Multi-Domain Fragmentation-Aware RSA Operations through Cooperative Hierarchical Controllers in SD-EONs

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Abstract: This paper investigates lightpath provisioning with fragmentation-aware routing and spectrum assignment across multiple software-defined elastic optical network (SD-EON) domains, with a hierarchical controller framework. The system design is implemented and demonstrated in a multi-national SD-EON control plane testbed.

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

1. Introduction

Elastic optical networking (EON) can allocate network resources flexibly at the optical layer in response to dynamic traffic demands. Software-defined EONs (SD-EONs) is a powerful combination of EON and SDN that offers network operators more programmability on network control and management (NC&M) with flexible allocation of network resources [1, 2]. In the mean time, it is very important to consider a NC&M mechanism that can work in the context of multi-domain SD-EONs. Previous studies have demonstrated OpenFlow (OF) based inter-domain service provisioning approaches [3, 4]. However, most of them used very simple routing and spectrum assignment (RSA) schemes for the resource allocation across multiple domains, but did not consider the impact from spectrum fragmentation [5]. For dynamic inter-domain lightpath provisioning, spectrum fragmentation can severely affect the end-to-end performance due to the spectrum continuity constraint. In this work, by leveraging hierarchical controller cooperation in the control plane, we design and implement an OF system to facilitate multi-domain fragmentation-aware RSA (MD-FA-RSA) operations. Specifically, we introduce a broker to coordinate the OF controllers (OF-Cs) of different domains, design an inter-domain protocol (IDP) to support the communications between the broker and OF-Cs, implement a new MD-FA-RSA algorithm in the system, and experimentally demonstrate the MD-FA-RSA operations in a multi-national SD-EON control plane testbed spanning USA and China. Experimental results show that the broker-based OF system with MD-FA-RSA can effectively improve the performance of inter-domain service provisioning by reducing the blocking probability and the number of optical-to-electrical-to-optical (O/E/O) conversions between the domains.

2. Operation Principle

Fig. 1(a) shows the network architecture of multi-domain SD-EON and the detailed procedure for implementing MD-FA-RSA. The control plane of each domain consists of an OF-C for centralized NC&M and a set of OF agents (OF-AGs) that each locally attaches to data plane equipment (*e.g.*, bandwidth-variable wavelength-selective switch (BV-WSS)), to manage data transmission according to the instructions from the OF-C. Each instruction contains the information for configuring a lightpath, including the input and output ports, the starting frequency and number of frequency slots (FS') for spectrum allocation, the modulation-format, *etc*. In order to coordinate the SD-EON domains for service provisioning, we introduce a broker that operates at a higher NC&M-level than the OF-Cs. Basically, the broker has a global view of the network, including information of the inter-domain links and virtualized network status

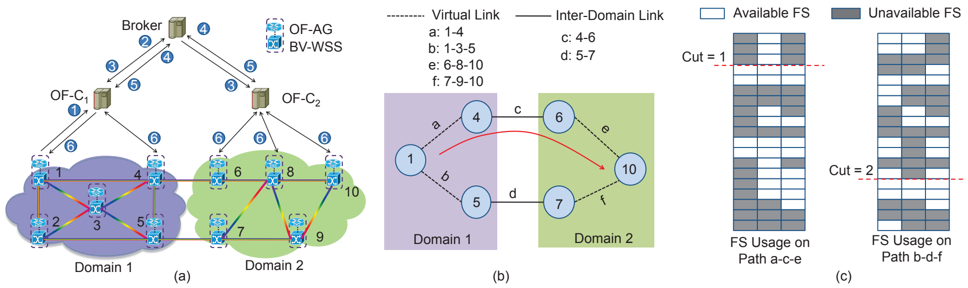

Fig. 1. (a) Hierarchical controller cooperation for multi-domain SD-EON, (b) Broker's global view of virtual topology for inter-domain service provisioning, (c) Example of MD-FA-RSA operation.

of each domain provided by the OF-Cs. We design an IDP to facilitate the communications between the broker and OF-Cs. Fig. 1(a) illustrates the procedure for setting up a lightpath with MD-FA-RSA as detailed below:

Step 1: A lightpath request $LR(s,d,B)$ arises in *Domain* 1, the related OF-C (*i.e.*, $OF\text{-}C_1$) checks the source and destination addresses (*i.e.*, s and d) and finds that it is for inter-domain. Here, B is the bandwidth requirement in Gb/s.

Step 2: $OF\text{-}C_1$ encodes the request in an *Inter_Domain_Request*, and forwards it to the broker for further processing.

Step 3: The broker requests the intra-domain network status from $OF\text{-}C_1$ and $OF\text{-}C_2$ using the *Status_Request* messages. Here, we consider a virtual topology approach to facilitate inter-domain service provisioning. Specifically, the OF-Cs abstract the related intra-domain path segments, *i.e.*, s to egress nodes, ingress nodes to egress nodes, and ingress nodes to d for the source, intermediate and destination domains, respectively, as virtual links. The virtual links represent the segments' information, including the spectrum utilizations and transmission distances.

Step 4: Each OF-C sends the virtual links' information to the broker with a *Status_Reply* message. Note that when reporting virtual links, an OF-C can disclose either full or partial intra-domain status, depending on the service contract. In this work, the OFCs disclose partial information and aggregate them into virtual links.

Step 5: The broker constructs a virtual topology with the virtual and inter-domain links, and performs MD-FA-RSA with it. Fig. 1(b) shows an example of the virtual topology for the lightpath provisioning from *Node* 1 to *Node* 10 in Fig. 1(a). Here, we extend the FA-RSA algorithm in [5] to consider the requirements of inter-domain provisioning, *e.g.*, translucent lightpath setup and quality-of-transmission (QoT) adaptive modulation-format selection. Specifically, the broker computes K-shortest paths in the virtual topology, and selects the RSA solution that causes the least number of spectral cuts. An example is given in Fig. 1(c) for the virtual topology in Fig. 1(b), and MD-FA-RSA will select *Path a-c-e*, since the RSA on it for 2 FS' results in less cuts. Then, the broker selects the modulation-format based on the path's QoT (*i.e.*, the transmission distance). When the QoT requirement cannot be satisfied or none of the paths carries an FS-block that is large enough to accommodate B, the broker instructs related ingress/egress nodes to insert necessary O/E/O conversions. The broker sends the RSA solution to OF-Cs using the *Inter_Domain_Reply* message.

Step 6: Each OF-C parses the *Inter_Domain_Reply* message, maps the selected virtual link to the physical path segment in its domain, and then instructs the corresponding OF-AGs to configure data plane equipment accordingly.

Fig. 2 shows the messages used in IDP, including *Inter_Domain_Request*, *Inter_Domain_Reply*, *Status_Request* and *Status_Reply*. Note that we illustrate both the messages' formats and the Wireshark captures of them in the experiments. Figs. 2(a)-(b) shows the messages that are from OF-Cs to the broker, *i.e.*, *Inter_Domain_Request* and *Status_Reply*. *Inter_Domain_Request* includes the information of an inter-domain lightpath request. An OF-C uses *Status_Reply* to report the physical lengths and spectrum utilizations of the virtual links in its domain, and when encoding *Status_Reply*, it can purposely hide some intra-domain information to protect its privacy. The messages that are for communications from the broker to OF-Cs are in Figs. 2(c)-(d). In *Inter_Domain_Reply*, we include a *Success_flag* field to indicate whether the broker can find a feasible RSA solution, and the last three fields tell the details of the RSA in a particular domain. Specifically, for each link (either inter-domain or virtual), there are sub-fields for the link ID, starting FS and number of FS' for the spectrum assignment, and the selected modulation-format. The broker requests for the virtual links' information with *Status_Request*, which contains the addresses of their ingress/egress nodes.

3. Experimental Demonstrations

The proposed MD-FA-RSA and IDP are implemented and evaluated in a multi-national SD-EON control plane testbed that have domains located in China (*Domain* 1) and USA (*Domain* 2), respectively. Fig. 3(a) shows the topology of

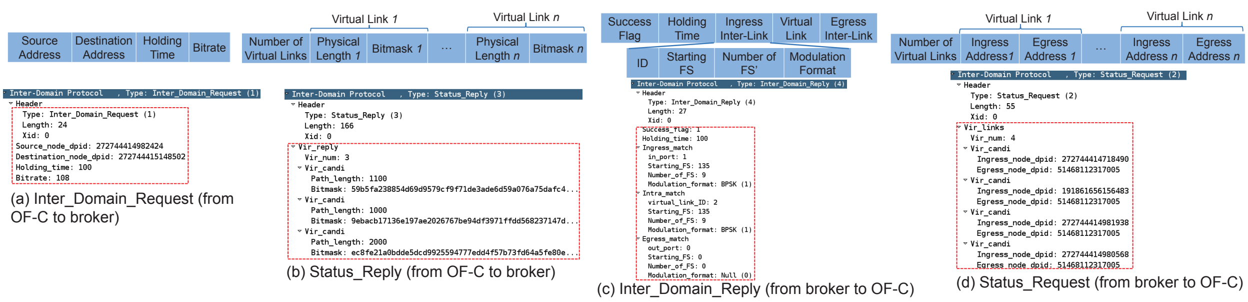

Fig. 2. Messages defined in IDP.

the OF-AGs that each is realized by running Open-vSwitch on an independent Linux server. Each domain has an OF-C that is implemented with the POX platform and directly connected to all the intra-domain OF-AGs, and the two OF-Cs are coordinated with a broker. Since this work focuses on the control plane operations, the BV-WSS' in the data plane are emulated with Ethernet connections. In the experiments, each OF-AG generates lightpath requests with the Poisson traffic model. For each request $LR(s,d,B)$, the bandwidth requirement B is uniformly distributed within $[12.5,250]$ Gb/s, and the destination d is randomly selected.

Figs. 2(a)-(d) show the Wireshark captures of the IDP messages for provisioning an inter-domain lightpath from *Node* 7 to *Node* 16 in Fig. 3(a). *Inter_Domain_Request* in Fig. 2(a) indicates that the bandwidth requirement is 108 Gb/s. In Figs. 2(b) and 2(d), we can see that the broker talks with the OF-Cs to obtain the spectrum usages and transmission distances of the virtual links by using the *Status_Request* and *Status_Reply* messages. Finally, the *Inter_Domain_Reply* in Fig. 2(c) indicates that the broker instructs $OF\text{-}C_2$ to use *Virtual Link* 2 (12→16) in *Domain* 2 with the assigned FS-block $[135,143]$, and selects the corresponding modulation-format as BPSK. The *Inter_Domain_Reply* message also shows that the FS-block assigned on the inter-domain link 9→12 is also $[135,143]$. Figs. 3(b)-(d) show the messages captured in sequence in the broker, $OF\text{-}C_1$, and $OF\text{-}C_2$, respectively, for setting up the lightpath. We observe that round-trip time between the broker and $OF\text{-}C_2$ is around 186 msec since the broker is located close to *Domain* 1, and the broker uses around 42 msec on MD-FA-RSA. Considering the processing delays in both domains, we can estimate that the total setup delay is around 405 msec.

Finally, we evaluate the performance of MD-FA-RSA with dynamic network operations in the testbed, and compare it with a benchmark that uses the shortest-path routing and first-fit spectrum assignment scheme for inter-domain lightpath provisioning (denoted as MD-SP-FF). The results on blocking probability is in Fig. 3(e), which show that MD-FA-RSA achieves much lower blocking probabilities than MD-SP-FF. Moreover, the results in Fig. 3(f) indicate that MD-FA-RSA also requires less O/E/O conversions per lightpath. These results verify that MD-FA-RSA can effectively improve the performance of inter-domain service provisioning. Note that, to obtain each data point in Figs. 3(e)-(f), the SD-EON serves 50000 dynamic requests.

4. Summary

We leveraged a hierarchical controller framework to design the system to enable MD-FA-RSA in SD-EONs. The proposed system was implemented and experimentally demonstrated in a multi-national SD-EON control plane testbed. The results showed that it could effectively improve the performance of inter-domain service provisioning.

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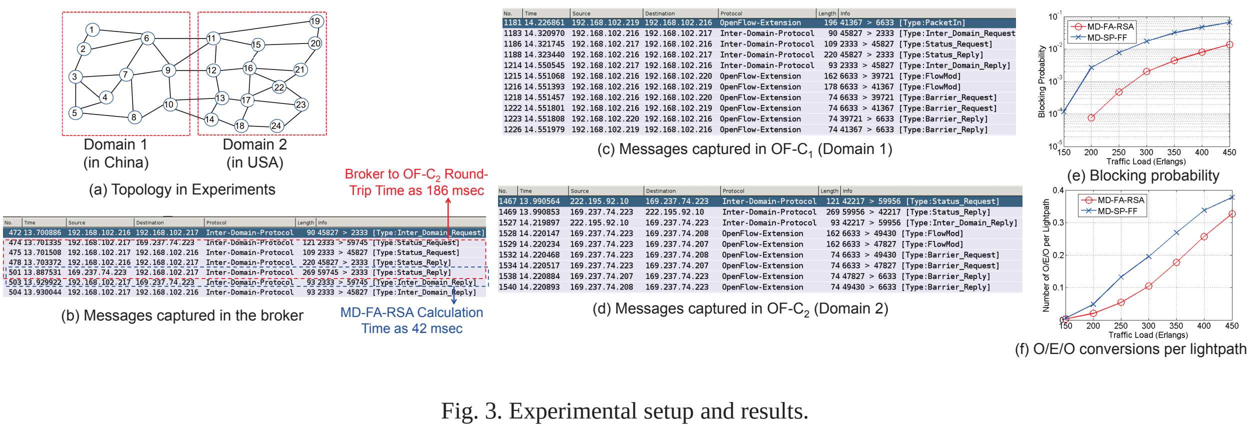

Fig. 3. Experimental setup and results.