Survivability with Adaptive Routing and Reactive Defragmentation in IP-over-EON after A Router Outage

Original Scientific Paper

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Abstract *–The occurrence of a router outage in the IP layer can lead to network survivability issues in IP-over-elastic-optical networks with consequent effects on the existing connections used in transiting the router. This usually leads to the application of a path to recover any affected traffic by utilizing the spare capacity of the unaffected lightpath on each link. However, the spare capacity in some links is sometimes insufficient and thus needs to be spectrally expanded. A new lightpath is also sometimes required when it is impossible to implement the first process. It is important to note that both processes normally lead to a large number of lightpath reconfigurations when applied to different unaffected lightpaths. Therefore, this study proposes an adaptive routing strategy to generate the best path with the ability to optimize the use of unaffected lightpaths to perform reconfiguration and minimize the addition of free spectrum during the expansion process. The reactive defragmentation strategy is also applied when it is impossible to apply spectrum expansion because of the obstruction of the neighboring spectrum. This proposed strategy is called lightpath reconfiguration and spectrum expansion with reactive defragmentation (LRSE+RD), and its performance was compared to the first Shortest Path (1SP) as the benchmark without a reactive defragmentation strategy. The simulation conducted for the two topologies with two traffic conditions showed that LRSE+RD succeeded in reducing the lightpath reconfigurations, new lightpath number, and additional power consumption, including the additional operational expense compared to 1SP.*

Keywords*: adaptive routing, spectrum expansion, reactive defragmentation, router outage, lightpath reconfiguration, IP-over-EON*

1. INTRODUCTION

The increasingly diverse use of internet-based applications is observed to have led to rapid traffic growth. Some of these application services include online gaming, video streaming, and smart systems requiring large and dynamic traffic, making it important to ensure efficient utilization of optical networks [1]. One of the promising solutions offered by transport network technology for efficient spectrum utilization is the elastic optical network (EON) [2]. The efficiency is associated with the possibility of dividing the spectrum in the EON into smaller spectra called frequency slots (FSs), which are adjustable based on demand [3]. The EON flexibility is linked to the capability of sliceable bandwidth variable transponders (SBVTs) to generate diverse optical flows that can be directed to different destinations [4]. Moreover, SBVTs have the capacity to accommodate dynamic traffic changes by expanding and contracting the slot width on a lightpath [5]. This shows that EON and IP technology are promising solutions to integrate the next IP-over-optical backbone networks [6].

Multilayer IP-over-EON offers flexibility and adaptivity in exchanging huge amounts of traffic. The existence of failure in one of the layers, either the IP or optical/EON layer, has the ability to cause data loss on the user side and decrease operator revenue. This is the reason it is very important to consider the survivability in IP-over-optical networks [7]. It is important to note that failures in the optical/EON layer can be caused by fiber optic cable cuts and those in the IP layer by router outages, which is more common than fiber optic failure [8]. Generally, a backup router is usually set up when the primary router experiences a problem [9], but this is not economical from the perspective of operators.

Network survivability in IP-over-EON is established in a multilayer manner by utilizing unused capacity in each layer after a failure in order to reduce the provision of backup routers [7, 10]. The process of handling survivability with a focus only on each layer causes an increase in network costs and results in inefficient use of network resources [7, 10]. The failure of routers can influence traffic flows, but they can be restored to unaffected lightpaths using the multilayer restoration (MLR) mechanism [11]. This usually leads to the selection of the path utilizing the spare capacity on the unaffected lightpath in each link. The determination of the best routing is necessary to obtain a path that can reduce the occurrence of lightpath reconfiguration to allow the optimization of network resources [12].

The shortest-path routing is often used because of its simplicity in pathfinding. It is normally applied offline based on network information, specifically in fixed and fixed alternate routing [13, 14]. However, this path sometimes does not provide optimal results due to the possibility of another path producing a better outcome. This means there is a need to consider all potential paths connecting the source to the destination for a better objective value. Therefore, adaptive routing is considered a solution to find the best path dynamically according to the current conditions of the network [15].

In addition to resolving routing issues, there is a need to consider maximizing the utilization of spare capacity for restoring affected traffic. This minimizes the need for setting up a new lightpath during the lightpath reconfiguration procedure. The MLR strategies [11] outline the lightpath reconfiguration procedure in IP-over-EON networks, which occurs under two conditions. The first involves the unaffected lightpath utilizing its spectrally expanded spare capacities to recover the affected traffic. The second arises when a new lightpath is established due to neighboring spectrum blocks hindering the spectrum expansion process. This occurs when the demand for spectrum from the affected traffic exceeds the spare capacity on the unaffected lightpath and the free spectrum. It is crucial to acknowledge that the second condition leads to a higher increase in the operational expense (OPEX) of the operator.

For this reason, spectrum defragmentation has to be performed reactively to ensure sufficient spectrum width for the expansion process. A typical example of the reactive defragmentation (RD) technique for avoiding traffic disruption is push-pull (PP) defragmentation [16]. This technique gradually shifts the unaffected spectrum step by step without making any spectrum leaps.

This work proposes two strategies for optimizing resource usage in IP-over-EON networks. The first strategy involves performing the best path selection to optimize the usage of unaffected lightpaths and minimize the need for spare spectrum expansion. To achieve this, we propose the lightpath reconfiguration and spectrum expansion (LRSE) algorithm, an extension of our previous work in [12]. The second strategy focuses on executing the RD algorithm using the PP defragmentation technique, specifically when the neighboring spectrum blocks hinder the expansion process. The primary goals of these strategies are to reduce lightpath reconfigurations, minimize the establishment of new lightpaths, decrease power consumption, and lower OPEX.

By implementing the LRSE+RD strategies, network operators can optimize the use of existing resources, which are often over-provisioned to handle peak traffic. This delay in adding network resources can have a positive impact on increasing operator revenue in the long run.

2. RELATED WORK

Adaptive routing in EONs has been proposed in several papers. In [13], a routing method was introduced by using distance-adaptive modulation and bit rate-adaptive techniques to enhance spectrum utilization efficiency. Another study by [17] focused on improved adaptive routing and proposed two algorithms to minimize rejected demands or the probability of bandwidth blocking. Additionally, [18] presented an adaptive routing algorithm that finds a path based on the maximum available free FSs. In the context of survivable EONs, [19] addressed adaptive routing for various traffic classes. The work by [20] took into account aspects of survivability during connection requests in EONs and employed several strategies to solve routing, spectrum allocation, and scheduling problems for multi-class traffic. To minimize the spectrum fragmentation problem for dynamic traffic conditions in EONs, [21] introduced an adaptive routing scheme with first-last-mixed-fit spectrum assignment. Combining distance and hop, [22] proposed a method to overcome the problem of dynamic traffic grooming by determining the route for each traffic demand based on the path length threshold.

Spectrum defragmentation strategy for EONs was explained in [16, 23-29]. Specifically, in [23], dynamic spectrum defragmentation was explored based on the current condition of the routing network. The study by [24] introduced a hitless reconfiguration strategy using the PP defragmentation mechanism to relocate existing lightpaths and accommodate incoming requests efficiently. By using the hop tuning technique, [25] studied reactive defragmentation to improve spectral efficiency. Moreover,

[26] presented a route partitioning strategy that utilizes the PP defragmentation technique to maximize allowed traffic in EONs. Proactive and reactive defragmentation processes were proposed to enhance spectrum utilization efficiency [16]. A metaheuristic approach was also suggested to simplify connection reconfiguration and FSs index realignment [27]. The work by [28] focused on reactive defragmentation and spectrum conversion, illustrating situations where a connection request cannot be fulfilled due to the unavailability of the same spectrum allocation on the selected path. In such cases, the existing connection was re-established on a shorter path, or the FSs allocation was shifted. Furthermore, [29] discussed optimal defragmentation and split spectrum techniques for serving connection requests. When spectrum allocation on a single path was insufficient, traffic demand was split across the shortest link-disjoint paths.

Table 1. The notations listed in this paper

Notation	Description
$G(V,E)$	the topology of the IP-over-EON, V symbolizes all routers, and E symbolizes all IP layer logical links.
B	the total number of FS on each EON layer link.
m	the lightpath modulation level is used to carry a logical link in the IP layer between two routers, where u and $v \in V$.
$tp_{u,v}$	the indicator is set to 1 if routers u and v can be connected by lightpaths; otherwise, it is set to 0 (u and $v \in V$).
R	the matrix is utilized to save all of the affected flow.
r	an affected traffic flow, $r = (s_r, d_r, t_r, ts_r) \in R$, where s_r and d_r are source and destination routers, t_r is the bit rate, and the number of FSs for t_r is ts_r.
P	the matrix is utilized to save all of the unaffected flow.
p	an unaffected traffic flow, $p = (s_p, d_p, FC_p, SC_p, FCs_p, SCs_p) \in P$, where sp and dp are source and destination routers, full and spare (unused) capacity in bit rate are FC_p and SC_p, and the number of FSs for FC_p and SC_p are FCs_p and SCs_p.
fsp	the number of free FSs that exist between any p and its neighbors.
fsp_{t-n}	the number of free FSs that exist between p_{target} (p is used to recover r) and $p_{neighbor}$ (p is exactly on the left and right of p_{target}).
PSC_p	the potential spare capacity of p, namely the sum of spare capacity and free FSs ($SCs_p + fsp_{t-n}$)
Δfsp_{t-n}	the number of free FSs that is still needed to recover t_r, where: $\Delta fsp_{t-n} = PSCp - ts_r$ (for spectrum expansion), or $\Delta fsp_{t-n} = fsp - ts_r$ (for setting up a new lightpath), if $\Delta fsp_{t-n} \geq 0$, $FSvalueList = 0$, and if $\Delta fsp_{t-n} < 0$, $FSvalueList = \Delta fsp_{t-n}$ (Algorithm 2).
rl	the indicator that returns 1 if the reconfigured lightpath is reused and 0 otherwise.
nrl	the number of reconfigured lightpaths (rl).
nLR	the number of lightpath reconfigurations in a path that is caused by spectrum expansion or setting up a new lightpath.
$ratioLR$	the ratio between nrl and nLR in a path.
$sumFSv$	the total number of negative values of all Δfsp_{t-n} in a path.
$maxm$	the highest modulation level value in a path.
ro	the broken router, router outage (ro), $ro \in V$.
n	the number of FSs that have just been recently assigned.
W_m	the power consumed by a frequency slot with modulation level (m) (Table 2).
W_0	a constant representing an SBVT's static power consumption ($W_0 = 100$ W).
α	the unit of the power consumption cost ($\alpha = 1$)
c_l	the additional cost of reconfiguring a lightpath
$\|R\|$	the number of affected flows due to a router outage.

Studies on spectrum expansion in EONs were covered in [30-34]. In [30], a dynamic traffic grooming algorithm was proposed, allowing the lightpath to expand and contract based on traffic conditions. The discussion in [31] revolved around the utilization of spectrum spacing between lightpaths to generate free adjacent FSs, accommodating new traffic requests by performing spectrum expansion through traffic grooming. Furthermore, [32] focused on survivable RSA and spectrum expansion or contraction under time-varying traffic conditions. Spectrum expansion or contraction could be simultaneously performed on primary and backup lightpaths when problems occurred in the optical layer. It is important to note that the path selection was based on weighted hop count. The problem of spectrum sharing and defragmentation to address dynamic traffic demands in EON was studied in [33]. Spectrum expansion or contraction was performed to adapt to traffic changes, and when neighboring spectra blocked the expansion process, spectrum defragmentation was executed to generate a free spectrum. The work by [34] proposed several path selection techniques to address the spectrum expansion/contraction problem with delay-variation constraints and multipath routing.

Several multilayer survivability algorithms have been proposed to overcome failures in IP-over-EON. In [10], multilayer survivability techniques were introduced to optimize primary and backup resources under various failure conditions. The work in [7] investigated integrated protection planning, preparing spare capacity between layers to address failures in the optical and IP layers. The study by [11] focused on cost-effective MLR to overcome IP router outages in IP-over-EONs through cross-layer orchestration. A paper [35] analyzed an MLR mechanism in IP-over-EONs, ensuring high-priority traffic was quickly recovered in the IP layer while best-efforts traffic was unloaded to the optical layer. Some MLR methods concentrated solely on the failure problem in the optical layer [36]. In [37], integer linear programming was used to design a multilayer survivability technique in IP-over-EON to overcome latency problems in multi-class traffic.

Table 2. Parameters related to lightpath modulation formats [11].

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

Multilayer optimization in IP-over-EON was studied in [12, 38-40]. For example, [38] presented an algorithm for reconfiguring multilayer networks to accommodate periodic IP traffic changes, utilizing spectrum expansion and reduction processes during adaptive bandwidth resizing. A study in [39] investigated dynamic traffic grooming and proposed adaptive modulation and topology integration based on cross-layer routing and spectrum allocation. In [40], cross-layer spectrum defragmentation was employed to improve spectrum usage in IP-over-EON. The process occurred in both layers by rearranging traffic flows in the IP layer as well as making routing and spectrum utilization changes in the optical layer. The study by [12] proposed adaptive routing to recover traffic after an IP router failure and introduced an ALRP routing strategy that reduced lightpath reconfigurations compared to conventional schemes.

This paper is the development of previous work [12], with a focus on optimizing the reconfigured lightpath usage and implementing a spectrum expansion process that involves reactive defragmentation to obtain sufficient free FSs with minimal addition. It is crucial to acknowledge that this approach differs from what was carried out in [18, 22]. In the reactive defragmentation technique, the PP defragmentation is used without spectrum conversion, and the best path is specifically chosen for recovering affected traffic, as opposed to [25, 28, 29]. When compared to [31, 34, 33], the proposed strategies do not require preparing spectrum spacing; rather, it utilizes existing free FSs to perform spectrum expansion on a selected path. To optimize remaining resources in both layers and reduce the setup of new lightpaths and the process of lightpath reconfiguration, various modulation formats and an adaptive routing strategy are employed, achieving better results than the ones presented in [11]. Furthermore, the approach differed from [39, 10, 35], and [37], as all affected traffic is restored using the same strategies (adaptive routing and reactive defragmentation). There is no prioritization of specific traffic, and the spare capacity of unaffected lightpath is utilized for MLR.

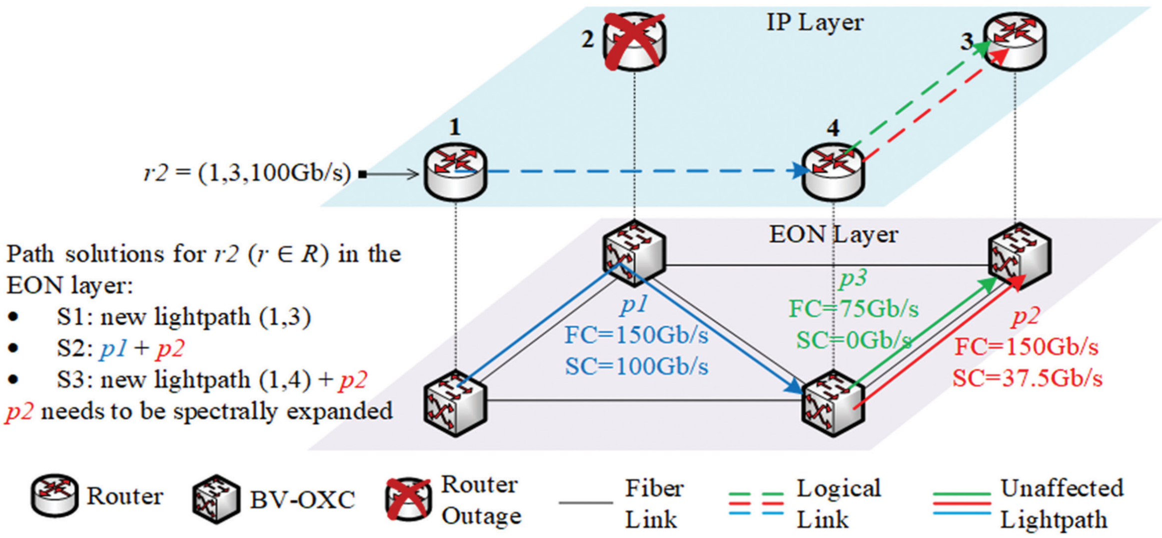


Fig. 1. IP-over-EON architecture after a router outage and three path solutions to recover affected traffic $r2$.

The main objective of the proposed strategies is to minimize lightpath reconfigurations, new lightpaths, power consumption, and OPEX. This study is necessary because the strategies can effectively reduce additional OPEX, leading to increased operator profitability. It is crucial to acknowledge that no recent study has integrated adaptive routing, spectrum expansion, and reactive defragmentation in IP-over-EON, specifically for recovering affected traffic caused by a router outage.

3. ADAPTIVE ROUTING AND REACTIVE DEFRAGMENTATION

3.1. NETWORK MODEL AND ARCHITECTURE

Figure 1 depicts an IP-over-EON multilayer network architecture with two layers interconnected using short-reach fibers. The notation $G(V,E)$ represents the IP-over-EON topology, where V corresponds to the set of IP routers, and E indicates the set of logical links. Two routers (u and $v \in V$) in the IP layer can be connected to one or more logical links, and a lightpath in the EON layer supports each logical link ($e \in E$). These logical links possess essential properties such as router pairs (source and destination), total capacity, spectrum allocation, and modulation level, providing crucial information about the EON layer.

In addition to serving as a destination router, an IP router can also function as an intermediate router. Data packets entering an IP router are then forwarded to the fiber optic cable in the EON layer for transmission until they reach the destination router, where further processing occurs [37]. In case an IP router experiences a failure, the operator removes the affected IP router ($v \in V$). Consequently, the IP-over-EON network state is updated, and all affected traffic is stored in R if the router outage occurs at an intermediate router. Spare capacities of the unaffected lightpaths are utilized to recover all this affected traffic. Due to the unpredictable nature of IP traffic, the utilization of these spare capacities may not have been fully optimized. Conversely, if the outage happens at the destination or source router, the impacted traffic can only be recovered once the IP router is repaired.

The affected traffic ($r \in R$) is groomed into an unaffected lightpath with sufficient spare capacity. However, when there is insufficient spare capacity to accommodate the impacted traffic, two recovery processes are employed, namely spectrum expansion or the establishment of a new lightpath [11]. This leads to the initiation of the lightpath reconfiguration procedure. Setting up a new lightpath is generally more common when the affected traffic is heavy or when limited available FSs exist between an unaffected spectrum and its neighbors, making it impossible to achieve maximum spectral expansion on the unaffected lightpath. Consequently, this causes increased OPEX due to lightpath reconfiguration procedures and higher use of SBVTs and FSs.

To minimize the recovery cost for each affected traffic, the LRSE+RD strategies are adopted. This approach helps to reduce the lightpath reconfiguration procedures and facilitates the process of spare spectrum expansion. This is made possible by leveraging the reactive defragmentation technique, which ensures sufficient free spectrum to meet the traffic demands. The notations utilized in this paper are shown in Table 1.

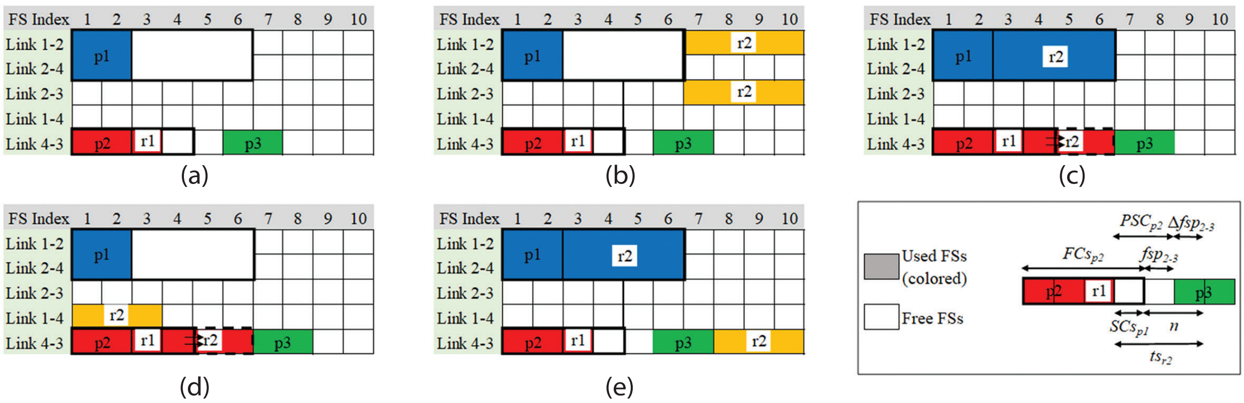


Fig. 2. Spectrum management of $r2$ for the three path solutions: (a) Initial condition; (b) $S1$ with LRSE+RD; (c) $S2$ with LRSE+RD; (d) $S3$ with LRSE+RD; and (e) $S2$ with LRSE-O.

3.2. PROPOSED STRATEGIES

This section elaborates on the mechanisms of both the LRSE and RD strategies. For example, Figs. 1 and 2 show the condition of the IP-over-EON network after a router outage ($ro = 2$) and the spectrum allocation of the three path solutions. In the EON layer, three unaffected lightpaths ($p1$, $p2$, and $p3$) possess varying full and spare capacities. Specifically, in router 1, an affected flow ($r2$) is being recovered to router 3, with affected traffic of 100 Gb/s. Based on the network condition in Fig. 1, three path solutions ($S1$, $S2$, and $S3$) are available for $r2$. All links are assumed to have a uniform distance of 1000 km. Fig. 2(a) shows the initial spectrum assignment condition of the three unaffected lightpaths and an affected flow $r1$, which has been recovered using the spare capacity of $p2$, amounting to 1 FS.

For the first path solution ($S1$), a new lightpath is established starting from BV-OXC 1, passing through BV-OXC 2, and terminating in BV-OXC 3. The distance of the new lightpath in the EON layer is 2000 km, and its modulation level (m) is 2, as seen in Table 2. This leads to one lightpath reconfiguration ($nLR = 1$) and a $ratioLR = 0$ ($nrl = 0$ since there is no reuse of the reconfigured lightpath). Furthermore, to recover affected traffic $r2$ ($ts_{r2} = 4$) on path $S1$, a minimum of four free FSs ($fsp \geq 4$) is required to fulfill the spectrum continuity and contiguity requirements. In case this condition is satisfied ($fsp \geq ts_{r2}$), a new lightpath can be established ($\Delta fsp = 0$, $sumFSv = 0$). Finally, $maxm$ is equal to 2, as only one modulation level is generated by one lightpath reconfiguration in $S1$. It should be noted that $S1$ only uses the LRSE strategy, and the RD strategy is not implemented. This is because, for setting up a new lightpath, there has to be sufficient free spectrum width that matches the needs of the affected traffic. If $S1$ is selected as the path solution, the result of allocating the spectrum for $r2$ can be seen in Fig. 2(b).

On the alternative path ($S2$), two unaffected lightpaths ($p1$ and $p2$) are used. Meanwhile, this spare capacity of $p1$ is sufficient to recover traffic $r2$, and $p2$ (distance = 1000 km, $m = 3$) has a smaller spare capacity ($SCs_{p2} = 1$) than traffic $r2$ ($ts_{r2} = 3$), necessitating spectral extension ($nLR = 1$). Figure 2(a) shows that between $p2$ and $p3$, only one free FS ($fsp_{2\text{-}3} = 1$) is available, leading to a shortage of 1 free FS ($\Delta fsp_{2\text{-}3} = -1$; $SCs_{p2} + fsp_{2\text{-}3} - ts_{r2} = 1 + 1 - 3$). The values for $maxm$ and $sumFSv$ are 3 and -1, respectively, indicating the need for only one lightpath reconfiguration procedure. Both LRSE and RD strategies are employed in $S2$, of which if $S2$ is selected as the best path in *Algorithm* 2, the PP defragmentation technique will be performed (*Algorithm* 3), leading to the shifting of spectrum $p3$ to the right by 1 FS. Successful reactive defragmentation allows spectrum expansion to recover traffic $r2$ into $p2$.

The result of $ratioLR$ in $S2$ is 1, resulting from the reuse of $p2$, which is previously utilized for traffic grooming $r1$ (nlr =1). Figure 2(c) shows the final spectrum assignment result of recovering traffic $r2$ into $p1$ and $p2$ using LRSE and RD strategies. In contrast, Fig. 2(e) shows the result if the path from $S2$ used only the LRSE strategy without the RD strategy (LRSE-O).

The path in $S3$ finally results from setting up a new lightpath from BV-OXC 1 to BV-OXC 4 (following a similar procedure to $S1$) and using $p2$ (as in $S2$). Based on these results, there are two lightpath reconfigurations (nLR = 2), $ratioLR$ = 0.5 (nlr = 1), $sumFSv = \Delta fsp_{2\text{-}3} = -1$ (obtained from using $p2$), and $maxm$ = 3 (both lightpath reconfigurations use the same modulation level). Figure 2(d) shows the spectrum assignment result of the affected flow $r2$ in $S3$. In this regard, the LRSE and RD strategies are executed.

Table 3. The results of the multiple criteria for the three path solutions are in Fig. 1.

Path Solution	*nLR*	*ratioLR*	*sumFSv*	*maxm*	Figure
*S*2	1	1/1	-1	3	2(c)
*S*1	1	0/1	0	2	2(b)
*S*3	2	1/2	-1	3	2(d)

Table 3 shows the outcome of the criteria for each path solution in Fig. 1, and after sorting (according to *Algorithm* 2, *Line* 25), $S2$ is determined to be the best path solution. The explanation of *Algorithm* 2 is provided in the following subsection.

3.3. PROPOSED ALGORITHMS

Algorithm 1 provides an overview of the entire procedure implemented in this study. This involves sorting all affected traffic (R) in descending order, and the recovery of each affected traffic utilizes a path obtained from *Algorithm* 2, while *Algorithm* 3 employs the reactive defragmentation strategy.

***Algorithm* 1**: Overall Procedure

while use the MLR algorithm in [11] **do**
  use *Algorithm* 2 to find a path solution;
  if $PSC_p < ts_r$ **then**
    use *Algorithm* 3 to perform the PP defragmentation technique;
    if the defragmentation process is successful **then**
      spectrum expansion process can be executed to restore ts_r;
    else
      continue the MLR algorithm;
    end
  end
end

The LRSE strategy in *Algorithm* 2 is designed to find the best path using multiple criteria. The procedure is as follows: all alternative paths are obtained from the pair of routers s_r and d_r, then searched for the combination of links (u, v) for each path s ($s \in S$) (*Line* 4). In this process, it is ensured that u or v is not a router outage on each link (u, v), and both can be connected ($tp_{u,v} = 1$). The specific link combinations of each path solution are shown in Fig. 1. In *Line* 6, each link (u, v) is compared with the existing ones in P. In case the result is blank (indicating the need to set up a new lightpath) or if it already existed but SCs_p is less than ts_r (representing the need to expand the spectrum p ($p \in P$)), an additional lightpath reconfiguration (nLR) is performed. Moreover, the modulation level (m) value in $maxm$ is adjusted when m is greater (*Lines* 7-9). Lower values for the variables nLR and $maxm$ lead to reduced additional OPEX costs. These variables are then sorted in ascending order (*Line* 25). Furthermore, in *Lines* 11-13, if a lightpath on the link (u, v) has been reconfigured before (for example, in Figs. 2(c) and 2(d), where $p2$ is used to recover $r1$), the same lightpath is re-selected to recover the next affected traffic (resulting in an increase in the value of nrl) and to save the difference of FSs ($\Delta fsp_{t\text{-}n}$) that are still needed to recover ts_r.

Lines 16 and 18 store the value of $\Delta fsp_{t\text{-}n}$ in preparation for setting up a new lightpath. Specifically, in *Line* 16, when there are not enough free FSs (fsp) to recover ts_r (the value of *FSvalueList* was *-Inf*), and in *Line* 18, when fsp is greater than or equal to ts_r. In the case of multiple conditions ($fsp \geq ts_r$), the fsp with the largest number of free FSs is selected. This ensures that when the lightpath is reused to recover the next affected traffic, some free FSs are still available for traffic grooming. After obtaining the results of both $ratioLR$ and $sumFSv$ variables (*Lines* 22-23), they are sorted in descending order in *Line* 25. The $ratioLR$ variable is prioritized using the reconfigured lightpath in the path selection, while the variable $sumFSv$ (sorted from smallest to largest negative values) aims to minimize $p_{neighbor}$ shift when the PP defragmentation technique (*Algorithm* 3) is executed on the links of the path.

***Algorithm* 2**: LRSE Strategy

Input: $G(V,E)$ after router outage, ro, $tp_{u,v}$, $r \in R$, and $p \in P$

Output: a path solution

1. find all paths between s_r and d_r, store them in matrix of path solutions S;
2. **for** each path $s \in S$ **do**
3. set nLR, $ratioLR$, $sumFSv$, $maxm$, nrl, $FSvalueList = 0$;
4. find and select the link combination (u, v) for path s, which does not originate from or end at ro with $tp_{u,v}$ =1;
5. **for** each link $(u,v) \in s$ **do**

save p $(p \in P)$, which has the same link as (u,v) to $OptionList$;
if $OptionList == \emptyset$ or $OptionList$ does not have $SCs_p \geq ts_r$ **then**
    $nLR = nLR + 1$;
    calculate m and update $maxm$ if it is higher;
end
if rl ==1 **then**
    $nrl = nrl + 1$;
    save $\Delta fsp_{t\text{-}n}$ to $FSvalueList$;
else
    if $OptionList == \emptyset$ and $fsp < ts_r$ then
        save -Inf to $FSvalueList$;
    else
        save $\Delta fsp_{t\text{-}n}$ to $FSvalueList$;
    end
end
end
calculate the ratio between nrl and nLR, and store them in $ratioLR$;
calculate the total negative values in $FSvalueList$, and store them in $sumFSv$;
end
sort S by nLR(min), $ratioLR$(max), $sumFSv$(max), and $maxm$(min);

Algorithm 3 represents the reactive defragmentation (RD) strategy that utilizes the PP defragmentation technique. Typically, it is executed whenever the spectrum expansion of p_{target} in the link (u, v) is obstructed by $p_{neighbor}$ due to a lack of free FSs ($\Delta fsp_{t\text{-}n} < 0$). In such cases, if there are $p_{neighbor}$ to the left and/or right of the p_{target}, their spectrum is shifted step by step towards the left and/or right until sufficient free FSs are obtained to recover ts_r (*Lines* 3-9). However, if the $p_{neighbor}$ shift fails to produce $\Delta fsp_{t\text{-}n} = 0$ ($PSC_p = ts_r$), the PP defragmentation technique is deemed unsuccessful, and the algorithm stops (*Lines* 10-13). In this scenario, the process continues by establishing a new lightpath in *Algorithm* 1.

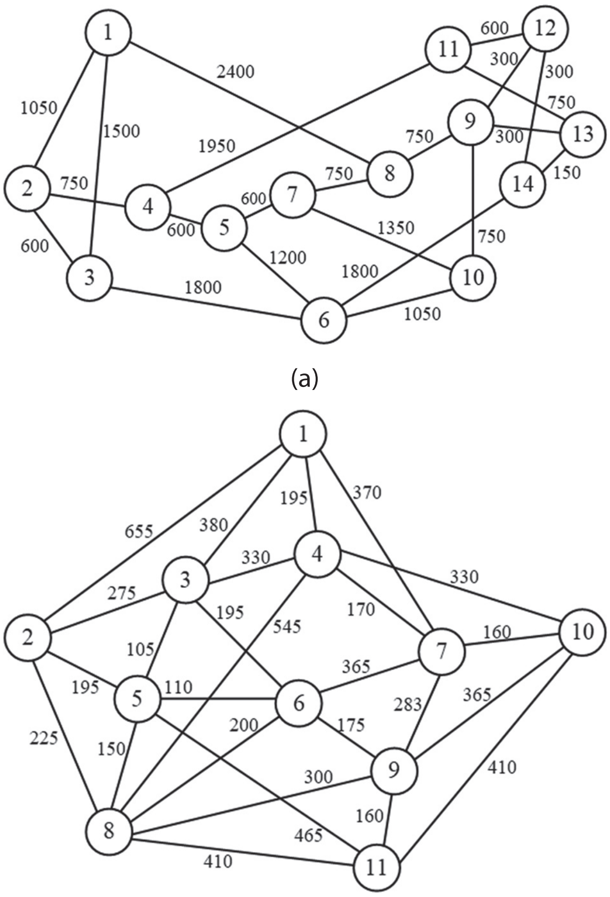
***Algorithm* 3**: RD Strategy

Input: $G(V,E)$ after router outage, $r \in R$, and $p \in P$

Output: enough free FSs for ts_r

1. find p_{target}, $p_{neighbor}$, and calculate $\Delta fsp_{t\text{-}n}$
2. **while** $\Delta fsp_{t\text{-}n} < 0$ **do**
3.   **if** $p_{neighbor}$ is on the left of p_{target} **then**
4.   shift $p_{neighbor}$ one step to the left;
5.   **end**
6.   **if** $p_{neighbor}$ is on the right of p_{target} then
7.   shift $p_{neighbor}$ one step to the right;
8.   **end**
9.   update $p_{neighbor}$, and $\Delta fsp_{t\text{-}n}$;
10.   **if** $p_{neighbor}$ cannot be shifted and $\Delta fsp_{t\text{-}n} < 0$ then
11. $DefragProcess$ = **False**;
12.   **break**;
13.   **end**
14. **end**

The optimization algorithm aims to minimize the additional OPEX (C) as shown in (1), where α represents the unit cost of power consumption, and its value is set to 1 for power cost normalization. Meanwhile, the additional power consumption is expressed as $W_m \cdot n + W_0$. In this aspect, W_m denotes the power consumption for using an FS at a modulation level (m), and its values can be seen in Table 2. W_0 represents a static value derived from the power usage of an SBVT [5]. When a new lightpath is established, W_0 is equal to 100 W; otherwise, the value is 0.



(b)

Fig. 3. IP-over-EON topologies (optical fiber length measured in kilometers); (a) NSFNET topology (14 nodes, 22 links), and (b) Cost239 topology (11 nodes, 26 links).

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

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

Equation (2) shows the number of newly used FSs (n), which is obtained from the difference in FSs between the affected traffic (ts_r) and the unaffected spare capacity (SCs_p). To calculate the number of FSs for an affected traffic t_r (in Gbps), (3) is used [39]. The same equation can also be used to determine the value of SCs_p. The value 12.5 represents the width of an FS (in GHz), and m denotes the modulation level of a lightpath (in bps/Hz). The value of m is significantly influenced by the transmission distance of the lightpath, as shown in Table 2.

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

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

In view of the upper limit of the total power cost (cl) in (4) and the primary objective of minimizing lightpath reconfiguration, various parameters are examined. The number of affected flows is denoted as $|R|$, and $\sum_{u,v \in V} tp_{u,v}$ represents the sum of all router pair indicators. Additionally, $\sum_{r \in R} [t_r / (12.5)]$ indicates the sum of all affected traffic divided by the width of an FS, which is the highest value of the number of FSs for all affected traffic. $max(W_m)$ refers to the highest value of W_m when recovering affected traffic requires more than one lightpath with varying power consumption. It is important to note that α, (1), (2), and (4) pertain to [11]. Sufficient resources are assumed to be available to recover all affected traffic (R) using the strategies in this current study.

4. PERFORMANCE EVALUATION

4.1. SIMULATION PARAMETERS

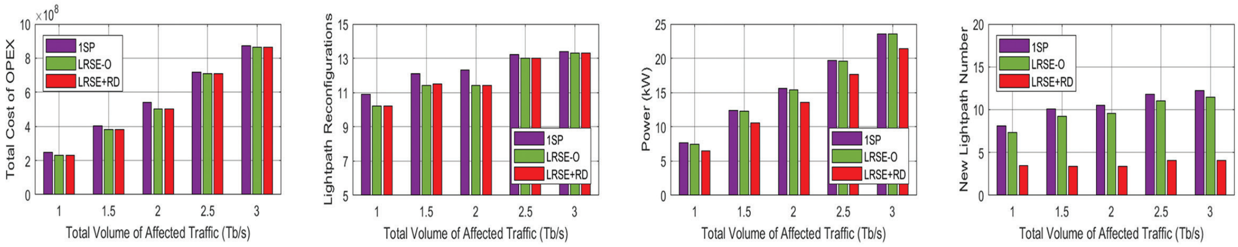
For testing the algorithms, the NSFNET topology [11] and the Cost239 topology [41] were employed as IP-over-EON, as shown in Figs. 3(a) and 3(b), respectively. To simulate the existing network conditions before a router outage occurred, several parameters were utilized. The maximum number of FSs for each fiber link was set to 358 FSs, with each FS having a bandwidth of 12.5 GHz. The capacity of the FS was determined by the modulation level, as shown in Table 2.

In the IP layer, connections for each router pair u-v ($tp_{u,v}$) were randomly selected from the range [0,1]. When both routers (u and v) could be connected ($tp_{u,v}$ = 1), one or more existing lightpaths in the EON layer were presented, with each consisting of several FSs. The number of existing lightpaths and their FSs were randomly chosen from the sets [1,4] and [1,10], respectively. It was noted that all existing lightpaths for the same router pair utilized the same physical routing path, which was randomly chosen from several path options in the EON layer.

For example, in the NSFNET topology, a pair of routers 1 and 4 could be connected ($tp_{1,4}$ = 1). From the random results, two existing lightpaths were obtained, each having a full capacity of 8 FSs. If the chosen physical path was 1-2-4, the first and second lightpaths connected routers 1-2 and routers 2-4, respectively, provided that $tp_{1,2}$ = 1 and $tp_{2,4}$ = 1. The configuration of each existing lightpath followed a first-fit spectrum assignment [14].

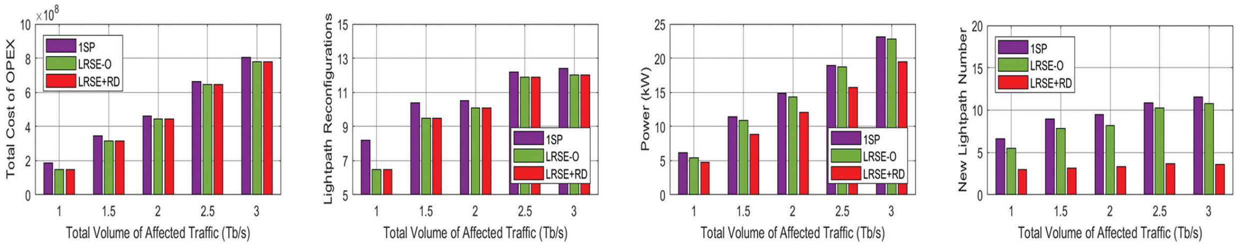
To simulate dynamic IP traffic conditions, spare capacity was randomly assigned to each existing lightpath. Two traffic conditions, namely heavy and moderate, were used to generate the spare capacity. Under heavy traffic conditions, each lightpath, on average, had 20% spare capacity, while the moderate condition had 40%. These values of 20% and 40% were determined by averaging the spare capacity of all existing lightpaths, leading to a more varied distribution of spare capacity (including the used capacity) for each existing lightpath.

After establishing the existing network conditions, a router outage was randomly selected, and all affected traffic in R was generated with fixed total traffic volumes ranging from 1 to 3 Tb/s (in increments of 0.5 Tb/s). The traffic in R was then sorted from largest to smallest, and each affected traffic ($r \in R$) was recovered using the aforementioned algorithms. Ten iterations were performed for each fixed total traffic volume, and the final data was obtained by averaging the results. The simulation program was developed using Matlab software and executed on a computer equipped with an Intel i7-7500U processor (clock speed of 2.7GHz), 8GB of RAM, and a Windows 10 operating system.



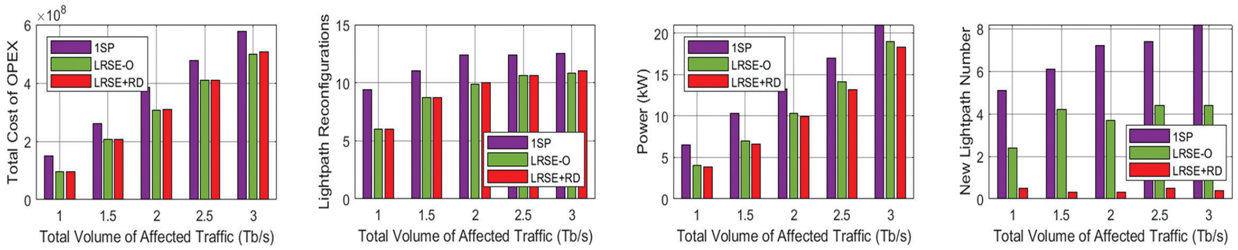
(a) (b) (c) (d)

Fig. 4. The results of the heavy traffic simulation in NSFNET topology: (a) total cost of OPEX; (b) lightpath reconfigurations; (c) power consumption; and (d) new lightpaths



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

Fig. 5. The results of the moderate traffic simulation in NSFNET topology: (a) total cost of OPEX; (b) lightpath reconfigurations; (c) power consumption; and (d) new lightpaths



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

Fig. 6. The results of the heavy traffic simulation in Cost239 topology: (a) total cost of OPEX; (b) lightpath reconfigurations; (c) power consumption; and (d) new lightpaths

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

Fig. 7. The results of the moderate traffic simulation in Cost239 topology: (a) total cost of OPEX; (b) lightpath reconfigurations; (c) power consumption; and (d) new lightpaths

The LRSE strategy utilized all the existing data to determine the best alternative path for recovering the traffic of the affected flow. In *Algorithm* 1, the LRSE path was processed with the RD strategy in *Algorithm* 3 (LRSE+RD) and without the RD strategy (LRSE-O). Additionally, *Algorithm* 1 was run without the RD strategy, using the first shortest path (1SP) as a benchmark [11]. All strategies were able to execute the spectrum expansion process to recover all affected traffic.

4.2. NSFNET TOPOLOGY SIMULATION RESULTS

During the simulation, 1SP, LRSE-O, and LRSE+RD were compared using the NSFNET topology. The results of the simulation under heavy traffic conditions are shown in Fig. 4. Figs. 4(a) and 4(b) show the total cost of OPEX as well as the number of lightpath reconfigurations, respectively. Both figures indicated that LRSE-O and LRSE+RD yielded similar results due to their use of the same path solution. However, the outcomes of both strategies were still lower than the benchmark, 1SP. As the total volume of affected traffic increased, the performance gap between LRSE-O and LRSE+RD with 1SP narrowed, as shown in Fig. 4(a), which is understandable since the gap in Fig. 4(b) also generated a similar trend.

At 1 Tb/s, the LRSE algorithm effectively identified a path that optimally utilized spare capacities on unaffected lightpaths in each link, allowing for the accommodation of some affected traffic and minimizing lightpath reconfigurations, as shown in Fig. 4(b). However, at 3 Tb/s, the gap became smaller as the heavier traffic of affected flows could no longer be accommodated within spare capacities on unaffected lightpaths, often necessitating reconfiguration procedures (such as spectrum expansion or setting up a new lightpath). It should be noted that the algorithm utilized still outperformed 1SP in Fig. 4(b).

Figure 4(c) shows the additional power consumption result, with LRSE-O slightly outperforming 1SP, while LRSE+RD achieved even lower power consumption. The same trend was observed in the number of new lightpaths shown in Fig. 4(d), with LRSE+RD obtaining the lowest result. This indicated that the lightpath reconfiguration number between LRSE-O and LRSE+RD was comparable in Fig. 4(b), but in Fig. 4(d), the number of new lightpaths created by LRSE+RD was further minimized, leading to reduced additional power consumption as seen in Fig. 4(c). As the total volume of affected traffic in Fig. 4(d) increased, the gap between LRSE+RD and the other two strategies also increased, suggesting that the use of the LRSE path and RD strategy maximized the spectrum expansion process, resulting in minimal increases in the number of new lightpaths at each data point.

Fig. 5 shows the simulation results under moderate traffic conditions, revealing similar graphical patterns to those shown in Fig. 4. However, in Fig. 5(b), a smaller lightpath reconfiguration number was observed compared to Fig. 4(b). This difference resulted from the larger average spare capacities of unaffected lightpaths in moderate traffic, which could be used to recover some affected traffic. All the simulations presented in Fig. 5 showed that LRSE+RD consistently generated lower values than 1SP.

4.3. COST239 TOPOLOGY SIMULATION RESULTS

Figs. 6 and 7 show the simulation results after the router outage occurred under heavy and moderate traffic conditions in the Cost239 topology. Specifically, Fig. 6 shows a trend similar to that in Fig. 4 but with lower values for all four test parameters. This result stemmed from the lower number of nodes in the Cost239 topology compared to the NSFNET topology, which resulted in the number of router pairs decreasing, leading to a higher number of available free FSs.

The abundance of free FSs impacted the number of new lightpaths generated by LRSE+RD in Fig. 6(d), which was substantially lower than that of LRSE-O and 1SP. In other words, the LRSE+RD strategy optimized the lightpath reconfigurations with a spectrum expansion process when there were more free FSs. Similar conditions are also observed in Fig. 7. The simulation results in Fig. 7 further confirmed the advantages of the LRSE+RD strategies over 1SP and LRSE-O.

5. CONCLUSION

This paper focuses on strategies for recovering all affected traffic following the failure of an IP router in IP-over-EON. Two key strategies were employed: adaptive routing and reactive defragmentation. The adaptive routing strategy utilized LRSE to optimize the utilization of unaffected lightpaths and expanded their spare spectrum minimally, generating the best path based on various criteria in the EON layer. Simultaneously, the RD strategy was applied to ensure sufficient free FSs through the push-pull defragmentation technique, which was triggered when the neighboring spectrum blocked the spectrum expansion process. The LRSE+RD strategies aimed to minimize lightpath reconfigurations, additional power consumption, and the setup of new lightpaths, leading to reduced OPEX. Through simulations conducted in both topologies (NSFNET and Cost239) under heavy and moderate traffic conditions, it became evident that the LRSE+RD strategies consistently exhibited the lowest values among all four test parameters compared to the 1SP benchmark. In comparison to LRSE-O, the LRSE+RD strategies achieved lower values in the number of new lightpaths and additional power consumption parameters, while the same positive results were obtained for the other two test parameters. Looking ahead, the future study will focus on applying a metaheuristic approach to enhance the proposed strategies.

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