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Routing and Spectrum Assignment for Dual Failure Path Protected Elastic Optical Networks

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ABSTRACT We present the design of a dual failure protected elastic optical network (EON) for different sharing capabilities of protection lightpaths. Routing and spectrum assignment (RSA) is considered for such a network so as to minimize the maximum number of frequency slots (FSs) used. The key principles for protection resource sharing among the first and the second protection lightpaths are identified for dedicated 1:1:1, mixed 1:1:1, 1+1:1, and 1+1+1 protection. Both integer linear programming (ILP) models and spectrum window plane (SWP)-based heuristic algorithms are proposed for RSA in dual failure protected EONs. Simulation results indicate that, apart from being efficient, the proposed SWP-based heuristic algorithm not only performs close to the ILP model but also does much better than a benchmark adaptive routing algorithm. We find that 1:1:1 protection technique performs better in terms of the maximum number of FSs used and the spare capacity redundancy than both the 1+1:1 and 1+1+1 techniques. In addition, the mixed 1:1:1 case outperforms the dedicated 1:1:1 case both in minimizing the maximum number of link FSs used and its spare capacity redundancy.

INDEX TERMS Elastic optical network (EON), dual failure, dedicated 1:1:1, mixed 1:1:1, 1+1:1, 1+1+1, ILP model, spectrum window plane (SWP).

I. INTRODUCTION

Even the failure of a single network element in an optical network can be a calamity since it may lead to the failure of several lightpaths simultaneously and consequently huge data loss. This problem gets further aggravated as lightpaths move to higher and higher bit rates, such as 40 Gb/s, 100 Gb/s, and beyond. Telecommunication networks are required to operate reliably and without interruption and, as per [1], the overall availability of such a network should be of the order of a percentage of 99.999 or even higher. Therefore, survivability would be a critical requirement for reliable services in optical networks so that they can withstand equipment and link failures.

Protection schemes for a single-link failure and its corresponding protection mechanisms have been extensively researched. However, relatively little work has been done for handling two-link failure scenarios even though these are becoming increasingly important. A two-link failure can happen if a second link fails before the first link failure can be repaired. It can also happen if two distinct physical links are routed through a common duct or physical channel which fails. Physical routing of links is based on rights of way obtained from utilities and railroad companies [2]. For example, links from New York to Washington and New York to Boston may both be routed together for some distance, e.g., through the Lincoln Tunnel. In such cases, failure of the commonly shared resources would result in simultaneous multiple link failures. These concerns indicate the need for addressing dual-failure in real networks [3]–[5] where mission critical services such as financial or military applications need to be supported. The dual failure problem may also arise in other applications. For example, Yuksel *et al.* [6] observed that 17% of link failures over a four-month period were dual failures in an operational IPTV network.

On the other hand, both because of high spectrum efficiency and flexibility in bandwidth allocation and the choice of modulation formats used [7], [8], elastic optical networks (EONs) have drawn extensive interest in recent years. In an EON, a fiber would carry a very large number of connections with high bandwidth. Therefore, survivability would be of even greater concern in an EON. The current studies of survivable EONs are mainly focused on single failure protection services, as in [9]–[32]. Among the protection techniques used, 1+1 or 1:1 path protection are the traditional approaches which have been extensively defined in ITU-T and other standards. 1:1:1, 1+1:1, and 1+1+1 path protection techniques extend the traditional 1+1 and 1:1 techniques to handle dual-link failures. Though researchers have examined the performances of these techniques in the context of mesh-like WDM networks [34], [35], these studies are still very minor and efficient spare capacity sharing among the first and second protection lightpaths is not fully explored yet. Moreover, none of the above dual failure protection techniques are used in EONs. To apply these three dual-failure protection techniques to EONs, the unique constraints for optical channels including spectrum contiguity and spectrum continuity must be taken into account. This makes the design of corresponding dual failure protected networks both more complicated and challenging.

This paper focuses on the design of dual-failure protected EON with different capabilities of sharing spare capacity. We first introduce *1+1:1 path protection*. This is a hybrid backup path protection technique where the first protection lightpaths are assigned with dedicated spare capacity, but FSs can be shared among multiple second protection lightpaths. We then introduce *dedicated 1:1:1 path protection*. This can provide more efficient spectrum utilization than 1+1:1 path protection as it also allows multiple first protection lightpaths to share spare capacity. Note that in this dedicated case, protection resources can only be shared in the same categories, i.e., the protection resources of a first protection lightpath and a second protection lightpath cannot be shared. For better utilization of limited network resources, apart from the *dedicated 1:1:1 protection* approach as in [35], we also introduce another way of providing 1:1:1 protection where the spare capacity of the first and second protection lightpaths can be shared by each other, this is referred to as *mixed 1:1:1 protection* in this paper. The main differences between the dedicated 1:1:1 and mixed 1:1:1 approaches are discussed later. As performance comparison benchmark, we also consider 1+1+1 protection which provides dedicated path protection with no capacity sharing among all the protection lightpaths.

The rest of this paper is organized as follows. In Section II, we review the related work. In Section III, we introduce dual failure path protection techniques for EONs, including 1+1:1 path protection, dedicated 1:1:1 protection, and mixed 1:1:1 protection. For the RSA problem of dual failure protected EON, we develop ILP models and efficient SWP-based heuristic algorithms in Sections IV and V, where both the ILP models and SWP-based heuristic algorithms can incorporate different modulation formats. Section VI presents case studies with their associated test conditions, and the results of using the different approaches proposed are presented and discussed. Section VII concludes the paper.

II. LITERATURE REVIEW

Protection technique can be broadly classified as providing *link-based protection* or *path-based protection*. Link-based mechanisms recover a network failure at the two end nodes of a failed link, while path-based mechanisms replace the end-to-end path between a source and its destination.

A. NETWORK PROTECTION FOR EON

As of date, several solutions for survivable EONs have been proposed to handle single link failure [9]–[32]. Link-based protection commonly uses three techniques, referred to as ring cover, span restoration, and *p*-cycle. Wei *et al.* [9] developed an ILP model for the ring cover scheme to minimize both the reserved protection capacity and the link spectra used in the entire network. Similarly, they also considered the span restoration (SR) technique for EONs under different spectrum conversion capabilities in [10]. For the *p*-cycle technique, Wu *et al.* [11] studied the static Survivable *p*-Cycle Routing and Spectrum Allocation (SC-RSA) problem in EONs. An ILP formulation and an Elastic *p*-Cycle Protection (ECP) heuristic algorithm were presented. For dynamic *p*-cycle configuration in EONs, different efficient algorithms were proposed in [12] and [13]. To provide 100% restorability, Chen *et al.* [14] further studied the resilience design with failure-independent path-protecting *p*-cycles (FIPP) for EONs. Oliveira and da Fonseca [15] also introduced an FIPP-Flex algorithm for providing FIPP *p*-cycle protection in EONs.

Path-based protection approaches are more capacity efficient for mesh-based networks compared to the link-based protection approaches [33]. For this, 1+1 dedicated path protection and shared backup path protection (SBPP) are two common path-based protection techniques. Klinkowski and Walkowiak [16] proposed a compact ILP model and an Adaptive Frequency Assignment with Dedicated Path Protection (AFA-DPP) heuristic algorithm of static RSA. They also applied the Genetic Algorithm (GA) metaheuristic to provide near-optimal solutions to the static RSA problem in [17]. Extending from the above algorithm, the authors [18] further developed an efficient Evolutionary Algorithm (EA) which outperforms other reference algorithms for the offline RSA/DPP problem. Sone *et al.* [19] proposed a bandwidth squeezed restoration (BSR) scheme in EON. The proposed scheme enables spectrally efficient and highly survivable network recovery for best-effort traffic and bandwidth guaranteed traffic. Shen *et al.* [20] developed an ILP model with the objective of minimizing both the required spare capacity and the maximum number of link FSs used for SBPP path protected EONs. Besides a novel ILP model, Walkowiak and Klinkowski [21] also presented effective heuristic algorithms for SBPP protected EONs. Chen *et al.* [22] proposed an ILP model and a Spectrum Aware Shared Protection (SASP) algorithm that considers joint failure probability. For maximal spare capacity sharing, Eira *et al.* [23] developed an ILP model and a heuristic algorithm for SBPP. Distance-adaptive EON with SBPP was studied in [24]–[26]. Specifically, Wang *et al*. [26] proposed protection lightpath-based hitless spectrum defragmentation for distance adaptive EONs. Kosaka *et al*. [27] proposed a shared protected elastic optical path network design algorithm that introduces an iterative path relocation procedure. Shao *et al*. [28] evaluated conservative and aggressive backup sharing in OFDM-based optical networks. By applying traffic grooming in the optical spectrum domain, Liu *et al*. [29] proposed a novel elastic shared path protection (ESPP) scheme to design a spectrum-efficient elastic network. Zhang *et al*. [30] proposed a novel shared-path protection algorithm with correlated risk. To study the spare capacity sharing problem, Yang *et al*. [31] presented a spectrum reservation matrix model for characterizing SPP problem.

In addition to the literature summarized above, we have also made a survey and perspective on approaches and mechanisms for survivable EONs recently in [32].

B. DUAL FAILURE PROTECTION

Related work on using link protection for double-link failure recovery can be found in [3] where Clouqueur and Grover presented experimental results on the amount of protection from dual-link failures that single-link protection approaches can provide. The restoration from two-link failures in mesh networks designed to fully restore any single link failure was also studied in [36]. Three different models were further developed in [37] to address the design of networks for surviving dual failures. A significant finding of this work is that the design for complete dual-failure restorability requires almost three times the amount of spare capacity. Lumetta and Tseng [38] compared the recovery performance of three link-restoration algorithms based on generalized loopback under double-link failures. Choi *et al.* [4] further considered three link-based protection methods for handling dual-link failures. They also presented an algorithm that precomputed backup paths for links in order to tolerate dual-link failures. Lumetta and Médard [39] proposed a hierarchical classification scheme for dual-link failures and identified various performance aspects for recovery algorithms. Ramasubramanian and Chandak [5] incorporated the backup link mutual exclusion (BLME) constraints in an ILP model and a polynomial time heuristic algorithm was further developed to protect connections from dual-link failures. In [40]–[42], the authors formulated and studied p-Cycle network design problems considering dual-failure restorability.

Path-based dual failure protection approaches can be found in [43], Assi *et al.* verified that resource sharability plays a significant role in the performance of network reprovisioning when two near simultaneous failures occur. Prinz *et al.* [44] proposed four multi-layer path protection models for enabling the client to protect its connections against dual failures in the server layer. Frederick *et al.* [45] evaluated and compared the performance of the sub-graph routing strategy and the backup multiplexing scheme for tolerating a second link fault in a network. Zhou *et al.* [46] presented a new concept for availability analysis called restoration-aware connection availability (RACA) that can be used to exactly evaluate survivability strategies with dedicated or shared spare capacities. Sivakumar and Sivalingam [47] developed a hybrid mechanism that provides maximum (close to 100%) dual-failure restorability with minimum additional spare capacity. Guo *et al.* [48] proposed a Dynamic Shared-Path Protection (DSPP) algorithm for protecting the multi-link failures of the dual-risk breakdowns in WDM mesh networks. He and Somani [49] identified the scenarios where the backup paths could share their wavelengths without violating 100% restoration guarantee (backup multiplexing). To optimize capacity utilization, they also used integer programming for both dedicated and shared-path protection schemes. Liu and Tipper [34] used aggregated spare provision matrix (SPM) to capture the spare capacity sharing for dual link failures under the 1+1:1, 1:1:1 path protection schemes. Also under the same protection schemes, Shen *et al*. [35] developed a waveplane-based regenerator placement algorithm for 1+1:1 and 1:1:1 protected lightpath services in the context of WDM.

C. SUMMARY

We can see that though there are extensive studies dedicated to single failure protection of EON and dual failure protection for WDM networks. Very few studies on dual failure protection have focused on end-to-end paths such as path-based 1+1:1 or 1:1:1, under which spare capacity sharing among the first and protection lightpaths is very complicated and challenging and have not been fully explored yet. Moreover, none of the above dual failure protection techniques are used in EONs. This paper first presents a comprehensive design of dual-failure protected EONs with different spectrum sharing capabilities using path-based protection techniques. The four typical dual failure protection techniques, i.e., mixed 1:1:1 protection, dedicated 1:1:1 protection, 1+1:1 protection and 1+1+1 protection are introduced and studied. The key principles for the different capabilities of protection resources sharing among first and second protection lightpaths are identified. We also adaptively allocate different modulation formats and number of FSs to a working lightpath and its two corresponding protection lightpaths for a dual failure protected service because these lightpaths may be of different physical lengths. For the RSA problem, we develop an integrated approach based on the concepts of spectrum window planes (SWPs) for establishing the working lightpath and spectrum windows (SWs) for choosing the protection lightpaths, respectively. This approach provides an efficient way to jointly choose the route and assign the spectrum for each lightpath.

III. 1+1:1 AND 1:1:1 PROTECTION

In an EON, apart from the working lightpath required for each service, two pre-defined protection lightpaths are needed to handle dual-link failures. It may be noted that these three lightpaths must be link-disjoint in order to provide survivability against dual-link failures. Even if such a dual-failure occurs, disconnecting both the working lightpath and the first protection lightpath, the second protection lightpath will be used to maintain service connectivity and recover the affected traffic. Extending the traditional techniques of 1 + 1 and 1:1 single failure protection, dual failure protection schemes may be proposed for an EON, i.e., 1:1:1, 1+1:1, and 1+1+1. These differ on how spare capacity is reserved for the protection lightpaths. The first "1" always represents a working lightpath, the following "1" represents the first protection lightpath, and the final "1" represents the second protection lightpath. The "+" indicates that the protection lightpath uses dedicated spare capacity while the ":" indicates that the protection lightpath uses shared spare capacity. In the following, we first introduce 1+1:1 protection. This is subsequently followed by the dedicated 1:1:1 and the mixed 1:1:1 protection schemes.

A. 1+1:1 PATH PROTECTION

In 1+1:1 path protection, the first "1" is for the working lightpath, the next "+1" is for the first protection lightpath using dedicated spare capacity, and the final ":1" means that the secondary protection lightpaths share their spare capacity. Thus, 1+1:1 is a protection technique where dedicated protection resources should be assigned on the first protection lightpath while the protection resources on a second protection lightpath can be shared by multiple other second protection lightpaths subject to an additional link-disjoint condition (given later).

Consider the example of 1+1:1 protection in an EON shown in Fig. 1 where we assume that there are two 1+1:1 services (i.e., services between node pairs (3, 4) and (1, 2)). W1 and W2 are the working paths of the two services. The corresponding first and second protection lightpaths of W1 are P11 and P12 for service (3, 4), and that of W2 are P21 and P22 for service (1, 2), respectively. We have dedicated protection capacity on the first protection lightpaths for "+1" but the protection capacity on the second protection lightpaths can be shared for ":1" in the same type with the additional requirement that the corresponding working and first protection lightpaths are not *pairwise joint* in any way. The sharing condition can be mathematically expressed by the following in (1)

$$\overline{(W1 \otimes W2) \cap (P11 \otimes P21)} \cap \overline{(W1 \otimes P21) \cap (P11 \otimes W2)} \tag{1}$$

Here, the symbol $\otimes$ indicates that two lightpaths have common link(s) (i.e., have overlap) and the "$A \cap B$" operation means that the two conditions, A and B, must be simultaneously satisfied. The "NOT" operation on X is defined as $\overline{X}$. Thus, $(W1 \otimes W2)$ means that working lightpaths $W1$ and $W2$ of the two services are joint, and $(W1 \otimes W2) \cap (P11 \otimes P21)$ means that the working lightpaths and the first protection lightpaths of the two services are *pairwise joint* on common links. Finally, (1) implies that the working and first protection lightpaths of the two services are not *pairwise joint* in any way.

In an EON, depending on the actual physical length of the lightpath, different modulation formats may need to be used on different lightpaths. The three lightpaths of a 1+1:1 service may use different modulation formats if they have different physical lengths. To support the same bandwidth, these may then be assigned correspondingly a different number of FSs. As an example in Fig. 1(a), in order to support the same bandwidth, a higher level modulation format (i.e., 8-QAM) and fewer FSs (i.e., 3 FSs) may be used by the working lightpath between node pair (3, 4) because of its shorter distance, and its corresponding first protection lightpath (3-7-8-4) works with a lower level modulation format (i.e., QPSK) and a little more FSs (i.e., 4 FSs) because of its longer distance. For the second protection lightpath (3-9-10-4), the lowest level modulation format (i.e., BPSK) and the most FSs (i.e., 5 FSs) are needed because of its even longer distance. Similar modulation formats and FSs allocation can also be carried out for node pair (1, 2) as shown in Fig. 1(a). Here, the working lightpath (W2), first protection lightpath (P21), and second protection lightpath (P22) have the modulation formats of 8-QAM, QPSK, and QPSK and need 2, 3, and 3 FSs, respectively.

Fig. 1(a) shows an example where there is no spare capacity sharing between the different second protection lightpaths. For 1+1:1 path protection, the protection capacity on each first protection lightpath dedicatedly protects its corresponding working lightpath. As shown in Fig. 1(a), this requires 7 FSs (from 1 to 7) to be reserved on the common link (7-8) traversed by the two first protection lightpaths (3-7-8-4) and (1-7-8-2). Since the corresponding working and first protection lightpaths are *pairwise joint* on links (5-6) and (7-8), respectively, i.e., $(W1 \otimes W2)$ and $(P11 \otimes P21)$, any spectrum resource on the common link (9-10) passed by the two second protection lightpaths (3-9-10-4) and (1-9-10-2) cannot be shared. Thus, on the common link (9-10), 8 FSs (from 1 to 8) would have to be reserved for this.

However, Fig. 1(b) shows a situation where spare capacity is shared on the common link (9-10) traversed by the two second protection lightpaths. Because the working and first protection lightpaths of services (3, 4) and (1, 2) are not *pairwise joint* in any way, the condition stated in (1) is satisfied and the two second protection lightpaths can share protection capacity on their common link(s). This implies that only 5 FSs (from 1 to 5) need to be reserved on link (9-10) traversed by the two second protection lightpaths of the two services.

B. DEDICATED 1:1:1 PROTECTION

Recall that for the dedicated 1:1:1 protection, the first "1" stands for the working lightpath, and the following two ":1" indicate that the primary and secondary protection lightpaths share their spare capacity within the same types. Thus, dedicated 1:1:1 protection allows spare capacity sharing among multiple protection lightpaths in the same categories subject to two additional link-disjoint conditions. The condition of protection resources sharing on the second protection lightpaths is the same as that for the 1+1:1 as given in (1), while the condition of protection resources sharing on the first protection lightpaths is given by (2)

$$\overline{(W1 \otimes W2) \cap (P12 \otimes P22)} \cap \overline{(W1 \otimes P22) \cap (P12 \otimes W2)} \tag{2}$$

Here, $(W1 \otimes W2) \cap (P12 \otimes P22)$ means that the working and the second protection paths of the two services are *pairwise joint*. Thus, (2) implies that the working and second protection paths of the two services are not *pairwise joint* in any way.

The two cases of dedicated 1:1:1 without capacity sharing and with capacity sharing on the second protection lightpaths are the same as that of 1+1:1 protection in Fig. 1. For spare capacity sharing on the first protection lightpath, when the working and second protection lightpaths are *pairwise joint* on common links, the two first protection lightpaths (3-7-8-4) and (1-7-8-2) cannot share spare capacity on their common link (7-8) under dedicated 1:1:1 protection. Thus, 7 FSs (from 1 to 7) are required on this link (note that, as shown in Fig 1(a), link (5-6) carries both W1 and W2, and link (9-10) carries both P12 and P22).

The case of spare capacity sharing on the first protection lightpaths is shown in Fig. 2. Protection capacity can be

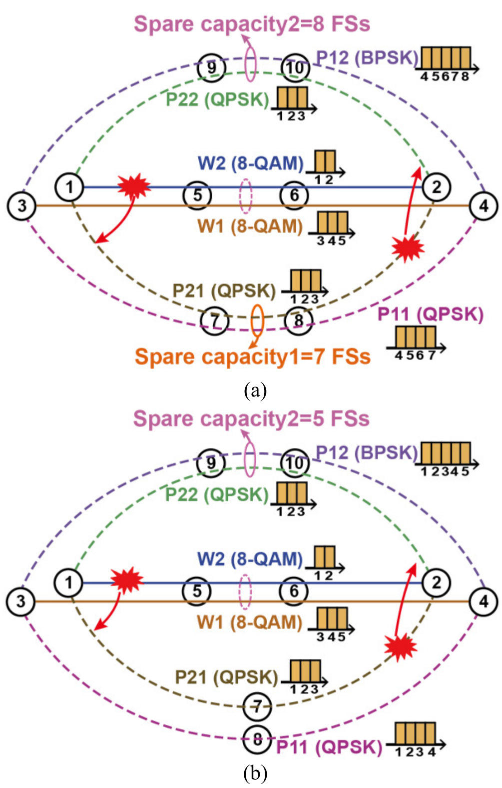

FIGURE 1. **1+1:1 example with/without spare capacity sharing. (a) Without capacity sharing. (b) Capacity sharing on the second protection lightpaths.**

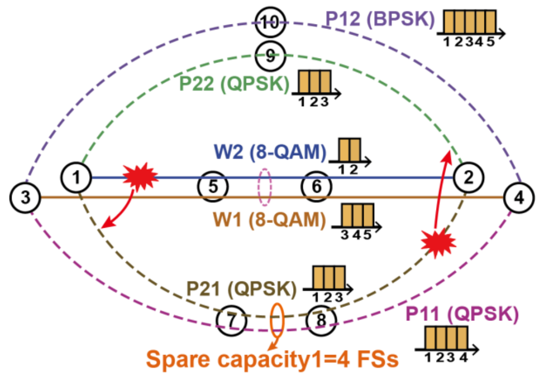

FIGURE 2. **Capacity sharing on the first protection lightpaths.**

shared on link (7-8) traversed by the two first protection lightpaths (3-7-8-4) and (1-7-8-2) as the working and second protection lightpaths of services (3, 4) and (1, 2) are not *pairwise joint* in any way, and therefore condition (2) is satisfied. Here, only 4 FSs (from 1 to 4) need to be reserved on link (7-8). This example effectively illustrates that dedicated 1:1:1 protection can achieve higher spectrum utilization than 1+1:1 protection because of its ability to share spare capacity between the first protection lightpaths.

C. MIXED 1:1:1 PROTECTION

Mixed 1:1:1 protection is an extension of dedicated 1:1:1 protection, which is more flexible in spare capacity sharing and can, therefore, provide higher spare capacity efficiency. Specifically, in addition to spare capacity sharing in the same categories as in dedicated 1:1:1 protection, mixed 1:1:1 protection also allows the protection lightpaths of different categories to share spare capacity. Protection resources on a first protection lightpath can be shared by a second protection lightpath, and vice versa, subject to the constraints imposed by two additional link-disjoint conditions in addition to the conditions of (1) and (2). Mathematically, the two additional sharing conditions are expressed as (3) and (4)

$$\overline{(W1 \otimes W2) \cap (P12 \otimes P21)} \cap \overline{(W1 \otimes P21) \cap (P12 \otimes W2)} \tag{3}$$

$$\overline{(W1 \otimes W2) \cap (P11 \otimes P22)} \cap \overline{(W1 \otimes P22) \cap (P11 \otimes W2)} \tag{4}$$

Here, (3) is the condition for spare capacity sharing between the first protection lightpath (P11) and the second protection lightpath (P22) between two different services. Similarly, (4) is the condition for spare capacity sharing between the second protection lightpath (P12) and the first protection lightpath (P21) between two different services. Mixed 1:1:1 protection contains four types of sharing conditions expressed as conditions (1)-(4).

Fig. 3(a) shows a situation where a first protection lightpath (P11) and a second protection lightpath (P22) can share spare capacity on their common link. For both dedicated and mixed 1:1:1 protection (Figs. 3(a) and (b)), the two second

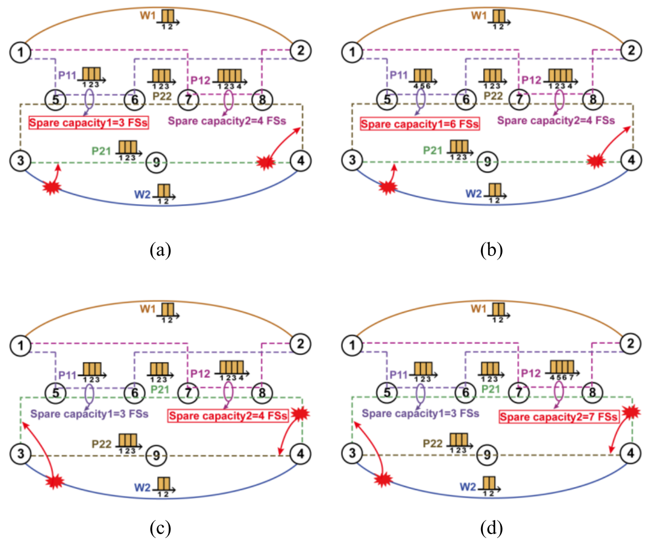

FIGURE 3. **Different capacity sharing of mixed 1:1:1 and dedicated 1:1:1. (a) Mixed 1:1:1 with capacity sharing (P11 and P22). (b) Dedicated 1:1:1 with capacity sharing (P12 and P22). (c) Mixed 1:1:1 with capacity sharing (P12 and P21). (d) Dedicated 1:1:1 with capacity sharing (P11 and P21).**

protection lightpaths (1-7-8-2) and (3-5-6-7-8-4) can share spare capacity on the common link (7-8) as condition (1) is satisfied in this example. Thus, only 4 FSs are reserved on this link. However, it may be noted that the working lightpath (W1) and second protection lightpath (P12) of service (1, 2) and the working lightpath (W2) and first protection lightpath (P21) of service (3, 4) are not *pairwise joint* in any way. As a result, the reserved spare capacity on link (5-6) traversed by P11 and P22 are only 3 FSs (from 1 to 3) under mixed 1:1:1 as shown in Fig. 3(a). However, if dedicated 1:1:1 protection is applied that only allows spare capacity sharing in the same categories in Fig. 3(b), 6 FSs are needed on link (5-6) even though condition (3) is satisfied. Similarly, in Fig. 3(c), the first protection lightpath (P21) and the second protection lightpath (P12) of the two services can share protection resources on their common link (7-8), and 4 FSs (from 1 to 4) are sufficient on this link to achieve 100% failure recovery. This is possible because the working lightpath (W1) and the first protection lightpath (P11) of service (1, 2) and working lightpath (W2) and the second protection lightpath (P22) of service (3, 4) are not *pairwise joint* in any way. Fig. 3(d) shows the case where spare capacity sharing is only allowed in the same categories under dedicated 1:1:1 protection. Therefore, the reserved spare capacity on link (7-8) traversed by P12 and P21 are 7 FSs. This example illustrates that mixed 1:1:1 protection can perform better than dedicated 1:1:1 protection in terms of spare capacity sharing.

IV. ILP DESIGN MODELS FOR DUAL FAILURE PROTECTION

A. PROBLEM STATEMENT

The problem of dual failure protection in an EON considered in this paper can be formally stated as:

Given:

(1) A general EON denoted by a graph $G(\mathrm{V, E})$, where V is the node set and E is the fiber link (bi-directional) set, each of which connects two nodes in V;

(2) A set D of static traffic demands which is given a priori. Each demand $d \in D$ is represented by a tuple (S_d, D_d, R_d), where S_d and D_d are the source and destination nodes of d respectively, and R_d is the requested bandwidth;

(3) A set of modulation formats M ={8-QAM, QPSK, BPSK}.

Find: Three link-disjoint lightpaths over the EON for every transported 1+1:1 or 1:1:1 service, along with their routing paths, subject to the following *assumptions* or *constraints*:

1) TUNABLE TRANSPONDERS

The optical transponders at each node are assumed to be fully tunable. Thus, the working and protection lightpaths of each 1:1:1 or 1+1:1 service may use different FSs.

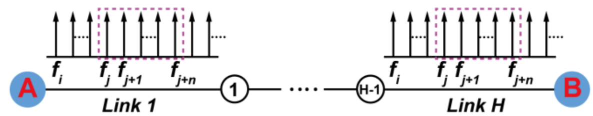

FIGURE 4. **Concepts of spectrum contiguity and spectrum continuity.**

2) SPECTRUM CONTIGUITY AND SPECTRUM CONTINUITY

Spectrum contiguity implies that all the FSs of a particular lightpath must be selected to be spectrally contiguous. For example, Fig. 4 shows a lightpath with contiguous spectrum with frequencies ranging from f_j to f_{j+n} on link 1 using $(n+1)$ FSs. *Spectrum continuity* is additionally required when the network nodes are not capable of doing spectrum conversion. In this case, the contiguous spectra assigned must remain the same over the entire lightpath, i.e., on all links of the lightpath. For this, consider the example shown in Fig. 4, where there is an H-hop path between the source-destination pair (A, B) which needs $(n + 1)$ FSs. In this case, the same contiguous spectra from f_j to f_{j+n} are reserved on each link from 1 to H.

3) MODULATION FORMAT SELECTION

A 1+1:1 or 1:1:1 service is established successfully only if the three link-disjoint lightpaths are established successfully. As mentioned earlier in Section II, it is possible that the three lightpaths may traverse actual physical distances which are sufficiently different so that they need different modulation formats to support the same service bandwidth and hence different number of FSs would be required for each of them. If F is the number of FSs required, B is the bandwidth of each FS, and SE is the spectrum efficiency of the selected modulation format (in units of bits/s/Hz) to support a service bandwidth requirement of R, then the condition $2 \cdot F \cdot B \cdot$

$SE \geq R$ would have to be satisfied. Here the factor of 2 corresponds to the x-polarization and the y-polarization where polarization division multiplexing (PDM) has been applied. The SEs for BPSK, QPSK, and 8-QAM are typically 1, 2, and 3 bit/s/Hz, respectively. If each FS is assumed to have a bandwidth of 12.5 GHz, Table 1 shows the transparent reach of each modulation format and the FS capacity (in multiples of 12.5 GHz).

TABLE 1. FS capacities and optical reaches of different modulation formats [50].

Modulation format	FS capacity (Gb/s)	Transparent reach (km)
BPSK	25	4000
QPSK	50	2000
8-QAM	75	1000

4) SPARE CAPACITY SHARING

When considering dual failure protection, we should ensure 100% failure protection for each service connection and moreover should maximally share spare capacity among multiple second protection lightpaths when sharing condition (1) is satisfied for 1+1:1 protection. For dedicated 1:1:1 protection, all protection lightpaths in the same category should share capacity maximally for each category as long as sharing conditions (1) and (2) are satisfied. Moreover, in addition to (1) and (2), conditions (3) and (4) must also be satisfied in the case of mixed 1:1:1 protection so as to achieve maximal spare capacity sharing.

The optimization problem has the objective of minimizing the maximum number of FSs used in the network. The solution to the problem is the routing and spectrum assignment of each lightpath including the working lightpath, the first protection lightpath, and the second protection lightpath, as well as their spare capacity sharing relationship. Based on the given input parameters and subject to the constraints mentioned earlier, the ILP models for the RSA problem of dual failure protected EONs are presented next. The model for dedicated 1:1:1 protection is presented first followed by the model for 1+1:1 protection. Finally, the model for mixed 1:1:1 protection is introduced.

B. MODEL FOR DEDICATED 1:1:1 PROTECTION

We present here an ILP model for the RSA problem of a dedicated 1:1:1 protected EON. For each dedicated 1:1:1 service, all the available link-disjoint k-shortest path routes are pre-calculated. From these, the first shortest one dedicatedly works for establishing working lightpath. If more than one such first shortest path exists, then any one of them can be randomly chosen. To set up the first and second protection lightpaths, we define two sets called $\boldsymbol{R_d}$ and $\boldsymbol{P_d^b}$ for computational convenience. For each service d, $\boldsymbol{R_d}$ is used to establish the first protection lightpath and it is a set of routes including all the link-disjoint k-shortest routes other than the shortest one. $\boldsymbol{P_d^b}$ is similarly a set from which the second protection lightpath is chosen, where if b is in $\boldsymbol{R_d}$, then it is excluded from $\boldsymbol{P_d^b}$. It follows that each pair of first and second protection lightpaths would be any combination of our considered link-disjoint k-shortest routes except the shortest one. For example, if service d has three link-disjoint routes named $l1$, $l2$, and $l3$, respectively, and they are found by the link-disjoint k-shortest algorithm (we set k maximally to be 100 in this paper so that practically all the candidate routes can be included) and listed according to the length of the routing paths in an ascending order. In this example, $l1$ dedicatedly works as working lightpath of d. The set of protection route pairs for d contains two route pairs that are ($l2$, $l3$) and ($l3$, $l2$). Thus, the successfully established pair of protection lightpaths is one of the two route pairs. Similar to the definitions of sets, parameters, and variables in [20], the sets, parameters, and variables of the ILP model are as follows.

Sets:

- $\boldsymbol{D}$ The set of node pairs in the network.
- $\boldsymbol{R_d}$ The set of the first protection routes between node pair d, each of which is link-disjoint from its corresponding working route.
- $\boldsymbol{P_d^b}$ The set of the second protection routes that can combine with route b ($b \in \boldsymbol{R_d}$) as candidate route-pairs of node pair d, each of which is link-disjoint with its corresponding working and first protection routes.

Parameters:

- F_d The number of required FSs on the working lightpath of node pair d to support the traffic demand between the node pair.
- B_d^a The number of required FSs for the first protection lightpath if a ($a \in \boldsymbol{R_d}$) is chosen as the first protection lightpath for node pair d to support the traffic demand between the node pair.
- $C_d^{a,b}$ The number of required FSs for the second protection lightpath if b ($b \in \boldsymbol{P_d^a}$, $a \in \boldsymbol{R_d}$) is chosen as the second protection lightpath for node pair d to support the traffic demand between the node pair.
- ε_d^t A binary parameter that equals 1 when the working routes of node pairs d and t share a common link; 0, otherwise.
- $\upsilon_d^{t,a}$ A binary parameter that equals 1 when the working route of node pair d and the first protection route a ($a \in \boldsymbol{R_t}$) of node pair t share a common link; 0, otherwise.
- $\tau_d^{t,a,b}$ A binary parameter that equals 1 when the working route of node pair d and the second protection route b ($b \in \boldsymbol{P_t^a}$, $a \in \boldsymbol{R_t}$) of node pair t share a common link; 0, otherwise.
- $\theta_{d,a,m}^{t,b,n}$ A binary parameter that equals 1 when the first protection route a ($a \in \boldsymbol{R_d}$, $m \in \boldsymbol{P_d^a}$) of node pair d and the first protection route b ($b \in \boldsymbol{R_t}$, $n \in \boldsymbol{P_t^b}$) of node pair t share a common link and their corresponding working and second protection routes are also *pairwise joint*; 0, otherwise.

$\lambda_{d,a}^{t,n,b}$ A binary parameter that equals 1 when the first protection route a ($a \in \boldsymbol{R_d}$) of node pair d and the second protection route b ($b \in \boldsymbol{P_t^n}$, $n \in \boldsymbol{R_t}$) of node pair t share a common link; 0, otherwise.

$\gamma_{d,m,a}^{t,n,b}$ A binary parameter that equals 1 when the second protection route a ($a \in \boldsymbol{P_d^m}$, $m \in \boldsymbol{R_d}$) of node pair d and the second protection route b ($b \in \boldsymbol{P_t^n}$, $n \in \boldsymbol{R_t}$) of node pair t share a common link and their corresponding working and first protection routes are also *pairwise joint*; 0, otherwise.

∇ A large value.

Variables:

ϕ_d^a A binary variable that equals 1 if the route a ($a \in \boldsymbol{R_d}$) of node pair d is chosen for first protection lightpath establishment; 0, otherwise.

$\varphi_d^{a,b}$ A binary variable that equals 1 if the route b ($b \in \boldsymbol{P_d^a}$, $a \in \boldsymbol{R_d}$) of node pair d is chosen for second protection lightpath establishment; 0, otherwise.

f^d An integer variable denoting the starting index of the FSs assigned to the working lightpath between node pair d.

$e^{d,a}$ An integer variable denoting the starting index of the FSs assigned to the first protection lightpath a ($a \in \boldsymbol{R_d}$) between node pair d.

$\rho^{d,a,b}$ An integer variable denoting the starting index of the FSs assigned to the second protection lightpath b ($b \in \boldsymbol{P_d^a}$, $a \in \boldsymbol{R_d}$) between node pair d.

x_d^t A binary variable that equals 1 when the starting FS index of working lightpath between node pair d is larger than that of the working lightpath between node pair t, i.e., $f^d > f^t$; 0, otherwise.

$s_d^{t,a}$ A binary variable that equals 1 when the starting FS index of working lightpath between node pair d is larger than that of the first protection lightpath a ($a \in \boldsymbol{R_t}$) between node pair t, i.e.,$f^d > e^{t,a}$; 0, otherwise.

$y_d^{t,a,b}$ A binary variable that equals 1 when the starting FS index of working lightpath between node pair d is larger than that of the second protection lightpath b ($b \in \boldsymbol{P_t^a}$, $a \in \boldsymbol{R_t}$) between node pair t, i.e., $f^d > \rho^{t,a,b}$; 0, otherwise.

$z_{d,a,m}^{t,b,n}$ A binary variable that equals 1 when the starting FS index of the first protection lightpath a($a \in \boldsymbol{R_d}$, $m \in \boldsymbol{P_d^a}$) between node pair d is larger than that of the first protection lightpath b ($b \in \boldsymbol{R_t}$, $n \in \boldsymbol{P_t^b}$) between node pair t, i.e., $e^{d,a} > e^{t,b}$; 0, otherwise.

$M_{d,a}^{t,n,b}$ A binary variable that equals 1 when the starting FS index of the first protection lightpath a ($a \in \boldsymbol{R_d}$) between node pair d is larger than that of the second protection lightpath b ($b \in \boldsymbol{P_t^n}$, $n \in \boldsymbol{R_t}$) between node pair t, i.e., $e^{d,a} > \rho^{t,n,b}$; 0, otherwise.

$N_{d,m,a}^{t,n,b}$ A binary variable that equals 1 when the starting FS index of the second protection lightpath a ($a \in \boldsymbol{P_d^m}$, $m \in \boldsymbol{R_d}$) between node pair d is larger than that of the second protection lightpath b ($b \in \boldsymbol{P_t^n}$, $n \in \boldsymbol{R_t}$) between node pair t, i.e., $\rho^{d,m,a} > \rho^{t,n,b}$; 0, otherwise.

C_{max} The maximum number of FSs used.

Objective:

$$Minimize \quad C_{max} \tag{5}$$

Constraints:

$$\sum\nolimits_{a\in \boldsymbol{R_d}} \phi_d^a = \sum\nolimits_{a\in \boldsymbol{R_d}} \sum\nolimits_{b\in \boldsymbol{P_d^a}} \varphi_d^{a,b} = 1 \;\forall d \in \boldsymbol{D} \tag{6}$$

$$C_{max} \geq f^d + F_d;\ C_{max} \geq e^{d,a} + B_d^a;$$
$$C_{max} \geq \rho^{d,a,b} + C_d^{a,b} \quad \forall d \in \boldsymbol{D}, \forall a \in \boldsymbol{R_d}, \forall b \in \boldsymbol{P_d^a} \tag{7}$$

$$f^t - f^d \leq \nabla \cdot (1 - s_d^{t,a} + 2 - \phi_t^a - v_d^{t,a}) - 1$$
$$\forall d, t \in \boldsymbol{D}, d \neq t \tag{8}$$

$$f^d + F_d - f^t \leq \nabla \cdot (x_d^t + 1 - \varepsilon_d^t) \forall d, t \in \boldsymbol{D}, d \neq t \tag{9}$$

$$e^{t,a} - f^d \leq \nabla \cdot (1 - s_d^{t,a} + 2 - \phi_t^a - v_d^{t,a}) - 1$$
$$\forall a \in \boldsymbol{R_t}, \forall d, t \in \boldsymbol{D}, d \neq t \tag{10}$$

$$f^d + F_d - e^{t,a} \leq \nabla \cdot (s_d^{t,a} + 2 - \phi_t^a - \upsilon_d^{t,a})$$
$$\forall a \in \boldsymbol{R_t}, \forall d, t \in \boldsymbol{D}, d \neq t \tag{11}$$

$$e^{t,a} + B_t^a - f^d \leq \nabla \cdot (1 - s_d^{t,a} + 2 - \phi_t^a - v_d^{t,a})$$
$$\forall a \in \boldsymbol{R_t}, \forall d, t \in \boldsymbol{D}, d \neq t \tag{12}$$

$$\rho^{t,a,b} - f^d \leq \nabla \cdot (1 - s_d^{t,a} + 2 - \phi_t^a - v_d^{t,a}) - 1$$
$$\forall a \in \boldsymbol{R_t}, \forall b \in \boldsymbol{P_t^a}, \forall d, t \in \boldsymbol{D}, d \neq t \tag{13}$$

$$f^d + F_d - \rho^{t,a,b} \leq \nabla \cdot (y_d^{t,a,b} + 2 - \varphi_t^{a,b} - \tau_d^{t,a,b})$$
$$\forall a \in \boldsymbol{R_t}, \forall b \in \boldsymbol{P_t^a}, \forall d, t \in \boldsymbol{D}, d \neq t \tag{14}$$

$$\rho^{t,a,b} + C_t^{a,b} - f^d \leq \nabla \cdot (1 - s_d^{t,a} + 2 - \phi_t^a - v_d^{t,a})$$
$$\forall a \in \boldsymbol{R_t}, \forall b \in \boldsymbol{P_t^a}, \forall d, t \in \boldsymbol{D}, d \neq t \tag{15}$$

$$e^{t,b} - e^{d,a} \leq \nabla \cdot (1 - z_{d,a,m}^{t,b,n} + 3 - \phi_t^b - \phi_d^a - \theta_{d,a,m}^{t,b,n}) - 1$$
$$\forall a \in \boldsymbol{R_d}, \forall m \in \boldsymbol{P_d^a}, \forall b \in \boldsymbol{R_t}, \forall n \in \boldsymbol{P_t^b}, \forall d, t \in \boldsymbol{D}, d \neq t \tag{16}$$

$$e^{d,a} + B_d^a - e^{t,b} \leq \nabla \cdot (z_{d,a,m}^{t,b,n} + 3 - \phi_t^b - \phi_d^a - \theta_{d,a,m}^{t,b,n})$$
$$\forall a \in \boldsymbol{R_d}, \forall m \in \boldsymbol{P_d^a}, \forall b \in \boldsymbol{R_t}, \forall n \in \boldsymbol{P_t^b}, \forall d, t \in \boldsymbol{D}, d \neq t \tag{17}$$

$$\rho^{t,n,b} - e^{d,a} \leq \nabla \cdot (1 - s_d^{t,a} + 2 - \phi_t^a - v_d^{t,a}) - 1$$
$$\forall a \in \boldsymbol{R_d}, \forall n \in \boldsymbol{R_t}, \forall b \in \boldsymbol{P_t^n}, \forall d, t \in \boldsymbol{D}, d \neq t \tag{18}$$

$$e^{d,a} + B_d^a - \rho^{t,n,b} \leq \nabla \cdot \left(M_{d,a}^{t,n,b} + 3 - \varphi_t^{n,b} - \phi_d^a - \lambda_{d,a}^{t,n,b}\right)$$
$$\forall a \in \boldsymbol{R_d}, \forall n \in \boldsymbol{R_t}, \forall b \in \boldsymbol{P_t^n}, \forall d, t \in \boldsymbol{D}, d \neq t \tag{19}$$

$$\rho^{t,n,b} + C_t^{n,b} - e^{d,a} \leq \nabla \cdot \left(1 - M_{d,a}^{t,n,b} + 3 - \varphi_t^{n,b} - \phi_d^a - \lambda_{d,a}^{t,n,b}\right)$$
$$\forall a \in \boldsymbol{R_d}, \forall n \in \boldsymbol{R_t}, \forall b \in \boldsymbol{P_t^n}, \forall d, t \in \boldsymbol{D}, d \neq t \tag{20}$$

$$\rho^{t,n,b} - \rho^{d,m,a} \leq \nabla \cdot (1 - s_d^{t,a} + 2 - \phi_t^a - v_d^{t,a}) - 1$$
$$\forall m \in \boldsymbol{R_d}, \forall a \in \boldsymbol{P_d^m}, \forall n \in \boldsymbol{R_t}, \forall b \in \boldsymbol{P_t^n}, \forall d, t \in \boldsymbol{D}, d \neq t \tag{21}$$

$$\rho^{d,m,a} + C_d^{m,a} - \rho^{t,n,b} \le \nabla \cdot (N_{d,m,a}^{t,n,b} + 3 - \varphi_t^{n,b} - \varphi_d^{m,a} - \gamma_{d,m,a}^{t,n,b})$$
$$\forall m \in \boldsymbol{R_d}, \forall a \in \boldsymbol{P_d^m}, \forall n \in \boldsymbol{R_t}, \forall b \in \boldsymbol{P_t^n}, \forall d, t \in \boldsymbol{D}, d \neq t \quad (22)$$

It is evident that a network will use its resources more efficiently if fewer FSs are required to accommodate all its service demands. This is ensured by objective (5) which minimizes the maximum number of FSs used in the network as this would be the criteria to measure the overall spectrum efficiency of the network.

We can have only one pair of first and second protection lightpaths for any connection; this is ensured by constraint (6). The importance of this constraint lies in the fact that it, in turn, implies that an affected lightpath can be recovered by using only one first or second protection route. Another requirement is that the maximum number of FSs used in the entire network must be no smaller than the ending FS index of the lightpath between any node pair; constraint (7) ensures this. For example, a C_{max} of 50 (i.e., 0-49) would be needed if the highest ending FS index in the whole network is 49. Constraints (8) and (9) together ensure that the spectrum is non-overlapping on any common link shared by the working lightpaths between different node pairs. Therefore, it follows that if the starting FS index of working lightpath A is larger than starting FS index of working lightpath B, then the starting FS index of lightpath A will also have to be higher than the ending FS index of lightpath B. Constraints (10)-(12) are similarly needed to ensure that the allocated spectra for the working lightpath and the first protection lightpath for different node pairs do not overlap on any common link. Similarly, we need constraints (13)-(15) to ensure that the allocated spectra for the working lightpath and the second protection lightpath for different node pairs do not overlap on any common link. We additionally require that the allocated spectra for the first protection lightpaths between different node pairs should not overlap on any common link if their corresponding working and second protection lightpaths are *pairwise joint*; this is ensured by constraints (16) and (17). Any overlap between the allocated spectra for the first and second protection lightpaths between different node pairs on any common link is avoided by ensuring constraints (18)-(20). In addition, constraints (21) and (22) are needed to ensure that there is no overlap on any common link between the allocated spectra for the second protection lightpaths between different node pairs if their corresponding working and first protection lightpaths are *pairwise joint*.

C. MODEL FOR 1+1:1 PROTECTION

The ILP model for 1+1:1 protection can be developed by suitably extending the ILP for dedicated 1:1:1 protection with the same set of constraints from (6) to (22). For the model of 1+1:1 path protection that only allows the second protection lightpaths to share spare capacity, we have the same model sets as those of dedicated 1:1:1 protection. However, since spare capacity sharing is not allowed on the first protection lightpaths under 1+1:1 protection, we can simplify the parameter $\theta_{d,a,m}^{t,b,n}$ and $z_{d,a,m}^{t,b,n}$ as follows.

- $\theta_{d,a}^{t,b}$ A binary parameter that equals 1 when the first protection route a ($a \in \boldsymbol{R_d}$) of node pair d and the first protection route b ($b \in \boldsymbol{R_t}$) of node pair t share a common link; 0, otherwise.
- $z_{d,a}^{t,b}$ A binary variable that equals 1 when the starting FS index of the first protection lightpath a ($a \in \boldsymbol{R_d}$) between node pair d is larger than that of the first protection lightpath b ($b \in \boldsymbol{R_t}$) between node pair t, i.e., $e^{d,a} > e^{t,b}$; 0, otherwise.

Because of the dedicated spare capacity for the first protection lightpath under 1+1:1 protection, if any pair of first protection lightpaths shares common link(s), then $\theta_{d,a}^{t,b}$ equals 1. Similarly, $z_{d,a,m}^{t,b,n}$ can be simplified to $z_{d,a}^{t,b}$. $\theta_{d,a}^{t,b}$ and $z_{d,a}^{t,b}$ are used in constraints (16) and (17) to replace $\theta_{d,a,m}^{t,b,n}$ and $z_{d,a,m}^{t,b,n}$, respectively. Constraints (16) and (17) ensure that the pair of first protection lightpaths does not overlap in their spectra at any time and would also include the case where the corresponding working and second protection lightpaths are mutually *pairwise disjoint* in any way. The above guarantees the important difference between dedicated 1:1:1 protection and 1+1:1 protection, i.e., spare capacity sharing is not allowed for the first protection lightpaths under 1+1:1 protection.

D. ILP MODEL FOR MIXED 1:1:1 PROTECTION

The ILP model for mixed 1:1:1 protection can be obtained by suitably extending the model for dedicated 1:1:1 protection with the same set of constraints from (6) to (22). For the model of mixed 1:1:1 protection, in addition to allowing spare capacity sharing among all protection lightpaths in the same categories, the spare capacity on a first protection lightpath can also be shared by a second protection lightpath, and vice versa. We have the same model sets as those of the dedicated 1:1:1 case. Since spare capacity sharing is not restricted to the same categories, we need to redefine the parameter $\lambda_{d,a}^{t,n,b}$ and $M_{d,a}^{t,n,b}$ as follows.

- $\lambda_{d,a,m}^{t,n,b}$ A binary parameter that equals 1 when the first protection route a ($a \in \boldsymbol{R_d}, m \in \boldsymbol{P_d^a}$) of node pair d and the second protection route b ($b \in \boldsymbol{P_t^n}, n \in \boldsymbol{R_t}$) of node pair t share a common link and the corresponding working and second protection routes of node pair d and the corresponding working and first protection routes of node pair t are also *pairwise joint*; 0, otherwise.
- $M_{d,a,m}^{t,n,b}$ A binary variable that equals 1 when the starting FS index of the first protection lightpath a ($a \in \boldsymbol{R_d}, m \in \boldsymbol{P_d^a}$) between node pair d is larger than that of the second protection lightpath b ($b \in \boldsymbol{P_t^n}, n \in \boldsymbol{R_t}$) between node pair t, i.e., $e^{d,a} > \rho^{t,n,b}$; 0, otherwise.

$\lambda_{d,a,m}^{t,n,b}$ and $M_{d,a,m}^{t,n,b}$ are used in constraints (18)-(20) to replace $\lambda_{d,a}^{t,n,b}$ and $M_{d,a}^{t,n,b}$, respectively. Constraints (18)-(20) ensure that the pair of P1 and P2 can share their spectra if the corresponding working and second protection lightpaths of P1 and the corresponding working and first protection lightpaths of P2 are *pairwise disjoint* in any way. The above guarantees the important difference between mixed 1:1:1 protection and dedicated 1:1:1 protection, i.e., spare capacity sharing is not allowed for the protection lightpaths in different categories under dedicated 1:1:1 protection.

In the above ILP models, for each dual failure protected lightpath service, the working route is fixed, while the two protection routes can be different, chosen from two predetermined route sets $\boldsymbol{R_d}$ and $\boldsymbol{P_d^b}$, respectively, by the ILP models. In addition, the computational complexities of all the models are the same and given as follows: the dominant number of variables is $O(|R_1|^2 \cdot |R_2|^2 \cdot |D|^2)$ and the dominant number of constraints is also $O(|R_1|^2 \cdot |R_2|^2 \cdot |D|^2)$, where $|R_1|$ is the total number of routes in $\boldsymbol{R_d}$, $|R_2|$ is the total number of routes in $\boldsymbol{P_d^b}$, and $|D|$ is the total number of traffic demands in the whole network.

V. HEURISTIC ALGORITHMS FOR SUB-OPTIMAL DESIGN

The ILP models will find optimal solutions to the RSA problems in dual failure protected EONs. Since these are NP-complete, for large or even reasonably sized networks, it would be computationally difficult to solve the ILP models to obtain an optimal solution within a reasonable time. Therefore, we develop efficient heuristic algorithms for the RSA problem of dual failure protected EON.

A. RELATED CONCEPTS

Assume that each source-destination pair requests an integer bandwidth R, based on which we can calculate the number of required FSs by using $F = \lceil R/(2 \cdot B \cdot SE) \rceil$. These F FSs are required to meet the constraints of *spectrum contiguity and continuity* along a lightpath. For this, we introduce a concept called spectrum window (SW) as in [51], which is made up of a certain number of continuous FSs. The size F of an SW is related to the user bandwidth requests and modulation formats. For example, S FSs are assigned per fiber link in an EON, and there are $S - x + 1$ SWs for a certain lightpath with x FSs. Note that x is different for different node pairs and different lightpaths. In the example of Fig. 5 (a), assume that each fiber link contains $S = 28$ FSs. As a result, there are a total of 25 (28-4+1) spectrum windows with the size of $x = 4$ (i.e., SW 0-SW 24) in the fiber link. In dual failure protection, for the working lightpath and "+1" protection, a SW is considered available only if all its F FSs are free as in Fig. 5(b). Therefore, if we consider the occupation status of each FS, there are only three SWs available, i.e., SW 0, SW 8, and SW 24. For ":1" protection of dual failure techniques, a SW is considered available if all its F FSs are free or are sharable as shown in Fig. 5(c). Therefore, if we consider the occupation status of each FS, there are four SWs available, i.e., SW 0, SW 8, SW 9, and SW 24.

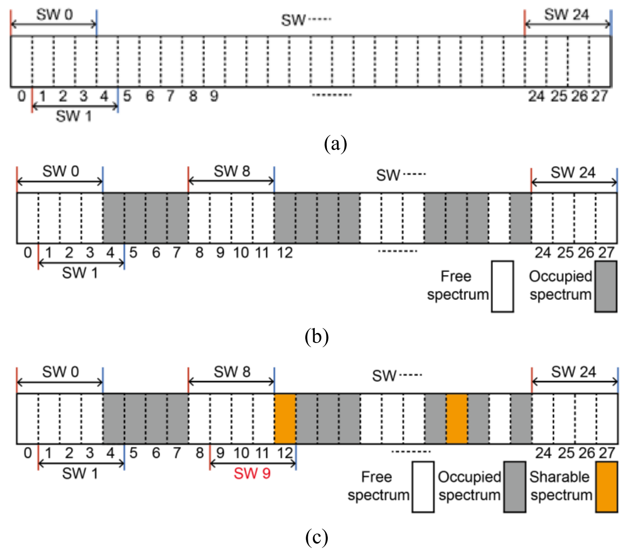

FIGURE 5. Spectrum windows (SWs) in a fiber link.

Based on the concept of SW, we then define a concept called *spectrum window plane* (SWP) [51] as shown in Fig. 6. In an EON, each SWP corresponds to an SW. We use *startindex* and *endindex* to denote the index of the starting and ending FSs assigned on each SWP, respectively. For example, in Fig. 6, one plane (layer) corresponds to a SW, e.g., layer 0 corresponds to SW 0. In each layer, a network virtual topology is constructed (e.g., n6s8 network in Fig. 6), wherein links are deleted from an original topology if corresponding SWs are not free on fiber links. For example, in Fig. 5(b) there are 25 SWs, so 25 spectrum window planes (i.e., layer 0 to layer 24) can be built. However, because only SW 0, SW 8, and SW 24 are available on the fiber link in Fig. 5(b), corresponding virtual links are only available on layers 0, 8, and 24.

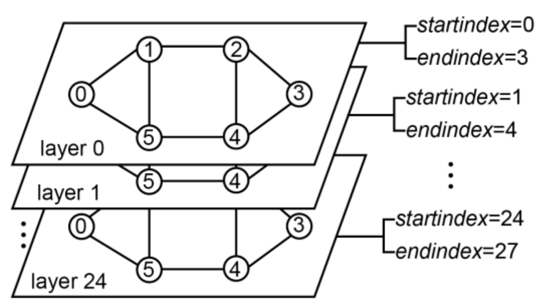

FIGURE 6. Spectrum window planes (SWPs) of the n6s8 network.

In addition, as in [51], we introduce a multi-iteration process to evaluate multiple shuffled demand sequences and choose the demand sequence with the best performance (i.e., to minimize the maximum number of FSs used in this paper) in order to handle the issue that of getting different performances because of different demand orders. A "shuffled demand sequence" is referred to as a list of dual failure services which is obtained by randomly shuffling an initial demand list.

B. INTRODUCTION OF HEURISTIC ALGORITHMS

For the heuristic algorithms, two main phases are taken to solve the RSA problem of dual failure protection. In the first phase, a working lightpath is dynamically established based on the concept of SWP. In the second phase, an optimal pair of first and second protection lightpaths is chosen from a predetermined route pair set based on the concept of SW. Only if all the three lightpaths are successfully established, can the service be considered successfully provisioned. When establishing all the lightpaths, we will increase the number of used FSs until each of them can be established.

Based on the concept of SWP, we first adaptively find a working lightpath for each request taking into account the SW availability on each link and an acceptable modulation format. Based on the concept of SW, we choose an optimal pair for the first protection and second protection routes from a predetermined route-pair set ***RP*** which consists of all combinations of the remaining link-disjoint routes after finding the working lightpath. As in [24], we also propose a *least cost* (*LC*) strategy for maximal protection capacity sharing among all available SWs. This is motivated by the observation that the cost of a link for protection path selection should go down if there are more protection lightpaths sharing that link. If the link is unused (i.e. has not yet been used for a protection lightpath) then its cost for sharing purposes should just be equal to its physical distance. For a link j, we quantify this as C_j given by (23)

$$C_j = \sum_{i=1}^{F} (d_j/F)/(m_i+1) \quad (23)$$

where d_j is the physical length of link j, F is the number of FSs of the SW, and m_i is the total number of protection lightpaths that share the i^{th} FS. This is a reasonable choice for setting the cost of sharing when the objective is to maximally share protection capacity, as that would correspondingly keep more free capacity in reserve for handling future connections in the network. Finally, we try all the route pairs in ***RP*** based on the current spectrum usage status to choose a route pair with the *least cost* by minimizing as in (24)

$$\arg\min_{r} \sum (r^1_{cost} + r^2_{cost}) \quad (24)$$

where r^1_{cost} and r^2_{cost} represent the costs of the two routes of a route pair r in ***RP***, respectively. In the following part, we introduce the heuristic algorithm of dedicated 1:1:1 protection followed by that of 1+1:1 protection and mixed 1:1:1 protection.

C. HEURISTIC ALGORITHM FOR DEDICATED 1:1:1 PROTECTION

We use two variables *w_path* and *w_startindex* to store the information on the successfully established working lightpath and its starting FS index, respectively. When choosing the pair of first protection and second protection lightpaths, for each route pair r in ***RP***, the three variables r^i_{route}, r^i_{index}, and r^i_{cost} are defined. Specifically, r^i_{route} is used to record the information of the successfully established first protection lightpath ($i = 1$) or second protection lightpath ($i = 2$), r^i_{index} is used to record the starting FS index assigned on the first protection lightpath ($i = 1$) or on the second protection lightpath (i = 2), and r^i_{cost} is used to record the route cost of the first protection lightpath ($i = 1$) or of the second protection lightpath ($i = 2$). Based on the concepts of SWP and SW, we present the heuristic algorithm for solving the dedicated 1:1:1 RSA problem as follows.

In the above algorithm, the steps for establishing the working lightpath are similar to those of our previous paper [24]. We minimize the maximum FSs used in the network subject to the condition that all the 100% dual link failure protected requests are served. The maximum number of FSs required in the network will be increased by one if no eligible working route can be found even after trying all the modulation formats. We then repeat the same searching and assignment process for the working lightpath once again.

For establishing the protection lightpaths with the concept of SW, the pair of protection lightpaths can be different, chosen from a predetermined route pair set ***RP*** which is calculated after establishing the working lightpath. When choosing a protection route pair, protection resource sharing is allowed on the two protection lightpaths in the same categories as long as the sharing conditions (1) and (2) are satisfied. The link cost is calculated by equation (23), rather than as simply the hop counts as was done for the working lightpath. We then use (24) to choose an optimal route pair with *least cost* from all route pairs for each node pair. If no route pair in ***RP*** is able to provide sufficient capacity for protection lightpath establishment, we will increase the maximum number of FSs used in each fiber link and then repeat the same process as before (lines 25-44).

After all the lightpath services are provisioned, we will record the number of FSs used and the sum of spare capacity reserved for the protection lightpaths. The SWP-based heuristic algorithm can perform efficiently as it considers all SWPs for the working lightpath, and all possible SWs and eligible pairs of protection routes with the *least cost* strategy. It is also efficient in allowing optimal spare capacity sharing between protection lightpaths in the same categories as long as the sharing conditions (1) and (2) are satisfied.

The computational complexity of the heuristic algorithm is discussed as follows. For setting up the working lightpath (lines 2-23), line 5 removes all unavailable SW links on each SWP, which correspond to a computational complexity of $O(|W| \cdot |L|)$. Here, $|W|$ is the number of FSs used in each fiber link and $|L|$ is the total number of network links. The complexity of the shortest path searching algorithm in line 7 dominates the computational complexity of lines 6-19. Since it is possible that all the SWPs may have to be scanned, its computational complexity is $O(|W| \cdot |N|^2)$, where $|N|$ is the total number of network nodes. As a result, the overall computational complexity of lines 3-19 is $O(|W| \cdot (|L| + |N|^2))$. Since multiple types of modulation formats are considered in the *for-loop* in line 2, the overall computational complexity of establishing a working lightpath is therefore

Algorithm 1 SWP-Based Heuristic Algorithm for Dedicated 1:1:1 RSA Problem

Input: a network topology $G(V, E)$ and a shuffled demand sequence $\boldsymbol{D}$.

1: **For** each demand request in $\boldsymbol{D}$ **do**
{*Phase 1: Setting up working lightpath*}
2: **For** each modulation format (MF) with a specific SE (from 8-QAM to BPSK in Table 1) **do**
3: Decide the number of FS for each SWP based on the modulation format as $F = \lceil R/(2 \cdot B \cdot SE)\rceil$;
4: Create the corresponding certain number of SWPs, each of which has F FSs;
5: Remove all the links from each of the SWPs if the corresponding SWs are not available, i.e., not all the F continuous FSs are free;
6: **For** each SWP (from the lowest to highest index) **do**
7: Use Dijkstra's algorithm to find a shortest route P_w based on distance;
8: **If** P_w is found and the distance of P_w is shorter than the transparent reach of the current MF **then**
9: **If** $w\_path == NULL$ **then**
10: $w\_path \leftarrow P_w$, $w\_startindex \leftarrow$ starting index of current SWP;
11: **Else**
12: **If** the number hops of P_w is smaller than that of w_path **then**
13: $w\_path \leftarrow P_w$, $w\_startindex \leftarrow$ starting index of current SWP;
14: **End if**
15: **End if**
16: **Else**
17: Move to next SWP;
18: **End if**
19: **End for**
20: **If** $w\_path == NULL$**then**
21: Move to next MF;
22: **End if**
23: **End for**
{*Phase 2: Setting up an optimal pair of protection lightpaths*}
24: Employ link-disjoint k-shortest algorithm to find all eligible paths that are link disjoint from *w_path*, then make a combination of two using all the eligible paths found to constitute a new set called protection route pairs ($\boldsymbol{RP}$);
25: **For** each candidate route pair r in $\boldsymbol{RP}$ **do**
26: **For** each route r^i_{route} of r (i from 1 to 2) **do**
27: Calculate the required number of FSs of r^i_{route} based on its MF as $F = \lceil R/(2 \cdot B \cdot SE)\rceil$. Create a list of SWs, each of which has F FSs;
28: r^i_{cost} is initiated to be ∞;
29: **For** each SW (from the lowest to highest index) **do**
30: **If** the SW on each link of r^i_{route} is available (all the continuous F FSs are free or sharable) **then**
31: Calculate route cost of r^i_{route} using (23), defined as C^i_r;
32: **If** $C^i_r < r^i_{cost}$ **then**
33: r^i_{index} ←starting index of current SW, $\leftarrow r^i_{cost} C^i_r$;
34: **End if**
35: **Else**
36: Move to next SW;
37: **End if**
38: **End for**
39: **If** $r^i_{cost} == \infty$ **then**
40: Try next candidate route pair in $\boldsymbol{RP}$;
41: **End if**
42: **End for**
43: **End for**
44: Find an optimal pair of protection routes with the *least cost*from $\boldsymbol{RP}$ using (24);
45: **End for**

$O(|M| \cdot |W| \cdot (|L| + |N|^2))$, where $|M|$ is the total number of considered modulation formats. Lines 24-44 are the steps of choosing an optimal pair of protection lightpaths. We first find all the remaining link-disjoint routes ($\boldsymbol{R_d}$) excluding the established working lightpath, which corresponds to a computational complexity of $O(|K| \cdot |N|^2)$. $|K|$ is the number of $\boldsymbol{R_d}$. Each pair of first and second protection lightpaths is any combination of all routes in $\boldsymbol{R_d}$. We then check all the eligible protection route pairs in the route pair set $\boldsymbol{RP}$ to choose an eligible pair of protection lightpaths with the *least cost* strategy. For each route of a route pair, the computational complexity is $O(|W| \cdot |L_i|)$ taken for the *least cost* calculation, where $|L_i|$ is the total number of links traversed by r^i_{route}. Thus, the total computational complexity for establishing the first and second protection lightpaths is $O(|K| \cdot |N|^2 + 2 \cdot |RP| \cdot |W| \cdot |L_i|)$, where $|RP|$ is the total number of protection route pairs.

D. HEURISTIC ALGORITHM FOR 1+1:1 PROTECTION

An SWP-based heuristic algorithm for 1+1:1 can be obtained by modifying the heuristic algorithm for dedicated 1:1:1. Here, the only difference is that there is no protection capacity sharing on the first protection lightpath and for the second protection lightpath capacity sharing, only condition (1) is required. Thus, for the case of 1+1:1 protection, the steps of establishing the working lightpath are the same as those of dedicated 1:1:1. We use the same approach to find all the protection route pairs and then employ (23) and (24) to calculate the total cost of each route pair. It should be noted that for the first protection route, because of dedicated protection, m_i will equal zero. The route pair with the lowest cost will be selected to establish the first and second protection lightpaths.

E. HEURISTIC ALGORITHM FOR MIXED 1:1:1 PROTECTION

Mixed 1:1:1 protection is more flexible as it can also consider the additional cases where spare capacity on a first protection lightpath can be shared by a second protection lightpath, and vice versa. Its heuristic algorithm is similar to that for the dedicated 1:1:1 protection. The only difference is that when sharing spare capacity among different categories of protection lightpaths, we also need to consider conditions (3) and (4) in addition to conditions (1) and (2).

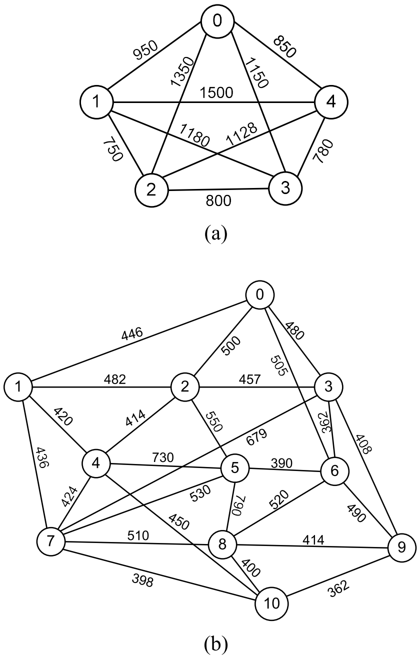

FIGURE 7. **Test networks. (a) 5-node, 10-link n5s10 network. (b) 11-node, 26-link COST239 network.**

VI. TEST CONDITIONS AND PERFORMANCE ANALYSES

A. TEST CONDITIONS

To evaluate the performance of the ILP models and the proposed SWP-based heuristic algorithms, we consider two test networks, a 5-node, 10-link (n5s10) network and an 11-node, 26-link (COST239) network as shown in Fig. 7. The link distance (in km) is shown next to each link. These two networks are highly connected to ensure that three link-disjoint routes can be found for any source-destination node pair such that working, first protection and second protection lightpaths can be established to support dual failure protection. Three modulation formats (i.e., BPSK, QPSK, and 8-QAM) are assumed to be used for the working lightpath and the two protection lightpaths.

Our traffic demand scenario is a static one where we assume that the traffic demand between each node pair is uniformly distributed over [200, X] Gb/s with X as the value of the maximum traffic demand. In our simulation studies, we select X randomly to be one of 400, 600, 800, 1000, and 1200. Given the bandwidth request thus obtained, we find the number of required FSs for the working, first protection, and second protection lightpaths depending on how these are routed and the corresponding route length if those routes are chosen to establish the lightpaths, i.e., the parameters F_d, B_d^a, and $C_d^{a,b}$. In addition, the list of demands (or node pairs) is shuffled many times (1000 times for n5s10 and 100 times for COST239), and the heuristic algorithm is run for each of demand sequences obtained by this shuffling. We use the minimum number of FSs obtained through this shuffling.

The candidate routes used for the ILP model were obtained based on the link-disjoint k-shortest path algorithm, in which the shortest route is used for the working lightpath, and the remaining routes are used for the first and second protection lightpaths as chosen by the ILP model. The ILP models were solved on a 64-bit machine with 2.4-GHz CPU and 8-GB memory using the commercial software AMPL/Gurobi (version 5.0.0) [53]. For the n5s10 test network, the longest solution time of ILP models is about 40,000 seconds among all the test cases and all the dual failure protection techniques. However, we could not obtain the ILP result for COST239 within a reasonable time due to its large size. Thus, we have only employed the heuristic algorithms to find sub-optimal solutions. The longest execution time among all heuristic algorithms is about 1003 seconds for n5s10 (1000 times) and 177 seconds for COST239 (100 times) for all the test cases and dual failure protection techniques.

For comparison, an adaptive routing (AR) algorithm which is extended from [52], was considered for evaluating the efficiency and comparing it with our proposed SWP-based heuristic algorithm. In the AR algorithm, the three lightpaths of a request are chosen adaptively based on the physical topology and the current link state of the network. To efficiently share protection capacity, we reuse the cost equation (23) to calculate the cost of each fiber link, where F equals the number of FSs in each fiber link, instead of the number of FSs of each SW, and i must start from 1. For spectrum assignment, we use the *least-cost* spectrum assignment strategy to maximally share protection capacity. Specifically, given a route r, for each eligible SW, we first use (23) to calculate the sum cost of all the links traversed by the route, and then choose an optimal SW with the least cost from all eligible SWs to assign the corresponding spectrum to r. The detailed calculation is given by (25) and (26).

$$C\left(w\right) = \sum_{j=1}^{L_r} \sum_{i=s_w}^{e_w} \left(d_j / \left(e_w - s_w + 1\right)\right) / \left(m_i + 1\right) \quad (25)$$

$$\mathrm{w_l} = \underset{w}{\operatorname{argmin}}\, C\left(w\right) \quad (26)$$

where w corresponds to an SW, s_w is the starting FS index of SW w, e_w is the ending FS index of SW w, and L_r is the total number of traversed links of route r. $\sum_{i=s_w}^{e_w} \left(d_j / \left(e_w - s_w + 1\right)\right) / \left(m_i + 1\right)$ finds the cost of link j on route r. Thus, (25) calculates the total cost of SW w along route r. Eq. (26) then finds the SW w_l that has the lowest cost.

In addition, for 1:1:1 services, to enable spare capacity sharing among of the first protection lightpaths, we need to know the route information of the second protection lightpaths so as to determine whether the sharing conditions (i.e., (2)-(4)) are satisfied. For this, we employ the strategy applied in [35]. Specifically, we first establish a 1+1:1 service, during which we ensure spare capacity sharing among the second protection lightpaths. Then without changing the route of the first protection lightpath, we release its assigned spectrum and re-assign it based on the above *least-cost* spectrum assignment strategy subject to the route information of the working and second protection lightpaths. We call this adaptive routing algorithm as the *AR Algorithm*. The detailed pseudocode of this algorithm is shown in Appendix A.

B. MAXIMUM NUMBER OF FREQUENCY SLOTS USED

In this section, we evaluate the maximum number of FSs used for accommodating all the lightpath services under 1:1:1, 1+1:1, and 1+1+1 protection. For the case of 1:1:1 protection, we consider separately the two subcases, i.e., dedicated 1:1:1 protection and mixed 1:1:1 protection. In Figs. 8(a)-(d), the legends "ILP," "SWP," and "AR" correspond to the results of the ILP model, SWP-based heuristic algorithm, and AR algorithm, respectively. The legends "D_1:1:1" and "M_1:1:1" correspond to the cases of dedicated and mixed 1:1:1 protection, respectively. The x-axis corresponds to the maximum amount of traffic demand in units of Gb/s between each node pair, i.e., X in the notation for the range of random traffic demand [200, X] Gb/s. The y-axis corresponds to the maximum number of frequency slots used, i.e., C_{max} in (5).

Figs. 8(a)-(d) indicate that the number of FSs used increases with increasing lightpath traffic demand. This is owing to the linear relationship between required FSs and traffic demand requested of each node pair. Figs. 8(a) and (c) compare the maximum number of FSs used by different approaches for dedicated 1:1:1, 1+1:1, and 1+1+1 protection. Note that results for the ILP models in COST239 are not shown due to its high computational complexity. We can observe that the 1+1+1 approach has the largest number of FSs, while the 1:1:1 approach has the smallest number of FSs, and the 1+1:1 approach lies in between. This reflects the protection resource sharing capabilities of the three protection approaches. 1+1+1 does not allow protection capacity sharing in any way. However, 1+1:1 approach allows the second protection lightpaths to share spare capacity with each other. The dedicated 1:1:1 scheme also allows the first protection lightpaths to share their protection resources. Thus, the dedicated 1:1:1 is the most flexible and requires the smallest number of FSs. Also, we see that, for all the schemes, including the ILP models in n5s10 network, the SWP-based algorithms, and the AR algorithms, the proposed SWP-based algorithms are very efficient as they perform very close to the ILP models in the n5s10 network. Specifically, the minimum and maximum percentage gaps between SWP-based heuristic algorithms and ILP models are 0% and 8%, respectively, which therefore verifies the efficiency of the proposed algorithms. However, for both n5s10 and COST239 networks, compared to the AR algorithms, the SWP-based algorithms can achieve much better performance by requiring a much smaller number of FSs. This is reasonable because even though the AR algorithm can adaptively search for the shortest cost routes for establishing the first

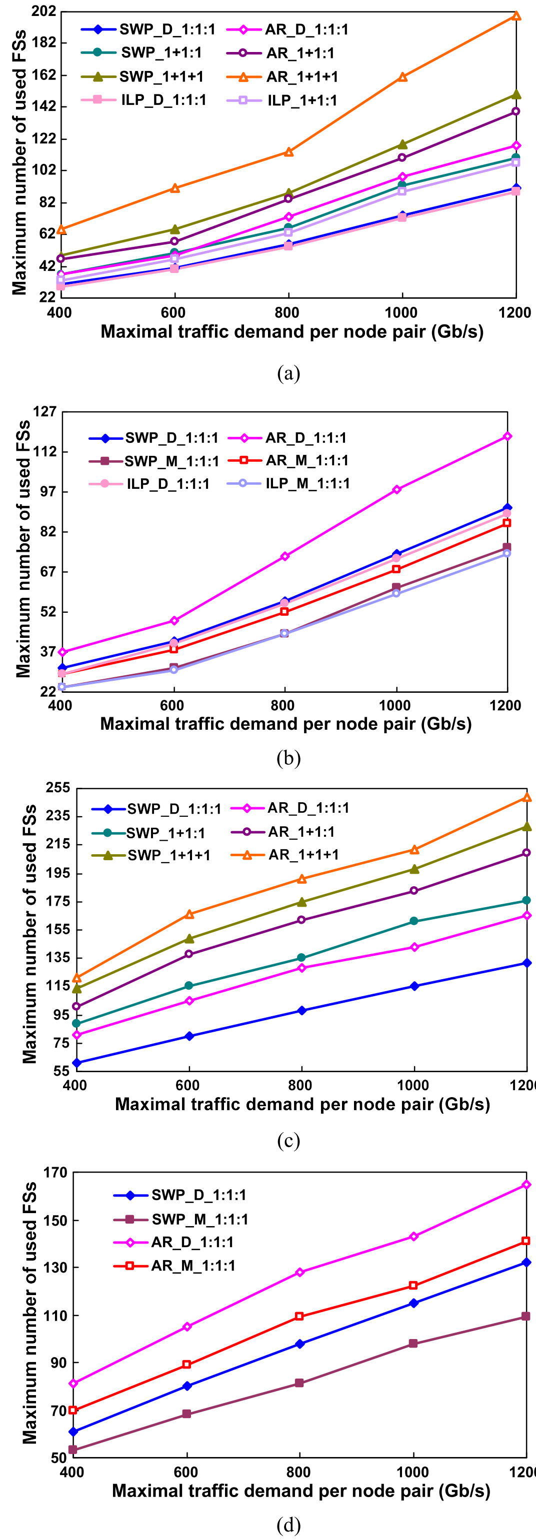

FIGURE 8. Maximum number of FSs used by different protection techniques. (a) n5s10 (Dedicated 1:1:1). (b) n5s10 (Mixed and dedicated 1:1:1). (c) COST239 (Dedicated 1:1:1). (d) COST239 (Mixed and dedicated 1:1:1).

and second protection lightpaths, the route selection is not based on each SWP; moreover, the spectrum resource sharing on the first protection lightpath is realized only after establishing the second protection lightpath following the

1+1:1 strategy. This does not allow the first protection lightpath to change its route when implementing sharing. All these therefore detrimentally affect the overall spectrum resource utilization. In contrast, the ILP model and the SWP-based heuristic algorithm always choose the optimal route pair with the *least cost* (as equation (24)) from a route-pair set based on the current spectrum usage status, thereby minimizing the maximum number of FSs used.

Figs. 8(b) and (d) shows the results for the two subcases of 1:1:1 protection: a) dedicated 1:1:1 that only allows spare capacity in the same categories; b) mixed 1:1:1 that also allows spare capacity sharing across different categories. We find that the mixed 1:1:1 approach can perform better than the dedicated 1:1:1 one in terms of lower values of the maximum number of FSs used; this is observed under both the SWP-based algorithm and the AR algorithm. The reason for this observation is attributed to greater flexibility of the mixed approach that allows spare capacity sharing between the first protection and second protection lightpaths, in addition to sharing among the same categories as for the dedicated 1:1:1 approach.

C. SPARE CAPACITY REDUNDANCY

Figs. 9(a)-(d) show the results of *spare capacity redundancy* which is defined as the ratio of the total protection capacity to the total working capacity in the whole network. In Figs. 9(a) and (c), the legend "Sj1" represents spare capacity redundancy of the first protection lightpath, the legend "Sj2" represents that of the second protection lightpath. The legend "Sj_D_1:1:1" corresponds to the total spare capacity redundancies of Sj1 and Sj2 under dedicated 1:1:1 protection. The legends "Sj_1+1:1" and "Sj_1+1+1" correspond to the total spare capacity redundancies of Sj1 and Sj2 under the 1+1:1 and 1+1+1, respectively. In Figs. 9(b) and (d), the legend "SWP_M" corresponds to the total spare capacity redundancies of Sj1 and Sj2 for the mixed 1:1:1 case under the SWP-based algorithm and the legend "SWP_D" corresponds to the case of dedicated 1:1:1 protection under the SWP-based algorithm. Similarly, the legends "AR_M" and "AR_D" correspond to the two subcases for 1:1:1 under the AR algorithm. For mixed 1:1:1, if an FS is first used as protection capacity by a first protection lightpath, we consider it as the first protection lightpath capacity Sj1 even if it is later shared by a second protection lightpath; similarly, if an FS is first used as protection capacity by a second protection lightpath, we consider it as the second protection lightpath capacity Sj2.

For both test networks and all protection algorithms, Figs. 9(a) and (c) show that the spare capacity redundancy of the 1+1+1 approach is the highest, while that of the dedicated 1:1:1 approach is the lowest, and that of the 1+1:1 approach is in between. This is in line with the results of a maximum number of FSs used discussed earlier in part *B*. Once again, this occurs because of different spare capacity sharing capabilities of the three protection schemes. Dedicated 1:1:1 protection allows the two protection lightpaths

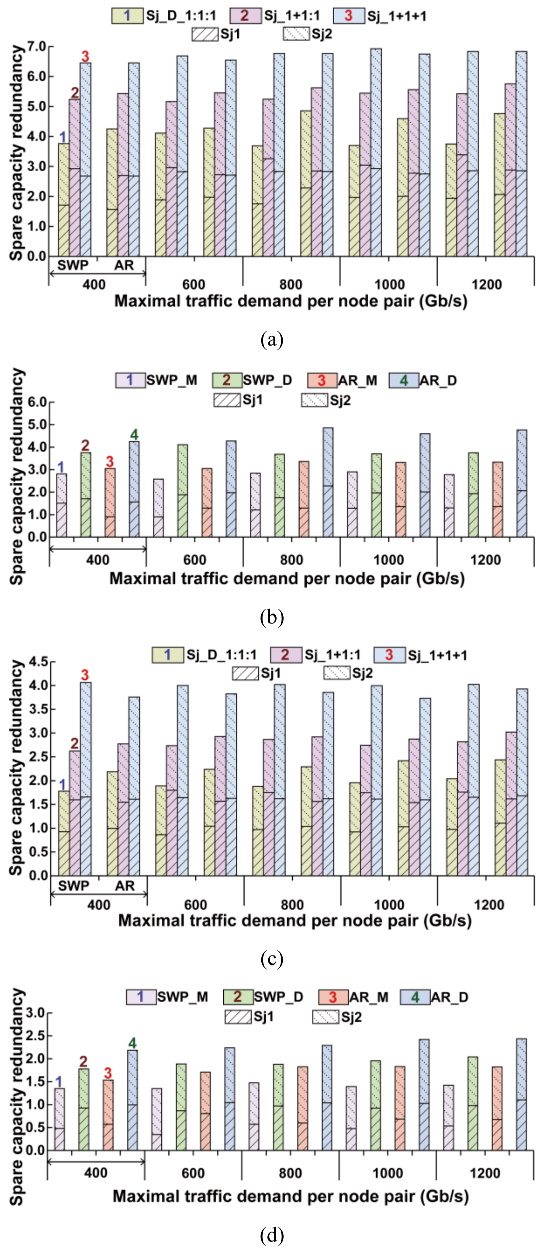

FIGURE 9. Spare capacity redundancies of different protection schemes under different maximal traffic demands per node pair. (a) n5s10 (Dedicated 1:1:1). (b) n5s10 (Mixed and dedicated 1:1:1). (c) COST239 (Dedicated 1:1:1). (d) COST239 (Mixed and dedicated 1:1:1).

to share protection resources in the same categories, which enables it to have the lowest spare capacity redundancy. 1+1:1 only allows second protection lightpaths to share protection resources, which requires more protection resources to be reserved for the first protection lightpaths and therefore a higher spare capacity redundancy. As no spare capacity sharing is allowed for 1+1+1 protection, its spare capacity redundancy is the highest.

In Figs. 9(b) and (d), we can observe that the mixed 1:1:1 case has a lower spare capacity redundancy than the dedicated 1:1:1 case. This is because the former allows spare capacity sharing in different categories in addition to the same categories, which leads to a more efficient spare capacity utilization.

VII. CONCLUSION

For a dual failure protected EON, we explored the 1:1:1, 1+1:1, and 1+1+1 path protection techniques with an adaptive modulation scheme. For the related RSA problem, we developed ILP models and SWP-based heuristic algorithms. By comparing the maximum number of FSs used and spare capacity redundancy, we find that the proposed SWP-based algorithms are efficient enough to perform very close to the ILP models and to significantly outperform the benchmark AR algorithms. In addition, compared with the 1+1:1 and 1+1+1 techniques, the 1:1:1 approach shows the best capacity efficiency in terms of the lowest values of the maximum number of FSs used and lowest spare capacity redundancy because of its ability to share spare capacity between the first and second protection lightpaths. Moreover, comparing the two subcases of 1:1:1, we find that mixed 1:1:1 protection can perform even better than dedicated 1:1:1 protection because it allows spare capacity sharing even between protection lightpaths in different categories.

APPENDIX A

We divide the AR algorithm into three steps, i.e., establishing the working lightpath, then the first protection lightpath, and finally the second protection lightpath. For 100% dual failure protection, the three lightpaths must be link-disjoint. When establishing each of the lightpaths, the maximum number of FSs required in the network will be increased by one in case an eligible working, first protection, or second protection route cannot be found after scanning all the modulation formats. We then repeat the same searching and assignment process for each of the lightpaths once again. The main steps for 1+1:1 service are listed below.

- Step 1 Get the network topology and traffic demand.
- Step 2 *Establishing working lightpath*: For each modulation format (MF) with a specific *SE* (from 8-QAM to BPSK in Table 1). Decide the required number of FS based on the modulation format as $F = \lceil R/(2 \cdot B \cdot SE) \rceil$. Search for a first eligible shortest route (R_w) that is within the transparent reach of a considered MF. Assign corresponding spectrum resource for R_w and then use R_w to establish the working lightpath.
- Step 3 *Establishing first protection lightpath*: Because it is based on 1+1 path protection, this step is similar to Step 2.
- Step 4 *Establishing second protection lightpath*: For each of the MFs, calculate the required number of FSs based on the modulation format as $F = \lceil R/(2 \cdot B \cdot SE) \rceil$. Then search for an eligible protection route with the lowest cost (i.e., with maximal protection capacity sharing) and within the transparent reach of the considered MF; establish the second protection lightpath on the route if continuous F FSs are satisfied with least cost spectrum assignment strategy (as per equations (25) and (26)). Note that protection resource sharing is allowed as long as the sharing condition of (1) is satisfied.

For a dedicated 1:1:1 service, the steps of establishing the working and second protection lightpaths are the same as those for 1+1:1. For establishing the first protection lightpath without changing its route from the way it was established using the 1+1:1 strategy, we first release its assigned spectrum and then re-assign it based on the above *least-cost* spectrum assignment strategy subject to the route information of the working and second protection lightpaths.

For mixed 1:1:1 service, its heuristic algorithm is similar to that for dedicated 1:1:1 protection. The only difference is that when sharing spare capacity among different categories of protection lightpaths, we also need to consider conditions (3) and (4) in addition to (1) and (2).

VIII. ACKNOWLEDGMENT

Part of this paper (focusing on 1+1:1) has been presented on ICNC 2016 [54].

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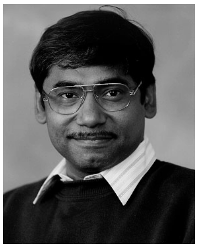

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