints cannot be satisfied, the lightpath establishment is blocked. Therefore, the blocking probability of lightpath establishment is an important performance metric in EONs.

Space Division Multiplexing using Multi-Core Fibers (MCFs) has attracted attention as a technology [8], [9]. MCFs enable multiplexed transmission over the same frequency

slots through multiple independent cores, allowing for a significant increase in transmission capacity of optical fibers. However, the use of MCFs causes inter-core crosstalk, which degrades the quality of optical signals passing through adjacent cores [10], [11]. Thus, it is also important to mitigate the impact of inter-core crosstalk in EON design.

This paper proposes a priority-based dynamic RCSA method for addressing blocking of lightpath establishment and inter-core crosstalk. The proposed RCSA method introduces a priority-based cost function for frequency resource assignment by taking into account the required frequency slot width of lightpath setup requests. Lightpaths are assigned to prioritized cores and frequency slots based on the cost function. By doing so, we expect to prevent spectrum fragmentation, which causes the blocking of lightpath establishment, and mitigate the impact of inter-core crosstalk.

## II. SYSTEM MODEL

Fig. 1 illustrates the system model of an EON targeted in this paper. This network is represented as a directed graph  $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ , where  $\mathcal{V}$  represents the set of nodes and  $\mathcal{E}$  represents the set of links. Each node has multiple input/output links composed of MCFs. Each fiber has the same number of cores, denoted by  $\mathcal{C} = \{1, 2, \dots, C\}$ . In the network, a set  $\mathcal{F} = \{1, 2, \dots, F\}$  of frequency slots, each with a bandwidth of 12.5 GHz, is assumed to be available. Frequency slots are numbered in ascending order, and different lightpaths can be simultaneously established in different cores using using the same frequency slots, as illustrated in Fig. 1. Note that each lightpath uses successive frequency slots and a 1-slot guard band is inserted to avoid interference between adjacent established lightpaths in each core.

In this paper, according to the traffic demand and modulation scheme, frequency slot width  $W_p$ , i.e., the number of frequency slots, required by a lightpath  $p$  is determined by

$$W_p = \lceil \frac{T}{B \cdot M_p} \rceil, \quad (1)$$

where  $T$  denotes the traffic demand [bps] of the lightpath and  $B$  denotes the basic transmission capacity per frequency slot when using 1 bits/symbol transmission such as Binary Phase Shift Keying (BPSK).  $M_p$  represents the modulation level, which is given according to the modulation scheme, e.g.,

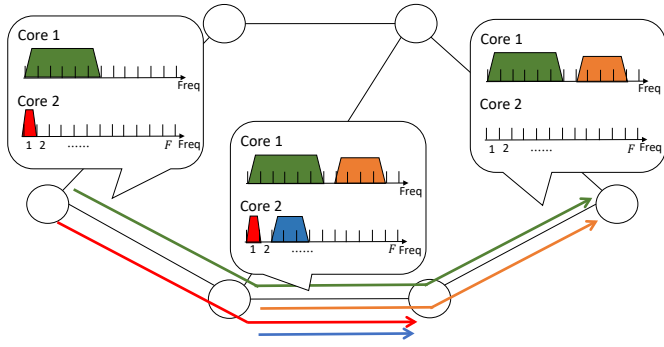


Fig. 1: System model.

$M_p = 1$  for BPSK,  $M_p = 2$  for Quadrature PSK (QPSK), and  $M_p = 4$  for 16-Quadrature Amplitude Modulation (16-QAM). The modulation scheme is selected based on the lightpath length.

### III. PROCEDURE OF PROPOSED METHOD

#### A. Overview

To reduce the blocking probability of lightpath establishment, it is important to select cores and frequency slots according to the required frequency slot width  $W_p$ . The proposed method preferentially assigns lightpaths requiring the same value of  $W_p$  to the same core. This strategy prevents the generation of spectrum fragmentation, thereby reducing the blocking probability [5], [7]. In addition, by determining the cores to be preferentially used based on the value of  $W_p$ , inter-core crosstalk is expected to be suppressed. In order to further reduce the blocking probability, the proposed method also assigns priorities to the frequency slots used in each core based on the value of  $W_p$ . This approach is expected to improve frequency utilization efficiency.

#### B. Candidate path construction

In the proposed method, multiple candidate paths are prepared in advance for each sender node  $i$  and receiver node  $j$  pair in the network. The set of candidate paths is denoted as  $P_{i,j} = \{p_1, p_2, \dots, p_K\}$ . A sender node selects an appropriate path from this set whenever a new lightpath setup request arrives. Note that an appropriate modulation level  $M_p$  is determined based on the length of selected path. In this paper, the following  $K$ -shortest path algorithm is used to construct these candidate paths for each sender node  $i$  and receiver node  $j$  pair.

1. The candidate path set  $P_{i,j}$  is initialized as empty and  $k$  is set to 1. Furthermore, the cost of each link is initialized to 1.
2. Dijkstra's algorithm is used to find the shortest path  $p_k$  from sender node  $i$  to receiver node  $j$  on graph  $\mathcal{G}$ .
3. The obtained path  $p_k$  is added to the candidate path set  $P_{i,j}$ , and the cost of all links along the path  $p_k$  is doubled.
4. If  $k \neq K$ ,  $k$  is incremented by 1 and return to step 2; otherwise, the algorithm terminates.

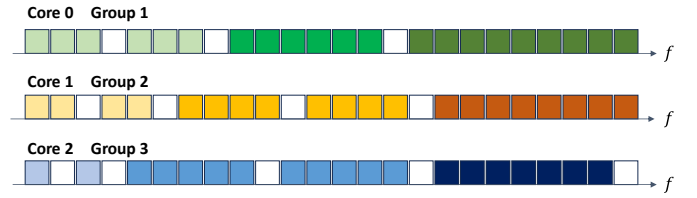


Fig. 2: Grouping-based core assignment.

#### C. Grouping for priority assignment

As mentioned above, the proposed method assigns lightpaths with the same required frequency slot width  $W_p$  to the same core in order to prevent spectrum fragmentation. However, the number of available cores is limited. On the other hand, the value of  $W_p$  takes various values depending on path length and traffic demand, as shown in (1). Therefore, it is not practical to assign a dedicated core for each  $W_p$ .

To address this issue, the proposed method classifies lightpath setup requests into some groups based on the value of  $W_p$ , and assigns each group to its prioritized cores. By consolidating the required slot numbers within each group into multiples of the fundamental required slot number, frequency allocation can be carried out more smoothly, and frequency fragmentation can be mitigated to some extent. Fig. 2 shows an example of priority setting for grouping in the proposed method. In this paper, we make three groups as follows. First, lightpath setup requests whose  $W_p$  values are multiples of 3 are classified into group  $g_1$  (i.e.,  $W_p = 3, 6, 9, \dots$ ). Then, requests that do not belong to  $g_1$  and whose  $W_p$  values are multiples of 2 are classified into group  $g_2$  (i.e.,  $W_p = 2, 4, 8, \dots$ ). The other requests are classified into group  $g_3$  (i.e.,  $W_p = 1, 5, 7, \dots$ ). This group classification allows for the optimization of resource allocation by assigning preferred cores and frequency slots to each group.

#### D. Lightpath establishment procedure

To achieve efficient resource allocation, the proposed method introduces a cost function  $\text{Cost}(W_p, c, f)$  that assigns priority to frequency slot  $f$  and core  $c$  based on the value of  $W_p$ . As discussed later, the proposed method selects a combination of frequency slots and cores such that the total value of the cost function is the smallest. To define the cost function, we first consider the following two indicator functions:  $\text{in\_F}(f, W_p)$  and  $\text{p\_C}(c, W_p)$ .  $\text{in\_F}(f, W_p)$  indicates whether frequency slot  $f$  is included in the preferred slot range for the lightpath setup requests requiring  $W_p$  slots. Specifically,  $\text{in\_F}(f, W_p)$  is given by

$$\text{in\_F}(f, W_p) = \begin{cases} 1, & \text{if } f_s(W_p) \leq f \leq f_e(W_p), \\ 0, & \text{otherwise,} \end{cases} \quad (2)$$

where  $f_s(W_p)$  and  $f_e(W_p)$  are parameters that represent frequency slot numbers given for each  $W_p$ . Their specific

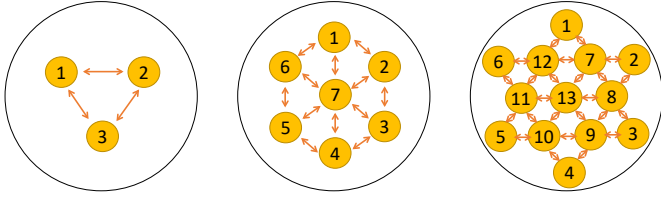


Fig. 3: Multi-core fibers.

TABLE I: Preferred core number ( $C = 3$ )

Group	Core number
$g_1$	3
$g_2$	2
$g_3$	1

values will be defined in the simulation experiments, which are discussed in Section IV.

$p\_C(c, W_p)$  indicates whether core  $c$  is preferentially assigned to lightpath setup requests requiring  $W_p$  slots, which is given by

$$p\_C(c, W_p) = \begin{cases} 1, & \text{if core } c \text{ is a preferred core for } W_p \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

In this paper, we assume three types of MCFs (i.e., 3, 7, and 13 cores) and numbers are assigned to the cores as shown in Fig. 3. According to the core numbers, we select preferred cores for each group of lightpath setup requests. Tables I, II, and III show the core numbers preferentially assigned to each group in 3, 7, and 13 core fibers, respectively. Note that the amount of inter-core crosstalk decreases exponentially as the distance between cores increases [6]. Thus, we take into account the impact of inter-core crosstalk between adjacent cores while we do not consider it between non-adjacent cores.

Considering these two indicator functions, the cost function  $\text{Cost}(W_p, c, f)$  for frequency slot  $f$  in core  $c$  for the lightpath setup request with  $W_p$  slots is defined as follows:

$$\text{Cost}(W_p, c, f) = \begin{cases} c, & \text{if } \text{in\_F}(f, W_p) = 1, p\_C(c, W_p) = 1, \\ 2C - c, & \text{if } \text{in\_F}(f, W_p) = 1, p\_C(c, W_p) = 0, \\ 3C - c, & \text{if } \text{in\_F}(f, W_p) = 0, p\_C(c, W_p) = 1, \\ 4C - c, & \text{if } \text{in\_F}(f, W_p) = 0, p\_C(c, W_p) = 0. \end{cases} \quad (4)$$

This function assigns priorities in four stages as follows:

- 1) **Within preferred frequency slot range and preferred core ( $c$ ):** If  $f$  is within the range and  $c$  is a preferred core, the cost increases, the cost becomes lowest, which means the highest priority assignment.
- 2) **Within preferred frequency slot range and non-preferred core ( $2C - c$ ):** If  $f$  is within the range and  $c$  is not a preferred core, the cost increases.
- 3) **Outside preferred frequency slot range and preferred core ( $3C - c$ ):** If  $f$  is outside the range and  $c$  is a preferred core, the cost further increases.

TABLE II: Preferred core number ( $C = 7$ )

Group	Core number
$g_1$	5, 6
$g_2$	3, 4
$g_3$	1, 2

TABLE III: Preferred core number ( $C = 13$ )

Group	Core number
$g_1$	5, 6, 11, 12
$g_2$	3, 4, 9, 10
$g_3$	1, 2, 7, 8

- 4) **Outside preferred frequency slot range and non-preferred core ( $4C - c$ ):** If  $f$  is outside the range and  $c$  is not a preferred core, the cost becomes highest.

This design prioritizes the reduction of blocking probability while efficiently utilizing spectrum resources and cores. Furthermore, by defining the cost function as in (4), cores with smaller numbers are preferentially used for each group. In this paper, by defining core numbers as illustrated in Fig. 3, lightpaths belonging to each group are preferentially established in non-adjacent cores. For example, in 7 core fibers, group  $g_1$  preferentially uses core 5 over core 6, even among its preferred cores. This is because in the case where  $\text{in\_F}(f, W_p) = 1$  and  $p\_C(c, W_p) = 1$ ,  $\text{Cost}(W_p, c, f)$  becomes 5 and 6 for core 5 and core 6, respectively. This approach is expected to not only reduce the blocking probability of lightpath establishment but also suppress inter-core crosstalk.

In the proposed method, whenever a lightpath setup request arrive at a sender node, lightpaths are established using the cost function defined in (4) according to the following procedure, where  $K$  is the number of candidate paths.

1.  $k$  is set to 1.
2. The required frequency slot width  $W_p$  for path  $p_k$  is calculated.
3. On each link  $l$  along path  $p_k$ , for each core  $c$  and each frequency slot  $f$ , the cost function  $\text{Cost}(W_p, c, f)$  is calculated. Similarly, the cost functions for frequency slots  $f + 1$  to  $f + W_p - 1$  are calculated. Then,  $S_l(f) = \min_{c \in C} \sum_{f'=f}^{f+W_p-1} \text{Cost}(W_p, c, f')$  is obtained.
4. If  $k \neq K$ ,  $k \leftarrow k + 1$  and return to step 2.
5. The combination of path  $p^*$  and frequency slot  $f^*$  that minimizes  $\sum_{l \in p_k} S_l(f)$  is selected and the lightpath is established using this combination. In each link along the path  $p^*$ , core  $c = \arg \min_{c \in C} \sum_{f'=f^*}^{f^*+W_p-1} \text{Cost}(W_p, c, f')$  is selected. Then, the procedure terminates. If there are no available combinations, the lightpath establishment is blocked.

## IV. PERFORMANCE EVALUATION

### A. Evaluation model

We evaluate the proposed RCSA method through simulation experiments using the NSFNET network shown in Fig. 4. The network has 14 nodes and 21 bidirectional links. All links in the network are assumed to have equal length and are

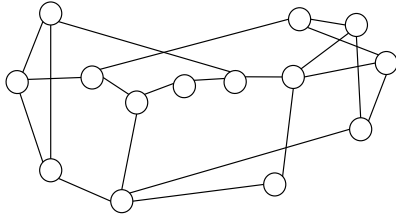


Fig. 4: NSFNET Network.

TABLE IV: Required frequency slot width  $W_p$ .

# of hops	Modulation level $M_p$	Required width $W_p$
$\leq 2$	4 (16QAM)	$T/4$
3	3 (8QAM)	$T/3$
4	2 (QPSK)	$T/2$
$> 5$	1 (BPSK)	$T/1$

composed of MCFs with 3, 7, or 13 cores shown in Fig. 3. The number  $F$  of available frequency slots is set to 320. We construct  $K = 3$  candidate paths using a  $K$ -shortest path algorithm.

Lightpath setup requests at each sender node arrives according to a Poisson process with a rate of  $\lambda$  [1/sec]. Their destinations are chosen uniformly at random. The holding time of lightpaths follows exponential distribution with an average of  $H$  [sec]. The offered load  $\rho$  per frequency slot in a core is given by

$$\rho = \frac{\lambda H}{FC}. \quad (5)$$

Traffic demand  $T$  [Gbps] for each request is randomly selected from [1, 10], and the transmission capacity  $B$  per frequency slot is 1 [Gbps]. Required frequency slot width  $W_p$  is determined based on the number of hops, as shown in Table IV, assuming that the path length is proportional to the number of hops. The preferred frequency slot range for each  $W_p$  discussed in (2) is shown in Table V, which is determined based on a preliminary experiment.

Simulation results are the average of 10 independent samples. We compare the proposed method with the First-Fit method, which prioritizes shortest paths and sequentially assigns available frequency slots to mitigate fragmentation. Additionally, we compare the proposed method with a core-priority method, which uses the same approach as the proposed method about preferred cores described in (3), but does not take into account the preferred frequency slot range discussed in (2).

## B. Results

Fig. 5(a) shows the blocking probability of lightpath establishment as a function of the offered load  $\rho$  where the number  $C$  of cores is 3. As we can see from this figure, the performance of the core-priority method is almost the same as the First-Fit method. This is because the number of cores is small and thus it is difficult for the core-priority method to prevent spectrum fragmentation. On the other hand, the proposed

TABLE V: Preferred frequency slot range for  $W_p$

Required width $W_p$	Group	$f_s(W_p)$	$f_e(W_p)$
1	$g_3$	1	108
2	$g_2$	1	160
3	$g_1$	1	301
4	$g_2$	161	301
5	$g_3$	109	301
6	$g_1$	302	309
7	$g_3$	302	320
8	$g_2$	302	309
9	$g_1$	310	320
10	$g_2$	310	320

method (labeled with “core & frequency priority”) efficiently reduces the blocking probability. This result indicates that assigning the preferred frequency slot range is effective for reducing the blocking probability.

Figs. 5(b) and (c) show the blocking probability of lightpath establishment as a function of the offered load  $\rho$  for  $C = 7$  and 13, respectively. From these figures, we observe that the core-priority method reduces the blocking probability more efficiently than the First-Fit method because the number of cores increases and assigning preferred cores works well. We also observe that the proposed method exhibits excellent performance in terms of the blocking probability.

Figs. 6(a)-(c) show the amount of inter-core crosstalk per lightpath establishment as a function of the offered load  $\rho$  for  $C = 3, 7,$  and 13, respectively. In this paper, the crosstalk amount is defined as the average number of crosstalk occurrences in each frequency slot, measured whenever an optical path is established. As shown in Fig. 6, the amount of inter-core crosstalk is almost the same for each method because the cores are adjacent to each other when  $C = 3$ . On the other hand, as we can see from Figs. 6(b) and (c), the core-priority method and the proposed method reduce the amount of inter-core crosstalk. The proposed method becomes more effective as the number of cores increases.

## V. CONCLUSION

In this paper, we proposed a priority-based dynamic RCSA method for preventing blocking of lightpath establishment and inter-core crosstalk. The proposed RCSA method introduces a priority-based cost function for frequency resource assignment by taking into account the required frequency slot width of lightpath setup requests. Through simulation experiments, we showed the effectiveness of the proposed method.

## ACKNOWLEDGEMENT

This research was supported by JSPS KAKENHI Grant Number 25K15103.

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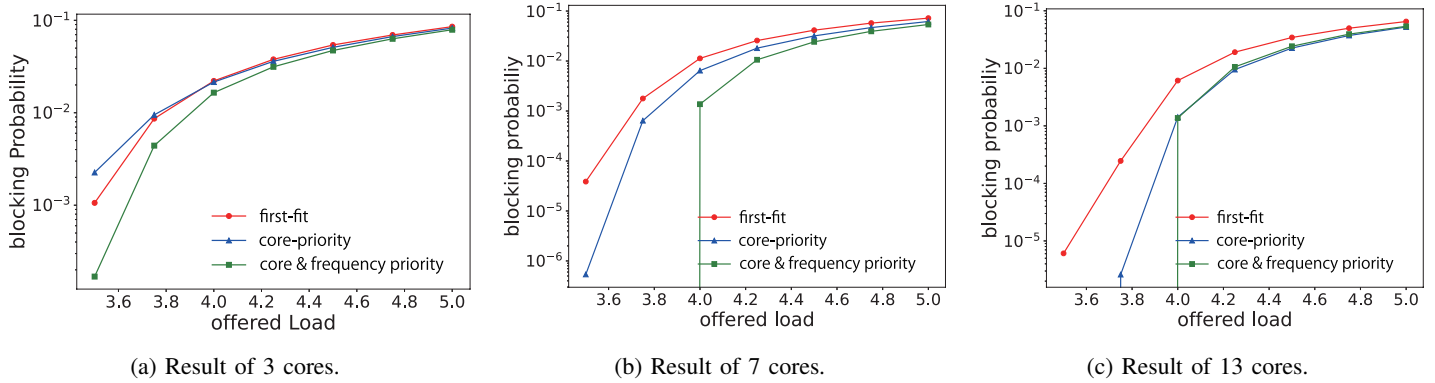


Fig. 5: Blocking probability.

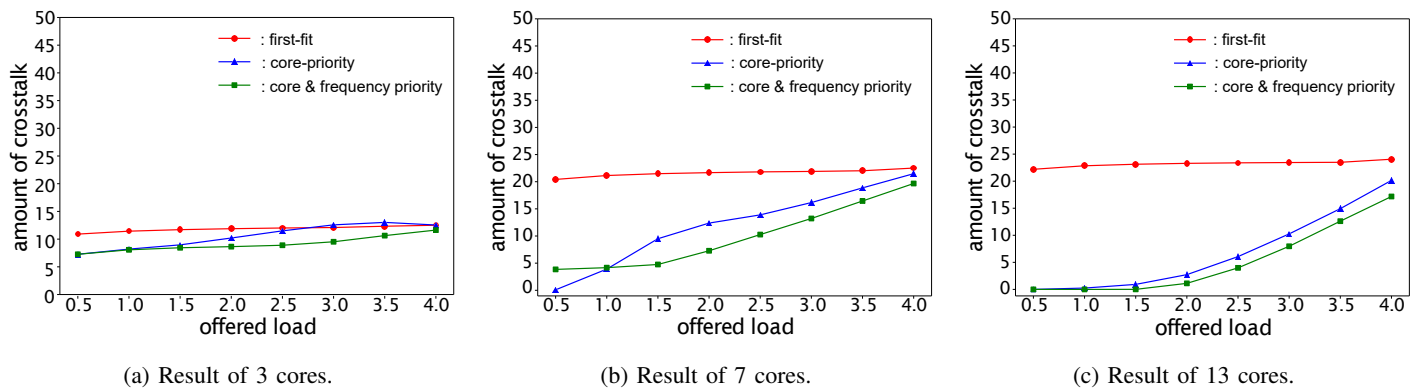


Fig. 6: Amount of inter-core crosstalk.

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