# SEC and Survival RSA Problem on EONs with Time-Varying Traffic

Der-Rong Din
Computer Science & Information Engineering
National Changhua University of Education
Changhua City, Taiwan, R. O. C.
deron@cc.ncue.edu.tw

***Abstract*—For serving *time-varying traffic* on an Elastic Optical Network (EON), the spectrum allocated for the connection request can be expanded or contracted to meet the traffic requirement. For the survival connection, both the primary and the backup lightpaths should be expanded/contracted at the same time. In this paper, the *Spectrum Expansion*/ *Contraction* (SEC) and Survival Routing and Spectrum Allocation (SRSA) problems on EONs with time-varying traffic for the dynamic case are studied. For each protecting scheme, two survival routing algorithms and the respective SEC operation are developed to solve it. These algorithms are examined through simulations and the results show that the proposed algorithms can achieve good results.**

***Keywords- spectrum expansion/contraction; survival routing; routing and spectrum allocation; time-varying traffic.***

## I. INTRODUCTION

*Elastic Optical Networks* (EONs), which employs *Optical-Orthogonal Frequency Division Multiplexing* (O-OFDM) technology, have been proposed to increase the flexibility of optical networks. The spectrum of a link in EONs is divided into *Frequency Slots* (FSs) and the necessary amount of consecutive FSs are assigned to support the connection request. Besides, more efficient spectrum allocation is achieved in these networks [1]. Specifically, a BW-variable O-OFDM transponder can assign an appropriate number of FSs to serve a lightpath [1].

In an optical network, each connection can be transmitted by an optical channel, which consists of a *central frequency* (CF) and a *size*. The size of the channel is determined by the requested bit-rate, the modulation technique applied, the (fixed) slice width, and the Guard Band (GB) introduced to separate two spectrum adjacent connections, among others. Due to the *spectrum continuity constraint* [1], the *Routing and Spectrum Assignment* (RSA) problem has emerged as the essential problem for spectrum management on EONs. For a given connection request, the goal of the RSA problem is to find a lightpath on the network and assign the required FSs.

### *A. Time-Varying Traffic*

Several *Spectrum Allocation* (SA) schemes that change the bandwidth dynamically have been studied in [2][3]. A general policy to allocate FSs to time-varying traffic was presented in [3]. For time-varying traffic demands on EONs, there are three SA schemes of different levels of elasticity [3]. The *elastic* scheme [3], both the assigned central frequency and the size can be subject to change by performing Spectrum Expansion/Contraction (SEC) in each time interval, is the most efficient method [2]. Recently, several SEC schemes have been considered and the EONs enable to expand/contract slot width of the channel [4]. Furthermore, future EONs will change slot width according to time-varying traffic by changing the number of FSs flexibility. Din et al., [5] studied the SEC problem for the multipath routing scheme for Routing, Modulation, and Spectrum Assignment (RMSA) on EONs was studied.

### *B. Survivable EONs*

In the traditional *Wavelength Division Multiplexing* (WDM) networks, network survivability has been extensively studied; several various network protection techniques were proposed in [6]. The protection techniques can be divided into the categories of *Dedicated Path Protection* (DPP) and *Shared Backup Path Protection* (SBPP) [6]. Dedicated path protection means that there is dedicated backup capacity to protect primary capacity. In contrast, shared protection means that the protection capacity can be shared among multiple protection lightpaths as long as their corresponding primary lightpaths do not fail simultaneously. Because of capacity sharing, the shared protection scheme are generally more capacity efficient than the dedicated protection scheme [6].

For the case of static traffic demand on the EON, Klinkowski et al. [7] focused on the problem of RSA with DPP. Shen et al. [8] developed Integer Linear Programming (ILP) models for the SBPP on EONs. For the case of dynamic traffic demand, Shao et al. [9] studied the shared-path protection on EONs for RSA model. A heuristic algorithm was proposed to solve this problem. N. G. Anoh et al. [10] studied a hybrid protection scheme with shared and dedicated backup paths resources for the RMSA model.

### *C. Studied Problem*

In this paper, the *Spectrum Expansion*/*Contraction* (SEC) and Survival Routing and Spectrum Allocation (SRSA) problem with time-varying traffic on EONs is studied. For a given EON and a sequence of survival connection requests, the goal is to add/delete/expand/contract (primary and backup) lightpaths and assigned suitable channels to the lightpaths to meet the traffic requirement of the survivable connection request such that the performance measure can be optimized. The RSA model is considered in this paper, that is, the transparent network only with single modulation format.

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Two protecting schemes DPP and SBPP are considered in this article. When a new connection request arrived, the *Survival Path Routing Algorithm* (SPRA) is performed to find a pair of link-disjoint primary and backup lightpaths. If the required bandwidth cannot be allocated, then the connection request is blocked. Otherwise, these lightpaths are established, the required FSs of lightpaths are allocated. If the connection request is an adjusted request (that is, there exists a pair of primary and backup lightpaths with the same source and destination nodes), based on the selected SEC policy, the allocated FSs of the existing lightpath are adjusted.

In this article, the elastic allocation scheme is used, that is, both the CF and the size of the lightpath can be adjusted (expanded or contracted). If the bandwidth variation can be accommodated, then the adjusted connection is updated. Otherwise, the SPRA is performed to route the new connection (after the old lightpaths are torn down). According to literature analysis by the author, only the SEC problems for single path [3] and multipath [5] were studied. Based on the survey, there is no article considered the SEC problem for survivable routing.

## II. Problem Definition

In the following, the assumptions, constraints, notations and the definitions of the studied problem are given.

### A. Notations

- $G = (V, E)$: The physical topology of the network, where $V = \{v_1, v_2, ..., v_n\}$ and $E = \{e_1, e_2, ..., e_m\}$ is the set of nodes and links, respectively.
- $r = (s, d, B_{sd}, q)$: The connection request, where $s \in V$ and $d \in V$ is the source and destination node of the request, respectively. $B_{sd}$ is the required bandwidth (Gb/s) of the lightpaths between nodes $s$ and $d$, $q$ ($0 \le q \le 1$) is the *protection level requirement* of the connection [11].
- $B$: The number of FSs provided with each link of the network. Assume that each spectrum slot occupies $C_f$ GHz bandwidth.
- $K$: The number of shortest paths for each node-pair are pre-computed for finding routing path.
- $P_{sd}$: The set of candidate routing paths for node pair s-d.
- $b_l(j)$: The bit-mask $b_l(j)$ of the link $e_l \in E$ ($j$ = 1, 2, ..., $B$ = 100), is the status of the $j^{th}$ FS of the link $e_l$.
- If the $j^{th}$ FS of link $e_l$ is occupied, then $b_l(j) = 1$; otherwise, $b_l(j)=0$.

When the link failure occurs on the primary path, the backup path can provide at least $q \times B_{sd}$ bandwidth. If $q = 0$, then there is no protection; $q = 1$ is *full protection* and 0< <1 is *partial protection*. If the request is supported by a single lightpath, the minimal required number of FSs of the primary lightpath (denoted as $N_{sd}$) can be computed by $N_{sd} = \lceil B_{sd}/C_f \rceil$ + GB, where $C_f$ is the bandwidth (Gb/s) provided by each FS. The minimal required number of FSs of the backup lightpath (denoted as $BN_{sd}$) can be computed by $BN_{sd} = \lceil (q \times B_{sd})/C_f \rceil$ + GB.

### B. Assumptions

The assumptions of the SEC problem for survivable routing on EONs are given as follows.

- For each link, there is a fiber connecting the end-nodes and signal can be transmitted bidirectional.
- All nodes in the network are equipped with *Bandwidth Variable Wavelength Cross-Connects* (BV-WXC) and *Bandwidth Variable Transceiver* (BVT).
- For simplicity, the numbers of FSs provided by links are all equal.
- A GB or guard subcarrier should be allocated between two lightpaths.
- The network is a 2-connected graph, only the single-edge failure case is considered.
- If the expansion is not possible, the current primary and backup paths are expanded as many numbers of FSs as possible.

Three constraints are considered in this paper, they are *spectrum continuity constraint*, *subcarrier consecutiveness constraint*, and *non-overlapping spectrum constraint*. Due to space limitation, the definition of these constraints can be found in [5].

## III. Survival Routing and SEC for DPP Scheme

In DPP scheme, for each connection request $r = (s, d, B_{sd}, q)$, a pair of link-disjoint primary and backup paths is found. Where the bandwidth provided by the primary path and backup path is greater than or equal to $B_{sd}$ and q × $B_{sd}$ Gb/s, respectively. In this section, two algorithms are proposed to solve the DPP routing problem and then the SEC operations are developed to perform traffic updating.

### A. Survival Path Routing Algorithm - DPP

In this subsection, the survival path routing algorithm for a new connection request for DPP scheme is developed. To find the routing paths of the request, two algorithms are proposed, they are *Dynamic Survival Path Routing Algorithm* (DSPRA) and S*emi-Dynamic Survival Path Routing Algorithm* (SDSPRA).

*1) Dynamic Survival Path Routing Algorithm (DSPRA):* In this subsection, the DSPRA is described. In DSPRA, for finding the primary path with $N_{sd}$ FSs, the layered graphs $LG^i$, $i$= 1, 2, ..., $B$-$N_{sd}$+1 of the network are constructed according to the current status of the network and connection request. The $i$-th layer graph is denoted as $LG^i$ ($V^i$, $E^i$), where $V^i = V$, $E^i = \{e_l | \sum_{j=i}^{i+Nsd-1} b_l(j)=0, e_l \in E\}$. On layered graph $LG^i$, if a path from $s$ to $d$ can be found, then there exists a path with $N_{sd}$ FSs on $G$ and it can serve as the primary path of the request. The K-shortest paths on $LG^i$ are found as the candidate paths of the primary lightpaths. If the primary path can be found on $LG^i$, then the resources of primary lightpath are temporarily allocated and the Backup Path Finding Algorithm (BPFA) is performed to find the backup path of the request. If both the primary and backup lightpaths can be found, then the resources are allocated. Otherwise, another possible primary path on the same layered graph or on the different layered graph is selected, and then the backup lightpath is examined again. In the BPFA, first, the links passed by the primary lightpath are removed. Then, the layered graph approach is applied again to find the backup path. The details of the DSPRA and the BPFA are described in Figure 1 and Figure 2, respectively.

**Algorithm 1** DSPRA

**Input :** $G(V, E)$, request $r = (s, d, B_{sd}, q)$;
**Output :** primary path and backup path of the request;
$i = 1$, $P^i_{sd} = \emptyset$
**while** ($i \leq B - N_{sd} + 1$) **do**
  Construct the layered graph $LG^i(V^i, E^i)$ of the network according to status of the network.
  Find the set $P^i_{sd}$ of $K$-shortest paths on $LG^i$ from $s$ to $d$.
  **if** ($P^i_{sd} \neq \emptyset$) **then**
    $j = 1$;
    **while** ($j \leq |P^i_{sd}|$) **do**
      Select the $j$–th path in $P^i_{sd}$ as the primary path $p_1$.
      Temporarily allocate FSs for the path $p_1$.
      Perform BPFA to find the backup path $p_2$ of the request.
      **if** ($p_2$ can be found) **then**
        Allocate FSs for the path $p_1$ and $p_2$, and **return** $p_1$ and $p_2$.
      **end if**
      Release all FSs allocated to $p_1$.
      $j = j + 1$;
    **end while**
  **end if**
  $i = i + 1$;
**end while**
**return** BLOCK.

Figure 1. DSPRA.

**Algorithm 2** Backup Path Finding Algorithm (BPFA)

**Input :** $G(V, E)$, request $r = (s, d, B_{sd}, q)$, primary path $p_1$;
**Output :** backup path $p_2$ of the request;
Remove links on primary path $p_1$ from $G$ to form a new graph $G'(V', E')$.
$i = 1$, $BN_{sd} = \lceil \frac{q \times B_{sd}}{C_f} \rceil$;
**while** ($i \leq B - BN_{sd} + 1$) **do**
  {
  Construct the layered graph $BLG^i(V^i, E^i)$ of the network $G'$ according to status. Where $V^i = V'$, $E^i = \{e_l | \sum_{j=i}^{i+BN_{sd}-1} b_l(j) = 0, e_l \in E'\}$.
  Find the shortest path $p_2$ on $BLG^i$ from $s$ to $d$.
  **if** ($p_2$ can be found) **then**
    **return** backup path $p_2$.
  **end if**
  $i = i + 1$;
  }
**end while**
**return false**.

Figure 2. BPFA.

*2) Semi-Dynamic Survival Path Routing Algorithm (SDSPRA):* In this subsection, the SDSPRA was proposed. First, a set $P_{sd}$ of candidate paths on $G(V, E)$ is found and paths in the $P_{sd}$ are sorted increasingly according to the length of the path. Path in $P_{sd}$ are examined in order. If the examined path can be allocated on the current network, then the primary lightpath is temporarily allocated and removed from the network, and then the BPFA (by using the layered graph approach) is performed to find the backup path of the request. The details of the Semi-Dynamic Survival Path Routing Algorithm are described in Figure 3.

### *B. SEC operation for DPP*

For the survivable connection request, if the connection changed to $r = (s, d, B_{sd}^{new}, q^{new})$, the currently deployed (primary and backup) lightpaths should be adjusted to meet the bandwidth requirement. If $B_{sd}^{new}$ is zero, the primary and backup lightpaths are deleted and the possessed resources are released. If $q^{new}$ is zero, the backup lightpath can be deleted and the possessed resources can be released.

If $B_{sd}^{new} > (N_{sd}\text{-}1) \times C_f$ and $q^{new} \times B_{sd}^{new} > C_f \times (BN_{sd}\text{-}1)$, the bandwidth of primary and backup lightpaths should be increased, respectively. Two lightpaths can be expanded separately. Several cases should be considered and described as follows.

- Case 1: If both primary and backup lightpaths can be expanded successfully, then the expansion operation is performed to meet the requirement.
- Case 2: If the primary lightpath can be expanded but the backup lightpath cannot, then the primary lightpath is expanded in the first step, and then, the original backup path is removed and the BPFA is performed to find a new backup lightpath.
- Case 3: If the backup lightpath can be expanded but the primary lightpath cannot, then the backup lightpath is expanded in the first step. Then, the primary path is removed and a new primary lightpath, which is link-disjoint to the backup lightpath, is found by performing the BPFA.
- Case 4: If both primary and backup lightpaths cannot be expanded, then the primary and backup lightpaths are removed. Then, the SPRA is performed to find a pair of new primary and backup lightpaths.
- Case 5: If the backup (or primary) lightpath cannot be found in the previous Cases 2 and 3, then the primary (or backup) lightpath is removed in the first step. Then, the respective SPRA (SSPRA, DSPRA, and SDSPRA) is performed to find a pair of new primary and backup lightpaths for the request. If failed to find the pair of lightpaths, then the request would be blocked.

For the case with $B_{sd}^{new} > (N_{sd}\text{-}1) \times C_f$ or $q^{new} \times B_{sd}^{new} > C_f \times (BN_{sd}\text{-}1)$, the bandwidth of primary lightpath or backup lightpath should be increased separately. The expansion action is expanded first, and then the respective lightpath is re-found. If these two actions cannot be done, then the old lightpaths are deleted and then a pair of new lightpaths are found by performing the respective SPRA to route the request. In the contraction, it is worth noting that the actually provided bandwidth $N_{sd} \times C_f$ may be greater than the newly required bandwidth $B_{sd}^{new}$. The similar situation can be applied to the backup path. If $B_{sd}^{new} \leq (N_{sd}\text{-}1) \times C_f$ and $q^{new} \times B_{sd}^{new} < (BN_{sd}\text{-}1) \times C_f$, then the bandwidth of the primary and backup path should be contracted, respectively. In the contraction, the higher-index FS allocated to the selected path will be contracted first.

**Algorithm 3** SDSPRA

**Input :** $G(V, E)$, request $r = (s, d, B_{sd}, q)$, $P_{sd}$: candidate set of paths;
**Output :** primary path and backup path of the request;
**while** ($P_{sd} \neq \emptyset$) **do**
  Select and remove a path $p_1$ from $P_{sd}$.
  **if** ($p_1$ can be allocate on network with required $N_{sd}$ FSs) **then**
    Temporarily allocate FSs for the path $p_1$.
    Perform BPFA to find the backup path $p_2$ of the request.
    **if** ($p_2$ can be found) **then**
      Allocate FSs for the path $p_1$ and $p_2$, and **return** $p_1$ and $p_2$.
    **end if**
    Release all FSs allocated to $p_1$.
  **end if**
**end while**
**return BLOCK**.

Figure 3. SDSPRA.

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## IV. SURVIVAL ROUTING AND SEC FOR SBPP SCHEME

In this section, the SBPP scheme is used. In SBPP scheme, two backup lightpaths, which pass through same fiber (or path), can share the spectrum resource on it, if their primary lightpaths are link-disjoint. In this section, two survival path routing algorithms and the SEC operations are developed to solve the problem.

### *A. SSPRA-SBPP*

In this subsection, for SBPP scheme, two algorithms static-SPRA-SBPP (SSPRA-SBPP) and dynamic-SPRA-SBPP (DSPRA-SBPP) are proposed to solve this problem. It is worth noting that these algorithms used the same algorithm to find the backup path of the primary lightpath.

*1) SSPRA-SBPP:* In SSPRA-SBPP, a set $P_{sd}$ of pre-computed paths are found as the candidate set of primary paths. All paths are sorted in increasing order according to the length of the paths. Then, a path in $P_{sd}$ is selected and examined sequentially as the primary path. If the selected path can be successful allocated, then the *Shared Backup Path Protecting Algorithm* (SBPPA) is performed to find the backup path. The details of the SSPRA-SBPP are described in Figure 4.

To describe the backup path-finding process, several notations used in the algorithm are listed as follows. The number of required FSs of the backup path is equal to $BN_{sd} = \lceil q \times B_{sd}/C_f \rceil$. Let $c_l$ be the basic cost of link $e_l \in E$, which is set to 1 initially. The value of $c'_l$ is determined by the current network state. Let $P_b$ be the set of existing backup paths whose respective primary paths are link-disjoint to the primary path $p_1$. It is worth noting that the primary and backup paths can use different starting indices of FSs.

To find the backup path with the great resource sharing of the primary path on layered graph $BLG^i$, the cost of links is dynamically adjusted according to the formula (1), and then the Dijkstra's algorithm is used to find a link-disjoint backup path with the minimum cost on $BLG^i$.

$$c'_l = \begin{cases} +\infty, & \text{if } e_l \in p_1 \\ c_l - \frac{B_{li}}{BN_{sd}}, & \text{if } ((e_l \notin p_1) \cap (e_l \in P_b)) \\ c_l, & \text{otherwise.} \end{cases} \quad (1)$$

On the layered graph $BLG^i$, the links having the same link with the primary path cannot be used, the cost of links is set to $+\infty$. If the link $e_l$ has not been used by any primary or backup path on $BLG^i$, the cost of $e_l$ is set to $c_l$. If the link $e_l$ is not passed by the primary path and there are some FSs used by other backup lightpaths whose respective primary path is link-disjoint to the path $p_1$, then the cost of link $e_l$ is set to $c_l – B_{li}/BN_{sd}$. Where $B_{li} = \Sigma_{z=i}^{i+BNsd-1} b^*_l(z)$ is the number of frequency slots of the link $e_l \in BLG^i$ used by some backup lightpaths. Moreover, $b^*_l(z)=1$ represents that the $z$-th FS of link $e_l$ is only used by backup paths; otherwise, $b^*_l(z)=0$. The cost of link $e_l$ is set to $c_l – B_{li}/BN_{sd}$ for increasing the resource-sharing ratio. In addition, the links that have reserved enough shared backup frequent slots have less link cost. If the backup path traverses these links, then there is no need to reserve new frequency-slots and the frequency sharing can be enhanced. The details of the SBPPA are described in Figure 5.

**Algorithm 4** SSPRA-SBPP

```
Input: G(V, E), request r = (s, d, B_sd, q);
Output : primary path and backup path of the request;
Pre-computed the set K paths between the nodes s and d and stored in
  P_sd. Paths are sorted in increasing order according to the length of the
  paths.
while (P_sd ≠ ∅) do
    Select and remove a path p_1 from P_sd and check whether the required
    bandwidth B_sd can be allocated alone the path p_1 on network G.
    if (success) then
        Temporarily allocate required number of FSs to the path p_1.
        Perform the SBPFA to find the backup path p_2 of the request.
        if (p_2 can be found) then
            return p_1 and p_2.
        end if
        Release all FSs allocated to p_1.
    end if
end while
return BLOCK.
```

Figure 4. SSPRA-SBPP.

**Algorithm 5** SBPPA

```
Input : G(V, E), connection request r = (s, d, B_sd, q), primary path
  p_1;
Output : backup path of the request;
Remove links on primary path p_1 from G to form a new graph
  G'(V', E').
i = 1, BN_sd = ⌈(q × B_sd)/C_f⌉;
while (i ≤ B − BN_sd + 1) do
    Construct the layered graph BLG^i of the network G' according to
    status. Where V^i = V', E^i = {e_l | Σ_{j=i}^{i+NB_sd−1} b*_l(j) = 0, e_l ∈
    E'}.
    Set up the cost c'_l of link e_l ∈ E^i according to the formula (1).
    Perform Dijkstra algorithm on graph G' to find the backup path p_2.
    if (backup path can be found) then
        Allocate resources for the backup path and return p_2.
    end if
    i = i + 1;
end while
return false.
```

Figure 5. SBPPA.

*2) DSPRA-SBPP:* In this subsection, the details of the DSPRA-SBPP is described. In the DSPRA-SBPP, the layered graph approach is applied. The main algorithm is the same as the proposed DSPRA described in Section III.A.1, except for the backup path-finding algorithm. The backup path-finding algorithm is changed to the SBPPA described in Figure 5.

### *B. SEC operation for SBPP*

The SEC operation for the SBPP scheme is more complex than that of the DPP scheme. In SBPP, the backup resources are shared by several backup lightpaths. If the bandwidth of a connection decreases, the backup resources cannot decrease directly. Since releasing the shared resources of a backup path directly may cause other primary paths unprotected. Moreover, for the SEC operation, the spectrum-sharing feature should be considered in designing the expansion and contraction algorithms to improve the spectrum sharing.

*1) Expansion:* For a bandwidth increasing connection, if both primary and backup paths can be expanded directly, then the resources of these paths are expanded and the paths are unchanged. When the backup path expansion is performed, the sharing status of FSs should be taken into consideration. To expanse a frequency slot for the allocated

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lightpath, if the FS of an edge to be expanded is free (not been allocated to any primary or backup lightpath), then the FS can be expanded directly. If the FS of an edge to be expanded is allocated to a primary lightpath, then the FS cannot be selected to expand.

If the FS of an edge to be expanded is allocated to several backup lightpaths, then the FS should be examined further. Assume $p_1$ and $b_1$ be the primary and backup lightpath to be expanded, respectively. For the edge $e_i \in b_1$ and the $j^{th}$ selected FS, let $PS=\{p^1_{ij}, p^2_{ij}, ..., p^z_{ij}\}$ be the set of primary lightpaths whose backup lightpaths pass through the edge $e_i$ and use the selected FS. If the selected FS of an edge to be expanded have the property that $p_1$ is link-disjoint to all paths in *PS*, then the FS can be expanded. For a selected FS to be expanded, if all edges of the backup path can be expanded, then the selected FS can be expanded. The cost of the selected FS to be expanded is defined as the resource sharing value. For the expandable $j^{th}$ FS of an edge $ei$, the weight (denoted as $w_{ij}$) of the FS is defined as the number of shared backup paths on it. For the expandable $j^{th}$ FS of a path *p*, the weight (denoted as $w_{jp}$) of the FS is defined as the total number of shared backup paths on all edges of the path. That is, $w_{jp}=\Sigma_{\forall ei \in p} w_{ij}$. For the backup path, the expandable method is selected by checking and selecting the expandable (immediate upper or lower index) FS with maximal weight repeatedly, until it meets the bandwidth requirement.

If the backup path cannot be expanded directly, then the currently allocated resources for the backup are temporarily contracted (by the method described later) as the first step. Then a new backup path is found by performing the SBPPA.

If the primary path cannot be expanded, then this is a new situation should be considered further. Since the sharing status of the backup path is determined based on the primary lightpath, once the primary path changes, the backup path should be changed accordingly. In this case, the current primary lightpath is removed and backup path is contracted (by the method described later). Then, the respective Survival Path Routing Algorithm for SBPP scheme (SSPRA-SBPP or DSPRA-SBPP) is performed to find a pair of new primary and backup lightpaths for the request. If failed to find the pair of lightpaths, then the request would be blocked.

*2) Deletion or Contraction:* If the demand of the new request is 0, then the primary path can be deleted and resources can be released directly. But the resources allocated to the backup lightpath should be considered further. If the selected FS of an edge is not shared by other lightpaths (used by the affected backup path only), then the resource can be released directly. If the selected FS of an edge is shared by other lightpaths, then the resource cannot be released directly. For each FS of an edge, a set of *path-allocating records* is used to store the sharing backup lightpaths and the respective primary lightpaths. The record of the released FS of an edge should be updated by deleting the affected backup path. For the contraction operation, the path-allocating record should be updated after releasing the selected FSs of the affected backup lightpath.

Consider the example shown in Figure 6, Figure 6(a) shows the primary and backup lightpaths of four requests and Figure 6(b) shows the allocated FSs and sharing status of the edges on the backup path $b_1$: 1→4 → 5 → 7 → 8. The number of allocated FSs for the backup lightpaths $b_1$, $b_2$, $b_3$, and $b_4$ are 18, 3, 3 and 10, respectively. The FS allocation for the primary lightpaths is not shown here. The backup lightpaths near to the right of the FSs allocation of lightpaths denoted as the path-allocating of the FS of the edge. For example, the first and second FSs are used by $b_2$ and 1-3 FSs of edges (1, 4) and (4, 5) are shared by the lightpaths $b_1$ and $b_2$. If backup lightpath $b_1$ is deleted, the FS allocation is shown in Figure 6(c) and 5 free FSs are released. If six FSs are contracted from the backup lightpath $b_1$, the best contraction method will be determined and selected, that is, the region of the allocated FSs will within 5-16 (as shown in Figure 6(d)).

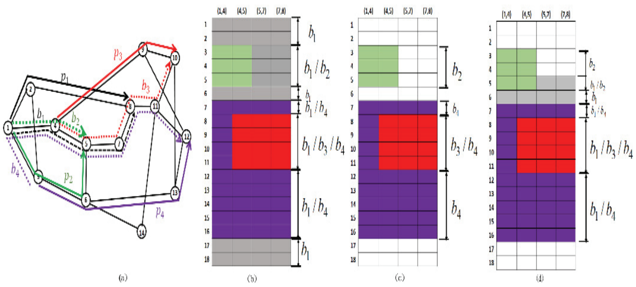

Figure 6. Examples of SEC for SBPP: (a) primary and backup lightpaths, (b) before deleting backup path $b_1$, (c) after deleting backup path $b_1$, (d) after contracting backup path $b_1$.

## V. SIMULATION RESULTS

The proposed algorithms were coded by using C++ programming language. All simulations were run on a notebook computer with Intel Core i7-4710 HQ CPU 2.5GHz, 16.0 GB RAM and with Windows 10 pro 64-bit operating system. Two topologies (COST239 and NSFNET showed in Figure 7) were used for simulations.

In the simulation, the arrival of request to the network follows the Poisson distribution with $\lambda$=20 connection requests per unit time and the connection-holding time obeys negative exponential distribution with a mean value of $1/\mu$=4 and 4000 connection requests are randomly generated. The updated traffic is randomly generated uniformly for different pairs of nodes. The expansion/contraction operations are performed according to the updated traffic comparing to the currently provided bandwidth. The value of *q* is randomly generated uniformly with [0, 1]. These connections are simulated for each algorithm for six different network loads.

For each proposed SEC method, a respective algorithm is also implemented for comparison. The method is denoted as

"*Release and Add* (RA)". That is, for each updated traffic, the established lightpaths and allocated FSs for original traffic demand are released and then the new primary and backup lightpaths are re-established. Several performance criteria are considered in this paper, they are (1) Blocking Ratio (BR), (2) Resource Utilization Ratio (RUR) which is the ratio of protecting resources to that of the primary resources and (3) total number of allocated FSs.

First, for the COST239 network, the simulation results are shown in Figure 8. Figure 8(a) shows that the BR of the algorithm with RA is worse than that of the respective SEC method, thus the SEC operation can get better performance than RA operation. For the proposed algorithms with DPP protection, the SDSPRA-DPP can get the lower BR than that of the DSPRA-DPP. For the proposed algorithms with SBPP protection, the DSPRA-SBPP can get the lower BR than that of the SSPRA-SBPP. Survival routing with SBPP scheme can get better BR performance than that of the method with DPP scheme. The BR increases as the network load increases. Figure 8(b) shows that the RUR of the algorithm with RA is lower than that of the algorithm since remove and re-find the primary and backup lightpaths can help to find better RUR paths. Survival routing with SBPP scheme can get better RUR performance than that of the DPP scheme. Figure 8(c) shows that the total FSs of the algorithm with RA is higher than that of the respective SEC algorithm. First, for the NSFNET network, similar simulation results can be obtained and not shown here.

## VI. CONCLUSIONS

In this paper, the spectrum expansion/contraction and survival routing problems with time-varying traffic on EONs have been studied. For a given EON and a set of connection requests, the goal is to design a spectrum expansion and contraction method to update the CF and the channel size of the lightpath so as to fit the required of the request. In the studied problem, the DPP and SBPP protecting schemes have been are considered and several routing algorithms and SEC operations have been proposed to solve this problem. Simulations were conducted to evaluate the performance of the proposed algorithms.

The proposed algorithms are heuristic algorithms and can be executed in a reasonable polynomial time. This work can be extended in the future to hand other failure cases, such as node-failure, two or more links (or nodes) failure.

## ACKNOWLEDGMENT

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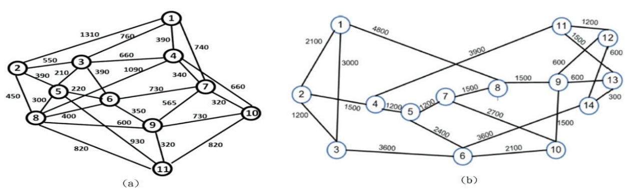

Figure 7. (a) COST239 network, (b) NSFNET

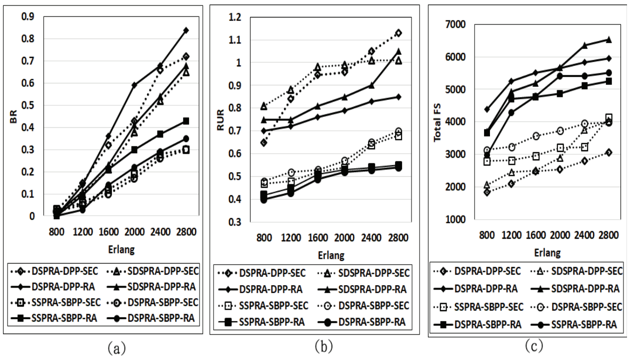


Figure 8. Simulation results on the COST239 network (a) BR, (b)RUR, (c) total number of FSs.

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