Multi-Layer Restoration to Address IP Router Outages in IP-over-EONs

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Abstract: We discuss how to cost-effectively address the IP router outages in IP over elastic optical networks (IP-over-EONs) with multi-layer restoration (MLR), and design an auxiliary-graph (AG) based algorithm that can minimize the additional operational expenses (OPEX).

OCIS codes: (060.1155) All-optical networks; (060.4251) Networks, assignment and routing algorithms.

1. Introduction

By leveraging advanced optical transmission and switching technologies, elastic optical networks (EONs) can allocate spectrum resources at a granularity of 12.5 GHz or less [1], and greatly increase the spectrum efficiency in the optical layer when being compared with the fixed-grid wavelength-division multiplexing (WDM) networks. Therefore, by manipulating narrow-band and spectrally-contiguous frequency slots (FS'), EONs can set up both sub-wavelength and super-channel lightpaths to adapt to various traffic demands [2]. Moreover, the flexibility of EONs has been further improved by the recent advances on sliceable bandwidth variable transponders (S-BVTs) [3], which makes dynamically expanding and contracting the spectrum assignment of a lightpath feasible. With all these advantages, EONs have been considered as a promising physical infrastructure for the next-generation backbone networks [4, 5]. On the other hand, the current Internet is essentially an IP-based network, and IP packet switching plays an important role in making the network adaptive and efficient to support the ever-growing traffic due to emerging applications. In light of this, we can foresee that building IP-over-EON networks can explore the advantages of both adaptive packet switching and flexible optical transmission, and thus would be beneficial for realizing highly-efficient service provisioning to support various applications [6]. In other words, a rational combination of IP and EON technologies would lead to significant savings on both capital expenses (CAPEX) and operational expenses (OPEX) [7].

Note that, since a backbone network usually carries a tremendous amount of traffic, a failure in it (*e.g.*, due to physical impairments [8], natural diasters [9], and system malfunctions [10]) can dramatically affect the operator's revenue and credit. Hence, the survivability of backbone networks is always a very important issue [11]. Previously, the protection and restoration schemes to ensure the survivability of EONs have been studied intensively [12–15]. However, since the approaches proposed in these studies only addressed the survivability of the EON layer, they cannot guarantee that a whole IP-over-EON would be intact during network failures. For instance, in the IP-over-EON shown in Fig. 1, even though each lightpath in the EON layer is protected with a dedicated backup path, the IP connections that are from *Router A* to *Router C* through *Router B* will still be interrupted when an outage occurs on *Router B*. Note that, according to a recent analysis conducted by researchers in Google on the failure events in their wide-area enterprise networks [10], router outages actually occurs much more frequently than fiber link failures. Hence, it is worthwhile to consider how to leverage multi-layer restoration (MLR) to address the IP router outages in IP-over-EONs for enhanced survivability [7]. Specifically, by leverage the flexibility in IP and EON layers, MLR tries to allocate resources in both layers dynamically and adaptively to recovery the affected traffic timely. By doing so, we avoid to reserve massive backup resources in both layers for failure recovery, and thus can significantly improve the resource utilization in IP-over-EONs.

In this paper, we summarize our research efforts on the MLR schemes to address IP router outages in IP-over-EONs [7]. More specifically, we consider the network scenario in which a single IP router outage occurs during the normal operation of an IP-over-EON, and study how to address this scenario with effective MLR for cost-effective failure recovery. Note that, as MLR introduces additional OPEX due to the incremental usage of SBV-Ts and FS' and lightpath reconfigurations, our MLR scheme tries to minimize such OPEX with an auxiliary graph (AG) based algorithm. By leveraging the spectrum expansion capability of SBV-Ts, the AG-based MLR algorithm can recover the affected traffic due to IP router outages cost-efficiently. Simulation results verify that our proposed MLR can significantly reduce the power cost caused by the additional usage of SBV-Ts and FS', while keeping the number of lightpath reconfigurations as relatively small.

2. Problem Formulation

Fig. 1 shows an example on the multi-layered network model of IP-over-EON, where the IP routers are physically connected with the collocated bandwidth-variable optical cross-connects (BV-OXCs). The BV-OXCs are interconnected with optical fibers and can set up lightpaths between each other for data transmission, *i.e.*, formulating the EON layer.

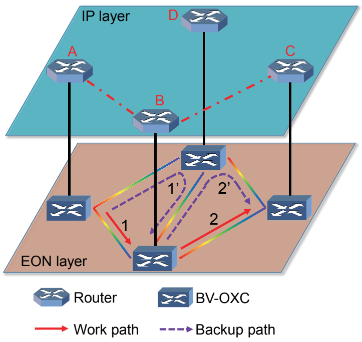


Fig. 1. An example on IP-over-EON.

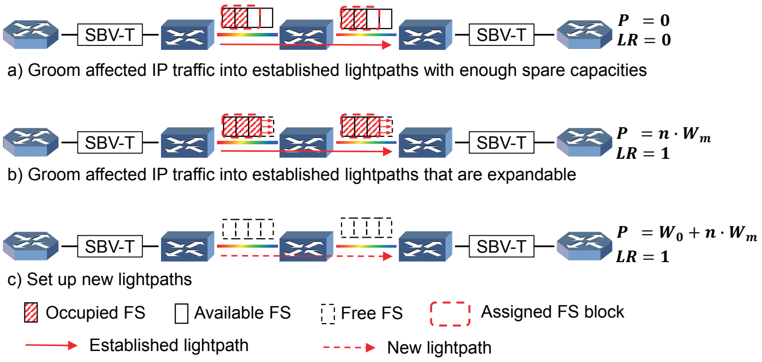


Fig. 2. Three MLR strategies (adapted from Fig. 2 in [7]).

On the other hand, the lightpaths in the EON layer can be utilized by the IP routers to realize virtual links in the IP layer, *i.e.*, the IP connections among routers. During an IP router outage, all the traffic that flows through the broken router would be affected. For example, if *Router B* in Fig. 1 is broken, all the traffic that is forwarded with routing path $A{\to}B{\to}C$ would be interrupted, and should be recovered with MLR. Apparently, during an IP router outage, the traffic that starts from or ends at the broken router would be lost anyway, and hence, our MLR scheme only tries to recover the affected traffic that uses the broken router as an intermediate router, and focuses on the single outage scenario, *i.e.*, only one IP router can be broken at any time instant.

We assume that the MLR can utilize the three strategies in Fig. 2. The first one in Fig. 2(a) tries to use the space capacity in existing lightpaths to recover the affected traffic, *i.e.*, the recovery is done in the IP layer and thus no additional usage of SBV-Ts and FS' or lightpath reconfigurations would occur. For the second strategy depicted in Fig. 2(b), we try to groom the affected traffic into lightpaths that can gain enough spare capacity by expanding their spectrum assignments. Since extra FS' are used in this strategy, the additional power cost is $P = W_m \cdot n$, where n is number of additional FS' used after the spectrum expansion. Note that, we model the power cost of a lightpath as $P = W_m \cdot n + W_0$, where W_m is the power cost of using an FS with modulation-level m, and W_0 is the power cost for turning on a new SBV-T. Here, we assume that four modulation-levels can be used in the IP-over-EON, whose transmission capacities, power costs and maximum reaches are shown in Fig. 4 [16], and set $W_0 = 100$ W. Also, each spectrum expansion involves an additional lightpath reconfiguration in the second strategy. The last strategy in Fig. 2(c) just tries to set up a new lightpath to recover the affect traffic. Hence, the corresponding power cost is $P = W_m \cdot n + W_0$ and one lightpath reconfiguration is needed. In the next section, we will design an MLR algorithm to minimize the additional OPEX due to the usage of SBV-Ts and FS' and lightpath reconfigurations, by using the three strategies.

3. Auxiliary-Graph based Multi-Layer Restoration

Here, we assume that the affected IP traffic is stored in matrix $\mathbf{R}_a$. Each flow r in $\mathbf{R}_a$ is represent as $r = (s, d, B)$, where s and d stand for the source and destination IP routers, respectively, and B is its bandwidth demand in Gbps. Fig. 3 illustrates an example on our proposed AG-based MLR, which uses the following procedure to recover each $r \in \mathbf{R}_a$. We first build the AG $G_a(V_a, E_a)$ as follows. Here, V_a includes all the normal routers after the outage, and $E_a = E_{a,1} \bigcup E_{a,2} \bigcup E_{a,3}$ consists of three kinds of virtual IP links, each of which matches to an MLR strategy in Fig. 2. Specifically, $E_{a,1}$ includes the virtual links that can carry r with their spare capacities, and their weights are set as $\varepsilon \ll 1$ in G_a; $E_{a,2}$ is the set that consists of the virtual links whose lightpaths have to be spectrally expanded to carry r, and their weights are as 1; and if new lightpaths need to be established between the routers in V_a, we include them in $E_{a,3}$ and set their weights as 1. Secondly, we try to restore r with the spare capacity in the IP-over-EON. By applying the shortest path algorithm in G_a, we find the least-weighted path from s to d. Then, if the path's weight is less than 1, which means there is no need to reconfigure a lightpath, we directly reroute r over the obtained path. Otherwise, we invoke the further optimization to restrict the number of lightpath reconfigurations while minimizing the additional power cost. To restrict the number of lightpath reconfigurations, we first acquire K shortest paths from s to d in G_a and store them in $\mathscr{P}$. Then, we update G_a by setting the weights of virtual links in $E_{a,2}$ as $n' \cdot W_m$ (*i.e.*, n' is the number of extra FS' to carry r), and the weights of the virtual links in $E_{a,3}$ are replaced with $W_m \cdot n + W_0$, where n is the number of FS' to carry r. Next, we calculate the power cost for each path in $\mathscr{P}$ with the updated weights, and choose the least-weighted path to recover r.

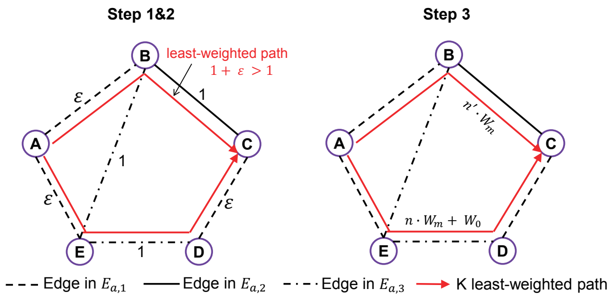
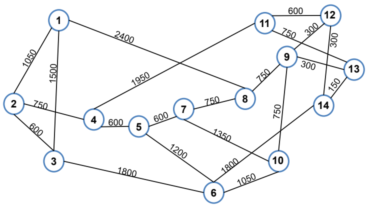


Fig. 3. Example on our proposed AG-based MLR.

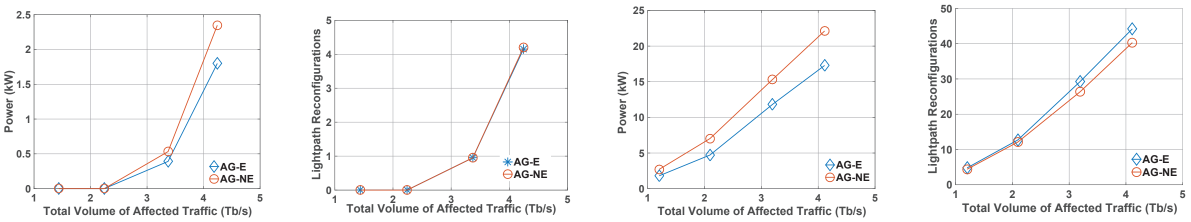


Modulation	BPSK	QPSK	8QAM	16QAM
Reach (km)	4800	2400	1200	600
Capacity per FS (Gbps)	12.5	25	37.5	50
W_m (W)	112.4	133.4	154.4	175.5

Fig. 4. NSFNET and information of modulation-levels.

4. Simulation Results

To evaluate our proposed MLR algorithm (*i.e.*, AG-E), we conduct simulations with the NSFNET topology in Fig. 4, where each bidirectional fiber link carries 358 FS', each of which is 12.5 GHz. We consider two scenarios, *i.e.*, the moderate and heavy background traffic scenarios, where the average spare capacity on a lightpath is set as 52.14 Gbps and 30.30 Gbps, respectively. Each simulation first randomly selects a broken router, assigns spare capacity on the lightpaths according to a background traffic scenario, and then generates the affected traffic matrix $\mathbf{R}_a$ randomly with a fixed total volume. For comparison, the benchmark is AG-NE in which the SBV-Ts do not have the spectrum expansion capability. For the moderate traffic scenario, the results are shown in Figs. 5(a) and 5(b), which indicates that when the spare capacity is rich, AG-E saves more power cost than AG-NE while does not induce more lightpath reconfigurations. For the heavy traffic scenario, the results in Figs. 5(c) and 5(d) suggest that AG-E is still more power-efficient than AG-NE, but it invokes slightly more lightpath reconfigurations than AG-NE when the total affect traffic volume is 4 Tb/s or higher. This is because AG-E might use many indirect IP routes to recover a flow in this situation.



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

Fig. 5. Simulation results (adapted from Figs. 5 and 6 in [7]).

5. Summary

We discussed how to cost-effectively address the IP router outages in IP-over-EONs with MLR, and design an AG-based algorithm that can minimize the additional OPEX.

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