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

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Abstract: We study how to address the IP router outages in an IP-over-EON with multi-layer restoration (MLR), and propose an auxiliary-graph (AG) based scheme that can minimize the additional OPEX of MLR with the help of the spectrum expansion capability of sliceable bandwidth-variable transponders (SBV-Ts).

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

1. Introduction

With the flexible and adaptive optical layer, elastic optical network (EON) has been considered as a promising physical infrastructure for the next-generation backbone networks. Meanwhile, it is known that a rational combination of IP and optical technologies can achieve significant capital expense (CAPEX) and operational expense (OPEX) savings [1]. Hence, it would be relevant to study the networking issues in multi-layer IP-over-EONs. Note that, in order to secure the large transport capability of IP-over-EONs consistently, we have to address network survivability properly [2]. However, the network survivability of an IP-over-EON can be affected not only by the failures in the optical layer (*e.g.*, fiber cuts) but also by the outages on IP routers. Previously, people have considered the protection and restoration schemes in the optical layer to address link failures in EONs [3,4]. Nevertheless, these schemes might not be able to recover the affected traffic in an IP-over-EON when an IP router outage happens. For instance, as shown in Fig. 1, although the two lightpaths have dedicated protection in the optical layer, an outage on *Router* C would still disrupt the IP traffic from *Router* A to *Router* D since the routers have been disconnected in the IP layer.

Previously, to enhance cross-layer network survivability in IP over wavelength-division multiplexing (WDM) networks, people have proposed protection schemes that pre-allocate backup resources in both optical and IP layers [5]. However, these schemes would lead to relatively low protection efficiency. Actually, by leveraging the flexibility in the IP layer, *i.e.*, each IP router can dynamically update its routing table, multi-layer restoration (MLR) can address IP router outages more cost-efficiently [2]. Specifically, an MLR scheme could try to combine optical layer reconfiguration with dynamic IP rerouting effectively. Meanwhile, as the MLR in IP-over-EONs might result in incremental usages of sliceable bandwidth-variable transponders (SBV-Ts) and frequency slots (FS') and invoke lightpath reconfigurations, the additional OPEX should be addressed properly. In this work, we consider the situation in which an IP router outage happens during the operation of an IP-over-EON, and propose an auxiliary-graph (AG) based scheme that can minimize the additional OPEX of MLR with the help of the spectrum expansion capability of SBV-Ts. Simulation results indicate that when recovering the disrupted IP traffics, our MLR scheme can reduce the power cost due to the incremental usages of SBV-Ts and FS' significantly and maintain the amount of lightpath reconfigurations well.

2. Problem Formulation

We model an IP-over-EON as $G(V,E) = \{G_o(V_o,E_o), G_i(V_i,E_i), E_c\}$, where $V = V_o \bigcup V_i$ is the switch set that includes both IP routers and bandwidth-variable optical cross connects (BV-OXCs), $E = E_o \bigcup E_i \bigcup E_c$ is the link set for fiber links in the optical layer, logical links in the IP layer, and local links that connect IP routers and BV-OXCs, $G_o(V_o,E_o)$ represents the EON topology, and $G_i(V_i,E_i)$ denotes the topology of the IP layer. In $G_o(V_o,E_o)$, there are established lightpaths to support the traffic from the IP layer. For each BV-OXC pair $(s_o,d_o) \in V_o^2$, we denote the set of established lightpaths as L_{s_o,d_o}. Note that, on each established lightpath, the IP traffic is dynamic and might not fully occupy its capacity all the time, and thus we use c_l to represent the spare capacity of a lightpath $l \in L_{s_o,d_o}$ before the MLR. In $G_i(V_i,E_i)$, each IP router $v_i \in V_i$ is locally connected to a BV-OXC $v_o \in V_o$, and we use function $f(\cdot): v_i \to v_o$ to record the mapping. Each logical link $e_i = (v_i,u_i) \in E_i$ corresponds to a lightpath $l \in LP_{f(v_i),f(u_i)}$ in $G_o(V_o,E_o)$, *i.e.*, more than one logical links can exist between an IP router pair in $G_i(V_i,E_i)$.

We consider the scenario that a single IP router outage happens during the operation of the IP-over-EON. After the outage, we update the IP layer topology $G_i(V_i,E_i)$ to remove the broken IP router v_i^b and get the affected IP traffics that transit v_i^b. Note that, since the IP traffics that originate from or end at v_i^b cannot be restored until v_i^b is fixed, we do not consider them in the MLR. The affected IP traffics are then recorded in a traffic matrix $\mathbf{R}_a$. Then, to restore each IP flow in $\mathbf{R}_a$, the MLR needs to either groom it into existing lightpath(s) that have enough spare capacities or set up/reconfigure lightpath(s) to support it from the optical layer. Specifically, it can leverage the three restoration strategies in Fig. 2. Apparently, the strategies might generate additional OPEX, which includes the power consumption

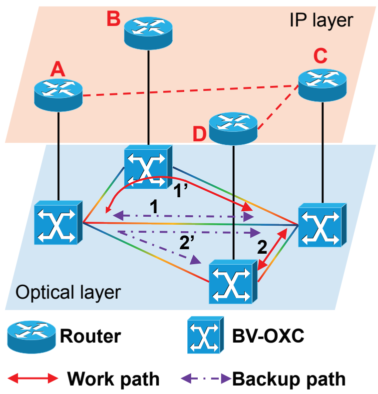


Fig. 1. Example on IP-over-EON.

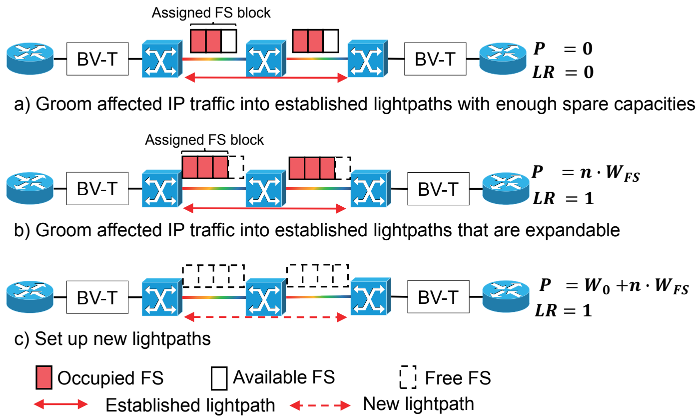


Fig. 2. Three MLR strategies.

due to incremental usages of SBV-Ts and FS' and the management cost due to lightpath reconfigurations. The power of a SBV-T is modeled as $P = W_{FS} \cdot n + W_0$, where W_{FS} is the power consumption for occupying an FS, n is the number of used FS', and W_0 is the static power consumption for turning on the SBV-T [6]. Here, according to [7], we assume that the value of W_{FS} depends on the modulation-level of the FS as shown in Fig. 3, while set $W_0 = 100$ W.

In order to design cost-efficient MLR schemes, we analyze the additional OPEX of the restoration strategies in Fig. 2 as follows. The first strategy in Fig. 2(a) grooms the affected traffic into an existing lightpath that has enough spare capacity. Since this strategy does not introduce incremental usages of SBV-Ts and FS', there is no additional power cost, and for the same reason, we do not need to reconfigure any lightpath in the optical layer. Hence, this strategy would not result in additional OPEX. In Fig. 2(b), the second strategy is to groom the IP affected traffic into an existing lightpath that does not have enough spare capacity but can be spectrally expanded by utilizing the the spectrum expansion capability of its SBV-Ts [6]. Note that, since new FS' will be activated in the procedure, additional power consumption would be generated, and in the mean time, the SBV-Ts are reconfigured once for the spectrum expansion. For the last strategy in Fig. 2(c), we just set up a new lightpath to restore the affected traffic. Then, the additional power consumption can be calculated based on the incremental usages of SBV-Ts and FS' of the new lightpath, and there is one lightpath reconfiguration too. Base on the analysis, we will propose an auxiliary-graph (AG) based MLR scheme in the next section, which can minimize the additional OPEX when recovering the affected IP traffics in $\mathbf{R}_a$. Note that, in this work, we assume that the SBV-Ts and FS' in the optical layer are enough for the MLR and thus there would be no IP traffic blocking.

3. Auxiliary-Graph based Multi-Layer Restoration

We model the IP traffic flow between two IP routers s and d ($s,d \in V_i$) in $\mathbf{R}_a$ as $r = (s,d,B)$, where B is its bit-rate in Gbps. Fig. 3 shows an example on our AG-based MLR, which uses the following procedure to recover each $r \in \mathbf{R}_a$.

Step 1: Build auxiliary graph $G_a(V_a, E_a)$. We have $V_a = V_i$ and $E_a = E_{a,1} \bigcup E_{a,2} \bigcup E_{a,3}$, where $E_{a,1}, E_{a,2}, E_{a,3} \subset E_i$. Here, $E_{a,1}$ includes the virtual links whose lightpaths still have enough spare capacity for carrying r, and we set their weights as $\varepsilon \ll 1$ in G_a. $E_{a,2}$ consists of the virtual links whose lightpaths do not have sufficient capacity for r but can be expanded to get enough capacity, and their weights are as 1. For any two routers in V_a, if the virtual link(s) between them do not belong to $E_{a,1}$ or $E_{a,2}$, we add a new virtual link between them, set its weight as 1, and include it in $E_{a,3}$.

Step 2: Try to restore r with spare capacity. We get the least-weighted path for $s \to d$ in G_a. If the path's weight is less than 1, we use the corresponding virtual links in the IP layer to restore r. Otherwise, we continue to **Step 3**.

Step 3: Restrict number of lightpath reconfigurations while fully exploit spare capacity. We first calculate K least-weighted paths for $s \to d$ in G_a, and store them in $\mathscr{P}$. Then, we replace the weights of virtual links in $E_{a,2}$ as $n' \cdot W_{FS}$ where n' is the smallest number of FS' that the virtual link's lightpath needs to be expanded for carrying r. The weights of virtual links in $E_{a,3}$ are replaced with $W_{FS} \cdot n + W_0$ where n is the smallest number of FS' to support r on a new lightpath. For each path in $\mathscr{P}$, we recalculate its weight with the updated link weights, and then choose the least-weighted path to use the corresponding virtual links in the IP layer to restore r.

4. Simulation Results

Our simulations use the NSFNET topology in Fig. 4 where each bidirectional fiber supports 358 FS', each of which is 12.5 GHz. In the IP-over-EON, we consider four modulation-levels in the optical layer, *i.e.*, BPSK, QPSK, 8QAM and 16QAM, and an FS with them can carry a capacity of 12.5 Gb/s, 25 Gb/s, 37.5 Gb/s and 50 Gb/s, respectively. For

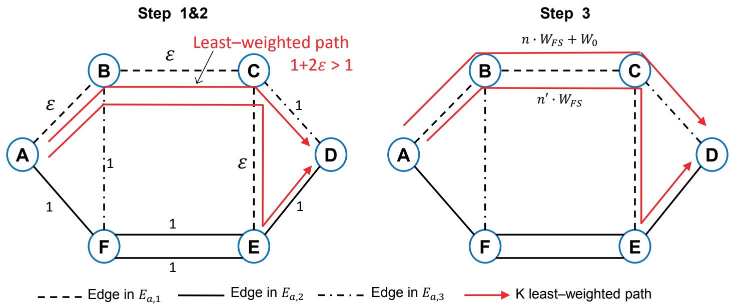
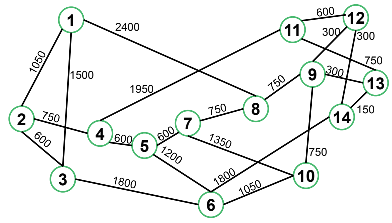


Fig. 3. Example on AG-based MLR scheme.



Modulation	BPSK	QPSK	8QAM	16QAM
Reach (km)	4800	2400	1200	600
W_{FS} (W)	112.4	133.4	154.4	175.5

Fig. 4. NSFNET and modulation table.

each pair of IP routers, the number of established lightpaths between them is within $[0, 14]$, and the bandwidth of each lightpath ranges within $[1, 13]$ FS'. Note that, the modulation-level used for each lightpath depends on its transmission length as explained in the table in Fig. 4. For each simulation, we first randomly select an IP router to fail in the IP-over-EON, then assign the spare capacities on the established lightpaths within $[0, 150]$ Gb/s with an averages as 52.14 Gb/s (*i.e.*, the moderate background traffic scenario) or 30.30 Gb/s (*i.e.*, the heavy background traffic scenario), and generate the affected IP traffic matrix $\mathbf{R}_a$ randomly with a fixed total volume. For each total affected traffic volume, we run 20 independent simulations and average the results to get the final data. In the AG-based algorithm, we set $K = 4$ in **Step 3**. For comparison, we also design a benchmark algorithm in which the SBV-Ts do not have the spectrum expansion capability. We name the proposed and benchmark algorithms as AG-E and AG-NE, respectively.

Fig. 5(a) shows the results on power increase due to incremental usages of SBV-Ts and FS' in MLR, for the moderate background traffic scenario. As expected, the power increase grows with the total affected IP traffic volume. AG-E achieves less power increases than AG-NE since it can leverage spectrum expansion to avoid turning on new SBV-Ts. The results on total number of lightpath reconfigurations are plotted in Fig. 5(b), which indicates that when AG-E and AG-NE performs similarly. Therefore, the results in Fig. 5 suggest that when the spare capacities on the established lightpaths are sufficient, AG-E achieves effective power saving while requires almost the same number of lightpath reconfigurations as AG-NE. The results for the heavy background traffic scenario are illustrated in Fig. 6. In Fig. 6(a), we can see that related to AG-NE, the power saving achieved AG-E becomes more significant. Meanwhile, it is interesting to notice that in Fig. 6(b), the lightpath reconfigurations from AG-E are slightly more than those from AG-NE when the total affect traffic volume is 4 Tb/s or higher. This is because AG-E optimizes the power increase prior to lightpath reconfigurations, which might make it choose indirect IP routes with a few expandable lightpaths for MLR when the background traffic load is relatively high. Meanwhile, since the lightpaths are not expandable for AG-NE, it would just try to set up new lightpaths to support direct IP connections in MLR.

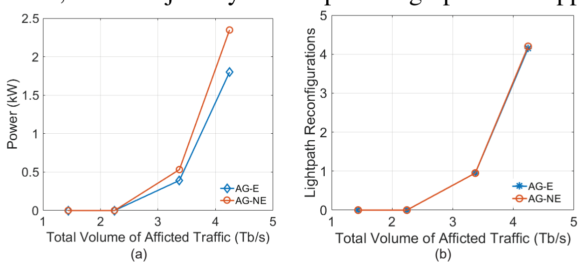


Fig. 5. Results for moderate traffic scenario.

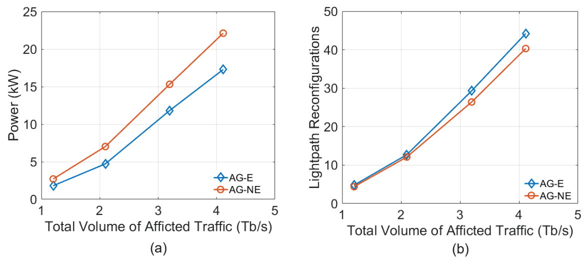


Fig. 6. Results for heavy traffic scenario.

5. Summary

We proposed an AG-based scheme to address IP router outages in IP-over-EONs. Simulation results showed that by leveraging the spectrum expansion capability of SBV-Ts, our proposed scheme could reduce the power increase due to the incremental usages of SBV-Ts and FS' significantly and maintain the amount of lightpath reconfigurations well.

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