Jointly Inter-Core XT and Impairment Aware Lightpath Provisioning in Elastic Optical Networks

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***Abstract*—Space-division multiplexing-based elastic optical networks (SDM-EONs) enhance the fiber capacity. Inter-core crosstalk (XT) and intra-core physical layer impairments (PLIs) occur in the multi-core fiber and degrade the optical signal. An existing model separately considers inter-core XT and intra-core PLIs, and sets a single XT threshold to each modulation format. This can lead to an unacceptable lightpath due to signal degradation or the occurrence of spectrum inefficiency. This paper proposes a routing, modulation, spectrum, and core allocation (RMSCA) model, which jointly considers inter-core XT and intra-core PLIs for SDM-EONs. The proposed model sets multiple XT thresholds for each modulation format based on inter-core XT and intra-core PLIs. We present an optimization problem and formulate it as an integer linear programming (ILP) problem. We introduce a heuristic algorithm for a network where the ILP problem is not tractable. Numerical results observe that the proposed model improves the spectrum efficiency by setting multiple XT thresholds to each modulation format.**

***Index Terms*—Elastic optical networks, Space-division multiplexing, Crosstalk, Optimization, Integer linear programing**

I. Introduction

Elastic optical networks (EONs) are regarded as promising techniques to achieve flexible utilization of spectrum resources. EONs increase the spectrum efficiency through rate-adaptive super-channels and distance-adaptive modulation [1] [2]. EONs adaptively allocate the minimum necessary number of spectrum slots to a lightpath based on its end-to-end physical conditions. The routing and spectrum allocation (RSA) problem finds an appropriate route for a source and destination pair and allocates suitable spectrum slots to the requested lightpath [3]. The spectrum slots are allocated to satisfy the spectrum contiguity and continuity constraints.

In EONs, distance-adaptive spectrum allocation is considered, which adopts an appropriate modulation format, and hence the spectrum efficiency is improved. There is a trade-off between transmission capacity per spectrum slot and the transmission reach. The number of allocated spectrum slots can be reduced for shorter paths by using a higher modulation format. Physical layer impairments (PLIs), which degrade the optical signal, occur in fibers and increase with transmission distance. Since the tolerance for signal degradation of each modulation format is different, the transmission reach differs among modulation formats. The modulation format is selected according to the path length.

Multi-core fiber (MCF) is one of the space-division multiplexing (SDM) technologies to enhance the fiber capacity in proportion to the number of cores per fiber [4]. In data centers and submarine cables, it is necessary to realize large-capacity data communication in limited spaces, so MCF's need is increasing. EONs adopted the SDM technologies are called SDM-EONs. From the network design perspective, the routing, spectrum, and core allocation (RSCA) problem is established in SDM-EONs. RSCA decides not only the routing and spectrum slot allocation but also the core allocation.

PLIs within a core, i.e., intra-core PLIs, and PLIs between cores, i.e., inter-core crosstalk (XT), occur in MCFs. Inter-core XT can degrade the quality of optical signals in two neighboring fiber cores, where the signals are transmitted in the same direction and spectrum [5]. Therefore, the RSCA problem becomes more complicated than the RSA problem due to the XT aspect. Furthermore, since the XT tolerance is different among modulation formats [6], the relationship between modulation formats and XT needs to be considered. The RSCA problem that additionally considers modulation is called the routing, modulation, spectrum, and core allocation (RMSCA) problem. Several existing works studied on XT-aware spectrum allocation in SDM-EONs [7]–[10]. These works allocate spectrum slots to a lightpath so that the estimated XT value, from which the lightpath suffers, does not exceed a given threshold. In RMSCA, the threshold of acceptable XT value is set to each modulation format. Muhammad et al. [7] calculated the maximum XT value by using an analytical model based on the coupled-power theory presented in [11]. According to [11], the XT value depends on the number of adjacent cores and the adjacent length of lightpaths. The model in [7] calculates the XT value by assuming that, even if the core used by a lightpath is adjacent to other active cores in only a part of the path, the core is adjacent to the active cores along the end-to-end path. This calculation may overestimate the actual XT value.

Yang et al. [8] estimated the precise XT (P-XT) value of a lightpath. The P-XT value is estimated by taking into account links and their distances where the core used by the lightpath is adjacent to the other active cores. The P-XT value is not proportional to the end-to-end transmission distance of a lightpath. The model in [8] does not consider intra-core PLIs.

Dharmaweera et al. [9] considered inter-core XT and intra-core PLIs jointly. The model in [9] calculates the signal to

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noise ratio (SNR) of a lightpath by adding P-XT to intra-core PLIs, and allocates spectrum slots so that the calculated SNR is greater than the SNR required for a modulation format. The intra-core PLI values are estimated by using the model in [12]. To reduce the complexity of the formulation, the model in [9] allocates each spectrum slot independently but not considering each lightpath request. In short, the spectrum contiguity constraint is not considered because of the complexity of the SNR calculation. As mentioned before, the contiguity constraint needs to be considered in the RSA problem, so the model in [9] is not applicable to solve the RSCA problem.

Klinkowski et al. [10] considered inter-core XT and intra-core PLIs of a lightpath in RMSCA. They considered intra-core PLIs by setting the transmission reach. They determined the transmission reach based on the value without accounting for the XT effect. The model in [10] allocates spectrum slots so that the XT value does not exceed the threshold, and the path length is within the transmission reach. This means that inter-core XT and intra-core PLIs are considered separately.

The following issues arise if inter-core XT and intra-core PLIs are considered separately. When the transmission reach is considered without accounting for the XT effect, a lightpath established in the network can be unable to achieve the transmission reach due to the signal degradation resulting from inter-core XT. When a margin of the transmission reach is made to realize the lightpath with the XT, the spectrum inefficiency occurs. Therefore, the degradation due to inter-core XT and intra-core PLIs need to be jointly considered in RMSCA to improve spectrum efficiency. There has been no work in SDM-EONs, which performs RMSCA considering inter-core XT and intra-core PLIs jointly.

This paper proposes an RMSCA model, which jointly considers inter-core XT and intra-core PLIs for SDM-EONs. The proposed model sets multiple XT thresholds and their corresponding transmission reaches. The proposed model considers the SNR penalty due to inter-core XT. The transmission reach corresponding to each XT threshold is set so that the optical signal degraded by inter-core XT and intra-core PLIs can ensure the required SNR for the demodulation. The XT threshold gets relaxed in the proposed model as the transmission reach becomes short since intra-core PLIs depend on the transmission reach. Conversely, the XT threshold gets severe as the transmission reach becomes long. Therefore, the proposed model enables transmission over a longer distance in a small value of XT and greater XT in transmission over a short distance. This is why the proposed model can improve spectrum efficiency. We present an optimization problem, which is based on the proposed model to minimize the maximum allocated spectrum slot index. We formulate the optimization problem as an integer linear programming (ILP) problem. We present a heuristic algorithm for the proposed RMSCA model. We evaluate the proposed model by comparing it with a benchmark model. Numerical results observe that the proposed model reduces the maximum index of allocated spectrum slots, compared to the benchmark model. This indicates that the proposed model can use more spectrum-efficient modulation format than the benchmark model during lightpath provisioning.

II. RMSCA MODEL BASED ON P-XT ESTIMATION

In this section, we describe an RMSCA model based on P-XT estimation, and introduce a benchmark model considered in this paper.

The RMSCA model in [10] sets the XT threshold and the transmission reach of each modulation format. This model calculates inter-core XT and decides the modulation format and the spectrum allocation of a lightpath so that the estimated P-XT value and the path distance do not exceed the XT threshold and the transmission reach, respectively.

The XT estimation based on the coupled-power theory [11] is used for estimating P-XT values. The XT value is expressed by $XT = \frac{N - N\exp(-(N+1)hL)}{1+N\exp(-(N+1)hL)}$, where N is the number of adjacent cores that use the same spectrum slot, L is the length of MCF, and h is a power-coupling coefficient. This equation is a more rigorous version of the linear model presented in [11], which is expressed by $XT \simeq NhL$. Since the difference between XT values estimated using the two equations is negligible, the latter equation is more tractable for estimating the XT value. The model in [10] calculates the P-XT value based on the latter equation.

According to [13], the end-to-end path XT is the sum of the XT on consecutive links of the path. $XT(p, w)$, which is the P-XT value of lightpath p on spectrum slot w, can be estimated by $XT(p, w) = \sum_{e \in \pi(p)} XT(p, e, w)$, where $\pi(p)$ is the set of link of p, and $XT(p, e, w)$ is the XT value of p on link e and spectrum slot w. $XT(l, e, w)$ is calculated as $XT(p, e, w) = N(p, e, w)h(e)L(e)$, where $N(p, e, w)$ is the number of active cores adjacent to the core used by lightpath p on link e and spectrum slot w, $h(e)$ is the power-coupling coefficient of e, and $L(e)$ is the length of e.

In the model [10], the transmission reach of each modulation format is set to the value without XT. If there is any degradation due to XT of the lightpath, it cannot realize the transmission reach, which is set by assuming that there is no XT. The model can be applied to RMSCA by making a margin to the transmission reach. We can set the margin by setting the transmission reach to a shorter value so that the lightpath can tolerate inter-core XT. We call the applicable model, which has a margin, the benchmark model in this paper. The benchmark model decides the modulation format and allocates spectrum slots and a core of a lightpath to satisfy the XT threshold and the transmission reach that has a margin.

III. PROPOSED MODEL

The proposed model considers inter-core XT and intra-core PLIs jointly. In the proposed model, inter-core XT is considered by setting multiple XT thresholds. Intra-core PLIs are considered by setting the transmission reach corresponding to each XT threshold.

We describe how to set multiple XT thresholds and corresponding transmission reaches. We set an XT value corresponding to each of the selected SNR penalties as the XT

TABLE I
XT VALUES [dB] CORRESPONDING TO SNR PENALTY FOR EACH MODULATION FORMAT, WHICH ARE SET BASED ON [14].

Modulation format	SNR penalty [dB] 0.25	0.5	0.75	1.0	1.5	2.0
BPSK	-19	-17	-15	-14	-12	-11
QPSK	-22	-20	-18	-17	-15	-14
8PSK	-27	-25	-23	-22	-21	-20
16QAM	-29	-27	-25	-24	-22	-21

TABLE II
TRANSMISSION REACH [km] OF EACH MODULATION FORMAT AT CERTAIN SNR PENALTY DUE TO XT.

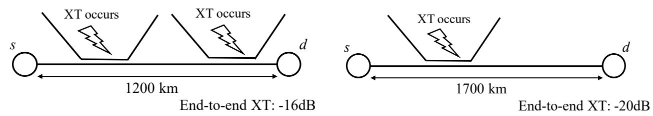
Modulation format	SNR penalty [dB] 0	0.25	0.5	0.75	1.0	1.5	2.0
BPSK	4000	3760	3560	3360	3160	2840	2520
QPSK	2000	1880	1780	1680	1580	1420	1260
8QAM	1000	940	890	840	790	710	630
16QAM	500	470	445	420	395	355	315

threshold by using the theoretical values in [14] [1]. The XT threshold is different by each modulation format, as shown in Table I. The transmission reach is set considering the SNR penalty due to XT. Table II shows the transmission reaches of each modulation format at a certain SNR penalty by assuming the PLIs are linear. For example, the transmission reach of the XT threshold for 1 dB SNR penalty is calculated by multiplying 0.79, which is equivalent to -1 dB, by the transmission reach without XT. In this paper, the transmission reach without XT of binary phase-shift keying (BPSK), quadrature PSK (QPSK), 8 quadrature amplitude modulation (8QAM), and 16QAM is assumed to be 4000, 2000, 1000, and 500 km, respectively, as in [15]. Combining Tables I and II, we can make Table III. We can get multiple thresholds and their corresponding transmission reaches from Table III. Note that the proposed model is also applicable when the non-linear PLIs are considered by setting the transmission reach.

We describe how the proposed model achieves higher spectrum efficiency than the benchmark model. We assume that the benchmark model sets the XT threshold for 1 dB SNR penalty and the corresponding transmission reach, as shown in Table IV. The proposed model improves spectrum efficiency in two cases. In the first case, the proposed model relaxes the XT threshold by making the transmission reach short since intra-core PLIs depend on the transmission reach. In the second case, the proposed model makes transmission reach long by setting the strict XT threshold. We show two examples using Fig. 1, which corresponds to the above two cases.

In Fig. 1a, we assume that the distance between source node s and destination node d is 1200 km, and the XT value of the lightpath is -16 dB. The lightpath cannot use QPSK when the benchmark model is adopted since the XT is more than -17 dB, which is the XT threshold of QPSK. On the other hand, the lightpath can use QPSK when the proposed model is adopted since the XT does not exceed -15 dB and the transmission distance is within 1420 km.

[1]We assume that the XT value corresponding to 1 dB SNR penalty for BPSK is -14 dB in this paper. Since the XT value corresponding to 1 dB SNR penalty for BPSK and QPSK are assumed to -14 dB and -17 dB, the XT thresholds for BPSK are assumed to be 3 dB larger than those for QPSK.



(a) Case 1. (b) Case 2.

Fig. 1. Demonstration of spectrum efficiency of proposed model.

In Fig. 1b, we assume that the transmission distance between s and d is 1700 km, and the XT value of the lightpath is -20 dB. The lightpath cannot use QPSK when the benchmark model is adopted since the transmission distance is more than 1580 km, which is the transmission reach of QPSK. On the other hand, the lightpath can use QPSK when the proposed model is adopted since the XT does not exceed -20 dB and the transmission distance is within 1780 km. Since the proposed model can use more efficient modulation than the benchmark model, the proposed model improves spectrum efficiency.

IV. OPTIMIZATION PROBLEM

A. Overview

We present an optimization problem in the proposed model to minimize the maximum allocated spectrum slot index. The problem provisions lightpaths for each traffic demand by considering inter-core XT and intra-core PLIs jointly. Each traffic demand is composed of the transmission capacity request and source and destination pair. The lightpaths for each traffic demand are provisioned by determining routing, spectrum slots and core allocation, and their modulation format. The optimization problem is formulated as an ILP problem.

B. Assumption and notations

A set of traffic demands, T, is given in network (V, E), where V is a set of nodes and E is a set of MCF links. The length of each link is denoted by d_{ij} for $(i, j) \in E$. We assume that every MCF link in the network has the same number and arrangement of cores. Let C denote a set of cores in each link and α denote a set of adjacent core pairs. Each core has the same number of spectrum slots. The set of spectrum slot indices is denoted by W. Let Q denote a set of modulation formats. A lightpath for each traffic demand is provisioned so as to satisfy both the transmission reach and XT threshold in Table III. Let K denote a set of XT levels.

The given parameters in the problem are described as follows. Traffic demand $t \in T$ is composed of transmission capacity request b_t [Gbps], and source and destination node pair (s_t, d_t). Let η_q denote the capacity of a single spectrum slot of modulation $q \in Q$. Let ϕ_k denote the XT value of XT level $k \in K$, which corresponds to the XT threshold in Table III. δ_k denotes the maximum length that a lightpath can be adjacent to other lightpaths at XT level $k \in K$. r_{qk} denotes the transmission reach of modulation $q \in Q$ in XT level $k \in K$, which corresponds to the transmission reach in

TABLE III

TRANSMISSION REACH [km] CORRESPONDING TO XT THRESHOLD [dB] FOR EACH MODULATION FORMAT.

Modulation format	XT threshold [dB] No XT	-29	-27	-25	-24	-23	-22	-21	-20	-19	-18	-17	-15	-14	-12	-11
BPSK	4000	3760	3760	3760	3760	3760	3760	3760	3760	3760	3560	3560	3360	3160	2840	2520
QPSK	2000	1880	1880	1880	1880	1880	1880	1780	1780	1680	1680	1580	1420	1260	-	-
8QAM	1000	940	940	890	840	840	790	710	630	-	-	-	-	-	-	-
16QAM	500	470	445	420	395	355	355	315	-	-	-	-	-	-	-	-

TABLE IV

ASSUMPTION OF XT THRESHOLD AND TRANSMISSION REACH FOR EACH MODULATION FORMAT IN BENCHMARK MODEL.

	XT threshold [dB]	Transmission reach [km]
BPSK	-14	3160
QPSK	-17	1580
8PSK	-22	790
16QAM	-24	395

Table III. Let A denote a value which is larger than or equal to any required transmission capacity, i.e., $A \geq b_t, \forall t \in T$. Let Γ denote a value which is larger than or equal to any lightpath length, i.e., $\Gamma \geq r_{qk}, \forall q \in Q, k \in K$.

Spectrum slots are allocated to a lightpath so as to satisfy the contiguity and continuity constraints. The core allocation is imposed on the spatial continuity constraints, i.e., the same core is used along a lightpath. The modulation format does not change over the lightpath.

To determine the spectrum slots, core allocation, and modulation format, decision variables are introduced as follows. F is the maximum allocated spectrum slot index in the network, which the optimization problem minimizes. e^t_{ij} is a binary variable that equals one if $t \in T$ uses $(i,j) \in E$, and zero otherwise. x^t_{cq} is a binary variable that equals one if $t \in T$ uses $c \in C$ and modulation format $q \in Q$, and zero otherwise. y^t_w is a binary variable that equals one if traffic demand $t \in T$ uses wth spectrum slot $(w \in W)$, and zero otherwise. $z^{tt'}_{wij}$ is a binary variable that equals one if traffic demands of $t, t' \in T$ use adjacent cores, in wth spectrum slot $(w \in W)$ of link $(i,j) \in E$, and zero otherwise. f_t is an integer variable that represents the starting spectrum slot index for traffic demand $t \in T$. τ^t_k is a binary variable that equals one if the lightpath for traffic demand $t \in T$ belongs to XT level $k \in K$, and zero otherwise.

C. Formulation

The optimization problem for the proposed model is formulated as follows.

$$\min F \tag{1a}$$

$$f_t + \sum_{w \in W} y^t_w - 1 \leq F, \forall t \in T \tag{1b}$$

$$\sum_{c \in C} \sum_{q \in Q} x^t_{cq} = 1, \forall t \in T \tag{1c}$$

$$f_t - w \leq (1 - y^t_w)|W|, \forall t \in T, w \in W \tag{1d}$$

$$f_t + \sum_{w' \in W} y^t_{w'} - w \geq (y^t_w - 1)|W| + 1, \quad \forall t \in T, w \in W \tag{1e}$$

$$\sum_{j:(i,j) \in E} e^t_{ij} - \sum_{j:(j,i) \in E} e^t_{ji} = 1, \forall t \in T, i = s_t \tag{1f}$$

$$\sum_{j:(i,j) \in E} e^t_{ij} - \sum_{j:(j,i) \in E} e^t_{ji} = 0, \forall t \in T, i \in V \backslash \{s_t, d_t\} \tag{1g}$$

$$b_t \leq \eta_q \sum_{w \in W} y^t_w + A \left(1 - \sum_{c \in C} x^t_{cq}\right), \forall t \in T, q \in Q \tag{1h}$$

$$\sum_{t' \in T \backslash \{t\}} \sum_{(i,j) \in E} d_{ij} z^{tt'}_{wij} \leq \sum_{k \in K} \delta_k \tau^t_k, \forall t \in T, w \in W \tag{1i}$$

$$\sum_{(i,j) \in E} d_{ij} e^t_{ij} \leq (r_{qk} - \Gamma) \left(\sum_{c \in C} x^t_{cq} + \tau^t_k - 1\right) + \Gamma, \quad \forall t \in T, q \in Q, k \in K \tag{1j}$$

$$z^{tt'}_{wij} \geq \sum_{q \in Q} x^t_{cq} + \sum_{q' \in Q} x^{t'}_{c'q'} + y^t_w + y^{t'}_w + e^t_{ij} + e^{t'}_{ij} - 5, \quad \forall t \in T, t' \in T \backslash \{t\}, (c, c') \in \alpha, w \in W, (i,j) \in E \tag{1k}$$

$$\sum_{q \in Q} x^t_{cq} + \sum_{q' \in Q} x^{t'}_{cq'} + y^t_w + y^{t'}_w + e^t_{ij} + e^{t'}_{ij} \leq 5, \quad \forall t \in T, t' \in T \backslash \{t\}, c \in C, w \in W, (i,j) \in E \tag{1l}$$

$$\sum_{k \in K} \tau^t_k = 1, \forall t \in T \tag{1m}$$

$$e^t_{ij} \in \{0,1\}, \forall t \in T, (i,j) \in E \tag{1n}$$

$$x^t_{cq} \in \{0,1\}, \forall t \in T, c \in C, q \in Q \tag{1o}$$

$$y^t_w \in \{0,1\}, \forall t \in T, w \in W \tag{1p}$$

$$z^{tt'}_{wij} \in \{0,1\}, \forall t \in T, t' \in T \backslash \{t\}, w \in W, (i,j) \in E \tag{1q}$$

$$f_t \in \mathbb{N}, f_t \in [1, |W|], \forall t \in T \tag{1r}$$

$$\tau^t_k \in \{0,1\}, \forall t \in T, k \in K \tag{1s}$$

Equation (1a) is the objective function that minimizes the maximum allocated spectrum slot index. Equation (1b) ensures that the index of the allocated spectrum slot does not exceed F. Equation (1c) represents that one core and one modulation are determined for each traffic demand; it is not changed over the used fibers along the lightpath. Equations (1d) and (1e) represent the spectrum contiguity constraint. The existence of y^t_w leads to the spectrum continuity constraint. Equations (1f) - (1g) represent the traffic flow constraint. Equation (1h) ensures that spectrum slots allocated to traffic demand t provide at least the required transmission capacity b_t. Equation (1i) estimates the XT level of a lightpath. The left side of (1i) computes the total length where the lightpath for traffic demand $t \in T$ is adjacent to other lightpaths; this is equivalent to the estimation of P-XT value of the lightpath. Equation (1j) ensures that path length does not exceed the transmission reach corresponding to XT level k. Equation (1k) ensures that $z^{tt'}_{wij}$ is one when traffic demands of $t, t' \in T$ use adjacent cores $(c, c') \in \alpha$, respectively, in wth spectrum slot $(w \in W)$ of link $(i,j) \in E$.

Equation (1l) ensures that traffic demands of $t, t' \in T$ do not use the same core, $c \in C$, in wth spectrum slot $(w \in W)$ of link $(i,j) \in E$. Equation (1m) represents that a lightpath belongs to only one XT level.

V. Heuristic algorithm

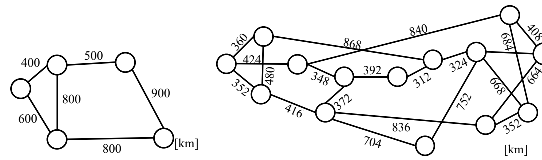
We introduce a heuristic algorithm for a network where the ILP problem in section IV-C is not tractable. The ILP problem provisions lightpaths for all traffic demands at once. On the other hand, the heuristic algorithm presented here chooses a set of traffic demands and provisions lightpaths for them greedily and do not change the lightpaths provisioned once. Let T' denote a set of traffic demands that are considered for provisioning lightpaths, where $T' \subset T$. When $|T'|$ lightpaths are provisioned, information of existing lightpaths that have been already provisioned is given as parameters. The information consists of the utilization status of links, spectrum slots, and cores for the existing lightpaths, and the tolerant XT level and the adjacent length in each lightpath. When the $|T'|$ lightpaths are provisioned, the XT value of each existing lightpath is ensured not to exceed the XT threshold of the XT level allocated to each existing lightpath.

In the heuristic algorithm, we use another ILP problem based on the ILP problem mentioned in section IV-C. The ILP problem used in the heuristic algorithm determines the routing of lightpaths and allocates spectrum slots and core to the lightpaths for the set of traffic demands T' to minimize the maximum spectrum slots index allocated to the $|T'|$ lightpaths. In the ILP problem, XT levels in K are indexed so that if $k < k'$ and $k, k' \in K$, then $\delta_k \leq \delta_{k'}$. We introduce a new decision variable, ζ^t_{cwij}, which is a binary variable that equals one if traffic demand $t \in T'$ is adjacent to an existing lightpath, which uses core $c \in C$ of link $(i,j) \in E$ in wth spectrum slot $(w \in W)$, and zero otherwise. The number of decision variables in the ILP problem in the heuristic algorithm is $|T'|(((|T'|-1)|W||E| + |C||W||E| + |C||Q| + |W| + |E| + |K| + 1) + 1$. The number of decision variables in the ILP problem in section IV-C is $|T|(|T||W||E| + |E| + |W| + |C||Q| + |K| + 1) + 1$. When the heuristic algorithm is adopted, we set a suitable $|T'|$ for the size of a problem. The ILP problem in the heuristic algorithm is more tractable than that in section IV-C.

VI. Evaluation

A. Evaluation environment

We evaluate the proposed and benchmark models in terms of the maximum allocated spectrum slot index and the computation time. The proposed and benchmark models allocate spectrum slots to traffic demands based on Tables III and IV, respectively. We solve the ILP problem in section IV-C and run the heuristic algorithm in section V, where $|T'|$ is set to one, to obtain the lightpath provisioning based on the proposed model. The benchmark model is evaluated by solving the ILP in section IV-C and running the heuristic algorithm in section V by setting only one XT threshold for each modulation format as shown in Table IV.



(a) 5-node network. (b) NSFNET.

Fig. 2. Evaluation networks.

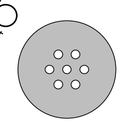


Fig. 3. 7-core MCF.

TABLE V
Average of maximum index of allocated spectrum slots (5-node).

Proposed (ILP)	Benchmark (ILP)	Proposed (heuristic)	Benchmark (heuristic)
7.4	7.9	7.6	7.9

We use a 5-node network and NSFNET, which are shown in Fig. 2. The MCF in a network is assumed to be seven core hexagonal fiber, as shown in Fig. 3. The capacities of a single spectrum slot of BPSK, QPSK, 8QAM, and 16QAM are assumed to be 12.5, 25, 37.5, and 50 [Gbps], respectively.

B. 5-node network

We use the ILP approach and the heuristic algorithm in a 5-node network, as shown in Fig. 2a. We generate ten different scenarios, each of which consists of ten traffic demands. Each traffic demand consists of a source and destination pair, which is randomly selected from all nodes; the source and the destination nodes must be different. The transmission capacity requirement of each traffic demand is selected from uniform random values between 100 and 200 [Gbps], which are multiples of 10. The number of available spectrum slots in each core is set to 10. The power-coupling coefficient of the MCF h is set to 1.0×10^{-8}.

Table V shows the maximum index of the allocated spectrum slots, which is the average of the ten scenarios. Compared to the benchmark model, the proposed model reduces the maximum index of the allocated spectrum slots. In the case of solving the ILP problem, the proposed model reduces the average maximum slot index by 6.3%, compared to the benchmark model. In the case of using the heuristic algorithm, the proposed model reduces the average maximum slot index by 3.8%, compared to the benchmark model.

The difference between the result in the ILP approach and that in the heuristic algorithm is 2.6% in the proposed model. The difference between the result in the ILP approach and that in the heuristic algorithm is not observed in the benchmark model.

The average computation time for solving the ILP of the proposed model and that of the benchmark model is 660.2 [sec] and 107.7 [sec], respectively. The average computation time for running the heuristic algorithm of the proposed model and that of the benchmark model is 1.23 [sec] and 0.78 [sec], respectively. The heuristic algorithm obtains a solution in less time than the ILP approach.

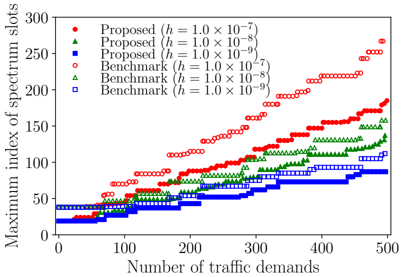


Fig. 4. Transition of maximum index of spectrum slots during running heuristic algorithm for 500 traffic demands.

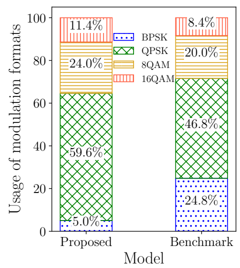


Fig. 5. Usage of modulation formats ($h = 1.0 \times 10^{-7}$).

C. NSFNET

Next, we consider a larger network. We use the 14-node 21-link NSFNET, which is shown in Fig. 2b [16], and use the heuristic algorithm. We generate 500 traffic demands, each of which occurs between a source and destination node pair, which is randomly selected from all nodes. The transmission capacity requirement of each traffic demand is selected from uniform random values between 100 and 500 [Gbps], which are multiples of 10. The number of available spectrum slots in each core is set to 320. We assume three scenarios, where the power-coupling coefficient of the MCF h is set to 1.0×10^{-7}, 1.0×10^{-8}, and 1.0×10^{-9}, respectively.

Figure 4 shows the transition of the maximum index of the allocated spectrum slots during running the heuristic algorithm for the 500 traffic demands. In each power-coupling coefficient, the proposed model reduces the maximum index, compared to the benchmark model. As well as in the 5-node network, the proposed model improves the spectrum efficiency in NSFNET. Compared to the benchmark model, the proposed model reduces the maximum index of allocated spectrum slots by 30.7%, 13.3%, and 22.3% when $h = 1.0 \times 10^{-7}, 1.0 \times 10^{-8}$, and 1.0×10^{-9}, respectively. When $h = 1.0 \times 10^{-7}$, since the effect of XT becomes large, the effectiveness of the proposed model clearly appears compared to other settings of h.

Figure 5 shows the usage of modulation formats when $h = 1.0 \times 10^{-7}$. In the proposed model, there are more opportunities to use spectrum-efficient modulation formats such as QPSK, 8QAM, and 16QAM than in the benchmark model. As a result, the proposed model uses fewer spectrum slots and suppresses the maximum index of the allocated spectrum slots, compared to the benchmark model.

The computation time for running the heuristic algorithm of the proposed model and that of the benchmark model are 10582 [sec] and 8394 [sec], respectively. The computation time difference between the proposed and benchmark models comes from the fineness in the XT level setting.

VII. Conclusion

This paper proposed an RMSCA model, which jointly considers inter-core XT and intra-core PLIs for SDM-EONs. The proposed model sets multiple XT thresholds and their corresponding transmission reaches by considering the SNR penalty due to XT. We presented an optimization problem and formulated it as an ILP problem. We introduced a heuristic algorithm for the proposed model. Numerical results observed that the proposed model reduces the maximum index of the allocated spectrum slots by at most 30.7% in our evaluation scenarios compared to the benchmark model. We observed that the proposed model uses a more spectrum-efficient modulation format than the benchmark model.

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