Routing and Spectrum Assignment for 1+1:1 Lightpath Services in Elastic Optical Networks

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Abstract—This paper extends single failure to dual failure recovery for an elastic optical network (EON) with 1+1:1 network protection. The issue of routing and spectrum assignment (RSA) is studied with objective of minimizing the maximal number of frequency slots (FSs) used. The key principle for protection capacity sharing among second protection lightpaths is identified. An Integer Linear Programing (ILP) model and a spectrum window plane (SWP)-based heuristic algorithm are developed for RSA of 1+1:1 protected EON. Simulation results show that the proposed SWP-based algorithm can achieve better capacity utilization than the shortest-path (SP) algorithm and is almost as efficient as the ILP model.

Keywords—spectrum window plane; 1+1:1; dual failure recovery; routing and spectrum assignment; elastic optical network

I. INTRODUCTION

With the maturity of network protection, a variety of survivability techniques have been proposed [1, 2]. Most of these techniques have focused on providing survivability for a single failure [3] anywhere in the network. However, many studies have indicated the need for addressing dual-failure in real networks [4] as this increased reliability and availability may be vital for mission-critical services such as military or financial applications. Extending the 1+1 and 1:1 single failure protection techniques, studies have been carried out to set up one more protection path to ensure dual-failure recovery [5]. These techniques include 1+1+1, 1+1:1, and 1:1:1 protection [6] which have been studied in the context of the traditional wavelength division multiplexing (WDM) optical network [7]. However, to the best of our knowledge, no work has been done on designing this type of dual failure protected networks in the context of an elastic optical network (EON). EONs have received extensive interest because of their high spectrum efficiency and flexibility both in terms of bandwidth allocation and modulation formats used [8, 9].

In this paper, we design an EON with 1+1:1 dual-failure recovery. 1+1:1 protection provides good survivability for services by setting up three lightpaths between each node pair. In addition to 1+1 protection which provides a pair of “working” and “first protection” lightpaths, one more protection path (called “the second protection lightpath”) is pre-planned in case both the first two paths fail simultaneously. Here the plus sign “+” means that the protection resources reserved on the first protection path are dedicated, while the colon “:” means that the protection resources on the second protection path can be shared.

To optimally design a 1+1:1 path protected EON, we develop an ILP model for routing and spectrum assignment (RSA). We also propose an integrated RSA heuristic algorithm based on the concept of SWP to jointly choose routes and assign spectra for 1+1:1 lightpath services. For both schemes, we consider the impact of the physical distance of each lightpath on the modulation format used as this may lead to different numbers of frequency slots (FSs) assigned on the working and protection lightpaths of a 1+1:1 protected service. We also compare the spectrum efficiency of the 1+1:1 technique with the 1+1+1 technique to evaluate the benefit of spare capacity sharing between the second protection lightpaths. Simulation studies show that apart from being better than the shortest-path (SP) scheme, the proposed SWP-based algorithm is efficient to perform almost as well as the ILP model. Moreover, by sharing the spare capacity between the second protection lightpaths, we can significantly reduce the spare capacity requirement compared to 1+1:1 protection.

The rest of this paper is organized as follows. In Section II, we introduce the 1+1:1 path protection technique in the context of EONs. In Section III, we present an ILP model for RSA of 1+1:1 path protected EONs. In Section IV, we develop a spectrum window plane (SWP)-based heuristic algorithm for the RSA problem that incorporates different modulation formats. Performance results are shown and discussed in Section V and Section VI concludes the paper.

II. 1+1:1 PATH PROTECTION

Each 1+1:1 path protected service consists of three lightpaths, which are the “working lightpath,” “the first protection lightpath,” and “the second protection lightpath,” respectively. The first protection lightpath is assigned with dedicated protection resources, while the second protection lightpath is allowed to share protection resources in the same category subject to an additional link-disjoint condition.

Fig. 1 illustrates an example of 1+1:1 protection technique in an EON. Assume that there are two 1+1:1 services (e.g., services between node pairs (1, 2) and (3, 4)). Their working paths are W1 and W2, their first protection lightpaths are P11 and P21, and their second protection lightpaths are P12 and P22, respectively. The protection capacity on the first protection lightpaths is dedicated, while the protection capacity on the second protection lightpaths is allowed to be shared in the same category as long as their corresponding working and first protection lightpath pairs do not pairwise joint. Mathematically, the sharing condition can be expressed as equation (1), given by
\[(W1\otimes W2) \cdot (P11\otimes P21) \cdot (W1\otimes P21) \cdot (P11\otimes W2)\] (1)

where the symbol \(\otimes\) denotes two paths are joint (i.e., have overlap) on some link(s) and \(X\) represents a “NOT” operation of \(X\). Thus, \((W1\otimes W2)\) means that working paths \(W1\) and \(W2\) are joint, and \((W1\otimes W2) \cdot (P11\otimes P21)\) means that the working and first protection paths of the two services are pairwise joint.

In an EON that employs different modulation formats according to the actual physical distance of a lightpath, the working lightpath and the two protection lightpaths may use different modulation formats and would be correspondingly assigned with different number of FSs in order for them to support the same bandwidth. For example, to transmit the same bandwidth, the working lightpath (1-7-8-2) between node pair (1, 2) is assigned with a higher level modulation format (e.g., 8-QAM) and more FSs (e.g., 3 FSs) for its shorter distance and its corresponding first protection lightpath (1-9-10-2) is assigned with a lower level modulation format (e.g., QPSK) and fewer FSs (e.g., 2 FSs) for its longer distance. Because of its longer distance, the second protection lightpath (1-5-6-2) is assigned with the lowest level modulation format (e.g., BPSK) and the most FSs (e.g., 4 FSs). Similar modulation format and FS allocation can be carried out for node pair (3, 4) as shown in Fig. 1(a), in which the working, first protection, and second protection lightpaths are assigned with the modulation formats of 8-QAM, QPSK, and QPSK and they use 2, 3, and 3 FSs, respectively.

Because the corresponding working and first protection lightpaths are pairwise joint on links (7-8) and (9-10), any spectrum resource on the common link (5-6) passed by both second protection lightpaths (1-5-6-2 and 3-5-6-4) cannot be shared. Thus, 7 FSs (from 1 to 7) are reserved on the common link (5-6).

In contrast, Fig. 1(b) shows a situation where two second protection lightpaths can share protection capacity on their common links traversed by the two second protection lightpaths can be shared. Thus, only 4 FSs (from 1 to 4) should be reserved on link (5-6).

### III. ILP MODEL FOR 1+1:1 TECHNIQUE

#### A. Problem Statement

We present a general EON as \((V, E)\), where \(V\) is the set of nodes and \(E\) is the set of (bi-directional) fiber links in the network. A request is represented by \(CR(S, D, R)\), where \(S\) and \(D\) are the respective source and destination nodes and \(R\) is the bandwidth of the request. The working lightpath and its two protection lightpaths are ensured to be fully link-disjoint for each request. Moreover, since the working and protection lightpaths may have different distances, they may be assigned different modulation formats and different number of FSs. We consider three modulation formats (i.e., BPSK, QPSK, and 8-QAM). Given a bandwidth \(R\), the required numbers of FSs for a certain modulation format can be found by a relationship of \(2 \cdot F \cdot B \cdot SE \geq R\), where \(2\) counts for polarization mode multiplexing, \(F\) is the number of required FSs, \(B\) is the bandwidth of each FS in units of GHz, and \(SE\) is the spectrum efficiency (in units of bit/s/Hz) of the adopted modulation format. For BPSK, QPSK, and 8-QAM, the corresponding \(SEs\) are 1, 2, and 3 bit/s/Hz, respectively. Moreover, these FSs are required to be spectrally contiguous and continuous along a lightpath. Spectrum contiguity means that all the FSs of a lightpath must be spectrally neighboring. In Fig. 2, the frequencies ranging from \(f_j\) to \(f_{j+n}\) on link 1 composes a contiguous spectrum. Spectrum contiguity requires the assigned contiguous spectra on all the fiber links of a lightpath to be the same when none of nodes in the network is capable of spectrum conversion. In Fig. 2, for an H-hop source-destination pair AB that requires \(n+1\) FSs, the same contiguous spectra whose frequencies ranging from \(f_j\) to \(f_{j+n}\) are allocated on all the traversed links (from 1 to \(H\)).

**TABLE 1. FS CAPACITIES AND OPTICAL REACHES OF DIFFERENT MODULATION FORMATS [10]**

<table>
<thead>
<tr>
<th>Modulation Format</th>
<th>FS Capacity (Gbit/sec)</th>
<th>Transparent Reach (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>25</td>
<td>4000</td>
</tr>
<tr>
<td>QPSK</td>
<td>50</td>
<td>2000</td>
</tr>
<tr>
<td>8-QAM</td>
<td>75</td>
<td>1000</td>
</tr>
</tbody>
</table>

For each modulation format, we assume a maximal optical transparent reach as shown in Table 1, in which the bandwidth of each FS is assumed to be 12.5 GHz and each row shows the
FS capacity and the transparent reach of each modulation format. Obviously, BPSK has the longest transparent reach, but the lowest FS capacity, while 8-QAM has the highest FS capacity, but the shortest transparent reach.

B. ILP Model

In this part, we present an ILP model for the RSA problem of a 1+1:1 path protected EON. For each 1+1:1 service, we consider all the link-disjoint k-shortest routes. The working and first protection lightpaths are always established along the shortest and the second shortest paths (e.g., $R_w$ and $R_{P1}$, respectively), and the corresponding second protection lightpath is established on one of the k-shortest routes that are link-disjoint from both $R_w$ and $R_{P1}$. The sets, parameters, variables, and formulation of the ILP model are as follows.

Sets:

- $D$: set of node pairs in the network.
- $R_d$: set of routes for second protection lightpath establishment between node pair $d$, each of which is link-disjoint from the corresponding working and first protection routes.

Parameters:

- $F_d$: number of required FSs on the working lightpath between node pair $d$.
- $F_{P1}^d$: number of required FSs on the first protection lightpath between node pair $d$.
- $F_{P2}^d$: number of required FSs on the second protection lightpath between node pair $d$ if protection route $b \in R_d$ is chosen for second protection lightpath establishment.

Variables:

- $\epsilon_d^a$: $\epsilon_d^t$: it equals 1 when the working lightpaths of node pairs $d$ and $t$ share a common link; 0, otherwise.
- $\eta_d^t$: it equals 1 when the working lightpath of node pair $d$ and the first protection lightpath of node pair $t$ share a common link; 0, otherwise.
- $\eta_d^b$: it equals 1 when the first protection lightpaths of node pairs $d$ and $t$ share a common link; 0, otherwise.
- $\zeta_d^b$: it equals 1 when the working lightpath of node pair $d$ and the second protection lightpath $b \in R_d$ of node pair $t$ share a common link; 0, otherwise.
- $\lambda_d^{a,b}$: it equals 1 when the first protection lightpath of node pair $d$ and the second protection lightpath $b \in R_d$ of node pair $t$ share a common link; 0, otherwise.
- $\phi^{b,t}_{a,d}$: a binary variable that equals 1 if route $b \in R_d$ 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 working lightpath between node pair $d$.
- $e^d$: an integer variable denoting the starting index of the FSs assigned to the first protection lightpath between node pair $d$.
- $q^d_b$: an integer variable denoting the starting index of the FSs assigned to the second protection lightpath $b \in R_d$ between node pair $d$.

Objective:

Minimize $\sum_{b \in R_d} \phi^{b,t}_{a,d}$

Subject to:

- $C \geq f^d + F_d; C \geq e^d + F_{P1}^d; C \geq q^d_b + F_{P2}^d$ for $\forall d \in D$ (3)
- $f^d - f^t \leq V \cdot (1 - x_1^d + 1 - e^t) - 1 \forall d, t \in D, d \neq t$ (4)
- $f^d + F_d - f^t \leq V \cdot (x_1^t + 1 - e^t) \forall d, t \in D, d \neq t$ (5)
- $e^t - f^d \leq V \cdot (1 - y_1^d + 1 - r_1^d) - 1 \forall d, t \in D, d \neq t$ (6)
- $e^t - f^d \leq V \cdot (y_1^d + 1 - r_1^d) \forall d, t \in D, d \neq t$ (7)
- $e^t + F_{P1}^d - f^d \leq V \cdot (1 - x_1^d + 1 - r_1^d) \forall d, t \in D, d \neq t$ (8)
- $e^t + F_{P1}^d - f^d \leq V \cdot (y_1^d + 1 - r_1^d) \forall d, t \in D, d \neq t$ (9)
- $q^d_b - f^d \leq V \cdot (1 - \delta^b_d + 2 - \phi^{b,t}_{a,d}) - 1$ (10)
- $q^d_b + F_{P2}^d - q^d_b \leq V \cdot (\delta^b_d + 2 - \phi^{b,t}_{a,d})$ (11)
- $q^d_b + F_{P2}^d - q^d_b \leq V \cdot (1 - \delta^b_d + 2 - \phi^{b,t}_{a,d})$ (12)
- $q^d_b - e^d \leq V \cdot (1 - \delta^b_d + 2 - \phi^{b,t}_{a,d}) - 1$ (13)
- $q^d_b + F_{P1}^d - q^d_b \leq V \cdot (\delta^b_d + 2 - \phi^{b,t}_{a,d})$ (14)
- $q^d_b + F_{P2}^d - q^d_b \leq V \cdot (1 - \delta^b_d + 2 - \phi^{b,t}_{a,d})$ (15)
- $q^d_b - e^d \leq V \cdot (1 - \delta^b_d + 2 - \phi^{b,t}_{a,d}) - 1$ (16)
- $q^d_b + F_{P1}^d - q^d_b \leq V \cdot (\delta^b_d + 2 - \phi^{b,t}_{a,d})$ (17)
- $q^d_b + F_{P2}^d - q^d_b \leq V \cdot (1 - \delta^b_d + 2 - \phi^{b,t}_{a,d})$ (18)
- $q^d_b - e^d \leq V \cdot (1 - \delta^b_d + 2 - \phi^{b,t}_{a,d}) - 1$ (19)

Objective (2) is to minimize the maximal number of used FSs used in the network. We use this criterion to measure the number of additional FSs consumed.
spectrum efficiency of a network and it is generally more efficient if fewer FSs are required to accommodate all the traffic demands.

Constraint (3) ensures that there is only one second protection lightpath selected for any node pair. Note that this constraint is important as all the reserved FSs must travel together along the same route and thus only one second protection route can be employed to recover the affected lightpath(s). Constraint (4) ensures that the maximal number of used FSs in the whole network should always be greater than the ending FS index of the lightpath between any node pair. Specifically, in the whole network, if the maximal used ending FS index is 29, then \( C \) equals to 30 (i.e., 0-29). Constraints (5) and (6) ensure that the allocated spectra for the working lightpaths between different node pairs do not overlap on any common link. Specifically, if the starting FS index of working lightpath \( A \) is larger than that of working lightpath \( B \), the starting FS index of lightpath \( A \) should also be larger than the ending FS index of lightpath \( B \). Similarly, constraints (7)-(9) ensure that the allocated spectra for the working lightpath and the first protection lightpath between different node pairs do not overlap on any common link. Constraints (10)-(12) ensure that the allocated spectra for the working lightpath and the second protection lightpath between different node pairs do not overlap on any common link. Constraints (13)-(15) ensure that the allocated spectra for the first and the second protection lightpaths between different node pairs do not overlap on any common link. Constraints (16) and (17) ensure that the allocated spectra for the first protection lightpaths between different node pairs do not overlap on any common link. Constraints (18) and (19) ensure that the allocated spectra for the second protection lightpaths between different node pairs do not overlap on any common link if their corresponding working and first protection lightpaths are pairwise joint.

C. Computational Complexity

We count the dominant numbers of variables and constraints to evaluate the computational complexity of the ILP model. In the above model, the dominant number of variables and constraints are both \( O(|R|^2 \cdot |D|^2) \), where \( |R| \) is the total number of routes in \( R_d \) and \( |D| \) is the total number of node pairs in the whole network.

IV. SWP-BASED HEURISTIC ALGORITHM

The RSA problem has been proved to be NP-complete. For large or even reasonably sized networks, the ILP model cannot be solved to obtain an optimal solution within a reasonably short time. Therefore, we develop an efficient heuristic algorithm for the 1+1:1 RSA problem. Specifically, we extend the spectrum window plane (SWP)-based algorithm [11] for this purpose. The detailed concepts on spectrum window (SW) and SWP can be referred to our previous works [11, 12]. In the heuristic algorithm, three steps are taken to establish a 1+1:1 lightpath service. Specifically, we first establish a working lightpath, then the first protection lightpath, and finally the second protection lightpath. Only if all the three lightpaths are successfully established, can the service be considered successfully provisioned. When establishing the three lightpaths, we will increase the number of used FSs until each of them can be established. The detailed steps of the algorithm are briefed as follows.

Step 1  Read 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), create a list of SWPs, in which the number of FSs on each SWP is calculated as \( F = \lceil R / (2 \cdot B \cdot SE) \rceil \). Remove all the links from each of the SWPs if corresponding SWs are not available, i.e., not all the \( F \) continuous FSs are free. Then, search for a first eligible shortest route on the SWPs that is within the transparent reach of a considered MF and establish the working lightpath on the route. Remove all the SWP links whose corresponding physical links are traversed by 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, create a list of SWPs as in Step 2. 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 in the SWP list; establish the second protection lightpath on the route thus found. Note that protection resource sharing is allowed as long as the sharing condition (1) is satisfied.

In Step 4, we apply a least cost (LC) strategy for maximal protection capacity sharing among protection lightpaths. We set the cost of each SWP link \( j \) that is free or sharable on each SWP as \( C_j = \sum_{l=1}^{L} (d_l / F) / (m_l + 1) \) where \( d_l \) is the physical length of link \( j \), \( F \) is the number of FSs on the SWP, and \( m_l \) is the total number of protection lightpaths that are sharing FS \( i \).

For each demand request between a pair of nodes, the overall computational complexities for establishing working and first protection lightpaths are both \( O(MW(L + N^2)) \), where \( M \) is the total number of available modulation formats, \( W \) is the total number of FSs in each fiber link, \( L \) is the total number of links in a network, and \( N \) is the total number of network nodes. The overall computational complexity of searching the second protection route with the lowest cost is \( O(MW(2L + N^2)) \), in which an additional \( O(WL) \) is the computational complexity of link cost calculation.

V. SIMULATIONS AND PERFORMANCE ANALYSES

To evaluate the performance of the proposed SWP-based heuristic algorithm, we consider two test networks, the 10-node, 22-link SmallNet network and a 14-node, 36-link (n14s36) network as shown in Fig. 3. The link distance (in km) is shown by each link. We assume that there are 320 FSs in each fiber link in both of the test networks. In addition, three modulation formats (i.e., BPSK, QPSK, and 8-QAM) are assumed to be used for the working lightpath and its corresponding two protection lightpaths.

We consider a static traffic demand where the traffic demand between each node pair is assumed to be uniformly distributed.
distributed within the range of \((200, X)\) Gb/s, where \(X\) is the maximal traffic demand. In this study, we set \(X\) to be five values, i.e., 400, 500, 600, 700 and 800. In addition, according to the observation in our previous study \([12]\), the performance of a demand serving algorithm is closely related to the sequence of served node pairs. We shuffle the list of node pairs many times (100 times in this study), and then for each of the shuffled node pair sequences, we run the heuristic algorithm to choose the minimal number of FSs used.

For performance comparison, we also considered 1+1+1 path protection. In addition, a shortest-path (SP) scheme was considered for efficiency evaluation of the SWP heuristic algorithm. The SP algorithm uses the first three link-disjoint shortest paths to establish the working, first protection, and second protection lightpaths. Finally, the candidate routes used for the ILP model were obtained based on the k-disjoint shortest path algorithm, in which the first two routes are used for the working and first protection lightpaths, and the remaining routes are used for the second protection lightpath chosen by the ILP model.

A commercial software AMPL/Gurobi (version 5.0.0) \([13]\) installed in a 64-bit server with 2.4-GHz CPU and 8-G memory was employed to solve the ILP model. The MIPGAP for the ILP solutions was set to be 0.1%. Because the ILP model cannot be solved to obtain an optimal solution for a large network within a reasonably short time, only 15 demands (node pairs) are assumed for SmallNet when the ILP model was applied to find its optimal solution.

### A. Maximal Number of Frequency Slots Used

In this section, we show the maximal number of FSs used for accommodating all the traffic demands under the 1+1:1 and 1+1+1 path protection techniques. In Figs. 4(a) and (b), legend "ILP" corresponds to the result of the ILP model. Legend "SWP" corresponds to the case of the SWP heuristic algorithm, in which the working and the two protection routes are not fixed but depend on the spectrum resource usage status. "FR_SWP" corresponds to a special case of "SWP," in which we require the working and first protection lightpaths to always use the first and second link-disjoint shortest routes \(R_w\) and \(R_p1\) between each node pair, and the second protection lightpath always uses one of the \(k\)-shortest routes that are link-disjoint from \(R_w\) and \(R_p1\). Legend "SP" corresponds to the case of fixed routes in which the first three \(k\)-disjoint shortest routes are used for the working, first protection and second protection lightpaths.

It is reasonable to expect that with the increase of traffic demand, the number of required FSs would increase. In addition, for all the schemes, including ILP model, SWP heuristic algorithm, and SP algorithm, 1+1:1 always requires smaller numbers of FSs than 1+1+1. This is attributed to the fact that 1+1:1 allows protection capacity sharing among multiple second protection lightpaths, while 1+1+1 cannot do that. In the SWP algorithm, the constraint of spectrum continuity can always be ensured if a route is found on a SWP. However, in the SP algorithm, there can be spectrum resource usage collision on a fixed route, which cannot ensure spectrum resource continuity available along the route and would therefore detrimentally affect spectrum resource utilization. Thus, we see that the SWP algorithm requires a smaller number of FSs than the SP algorithm.

Comparing the number of FSs required by the schemes of “FR_SWP” and “ILP,” we notice that their results are very close, which implies that the proposed SWP algorithm is spectrally efficient. In addition, for the SWP algorithm that allows the working and protection lightpaths to choose different routes instead of the fixed first and second shortest routes, we see that its result is even better than that of the ILP model to require even fewer FSs. This is attributed to the flexibility in route selection by the SWP algorithm.

It is not feasible to use the ILP approach to find an optimal solution for the n14s36 network because of the high computational complexity involved. Therefore, we implemented the heuristic algorithms to evaluate performance and the results are shown in Fig. 4(b). Similar observations can be made as follows. The SWP algorithm can achieve better performance to require a smaller number of FSs due to its flexibility in choosing different routes for the working and protection lightpaths. In addition, for all the schemes, 1+1:1 protection always requires a smaller number of FSs than 1+1+1 protection due to protection capacity sharing among the second protection lightpaths under 1+1:1.

![Fig. 3. Test networks.](image)

![Fig. 4. Maximal numbers of FSs used by different protection techniques under different design schemes.](image)

### B. Spare Capacity Efficiency

Figs. 5(a) and (b) show the results of spare capacity redundancy (which is defined as the ratio of the total...
We separately compare spare capacity redundancy of the first protection lightpath (i.e., $S_j_1$) and that of the second protection lightpath (i.e., $S_j_2$). Figs. 5(a) and (b) show the results of both test networks.

Under 1+1:1 protection ($S_j_1_1+1:1$ and $S_j_2_1+1:1$), we find that $S_j_2$ is lower than $S_j_1$ in both SWP and SP algorithms. This is attributed to the fact that spare capacity sharing is allowed on the second protection lightpath, while the first protection lightpath does not. In addition, the spare capacity redundancy of the second protection lightpath in the SWP algorithm is lower than that in the SP algorithm. This is because the SWP approach is flexible to search the first and second protection lightpaths according to the current spectrum resource usage status. Thus, the second protection lightpath can maximally share protection resources in the network. In contrast, in the SP algorithm, the second protection lightpath is always fixed, which cannot ensure maximal spare capacity sharing among the second protection lightpaths.

For 1+1+1 protection ($S_j_1_1+1+1$ and $S_j_2_1+1+1$), we see that for both of the algorithms the second protection lightpath shows a higher spare capacity redundancy than the first protection lightpath. This is because there is no spare capacity sharing and the second protection lightpath is generally longer than the first protection lightpath. For the spare capacity redundancy of the second protection lightpath, the 1+1+1 technique is higher than the 1+1:1 technique because of spare capacity sharing opportunities among the second protection lightpaths in the latter.

We developed an ILP optimization model and a SWP-based heuristic algorithm. By comparing the maximal number of FSs used in the whole network and spare capacity redundancy, we show that the proposed SWP-based algorithm is efficient. It significantly outperforms the SP-based algorithm and its performance is close to that of the ILP model. In addition, because 1+1:1 protection allows spare capacity sharing among the second protection lightpaths, it can achieve much higher spare capacity efficiency than the 1+1+1 protection scheme that does not allow such sharing. Based on the current 1+1+1 work, our future research will look into 1:1:1 protection in the context of EON. We will evaluate how protection capacity sharing of the first protection lightpath can further improve network spare capacity utilization.

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