# Dynamic OpenFlow-based Lightpath Restoration in Elastic Optical Networks on the GENI Testbed

(*Invited Paper*)

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***Abstract*—Elastic optical networking (EON), with its flexible use of the optical spectrum, is a promising solution for future metro/core optical networking. For the deployment of EON in a real operational scenario, the dynamic lightpath restoration, driven by an intelligent control plane, is a necessary network function. Dynamic restoration can restore network services automatically, and thus greatly reduce the operational cost, compared with traditional manual or semi-static lightpath restoration strategies enabled by network operators via a network management system. To this end, in this paper, we present OpenFlow-enabled dynamic lightpath restoration in elastic optical networks, detailing the restoration framework and algorithm, the failure isolation mechanism, and the proposed OpenFlow protocol extensions. We quantitatively present the restoration performance via control plane experimental tests on the Global Environment for Network Innovations (GENI) testbed.**

***Index Terms* — Software-Defined Networking (SDN), OpenFlow, Global Environment for Network Innovations (GENI), restoration, elastic optical network**

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## I. Introduction

THE optical metro and core networks are evolving from the traditional fixed wavelength grid to a flexible grid paradigm [1]. Such networks are usually referred to as flexi-grid optical networks or elastic optical networks (EONs) [2]. In EON, the optical spectrum of a lightpath (i.e., an optical connection) can be adaptively allocated in multiples of a basic spectrum slot width (e.g.,12.5 GHz) according to the traffic demands [3]. Compared with the traditional fixed-grid optical networking, such as the wavelength switched optical network (WSON), EON can greatly improve the network resource efficiency, reduce the network cost, and agilely handle traffic variations and large traffic (i.e. super-channels) [4, 5]. Therefore, the EON is a promising technology for future metro/core optical networks.

The role of a control plane is critically important in EONs, not only for connection provisioning, but also for restoring services, either in case of link failures or signal quality degradation. Recently, Software-Defined Networking (SDN) and, in particular, the OpenFlow (OF) [6] architecture and its associated protocol have attracted strong interest from both academia and industry, and many studies have extended OpenFlow to control optical networks [7-15]. The centralized SDN /OpenFlow-based control plane provides flexibility for the operators to control a network given its open interfaces and the open nature of its source code [16, 17].

Although a number of previous works have investigated OpenFlow-based EONs, these works mainly focused on dynamic connection provisioning [18-21]. To the best of our knowledge, only the works in [22, 23] have investigated OpenFlow-enabled restoration in EONs. Ref. [22] presented a proof-of-concept demonstration of OpenFlow-controlled dynamic recovery for only one failed connection on a real EON testbed employing a flexible transmitter (Tx) and receiver (Rx). Ref. [23] proposed a fast OpenFlow-based restoration scheme to minimize the parallel hardware configuration delay. However, physical impairments in the network are not considered in [23]. Since the restoration path usually has a different length and hop count compared to the working path, the consideration of physical layer impairments, modulation formats, or even bandwidth squeezed restoration [24] is important in order to attain successful service recovery.

In light of the above, in this work, we investigate OpenFlow-based dynamic lightpath restoration in EONs by considering all the above factors into account. We propose an OpenFlow-based failure isolation mechanism and a new OpenFlow OFPT_ALARM message. Based on these, a two-phase restoration routing, spectrum, and modulation format assignment (RSMA) algorithm is presented. More importantly, control plane experimental tests are carried out on the Global Environment for Network Innovations (GENI) [25] testbed, which includes many GENI racks, regional and national backbone networks around the United States. This allows validating the overall feasibility of the approach and provides valuable insights into its potential for possible deployment in the future.

The rest of this paper is organized as follows: Section II presents the network architecture of OpenFlow-controlled EON with flexible transmitters and receivers. Section III introduces the key enabling techniques. Section IV reports the testbed setup and results. We conclude in Section V by summarizing our contributions.

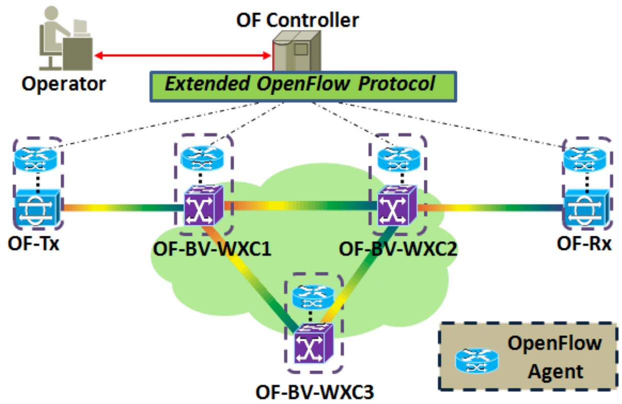


Fig. 1. Network architecture for OpenFlow-controlled EON.

## II. Network Architecture

The data plane of an OpenFlow-based EON includes bandwidth-variable wavelength cross-connects (BV-WXCs) and flexible transmitters/receivers (Txs/Rxs), as shown in Fig.1. As illustrated in [3], the BV-WXC is implemented by using multiple bandwidth-variable wavelength selective switch (BV-WSS). The flexible Txs/Rxs are able to send/receive optical signals with different bit rates and modulation formats without hardware modification. As mentioned in our previous work [20, 26], the Tx/Rx utilize the direct-detected optical orthogonal frequency division multiplexing (DDO-OFDM) [27, 28] technique. However, it is important to note that the proposed restoration scheme applies to any other transmission technique such as coherent OFDM, coherent optical wavelength-division multiplexing (WDM) or Nyquist WDM.

Fig.2(a) and Fig.2(b) describe the Tx and Rx processing for DDO-OFDM supported by advanced digital signal processing respectively. At the Tx, the random binary bits are firstly mapped to the pre-defined Quadrature Amplitude Modulation (QAM) symbols such as 4-, 16-, or 64QAM, and, along with a radio frequency (RF) pilot tone [29], converted to time domain using a 128-point Inverse Fast Fourier Transform (IFFT). A cyclic prefix with a length of ~(1/16 x symbol duration) is added at the head of each OFDM symbol to prevent the inter-symbol interference (ISI). After that, 4x oversampling is performed to model the output analog signals to increase the reliability of the results. The generated signal is used to drive a linear IQ modulator fed by a narrow-linewidth laser. The output of the modulator is sent to the EON. At the Rx, a square-law photodiode is used to down-convert the received signals to the electrical baseband. After down-sampling (by analog-to-digital converter, ADC), signal processing such as cyclic prefix removal, FFT, channel estimation and equalization, QAM de-mapping are performed to recover the transmitted signals.

As Fig. 1 Illustrates, an OpenFlow agent which implements the extended OpenFlow protocol will be on top of each network element (NE), including NEs with a BV-WXC, Tx and Rx. The combination of the OpenFlow agent and its corresponding data plane hardware is referred to as OpenFlow-enabled BV-WXC (OF-BV-WXC), OpenFlow-enabled transmitter (OF-Tx) and OpenFlow-enabled receiver (OF-Rx) respectively. A centralized OF controller will communicate with all OpenFlow agents through the extended OpenFlow protocol, and in turn, control the hardware in the data plane.

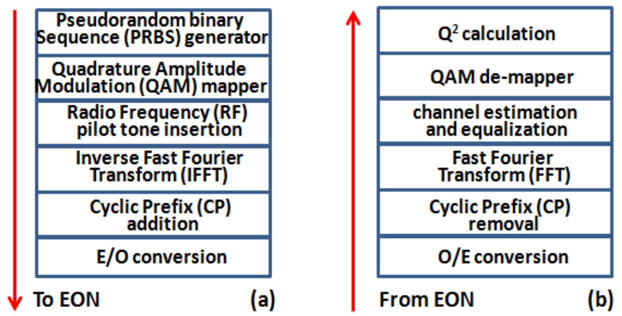


Fig. 2. (a) Tx and (b) Rx processing for DDO-OFDM supported by advanced digital signal processing.

## III. Key Enabling Techniques

### *A. OpenFlow Protocol Extensions*

The OpenFlow protocol is originally designed for packet-switched networks. Therefore, in order to control an EON, the OpenFlow protocol needs to be extended with EON features. The key extensions, as investigated in previous works [18], include:

(1) The OFPT_FEATURES_REPLY message is extended to advertise the features of an EON node (e.g., flexi-grid switching capability, neighbor information, available spectrum slots, etc.) to the OF controller;

(2) The OFPT_PACKET_IN message is extended to carry the bit rate information of the incoming client traffic, and used

to trigger the establishment of the optical connection;

(3) The OFPT_FLOW_MOD message is extended to encapsulate the RSMA results from the OF controller, including input/output ports, central frequency, assigned spectrum slots, and modulation format, etc., for each OpenFlow agent to control the underlying hardware.

In addition to the above protocol extensions, we also need to introduce a new OpenFlow protocol extension to notify link failures, enabling dynamic restoration. This can be achieved by either extending the OFPT_PORT_STATUS message or introducing a new OFPT_ALARM message. In this work, we used the latter approach and Fig.3 illustrates the packet format of such a new OFPT_ALARM message. Similarly with the concept of "unnumbered link" from GMPLS, the OFPT_ALARM message carries the Datapath ID field (8 bytes) for indicating the node address, and an interface ID field (4 bytes) for indicating the port associated to the failed link. Once the OF controller receives an OFPT_ALARM message, it can identify a potentially failed link from the Datapath ID and interface ID information encapsulated in this message. However, it should be noted that for a given connection, an upstream link failure may cause all downstream BV-WXCs to send out alarms. Therefore, a failure isolation mechanism is required by the OF controller to determine the exact failed point, as will be detailed in section III.B.

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 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    Version    |     Type      |            Length             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Transaction ID                         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                           Buffer ID                           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|          Total Length         |            In Port            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Reason    |   Alarm Type  |              Pad              |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      Affected Datapath ID                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      Affected Datapath ID                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     Affected Interface ID                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                            Reserved                           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Fig. 3. The proposed OFPT_ALARM message.

## *B. Failure Isolation Mechanism*

We assume that each BV-WXC is equipped with optical power monitors to detect the loss of light when a link failure happens. In this case, an upstream link failure may cause all downstream BV-WXCs to send out alarms for a given connection. As shown in the example in Fig.4, once a link failure occurs between the link WXC2-3, affecting an existing connection Tx-WXC1-2-3-4-Rx, both WXC3 and WXC4 will send out OFPT_ALARM messages to the OF controller, reporting the loss of light failure on links WXC2-3 and WXC3-4 respectively. Therefore, the OF controller needs to run a failure isolation mechanism to determine the exact failed point. Thanks to the centralized architecture, the OF controller can easily understand the entire network information for its global view. Although a control node in a distributed control plane architecture such as GMPLS can also have a global view through dynamic dissemination of Open Shortest Path First–Traffic Engineering (OSPF-TE) link state advertisement (LSA), such an operation is more complicated and accompanies higher overhead. With this global view, the OF controller can combine these affected links into a segment to check if it belongs to existing connections. If true, the OF controller localizes the first link of the segment as the failed point. As the example in Fig.4 illustrates, the OF controller receives OFPT_ALARM messages to report the loss of light on links WXC2-3 and WXC3-4 respectively, and then the OF controller can combine the affected links into a segment WXC2-3-4. After that, the OF controller proceeds to check if the segment WXC2-3-4 belongs to any lightpath connections or not. In this example, it belongs to an existing connection Tx-WXC1-2-3-4-Rx. Therefore, the OF controller can localize the first link of the segment, i.e., the link WXC2-3, as the exact failure point.

Note that, the control plane is commonly using the carriers' data communications network (DCN), which has a transmission delay for control messages, usually ranging from several milliseconds to several tens of milliseconds depending on the network size and the hop count. In this case, the OFPT_ALARM messages, generated by different nodes for a given link failure event, may arrive at the OF controller at different times. As the proposed failure isolation mechanism has to collect all the OFPT_ALARM messages to make an exact decision on the failed point, waiting time $\Delta t$ is required by the OF controller to receive all the corresponding alarm messages for a link failure event. That is to say, once an OFPT_ALARM message is received, the OF controller will wait for a time period $\Delta t$ to collect other alarm messages, and make a decision after $\Delta t$ expires. The selection of $\Delta t$ value can be made by the network carriers according to the network size and the placement of the OF controller. In addition, the processing latency of controller and the possible message queue delay may also affect the time for failure isolation. Considering these factors and assuming that the control message propagation times from WXC1, 2, …N to the OF controller are $t_1$, $t_2$, ...$t_N$ respectively, $\Delta t$ can be selected slightly larger than the maximum value of $t_1$, $t_2$, ...$t_N$, which is the worst case that the OF controller has to wait to receive all the failure alarms for a link failure event.

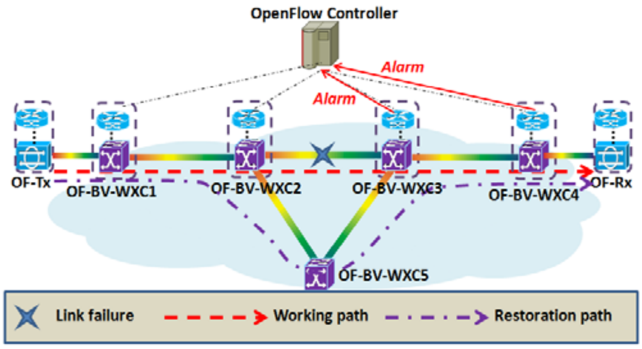


Fig. 4. OpenFlow-based lightpath restoration.

### C. Dynamic Restoration Procedure

When the physical link failure happens, all the flow entries in the flow tables for the affected connections still exist. Therefore, from the control plane point of view, after the link failure happens, the OF controller needs to decide (a) to delete the flow entries for affected connections firstly or (b) to provision the new connection firstly. The case (a) is usually referred to break-before-make (BBM) and the case (b) is referred to as make-before-break (MBB). The proposed method adopts the BBM scheme, wherein the working path is deleted prior to set up the restoration path. Compared with the MBB scheme, the BBM can cause a longer latency for restoration since the working path has to be released firstly, but it is easier to manage the flow entries in the BBM scheme, and the released resources can be used immediately by other incoming connections, which is also helpful for effective network resource utilization. Once an OFPT_ALARM message is received, the OF controller starts to run the failure isolation mechanism detailed in section III.B, and restore the affected connections, releasing them and setting them up with a new path that excludes the failed link. For this, after the failure point is identified, the OF controller performs a two-phase restoration RSMA algorithm (as detailed in section III.D), and then controls corresponding Tx, Rx and WXCs to create a restoration path through extended OFPT_FLOW_MOD messages.

### D. Two-Phase Restoration RSMA Algorithm

Considering the fact that fully dynamic RSMA computation is complex and is likely to be CPU-intensive, as well as that a single link failure may affect multiple connections, to reduce restoration time and to mitigate the effect of centralized restoration, we implement a two-phase restoration RSMA algorithm in the OF controller, and we use the $Q^2$ factor [27] as the signal quality indicator.

In the first phase, executed off-line, the *K*-shortest paths for each source-destination node pair are calculated. After that, pre-computed tables comprise the $Q^2$ factor values (in dB) and optical spectrum width (in GHz) information for given net data rates, modulation formats, path distances and hop counts are generated, which are the results of the simulation of DDO-OFDM transmission. For longer paths not considered during the off-line planning, the most robust modulation format is assigned to guarantee the signal quality at the Rx. The second phase, during the actual dynamic restoration, encompasses path selection and resource assignment when a failure alarm is received and the exact failure point is identified. The OF controller performs a lookup for pre-computed static planning tables and checks the pre-computed paths which do not include the failed link as the potential restoration paths. In this step, the OF controller firstly tries to find restoration paths that can support the same data rate of the working path. If such a restoration path does not exist, the OF controller then reduces the data rate and checks static planning tables again (i.e. bandwidth squeezed restoration). The OF controller serves failed connections one by one, and if multiple combinations are possible with the same data rate, the criterion is to minimize the resulting optical spectrum.

## IV. Experimental Setup, Results and Discussion

We set up an OpenFlow control plane network over the GENI testbed by using GENI racks [25], as shown in Fig.5, which is a snapshot of the FLACK GUI [25]. Note that it is a testbed with only OpenFlow-based control plane without any real associated optical hardware in the data plane. The data plane topology is emulated by using the control plane. As shown in Fig.5, the emulated data plane comprises 14 BV-WXC nodes, which are connected through emulated fiber links with different lengths. All the nodes are connected to a dedicated OF controller based on NOX [30] running in Linux Ubuntu 10.04. The DWDM links are characterized by 128 individual slots of 6.25 GHz each. Linear standard single mode fiber (SSMF) links are assumed, featuring an attenuation of 0.2 dB/km and a chromatic dispersion coefficient of 16 ps/nm•km. The input power to fibers is 0dBm. We use $K$=3 for the *K*-shortest paths algorithm, restricted to a maximum number of 5 hops. For each link, the maximum span length is limited to 80 km. Each span contains an erbium doped fiber amplifier (EDFA) compensating exactly the loss of each span with a fixed noise figure of 6 dB. Each ROADM is modeled as a 4th-order Gaussian-shaped filter with its 3dB-bandwidth covering ~1.5 times the signal bandwidth. The target $Q^2$ factor is 8.53 dB [27] which is the threshold of the hard-decision forward error correction. According to our experimental setup in Fig. 5, we measure the maximum latency from a node to the OF controller, which is slightly less than 5ms. Therefore, according to the policy that we presented in section III.B, in our experiment, we set $\Delta t$ as 5ms. Note that the selection of $\Delta t$ may affect the performance. If $\Delta t$ is too small, the OF controller may not be able to collect all the failure alarms, which may lead to incorrect failure isolation and thus reduce the successful rate of the restoration. If $\Delta t$ is too large, the restoration latency is increased accordingly. Different modulation formats such as 4-, 16- and 64-QAM, and various data rates including 10, 40, and 100 Gb/s are discussed.

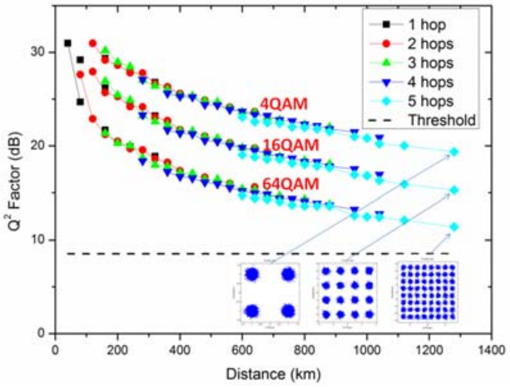


Fig. 6. $Q^2$ factor (in dB) at the Rx for different distances and hop count corresponding to different modulation formats (4QAM, 16QAM, 64QAM) at 10Gb/s DDO-OFDM transmission.

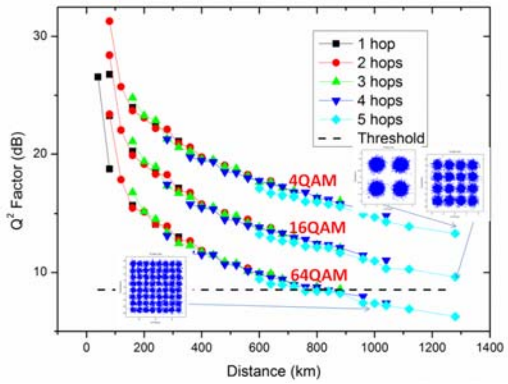


Fig. 7. $Q^2$ factor (in dB) at the Rx for different distances and hop count corresponding to different modulation formats (4QAM, 16QAM, 64QAM) at 40Gb/s DDO-OFDM transmission.

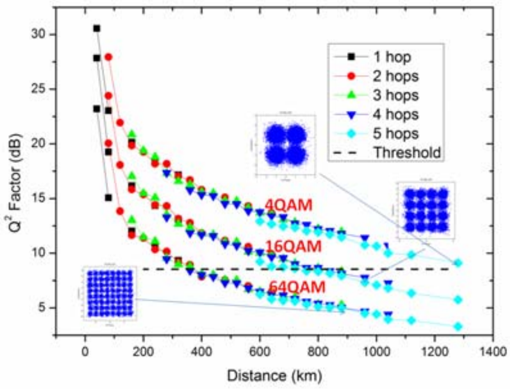


Fig. 8. $Q^2$ factor (in dB) at the Rx for different distances and hop count corresponding to different modulation formats (4QAM, 16QAM, 64QAM) at 100Gb/s DDO-OFDM transmission.

Fig.6, Fig. 7 and Fig.8 show the off-line network planning results for the restoration paths, which are obtained via Matlab simulation. $Q^2$ factors at the Rx side are measured for different distances and hop counts corresponding to different modulation formats (4-, 16-, 64-QAM) at 10, 40, and 100 Gb/s DDO-OFDM transmissions. Table 1 shows the signal bandwidth for DDO-OFDM with different modulation formats. As expected, the 4QAM constellation is more robust to physical impairments, whereas the 64QAM constellation gives the highest spectral efficiency. It can be observed that all the 4QAM cases achieve above the targeted $Q^2$ factor threshold, whereas when using 16QAM at 100 Gb/s, 64QAM at 40 Gb/s, and 64QAM at 100 Gb/s, the attainable distance is limited. These results are stored in the pre-computed static planning tables in the NOX for dynamic restoration path selection. Once the off-line network planning tables are produced, in this work, there is no further verification of any transmission properties during the dynamic restoration procedure, due to the lack of optical gears (e.g., optical performance monitors) in the GENI testbed.

TABLE I
SIGNAL BANDWIDTH AND REQUIRED SPECTRUM SLOTS FOR DDO-OFDM WITH DIFFERENT MODULATION FORMATS

| Modulation Format | | 10G bit/s | 40G bit/s | 100G bit/s |
|---|---|---|---|---|
| 4QAM | Signal Bandwidth (GHz) | 10.625 | 42.5 | 106.25 |
| | Number of Spectrum Slots[a] | 2 | 7 | 17 |
| 16QAM | Signal Bandwidth (GHz) | 5.3125 | 21.25 | 53.125 |
| | Number of Spectrum Slots[a] | 1 | 4 | 9 |
| 64QAM | Signal Bandwidth (GHz) | 3.5417 | 14.1667 | 35.4167 |
| | Number of Spectrum Slots[a] | 1 | 3 | 6 |

[a]Each spectrum slot: 6.25GHz

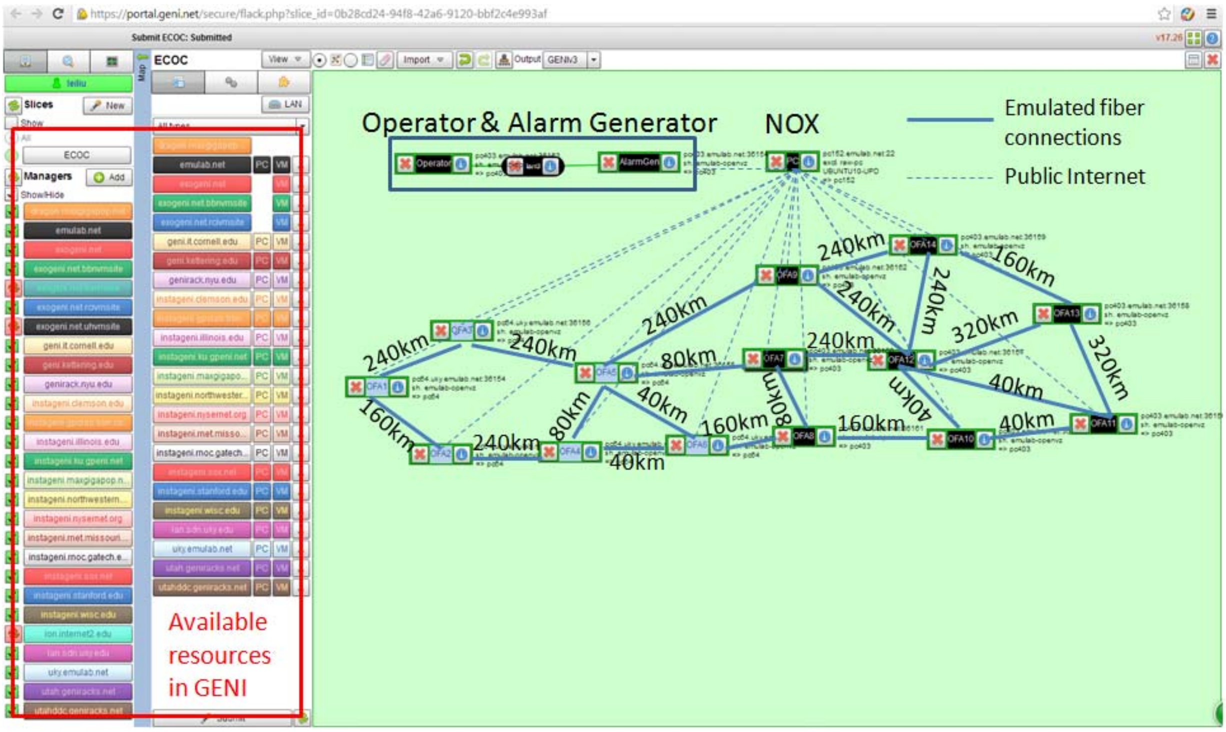


Fig. 5. Experimental setup on GENI testbed.

After the off-line network planning results for the restoration paths are obtained, we conduct control plane experimental tests to measure the performance of the proposed restoration approach over the GENI testbed. Compared with a lab environment, the experimental tests on the GENI testbed allow the control plane performance to be obtained over a real national backbone network, which can facilitate to validate the overall feasibility of the approach and provide valuable insights into its potential for possible deployment in a real operational scenario in future. In the control plane experimental tests, we firstly configure the connection database in the NOX controller to make sure the average link resource utilization is 30%, 40%, 50% and 60% respectively, and then the NOX sets up these connections according to the connection database. The placement of connections is uniformly distributed among all the candidate links. Given the 30% case as an example, if the whole network has 5,632 spectrum slots in total, then we set up a number of connections so that ~1,690 spectrum slots are occupied by connections. The source, destination, modulation format, and bit rate of these connections are all randomly selected from the candidate pool. After these connections are established, we randomly select a link as the failed point and directly send the OFPT_ALARM messages to the NOX to emulate link failure events. This failed link is randomly and uniformly distributed among all the links. Fig.9 shows the Wireshark capture of an OFPT_ALARM message, which encapsulates the alarm type and the identifier of the failed link. When such a failure alarm is received, the NOX performs the two-phase RSMA computation as detailed above. If a restoration path is found, the NOX controls the nodes to set up the restoration path through extended OFPT_FLOW_MOD messages. We introduce one failure each time and count the number of affected connections, and then we repeat this procedure from scratch until ~1000 connections have been affected in different link utilization scenarios in total. We measure the control plane processing latency and the restorability for dynamic restoration on the given network scenario, as shown in Fig.10 and Fig.11 respectively. Note that these results are measured on an OpenFlow control plane testbed, and optical hardware gears for elastic optical networking are not included. Therefore, the restoration latencies do not take into account hardware configuration delay. As previously investigated in [18, 31], the control and configuration of elastic optical network data plane hardware may need several tens to hundreds of milliseconds, which should be added to the overall restoration latency if the data plane hardware is included. For comparison purposes we also measure the performance in Fig.11 with the same experimental setup mentioned above, of the previously proposed OpenFlow-enabled dynamic restoration approach, which does not consider the physical impairments and bandwidth squeezed restoration (such as [23]). These performance results validate the overall feasibility of the proposed OpenFlow-controlled restoration in an EON testbed emulated by the GENI infrastructure, and the proposed dynamic restoration approach outperforms the previous OpenFlow-based restoration in terms of restorability. One of the reasons is that, by using the previous OpenFlow-based restoration approach, even if the OF controller successfully finds a restoration path, this path may not have a satisfied $Q^2$ factor at the receiver side, which results in a lower restorability.

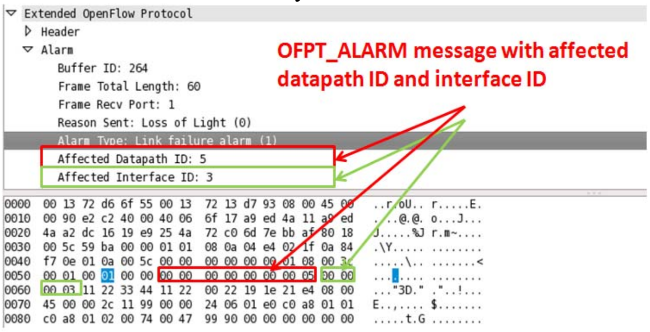


Fig. 9. Wireshark capture of the new OFPT_ALARM message.

Macroscopically, from a control plane perspective, the centralized SDN/OpenFlow controller has some similar features (e.g. network topology or connection management) with the path computation element (PCE), in particular, the active stateful PCE [32], in which the PCE is able to affect (modify or suggest the modification of) the state of network connections. Both the OpenFlow controller and the active stateful PCE also complement each other, since a PCE is responsible mainly for path computation accessible via an open, standard, and flexible protocol (i.e. PCE communication protocol, PCEP [33]), and the OpenFlow controller performs the task of the actual data plane forwarding provisioning. In light of this, in our previous paper [34], we have proposed the design and implementation of a centralized control plane based on a stateful PCE, acting as an OpenFlow controller, to control optical networks. The functions proposed in this paper can also by applied by such a stateful PCE / OpenFlow integrated controller.

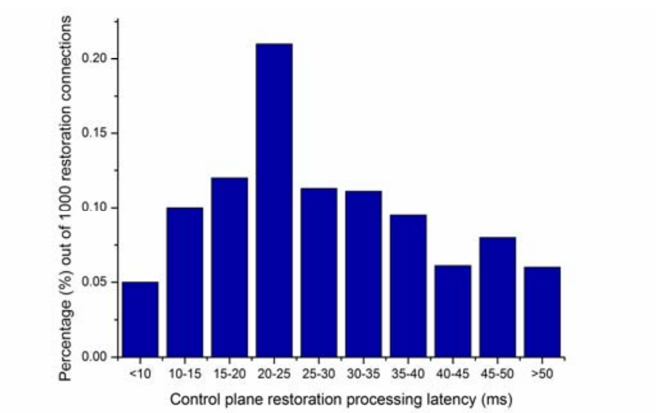


Fig. 10. Control plane restoration latency.

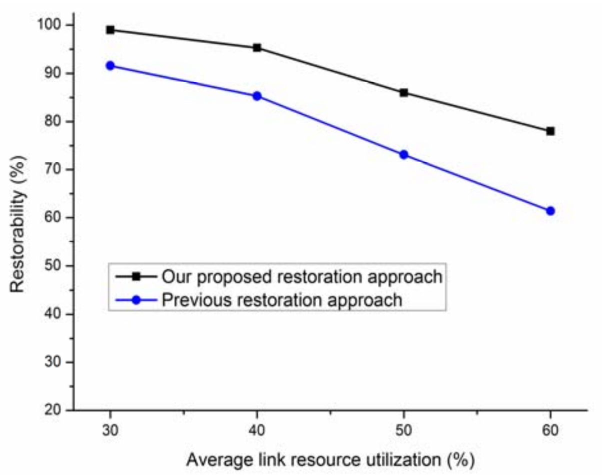


Fig. 11. Restorability under different network status (different resource utilization ratio).

## V. Conclusions

In this paper, we present OpenFlow-based dynamic connection restoration for a software-defined EON. The overall feasibility and efficiency of the proposed solutions, including the control framework, the failure isolation mechanism, the restoration algorithm, and protocol extensions are validated and quantitatively evaluated in terms of restoration latencies and restorability on the GENI testbed.

In a more general context, the proposed restoration approach can be applied to IP over EON paradigm, where the OF controller can provide the unified control plane functions for both IP and the EON layers. The failure of optical components in the EON layer may lead to multiple link failures in the IP layer. In this case, the OF controller can also insert new flow entries into the corresponding IP routers to restore the IP flows, thanks to the global view of the controller. In addition, we also believe the proposed approach can coordinate and support the IP network which has the feature like fast reroute (FRR), but in this case, further studies regarding the cross-layer planning and algorithm design are needed [35], which will be our future works.

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