Crosstalk-Derived Fragmentation-Aware Lightpath Provisioning Model in Spectrally-Spatially Elastic Optical Networks

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***Abstract*—A fragmentation-aware lightpath provisioning model, which suppresses the fragmentation caused by allocating spectrum slots to lightpaths and due to inter-core crosstalk, is proposed. The proposed model suppresses the blocking probability in spectrally-spatially elastic optical networks.**

***Index Terms*—Elastic optical networks, Space-division multiplexing, Crosstalk, Fragmentation**

I. Introduction

Elastic optical networks (EONs) offer better resource utilization than conventional optical networks [1]. In EONs, rate-adaptive super-channels and distance-adaptive modulation are typically used to increase spectrum efficiency [1]. The required number of spectrum slots is allocated to a lightpath according to its end-to-end physical conditions. Routing and spectrum allocation (RSA) is one of the challenging issues in EONs, which finds an appropriate route for a lightpath request and allocates suitable spectrum slots to it while satisfying the spectrum contiguity and continuity constraints [2].

During RSA, fragmentation is one of the major issues [3]. Vacant spectrum slots that are neither aligned along the lightpath route nor contiguous in the spectrum are called fragmented slots. There is a high possibility that the fragmented slots cannot satisfy future lightpath requests due to the spectrum contiguity and continuity constraints. Since the fragmented slots lead to inefficient utilization of spectrum resources, they need to be suppressed.

To enhance a fiber capacity, multi-core fiber (MCF) is typically used, which is one of the space-division multiplexing (SDM) technologies [4]. In data centers and submarine cables, large-capacity data transmission needs to be achieved in small spaces, and hence the demand for MCF is growing. The EONs incorporating SDM technologies are called spectrally-spatially EONs (SS-EONs). In SS-EONs with MCF, the core allocation needs to be considered in addition to RSA; this is called the routing, spectrum, and core allocation (RSCA) problem.

In MCFs, when signals are transmitted in the same direction and use the same spectrum slots in two neighboring fiber cores, inter-core crosstalk (XT) occurs and degrades the signal quality [5]. As a result, RSCA becomes more complicated than RSA due to inter-core XT. Moreover, as different modulation formats have different XT tolerance limits [6], the relationship between inter-core XT and modulation formats needs to be considered. When we consider modulation formats in RSCA, it is called the routing, modulation, spectrum, and core allocation (RMSCA) problem.

In SS-EONs, several researches have been conducted to deal with inter-core XT from the networking aspect [7]–[10]. These works can be classified into two approaches. The first approach allocates spectrum slots to a lightpath to prevent inter-core XT occurrence without estimating a XT value when each lightpath is provisioned [7], [8]. This approach is called the XT-avoided approach. The XT-avoided approach does not allocate the same spectrum to any pair of lightpaths that traverse through adjacent cores so that the XT does not occur. Since the same spectrum cannot be utilized in both adjacent cores at the same time, spectrum utilization becomes inefficient. The second approach allocates spectrum slots to a lightpath so that the estimated XT value must be smaller than the given threshold [9], [10]. The coupled-power theory is used to estimate the XT value [11]. The XT threshold is different for each modulation format. This approach is called a XT-estimated approach. In the XT-estimated approach, spectrum slots in all cores are available as long as the XT value of a lightpath is not more than the XT threshold. The XT-estimated approach can use spectrum resources more efficiently than the XT-avoided approach at the cost of XT computation and its management.

In the XT-estimated approach, a vacant spectrum slot is considered unavailable if allocating it to a new lightpath violates the XT threshold of at least one existing lightpath. In other words, some vacant spectrum slots cannot be allocated to a lightpath due to inter-core XT; we name these slots *unavailable vacant slots*. The vacant slots that are used for lightpath allocation are named *available vacant slots*.

The fragmentation needs to be suppressed in SS-EONs. Lechowicz et al. [12] presented a fragmentation-aware lightpath provisioning model with a XT-estimated approach. This model introduces a fragmentation metric, which indicates the degree of fragmentation occurring in the network, and allocates spectrum slots to a lightpath to reduce the fragmentation metric. The XT threshold is set to guarantee signal quality; lightpaths are provisioned by satisfying the XT threshold. When a lightpath is provisioned, the fragmentation metric is

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calculated for each candidate path and the path is selected whose fragmentation metric is the lowest.

The conventional fragmentation-aware model with the XT-estimated approach calculates the fragmentation metric by distinguishing spectrum slots as vacant or not [12]. Even though vacant slots are contiguous, the available vacant slots are fragmented if available vacant and unavailable vacant slots are intermingled in the contiguous vacant slots. The fragmented available vacant slots can cause to fail to accept a lightpath request. In addition to allocating spectrum slots to lightpaths, the occurrence of inter-core XT can cause fragmentation. The conventional fragmentation-aware model only suppresses fragmentation without separation of available vacant and unavailable vacant slots. If the fragmentation is suppressed without separating available vacant and unavailable vacant slots, the fragmented available vacant slots can be increased in the network. The fragmentation due to inter-core XT, which is caused by fragmented available vacant slots, leads to inefficient utilization of spectrum resources; it is required to suppress fragmented available vacant slots in the network. A question arises; how can we deal with the fragmentation derived from inter-core XT when provisioning a lightpath?

This paper proposes a fragmentation-aware lightpath provisioning model to address the above question by introducing fragmentation derived from inter-core XT. The proposed model suppresses the fragmentation caused by allocating spectrum slots to lightpaths and from inter-core XT. In the proposed model, vacant spectrum slots are classified into available vacant slots and unavailable vacant slots to suppress the fragmentation due to inter-core XT. To suppress the fragmentation, a lightpath provisioning problem is presented, which is based on the proposed model. A lightpath provisioning algorithm is introduced to solve the problem. We evaluate the performance of the proposed model in terms of the blocking probability, and compare it to a benchmark model.

II. Fragmentation-aware model with XT-estimated approach

This section presents a fragmentation-aware model with the XT-estimated approach. The fragmentation-aware model estimates the XT value to satisfy the XT threshold and uses a fragmentation metric. The descriptions of the XT-estimated approach and the fragmentation metric are as follows.

A. XT-estimated approach

The XT-estimated approach estimates the XT value when a lightpath is provisioned. The estimated XT value does not exceed the given threshold. In the approach, the XT threshold and the transmission reach are set for each modulation format.

To estimate the XT value, the coupled-power theory [11] is used. The XT value is calculated by a simplified linear model:

$$XT \simeq NhL, \tag{1}$$

where N denotes the number of adjacent cores that utilize the same spectrum slot, L denotes the MCF length, and h denotes the power-coupling coefficient. The difference between the estimated values of XT calculated by (1) and a strict model presented in [11] is negligible.

There are two ways to estimate the XT value of a lightpath. One assumes that, even if a pair of lightpaths uses the same spectrum in an adjacent core pair in only a part of the path, the XT occurs along the end-to-end path. The XT estimated by this way is called worst-case XT (WC-XT). The WC-XT value of a lightpath in a specific spectrum slot depends on the number of adjacent cores in which the spectrum slot is used by other lightpaths sharing a link. We call the number of such adjacent cores the lightpath-adjacent number. The WC-XT value of a lightpath in the wth spectrum slot can be calculated by:

$$XT \simeq N_w hL', \tag{2}$$

where N_w denotes the lightpath-adjacent number in the wth spectrum slot, and L' denotes the end-to-end transmission distance of the lightpath. The other way to estimate the XT value takes into account links and their distances where the lightpath is adjacent to the other lightpaths. The XT estimated by this way is called precise XT (P-XT).

In this paper, we discuss the XT-estimated approach with the WC-XT as the existing fragmentation-aware model with the XT-estimated approach [13].

B. Fragmentation metric

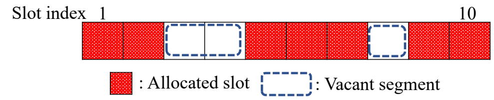
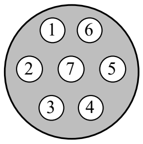


Fig. 1. Illustration of allocated slots and vacant segments in a core of a link.

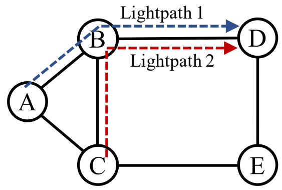
To evaluate fragmentation in a network, several fragmentation metrics are introduced in [12]. One of them is the root mean square factor (RMSF). The fragmentation metric of each link is calculated using a metric. The fragmentation of a link is called link fragmentation. The RMSF accounts for sizes of all vacant segments, the number of vacant segments, and the highest allocated slot index on each core. The RMSF decreases when (i) the highest slot allocated in each core decreases, (ii) the number of vacant segments decreases on each core, and (iii) the size of larger segments increases at the cost of decreasing the size of smaller ones. The link fragmentation using the RMSF of link (i, j) is presented by:

$$\frac{1}{|C|}\sum_{c\in C}\frac{F_{cij}|\Xi_{cij}|}{\sqrt{\frac{\sum_{\xi\in\Xi_{cij}}|\xi|^2}{|\Xi_{cij}|}}}, \tag{3}$$

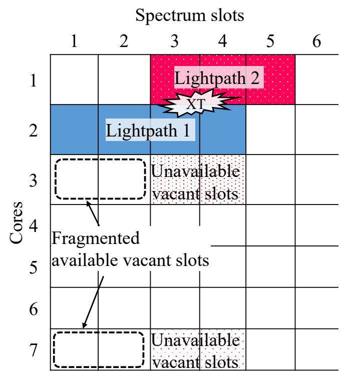
where C is a set of cores, F_{cij} is the maximum index of allocated spectrum slots in core $c \in C$ of link (i, j), and Ξ_{cij} is a set of vacant segments in core $c \in C$ of link (i, j). Figure 1 shows an illustration of allocated slots and vacant segments in a core of a link. In this example, $F_{cij} = 10$ and $|\Xi_{cij}| = 2$. The whole network fragmentation is calculated as an average of link fragmentation [12].



(a) 7-core MCF.



(b) Network and lightpaths.



(c) Spectrum slot utilization in link B–D.

Fig. 2. Unavailable vacant slots and fragmented slots due to inter-core XT.

III. Proposed model

The proposed model suppresses fragmentation derived from inter-core XT in addition to that caused by allocating spectrum slots to lightpaths. In the proposed model, vacant spectrum slots are classified into available vacant slots and unavailable vacant slots. The XT-estimated approach allocates spectrum slots to a lightpath so that the XT value of each lightpath does not exceed its XT threshold. If a lightpath cannot accept more XT than that currently accepted, the vacant spectrum slots adjacent to the lightpath become unavailable vacant slots.

The proposed model provisions a lightpath for a traffic demand under the existence of lightpaths which have already been provisioned. Since the transmission distance of an existing lightpath is constant, i.e., its route is not changed, the WC-XT value of the existing lightpath depends on the lightpath-adjacent number. The XT threshold of an existing lightpath can be translated into the acceptable lightpath-adjacent number.

The fragmentation derived from inter-core XT is explained using Fig. 2. Each link in a network is assumed to be a 7-core MCF, as shown in Fig. 2a. Two lightpaths are provisioned in the network, as shown in Fig. 2b. Spectrum slots are allocated to each lightpath, as shown in Fig. 2c. The coupling-power efficient of the MCF, h, is assumed to be 1.0×10^{-8}. The transmission distance of lightpath 1 is assumed to be 1000 km, and the XT threshold of lightpath 1 is assumed to be -20 dB. The acceptable lightpath-adjacent number of lightpath 1 can be calculated to be one by (2). Since lightpath 1 is adjacent to lightpath 2 in core 1 at slots 3 and 4, cores 3 and 7 at slots 3 and 4 on links A-B and B-D cannot be used by any other lightpath. Therefore, slots 3 and 4 in cores 3 and 7 on links A-B and B-D are unavailable vacant slots. In this way, unavailable vacant slots arise due to inter-core XT.

Though vacant slots in core 3 are contiguous, available vacant slots 1 and 2 become fragmented slots due to the existence of unavailable vacant slots 3 and 4. This is why inter-core XT can cause fragmentation. We call it the fragmentation derived from inter-core XT.

IV. Lightpath provisioning problem

A. Overview

We present a lightpath provisioning problem using the proposed model to suppress fragmentation. The fragmentation in the lightpath provisioning problem is considered by classifying vacant spectrum slots into available vacant slots and unavailable vacant slots. A traffic demand, which consists of a transmission capacity and a source-destination node pair, is given. A lightpath for the traffic demand is provisioned by determining routing, modulation, spectrum, and core allocation in the problem. When a lightpath is provisioned, both XT threshold and transmission reach, which are different by each modulation format, need to be satisfied.

B. Assumption and notations

A traffic demand is given in an optical network (V, E), where V is a set of nodes and E is a set of MCF links. The lightpath for traffic demand is denoted by p_{new}, and RMSCA of p_{new} is decided in the optimization problem. In the network, there is a set of existing lightpaths P. When provisioning lightpath p_{new}, RMSCA of existing lightpaths is not changed. The length of each link is denoted by d_{ij} for $(i, j) \in E$. We assume that each MCF link has the same number of cores, and their arrangement is identical. Let C denote a set of cores in each link and Φ denote a set of adjacent core pairs. The same number of spectrum slots is available in each core. Let C_c denote the set of cores adjacent to core $c \in C$. W denotes a set of indices of the spectrum slots. A set of modulation formats is represented by Q.

The given parameters in the problem are described below. The traffic demand requires transmission capacity b, and has source and destination node pair (s, d). The capacity per spectrum slot of modulation format $q \in Q$ is represented by η_q. The transmission reach of modulation format $q \in Q$ is represented by r_q. The XT threshold for modulation $q \in Q$ is represented by θ_q. The power-coupling coefficient of a MCF in the network is represented by h. When lightpath p_{new} is provisioned, information of existing lightpaths that have already been provisioned is given as parameters. Information of existing lightpaths is given as $\mathcal{I}$. $\mathcal{I}$ includes the RSCA information of lightpath $p \in P$. $\mathcal{I}$ also includes the acceptable number of lightpaths that can be additionally adjacent to p. Let N_w^p denote an integer parameter that denotes the number of lightpaths that can be additionally adjacent to lightpath $p \in P$ in the wth spectrum slot ($w \in W$). X^p denotes the core allocated to p. Y^p denotes the set of spectrum slots allocated to p. E^p denotes the set of links, which are used to the route of p. Status of spectrum slots in the network is given as $\mathscr{S}$. $\mathscr{S}$ consists of S_{cij}^a and S_{cij}^u, each of which represents the status of spectrum slots of core $c \in C$ in link $(i, j) \in E$. S_{cij}^a is

Algorithm 1 Lightpath provisioning algorithm

Input: Network (V, E), $C, Q, \mathcal{I}, \mathscr{S}$, traffic demand of p_{new}, and R_{a}.
Output: RMSCA for lightpath p_{new}; $(X^{p_{\mathrm{new}}}, Y^{p_{\mathrm{new}}}, E^{p_{\mathrm{new}}}, M^{p_{\mathrm{new}}})$

1: **Initialize:**
  Value of RMSF $\Omega \leftarrow \infty$
2: **for all** $R \in R_{\mathrm{a}}$ **do**
3:   **for all** $c \in C$ **do**
4:     $S_{Rc} = $ GETCANDIDATESEGMENT$(R, c, \mathscr{S})$
5:     **for all** $q \in Q$ **do**
6:       **if** $r_q \geq l_R$ **then**
7:         $\varsigma \leftarrow \lceil b/\eta_q \rceil$
8:         **for all** $W_{Rc} \in S_{Rc}$ **do**
9:           **if** $|W_{Rc}| \geq \varsigma$ **then**
10:             $Y', \Omega' = $ ALLOCATESLOT$(R, c, W_{Rc}, q, \varsigma, \mathcal{I})$
11:             **if** $\Omega > \Omega'$ **then**
12:               $X^{p_{\mathrm{new}}} \leftarrow c, Y^{p_{\mathrm{new}}} \leftarrow Y', E^{p_{\mathrm{new}}} \leftarrow R, M^{p_{\mathrm{new}}} \leftarrow q$
13:               $\Omega \leftarrow \Omega'$
14: **if** $\Omega = \infty$ **then**
15:   lightpath p_{new} is blocked

1: **function** GETCANDIDATESEGMENT$(R, c, \mathscr{S})$
2:   $A_s \leftarrow W, S_{Rc} \leftarrow \{\}, W_{Rc} \leftarrow \{\}$
3:   **for all** $(i, j) \in R$ **do**
4:     **for all** $w \in A_s$ **do**
5:       **if** $w \in S^{a}_{cij} \cup S^{u}_{cij}$ **then**
6:         Remove w from A_s
7:   $pred \leftarrow$ MIN$(A_s) - 1$
8:   **for** $w \in A_s$ **do**
9:     **if** $w \neq pred + 1$ **then**
10:       Add W_{Rc} in S_{Rc}
11:       $W_{Rc} \leftarrow \{\}$
12:     Add w in W_{Rc}
13:     $pred = w$
14:   Add W_{Rc} in S_{Rc}
15:   **return** S_{Rc}

a set of indices of allocated spectrum slots of core $c \in C$ in link $(i, j) \in E$. S^{u}_{cij} is a set of indices of unavailable vacant spectrum slots of core $c \in C$ in link $(i, j) \in E$.

The spectrum contiguity and continuity constraints are imposed in provisioning lightpaths. We assume that a switch in the network cannot change the core during transmission; the core continuity constraint is imposed. The modulation format is unchangeable over a lightpath.

When lightpath p_{new} is provisioned, the XT value of each existing lightpath is ensured not to exceed the acceptable XT value of each existing lightpath.

C. Lightpath provisioning algorithm

We introduce a lightpath provisioning algorithm for the lightpath provisioning problem of the proposed model. The lightpath provisioning algorithm divides the RMSCA problem into the routing problem and modulation, spectrum, and core allocation (MSCA) problem. Using the k-shortest path algorithm [14], a set of candidate routes is determined in advance, which is given as R_{a}. Route R is an element of R_a, i.e., $R \in R_a$, which is a set of links. The distance of the route is presented as l_R.

Algorithm 1 examines the allocation of spectrum slots to minimize RMSF for each route $R \in R_a$, core $c \in C$, and modulation format $q \in Q$, and provisions lightpath p_{new} by using the allocation with the lowest RMSF. The Algorithm 1 runs as follows. Line 1 initializes Ω, which is a temporal value of RMSF, as ∞. Line 4 gets a set of candidate available vacant segments along $R \in R_a$ in $c \in C$. In lines 5–13, the slot allocation in R of c, whose RMSF is the lowest, is obtained for each $q \in Q$. If the reach of modulation q, r_q, is shorter than the distance of route R, l_R, modulation q is not available for lightpath p_{new}. Otherwise, the required number of slots, ς, is calculated in line 7. In lines 8–13, the slot allocation in R of c with q, whose RMSF is the lowest, is obtained. If the size of vacant available segment W_{Rc} is less than ς, available vacant segment W_{Rc} is not available for lightpath p_{new}. Otherwise, the slot allocation is tried with available vacant segment W_{Rc} in line 10. If the slot allocation is successful and its RMSF is lower than the temporal RMSF Ω, Ω and RMSCA are updated in lines 11–13. If Ω is not updated through the above process, lightpath p_{new} is blocked (lines 14 and 15).

Function GETCANDIDATESEGMENT gets the set of candidate available vacant segments along route R in core c. In lines 2–6, a set of slots, which are available along R in c is obtained as A_s. In lines 7–14, A_s is divided to a set of segments, each of which is spectrally contiguous.

Function ALLOCATESLOT gets the slot allocation using available vacant segment W_{Rc}, whose RMSF is the minimum

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1: **function** ALLOCATESLOT$(R, c, W_{Rc}, q, \varsigma, \mathcal{I})$
2:   $n \leftarrow \lfloor \theta_q / h \rfloor, removed\_slot \leftarrow \{\}, \Omega \leftarrow \infty, f \leftarrow 0$
3:   **for all** $w \in W_{Rc}$ **do**
4:     **for all** $(i, j) \in R$ **do**
5:       $count \leftarrow 0$
6:       **for** $c_a \in C_c$ **do**
7:         **if** $w \in S^{a}_{c_a ij}$ **then**
8:           $count \leftarrow count + 1$
9:       **if** $count \geq n + 1$ **then**
10:         Add w in $removed\_slot$
11:         **break**
12:   $W'_{Rc} \leftarrow W_{Rc} - removed\_slot$
13:   **for all** $w \in W'_{Rc} \setminus \{MAX(W'_{Rc}) - \varsigma + 1, \cdots,$ MAX$(W'_{Rc})\}$ **do**
14:     **if** $\{w, \cdots, w + \varsigma - 1\} \subseteq W'_{Rc}$ **then**
15:       $\mathscr{S}' \leftarrow$ UPDATESLOTSTATUS$(R, c, w, \varsigma, n, \mathscr{S}, \mathcal{I})$
16:       $\Omega' = $ CALCULATERMSF$(\mathscr{S}')$
17:       **if** $\Omega > \Omega'$ **then**
18:         $\Omega \leftarrow \Omega', f \leftarrow w$
19:   **if** $f = 0$ **then**
20:     $Y^{p_{\mathrm{new}}} \leftarrow \{\}$
21:   **else**
22:     $Y^{p_{\mathrm{new}}} \leftarrow \{f, \cdots, f + \varsigma - 1\}$
23:   **return** $Y^{p_{\mathrm{new}}}, \Omega$

1: **function** UPDATESLOTSTATUS$(R, c, w, \varsigma, n, \mathscr{S}, \mathcal{I})$
2:   $P' \leftarrow \{\}$
3:   **for all** $p \in P$ **do**
4:     **if** $X^p \in C_c$ and $w' \in Y^p$ and $R \cap E^p \neq \emptyset$ **then**
5:       Add p in P'
6:   **for all** $(i, j) \in R$ **do**
7:     Add $\{w, \cdots, w + n - 1\}$ in S^{a}_{cij}
8:   **for** $w' = w, \ldots w + \varsigma - 1$ **do**
9:     $\mathscr{C} \leftarrow \{\}$
10:     **for all** $c' \in C_c$ **do**
11:       **if** $w' \in S^{a}_{c'ij}$ **then**
12:         Add c' in $\mathscr{C}$
13:     **if** $|\mathscr{C}| = n$ **then**
14:       **for all** $c' \in C_c \setminus \mathscr{C}$ **do**
15:         **for all** $(i, j) \in R$ **do**
16:           $S^{u}_{c'ij} \leftarrow S^{u}_{c'ij} \cup \{w'\}$
17:     **for all** $p \in P'$ **do**
18:       **if** $N^{p}_{w'} = 1$ **then**
19:         **for all** $c_a \in C_{X^p} \setminus \{c\}$ **do**
20:           **for all** $(i, j) \in R$ **do**
21:             **if** $w' \notin S^{a}_{c'ij}$ **then**
22:               $S^{u}_{c_a ij} \leftarrow S^{u}_{c_a ij} \cup \{w'\}$
23:   **return** $\mathscr{S}$

of route R in core c with modulation q. In line 2, lightpath-adjacent number n is calculated. In lines 3–12, vacant slots, which are not available because XT is more than threshold of modulation q, are removed from W_{Rc}. Lines 13–19 get starting slot index f, where slots are allocated with the minimum RMSF in R of c with q. In line 13, $\{\textsc{Max}(W'_{Rc}) - \varsigma + 1, \cdots, \textsc{Max}(W'_{Rc})\}$ is the candidate starting slot index. Line 14 checks whether there is ς contiguous slots from the wth slot. Lines 15 and 16 get the slot status $\mathscr{S}'$ and RMSF Ω', where the wth to $(w+\varsigma-1)$th slots are allocated to lightpath p_{new}, respectively. In lines 17–19, if the RMSF Ω' gotten in line 16 is smaller than the temporal RMSF Ω, Ω and f are updated to Ω' and w, respectively. In lines 20–24, if $f = 0$, i.e., there is no allocation for lightpath p_{new} using W_{Rc}, R, c, and q, the RMSF is returned as ∞. Otherwise, the slot allocation and the RMSF are returned as $Y^{p_{\text{new}}}$ and Ω, respectively.

Function UPDATESLOTSTATUS updates the slot status, where ς slots from the wth slot are allocated along route R of core c for lightpath p_{new}. In lines 2–5, a set of lightpaths, which are adjacent to p_{new}, is obtained as P'. In lines 6 and 7, allocated slots for p_{new} are added to S^a_{cij}. In lines 8–22, additional unavailable vacant slots are added to S^u_{cij}. Lines 10–12 get the set of lightpath adjacent cores as $\mathscr{C}$ in w'th slot. In lines 13–16, if the lightpath adjacent number is equal to acceptable lightpath-adjacent number in the w'th slot and the w'th slot is vacant along R of core c', the w'th slot along R of core c' is considered as an unavailable vacant slot. In lines 17–20, if the additional acceptable lightpath-adjacent number of existing lightpath $p \in P'$ in the w'th slot is equal to one, the vacant slots adjacent to lightpath p are considered as unavailable vacant slots.

Function CALCULATERMSF calculates the value of RMSF of the network, whose slot status is $\mathscr{S}$. The value of RMSF is calculated as described in Section II-B.

V. EVALUATION

This section presents the performance evaluation environment followed by the numerical results of the proposed model and a benchmark model. The benchmark model calculates the RMSF without classifying vacant slots into available ones and unavailable ones. The difference between the proposed and benchmark models is whether vacant slots are classified or not.

A. Evaluation environment

The proposed model is evaluated by comparing it with the benchmark model in terms of the blocking probability using the lightpath provisioning algorithm presented in Section IV-C.

The traffic demands are generated randomly based on a Poisson distribution process with an arrival rate of (λ). The holding time of traffic demands follows an exponential distribution (H). The traffic load is given in Erlang by λH. The source-destination pair of each traffic demand are randomly generated. Each traffic demand is independent from the previous one.

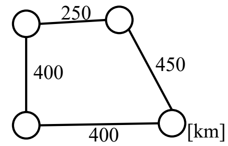

Fig. 3. 4-node network.

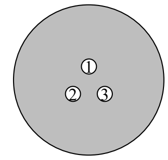

Fig. 4. 3-core MCF.

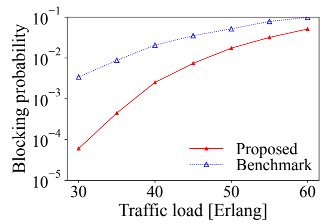

Fig. 5. Blocking probability (4-node network).

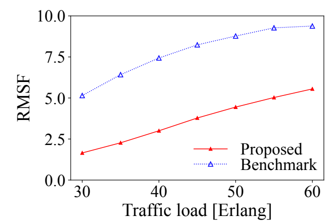

Fig. 6. Average RMSF (4-node network).

The transmission is realized using super channels (Schs). A Sch consists of optical carriers, each of which consists of three slots (37.5 GHz). Four types of modulation formats, 16-QAM, 8-QAM, QPSK, and BPSK, are considered. The capacities of a Sch of 16-QAM, 8-QAM, QPSK, and BPSK are assumed to be 200, 150, 100, and 50 [Gbps], respectively [15]. The respective transmission reaches are, 600, 1200, 3500, 6300 [km], respectively [16]. The XT thresholds of each modulation formats are -25, -21, -18.5, -14 [dB], respectively [16]. The power-coupling coefficient is set to 1.0×10^{-8}.

Results of the blocking probability are obtained with a 95% confidence interval. The interval is not greater than 5% and 10% of the average blocking probability when the average blocking probability is more than 0.01 and otherwise, respectively.

In the evaluation, we consider a specified blocking probability that the network operator guarantees. We compare the proposed and benchmark models by the admissible traffic load within the guaranteed blocking probability. We assume that the guaranteed blocking probability is 0.01.

B. 4-node network

The proposed and benchmark models are evaluated in a 4-node network, which is shown in Fig. 3. The MCF in the 4-node network is assumed to be 3-core fiber, as shown in Fig. 4. 30 slots are available in each core; ten Schs are available. The required transmission capacity for each traffic demand is selected from uniform random values between 100 and 200 [Gbps], which are multiples of 50. We use only 16-QAM, 8-QAM, and QPSK in this evaluation. To reach the network steady state, initially, 1000 lightpaths are processed.

The blocking probability of each model is shown in Fig. 5. In each traffic load, the blocking probability of the proposed model is less than that of the benchmark model. When the blocking probability is 0.01, the proposed model accommodates 30.3% more traffic than the benchmark model.

The average RMSF considering unavailable vacant slots is shown in Fig. 6. The average RMSF of the proposed model is

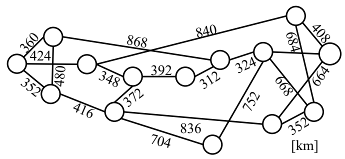

Fig. 7. NSFNET.

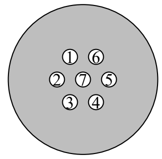

Fig. 8. 7-core MCF.

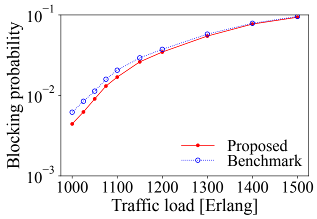

Fig. 9. Blocking probability (NSFNET).

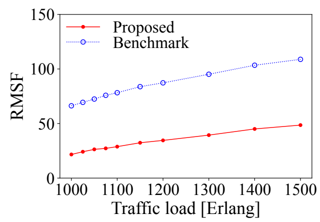

Fig. 10. Average RMSF (NSFNET).

less than that of the benchmark model. From this observation, suppressing RMSF considering unavailable vacant slots leads to decrease in the blocking probability.

C. NSFNET

We evaluate the proposed and benchmark models in NSFNET, as shown in Fig. 7. The MCF in NSFNET is assumed to be 7-core fiber, as shown in Fig. 8. In this evaluation, a 4 THz bandwidth is split into 320 slots, each of which is 12.5 GHz. The required transmission capacity for each traffic demand is selected from uniform random values between 100 and 500 [Gbps], which are multiples of 50. To reach the network steady state, initially, 3000 lightpaths are processed.

The blocking probability of the proposed and benchmark models is shown in Fig. 9. In each traffic load, the blocking probability of the proposed model is less than that of the benchmark model. When the blocking probability is 0.01, the proposed model accommodates 1.44% more traffic than the benchmark model.

The average RMSF considering unavailable vacant slots is shown in Fig. 10. The average RMSF of the proposed model is less than that of the benchmark model. From this observation, suppressing RMSF considering unavailable vacant slots leads to decrease in the blocking probability.

VI. Conclusion

This paper proposed a fragmentation-aware lightpath provisioning model, which suppresses the fragmentation caused by allocating spectrum slots to lightpaths and the fragmentation due to inter-core XT. In the proposed model, vacant spectrum slots are classified into available vacant slots and unavailable vacant slots. To suppress the fragmentation, a lightpath provisioning problem is presented, which is based on the proposed model. A lightpath provisioning algorithm is introduced to solve the problem. We evaluated the performance of the proposed model in terms of the blocking probability, and compared it to a benchmark model. Numerical results showed that the proposed model suppresses the blocking probability compared to the benchmark model. We observed that the proposed model accommodates 1.44% more traffic than the benchmark model in our evaluation scenario in NSFNET.

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