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IP-over-EON survivability against a router outage using spectrum management strategies

***Abstract**. A single instance of a router outage in IP over elastic optical networks affects multiple traffic. This traffic can be recovered using the spare capacities of unaffected flows. When the spare capacities do not suffice for grooming affected traffic, spectrum expansion is possible as long as there is no interference from the neighboring spectrum. However, a new lightpath must be prepared if that is the case. Such a condition leads to increased operator's operating expense (OPEX). To deal with this issue, we propose an algorithm that combines the spectrum expansion technique with reactive hitless defragmentation, where spectrum defragmentation is carried out to obtain a sufficient number of free frequency slots, allowing the processing of spectrum expansion. Based on the results of simulations, our proposed algorithm, in comparison to the benchmark algorithm, can successfully minimize the number of new lightpaths, which includes reducing the number of lightpath reconfigurations and minimizing additional power consumption to decrease the total cost of additional OPEX.*

Streszczenie.** Pojedyncze wystąpienie awarii routera w protokole IP w elastycznych sieciach optycznych wpływa na ruch wielokierunkowy. Ruch ten można odzyskać, korzystając z wolnych mocy przepływów, na które nie ma on wpływu. Gdy wolne moce przepustowe nie wystarczą do oczyszczenia ruchu, na który ma to wpływ, rozszerzenie widma jest możliwe, o ile nie ma zakłóceń z sąsiedniego widma. Jednak w takim przypadku należy przygotować nową ścieżkę świetlną. Taki stan prowadzi do wzrostu kosztów operacyjnych operatora (OPEX). Aby poradzić sobie z tym problemem, proponujemy algorytm łączący technikę rozszerzania widma z reaktywną defragmentacją bez trafień, w której defragmentacja widma jest przeprowadzana w celu uzyskania wystarczającej liczby wolnych szczelin częstotliwości, umożliwiających przetwarzanie rozszerzenia widma. Na podstawie wyników symulacji zaproponowany przez nas algorytm, w porównaniu z algorytmem wzorcowym, może z powodzeniem zminimalizować liczbę nowych ścieżek świetlnych, co obejmuje zmniejszenie liczby rekonfiguracji ścieżek świetlnych i zminimalizowanie dodatkowego zużycia energii w celu zmniejszenia całkowitego kosztu dodatkowego OPEX. **(Przetrwanie IP-over-EON w przypadku awarii routera przy użyciu strategii zarządzania widmem)

Keywords: Hitless Spectrum Defragmentation, IP-over-EON, Router Outage, Spectrum Expansion, Spectrum Management.
Słowa kluczowe: Bezproblemowa defragmentacja widma, IP-over-EON, awaria routera, rozszerzenie widma, zarządzanie widmem.

Introduction

Elastic optical networks (EONs) hold great promise for next-generation backbone networks as they are capable of accommodating the large-scale, changing needs of various IP-based Internet application services, i.e., high-quality video streaming, and cloud computing [1], [2]. EONs can better allocate traffic demands, and with the existence of sliceable bandwidth variable transponders (SBVTs), a lightpath may expand and contract dynamically when a traffic change occurs [3], [4]. Therefore, these two technologies, IP packet switching and EON network flexibility in the IP over elastic optical network (IP-over-EON) architecture, have become a research focus, including network survivability.

Survivability refers to a network's ability to recover after a failure using a mechanism that needs to be prepared in advance so that data loss of a considerable size can be avoided [5]. Currently, to increase the effectiveness of the failure handling mechanism, IP-over-EON survivability is carried out with a multilayer approach. The aim is to use the interaction between two layers (IP and optical), maximizing the resources available on every layer with better efficiency to recover all affected traffic [6]. One of the problems frequently occurring in IP-over-optical networks is router outages [7], [8]. This problem is responsible for millions of packets lost despite intact traffic-forming lightpaths [9]. Previous studies have prepared backup routers for outages [10]–[12], where all the impacted flows are redirected to a backup router and later forwarded to the destination. However, the idle excess of spare resources certainly impacts the operator's income [13].

Reference [14] proposed three multilayer restoration (MLR) strategies during router outages in IP-over-EONs. Instead of preparing a spare resource, MLR optimizes spare capacity for each unaffected flow. In the second MLR strategy, affected traffic is recovered using the spare capacity of unaffected traffic. However, because free FSs are insufficient, spectrum expansion is performed. If the traffic of an affected flow is high, the spectrum expansion process is unimplementable due to blocking by neighboring unaffected flows spectrum. If so, a new lightpath must be prepared (the third MLR strategy). Such a condition will increase the operator's operating expense (OPEX).

For a free spectrum suiting the traffic demand of an affected flow to be available during spectrum expansion, the blocking unaffected flows need reconfiguration. This process is similar to reactive spectrum defragmentation techniques [15]. The reactive techniques used are hitless defragmentation, which ensures that the spectrum defragmentation process does not cause traffic disruptions [16], namely, push-pull (PP) [17] and make-before-break (MBB) techniques [18]. Both generate available FSs that can maximize the spectrum expansion process. Therefore, we propose spectrum expansion with reactive hitless defragmentation (SERHiD), which aims to minimize new lightpaths, power consumption, lightpath reconfigurations, and additional OPEX.

Related Work

Researchers have been concerned about reactive defragmentation in EONs in their efforts to address the problem of spectrum fragmentation [17]–[23]. Castro *et al*. have proposed the spectrum reallocation scheme, where spectrum defragmentation is triggered when the spectrum required in one of the shortest paths does not suffice to serve new connection demands. Therefore, the spectrum on that path needs reallocation [19]. Reference [20] combined proactive and reactive defragmentation to increase the efficiency of spectrum use periodically and address the problem when connection demands are not met with sufficient space. The reactive defragmentation algorithm uses the MBB method. Wang and Mukherjee [21] proposed a hitless optical path shift (HOPS) based on the PP technique. The reactive HOPS process can be undertaken by relocating the spectrum of existing lightpaths to lower and/or higher indexes. Relevant lightpaths make as little a shift as possible to serve incoming demands.

Reference [22] combines the spectrum expansion/contraction (SEC) and spectrum defragmentation schemes. Several schemes are offered where the spectrum defragmentation process uses the PP technique and one modulation level. The reactive defragmentation strategy with spectrum conversion was investigated in [23]. When a connection request fails, the existing connections are rerouted or removed to new frequency slots (FSs). By utilizing spectrum conversion, the problem of spectrum continuity is thus relaxed when the availability of spectrum on the selected path is impossible. However, all the work above focused on defragmentation in the optical layer.

Besides the defragmentation solution explained above, the expansion technique is extensively proposed to accommodate traffic changes [24], [25]. Santos *et al*. [24] examined the distance between the spectrum on every lightpath; hence, when a traffic request comes in, free neighboring slots can expand the existing lightpath through traffic grooming. Reference [25] studied SEC with survivable routing and spectrum allocation in the case of single-layer survivability. When time-varying traffic occurs, primary and backup lightpaths perform expansion/contraction to accommodate the connection request. Nonetheless, this expansion technique cannot be done to get free spectrum width due to blocking by neighboring spectrum, particularly when there is a new high-load traffic connection request.

Furthermore, the authors developed numerous techniques for addressing the survival issue in IP-over-EONs. In [6] and [9], the resource need has been calculated in advance for it to be applicable when a failure happens. Reference [6] proposed an algorithm for pre-calculating the resources needed during several failure scenarios in IP-over-EONs, whether in the optical or the IP layer, by simultaneously using backup resources. Reference [9] investigated the use of spare capacity between layers in planning combined multilayer protection in IP-over-EONs that can be used to tackle failures in both layers, hence minimizing spectrum use and the number of operating and backup lightpaths.

Additionally, cross-layer optimization with various techniques has been conducted in [14], [26]–[28]. Amar et al. [26] proposed a mechanism to ensure quick recovery for IP layer traffic with high priority and optical layer traffic with the best effort using transponder data rate flexibility. In [27], integrated topology and adaptive modulation are proposed to deal with the dynamic traffic grooming problem; that is, by merging virtual and physical topologies to allow them to be used in selecting a route with a minimum weight. A technique for defragmenting the cross-layer spectrum in IP-over-EON is proposed in [28]. The technique employed is multilayer traffic grooming, that is, in the IP layer, by rearranging the existing lightpath traffic flow, including modifying route selection and spectrum use in the optical layer. In [14], cross-layer orchestration was used in IP-over-EONs during an IP router outage while maintaining cost-effective MLR. The remaining capacity on each lightpath can be used to recover impacted traffic. It is possible because IP traffic in every existing lightpath is dynamic, and sometimes the capacity is not used entirely.

In contrast to what was conducted in [22], our MLR-based research in IP-over-EONs uses several modulation levels, as in [14], [29], and considers simultaneous resource use in both layers when a router outage happens. We employ two reactive hitless defragmentation techniques to reduce new lightpath additions in [14]: PP and MBB. It aims to produce a sufficient free spectrum width to recover affected traffic. The PP procedure refers to [17], [21], and [22], while the MBB procedure uses [18] and [30]. Furthermore, unlike [28], the SERHiD algorithm only allocates free FSs as needed. Thus, only the existing neighboring spectrum blocks the expansion process involved in the defragmentation procedure. Finally, our work is relevant as it offers a strategy that can be implemented to optimize the spectrum expansion process at a time of router outage, which results in the operator's OPEX saving.

Spectrum Expansion with Reactive Hitless Defragmentation

A. Network Architecture and Model

A multilayer IP-over-EON network architecture consists of an EON and IP layers, as presented in Fig. 2. The devices between both layers are connected with fibers with a short reach. An IP router may function as an intermediary or a destination router. An IP router will forward all incoming data packets to a destination router through fiber optic long-distance transmissions in the EON layer when functioning as an intermediary router. When optical signals arrive at their destination, they are converted into electrical packets in the IP router to be processed further.

An IP-over-EON network is modeled as $G(V,E)$, where A group of routers is represented by V, and E represents a group of IP layer logical links. A lightpath in the EON layer supports each logical link $e \in E$. Thus, if two routers, u and v, can be connected to one logical link or more in the IP layer, one or more lightpaths in the EON layer connect their bandwidth-variable optical cross-connects (BV-OXCs). Table 1 presents the notations used in this paper.

When a router outage happens, the incoming and outgoing traffic flows are lost. The operator erases the router and updates the network condition. When an intermediary IP router fails, every impacted traffic that travels over the router is stored in R and then restored using the lightpath capacities, which are sometimes not fully utilized. As for the IP router as the traffic destination/source, we do not consider the affected traffic because the traffic is recoverable only when the router is fixed.

To recover affected traffic, the paths to be used are first determined. The unaffected flow with more spare capacity than the affected traffic ($r \in R$) is then groomed. When the traffic from an affected flow exceeds the spare capacity, two methods exist to recover it [14]. First, if it is still possible to perform expansion spectrally, then the unaffected flow performs spectrum expansion. If impossible, the second is to set up a new lightpath.

The second method is frequently preferred since the free spectrum between unaffected flows is limited. It causes an increase in OPEX due to the new lightpaths created in the form of SBVTs and FSs. To reduce the OPEX, we conduct spectrum management using SERHiD strategies to make the spectrum available in a width that suits the traffic demand of affected flows for the spectrum expansion.

B. SERHiD Strategies

Figure 1 shows the mechanism of spectrum management for recovering affected traffic using the spare capacities of existing lightpaths. Fig. 1(a) presents the initial condition of the spectrum after the router outage. There are spectrum allocations from six unaffected flows ($p1$, $p2$, $p3$, $p4$, $p5$, and $p6$), two affected flows ($r1$ and $r2$), and four links (every link consisting of 12 FSs). Under this condition, only $p1$ (FCs_{p1} = 2) has a spare capacity of 1 FS (SCs_{p1} = 1). Meanwhile, $p2$, $p3$, $p5$, and $p6$ are already entirely used in their spectrum allocations. Note that the spare capacity of $p4$ has been used to recover the traffic of $r1$ by expanding the spectrum allocation of $p4$ using the spectrum expansion ability of SBVT [4]. The initial condition of the logical links and lightpaths in Fig. 1(a) can be observed in Fig. 2(a).

Table 1. The notations used in this work

Notation	Description
$G(V,E)$	V represents all the routers, and E represents all the IP layer logical links in the IP-over-EON topology.
B	the number of FSs in total on each of the EON's fiber links.
m	the lightpath modulation level between two routers (u and $v \in V$) is used to connect the logical link.
$lp_{u,v}$	lightpaths can connect two routers (u and $v \in V$) if this indicator is set to 1; otherwise, it equals 0.
R	the matrix contains all traffic from the affected flows.
r	an affected flow in R, $r = (s_r, d_r, t_r, ts_r) \in R$, s_r is the source router, d_r is the destination router, its traffic in bit rate (t_r) and the number of FSs for t_r (ts_r).
P	the matrix is used to store all unaffected flow.
p	an unaffected flow, $p = (s_p, d_p, FC_p, SC_p, FCs_p, SCs_p) \in P$, s_p is the source router, d_p is the destination router, FC_p and SC_p are full and spare capacity in bit rate, FCs_p, and SCs_p are the numbers of FSs for FC_p and SC_p, respectively.
fp	the number of free FSs between any p and its neighbors.
$fp_{t\text{-}n}$	the number of free FSs between p_{target} (p is applied to recover r) and $p_{neighbor}$ (p is exactly on the left and right of p_{target}).
$\Delta fp_{t\text{-}n}$	The number of free FSs is still needed to recover t_r after PP defragmentation is conducted, where $\Delta fp_{t\text{-}n} = ts_r - SCs_p - fp_{t\text{-}n}$
p_m	an unaffected flow, $p_m \in P$, where p_m is an option for the MBB defragmentation process.
fp_p_m	the number of free FSs between p_m neighbors after p_m does MBB defragmentation.
k	the number of shortest paths that exist between s_r and d_r.
n	the number of new FSs assigned.
W_m	the power required to occupy an FS with a level of modulation (m) (Table 2)
W_0	the static power usage of an SBVT, where W_0 equals 100 W.
α	the power consumption unit cost
c_l	the lump-sum cost of a lightpath reconfiguration
$\|R\|$	the number of affected flows

It is assumed that there is an attempt to recover the affected flow $r2$ through A-B and B-C links. On those links, there is $p1$, which can be used to groom traffic $r2$. If traffic $r2$ does not exceed 1 FS ($ts_{r2} \leq SCs_{p1}$), then the spare capacity of $p1$ can be used, as shown in Fig. 1(b). Note that this condition does not result in an OPEX increase. If traffic $r2$ requires a spectrum allocation greater than 1 FS ($ts_{r2} > 1$), several strategies exist to recover it. If ts_{r2} = 2, conducting a traffic grooming process is still possible by using 1 free FS between $p1$ and $p3$ ($fp_{1\text{-}3}$ = 1, occupying the third FS index in Fig. 1(a)). As in Fig. 1(c), a spectrum expansion is carried out in this condition. It is like the recovery of traffic $r1$ to $p4$.

However, if traffic $r2$ is 3 FSs (ts_{r2} = 3) or 4 FSs (ts_{r2} = 4), spectrum expansion is unimplementable as it is blocked by $p3$. Therefore, SERHiD strategies are necessary to make free contiguous slot blocks ($fp_{1\text{-}3}$) available, which will be sufficient for recovering the traffic of affected flow $r2$. Figs. 1(d) and 1(e) show the results of the two SERHiD strategies we consider in this work. In the first one, when ts_{r2} = 3, there is a deficit in free FS of 1 FS. Hence, the PP defragmentation technique is applied, where all p ($p3$, $p4$, and $p5$) that block the spectrum expansion of $r2$ are shifted to the right by 1 FS. The shift of FSs is possible since there is 1 free FS available in the ninth FS index (Fig. 1(a)). Because there are 3 free FSs (SCs_{p1} = 1 and $fp_{1\text{-}3}$ = 2, hence $\Delta fp_{1\text{-}3}$ = 0) that can accommodate ts_{r2}, it is possible to carry out a spectrum expansion process, as seen in Fig. 1(d).

The second strategy uses the PP and MBB defragmentation techniques. This strategy is applied when traffic $r2$ increases. For instance, ts_{r2} = 4, if there is still a deficit in free FS after a maximum attempt of PP defragmentation, then the MBB defragmentation technique is employed. According to Fig. 1(d), there are only two free FSs available ($fp_{1\text{-}3}$ = 2); thus, an addition of 1 FS is needed to recover $r2$ ($\Delta fp_{1\text{-}3}$ = 1; ts_{r2} - SCs_{p1} - $fp_{1\text{-}3}$ = 4 - 1 - 2).

Therefore, the unaffected flows that block the spectrum expansion of $p1$ are stored. Of the options available, one p_m or more are selected for rerouting to make up the deficit in FS ($\Delta fp_{1\text{-}3}$). Note that we minimize the number of p_m selected by finding $\sum fp\_p_m$ that approaches the FS deficit size ($\Delta fp_{t\text{-}n}$). In this case, there are 2 p_m, $p3$, and $p4$. However, only $p3$ is selected for rerouting as it produces 1 free FS (fp_p_m = 1), in which case the result meets the $\Delta fp_{1\text{-}3}$ need. Note that $p4$ is not an option as it is already used to groom traffic $r1$. The MBB defragmentation technique reroutes $p3$ (p_m) to the D-A link and places it in the first FS index. Afterward, traffic $r2$ (ts_{r2} = 4) is recovered, as illustrated in Fig. 1(e). Figure 2(b) depicts logical links and lightpaths condition after $p3$ is successfully rerouted.

The three strategies above result in an OPEX increase with an increased number of FSs used (Figs. 1(c), 1(d), and 1(e)) because $p1$ lacks sufficient spare capacity (SCs_{p1} = 1) to accommodate traffic $r2$. Since all the strategies increase the number of FSs, there is additional power consumption and lightpath reconfigurations due to spectrum expansion.

As shown in Fig. 1(f), a new spectrum allocation is created to accommodate traffic $r2$ (ts_{r2} = 5), since after the two SERHiD strategies are applied, a deficit of 1 FS remains ($\Delta fp_{1\text{-}3}$ = 1; ts_{r2} - SCs_{p1} - $fp_{1\text{-}3}$ = 5 - 1 - 3). The change in the logical links and lightpaths resulting from this new spectrum allocation can be seen in Fig. 2(c). It establishes of new lightpath results in additional OPEX, including power consumption (increased use of SBVT and FSs) and lightpath reconfiguration.

Table 2. Modulation formats of lightpaths [14]

Modulation Format	Optical reach (km)	Modulation level (m)	FS Capacity (Gb/s)	Dynamic power usage (W_m)
BPSK	4800	1	12.5	112.4
QPSK	2400	2	25	133.4
8QAM	1200	3	37.5	154.4
16QAM	600	4	50	175.5

C. Proposed Algorithm

As explained previously, the two SERHiD strategies we proposed in Figs. 1(d) and 1(e) are developments of the strategy in Fig. 1(c). Meanwhile, the three strategies in Figs. 1(b), 1(c), and 1(f) refer to the MLR strategies in [14]. In general, all the procedures conducted in this research are illustrated in *Algorithm* 1, where all traffic from the affected flows (R) is ordered descendingly, and it is attempted to recover every $r \in R$ through one of the k shortest paths (KSP) from s_r to d_r.

Using hitless defragmentation, such as in SERHiD I (PP defragmentation only) or SERHiD II (a combination of PP and MBB defragmentation) reactively aims to obtain enough FSs room, which is initially blocked by $p_{neighbor}$. As a result, because the spectrum slots from SCs_p and $fp_{t\text{-}n}$ have sufficed for spectrum expansion, ts_r can eventually be groomed into p_{target}.

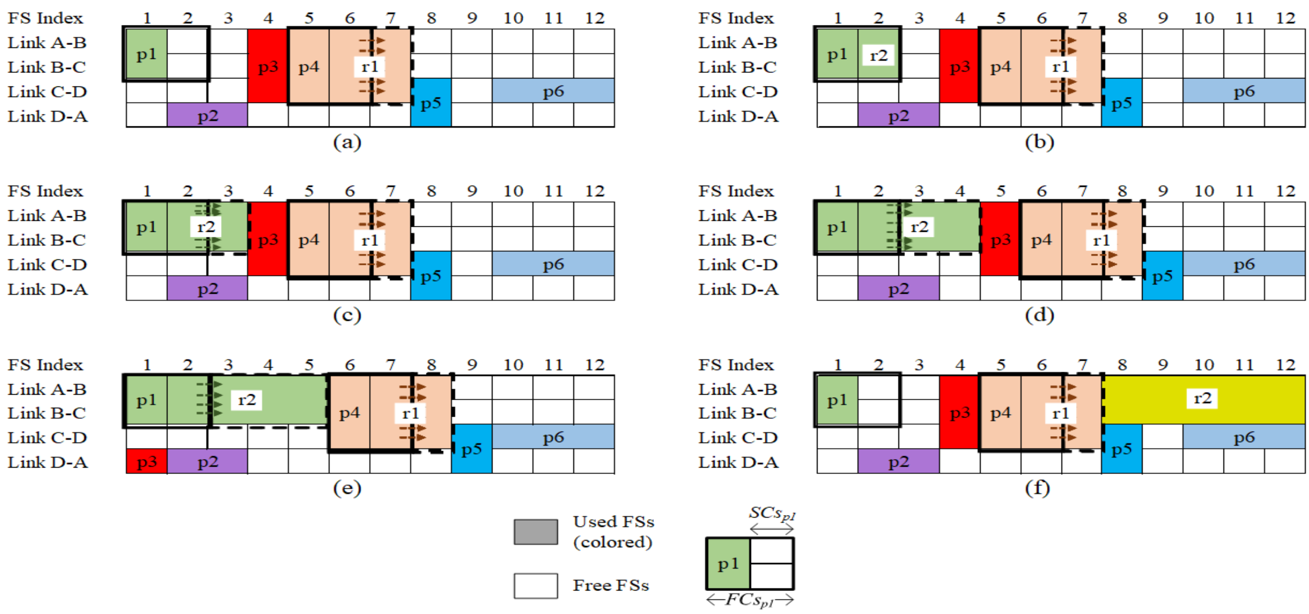


Fig. 1. Spectrum management strategies after a router outage: (a) Initial condition; (b) Spare capacity $p1$ is sufficient to groom ts_{r2} ($SCs_{p1} \geq ts_{r2}$); (c) Spectrum expansion only, ($ts_{r2} > SCs_{p1}$); (d) SERHiD Strategy I (spectrum expansion and PP defragmentation); (e) SERHiD Strategy II (spectrum expansion, PP, and MBB defragmentation); (f) New spectrum allocation ($r2$).

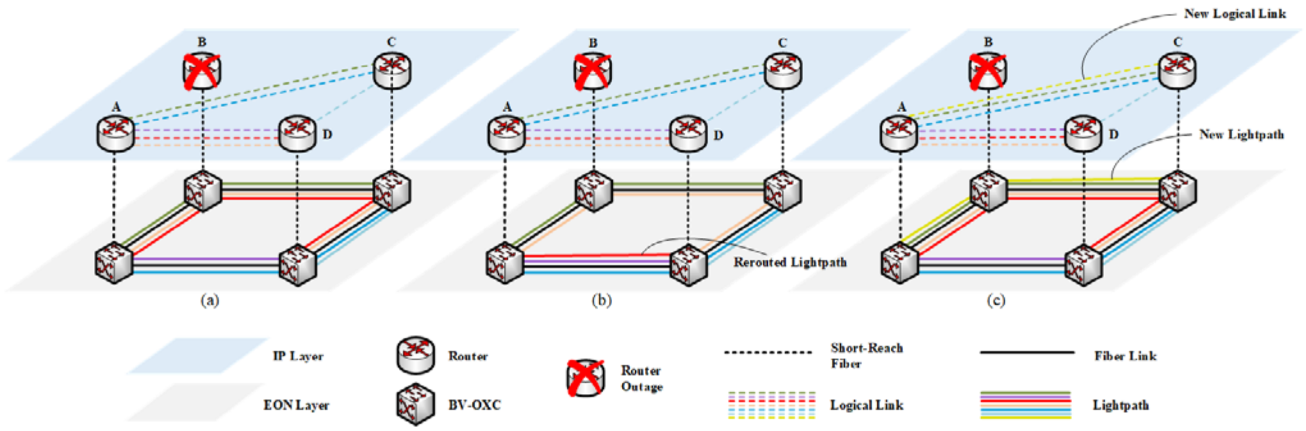


Fig. 2. IP-over-EON architecture, conditions in logical links and lightpaths when spectrum management occurs: (a) Following a router outage (initial condition); (b) When $p3$ is rerouted; (c) When $r2$ is created a new lightpath.

The procedure of the SERHiD strategies can be seen in *Algorithm* 2. Reference [31] proposed four sub-problems for designing a defragmentation procedure in EONs, i.e., how, when, what to reconfigure, and how to migrate traffic. We will answer all of those questions after explaining *Algorithm* 2 below.

First, the PP defragmentation technique is applied (*Lines* 2-15), where $p_{neighbor}$ is shifted until $fp_{t\text{-}n} \geq ts_r$ - SCs_p is obtained. After the determination of p_{target}, $p_{neighbor}$, and $fp_{t\text{-}n}$, searches are carried out (*Line* 2). Then, in the PP process loop, $p_{neighbor}$ is shifted to the left and/or right gradually (*Lines* 4-9), including all $p \in P$ that block the shift of $p_{neighbor}$. If the $p_{neighbor}$ shift can no longer be performed and $fp_{t\text{-}n} < ts_r$ - SCs_p, the loop process is ended (*Lines* 11-15). *Algorithm* 2 is terminated if the PP defragmentation process is successful (*Line* 16).

Second, if the PP defragmentation technique fails, the process is resumed using the MBB defragmentation (*Lines* 17-33). An MBB defragmentation process is conducted after $fp_{t\text{-}n}$, p_m, and $\Delta fp_{t\text{-}n}$ are known. In *Lines* 20-21, it is ensured that $p_{neighbor}$ is preferred as p_m for rerouting. Meanwhile, in *Line* 22, it is ensured that the p_m preferred meets the condition $\sum fp\_p_m \geq \Delta fp_{t\text{-}n}$. Then, if one or more p_m is selected, rerouting is carried out, including $\Delta fp_{t\text{-}n}$, $fp_{t\text{-}n}$, and p_m is updated (*Lines* 25-27). In this case, p_m is rerouted to a path that is link-disjointed (LD) from the original path and whose spectrum is allocated to available slots with the lowest index (first fit, FF) [32]. The execution of *Algorithm* 2 is terminated if the MBB process has yet to provide sufficient $fp_{t\text{-}n}$ to accommodate ts_r (*Lines* 33-34). Affected traffic t_r recovery is then conducted by setting up a new lightpath by finding several free contiguous FSs (ts_r).

Algorithm 1: Overall Procedure

```
while invoke the MLR algorithm in [14] do
if an unaffected flow is selected for grooming t_r in a link,
but SC_p and free FSs are insufficient to be spectrally
expandable then
  invoke Algorithm 2 to do the SERHiD strategies;
  if Algorithm 2 is successful then
    an unaffected flow can perform spectrum expansion;
  else
    continue the MLR algorithm;
  end
end
end
```

The answers are from using the SERHiD algorithm to the four questions posed when designing a defragmentation procedure [31]. How to reconfigure: $p_{neighbor}$ is shifted to the left and/or right (*Algorithm* 2, *Lines* 4-9), and p_m is rerouted (*Algorithm* 2, *Lines* 20-27). The p_m rerouting and spectrum allocation processes use LD and FF. How to migrate traffic: Migration is conducted by the PP and MBB defragmentation techniques. When to reconfigure: SERHiD is executed when the spectrum expansion process is inexecutable due to insufficient free FSs. What to reconfigure: all unaffected flows ($p_{neighbor}$ and p_m) block p_{target} to recover t_r through spectrum expansion.

Algorithm 2: SERHiD Algorithm

```
Input   :  G(V,E) after router outage, p ∈ P, and  r ∈ R
Output  :  an SERHiD strategy to recover r ∈ R
1   while True
2     find p_neighbor and fp_t-n;
3     while fp_t-n < ts_r - SCs_p do
4       if p_neighbor is on the left of p then
5         p_neighbor do PP one step to the left;
6       end
7       if p_neighbor is on the right of p then
8         p_neighbor do PP one step to the right;
9       end
10      update p_neighbor and fp_t-n;
11      if p_neighbor cannot do PP and fp_t-n < ts_r - SCs_p then
12        DefragStatus = False;
13        break;
14      end
15    end
16    if fp_t-n ≥ ts_r - SCs_p then break end
17    update fp_t-n, p_m;
18    calculate Δfp_t-n;
19    while Δfp_t-n > 0 do
20      if p_m is neighbor of p_target and FCs_p of p_m ≥ Δfp_t-n then
21        select p_m to reroute;
22      else
23        select p_m where fp_p_m ≥ Δfp_t-n
          (if p_m > 1 needed, then select every p_m to fulfill ∑fp_p_m ≥
          Δfp_t-n);
24      end
25      if any p_m is selected to reroute then
26        reroute p_m;
27        update Δfp_t-n, fp_t-n, p_m;
28      else
29        DefragStatus = False;
30        break;
31      end
32    end
33    if DefragStatus = False then
34      break;
35    end
36  end
```

Equation (1) is used to calculate the additional OPEX resulting from the use of the four strategies discussed above (Figs. 1(c) - 1(f)).

(1) $$C = \alpha \cdot (W_m \cdot n + W_0) + c_l$$

The additional power consumption is denoted by $W_m \cdot n + W_0$ [33], where W_m denotes the power consumed when occupying an FS with a level of modulation (m). The W_0 value for Fig. 1(f) is 100 W, which resulted from the increased usage of SBVT due to setting up a new lightpath. Besides, $W_0 = 0$. In eq. (2), n is the number of newly assigned FSs, which is resulted from reducing FSs from the traffic of an affected flow (ts_r) by the spare capacity of an unaffected flow (SCs_p).

The number of FSs needed by affected traffic t_r (given in Gbps) can be seen in eq. (3) [19], where 12.5 represents slot width (given in GHz), and m indicates modulation format (bps/Hz). The m value is strongly determined by the optical reach of the lightpath (Table 2). The SCs_p value can be obtained in the same manner as in eq. (3).

(2) $$n = ts_r - SCs_p$$

(3) $$ts_r = \left\lceil \frac{t_r}{12.5 \cdot m} \right\rceil$$

(4) $$c_l = |R| \cdot \left(\sum_{u,v \in V} tp_{u,v} \right) \cdot \left(\sum_{r \in R} \left\lceil \frac{t_r}{12.5} \right\rceil \cdot \max(W_m) + W_0 \right)$$

Equation (4) is the maximum overall power cost, primarily aiming to minimize lightpath reconfigurations. The unit cost of power consumption is denoted by α, and to normalize the power cost, $\alpha = 1$ [14]. It is attempted to minimize the C value in (1) using the SERHiD strategies. Note that (1), (2), and (4), and the mechanism of affected flows ($r \in R$) recovery used the MLR algorithms in [14]. In addition, it is assumed that there are enough resources to execute all the strategies above.

Performance Evaluation

A. Simulation Parameters

As depicted in Fig. 3, we use the NSFNET topology for IP-over-EON in this study [14]. The existing condition is generated based on several assumptions; an FS has a 12.5 GHz bandwidth, and its capacity is determined by its level of modulation (Table 2). Each link in the EON layer consists of 358 FSs [27]. The connection between each router pair in the IP layer ($tp_{u,v}$) is randomly generated [0,1]. If a router pair is connected ($tp_{u,v} = 1$), one and more existing lightpaths exist in the EON layer, and each lightpath has multiple FSs. Both are randomly selected in the range of [1,10] lightpaths and [1,10] FSs. In the EON layer, the physical routing path is regarded as the same for all lightpaths between the same router pair utilizing shortest path routing. The FF spectrum assignment is used to configure each lightpath.

We consider two traffic conditions: heavy traffic, with all existing lightpaths having a spare capacity of 20% on average, and moderate traffic, with an average spare capacity of 40%. The spare capacity for each lightpath is randomly generated to imitate the dynamic IP traffic. Afterward, a router is selected at random to fail. All impacted flows are saved in matrix R, and the traffic of every impacted flow is randomly generated with fixed total traffic volumes. There is also a matrix P, which contains all unaffected flows and is subsequently used to recover affected flows. There is a KSP (k = 4) for each affected flow $r \in R$. Then, a path that can minimize the C value in equation (1) is chosen. Note that there is at least one path to recover each affected flow. In the simulations, every total traffic volume is subjected to 10 iterations. The results are averaged to gain final data.

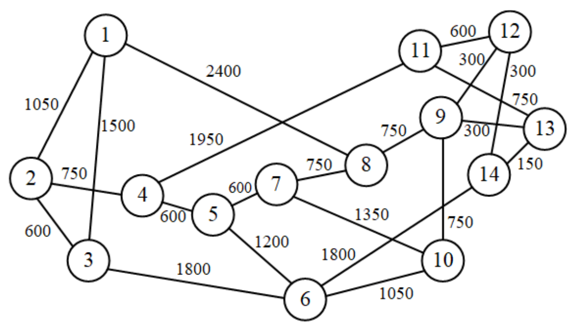
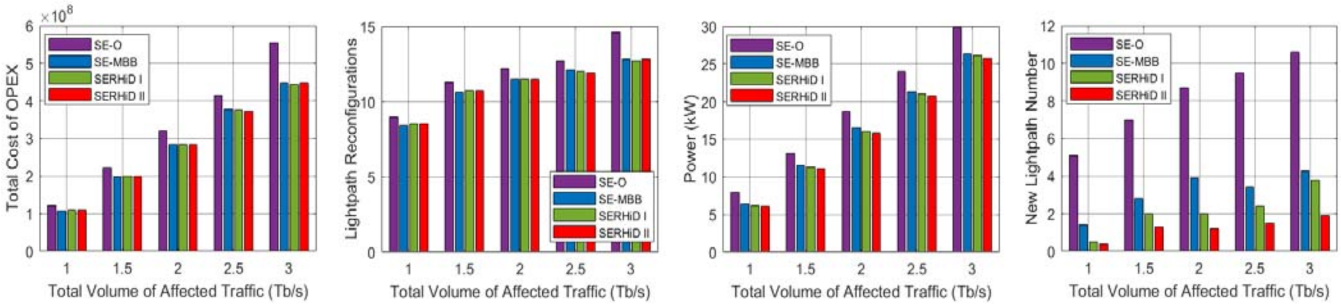
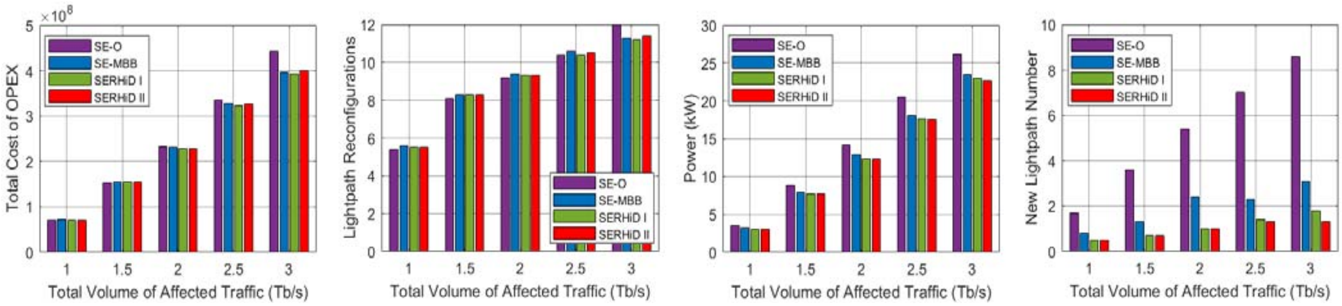


Fig. 3. NSFNET topology for IP-over-EON with fiber link lengths kilometers (14 nodes and 22 links).



(a) (b) (c) (d)

Fig. 4. Result of heavy traffic: (a) total cost of additional OPEX; (b) lightpath reconfigurations (spectrum expansion and new lightpath); (c) power consumption; and (d) new lightpath number.



(a) (b) (c) (d)

Fig. 5. Result of moderate traffic: (a) total cost of additional OPEX; (b) lightpath reconfigurations (spectrum expansion and new lightpath); (c) power consumption; and (d) new lightpath number.

For the benchmark, we use the second strategy of the MLR strategies in [14], which only uses spectrum expansion (SE-O) to recover affected traffic. Furthermore, to provide a more comprehensive result of using the defragmentation technique in a router outage case, we present the results from spectrum expansion with MBB defragmentation (SE-MBB). The MBB defragmentation process is executed by rerouting $p_{neighbor}$ one by one, which blocks the spectrum expansion process from p_{target}.

B. Simulation Results

Figure 4 depicts the results for several strategies under heavy traffic conditions. Figure 4(a) indicates that the proposed algorithm has the lowest total cost for all the total volume of affected traffic compared to the benchmark SE-O. Furthermore, we observed the number of lightpath reconfigurations in Fig. 4(b) and as the additional power consumption in Fig. 4(c) when the four strategies were used. The results of the SERHiD strategies in Fig. 4(b) are slightly better than those of the SE-O strategy at reducing the number of lightpath reconfigurations used to recover affected flows. It shows that our algorithm can optimize the spectrum expansion process, resulting in chosen paths that can minimize the use of unaffected flows. The results on additional power consumption in Fig. 4(c) indicate that the SERHiD II yields the lowest results and SE-O produces the highest. At the same time, the results from SERHiD I and SE-MBB are comparable. It confirms that the number of additional FSs and SBVTs used can be minimized using PP and MBB defragmentation.

Although the results from using three strategies, SE-MBB and the SERHiD strategies, presented in Figs. 4(a) and 4 (b) are comparable. The number of new lightpaths set up using the SERHiD II strategy is the lowest, followed by SERHiD I and SE-MBB, as shown in Fig. 4(d). The performance gaps between SE-O and SERHiD I and II increase with the total volume of affected traffic. It is because the spare capacities of unaffected flows and the free FSs between unaffected flows, cannot accommodate the traffic of the affected flows in SE-O. Therefore, the setting up of new lightpaths becomes more frequent. In the case of SE-MBB, sometimes, unaffected flows cannot be conducted during rerouting because they have been used to recover affected traffic. As a result, it is impossible to perform spectrum expansion due to a lack of free FSs, leading to more additional new lightpaths being used than those used in our algorithm.

Figure 5 depicts the results for the moderate traffic condition. It obtained similar trends as those in Fig. 4. However, in Fig. 5(b), we find that the outcomes of the four strategies on the number of lightpath reconfigurations are comparable. It is because each unaffected flow in moderate traffic has a higher average spare capacity than in heavy traffic. As a result, all the strategies can recover some affected traffic using the spare capacity of unaffected flows. These findings are supported by Fig. 5(c), which shows that the additional power consumption is lower than in Fig. 4(c). However, SE-O has the highest additional power consumption in Fig. 5(c) since it obtains more new lightpaths than the other strategies. Nonetheless, as shown in Fig. 5(d), the SERHiD strategies continue to produce the lowest number of new lightpaths.

Conclusions

In this work, we investigated how to solve the spectrum management problem by reducing the setup of new lightpaths when recovering affected traffic after a router fail in IP-over-EON. We specifically evaluated the situation during the spectrum expansion process, employing the spare capacity of an unaffected flow during the affected traffic recovery. However, it was inapplicable due to blockage by the neighboring spectrum. We proposed an algorithm, namely SERHiD, to minimize the additional OPEX resulting from such a condition. We designed two SERHiD strategies using two hitless spectrum defragmentation techniques to conduct spectrum reallocation. The algorithm proposed was simulated using two traffic conditions. The simulation results indicated that the SERHiD strategies could reduce the number of new lightpaths better than the benchmark algorithm (SE-O). It means that our algorithm effective allocated enough spectrum width for the process of spectrum expansion. It resulted in lower additional power consumption due to reduced SBVTs and FSs use and fewer lightpath reconfigurations, resulting in minimal additional OPEX. It was also shown that the results of using both SERHiD strategies were superior in four simulation parameters over the other strategies. These simulation results confirmed the importance of using spectrum defragmentation to recover traffic from affected flows due to a router outage. Furthermore, other paths may have better existing spare capacity than KSP, which can reduce the spectrum defragmentation process. As a result, our algorithm will include adaptive routing in the near future to reduce the additional OPEX further.

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