On the Cross-Layer Orchestration to Address IP Router Outages with Cost-Efficient Multi-Layer Restoration in IP-over-EONs [Invited]

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***Abstract*—Due to the flexibility and adaptivity of elastic optical networks (EONs), IP-over-EON would be a promising infrastructure for the next-generation backbone networks. As a backbone network usually carries massive traffic, one always needs to properly address the network survivability issue in it. The network survivability of an IP-over-EON can be affected not only by the fiber cuts in the EON layer, but also by the router outages in the IP layer. In this work, we study how to realize the cross-layer orchestration to address IP router outages with cost-efficient multi-layer restoration (MLR) in IP-over-EONs. Specifically, we consider the situation in which a single router outage happens in an IP-over-EON, and propose MLR algorithms to minimize the additional operational expense (OPEX) due to MLR. We first design three MLR strategies to fully explore the flexibility and adaptivity of IP-over-EONs. Then, with the strategies, we formulate an integer linear programming (ILP) model to find the MLR scheme in which the additional OPEX due to incremental usages of sliceable bandwidth-variable transponders (SBV-Ts) and frequency slots (FS') and lightpath reconfigurations is minimized. We also propose an auxiliary graph (AG) based heuristic algorithm to reduce the time complexity. The proposed algorithms are evaluated with extensive simulations, and the results indicate that compared with an existing benchmark, they can effectively reduce the additional OPEX of MLR.**

***Index Terms*—IP over Elastic optical networks (IP-over-EONs), Multi-layer restoration (MLR), Cross-layer orchestration, Network survivability.**

I. INTRODUCTION

ENABLED by the advanced optical transmission and switching technologies, flexible-grid elastic optical networks (EONs) have brought down the bandwidth allocation granularity in the optical layer to 12.5 GHz or even smaller [1, 2]. Hence, compared with the traditional fixed-grid wavelength-division multiplexing (WDM) networks, EONs improve the spectrum efficiency of optical transmission and facilitate agile spectrum management in the optical layer. For instance, with the recent advances on sliceable bandwidth-variable transponders (SBV-Ts), people have demonstrated that dynamic expansion and contraction of a lightpath's spectrum assignment can be realized in EONs [3]. Therefore, EONs effectively enhance the flexibility and adaptivity of optical networks and are considered as a promising physical infrastructure for the next-generation backbone networks [4, 5].

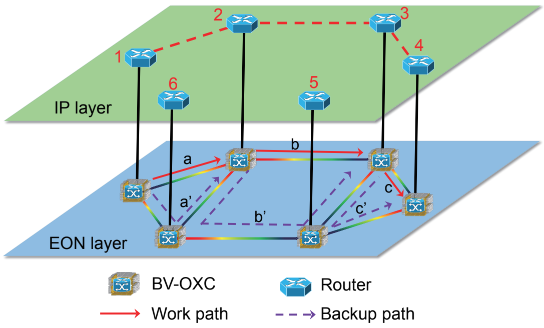

Fig. 1. An example of IP-over-EON.

Meanwhile, although EONs have the aforementioned advantages, they are still based on circuit switching. To support the ever-growing IP-based Internet applications, *e.g.*, teleconferencing, e-Science, and big data analytics, the operators need a packet switching based IP layer to deliver their services cost-effectively. Hence, a rational combination of IP and EON technologies would be inevitable [6]. Specifically, in such an IP-over-EON based backbone network in Fig. 1, we have an EON as the underlying optical transport layer, which sets up lightpaths as the high throughput pipes to transfer data traffic over long distances, while an IP network is built over the EON for switching packets among the lightpaths. As sufficient flexibility and adaptivity are provided in both the IP and EON layers, an IP-over-EON can facilitate efficient resource utilization when carrying highly dynamic application traffic, and thus significant capital expense (CAPEX) and operational expense (OPEX) savings can be achieved for the operator [6].

Note that, since a backbone network usually carries massive traffic, a network failure in it can cause tremendous data loss to the end users, which will in turn lead to huge revenue loss to the operator. Therefore, one always needs to properly address the network survivability issue in backbone networks to secure their data transport capability consistently [7]. Previously, to guarantee the network survivability during a single fiber cut, researchers have proposed various protection and restoration schemes for EONs [8–12]. However, the network survivability of an IP-over-EON can be affected not only by the fiber cuts in the EON layer but also by the router outages in the IP layer. For instance, a recent analysis on the failure events within Google's network [13] has suggested that in both of the company's wide-area networks (WANs), *i.e.*, B2 and B4, router outages due to hardware/software issues (*e.g.*, linecard and routing engine failures, software bugs and device resource overruns) actually happened much more frequently than fiber

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link failures. Apparently, the traffic loss due to these router outages cannot be recovered by the protection and restoration schemes in the EON layer without an effective cross-layer orchestration mechanism.

For example, in Fig. 1, even though the lightpaths for 1-2, 2-3 and 3-4 have dedicated protection in the EON layer, an outage on the router on *Node* 3 would still disrupt the IP traffic between *Nodes* 1 and 4, since the corresponding routers have been disconnected in the IP layer while the EON layer is unaware of this incident. Although the affected IP traffic will eventually be recovered when the routers detect the failure and update their routing tables accordingly, waiting for the routing tables to converge can take a relatively long time and rerouting the affected IP traffic on other lightpaths can cause congestions when the network has already been crowded. Therefore, we argue that to address the network survivability in IP-over-EONs properly, one needs to develop an effective cross-layer orchestration mechanism to handle IP router outages with multi-layer restoration (MLR). Note that, the demonstration in [14] has indicated that by leveraging software-defined networking (SDN), MLR can address the fiber cuts in IP-over-optical networks more timely and cost-efficiently. Since the SDN-based MLR uses a centralized controller to reconfigure the network elements in IP and EON layers directly without waiting for the IP tables to converge, it performs similarly in terms of recovery time as the existing fast IP recovery mechanisms, *e.g.*, the multi-protocol label switching (MPLS) based fast rerouting and dual-plane protection using equal-cost multipath (ECMP) [15]. Meanwhile, as the SDN-based MLR calculates the restoration schemes on demand but does not reserve backup resources, it can potentially achieve higher resource utilization [14]. However, although the experimental results in [14] were very promising, the authors did not either elaborate on the actual MLR algorithm or consider the failure events due to IP router outages.

In this work, we extend our preliminary study in [16] to investigate how to realize the cross-layer orchestration to address IP router outages with cost-efficient MLR in IP-over-EONs. Specifically, we consider the situation in which a single router outage happens during the normal operation of an IP-over-EON, and propose MLR algorithms to minimize the additional OPEX due to MLR. Note that, since the application traffic in the IP layer is highly dynamic, the operator of an IP-over-EON would usually over-provision bandwidths to the lightpaths in the EON layer based on the peak traffic loads. Hence, when a router outage happens, the spare capacity on existing lightpaths can be leveraged for MLR. Meanwhile, the spare spectra in the EON layer can also be utilized for MLR, *i.e.*, setting up new lightpaths and/or reconfiguring existing ones with spectrum expansion [3] to accommodate the IP traffic affected by the router outage. Therefore, we follow the architectural design in [14], and assume that when a router outage happens in an IP-over-EON, the MLR scheme in it can combine optical layer reconfiguration with IP rerouting to recover all the affected traffic and there are sufficient spare resources in the network for this. Note that, if the resources are insufficient, certain affected flows might become irrecoverable, which means that the MLR scheme has to consider differentiated services. We will study this scenario in our future work.For the MLR scheme considered in this work, the additional OPEX comes from the incremental usages of SBV-Ts and frequency slots (FS') and lightpath reconfiguration operations, which will be minimized in our proposed algorithms.

Based on the aforementioned considerations, we first design three MLR strategies to fully explore the flexibility and adaptivity of IP-over-EONs. Then, with the strategies, we formulate an integer linear programming (ILP) model to find the MLR scheme for handling single router outages in an IP-over-EON, while the additional OPEX due to the incremental usages of SBV-Ts and FS' and lightpath reconfigurations is minimized. Next, we propose an auxiliary graph (AG) based heuristic algorithm to reduce the time complexity. The proposed algorithms are evaluated with extensive simulations. Simulation results indicate that compared with an existing benchmark, our algorithms can effectively reduce the additional OPEX of MLR, which is realized by maintaining the power cost due to the incremental usages of SBV-Ts and FS' and reducing the number of lightpath reconfigurations significantly.

The rest of the paper is organized as follows. Section II provides a brief survey on the related work. The network model of an IP-over-EON and the three MLR strategies for addressing single router outages in it are described in Section III. We present the ILP model and the AG-based heuristic algorithm for MLR in Sections IV and V, respectively. The performance evaluation is discussed in Section VI. Finally, Section VII summarizes the paper.

II. RELATED WORK

Due to the massive traffic carried by backbone networks, the survivability of them is always a key issue. To avoid the tremendous revenue loss caused by network failures, researchers have developed both single-layer and multi-layer scenarios to enhance network survivability. For IP-over-EONs, the single-layer scenario usually tries to address a single fiber cut in the EON layer with various protection and restoration schemes [8–12]. However, as we have explained above, the single-layer scenario cannot recover the traffic loss due to router outages in the IP layer without an effective cross-layer orchestration mechanism [16].

For the multi-layer scenario, people have tried to allocated backup resources in the phase of network planning to address failures in both the IP and optical layers [15, 17, 18]. Ruiz *et al.* [17] considered how to design the IP-over-optical networks that can survive from the failures on IP routers, opto-electronic ports and fiber links and formulated an ILP model to minimize the CAPEX in network planning. The work in [18] studied the network planning to realize survivable overlay multicast in IP-over-EONs, and designed a multi-layer protection scheme that protects IP routers with dual-home and redundant multicast trees and secures lightpaths with dedicated backup paths. Nevertheless, the studies in [17, 18] pre-allocated backup resources in both the IP and optical layers and could lead to relatively low protection efficiency. The authors of [15] considered MLR instead of multi-layer protection, and proposed algorithms to pre-calculate the MLR schemes that can increase backup resource sharing when addressing different failure scenarios. However, since the application traffic in the IP layer is usually highly dynamic, the pre-calculated MLR schemes might not always be effective when the network failures actually happen.

Therefore, for MLR, one needs the network control and management (NC&M) mechanism that can monitor the network status proactively and calculate the MLR schemes on-demand. By leveraging the idea of SDN, this can be achieved, and the demonstration in [14] has verified that on-demand MLR can address fiber cuts in IP-over-optical networks more timely and cost-efficiently. However, the study in [14] neither elaborated on the actual MLR algorithm nor considered the failure events due to router outages. For MLR algorithms, Tornatore *et al.* [19] studied the grooming algorithms in IP-over-WDM networks to dynamically provision services with guaranteed availability. However, as the work was based on IP-over-WDM networks, the proposed algorithms cannot be directly applied to IP-over-EONs. Because for lightpath setup and reconfiguration, EONs introduce unique constraints. For instance, dynamic expansion and contraction of a lightpath's spectrum assignment is not feasible in fixed-grid WDM networks. The authors of [20] designed several MLR algorithms to address single fiber cuts in IP-over-EONs. However, they did not consider the failures due to router outages. In [16], we addressed the situation in which an IP router outage happens during the operation of an IP-over-EON, and proposed an AG-based on-demand MLR scheme that can minimize the additional OPEX of MLR with the help of SBV-Ts' spectrum expansion capability. This paper extends our work in [16] by formulating an ILP model that can solve the problem exactly and improving the performance of the AG-based heuristic.

TABLE I
PARAMETERS REGARDING MODULATION FORMATS OF LIGHTPATHS

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

III. MULTI-LAYER RESTORATION (MLR) IN IP-OVER-EONS

A. *Network Model*

Fig. 1 shows the network architecture of an IP-over-EON, which consists of an IP layer, an EON layer, and the links that interconnect the two layers. The topology of the EON layer can be denoted as $G_o(V_o, E_o)$, where V_o represents the set of bandwidth-variable optical cross-connects (BV-OXCs) and E_o is the set of bi-directional fiber links that connect BV-OXCs in V_o. On top of the EON layer, we have the IP layer as $G_i(V_i, E_i)$, where each IP router in V_i locally connects to a BV-OXC in V_o, and E_i denotes the set of logical links between the IP routers. Each logical link $e_i \in E_i$ is supported by a lightpath in the EON layer. Here, for simplicity, we assume that for any two routers v_i and u_i, whether lightpath(s) can be set up to connect their BV-OXCs (*i.e.*, v_o and u_o) is predetermined. More specifically, if lightpaths can be set up to connect v_o and u_o, the corresponding v_i and u_i can be directly connected by one or more logical links in $G_i(V_i, E_i)$, each of which corresponds to a lightpath that uses the shortest-path routing and first-fit spectrum assignment in the EON layer, *i.e.*, for all the lightpaths between the same router pair, their physical routing paths in the EON layer are the same. Otherwise, v_i and u_i are not directly connected in $G_i(V_i, E_i)$[1].

Therefore, a logical link $e_i \in E_i$ has a few attributes, *i.e.*, its source and destination router v_i and u_i, and total capacity, spectrum assignment, and modulation-level of the lightpath that carries it. Here, a modulation-level m as 1, 2, 3 and 4 corresponds to the modulation formats of BPSK, QPSK, 8QAM and 16QAM, respectively, and the modulation-level of a lightpath should be determined by its physical transmission distance [21, 22]. Specifically, according to the experimental results in [23], Table I lists the mapping. Meanwhile, based on the spectral efficiency of the modulation formats, the capacity of a lightpath with modulation-level m can be obtained as $12.5 \cdot m \cdot n$ Gb/s, if it has been assigned n FS' (*i.e.*, each has a bandwidth of 12.5 GHz) for data transmission. To this end, we can see that the model of the IP-over-EON can actually be simplified as $G(V, E)$, where V is the set of IP routers and E denotes the set of logical links in the IP layer. Meanwhile, the information regarding the EON layer is represented by the attributes of the logical links in E.

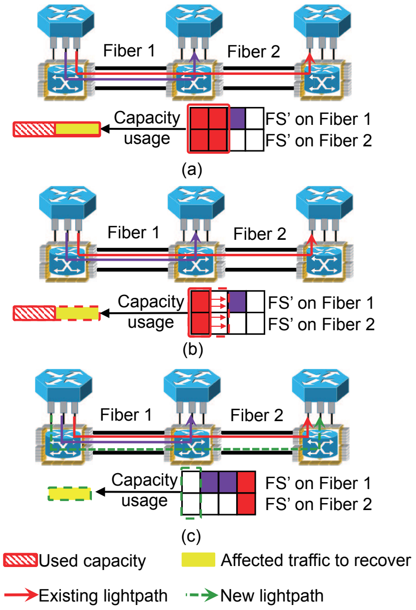

Fig. 2. Three MLR strategies.

B. *MLR Strategies*

We consider the scenario in which a single router outage happens during the operation of the IP-over-EON $G(V, E)$

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[1] With this assumption, we can simplify the routing and spectrum assignment (RSA) scenario in the EON layer, and concentrate our algorithm design more on MLR. Meanwhile, we also admit that the assumption might restrict the flexibility of MLR and we will address this issue in our future work.

and disables a router $v \in V$. After the outage, the operator updates the IP-over-EON to remove the broken router v and gets the affect IP traffic that transits v. Note that, since the affected traffic that originates from or ends at v cannot be recovered until the router is fixed, we do not consider it in the MLR [16]. For the rest of the affected traffic that uses v as an intermediate router, we record it in a traffic matrix $\mathbf{R}$ and try to restore it with the MLR. Note that, since the IP traffic on each established lightpath in the IP-over-EON is dynamic and might not always fully occupy its capacity, we can use the spare capacity on the lightpath to restore the affected traffic in $\mathbf{R}$. In addition to this MLR strategy that uses IP rerouting, we can reconfigure the lightpaths in the EON layer to accomplish the MLR. Apparently, the MLR would result in additional OPEX, and in this work, we define its OPEX as the summation of the additional power cost that comes from the incremental usages of SBV-Ts and FS' and the lump-sum cost due to lightpath reconfigurations. We will try to minimize the MLR's OPEX to make the operator more profitable.

Fig. 2 shows the three MLR strategies that we consider in this work. The first one in Fig. 2(a) is the simplest, which tries to groom the affected traffic into an existing lightpath that has sufficient spare capacity. Since this strategy does not involve any operation in the EON layer, it does not result in any additional OPEX by definition. The second strategy in Fig. 2(b) tries to groom the affected traffic into an existing lightpath that does not have enough spare capacities but can be spectrally expanded with the spectrum expansion capability of its SBV-Ts [3]. Since additional FS' will be allocated in the procedure, this strategy induces additional OPEX due to the incremental usage of FS', and in the mean time, the lightpath is reconfigured once for the spectrum expansion. For the last strategy in Fig. 2(c), we set up a new lightpath to recover the affected traffic. Hence, the additional OPEX comes from both the incremental usages of SBV-Ts and FS' and one lightpath reconfiguration operation. Here, we assume that for the MLR, the spare network resources (*i.e.*, router ports, SBV-Ts and FS') are sufficient such that at least one of the three MLR strategies can be used to recover all the affected traffic.

Note that, the additional OPEX due to the incremental usages of SBV-Ts and FS' can be quantified with their power consumptions. Specifically, the additional power consumption can be modeled as $P = W_m \cdot n + W_0$, where W_m is the power consumption for occupying an FS whose modulation-level is m, n is the number of newly-assigned FS', and W_0 is the static power usage of an SBV-T [3]. Here, based on the power model in [24], we use the values shown in Table I for W_m and set $W_0 = 100$ W. Meanwhile, the additional cost of a lightpath reconfiguration can be modeled as a lump-sum cost c_l [25, 26]. Therefore, for the three MLR strategies in Fig. 2, we obtain the additional OPEX for them as

$$C = \begin{cases} 0, & \text{First Strategy,} \\ \alpha \cdot W_m \cdot n + c_l, & \text{Second Strategy,} \\ \alpha \cdot (W_m \cdot n + W_0) + c_l, & \text{Third Strategy,} \end{cases} \tag{1}$$

where α is the unit cost of power consumption.

IV. INTEGER LINEAR PROGRAMMING MODEL

Based on the discussions in the previous section, we can see that the problem is to handle a router outage in the IP-over-EON with the three MLR strategies such that all the affected traffic in $\mathbf{R}$ can be recovered successfully[2] and the additional OPEX defined in Eq. (1) is minimized. We first formulate an ILP model to solve the problem exactly.

Notations:

- $G(V, E)$: the topology of the IP-over-EON, where V is the set of routers and E represents the set of logical links in the IP layer.
- B: the total number of FS' on each fiber link in the EON.
- $K_{u,v}$: the number of existing logical links between adjacent routers u and v ($u, v \in V$) before the MLR.
- $m_{u,v}$: the modulation-level of the lightpath to carry the logical link between adjacent routers u and v ($u, v \in V$).
- $tp_{u,v}$: the indicator that equals 1 if lightpaths can be set up to connect routers u and v ($u, v \in V$), and 0 otherwise.
- $\mathbf{R}$: the traffic matrix to store all the affected traffic.
- r: a flow of affected traffic in $\mathbf{R}$, *i.e.*, $r = (s_r, d_r, t_r) \in \mathbf{R}$, where s_r and d_r are the source and destination routers of the flow, and t_r is its bit-rate.
- e: a logical link in E, which can also be denoted as $e = (u, v, k)$, meaning the k-th logical link between adjacent routers u and v ($u, v \in V$) before the MLR.
- b_e: the used capacity of logical link $e \in E$ before the MLR.
- w'_e: the start FS index of the spectrum assignment of the lightpath that carries logical link $e \in E$ before the MLR.
- z'_e: the end FS index of the spectrum assignment of the lightpath that carries logical link $e \in E$ before the MLR.
- g_e: the indicator that equals 1 if logical link $e = (u, v, k) \in E$ exists before the MLR, and 0 otherwise.
- $o_{e,e'}$: the indicator that equals 1 if $w'_e < w'_{e'}$ for two logical links e and e' before the MLR, and 0 otherwise.
- $p_{e,e'}$: the indicator that equals 1 if the lightpaths that carry two logical links e and e' share fiber link(s) with each other, and 0 otherwise.
- W_0: the static power consumption of an SBV-T.
- W_m: the power consumption for occupying an FS whose modulation-level is m.
- α: the unit cost of power consumption.
- c_l: the lump-sum cost of reconfiguring a lightpath.

Variables:

- $x^r_{(u,v,k)}$: the boolean variable that equals 1 if we use logical link $e = (u, v, k)$ to restore flow $r \in \mathbf{R}$, and 0 otherwise.
- $y_{(u,v,k)}$: the boolean variable that equals 1 if we expand the spectrum assignment of the lightpath carrying logical link (u, v, k) in the MLR, and 0 otherwise.
- $\Delta^w_{(u,v,k)}$: the integer variable that indicates the number of new FS' to the lower-end, if a spectrum expansion has been conducted on the lightpath that carries logical link (u, v, k) in the MLR.

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[2] Note that, in this work, we assume that the SBV-Ts and FS' in the EON layer are sufficient for the MLR and thus do not consider the scenario of IP traffic blocking during the MLR.

- $\Delta^z_{(u,v,k)}$: the integer variable that indicates the number of new FS' to the upper-end, if a spectrum expansion has been conducted on the lightpath that carries logical link (u,v,k) in the MLR.
- $w_{(u,v,k)}$: the integer variable that indicates the start FS index of the spectrum assignment of the lightpath that carries logical link (u,v,k) after the MLR.
- $z_{(u,v,k)}$: the integer variable that indicates the end FS index of the spectrum assignment of the lightpath that carries logical link (u,v,k) after the MLR.
- $g_{(u,v,K_{u,v}+1)}$: the boolean variable that equals 1 if a new lightpath is set up between routers u and v $(u,v \in V)$ in the MLR, and 0 otherwise.
- $h_{u,v}$: the integer variable that indicates the number of FS' assigned to the new lightpath between routers u and v $(u,v \in V)$ in the MLR.

Objective:

The optimization objective is to minimize the additional OPEX induced by the MLR, *i.e.*,

$$Minimize \quad \hat{C}, \tag{2}$$

where the total additional OPEX $\hat{C}$ can be calculated as

$$\begin{aligned}\hat{C} =& c_l \cdot \left[\sum_{u,v\in V}\sum_{k=1}^{K_{u,v}} y_{(u,v,k)} + \sum_{u,v\in V} g_{(u,v,K_{u,v}+1)}\right] \\ &+ \alpha \cdot \sum_{u,v\in V}\sum_{k=1}^{K_{u,v}} \left[\Delta^w_{(u,v,k)} + \Delta^z_{(u,v,k)}\right] \cdot W_{m_{u,v}} \\ &+ \alpha \cdot \sum_{u,v\in V}\left[h_{u,v}\cdot W_{m_{u,v}} + g_{(u,v,K_{u,v}+1)}\cdot W_0\right].\end{aligned} \tag{3}$$

Here, on the right side of Eq. (3), the first item is total lump-sum cost due to lightpath reconfigurations in the MLR, the second one is the total power cost due to the spectrum expansions on existing lightpaths, and the last one is the total power cost due to new lightpaths. Note that, since lightpath reconfigurations can prolong the recovery time of the MLR and introduce additional operation complexity, we set $c_l \gg \alpha$ to ensure that the primary objective is to minimize the number of lightpath reconfigurations, while the second one is to reduce the additional power consumption.

Constraints:

$$\sum_{v\in V}\sum_{k=1}^{K_{u,v}+1} x^r_{(u,v,k)} - \sum_{v\in V}\sum_{k=1}^{K_{v,u}+1} x^r_{(v,u,k)} = \begin{cases} 1, & u = s_r, \\ -1, & u = d_r, \\ 0, & \text{others}, \end{cases} \quad \forall r \in \mathbf{R}, \tag{4}$$

$$\sum_{v\in V}\sum_{k=1}^{K_{u,v}+1} x^r_{(u,v,k)} \le 1, \quad \forall r \in \mathbf{R},\ u \in V, \tag{5}$$

$$\sum_{u\in V}\sum_{k=1}^{K_{u,v}+1} x^r_{(u,v,k)} \le 1, \quad \forall r \in \mathbf{R},\ v \in V. \tag{6}$$

Eqs. (4)-(6) ensure that we use at most one lightpath to restore a traffic flow $r \in \mathbf{R}$. This is because splitting a traffic flow over multiple lightpaths can introduce a differential delay at its destination [27], which can only be addressed with complicated packet reordering. Moreover, Eqs. (4)-(6) also suggest that to restore all the affected traffic in $\mathbf{R}$, we would set up at most one new lightpath between a router pair u-v $(u,v \in V)$. This assumption is also reasonable because an EON allows flexible spectrum allocation for each lightpath and thus multiple new lightpaths can be merged into one.

$$\begin{cases} \Delta^w_e + \Delta^z_e \le B \cdot y_e \le B \cdot (\Delta^w_e + \Delta^z_e), \\ w_e = w'_e - \Delta^w_e, \\ z_e = z'_e + \Delta^z_e, \end{cases} \\ \{e = (u,v,k) : \forall (u,v,k) \in E,\ k \le K_{u,v}\}. \tag{7}$$

Eq. (7) ensures that the values of the variables regarding the spectrum expansions are chosen correctly.

$$\begin{cases} z_e = w_e + h_{u,v} - g_e, \\ w_e \le B \cdot g_e \le B \cdot w_e, \\ h_{u,v} \le B \cdot g_e \le B \cdot h_{u,v}, \end{cases} \\ \{e = (u,v,k) : \forall (u,v,k) \in E,\ k = K_{u,v} + 1\}. \tag{8}$$

Eq. (8) ensures that the values of the variables regarding the new lightpaths are chosen correctly.

$$\begin{cases} g_e + z_{e'} - w_e \le B \cdot (1 + o_{e,e'} - p_{e,e'}), \\ g_{e'} + z_e - w_{e'} \le B \cdot (2 - o_{e,e'} - p_{e,e'}), \\ -B \cdot o_{e,e'} \le w_e - w_{e'} \le B \cdot (1 - o_{e,e'}) + \frac{1}{2} \cdot (g_e - g_{e'} - 1), \\ g_{e'} - g_e \le o_{e,e'} \le g_{e'}, \end{cases} \\ \{e = (u,v,k), e' = (u',v',k') : \forall e \ne e',\ k \le K_{u,v} + 1, \\ k' \le K_{u',v'} + 1\}. \tag{9}$$

Eq. (9) ensures that if the MLR invokes lightpath reconfigurations, the spectrum assignments of any two lightpaths that share fiber link(s) do not overlap.

$$12.5 \cdot m_{u,v} \cdot (z_e - w_e + g_e) \ge b_e + \sum_{r\in\mathbf{R}} x^r_e \cdot t_r, \\ \{e = (u,v,k) : \forall (u,v,k) \in E,\ k \le K_{u,v} + 1\}. \tag{10}$$

Eq. (10) ensures that the total bit-rate of the traffic flows on a lightpath does not exceed its capacity.

$$x^r_e \le g_e, \\ \{e = (u,v,k) : \forall (u,v,k) \in E,\ k \le K_{u,v} + 1\}. \tag{11}$$

Eq. (11) ensures that a traffic flow can only be routed on an existing lightpath.

$$g_{(u,v,k)} \le tp_{u,v}, \quad k = K_{u,v} + 1,\ \forall u,v \in V. \tag{12}$$

Eq. (12) ensures that all the new lightpaths are set up correctly based on the predetermined network planning.

$$x^r_{(u,v,k)} \in \{0,1\}, \quad \forall (u,v,k) \in E,\ r \in \mathbf{R}, \tag{13}$$

$$y_{(u,v,k)},\ g_{(u,v,k)} \in \{0,1\}, \quad \forall (u,v,k) \in E, \tag{14}$$

$$\Delta^w_{(u,v,k)},\ \Delta^z_{(u,v,k)},\ h_{u,v} \in [0,B], \quad \forall (u,v,k) \in E, \tag{15}$$

$$w_{(u,v,k)},\ z_{(u,v,k)} \in [1,B], \quad \forall (u,v,k) \in E. \tag{16}$$

Eqs. (13)-(16) limit the ranges of the variables.

V. HEURISTIC ALGORITHM DESIGN

Solving the ILP model in the previous section is time consuming, and the model can become intractable when the scale of the IP-over-EON is relatively large. To address this issue, we design a time-efficient heuristic algorithm in this section, which leverages an auxiliary graph (AG) [28] to find the cost-efficient MLR scheme to recover the affected traffic in $\mathbf{R}$. Previously, in [16], we have designed an AG-based heuristic (*i.e.*, AG-E) for realizing cost-efficient MLR. However, due to the fact that AG-E handles the affected traffic flows in $\mathbf{R}$ sequentially, it still bears a few drawbacks. Specifically, since the affected flows are processed separately, AG-E may expand a lightpath multiple times and/or set up multiple new lightpaths between a router pair. Hence, additional OPEX due to unnecessary lightpath reconfigurations and/or SBV-T usage can be introduced. To address this issue, we propose a heuristic that handles all the affected flows in $\mathbf{R}$ jointly to come up with an MLR scheme that would only expand a lightpath once and set up one new lightpath between a router pair, *i.e.*, AG-E-J.

Between a router pair u-v in the IP-over-EON, there may exist multiple logical links (*i.e.*, lightpaths), which can be denoted with a set $E_{u,v}$. Then, in $E_{u,v}$, we use $(u,v,\hat{k})$ to denote the lightpath that has the largest spare capacity, and refer to the lightpath that has the largest potential spare capacity as $(u,v,\tilde{k})$. Here, the potential spare capacity of a lightpath refers to the spare capacity on it after being spectrally expanded to the maximum extent. We use $f_{u,v}$ to indicate whether an existing lightpath between u-v should be reconfigured or a new lightpath should be set up there. If we need to expand a lightpath for the router pair u-v (*i.e.*, lightpath reconfiguration), we store the lightpath $(u,v,\tilde{k})$ in $f_{u,v}$, *i.e.*, $f_{u,v}=(u,v,\tilde{k})$, if we need to set up a new lightpath between u-v, we have $f_{u,v}=(u,v,K_{u,v}+1)$, and we set $f_{u,v}=\emptyset$ otherwise. For a lightpath e in the IP-over-EON $G(V,E)$, we use $e.s$ and $e.ps$ to denote its spare capacity and potential spare capacity, respectively. *Algorithm* 1 shows the procedure for building an AG to reroute an affected traffic flow $r \in \mathbf{R}$.

Algorithm 1: Building an AG for an Affect Flow

```
Input: affected flow $r=(s_r,d_r,t_r)$, current network
       status of IP-over-EON $G(V,E)$, and network
       planning indicators $\{tp_{u,v}\}$
Output: a weighted AG $G_a(V_a,E_a)$
1  $V_a=V$;
2  for each node pair $u$-$v$ with $tp_{u,v}=1$ do
3      connect $u$ and $v$ directly in $G_a(V_a,E_a)$;
4      if $(u,v,\hat{k}).s \geq t_r$ then
5          assign weight of $(u,v)$ in $G_a$ as $w_{u,v}=\varepsilon^2$;
6      else if $f_{u,v} \neq \emptyset$ then
7          assign weight of $(u,v)$ in $G_a$ as $w_{u,v}=\varepsilon$;
8      else
9          assign weight of $(u,v)$ in $G_a$ as $w_{u,v}=1$;
10     end
11 end
12 return $G_a(V_a,E_a)$;
```

To build the AG $G_a(V_a,E_a)$ based on the current network status of the IP-over-EON $G(V,E)$, *Line* 1 in *Algorithm* 1 first sets $V_a=V$. Then, the for-loop that covers *Lines* 2-11 checks each node pair u-v with $tp_{u,v}=1$ in $G(V,E)$ to insert a weighted link to directly connect u and v in $G_a(V_a,E_a)$. Specifically, if the lightpath with the largest spare capacity between u and v can accommodate the capacity of the affected flow r, *Lines* 4-5 set the weight of link (u,v) in G_a as $w_{u,v}=\varepsilon^2$. Here, we define the coefficient ε as

$$\varepsilon=\frac{1}{\left(1+\sum\limits_{u,v\in V} tp_{u,v}\right)}. \tag{17}$$

Otherwise, if a lightpath between u and v has already been selected for spectrum expansion or a new lightpath will be established there, we assign the weight of link (u,v) in G_a as $w_{u,v}=\varepsilon$, as shown in *Lines* 6-7, which encourages multiple affected flows to share the same lightpath with spectrum expansion or the new lightpath. Finally, if none of the lightpaths between u and v has been selected for spectrum expansion and none of them has enough spare capacity to accommodate the affected flow r and no new lightpath has been selected to set up, we will need to set up a new lightpath there (*i.e.*, a new lightpath reconfiguration) and thus the weight of link (u,v) is set as $w_{u,v}=1$ in *Lines* 8-9. Then, the AG has been built, and by applying the shortest-path routing algorithm in it, we can find the most cost-efficient way to reroute the affected flow r in the IP-over-EON, which not only fully utilizes the spare capacities on existing lightpaths but also minimizes the lightpath reconfigurations.

Algorithm 2 shows the detailed procedure of AG-E-J to achieve cost-efficient MLR. Firstly, *Line* 1 sorts the affected flows in $\mathbf{R}$ in descending order of their bit-rates. Then, the for-loop that covers *Lines* 2-34 restores all the affected flows in $\mathbf{R}$ in the sorted order. By processing the flows with larger bit-rates earlier, we can encourage the flows with smaller bit-rates to reuse the reconfigured and/or newly-established lightpaths, and thus reduce the additional OPEX of the MLR. For an affected flow r, *Lines* 3-4 are for the initialization, which build an AG for it by invoking *Algorithm* 1 and calculate K shortest paths between s_r and d_r in the AG. The obtained paths are stored in path set $\mathcal{P}$, which actually offers us the options to reroute affected flow r in $G(V,E)$ with relatively small numbers of lightpath reconfigurations. Then, with the for-loop covering *Line* 5-31, we select lightpaths on each $p \in \mathcal{P}$ to reroute r with the smallest additional power cost. The selected lightpaths are stored in a link set L_p for each path $p \in \mathcal{P}$. In the process, we also try to leave more spare capacity for future traffic grooming, *i.e.*, in *Lines* 9-10, 12-19, and 21-28. Finally, after checking all the paths in $\mathcal{P}$ for affected flow r, *Lines* 32-33 find the path $p^* \in \mathcal{P}$ that has the smallest power cost, and use the lightpaths in L_{p^*} to reroute r. Note that, in *Algorithm* 2, between any router pair u-v, we either set up or reconfigure at most one lightpath.

Complexity Analysis: In *Algorithm* 2, the time complexity of sorting the affected flows is $O(|\mathbf{R}|\cdot\log(|\mathbf{R}|))$, where $|\mathbf{R}|$ is the number of affected flows. The complexity of calculating K shortest paths in an AG is $O(|\mathbf{R}|\cdot|E|\cdot|V|^2)$. To find the exact lightpaths to reroute an affected flow, we may need to

Algorithm 2: AG-E-J Algorithm for MLR Design

```
Input: traffic matrix for affected flows $\mathbf{R}$, and network
       status of IP-over-EON $G(V, E)$ after router outage
Output: a MLR scheme to recover the flows in $\mathbf{R}$
sort flows in $\mathbf{R}$ in descending order of their bit-rates;
for each flow $r \in \mathbf{R}$ in the sorted order do
    invoke Algorithm 1 to build an AG $G_a(V_a, E_a)$ based
    on the current network status;
    calculate $K$ shortest paths between $s_r$ and $d_r$ in
    $G_a(V_a, E_a)$ and store them in path set $\mathcal{P}$;
    for each path $p \in \mathcal{P}$ do
        $L_p = \emptyset$;
        for each link $(u, v) \in p$ do
            if $w_{u,v} = \varepsilon^2$ then
                select the lightpath $e \in E_{u,v}$ that has the
                smallest $e.s$ and can accommodate $t_r$;
                add $e$ into link set $L_p$;
            else if $w_{u,v} = \varepsilon$ then
                if $f_{u,v}.ps \geq t_r$ then
                    add $f_{u,v}$ into link set $L_p$;
                else
                    set up a new lightpath $e'$ between $u$
                    and $v$;
                    move all the traffic on $f_{u,v}$ to $e'$;
                    $f_{u,v} = e'$;
                    add $e'$ into link set $L_p$;
                end
            else
                if $(u, v, \tilde{k}).ps \geq t_r$ then
                    add $(u, v, \tilde{k})$ into link set $L_p$;
                    $f_{u,v} = (u, v, \tilde{k})$;
                else
                    set up a new lightpath $e'$ between $u$
                    and $v$;
                    $f_{u,v} = e'$;
                    add $e'$ into link set $L_p$;
                end
            end
        end
    end
    find the path $p^* \in \mathcal{P}$ with the smallest power cost;
    use the links in $L_{p^*}$ to reroute affected flow $r$ and
    update network status;
end
```

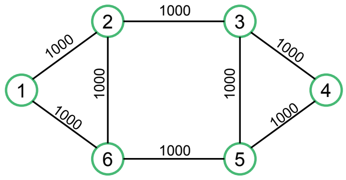
check all the logical links in E in the worst case, and thus the complexity of this part is $O(|\mathbf{R}| \cdot |E|)$. Finally, the overall complexity of *Algorithm* 2 is $O(|\mathbf{R}| \cdot |E| \cdot |V|^2 + |\mathbf{R}| \cdot \log(|\mathbf{R}|))$.

VI. PERFORMANCE EVALUATION

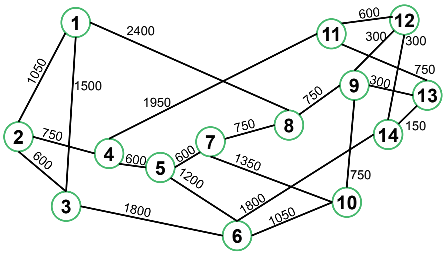
In this section, we evaluate the performance of the proposed MLR algorithm with extensive numerical simulations.

A. Simulation Setup

The simulations consider two topologies for the IP-over-EON, *i.e.*, the six-node topology and the NSFNET topology shown in Fig. 3 [29]. In the EON layer, we assume that each fiber link can accommodate 358 FS', each of which has a bandwidth of 12.5 GHz [30]. The capacity of an FS depends on the modulation-level that it uses, as shown in Table I. The network planning of the IP layer is generated by selecting $tp_{u,v}$ randomly for each router pair u-v, and we also make sure that the IP topology would not become isolated subgraphs after any single router outage.



(a) Six-node topology



(b) NSFNET topology

Fig. 3. IP-over-EON topologies with lengths in km marked on fiber links.

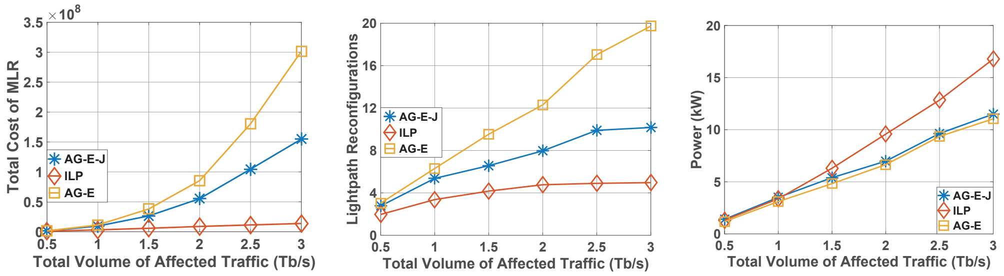
Then, we set up the existing lightpath in the EON layer to support the logical links in the IP topology. Specifically, the number of existing lightpaths between a router pair is randomly selected within $[0, 4]$, and the bandwidth of each lightpath is uniformly distributed within $[1, 10]$ FS'. To emulate the dynamic IP traffic, we assign the spare capacity on each lightpath randomly, and consider two traffic scenarios, *i.e.*, the heavy and moderate traffic scenarios. Specifically, for the heavy traffic scenario, we assume that each lightpath has 20% spare capacity on average, while the average spare capacity on each lightpath in the moderate traffic scenario is 40%. Next, we randomly select an IP router to fail and generate the traffic matrix for affected flows $\mathbf{R}$ randomly with fixed total traffic volumes. For the MLR schemes, their additional OPEX is calculated with Eq. (1) in Section III, where we set $\alpha = 1$ to normalize the power cost and have

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

which is the upper-bound of the total power cost. This is to ensure that the primary objective is to minimize the number of lightpath reconfigurations. The K shortest-path routing in *Algorithm* 2 has $K = 4$. We use the AG-E algorithm in [16] as the benchmark algorithm. In the simulations, we obtain each data point by averaging the results from 30 independent simulations to maintain sufficient statistical accuracy.

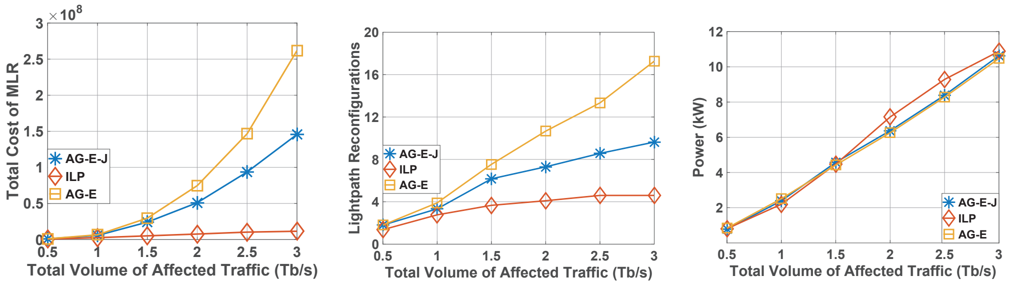
B. Simulation Results with Six-Node Topology

The simulations compare the ILP, AG-E-J, and AG-E in six-node topology. Fig. 4 shows the results of the heavy traffic scenario. In Fig. 4(a), we observe that the ILP provides the



(a) Total cost of MLR (b) Lightpath reconfigurations (c) Additional power consumption

Fig. 4. Simulation results for the heavy traffic scenario in six-node topology.



(a) Total cost of MLR (b) Lightpath reconfigurations (c) Additional power consumption

Fig. 5. Simulation results for the moderate traffic scenario in six-node topology.

TABLE II
RUNNING TIME OF ALGORITHMS

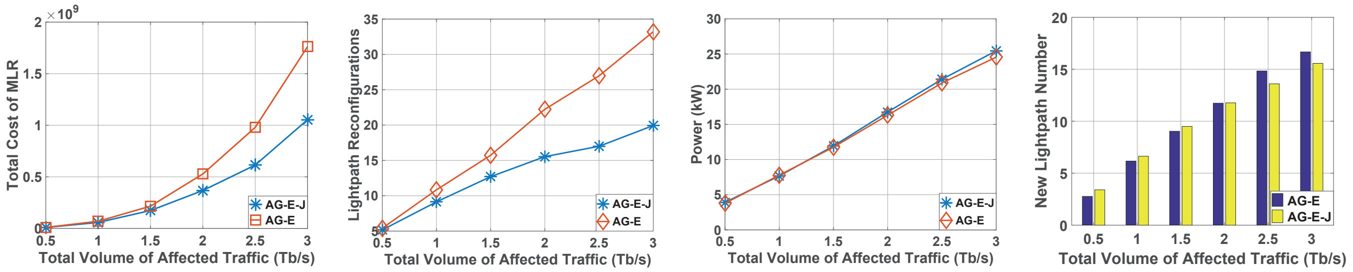
	Moderate Traffic Load			Heavy Traffic Load		
Affected Traffic Volume (Tb/s)	0.5	1.5	3	0.5	1.5	3
ILP	16.1	95.3	1943.8	38.7	151.9	611.0
AG-E-J	0.11	0.17	0.24	0.10	0.17	0.23
AG-E	0.12	0.25	0.40	0.14	0.26	0.38

lowest total cost, followed by AG-E-J, while total cost from AG-E is the highest. More promisingly, with the increase of the total volume of affected traffic, the performance gaps between our proposed algorithms and the benchmark AG-E actually increase, which verifies the effectiveness of the ILP and AG-E-J further. Figs. 4(b) and 4(c) illustrate the algorithms' performance on the number of lightpath configurations and additional power consumption of MLR, respectively. It can be seen that compared with AG-E, the ILP and AG-E-J can effectively reduce the number of lightpath reconfigurations, which confirms that the primary optimization objective of the MLR problem gets handled well. However, the results on additional power consumption in Fig. 4(c) indicates that the results from AG-E-J and AG-E are comparable, while those from the ILP are higher than them. This is because to minimize the overall cost, the ILP sacrifices certain performance of additional power consumption to reduce the number of lightpath reconfigurations. Specifically, by analyzing the MLR schemes from the ILP, we find that to avoid lightpath reconfigurations, the algorithm may use many lightpaths to recover an affected traffic flow, which might lead to relatively high power consumption.

For the moderate traffic scenario, Fig. 5 shows the results, which follow the similar trends as those in Fig. 4. However, we notice that in Fig. 5(c), the gap on additional power consumption between the ILP and AG-E becomes much smaller. This is because the moderate traffic scenario leaves more spare capacities on the existing lightpaths, which helps to avoid using many lightpaths to recover an affected traffic flow and thus saves certain power consumption. We also record the results on running time of the algorithms and list them in Table II, which suggest that our proposed algorithm AG-E-J is the most time-efficient one among them. This is because AG-E-J handles all the affected traffic flows jointly, and thus can save the time complexity on determining the schemes of lightpath reconfiguration and new lightpath setup, compared with AG-E. Meanwhile, as expected, the ILP takes the longest running time, and its running time increases exponentially with the total volume of affected traffic, which will make it impractical for solving large scale MLR problems. Therefore, in the next subsection, the simulations using the NSFNET topology only compare AG-E with AG-E-J.

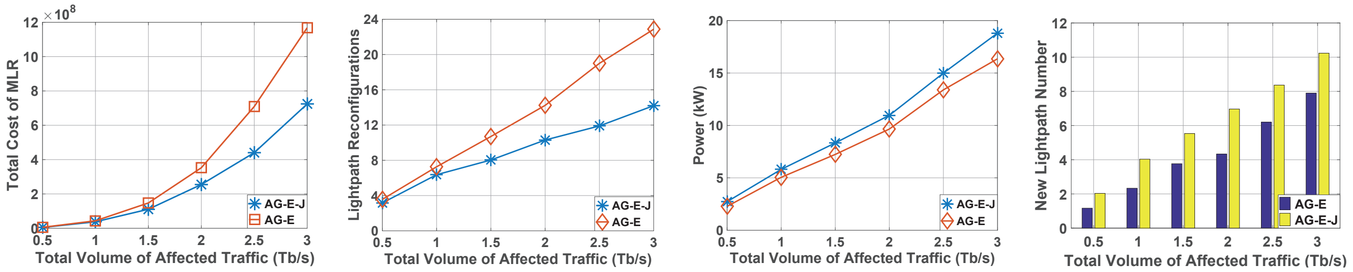
C. Simulation Results with NSFNET Topology

Fig. 6 shows the simulation results of the heavy traffic scenario with the NSFNET topology, which also follow the similar trends as those in Fig. 4. Note that, as indicated by the results in Figs. 6(b) and 6(c), the additional power consumption from AG-E-J is comparable to that from AG-E, but AG-E-J invokes much less lightpath configurations. These results suggest that when the spare capacities on existing lightpaths are not abundant, AG-E-J can maintain its additional power consumption as low as that of AG-E but invokes much less lightpath configurations to save the total cost of MLR. The results of the moderate traffic scenario in Fig. 7 still verify the advantages of AG-E-J over AG-E. However, in Fig. 7(c),



(a) Total cost of MLR (b) Lightpath reconfigurations (c) Additional power consumption (d) Number of new lightpaths

Fig. 6. Simulation results for the heavy traffic scenario in NSFNET topology.



(a) Total cost of MLR (b) Lightpath reconfigurations (c) Additional power consumption (d) Number of new lightpaths

Fig. 7. Simulation results for the moderate traffic scenario in NSFNET topology.

we notice that the additional power consumption from AG-E-J is slightly higher than that from AG-E. Note that, since AG-E-J tries to handle the affected traffic flows jointly with those having larger traffic volumes earlier, it can set up more new lightpaths than AG-E in the moderate traffic scenario. Specifically, since the spare capacities in existing lightpaths are abundant, the sequential processing in AG-E can fit more affected traffic flows in the existing lightpaths than the joint processing in AG-E-J. Hence, certain new lightpaths set up by AG-E-J can be under-utilized, which pushes up its additional power consumption. This explains the trend in Fig. 7(c). To verify this analysis, we plot the results on number of new lightpaths in the heavy and moderate traffic scenarios in Figs. 6(d) and 7(d), respectively. It can be seen clearly that in the heavy traffic scenario, the number of new lightpaths from AG-E-J is comparable to or even smaller than that from AG-E, while in the moderate traffic scenario, the number of new lightpaths from AG-E-J is always larger than that from AG-E.

Note that, the simulations above use a semi-static scenario that generates the affected traffic matrix $\mathbf{R}$ randomly with a fixed total volume, but does not consider the dynamic provisioning of traffic flows. Hence, to further verify the effectiveness of AG-E-J, we perform simulations with a more practical scenario that considers dynamic provisioning. Specifically, in each simulation, we generate dynamic traffic flows according to the Poisson traffic model, and provision them in the IP-over-EON with AG-E. Then, we emulate a router outage by bringing down 1 to 3 routers randomly. Next, we store the recoverable affected flows in $\mathbf{R}$, and restore them with an MLR algorithm. Before the router outage, the number of lightpaths between a router pair ranges within $[1, 10]$, and each of them uses $[1, 9]$ FS' and has a spare capacity within $[0.5, 150]$ Gb/s. As we fail 1 to 3 routers randomly, the total volume of $\mathbf{R}$ can be different in the simulations. In Fig. 8(a), we observe the total cost of MLR from AG-E-J is still lower than that from AG-E, which follows the similar trend in Figs. 6(a) and 7(a). This suggests that the effectiveness of our proposed algorithm would not be affected by the simulation scenario. This analysis can be further verified with the results in Figs. 8(b) and 8(c), which indicate that compared with AG-E, AG-E-J reduces the number of lightpath reconfigurations effectively while uses similar additional power.

VII. CONCLUSION

In this work, we investigated how to realize cost-efficient MLR to address router outages in IP-over-EONs. Specifically, we considered the situation in which a single router outage happens during the normal operation of an IP-over-EON, and proposed MLR algorithm to minimize the additional OPEX due to MLR. We first designed three MLR strategies to fully explore the flexibility and adaptivity of IP-over-EONs. Then, with the strategies, we formulated an ILP model to find the MLR scheme to minimize the additional OPEX due to the incremental usages of SBV-Ts and FS' and lightpath reconfigurations. We also proposed an AG based heuristic, namely, AG-E-J, to reduce the time complexity. The proposed algorithm was evaluated with extensive simulations and the results indicated that compared with an existing benchmark (*i.e.*, AG-E in [16]), it could effectively reduce the additional OPEX of MLR, which was realized by maintaining the power cost due to the incremental usages of SBV-Ts and FS' and reducing the number of lightpath reconfigurations significantly.

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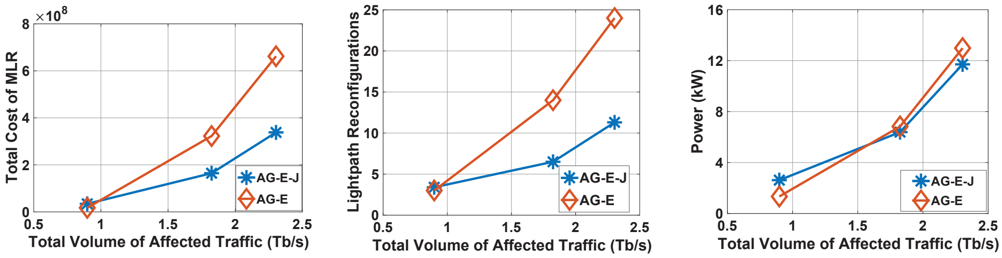

(a) Total cost of MLR (b) Lightpath reconfigurations (c) Additional power consumption

Fig. 8. Simulation results when considering dynamic provisioning in NSFNET topology.

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