OpenFlow-Controlled Online Spectrum Defragmentation in Software-Defined Elastic Optical Networks

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***Abstract*—This work studies how to take the advantage of the centralized network control and management (NC&M) provided by OpenFlow-controlled software-defined elastic optical networks (SD-EONs) for online spectrum defragmentation. We design a control plane framework, and conduct control plane experiments in an SD-EON testbed to demonstrate the effectiveness of the framework. Experimental results indicate that the framework can improve the network performance in an effective way.**

***Index Terms*—Elastic optical network (EON), OpenFlow (OF), Software-defined networking (SDN), Defragmentation (DF)**

I. Introduction

It is well known that the elastic optical networks (EONs) with agile bandwidth management in the optical layer can improve the spectral efficiency of lightpaths and bring intelligence into optical networks [1]. Different from the traditional wavelength division multiplexing (WDM) networks that use a fixed grid at 50 GHz or 100 GHz, EONs can divide the optical spectra into frequency slots (FS') that are at 12.5 GHz or less [2]. Therefore, a few narrow-band FS' that are spectrally contiguous can provision lightpaths with various bandwidths.

Due to the relatively small spectrum granularity and dynamic network operations in EONs, spectrum fragmentation, which refers to the existing of non-aligned, isolated, and small-sized unused FS blocks in network spectra, can happen and lead to low spectrum utilization and high blocking probability. Hence, it becomes a serious issue for EONs [3]. In order to reduce spectrum fragmentation in EONs, researchers have proposed a few defragmentation (DF) techniques that leverage lightpath reconfigurations [3, 4].

To deal with DF with lightpath reconfigurations, a centralized network control and management (NC&M) for EONs is required. By decoupling the data and control planes of a network, software-defined networking (SDN) with OpenFlow (OF) makes the network programmable, dynamic and application-aware. When combining SDN with EONs, we have software-defined EONs (SD-EONs), which bring intelligent and centralized NC&M into EONs. In this paper, we discuss OF-controlled online spectrum DF in SD-EONs. The rest of the paper is organized as follows. Section II elaborates on the system architecture of SD-EONs, and designs a control plane framework to support online spectrum DF with routing and spectrum assignment (RSA) reconfigurations. The implementation of the framework in a control plane SD-EON testbed is discussed in Section III. Then, we show experimental demonstrations of online DF in the SD-EON testbed in Section IV. Finally, Section V summarizes the paper.

II. OF-based Software Defined Elastic Optical Networks (SD-EONs)

In this section, we present the OF-based SD-EON system that facilitates both RSA and online spectrum DF. We first discuss the overall network architecture and then show the functional design of the control plane.

A. Network Architecture

Fig. 1 shows the overall network architecture of an SD-EON. The data plane is built with edge routers (ERs) and bandwidth-variable wavelength-selective switches (BV-WSS'). On top of the data plane, we have an SDN-based control plane that consists of one centralized OpenFlow controller (OF-C) and several OpenFlow agents (OF-AGs) that each attaches to a data plane equipment (*i.e.*, an ER or a BV-WSS). OF-C functions as the "brain" of the control plane, while OF-AG is used to configure the ER or BV-WSS according to the flow-entries from OF-C. Each OF-AG talks with OF-C through an extended OF protocol [5].

B. Functional Design

The functional design of the control plane (*i.e.*, OF-C and OF-AG) is illustrated in Fig. 2. In an OF-AG, OF-Client is used to communicate with OF-C, the local traffic database (LTD) stores the flow-entries that are used by the equipment controller to configure the data plane equipment. The architecture of OF-C is also illustrated, in which the resource provision module (RPM) interacts with OF-AGs and the resource computation module (RCM) for handling the OF messages. Upon receiving a request from an OF-AG, RPM instructs RCM to perform a RSA calculation with the network

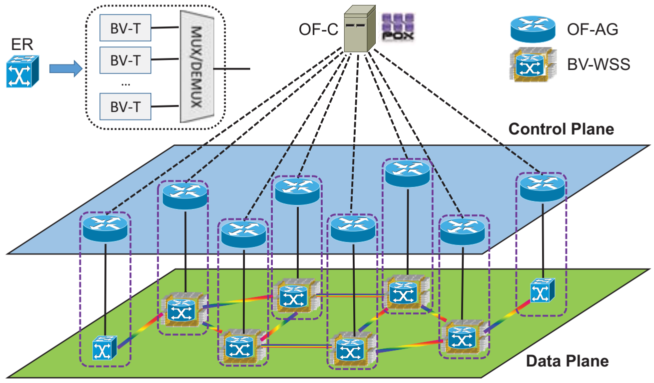


Fig. 1. Network architecture of an SD-EON.

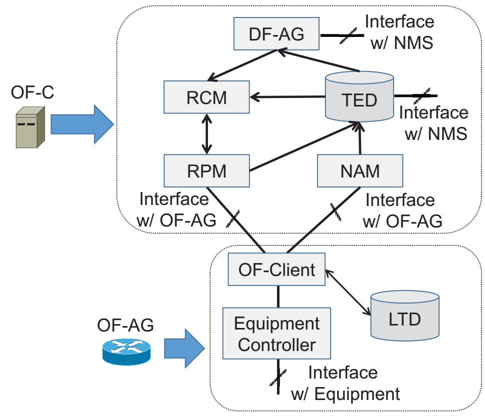


Fig. 2. Functional design for the control plane of SD-EONs.

status in the traffic engineering database (TED). RCM also serves the defragmentation agent (DF-AG) in the way of performing Re-RSA calculations (*i.e.*, recalculating the RSA results for the lightpaths to be reconfigured). If there is a feasible solution, RCM instructs RPM to build corresponding flow-entries and forward to the related OF-AGs. Moreover, RPM also updates the information of in-service lightpaths in SD-EONs in TED. The network abstract module (NAM) communicates with OF-AGs, collects the SD-EON's topology information, and abstracts the data plane equipments for TED.

III. Implementation of Control Plane Testbed

We implement the aforementioned control plane framework in a testbed that consists of an OF-C and several OF-AGs. Each OF-AG is programmed based on the Open-vSwitch, while the OF-C is implemented with the POX platform. The OF-C and OF-AGs are both implemented on high-performance Linux servers (ThinkServer RD530), as shown in Fig. 3(a). The topology of the testbed is illustrated in Fig. 3(b), which includes 14 stand-alone OF-AGs connected according to the NSFNET topology. Fig. 4 shows the detailed procedure of an online DF operation in SD-EON.

- **Step 1**: DF-AG in OF-C invokes a DF operation, selects a certain portion of in-service lightpaths in TED to reconfigure, and instructs RCM to re-calculate RSAs for them. Note that DF-AG can either invoke a DF operation automatically by monitoring the network status in TED or be instructed to do so by the network operator through the external network management system (NMS).
- **Step 2**: RCM requests the current network status from TED, re-optimizes the RSAs for the selected lightpaths with the objective to minimize spectrum fragmentation.
- **Step 3**: Based on the new RSA solutions, RCM obtains the reconfiguration sequence using the algorithm in [6], and instructs RPM to build flow-entries accordingly.

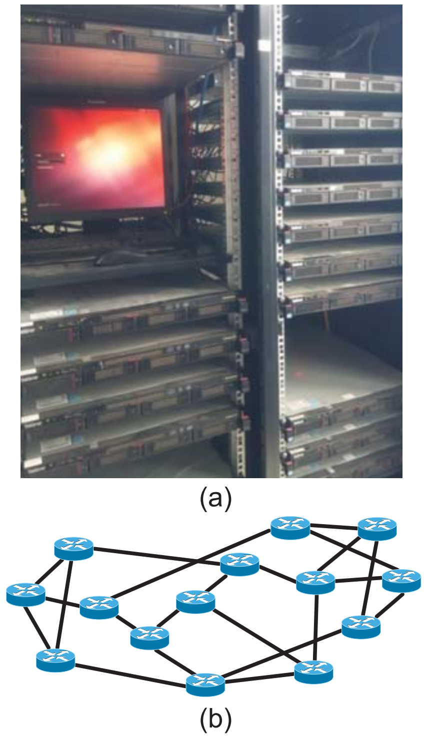


Fig. 3. Control plane testbed of SD-EON.

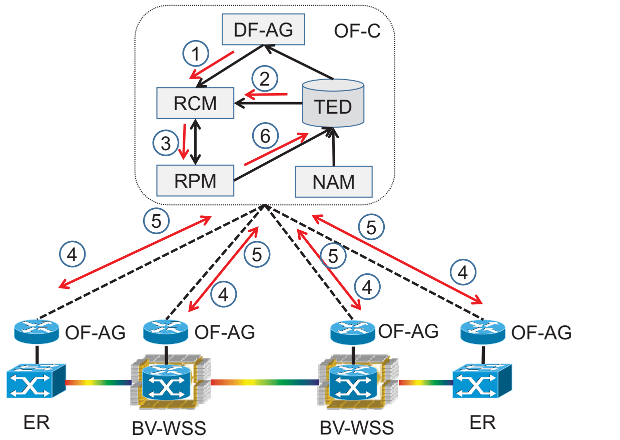


Fig. 4. Detailed procedure for an online DF operation in SD-EON.

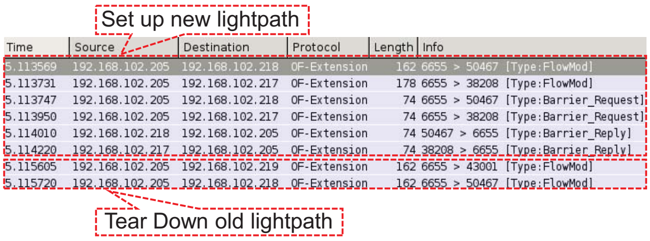


Fig. 5. Wireshark capture for reconfiguration of a lightpath.

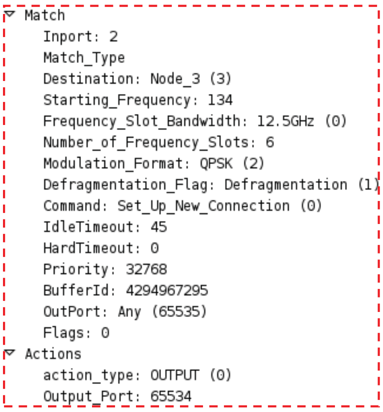


Fig. 6. Wireshark capture for a *Flow-Mod* message.

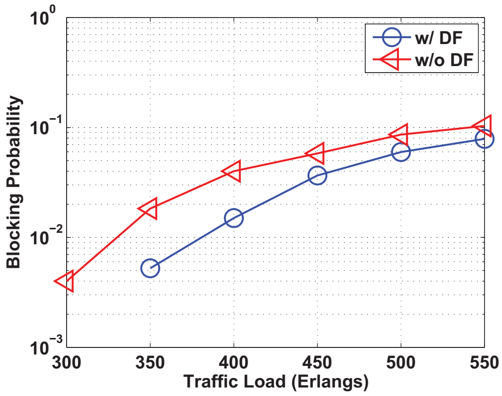
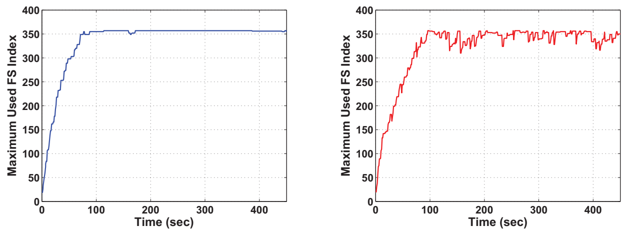


Fig. 7. Experimental results on blocking probability for online DF.



(a) Without DF.

(b) With DF.

Fig. 8. Results on the maximum used FS index in SD-EON.

- **Step 4**: For each lightpath reconfiguration, RPM encodes the flow-entries in *Flow-Mod* messages, turns on the *Defragmentation_Flags* in them, and sends the messages to the related OF-AGs.
- **Step 5**: Each related OF-AG parses the flow-entry, configures its data plane equipment accordingly with the "make-before-break" scheme, and then returns the result to OF-C using a *Barrier-Reply* message.
- **Step 6**: RPM updates TED accordingly when the lightpath reconfigurations have been finished.

IV. Experimental Demonstration of Online Defragmentation

We conduct online DF experiments in the control plane testbed. Fig. 5 shows the wireshark capture of the OF messages for a lightpath reconfiguration in online DF, from which we can see that the "make-before-break" scheme is successfully implemented. Fig. 6 shows the wireshark capture of a *Flow-Mod* message that is sent to the destination ER of the lightpath by OF-C, where the *Defragmentation_Flag* is turned on to indicate that the message is used for lightpath reconfiguration.

Note that on each OF-AG in the testbed, lightpath requests are generated according to the Poisson traffic model and the lightpaths' destinations are selected randomly. The bandwidth requirement of each request is uniformly distributed within [25, 500] Gb/s, and we assume that each fiber link in the SD-EON can accommodate 358 FS' with a bandwidth of 12.5 GHz. The experiments also measure the requests' blocking probability in the SD-EON, and the results are plotted in Fig. 7, from which we can see clearly that OF-controlled online DF can reduce the blocking probability effectively.

In order to measure each data point in Fig. 7, we make OF-C serve 14000 incoming requests from the 14 OF-AGs in the testbed. For the online DF, we set the portion of in-service lightpaths for reconfiguration as 50%. Fig. 8 illustrates the maximum used FS index on all the fiber links, in the experiments that have the traffic load as 450 Erlangs. We observe that for the scenario without DF, the maximum used index reaches its maximum value faster than the one with DF, and the value never declines. While for the scenario with DF, the maximum used FS index decreases repeatedly after each DF operation, which enables the SD-EON to take more requests.

V. Conclusion

This paper investigated the implementation of OF-controlled online DF in SD-EONs. We first discussed the overall SD-EON architecture to facilitate online DF and the detailed procedure of the online DF operation. Then, we conducted experiments to demonstrate the effectiveness of the online DF in a control plane testbed. Experimental results indicated that the proposed control plane framework could improve network performance effectively.

Acknowledgments

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