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# Modulation-Adaptive Link-Disjoint Path Selection Model for 1 + 1 Protected Elastic Optical Networks

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**ABSTRACT** In elastic optical networks (EONs), an appropriate modulation technique is adapted according to the distance of an optical path. A robust modulation technique with a large number of spectrum slots is considered for longer distance optical paths, and a less robust modulation technique with a small number of spectrum slots is used for shorter distance optical paths. When an optical path is configured, the number of required spectrum slots is determined based on the nonlinear relationship between the optical path length and the number of utilized spectrum slots. Minimizing the total path lengths does not always minimize the total number of required spectrum slots for configuring an optical path, which decreases the spectrum utilization. This paper introduces a modulation-adaptive link-disjoint path selection model by considering a step function based on realistic modulation formats in order to minimize the total number of utilized spectrum slots in 1+1 protected EONs. We formulate the modulation-adaptive link-disjoint path selection problem as an integer linear programming (ILP). We prove that the modulation-adaptive link-disjoint path selection problem is NP-complete. By using an optimization solver, we solve the ILP problem for different backbone networks, namely, Japan Photonic Network (JPN48), German 17 Network, and COST 239 Network, within a practical time. Numerical results obtained from performance evaluation indicate that the introduced model reduces the number of utilized spectrum slots compared to the conventional schemes.

**INDEX TERMS** Optical fiber communication.

## I. INTRODUCTION

In elastic optical networks (EONs), spectrum slots, sometime referred as frequency band, are used to transmit the information between a source-destination pair. Once an optical path is configured, the frequency band is assigned to a request and allocated to the spectrum slots [1], [2].

Modulation is the process of transforming digital information into analog signals; the information is modulated with a carrier spectrum. Several modulation techniques, namely Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), and Quadrature Amplitude Modulation (QAM), are typically used in EONs. These modulation techniques differ from each other based on achieving distance and number of required spectrum slots. For example, 32-QAM is used for shorter distance and it requires fewer number of spectrum slots. Whereas, QPSK covers long distance, but it requires a large number of spectrum slots. The modulation is performed by changing parameters of either amplitude, frequency, or phase of the spectrum.

In EONs, an appropriate modulation technique is adapted according to the user's bandwidth requirement and the optical path length [3]–[7]. The number of required spectrum slots is then determined [8]–[10] based on the nonlinear relationship between the optical path length and the number of utilized spectrum slots. If an appropriate modulation technique is adapted, the spectrum can be utilized properly, which enhances the spectrum efficiency. With the increasing

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efficiency of spectrum usage, each link accommodates a large number of requests in EONs, which yields high volume of traffic in each link.

As EONs carry a huge amount of traffic (in the order of Tb/s), including big data [11], any interruption of the data flow leads to massive data loss, and hence fault resilience is treated with an ultimate importance. 1+1 path protection [12] is considered one of the efficient fault resilience techniques, which adapts disjoint paths scheme that do not share any common link between the primary and the backup paths. In 1 + 1 path protection [12], the information is duplicated and transmitted over both primary and backup paths to the destination. The destination receives the information from the primary path in a case without a failure. Once the primary path fails, the destination switches to backup path in order to receive the information.

Several disjoint paths selection schemes [13], [14] were introduced in order to minimize the total distance between a source-destination pair. These disjoint path selection schemes have been adopted for survivable EONs. Taking this direction, Klinkowski and Walkowiak [15] and Klinkowski *et al.* [16] presented an offline routing and spectrum allocation (RSA) scheme with dedicated path protection (DPP) consideration in an EON scenario with static traffic demands. The work in [13] introduced an integer linear programming (ILP) formulation followed by a heuristic algorithm, named adaptive frequency assignment with dedicated path protection (AFA-DPP), in order to provide near-optimal solutions for larger networks. The work presented in [15] was extended in [16]; a tabu search-based algorithm to solve the RSA problem with DPP was introduced, which is an effective metaheuristic for providing near-optimal solutions for large-scale optimization problems.

A multi-objective framework to jointly optimize cost and spectrum in survivable EONs with multiple transponder profiles was presented by Eira *et al.* [17], [18]. The work in [18] uses an evolutionary algorithmic approach in order to show cost/spectrum design trade-off according to different backup resource sharing policies.

In the above mentioned schemes [13]–[18], when an optical path is configured, the number of required spectrum slots is determined based on the nonlinear relationship between the optical path length and the number of utilized spectrum slots. Thus, the total number of required spectrum slots for configuring an optical path is not always minimized, which decreases the spectrum utilization.

The work in [19] presented a link-disjoint path selection scheme to minimize the number of utilized spectrum slots from a nonlinear table; the required number of spectrum slots is not exactly proportional to the total path length. An ILP was introduced for the path selection problem from the nonlinear table [20]. A linear formulation was provided from the nonlinear table by obtaining the number of utilized spectrum slots for each increment of the optical path length. The work in [19] adopts a non-decreasing function, and hence the optimum solution was not obtained in several cases due to a large computational time. As a result, the ILP model introduced in [19] cannot be solved in a practical time. This motivates us to address a more tractable modulation-adaptive link-disjoint path selection model for 1 + 1 protected EONs in order to minimize the number of utilized spectrum slots.

To address the above issue, this paper introduces a modulation-adaptive link-disjoint path selection model by considering a step function based on realistic modulation formats in order to minimize the total number of utilized spectrum slots in 1 + 1 protected EONs. The step function is used as a constraint to relate the optical path length with the number of utilized spectrum slots. By considering the behavior of step function, we formulate the modulation-adaptive link-disjoint path selection problem as an optimization problem. We prove that the modulation-adaptive link-disjoint path selection problem is NP-complete. The performance of the introduced modulation-adaptive link-disjoint path selection model is evaluated in different backbone networks, namely Japan Photonic Network (JPN48) [21], [22], German 17 network [23], and COST 239 network [24], within a practical time by using an optimization solver. Numerical results obtained from performance evaluation indicate that the introduced model reduces the number of utilized spectrum slots compared to the conventional schemes, and it requires some extra times compared to the conventional schemes to estimate the minimum number of utilized spectrum slots.

Note that the introduced optimum model is one of the routing-modulation-spectrum allocation (RMSA) problems, which provides the minimum number of utilized spectrum slots in 1 + 1 protected EONs. In literature, there exists several works [4], [25], [26] on distance-adaptive modulation based spectrum allocation in unprotected EONs, which can be extended for 1 + 1 protected EONs by considering link-disjoint paths. Adopting the existing works on distance-adaptive modulation based spectrum allocation in 1 + 1 protected EONs does not always provide a solution that minimizes the number of utilized spectrum slots. To best of our knowledge, there exists no work that estimates the minimum number of utilized spectrum slots considering both working and backup paths at a time for 1 + 1 protected EONs. This paper, first time, addresses this issue and provides an optimum model to minimize the number of utilized spectrum slots in 1 + 1 protected EONs.

The remainder of this paper is organized as follows. Section II discusses conventional schemes for selection of link-disjoint paths between a source-destination pair. The modulation-adaptive link-disjoint path selection model is introduced in Section III. Section IV presents the proof of NP-completeness of the link-disjoint path selection problem. We evaluate the performance of the introduced model in Section V. Section VI provides the applicability of the introduced model. The related works are presented in Section VII. Finally, Section VIII concludes this paper.

## II. CONVENTIONAL PATH SELECTION SCHEMES

The conventional path selection scheme minimizes the total path length of link-disjoint paths between a source-destination pair. In this scheme, when the link cost is set to 1, it becomes a link-disjoint path selection scheme that minimizes the total number of hops of disjoint paths between a source-destination pair. We call the former approach the total path length-minimizing scheme, and the latter approach the total hop count-minimizing scheme. These conventional schemes are solved within a polynomial time, which is $O(|K|(|E| + |V|)\log|V|)$ [27], where $K$, $E$ and $V$ are sets of link-disjoint paths, links and nodes in a network, respectively.

In EONs, an appropriate modulation technique is adapted according to the path length in order to improve the spectrum utilization. However, the link-disjoint paths selection problem in EONs estimates the number of required slots based on the nonlinear relationship between the number of used slots and path length. Therefore, when link-disjoint paths are selected, the number of required slots for configuring an optical path is not always minimized, which is explained in the following.

The maximum distance achieved by each modulation technique and the number of utilized spectrum slots of each modulation are considered according to Table 1 [28], when the bandwidth requirement is 100 Gbps.

**TABLE 1.** Maximum distance and utilized spectrum slots of each modulation technique [28].

| Modulation technique | QPSK | 16-QAM | 32-QAM |
|---|---|---|---|
| Reachable distance [km] | 2000 | 800 | 400 |
| Used slots | 3 | 2 | 1 |

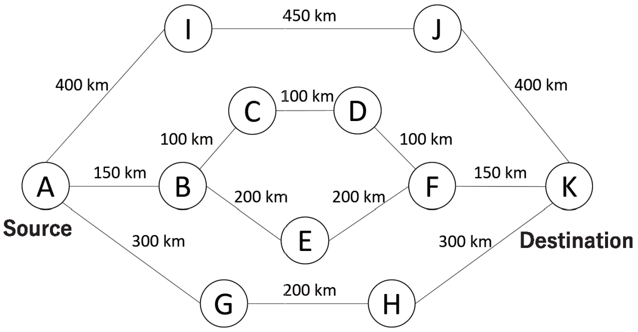

**FIGURE 1.** Sample network.

To demonstrate the conventional schemes, we consider a sample network, which is shown in Fig. 1. It is assumed that an optical path from source node A to destination node K is requested. Note that each link between a node pair is considered bi-directional with equal length. If the conventional total path length-minimizing scheme is applied, two link-disjoint paths, A-B-C-D-F-K with a distance of 600 km and A-G-H-K with a distance of 800 km, are selected; the total path length of both link-disjoint paths is 1400 km. The adapted modulation technique is 16-QAM for both of them according to Table 1. Since the total number of links used in the two link-disjoint paths is eight and the number of used slots in 16QAM is two, the total number of required slots for configuring both link-disjoint paths is 16 (= 2 × 8).

Next, if the conventional total hop count-minimizing scheme is applied, two link-disjoint paths, A-I-J-K with a distance of 1250 km and A-G-H-K with a distance of 800 km, are selected; the total number of hop counts is six. The adapted modulation techniques for path A-I-J-K is QPSK. The other path, A-G-H-K, adapts 16-QAM modulation technique. Since three links are used for QPSK with three slots and three links are used for 16-QAM with two slots, the total number of required slots for configuring both link-disjoint paths is 15 (= 3 × 3 + 2 × 3).

The total path length of other two link-disjoint paths from node A to node K, A-B-E-F-K with a distance of 700 km and A-G-H-K with a distance of 800 km, is 1500 km. The adapted modulation technique is 16-QAM for both of them. Since the total number of links used in the two link-disjoint paths is seven and the number of used slots in 16-QAM is two, the total number of required slots for configuring both link-disjoint paths is 14 (= 2 × 7).

Thus, it is not obvious that both total path length-minimizing scheme and total hop count-minimizing scheme minimize the number of required spectrum slots for configuring an optical path. The following cases can reduce the number of required spectrum slots. (i) Instead of adapting a modulation technique with large number of utilized spectrum slots of both link-disjoint paths, it is possible to select one path from link-disjoint paths, which can adapt a modulation technique with small number of utilized spectrum slots by selecting a different link-disjoint path. (ii) Instead of adapting a modulation technique with large number of utilized spectrum slots, it is possible to select the path that can use a modulation technique with fewer number of slots.

## III. MODULATION-ADAPTIVE LINK-DISJOINT PATH SELECTION MODEL

The introduced modulation-adaptive link-disjoint path selection model is intended to minimize the number of required spectrum slots for configuring both link-disjoint paths between a source-destination pair in EONs. We formulate the introduced modulation-adaptive link-disjoint path selection model as an ILP in the following.

### A. FORMULATION WITHOUT SPECTRUM ALLOCATION

The network is represented as a directed graph $G = (V, E)$, where $V$ is a set of nodes and $E$ is a set of links. $K$ is the set of link-disjoint paths. $(i, j) \in E$ is the link from node $i \in V$ to node $j \in V$. $l_{ij}$ is the link length of the link $(i, j)$. The decision variable is $x_{ij}^{k}$ and it is 1 if path $k \in K$ uses the link $(i, j)$, and 0 otherwise. The link-disjoint path selection problem is formulated in Eqs. (1a)-(1e).

$$\min \sum_{k\in K}\sum_{(i,j)\in E} S\left(\sum_{(i',j')\in E} l_{i'j'}\cdot x_{i'j'}^{k}\right)\cdot x_{ij}^{k} \qquad (1a)$$

$$\sum_{j:(i,j)\in E} x^k_{ij} - \sum_{j:(i,j)\in E} x^k_{ji} = 1, \quad \text{if } i = p \tag{1b}$$

$$\sum_{j:(i,j)\in E} x^k_{ij} - \sum_{j:(i,j)\in E} x^k_{ji} = 0,$$
$$\forall i \in V \backslash \{p, q\}, \quad \forall k \in K \tag{1c}$$

$$\sum_{k\in K} x^k_{ij} \leq 1, \quad \forall (i,j) \in E \tag{1d}$$

$$x^k_{ij} \in \{0, 1\}, \quad \forall (i,j) \in E,\ \forall k \in K \tag{1e}$$

Eq. (1a) is the objective function, which minimizes the sum of the number of utilized spectrum slots in all links for $|K|$ link-disjoint paths. $S(\theta_k)$ is a function, which gives the number of utilized spectrum slots of length $\theta_k$; length $\theta_k$ is obtained for $k$th path between a source-destination pair. The length of $k$th path is represented by $\theta_k = \sum_{(i',j')\in E} l_{i'j'} \cdot x^k_{i'j'}$, integer value. Since the spectrum slot is used for each used link, the total number of utilized spectrum slots in all paths is $S\left(\sum_{(i',j')\in E} l_{i'j'} \cdot x^k_{i'j'}\right) \cdot x^k_{ij}$. Eqs. (1b) and (1c) represent the traffic flow constraints, which ensure that all traffic leaving a source node $p \in V$ is routed to its destination node $q \in V$ without any traffic lost. The constraint on the destination node is not added, as it has been proved to be redundant when the constraints at the source in Eq. (1b) and the intermediate nodes in Eq. (1c) are stated [20]. Eq. (1d) represents the condition of link-disjoint paths, and link $(i,j)$ is used in $|K|$ paths at most one time.

Note that considering node-disjoint paths, which do not share any common node excepting the source and destination nodes, the concept of this work, which minimizes the total number of utilized spectrum slots, can be applied by replacing Eq. (1d) with the following constraint.

$$\sum_{k\in K} \sum_{j\in V:(i,j)\in E} x^k_{ij} \leq 1, \quad \forall i \in V \backslash \{p\} \tag{2}$$

$S\left(\sum_{i',j')\in E} l_{i'j'} \cdot x^k_{i'j'}\right) \cdot x^k_{ij}$ is a nonlinear function, which cannot be directly handled by linear programming. Therefore, we devise it in a linear expression as follows.

$$\sum_{d\in D} y^k_d = 1, \quad \forall k \in K \tag{3}$$

$$y^k_d \in \{0, 1\}, \quad \forall d \in D,\ \forall k \in K \tag{4}$$

$D$ is a set of path lengths. $y^k_d$ is a binary decision variable; it is set to 1 if the path length is exactly the same as $d \in D$, and 0 otherwise.

$$\sum_{(i,j)\in E} l_{ij} \cdot x^k_{ij} = \sum_{d\in D} d \cdot y^k_d, \quad \forall k \in K \tag{5}$$

The path length is obtained by the sum of the lengths of used links.

The nonlinear table is transformed into a linear form by giving the path length $d$ as the step width $\Delta d$ and obtaining used spectrum slot in $d \in D$, where $D = \{d = \Delta d \times k : k = 1, 2, \cdots, \frac{d_{max}}{\Delta d}\}$. $d_{max}$ is considered the maximum distance achieved by a modulation. For example, $d_{max}$ is set to 2000 [km], when the modulation technique is adapted as QPSK. The solving time of ILP increases with increase in decision variables, and hence the introduced ILP can only solve small scale networks.

In EONs, the relationship between path length and utilized spectrum slots is a step function, and the above formulas is revised to suppress the computation time.

$$\sum_{c\in C} y^k_c = 1, \quad \forall k \in K \tag{6}$$

$$y^k_c \in \{0, 1\}, \quad \forall c \in C, \forall k \in K \tag{7}$$

$C = \{1, \cdots, |C|\}$ is a set of path length classes, and an available modulation technique is defined for each path length class. $y^k_c$ is a binary decision variable; it is set to 1 if the path length class $c \in C$, and 0 otherwise. Eq. (6) indicates that the length of path $k$ belongs to the only path length class with $y^k_c = 1$. Let $L_c$ be the upper limit of the path length $c \in C$. The path length class of path $k$ is determined by Eq. (8).

$$\sum_{(i,j)\in E} l_{ij} \cdot x^k_{ij} \leq \sum_{c\in C} L_c \cdot y^k_c, \quad \forall k \in K \tag{8}$$

Eq. (8) also indicates that the path length is less than or equal to the upper limit of the path length of path length class $c$ to which the path length belongs. Eq. (1a) is expressed by Eq. (9) along with Eqs. (6)-(8).

$$\min \sum_{k\in K} \sum_{(i,j)\in E} \sum_{c\in C} n_c \cdot x^k_{ij} \cdot y^k_c \tag{9}$$

$n_c$ is a given parameter, which is the number of utilized spectrum slots, when the path length belongs to the path length class $c$. Since two variables are multiplied in Eq. (9), this formula is a nonlinear form. In order to transform into linear, we prepare the decision variable $z^{kc}_{ij}$ that satisfies Eqs. (10)-(13).

$$z^{kc}_{ij} \leq x^k_{ij}, \quad \forall (i,j) \in E,\ \forall k \in K,\ \forall c \in C \tag{10}$$
$$z^{kc}_{ij} \leq y^k_c, \quad \forall (i,j) \in E,\ \forall k \in K,\ \forall c \in C \tag{11}$$
$$z^{kc}_{ij} \geq y^k_c + x^k_{ij} - 1, \quad \forall (i,j) \in E,\ \forall k \in K,\ \forall c \in C \tag{12}$$
$$z^{kc}_{ij} \in \{0, 1\}, \quad \forall (i,j) \in E,\ \forall k \in K,\ \forall c \in C \tag{13}$$

Eq. (9) is represented as follows by using $z^{kc}_{ij}$.

$$\min \sum_{k\in K} \sum_{(i,j)\in E} \sum_{c\in C} n_c \cdot z^{kc}_{ij} \tag{14}$$

The linear form of the ILP for the introduced modulation-adaptive link-disjoint path selection mode is summarized in the following. The decision variables are $x^k_{ij}$, $y^k_c$, and $z^{kc}_{ij}$.

$$\min \sum_{k\in K} \sum_{(i,j)\in E} \sum_{c\in C} n_c \cdot z^{kc}_{ij} \tag{15a}$$

$$\sum_{j:(i,j)\in E} x^k_{ij} - \sum_{j:(i,j)\in E} x^k_{ji} = 1,$$
$$\text{if } i = p, \quad \forall k \in K \tag{15b}$$

$$\sum_{j:(i,j)\in E} x_{ij}^k - \sum_{j:(i,j)\in E} x_{ji}^k = 0, \quad \forall i \in V\backslash\{p,q\}, \quad \forall k \in K \tag{15c}$$

$$\sum_{k\in K} x_{ij}^k \leq 1, \quad \forall (i,j) \in E \tag{15d}$$

$$\sum_{(i,j)\in E} l_{ij} \cdot x_{ij}^k \leq \sum_{c\in C} L_c \cdot y_c^k, \quad \forall k \in K \tag{15e}$$

$$\sum_{c\in C} y_c^k = 1, \forall k \in K \tag{15f}$$

$$z_{ij}^{kc} \leq x_{ij}^k, \quad \forall (i,j) \in E, \quad \forall k \in K, \forall c \in C \tag{15g}$$

$$z_{ij}^{kc} \leq y_c^k, \quad \forall (i,j) \in E, \ \forall k \in K, \forall c \in C \tag{15h}$$

$$z_{ij}^{kc} \geq y_c^k + x_{ij}^k - 1, \quad \forall (i,j) \in E, \quad \forall k \in K, \ \forall c \in C \tag{15i}$$

$$x_{ij}^k \in \{0,1\}, \quad \forall (i,j) \in E, \ \forall k \in K \tag{15j}$$

$$y_c^k \in \{0,1\}, \quad \forall k \in K, \quad \forall c \in C \tag{15k}$$

$$z_{ij}^{kc} \in \{0,1\}, \quad \forall (i,j) \in E, \ \forall k \in K, \ \forall c \in C \tag{15l}$$

### *B. FORMULATION OF SPECTRUM ALLOCATION CONSIDERING CONSTRAINTS OF SPECTRUM CONTINUITY AND CONTIGUITY*

To consider spectrum allocation, the constraints of spectrum continuity and contiguity are needed. Let $F$ be a set of spectrum slots in the network. Path $k \in K$ contains $\sum_{c\in C} n_c \cdot y_c^k$ consecutive spectrum slots. $a_{fij}^k$ is a binary decision variable that is set to 1 if slot index $f \in F$ is the lowest spectrum slot index for request path $k \in K$ that is allocated on link $(i,j) \in E$, and 0 otherwise. $b_{fij}^k$ is a binary decision variable that is set to 1 if slot index $f \in F$ is used for path $k \in K$ on link $(i,j) \in E$, and 0 otherwise. Let $G$ be a set of unavailable slots, which are used by existing lighpaths. Triplet $(f,i,j) \in G$ indicates that slot $f \in F$ on $(i,j) \in E$ is unavailable. The constraints for spectrum allocations are as follows.

$$\sum_{f\in F} a_{fij}^k = 1, \quad \forall k \in K, \ (i,j) \in E \tag{16}$$

$$a_{fij}^k \leq b_{f'ij}^k, \quad \forall k \in K, f \in \{1, \cdots, |F| - q_k + 1\}, \quad f' \in \{f, \cdots, f + q_k - 1\}, \quad (i,j) \in E \tag{17}$$

$$a_{fij}^k = 0, \quad \forall k \in K, (i,j) \in E \quad f \in \{|F| - q_k + 2, \cdots, |F|\} \tag{18}$$

$$q_k = \sum_{c\in C} n_c y_c^k, \quad \forall k \in K \tag{19}$$

$$a_{fij}^k = a_{fi'j'}^k \quad \forall k \in K, f \in F, \quad (i,j), (i',j') \neq (i,j) \in E \tag{20}$$

$$\sum_{k\in K} b_{fij}^k = 0, \quad \forall (f,i,j) \in G \tag{21}$$

$$\sum_{f\in F} b_{fij}^k = \sum_{c\in C} n_c \cdot y_c^k, \forall k \in K, (i,j) \in E \tag{22}$$

$$a_{fij}^k, b_{fij}^k \in \{0,1\}, f \in F, \quad (i,j) \in E, k \in K \tag{23}$$

Eqs. (16)-(19) provides the contiguous constraints for EON. Eq. (16) guarantees that one lowest spectrum slot index exists for each path. Eq. (17) represents that the lowest spectrum slot index must be the lowest index of allocated path. Eq. (18) excludes the impossible lowest spectum slot index. Eq. (19) indicates the number of spectrum slots used for path $k \in K$. Eq. (20) is a continuous constraint specifying that path $k \in K$ uses the same slot $f \in F$ on every link. Eq. (21) assures that the path is not assigned on unavailable slots. Eq. (22) indicates the utilized sprctrum slots on each link of path $k \in K$.

We consider to express Eqs. (17)-(19) in linear forms. We define binary parameters $\mu_{cf}$, $c \in C, f \in F$, and $\nu_{cff'}$, $c \in C, f \in F, f' \in \{f, \cdots, |F|\}$, whose values are set in the following rule. $\mu_{cf}$ is set to 1 if $f$ is in $\{|F|-n_c+2, \cdots, |F|\}$, and 0 otherwise, $\nu_{cff'}$ is set to 1 if $f$ is in $\{1, \cdots, |F|-n_c+1\}$ and $f'$ is in $\{f, \cdots, f + n_c - 1\}$, and 0 otherwise.

Eqs. (17)-(19) are expressed by,

$$a_{fij}^k y_c^k \leq b_{f'ij}^k, \forall k \in K, c \in C, f \in F, \quad f' \in \{f, \cdots, |F|\}, (i,j) \in E, \quad \text{if } \nu_{cff'} = 1 \tag{24}$$

$$a_{fij}^k y_c^k = 0, \quad \forall k \in K, \ c \in C, \ f \in F, (i,j) \in E, \ \text{if } \mu_{cf} = 1. \tag{25}$$

We introduce binary variable $\pi_{cfij}^k = a_{fij}^k y_c^k, k \in K, c \in C, f \in F, (i,j) \in E$. Eqs. (24)-(25) are expressed by the following linear forms.

$$\pi_{cfij}^k \leq b_{f'ij}^k, \quad \forall k \in K, \ c \in C, \ f \in F, \quad f' \in \{f, \cdots, |F|\}, \quad (i,j) \in E, \ \text{if } \nu_{cff'} = 1 \tag{26}$$

$$\pi_{cfij}^k = 0, \quad \forall k \in K, \ c \in C, \ f \in F, \ (i,j) \in E, \quad \text{if } \mu_{cf} = 1 \tag{27}$$

$$\pi_{cfij}^k \leq a_{fij}^k, \quad \forall k \in K, \ c \in C, \ f \in F, \ (i,j) \in E \tag{28}$$

$$\pi_{cfij}^k \leq y_c^k, \quad \forall k \in K, \ c \in C, \ f \in F, \ (i,j) \in E \tag{29}$$

$$\pi_{cfij}^k \geq a_{fij}^k + y_c^k - 1, \quad \forall k \in K, \ c \in C, \quad f \in F, (i,j) \in E \tag{30}$$

$$\pi_{cfij}^k \in \{0,1\}, \quad \forall k \in K, \ c \in C, \ f \in F, \ (i,j) \in E \tag{31}$$

The ILP problem for the introduced modulation-adaptive link-disjoint path selection mode with considering spectrum slot allocation is summarized in the following. The decision variables are $x_{ij}^k$, $y_c^k$, $a_{fij}^k$, $b_{fij}^k$, $\pi_{cfij}^k$, and $z_{ij}^{kc}$.

$$\text{Objective Eq. (15a)} \tag{32a}$$

$$\sum_{f\in F} a_{fij}^k = 1, \quad \forall k \in K, \ (i,j) \in E \tag{32b}$$

$$a_{fij}^k = a_{fi'j'}^k \quad \forall k \in K, \ f \in F, \quad (i,j), (i',j') \neq (i,j) \in E \tag{32c}$$

$$\sum_{k\in K} b_{fij}^k = 0, \quad \forall (f,i,j) \in G \tag{32d}$$

$$\sum_{k\in K} a_{fij}^k = 0, \quad \forall (f,i,j) \in G \tag{32e}$$

$$\sum_{f\in F} b^k_{fij} = \sum_{c\in C} n_c \cdot y^k_c, \quad \forall k \in K, (i,j) \in E \tag{32f}$$

$$\pi^k_{cfij} \le b^k_{f'ij}, \quad \forall k \in K,\ c \in C, f \in F, \quad f' \in \{f, \cdots, |F|\}, \quad (i,j) \in E,\ \text{if } \nu_{cff'} = 1 \tag{32g}$$

$$\pi^k_{cfij} = 0, \quad \forall k \in K,\ c \in C,\ f \in F,\ (i,j) \in E, \quad \text{if } \mu_{cf} = 1 \tag{32h}$$

$$\pi^k_{cfij} \le a^k_{fij}, \quad \forall k \in K,\ c \in C,\ f \in F,\ (i,j) \in E \tag{32i}$$

$$\pi^k_{cfij} \le y^k_c, \quad \forall k \in K,\ c \in C,\ f \in F,\ (i,j) \in E \tag{32j}$$

$$\pi^k_{cfij} \ge a^k_{fij} + y^k_c - 1, \quad \forall k \in K,\ c \in C, \quad f \in F, (i,j) \in E \tag{32k}$$

$$\pi^k_{cfij} \in \{0, 1\}, \quad \forall k \in K,\ c \in C,\ f \in F, (i,j) \in E \tag{32l}$$

$$a^k_{fij}, b^k_{fij} \in \{0, 1\}, \quad f \in F, (i,j) \in E,\ k \in K \tag{32m}$$

$$\text{Eqs. (15b)-(15l)} \tag{32n}$$

It should be noted that a consideration to suppress the spectrum fragmentation can be included by adopting the first-fit spectrum allocation policy [1] into the formulation. By doing this, the objective function Eq. (15a) is modified as

$$\min \sum_{k\in K} \sum_{(i,j)\in E} \sum_{c\in C} n_c \cdot z^{kc}_{ij} + \epsilon \left( \sum_{(i,j)\in E} \sum_{f\in F} \sum_{k\in K} a^k_{fij} \cdot f \right). \tag{33a}$$

The first term minimizes the sum of the number of utlized spectrum slots in all links. The second term selects the spectrum slots among the possible solutions that minimize the first term, to minimize the index of utilized spectrum slots as the first-fit policy. $\epsilon$ is set to a suffiently small value, compared to the first term.

### C. SAME MODULATION FOR LINK-DISJOINT

In the ILP problems presented in Eqs. (15a)-(15l) and Eqs. (32a)-(32m), in case that there is a condition that the modulation of every path that belongs to the set of disjoint paths must be the same, $y^k_c$ is changed to $y_c$, which does not depend on $k$, and the ILP problem is modified accordingly. and the ILP problems are modified accordingly.

$$\text{Objective Eq. (15a)} \tag{34a}$$

$$\sum_{(i,j)\in E} l_{ij} \cdot x^k_{ij} \le \sum_{c\in C} L_c \cdot y_c, \quad \forall k \in K \tag{34b}$$

$$\sum_{c\in C} y_c = 1 \tag{34c}$$

$$z^{kc}_{ij} \le y_c, \quad \forall (i,j) \in E,\ \forall k \in K,\ c \in C \tag{34d}$$

$$z^{kc}_{ij} \ge y_c + x^k_{ij} - 1, \quad \forall (i,j) \in E, \quad \forall k \in K,\ c \in C \tag{34e}$$

$$y_c \in \{0, 1\}, \quad \forall c \in C \tag{34f}$$

$$\sum_{f\in F} b^k_{fij} = \sum_{c\in C} n_c \cdot y_c, \quad \forall k \in K,\ (i,j) \in E \tag{34g}$$

$$\pi^k_{cfij} \le y_c, \quad \forall k \in K,\ c \in C,\ f \in F, (i,j) \in E \tag{34h}$$

$$\pi^k_{cfij} \ge a^k_{fij} + y_c - 1, \quad \forall k \in K,\ c \in C, \quad f \in F, (i,j) \in E \tag{34i}$$

$$\text{Eqs. (15b)-(15d), Eq. (15g), Eq. (15j), Eq. (15l), Eqs. (32b)-(32e), Eqs. (32g)-(32i), and Eqs. (32l)-(32m)} \tag{34j}$$

## IV. PROOF OF NP-COMPLETENESS

We define $P_0$, which is a decision problem, as:

*Definition $P_0$:* Graph $G = (V, E)$, non-negative length $l(e)$ for link $e \in E$, source and destination $s, t \in V$, positive integer $N$, and maximum reachable distance with $k$ spectrum slots $r(k)$. Are there two link-disjoint paths from $s$ to $t$, in which the total number of used slots is at most $N$?

*Theorem 1:* $P_0$ is NP-complete.

*Proof:* $P_0$ is in NP, as we can verify whether a given solution of $P_0$ is feasible in polynomial time.

First, we discuss a problem finding link-disjoint two paths with distance restriction [29], $P_1$, which is related to $P_0$. We define $P_1$ in the following as:

*Definition $P_1$:* Graph $G = (V, E)$, non-negative length $l(e)$ for link $e \in E$, source and destination $s, t \in V$, and positive integer $L$, are given. Are there two link-disjoint paths from $s$ to $t$, whose length of each is at most $L$?

$P_1$ is proven to be NP-complete by showing that the partition problem [30], which is known to be NP-complete, is polynomial-time reducible to $P_1$. The partition problem is defined as: if $n$ positive integers, $a_1, a_2, \cdots, a_n$, are given, is there any set $I \subseteq M$ that satisfies $\sum_{i\in I} a_i = \sum_{i\in M-I} a_i$?

$P_1$ is in NP, as we can verify whether a given solution of $P_1$ is feasible in polynomial time. We construct $G = (V, E)$ in $P_1$, as shown in Figure 2, where $|V| = n+1$, $|E| = 2n$, and $L = \frac{(n+1)(a_1+a_2+\cdots+a_n)}{2} + n$. The cost of upper link between $v_i$ and $v_{i+1}$ is $(n+1)a_i$, and the cost of lower link between $v_i$ and $v_{i+1}$ is 1. If there are two link-disjoint paths from $s$ to $t$ whose length of each is at most $L$, the sum of the upper link lengths included in each path is $\frac{(n+1)\sum_{i=1}^{n} a_i}{2}$. This means that the partition problem is feasible. Conversely, if the partition problem is feasible, we find two link-disjoint paths whose length of each is at most $L$ in $G$ by taking links with length $(n+1)a_i$ corresponding $a_i$ belonging to each set that is the solution of partition problem. Therefore, $P_1$ is NP-complete.

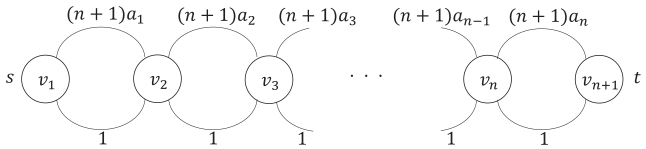

**FIGURE 2.** Graph $G = (V, E)$ in problem finding link-disjoint two paths with distance restriction, $P_1$.

In addition, each link-disjoint path from $s$ to $t$ obtained in the proof that $P_1$ is NP-complete is composed of the minimum links, $n$, and $P_1$ is still NP-complete in the restriction.

In $P_1$, we assume that, if the length of each link-disjoint path from $s$ to $t$ is at most $L$, one slot is required, and, if it exceeds $L$, two slots are required. In other words, $r(1) = L$ and $r(2) = L'$, where $L < L'$. If $N = (1 \text{ (slot)} \times n \text{ (hops)}) \times 2 \text{ (paths)} = 2n \text{ (slots)}$ is set, $P_0$ includes $P_1$ as a partial problem. Thus, $P_0$ is NP-complete. ■

We define $Q$, where spectrum continuity and contiguity constraints are imposed into $P_0$, as:

Definition $Q$. Graph $G = (V, E)$, non-negative length $l(e)$ for link $e \in E$, source and destination $s, t \in V$, positive integer $N$, and maximum reachable distance with $k$ spectrum slots $r(k)$, with spectrum continuity and contiguity constraints. Are there two link-disjoint paths from $s$ to $t$, in which the total number of used slots is at most $N$?

*Theorem 2:* $Q$ is NP-complete.

*Proof:* $Q$ is in NP, as we can verify whether a given solution of $Q$ is feasible in polynomial time. $P_0$ is a subset of $Q$. As $P_0$ is NP-complete, $Q$ is NP-complete. ■

## V. PERFORMANCE EVALUATION

This section evaluates the performances of the introduced modulation-adaptive link-disjoint path selection model for 1 + 1 protected EONs, and compares it with conventional schemes. The considered conventional schemes are (i) total path length-minimizing scheme, named TPLM, and (ii) total hop count-minimizing scheme, named THCM. The link-disjoint path selection problems using TPLM and THCM are solved according to the algorithm of [13]. As, in literature, there exists no work that estimates the minimum number of utilized spectrum slots for both working and backup paths at a time for 1 + 1 protected EONs considering distance-adaptive modulation, we also compare our proposed model to the two-step link-disjoint-path selection approach, described in [28, Ch. 3], where (iii) first and second link-disjoint shortest paths are considered as working and backup paths, respectively, named two-step for path length (2SPL), and (iv) first and second link-disjoint minimum-hop paths are considered as working and backup paths, respectively, named two-step for hop count (2SHC). In both 2SHC and 2SPL schemes, distance-adaptive modulation is considered to estimate the number of utilized spectrum slots for both working and backup paths. The 2SPL and 2SHC schemes search the second shortest and minimum hop paths, respectively, after eliminating the links used in the first shortest and minimum hop paths. We adopt JPN48, Cost 239 network [24], and German 17 network [23] as network topologies, which are shown in Figs. 3, 4, and 5, respectively. For these networks, the source and destination nodes are set to an arbitrary node in order to maintain the length of each link-disjoint path is less than 2000 km. We consider two link-disjoint paths between each source-destination pair. The relationship between the number of used slots and the path length is defined in Table 1. We set $C = \{1, 2, 3\}$ for the set of path length classes $C$, where $L_1 = 400$ km, $L_2 = 800$ km, and $L_3 = 2000$ km. We assume that all spectrum slots are available to focus on the effectiveness of introduced modulation-adaptive link-disjoint path selection model. The link-disjoint paths between source-destination pair with the number of required slots in the introduced model are obtained by solving the ILP introduced in Eqs. (15a)-(15l), or (32a) - (32n). The ILP model was solved by the IBM(R) ILOG(R) CPLEX(R) Interactive Optimizer

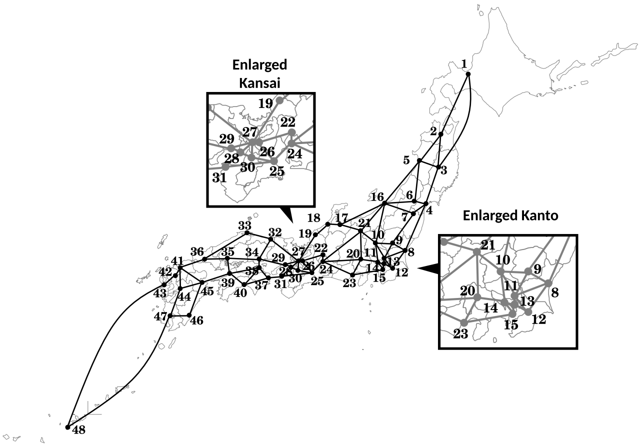

**FIGURE 3.** JPN 48 network model.

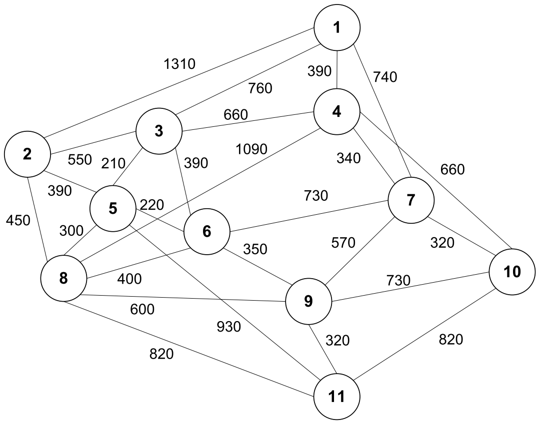

**FIGURE 4.** Cost 239 network model.

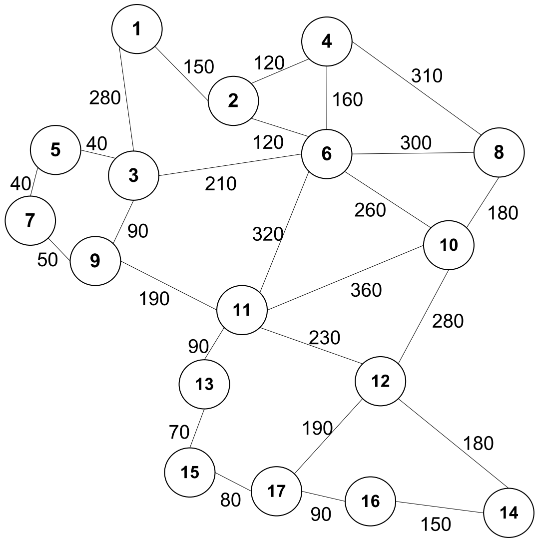

**FIGURE 5.** German 17 network model.

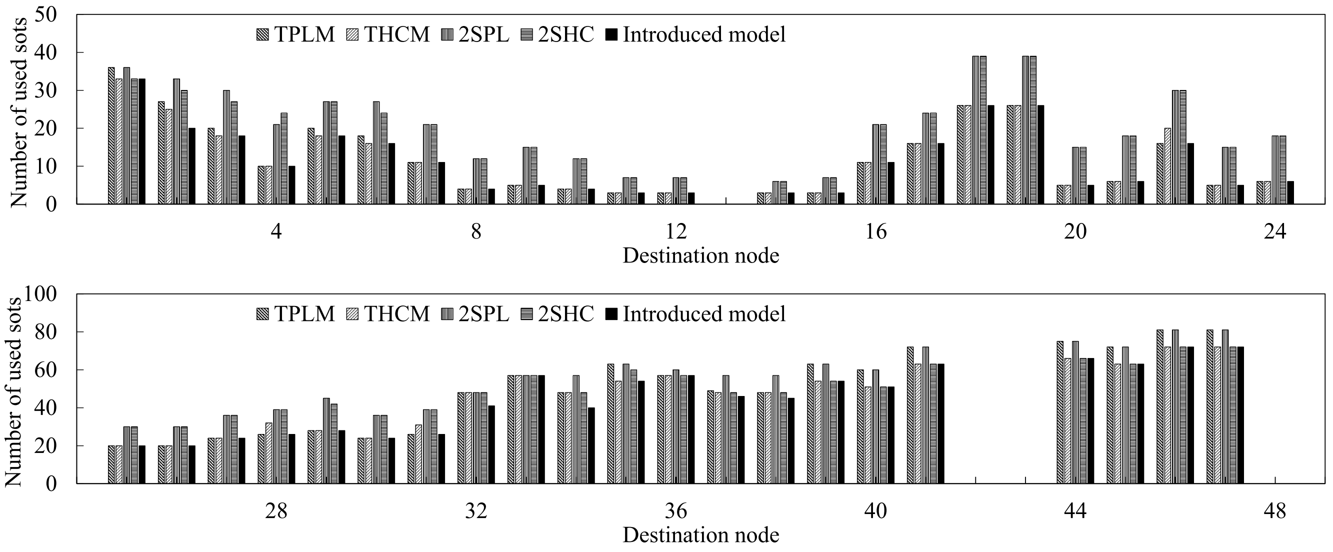

**FIGURE 6.** Number of used slots from node 13 to other nodes in JPN 48 network.

**TABLE 2.** Average number of required slots from node 13 to other nodes in JPN 48.

| | TPLM | THCM | 2SPL | 2SHC | Introduced model |
|---|---|---|---|---|---|
| Average number of used slots | 30.14 | 28.57 | 37.23 | 34.77 | 27.66 |
| Reduction rate of introduced model | 8.22% | 3.18% | 25.70% | 20.46% | - |

12.6.1.0 [31] using Intel (R) Xeon (R) CPU E5-2609 2.5 GHz 8-core, 64 GB memory. We use the same computer to solve TPLM, THCM, 2SPL, 2SHC, and our introduced model.

### A. CONSIDERING SINGLE SOURCE-DESTINATION PAIR

This subsection evaluates the performance of the introduced modulation-adaptive link-disjoint path selection model considering single source-destination pair. In the following, first our discussion focuses on slot utilization followed by computational time.

#### 1) SLOT UTILIZATION

The number of required spectrum slots for each destination node from source node 13 for JPN 48 is captured in Fig. 6. We observe that, when the distance of an optical path is large, the difference between the numbers of required slots using TPLM and the introduced model is high. The number of required slots using THCM and the introduced model is comparable, when the distance of an optical path is long. Both 2SPL and 2SHC schemes need more slots than the introduced model. Finding two shortest paths by considering the first and second link-disjoint shortest paths may not obtain the shortest pair of disjoint paths in terms of number of required slots; more slots are needed, compared to that of the introduced model. Table 2 shows the average number of required slots in JPN 48 network from node 13 to other nodes for different approaches; the average numbers of used slots using TPLM, THCM, 2SPL, 2SHC, and the introduced model are 30.14, 28.57, 37.23, 34,77, and 27.66, respectively. We estimate that the introduced model reduces the average number of used slots compared to both conventional schemes in JPN 48; the spectrum slot usage using the introduced model is 8.22%, 3.18%, 25.70%, and 20.46%, less than that of TPLM, THCM, 2SPL, and 2SHC, respectively.

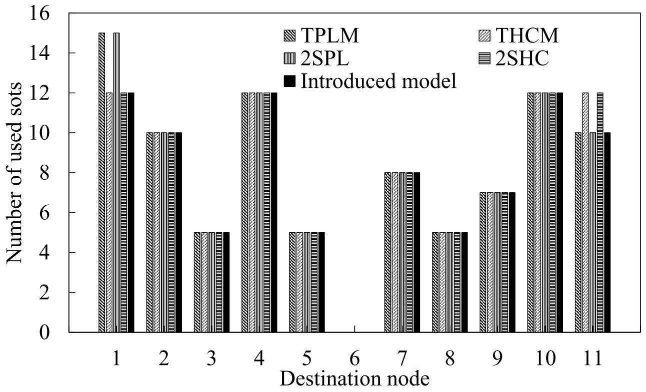

**FIGURE 7.** Number of used slots from node 6 to other nodes in Cost 239 network.

The number of required spectrum slots for each destination node from source node 6 for Cost 239 network is captured in Fig. 7. We observe that TPLM and 2SPL have the larger number of used slots than other schemes at destination node 1, and THCM and 2SHC have the larger number of used slots than other schemes at destination node 11. Table 3 indicates that the introduced model reduces the average number of used slots compared to all the conventional schemes in Cost 239; the average numbers of used slots using TPLM, THCM, 2SPL, 2SHC, and the introduced model are 8.90, 8.80, 8.90, 8.80, and 8.60, respectively. The spectrum slot usage using the introduced model is 3.37%, 2.27%, 3.37%, and 2.27% less than that of TPLM, THCM, 2SPL, and 2SHC, respectively.

**TABLE 3.** Average number of required slots from node 6 to other nodes in Cost 239.

| | TPLM | THCM | 2SPL | 2SHC | Introduced model |
|---|---|---|---|---|---|
| Average number of used slots | 8.90 | 8.80 | 8.90 | 8.80 | 8.60 |
| Reduction rate of introduced model | 3.37% | 2.27% | 3.37% | 2.27% | - |

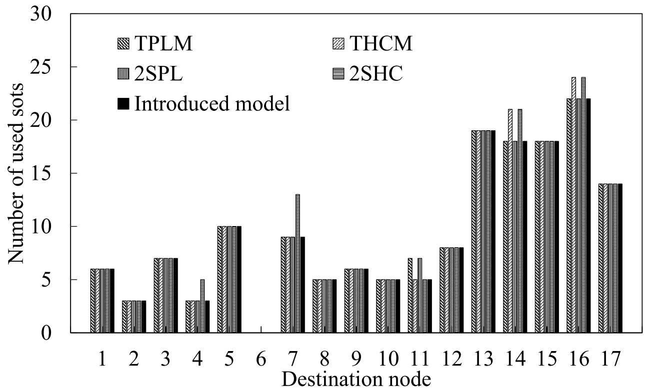

**FIGURE 8.** Number of used slots from node 6 to other nodes in German 17 network.

**TABLE 4.** Average number of required slots from node 6 to other nodes in German 17.

| | TPLM | THCM | 2SPL | 2SHC | Introduced model |
|---|---|---|---|---|---|
| Average number of used slots | 10.00 | 10.19 | 10.00 | 10.56 | 9.88 |
| Reduction rate of introduced model | 1.25% | 3.07% | 1.25% | 6.51% | - |

Figure 8 indicates that TPLM and 2SPL have the larger number of used slots than the introduced model at destination node 11. THCM has the larger number of used slots than the introduced model at destination nodes 14 and 16. 2SHC has the larger number of used slots than the introduced model at destination nodes 4, 7, 14, and 16. Table 4 shows that the introduced model reduces the average number of used slots compared to all the conventional schemes in German 17; the average numbers of used slots using TPLM, THCM, 2SPL, 2SHC, and the introduced model are 10.00, 10.19, 10.00, 10.56, and 9.88, respectively. The spectrum slot usage using the introduced model is 1.25%, 3.07%, 1.25%, and 6.51% less than that of TPLM, THCM, 2SPL, and 2SHC, respectively.

### 2) COMPUTATION TIME

Tables 5-7 show the computation time for JPN 48, Cost 239, and German 17 networks, respectively; node 13, node 6, and node 6 are considered as source nodes in JPN 48, Cost 239, and German 17 networks, respectively, for different approaches.

**TABLE 5.** Comparison of computation times in [sec] for JPN 48 network.

| Destination node | TPLM | THCM | 2SPL | 2SHC | Introduced model |
|---|---|---|---|---|---|
| 1 | 0.10 | 0.10 | 0.04 | 0.02 | 0.64 |
| 2 | 0.11 | 0.11 | 0.03 | 0.02 | 0.90 |
| 3 | 0.11 | 0.11 | 0.03 | 0.03 | 1.14 |
| 4 | 0.11 | 0.10 | 0.03 | 0.04 | 1.23 |
| 5 | 0.11 | 0.11 | 0.03 | 0.03 | 1.12 |
| 6 | 0.10 | 0.11 | 0.03 | 0.03 | 1.50 |
| 7 | 0.11 | 0.11 | 0.02 | 0.03 | 1.08 |
| 8 | 0.10 | 0.11 | 0.02 | 0.02 | 0.73 |
| 9 | 0.11 | 0.11 | 0.02 | 0.02 | 1.00 |
| 10 | 0.11 | 0.11 | 0.02 | 0.02 | 1.08 |
| 11 | 0.11 | 0.11 | 0.02 | 0.02 | 0.98 |
| 12 | 0.11 | 0.11 | 0.03 | 0.02 | 1.10 |
| 13 | - | - | - | - | - |
| 14 | 0.10 | 0.10 | 0.02 | 0.02 | 1.02 |
| 15 | 0.11 | 0.10 | 0.02 | 0.02 | 1.38 |
| 16 | 0.10 | 0.11 | 0.03 | 0.02 | 1.21 |
| 17 | 0.11 | 0.11 | 0.02 | 0.03 | 1.03 |
| 18 | 0.11 | 0.11 | 0.03 | 0.02 | 3.38 |
| 19 | 0.11 | 0.11 | 0.03 | 0.02 | 2.61 |
| 20 | 0.11 | 0.11 | 0.03 | 0.02 | 1.11 |
| 21 | 0.11 | 0.11 | 0.03 | 0.02 | 1.29 |
| 22 | 0.13 | 0.11 | 0.03 | 0.02 | 1.37 |
| 23 | 0.10 | 0.11 | 0.03 | 0.03 | 1.18 |
| 24 | 0.11 | 0.10 | 0.03 | 0.03 | 0.93 |
| 25 | 0.11 | 0.11 | 0.03 | 0.03 | 1.20 |
| 26 | 0.11 | 0.12 | 0.03 | 0.03 | 1.20 |
| 27 | 0.11 | 0.12 | 0.03 | 0.03 | 1.37 |
| 28 | 0.11 | 0.11 | 0.03 | 0.03 | 1.10 |
| 29 | 0.11 | 0.11 | 0.02 | 0.03 | 1.35 |
| 30 | 0.11 | 0.11 | 0.03 | 0.03 | 1.53 |
| 31 | 0.11 | 0.11 | 0.04 | 0.03 | 1.08 |
| 32 | 0.11 | 0.11 | 0.03 | 0.02 | 1.30 |
| 33 | 0.11 | 0.11 | 0.03 | 0.04 | 1.83 |
| 34 | 0.11 | 0.11 | 0.03 | 0.04 | 1.07 |
| 35 | 0.11 | 0.11 | 0.03 | 0.04 | 0.74 |
| 36 | 0.11 | 0.11 | 0.02 | 0.03 | 1.04 |
| 37 | 0.11 | 0.11 | 0.02 | 0.03 | 1.07 |
| 38 | 0.10 | 0.11 | 0.02 | 0.03 | 1.25 |
| 39 | 0.11 | 0.11 | 0.02 | 0.03 | 0.98 |
| 40 | 0.11 | 0.11 | 0.02 | 0.02 | 0.76 |
| 41 | 0.11 | 0.10 | 0.02 | 0.02 | 0.95 |
| 42 | 0.11 | 0.11 | 0.03 | 0.02 | 0.45 |
| 43 | 0.11 | 0.10 | 0.02 | 0.03 | 0.41 |
| 44 | 0.11 | 0.10 | 0.03 | 0.03 | 0.80 |
| 45 | 0.11 | 0.11 | 0.03 | 0.03 | 0.61 |
| 46 | 0.11 | 0.11 | 0.03 | 0.03 | 0.82 |
| 47 | 0.12 | 0.10 | 0.03 | 0.03 | 0.89 |
| 48 | 0.11 | 0.11 | 0.02 | 0.03 | 0.35 |
| Average | 0.11 | 0.11 | 0.03 | 0.03 | 1.13 |

Table 5 indicates that the computation time of the introduced model is larger than that of other schemes. The average computation times using TPLM, THCM, 2SPL, 2SHC, and the introduced model are 0.11 [sec], 0.11 [sec], 0.03 [sec], 0.03 [sec], and 1.13 [sec], respectively. Table 6 indicates that the average computation time of all the conventional schemes are the same but the average computation time of the introduced model is larger than that of all the conventional schemes; the average computation times of TPLM, THCM, 2SPL, 2SHC, and the introduced model are 0.01 [sec], 0.01 [sec], 0.01 [sec], 0.01 [sec], and 0.08 [sec], respectively. Table 7 indicates that the computation time of the introduced model is larger than that of other schemes; the average computation times using TPLM, THCM, 2SPL, 2SHC, and the introduced model are 0.03 [sec], 0.03 [sec], 0.01 [sec], 0.01 [sec], and 0.11 [sec], respectively.

**TABLE 6.** Comparison of computation times in [sec] for Cost 239 network.

| Destination node | TPLM | THCM | 2SPL | 2SHC | Introduced model |
|---|---|---|---|---|---|
| 1 | 0.01 | 0.01 | 0.01 | 0.01 | 0.09 |
| 2 | 0.01 | 0.01 | 0.01 | 0.01 | 0.09 |
| 3 | 0.01 | 0.01 | 0.01 | 0.01 | 0.09 |
| 4 | 0.01 | 0.01 | 0.01 | 0.01 | 0.09 |
| 5 | 0.01 | 0.01 | 0.01 | 0.01 | 0.09 |
| 6 | - | - | - | - | - |
| 7 | 0.01 | 0.01 | 0.01 | 0.01 | 0.06 |
| 8 | 0.01 | 0.01 | 0.01 | 0.01 | 0.08 |
| 9 | 0.01 | 0.01 | 0.01 | 0.01 | 0.09 |
| 10 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05 |
| 11 | 0.01 | 0.01 | 0.01 | 0.01 | 0.09 |
| Average | 0.01 | 0.01 | 0.01 | 0.01 | 0.08 |

**TABLE 7.** Comparison of computation times in [sec] for German 17 network.

| Destination node | TPLM | THCM | 2SPL | 2SHC | Introduced model |
|---|---|---|---|---|---|
| 1 | 0.03 | 0.03 | 0.02 | 0.01 | 0.11 |
| 2 | 0.03 | 0.03 | 0.01 | 0.01 | 0.11 |
| 3 | 0.03 | 0.03 | 0.01 | 0.01 | 0.12 |
| 4 | 0.03 | 0.03 | 0.01 | 0.01 | 0.10 |
| 5 | 0.03 | 0.03 | 0.01 | 0.01 | 0.13 |
| 6 | - | - | - | - | - |
| 7 | 0.03 | 0.03 | 0.01 | 0.01 | 0.12 |
| 8 | 0.03 | 0.03 | 0.01 | 0.01 | 0.12 |
| 9 | 0.03 | 0.03 | 0.01 | 0.01 | 0.10 |
| 10 | 0.03 | 0.03 | 0.01 | 0.01 | 0.10 |
| 11 | 0.03 | 0.03 | 0.01 | 0.01 | 0.11 |
| 12 | 0.03 | 0.03 | 0.01 | 0.01 | 0.11 |
| 13 | 0.03 | 0.03 | 0.01 | 0.01 | 0.11 |
| 14 | 0.03 | 0.03 | 0.01 | 0.01 | 0.10 |
| 15 | 0.03 | 0.03 | 0.01 | 0.01 | 0.11 |
| 16 | 0.03 | 0.03 | 0.01 | 0.01 | 0.10 |
| 17 | 0.03 | 0.03 | 0.01 | 0.01 | 0.11 |
| Average | 0.03 | 0.03 | 0.01 | 0.01 | 0.11 |

## B. CONSIDERING ALL POSSIBLE DESTINATIONS FOR EACH SOURCE NODE IN NETWORK

This subsection evaluates the performance of the introduced modulation-adaptive link-disjoint path selection model considering all possible destinations for each source node in the network. In the following, first our discussion focuses on slot utilization followed by computational time.

### 1) SLOT UTILIZATION

The average number of required spectrum slots from any arbitrary source node to all possible destination nodes for JPN 48, Cost 239, and German 17 networks are captured in Figs. 9-11, respectively. The average number of required slots in the network for all source-destination pairs using different approaches for JPN 48, Cost 239, and German 17 are shown in Tables 8-10, respectively.

Table 8 indicates that the introduced model reduces the average number of used slots compared to both conventional schemes in JPN 48. The average numbers of used slots using TPLM, THCM, 2SPL, 2SHC, and the introduced model are 31.16, 29.06, 42.18, 38.15, and 28.05, respectively. The spectrum slot usage using the introduced model is 9.97%, 3.48%, 33.50%, and 26.47% less than that of TPLM, THCM, 2SPL, and 2SHC, respectively. Table 9 indicates that the introduced model reduces the average number of used slots compared to both conventional schemes in Cost 239. The average numbers of used slots using TPLM, THCM, 2SPL, 2SHC, and the introduced model are 10.32, 9.71, 10.94, 10.16, and 9.62, respectively. The spectrum slot usage using the introduced model is 6.75%, 0.94%, 12.01%, and 5.32% less than that of TPLM, THCM, 2SPL, and 2SHC, respectively. Table 10 indicates that the introduced model reduces the average number of used slots compared to both conventional schemes in German 17 network. The average numbers of used slots using TPLM, THCM, 2SPL, 2SHC, and the introduced model are 15.36, 15.37, 15.56, 15.83, and 14.63, respectively. The spectrum slot usage using the introduced model is 4.76%, 4.78%, 5.95%, and 7.57%, less than that of TPLM, THCM, 2SPL, 2SHC, respectively.

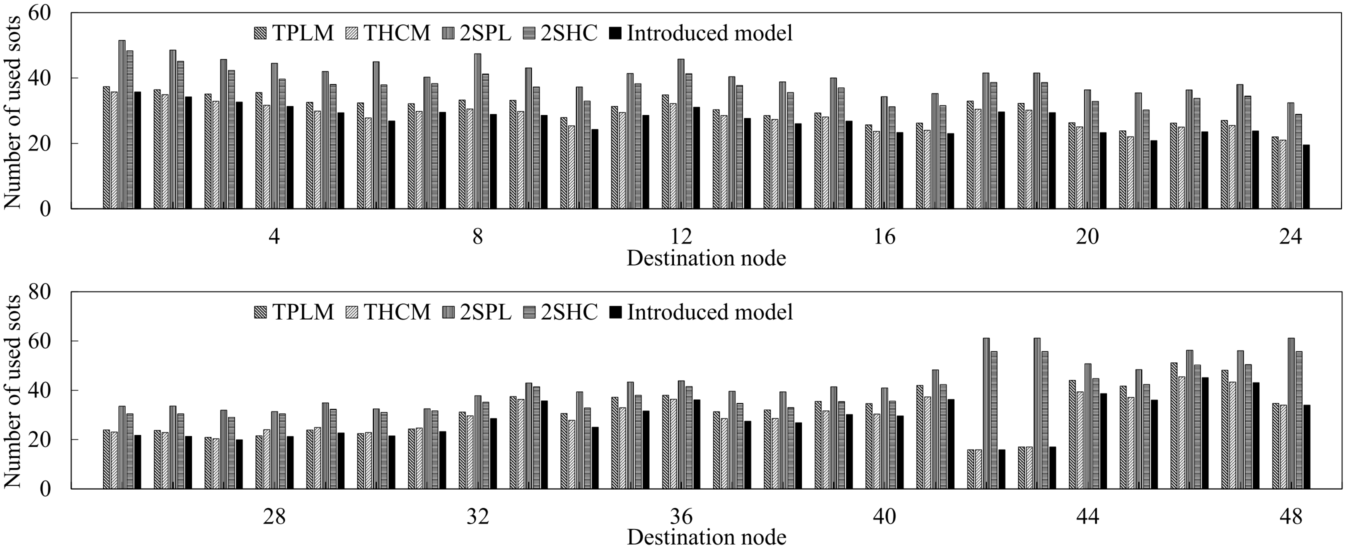

**FIGURE 9.** Average number of used slots from any arbitrary source node to all possible destination nodes in JPN 48 network.

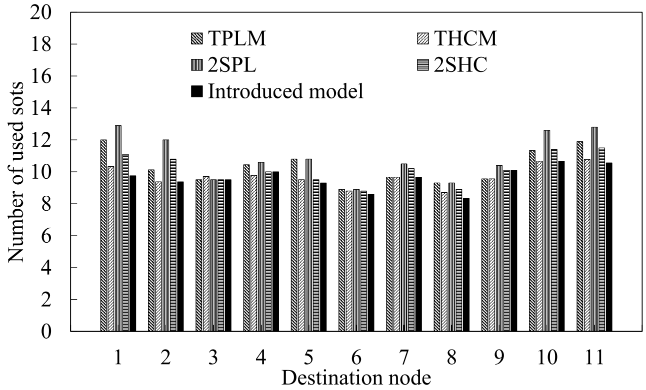

**FIGURE 10.** Average number of used slots from any arbitrary source node to all possible destination nodes in Cost 239 network.

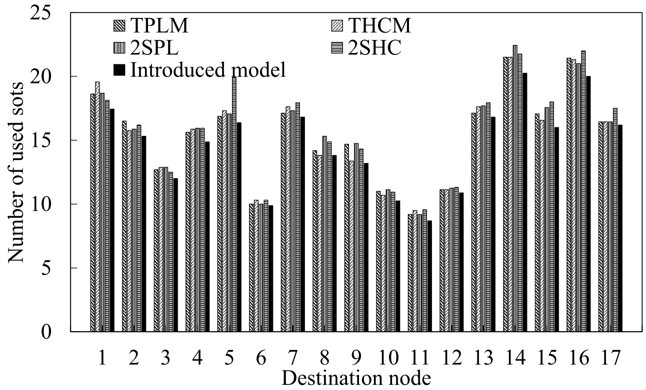

**FIGURE 11.** Average number of used slots from any arbitrary source node to all possible destination nodes in German 17 network.

**TABLE 8.** Average slot requirement for all possible source-destination pairs in JPN 48 network.

| | TPLM | THCM | 2SPL | 2SHC | Introduced model |
|---|---|---|---|---|---|
| Average number of required slots | 31.16 | 29.09 | 42.18 | 38.15 | 28.05 |
| Reduction rate of introduced model | 9.97% | 3.48% | 33.50% | 26.47% | - |

**TABLE 9.** Average slot requirement for all possible source-destination pairs in Cost 239 network.

| | TPLM | THCM | 2SPL | 2SHC | Introduced model |
|---|---|---|---|---|---|
| Average number of required slots | 10.32 | 9.71 | 10.94 | 10.16 | 9.62 |
| Reduction rate of introduced model | 6.75% | 0.94% | 12.01% | 5.32% | - |

### 2) COMPUTATION TIME

Tables 11-13 show the computation times for JPN 48, Cost 239, and German 17 networks, respectively, for all source-destination pair in the network for different approaches.

Tables 11, 12, and 13 indicate that the computation time of the introduced model is larger than that of other schemes.

**TABLE 10.** Average slot requirement for all possible source-destination pairs in German 17 network.

| | TPLM | THCM | 2SPL | 2SHC | Introduced model |
|---|---|---|---|---|---|
| Average number of required slots | 15.36 | 15.37 | 15.56 | 15.83 | 14.63 |
| Reduction rate of introduced model | 4.76% | 4.78% | 5.95% | 7.57% | - |

**TABLE 11.** Comparison of computation times in [sec] for JPN 48 network.

| Source node | TPLM | THCM | 2SPL | 2SHC | Introduced model |
|---|---|---|---|---|---|
| 1 | 0.11 | 0.11 | 0.03 | 0.03 | 0.68 |
| 2 | 0.11 | 0.11 | 0.03 | 0.03 | 0.98 |
| 3 | 0.11 | 0.11 | 0.03 | 0.03 | 0.98 |
| 4 | 0.11 | 0.11 | 0.03 | 0.03 | 1.04 |
| 5 | 0.11 | 0.11 | 0.03 | 0.03 | 0.97 |
| 6 | 0.11 | 0.11 | 0.03 | 0.03 | 1.09 |
| 7 | 0.11 | 0.11 | 0.03 | 0.03 | 0.94 |
| 8 | 0.11 | 0.11 | 0.03 | 0.03 | 1.05 |
| 9 | 0.11 | 0.11 | 0.03 | 0.03 | 1.05 |
| 10 | 0.11 | 0.11 | 0.03 | 0.03 | 1.08 |
| 11 | 0.11 | 0.11 | 0.03 | 0.03 | 0.97 |
| 12 | 0.11 | 0.11 | 0.03 | 0.03 | 1.07 |
| 13 | 0.11 | 0.11 | 0.03 | 0.03 | 1.13 |
| 14 | 0.11 | 0.11 | 0.03 | 0.03 | 1.00 |
| 15 | 0.11 | 0.11 | 0.03 | 0.03 | 0.95 |
| 16 | 0.11 | 0.11 | 0.03 | 0.03 | 1.00 |
| 17 | 0.11 | 0.11 | 0.03 | 0.03 | 0.95 |
| 18 | 0.11 | 0.11 | 0.03 | 0.03 | 0.98 |
| 19 | 0.11 | 0.11 | 0.03 | 0.03 | 0.96 |
| 20 | 0.11 | 0.11 | 0.02 | 0.03 | 0.91 |
| 21 | 0.11 | 0.11 | 0.02 | 0.03 | 1.07 |
| 22 | 0.11 | 0.11 | 0.02 | 0.03 | 1.06 |
| 23 | 0.11 | 0.11 | 0.03 | 0.03 | 0.95 |
| 24 | 0.11 | 0.11 | 0.02 | 0.03 | 0.97 |
| 25 | 0.11 | 0.11 | 0.03 | 0.03 | 0.88 |
| 26 | 0.12 | 0.12 | 0.03 | 0.03 | 1.01 |
| 27 | 0.12 | 0.12 | 0.03 | 0.03 | 0.86 |
| 28 | 0.11 | 0.11 | 0.03 | 0.03 | 1.01 |
| 29 | 0.11 | 0.11 | 0.03 | 0.03 | 1.03 |
| 30 | 0.11 | 0.11 | 0.03 | 0.03 | 0.89 |
| 31 | 0.11 | 0.11 | 0.03 | 0.03 | 0.94 |
| 32 | 0.11 | 0.11 | 0.03 | 0.03 | 0.97 |
| 33 | 0.11 | 0.11 | 0.03 | 0.03 | 0.99 |
| 34 | 0.11 | 0.11 | 0.03 | 0.03 | 1.17 |
| 35 | 0.11 | 0.11 | 0.03 | 0.03 | 0.88 |
| 36 | 0.11 | 0.11 | 0.03 | 0.03 | 0.85 |
| 37 | 0.11 | 0.11 | 0.03 | 0.03 | 0.83 |
| 38 | 0.11 | 0.11 | 0.03 | 0.03 | 0.88 |
| 39 | 0.11 | 0.11 | 0.03 | 0.03 | 0.87 |
| 40 | 0.11 | 0.11 | 0.03 | 0.03 | 0.89 |
| 41 | 0.11 | 0.11 | 0.03 | 0.03 | 0.81 |
| 42 | 0.11 | 0.11 | 0.03 | 0.03 | 0.54 |
| 43 | 0.11 | 0.11 | 0.03 | 0.03 | 0.44 |
| 44 | 0.11 | 0.11 | 0.03 | 0.03 | 0.84 |
| 45 | 0.11 | 0.11 | 0.03 | 0.03 | 0.82 |
| 46 | 0.11 | 0.11 | 0.03 | 0.03 | 0.87 |
| 47 | 0.11 | 0.11 | 0.03 | 0.03 | 0.69 |
| 48 | 0.11 | 0.11 | 0.03 | 0.03 | 0.10 |
| Average | 0.11 | 0.11 | 0.03 | 0.03 | 0.91 |

In JPN 48, the average computation times of TPLM, THCM, 2SPL, 2SHC, and the introduced model are 0.11 [sec], 0.11 [sec], 0.03 [sec], 0.03 [sec], and 0.91 [sec], respectively. In Cost 239, the average computation times of

**TABLE 12. Comparison of computation times in [sec] for Cost 239 network.**

| Source node | TPLM | THCM | 2SPL | 2SHC | Introduced model |
|---|---|---|---|---|---|
| 1 | 0.01 | 0.01 | 0.01 | 0.01 | 0.04 |
| 2 | 0.01 | 0.01 | 0.01 | 0.01 | 0.06 |
| 3 | 0.01 | 0.01 | 0.01 | 0.01 | 0.08 |
| 4 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05 |
| 5 | 0.01 | 0.01 | 0.01 | 0.01 | 0.09 |
| 6 | 0.01 | 0.01 | 0.01 | 0.01 | 0.08 |
| 7 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05 |
| 8 | 0.01 | 0.01 | 0.01 | 0.01 | 0.08 |
| 9 | 0.01 | 0.01 | 0.01 | 0.01 | 0.06 |
| 10 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05 |
| 11 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 |
| Average | 0.01 | 0.01 | 0.01 | 0.01 | 0.06 |

**TABLE 13. Comparison of computation times in [sec] for German 17 network.**

| Source node | TPLM | THCM | 2SPL | 2SHC | Introduced model |
|---|---|---|---|---|---|
| 1 | 0.03 | 0.03 | 0.01 | 0.01 | 0.14 |
| 2 | 0.03 | 0.03 | 0.01 | 0.01 | 0.14 |
| 3 | 0.03 | 0.03 | 0.01 | 0.01 | 0.14 |
| 4 | 0.03 | 0.03 | 0.01 | 0.01 | 0.14 |
| 5 | 0.03 | 0.03 | 0.01 | 0.01 | 0.13 |
| 6 | 0.03 | 0.03 | 0.01 | 0.01 | 0.12 |
| 7 | 0.03 | 0.03 | 0.01 | 0.01 | 0.15 |
| 8 | 0.03 | 0.03 | 0.01 | 0.01 | 0.13 |
| 9 | 0.03 | 0.03 | 0.01 | 0.01 | 0.14 |
| 10 | 0.03 | 0.03 | 0.01 | 0.01 | 0.11 |
| 11 | 0.03 | 0.03 | 0.01 | 0.01 | 0.12 |
| 12 | 0.03 | 0.03 | 0.01 | 0.01 | 0.11 |
| 13 | 0.03 | 0.03 | 0.01 | 0.01 | 0.16 |
| 14 | 0.03 | 0.03 | 0.01 | 0.01 | 0.13 |
| 15 | 0.03 | 0.03 | 0.01 | 0.01 | 0.14 |
| 16 | 0.03 | 0.03 | 0.01 | 0.01 | 0.14 |
| 17 | 0.03 | 0.03 | 0.01 | 0.01 | 0.12 |
| Average | 0.03 | 0.03 | 0.01 | 0.01 | 0.13 |

TPLM, THCM, 2SPL, 2SHC, and the introduced model are 0.01 [sec], 0.01 [sec], 0.01 [sec], 0.01 [sec], and 0.061 [sec], respectively. In German 17, the average computation times of TPLM, THCM, 2SPL, 2SHC, and the introduced model are 0.03 [sec], 0.03 [sec], 0.01 [sec], 0.01 [sec], and 0.132 [sec], respectively.

From the above analysis, we can summarize that the introduced model reduces the number of average used slots compared to all the conventional schemes for our examined networks by consuming some extra times.

### C. COMPARISON OF DIFFERENT MODULATIONS AND SAME MODULATION FOR LINK-DISJOINT PATH SELECTION

Figures 12-14 compare the number of used slots in the case that different modulations for link-disjoint paths are allowed to use with that of case that the same modulation is used. For the latter case, we solve the ILP problem in Eqs. (34a)-(34j). For all sample topologies, the average numbers of used slots in the scenario of the same modulation are 11.6%, 11.6%, and 3.0% higher than that of the different modulation for Cost 239, German 17, and JPN 48, respectively. The scenario of different modulations is beneficial in terms of the number of used slots, while it increases the complexity of network systems. These results help network operators to choose a suitable scenario between the two scenarios.

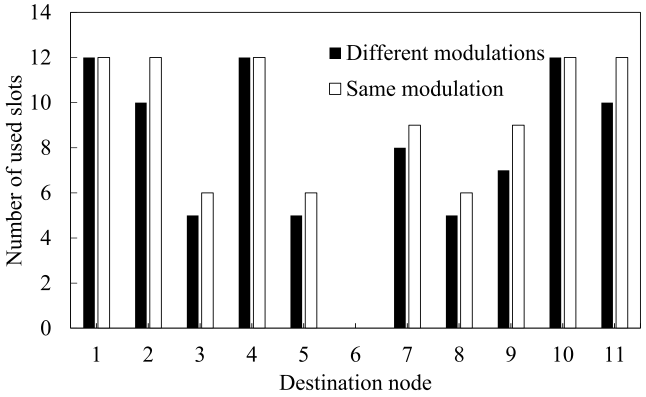

**FIGURE 12.** **Comparison of different modulations and same modulation for link-disjoint path selection in Cost 239 network.**

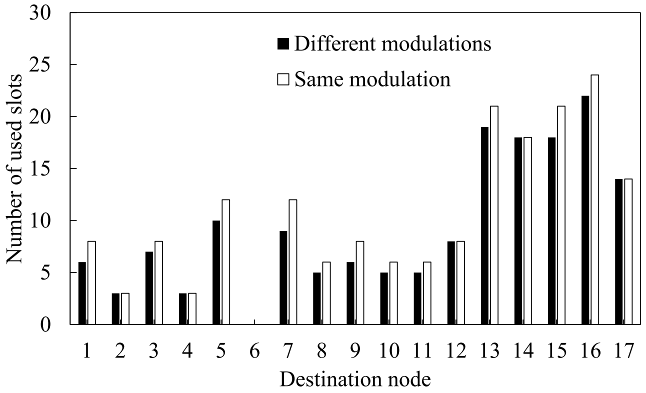

**FIGURE 13.** **Comparison of different modulations and same modulation for link-disjoint path selection in German 17 network.**

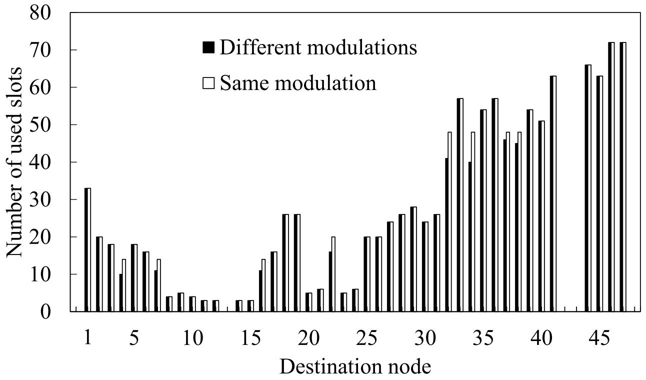

**FIGURE 14.** **Comparison of different modulations and same modulation for link-disjoint path selection in JPN 48 network.**

## VI. APPLICABILITIES OF OUR MODEL

The modulation-adaptive link-disjoint path selection model is intended to minimize the number of required spectrum slots for an individual lightpath request by introducing a step function as a constraint to relate the optical path length with the number of utilized spectrum slots. The developed link-disjoint path selection model in this paper can have several applicabilities that are described in the following.

(i) *Static scenario:* Considering multiple requests, the introduced model can be adopted for planning problems to design a physical network and resource allocation problems.
   - The introduced model can be adopted by network operators for planning problems in survivable networks. In those planning problems, the objective function used in this paper can be modified; the introduced step function based on realistic modulation formats can be adopted.
   - Heuristic approaches are considered, typically in practice, to handle resource allocation problems for each connection request individually; each solution is incrementally assigned in an iterative manner for a full-fledged optical networks. Our introduced model can be used to solve an individual connection by incorporating constraints of spectrum continuity and contiguity.

(ii) *Dynamic scenario:* The introduced model can be applied for a dynamic scenario in optical networks, where lightpath provisioning and releasing can be performed anytime, for lightpath provisioning of each request by incorporating constraints of spectrum continuity and contiguity. The solution for each request is incrementally assigned in an iterative manner for a full-fledged optical networks.

## VII. RELATED WORKS

Any interruption of the data flow in EONs leads to massive data and revenue losses. To avoid the problem, optical researchers have been focusing on reliability issues in EONs. They consider different fault resilient techniques [12], [32], [33], which are span or path restoration, p-Cycles, shared path protection, and 1 + 1/1:1 end-to-end path protection for EONs.

As the resource utilization using the restoration technique is typically increased, the work in [34] provided a restoration scheme based on spans in EONs. An ILP model was introduced in order to reduce both spare capacity and maximum used slots index in the network. Likewise, Wei *et al.* [35] presented a P-cycle technique in EONs to minimize the maximum number of used frequency slots. The bandwidth squeezed restoration (BSR) technique [36] is used in both works presented in [34] and [35] to achieve the maximum level of restoration for the affected service flow.

Among these fault resilience techniques, protection techniques, namely shared and dedicated protection techniques, are extensively used for recovery purposes. To offer complete protection against single and double link failures, the work in [37] presented algorithms for protected EONs, which offer better resource utilization. To provide the maximum shared capacity on the backup paths considering static traffic, Kosaka *et al.* [40] and Walkowiak and Klinkowski [41] presented efficient heuristic algorithms for network's resource sharing.

To investigate the impact of lightpaths considering distance adaptive modulation in EONs, the work in [40] presented routing and slot assignment algorithms for lightpaths with the capabilities of distance adaptive modulation. Takagi *et al.* [40] introduced two efficient algorithms for 1 + 1 dedicated path protected ring networks to enhance the resource utilization.

The work in [41] toggles the functions of the lightpaths in a 1 + 1 path protection from the primary state to the backup state to allow initially primary lightpaths to be reallocated for defragmentation purpose. This work minimizes the spectrum fragmentation in EON with 1 + 1 protection but it does not consider distance adaptive modulation.

Cai *et al.* [42] considered distance-adaptive spectrum allocation in order to minimize the required spectrum resources for accommodating all multicast requests by applying multicast routing, modulation, and spectrum assignment with shared protection.

As managing dynamic traffic in EONs is one of the key challenges, the works in [43] and [44] introduced shared backup path protection schemes for EONs. To increase the spectrum utilization, Tarhan and Cavdar [43] provided a spectrum allocation algorithm for assigning primary and backup resources using distance adaptive modulation; the first-fit and modified last-fit policies are used for allocating primary and backup paths, respectively. Tarhan and Cavdar [43] analyzed aggressive and conservative backup sharing policies for EONs under dynamic traffic.

Dedicated protection techniques [45]–[47] are considered for the fastest recover technique and it is able to recover multiple link failures simultaneously. The features of dedicated protection techniques motivated Klinkowski [47] to present a dedicated path protection scheme in EONs under static traffic. The work in [46] presented a 1 + 1 path protection defragmentation approach in EONs under the dynamic traffic scenario to improve the traffic admissibility.

Shen *et al.* [12] provided a comprehensive survey on survivable EONs by investigating spectrum resource sharing approaches among backup lightpaths, and discussed the current research issues and forthcoming challenges on spectrum defragmentation. The work in [32] investigated the advantage optical transport networks by implementing the flexible technology in the context of network resilience considering distance-adaptive modulation.

The work in [49] introduced an ILP formulation to minimize the maximum number of utilized slots. It considers a modulation format to allocate spectrum slots for a request.

Only the same modulation is considered for a link-disjoint path.

The work in [50] evaluated the effect of rerouting and spectrum defragmentation by considering distance adaptive modulation for each single lightpath request. Each path is established on an alternative route and assigned frequency slots before releasing the original path to minimize the disruption time. This work does not consider the 1 + 1 protection.

The work in [19] presented a modulation-adaptive link-disjoint path selection scheme to minimize the number of required spectrum slots in 1 + 1 protected EONs. The work in [19] considered a linear formulation from the nonlinear table by obtaining the number of required spectrum slots for each increment of the optical path length and adopted a non-decreasing function. As a result, the optimum solution was not obtained in several cases due to a large computational time. The ILP model introduced in [19] cannot be used practically, which motivates us to address a more tractable modulation-adaptive link-disjoint path selection model for 1 + 1 protected EONs in order to minimize the number of utilized spectrum slots.

## VIII. CONCLUSION

This paper introduced a modulation-adaptive link-disjoint path selection model by considering a step function based on realistic modulation formats in order to minimizes the total number of utilized spectrum slots in 1 + 1 protected EONs. We formulated the modulation-adaptive link-disjoint path selection problem as an integer linear programming (ILP). We proved that the modulation-adaptive link-disjoint path selection problem is NP-complete. By using an optimization solver, we solved the ILP problem for different backbone networks, namely Japan Photonic Network (JPN48), German 17 network, and Cost 239 network, within a practical time. We observed that the introduced model reduces the number of used slots compared to conventional schemes for our examined networks, and it requires some extra times compared to the conventional schemes to estimate the minimum number of utilized spectrum slots.

Considering more complex network scenarios and optical data center networks, where data centers are located at the edge of EONs [51], is left as part of a future work.

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