First Proof-of-Concept Demonstration of OpenFlow-Controlled Elastic Optical Networks Employing Flexible Transmitter/Receiver

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Abstract—**In this paper, for the first time, we experimentally demonstrate an OpenFlow-controlled elastic optical network (EON) employing a flexible transmitter/receiver. The flexible transmitter can switch the symbol rate and modulation format of the optical signal without modifying the hardware, and the flexible receiver can automatically detect different modulation formats and measure the bit-error rate (BER) for lightpath diagnosis. By using an OpenFlow-based control plane with significant protocol extensions, we successfully verify the seamless interworking between the control plane and all the network elements, and experimentally validate elastic path provisioning, dynamic service recovery and lightpath restoration on an actual EON testbed.**

Keywords-OpenFlow; control plane; elastic optical networks (EON); flexible transmitter/receiver; modulation format

I. Introduction

Elastic Optical Networks (EON) [1] and the OpenFlow architecture and protocol [2] are currently the hottest topics in the optical networking research community and will be extremely important for the networks of the future. This is because the former provides efficient resource utilization since it allows the allocation of an appropriate optical spectrum range to an optical path according to the client traffic demand [1], and, the latter, has the potential to provide the maximum flexibility and manageability for the carrier to control a network (i.e., a software-defined optical network) [3-5].

Due to the overwhelming advantages, there have been a lot of advances in both EON and OpenFlow in recent years. In [5], an extended OpenFlow-based control plane is proposed for EON, and the benefits for OpenFlow/EON combination are highlighted. In this paper, for the first time, we experimentally present an OpenFlow-controlled EON employing a flexible transmitter/receiver on a real network testbed, verifying the overall feasibility and efficiency for dynamic and intelligent EON control through OpenFlow.

II. OpenFlow-Controlled Elastic Optical Network

A. Network Architecture

The network architecture for an OpenFlow-controlled EON is shown in Fig.1. The EON is configured with the bandwidth-variable wavelength cross-connects (WXC), which are implemented by using bandwidth-variable wavelength selective switches [1]. Flexible transmitters (Flexi-Tx) and receivers (Flexi-Rx) are connected to ingress and egress WXCs respectively. Our designed Flexi-Tx (as detailed in section II.B) is able to switch the symbol rate and generate various modulation formats, including binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 8-ary quadrature amplitude modulation (8QAM), and 16QAM without modifying the hardware. The Flexi-Rx is based on a coherent detection scheme which can automatically detect different modulation formats/symbol rates and measure the bit-error rate (BER) without external control. All the network elements (NEs) are controlled by OpenFlow agents, and are referred to as OpenFlow-enabled Flexi-Tx, Flexi-Rx, and WXC (OF-Fle-Tx, OF-Fle-Rx, and OF-WXC for short) respectively. A centralized OpenFlow controller (e.g. NOX [6]) is introduced to control all the NEs through the extended OpenFlow protocol (as detailed in section II.D).

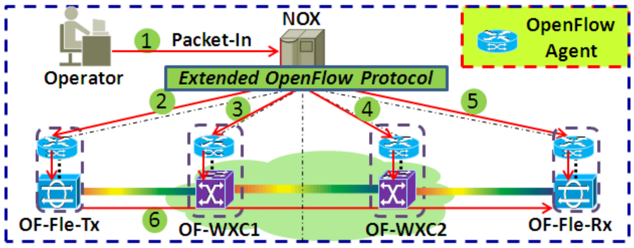

Figure 1. Network architecture for an OpenFlow-controlled EON.

B. Flexible Transmitter/Receiver

The Flexi-Tx was implemented by a cascade of dual-drive Mach-Zehnder modulator (DD-MZM) and dual-parallel MZM (DP-MZM) with electrical binary drive signals [7], as shown in Fig.2(a). Here, $v_i(t)$ and A_i (i = 1, 2, 3, and 4) represent the binary data and its corresponding amplitude, respectively. For BPSK and QPSK generation, DD-MZM is turned off (i.e., transparent) and DP-MZM makes the typical BPSK and QPSK signals. 8QAM and 16QAM are formed by adjusting the amplitudes (A_1 and A_2) of two drive signals applied to each arm of DD-MZM while DP-MZM produces a QPSK output [7]. For this operation, the gain of the drive amplifiers is controlled by adjusting a DC bias voltage. For the Flexi-Rx, the self-homodyne coherent receiver is realized by using a 90^o optical hybrid followed by two balanced photodetectors (BPDs) and analog-to-digital converters (ADCs), as shown in Fig.2(b). Here, we utilize a 50-GS/s digital storage oscilloscope with 16-GHz bandwidth as ADCs. The sampled data is then processed offline and BER can be finally measured [8].

Furthermore, the Flexi-Tx/Rx is controlled by the OpenFlow-based control plane, as the interface depicted in Fig.2(c). On one hand, the NOX can send the symbol rate, modulation format, etc. information to an OpenFlow agent through an extended *Flow Mod* message and, in turn, the OpenFlow agent parses this information and configures the Flexi-Tx accordingly, via a Matlab program. On the other hand, the OpenFlow agent periodically reads the BER information which is measured by the Flexi-Rx. If the BER is higher than a pre-determined threshold or a link failure happens, the OpenFlow agent automatically sends an alarm (based on the OpenFlow *Packet In* message, as detailed in section II.D) to the NOX controller to notify the signal degradation or link failure.

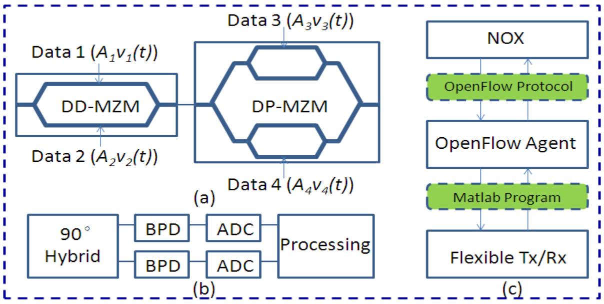

Figure 2. (a) Flexible transmitter; (b) Flexible receiver; (c) Interface between Flexible Tx/Rx and the OpenFlow-based control plane.

C. *Procedures for Flexible Path Provisioning/Restoration*

1) Elastic path provisioning according to the bit-rate information of the incoming flow

The procedure for the elastic path provisioning is depicted in Fig.1. According to the OpenFlow methodology, the path provisioning is triggered by a *Packet In* event as shown in the step 1 in Fig.1. Here, we assume that the *Packet In* message is sent from an operator via a network management system (NMS), and we extend the *Packet In* message to carry the bit rate information. This requires the operator/NMS can detect or monitor the bit rate of the incoming flow, and the approach for this detection is beyond the scope of this paper. According to the source/destination addresses and bit rate of the flow, the NOX performs a routing and spectrum assignment (RSA) algorithm [9], allocating suitable frequency slots and modulation format, and then controls corresponding Flexi-Tx and WXCs to create a path with appropriate optical spectrum range through extended OpenFlow *Flow Mod* messages.

2) Dynamic service recovery when link losses are increased

The procedure for OpenFlow-controlled dynamic service recovery is depicted in Fig.3. Suppose a working lightpath is provisioned between a Flexi-Tx and a Flexi-Rx, through the route WXC1→WXC2. The Flexi-Rx monitors the BER for this working lightpath, and reports the measured value to its OpenFlow agent, as shown in the step 2 in Fig.3. When the OpenFlow agent detects that the BER value is worse than a pre-defined threshold, it automatically sends an "Unsatisfied BER" alarm (step 3). If such an alarm is received by the NOX, the NOX selects a new modulation format with a lower-order QAM size to improve the optical signal-to-noise ratio (OSNR) tolerance and retain the system margin. In addition, the NOX also assigns a higher baud rate to preserve the transmission rate of the new modulation format if possible. Note that the new modulation format and baud rate causes a change of the required spectrum of the optical path. Therefore, the newly selected modulation format and baud rate, as well as the new central frequency and slot width information are inserted into extended *Flow Mod* messages, and are automatically delivered to the Flexi-Tx and corresponding WXCs to re-configure the optical path for dynamic service recovery (step 4 ~ step 7).

3) Dynamic lightpath restoration in the case of link failure

The procedure for the dynamic lightpath restoration is depicted in Fig.4. Suppose a link failure happens affecting the working path WXC1→WXC2. The Flexi-Rx detects this failure and then reports it to its OpenFlow agent (step 2), which automatically sends a "Link Failure" alarm to the NOX (step 3). Accordingly, the NOX automatically establishes a restoration path (step 4~step 8). Note that, due to the different physical characteristics of the backup path (e.g. path length, number of optical nodes), a new modulation format and a new symbol rate may be assigned by the NOX to ensure the signal quality and maximize the spectral efficiency of the backup path (i.e., a lower-order QAM size for longer backup path, and vice versa).

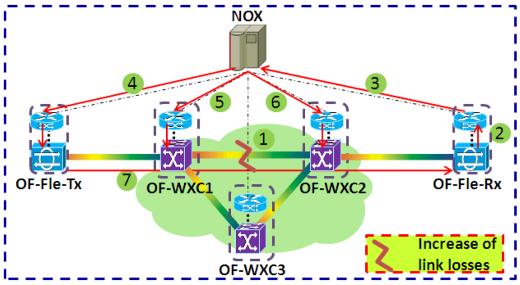

Figure 3. Procedures for OpenFlow-controlled dynamic service recovery.

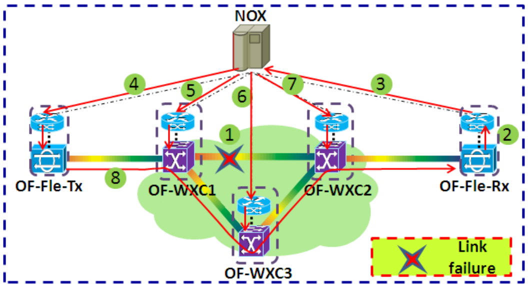

Figure 4. Procedures for OpenFlow-controlled dynamic lightpath restoration.

D. *OpenFlow Protocol Extensions*

In order to support the aforementioned functionalities, we enhanced the standard OpenFlow protocol (v1.0) with the following new extensions. (1) The *Feature Reply* message is extended to report the new features of an EON testbed (e.g., flexi-grid switching capability, available spectrum ranges, etc.) to the NOX controller; (2) The *Packet In* message is extended to carry the bit rate information for the NOX to perform RSA computation. (3) To perform alarm notification, new message types (e.g. *Alarm* message) should be introduced to the standard OpenFlow protocol. However, to simplify the control plane design in this experiment, we use an extended OpenFlow *Packet In* message to perform alarm notification, by inserting different alarm types including "Unsatisfied BER" and "Link Failure". (4) The *Flow Mod* message is extended to control Flexi-Tx/Rx and WXCs. This extended message carries the RSA results from the NOX, including input and output ports, central frequency, slot width, and modulation format, etc.

III. Experimental Setup, Results and Discussions

To evaluate the overall feasibility and efficiency of the proposed solutions, we set up an OpenFlow-controlled EON testbed as shown in Fig.5. In the data plane, we deployed four WXCs with real hardware. Note that only WXC1 had the flexi-grid switching capability (based on Finisar Waveshaper 4000S [10]), and the other WXCs were introduced to construct a mesh network in order to perform dynamic lightpath restoration. A Flexi-Tx and a Flexi-Rx are attached to WXC2 and WXC3 respectively. In the control plane, a dedicated NOX controller and several OpenFlow agents were deployed to control the whole testbed through the extended OpenFlow protocol.

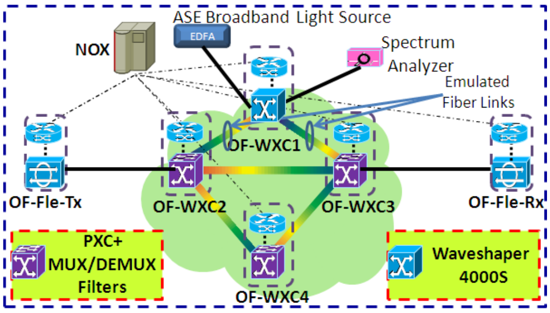

Figure 5. Experimental setup.

We firstly demonstrated the elastic path provisioning by setting up a path WXC2→WXC1→WXC3 for an incoming flow. Fig.6(a) shows the Wireshark capture of the extended *Packet In* message. It can be seen that the bit rate information is encapsulated in this message for the NOX to allocate a suitable spectrum bandwidth along the path. By using an amplified spontaneous emission (ASE) broadband light source and an optical spectrum analyzer attached at WXC1, we firstly observed the filter profiles of the Waveshaper by allocating 16 continuous spectrum slots (12.5GHz per slot [10]) for this incoming flow, as shown in Fig.6(b). Note that, for a densely packed modulation format (e.g., 16QAM), a smaller slot width could be allocated by the NOX accordingly to improve the spectrum utilization (as shown in Fig.6(c)). After that, to verify dynamic service recovery, we established a path Flexi-Tx→ WXC2→WXC3→Flexi-Rx via the OpenFlow control plane using 12.5GBd 16QAM. Then we increased the link loss between WXC2 and WXC3. Fig.7(a) shows measured BER values while varying the link losses. With the increase of link losses, BER of the 12.5GBd 16QAM signal was finally worse than $4x10^{-3}$ which corresponds to the BER threshold of forward error correction (FEC) with 7% overhead [11] (indicated by dashed line in Fig.7(a)). At this moment, the NOX received an "Unsatisfied BER" alarm and then automatically controlled the Flexi-Tx to switch optical signals from 12.5GBd 16QAM to 25GBd QPSK, aiming at improving the OSNR sensitivity while preserving the transmission rate. Finally, we investigated dynamic lightpath restoration. We established a working path Flexi-Tx→WXC2→WXC3→Flexi-Rx with 25GBd 16QAM, and then we cut the fiber between WXC2 and WXC3. In turn, the NOX received a "Link Failure" alarm, and then automatically set up a restoration path with the route Flexi-Tx→WXC2→WXC4→WXC3→Flexi-Rx by using 25GBd 8QAM to guarantee the OSNR margin, as shown in Fig.7(b). In our experiment, we observed that both dynamic service recovery and lightpath restoration could be completed around 6 seconds. The processing in the OpenFlow-based control plane was very fast (<50ms). The major contributor of this latency was the offline processing time in the Flexi-Rx for BER measurement. We believe that by using an on-line monitoring approach, the service recovery and lightpath restoration can be finished within hundreds of milliseconds, if not lower.

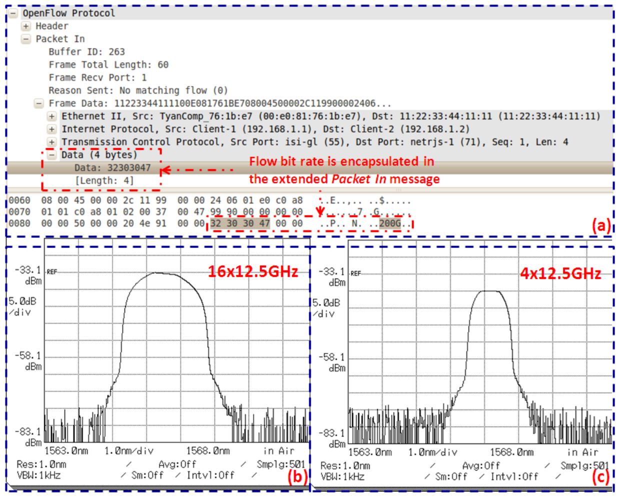

Figure 6. Experimental results for elastic path provisioning. (a) Extended *Packet In* message; (b) (c) Filter profiles of Waveshaper.

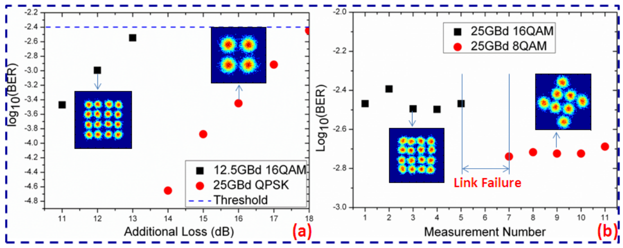

Figure 7. Experimental results. (a) BER measurements during dynamic service recovery; (b) BER measurements during dynamic lightpath restoration.

IV. Conclusions

In this paper, for the first time, we present a proof-of-concept demonstration of an OpenFlow-controlled EON employing a flexible transmitter/receiver. We successfully verified seamless interworking operations between an extended OpenFlow-based control plane and all the network elements, and we experimentally demonstrated elastic path provisioning, dynamic service recovery and lightpath restoration on a real EON testbed. We hope this work will be beneficial for industrial deployment of OpenFlow/EON and shed light on the future researches for this issue.

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