

OpenFlow-Assisted Online Defragmentation in Single-/Multi-Domain Software-Defined Elastic Optical Networks [Invited]

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Abstract—Spectrum fragmentation limits the efficiency of spectrum utilization in elastic optical networks (EONs). This paper studies how to take advantage of the centralized network control and management provided by software-defined EONs (SD-EONs) for realizing OpenFlow-assisted implementation of online defragmentation (DF). We first discuss the overall system design and OpenFlow protocol extensions to support efficient online DF and conduct DF experiments with routing and spectrum assignment (RSA) reconfigurations in a single-domain SD-EON. Then, we propose to realize fragmentation-aware RSA (FA-RSA) in multi-domain SD-EONs with the cooperation of multiple OpenFlow controllers. In order to provision inter-domain lightpaths with restricted domain visibility on intra-domain resource utilization, we design and implement an inter-domain protocol to facilitate FA-RSA in multi-domain SD-EONs and demonstrate controlling the spectrum fragmentation on inter-domain links with FA-RSA. Our experimental results indicate that the OpenFlow-controlled DF systems perform well and can improve the performance of SD-EONs effectively.

Index Terms—Defragmentation (DF); Elastic optical networks (EONs); Multi-domain service provisioning; Software-defined network (SDN).

I. INTRODUCTION

Recently, spectrum-sliced elastic optical networks (EONs) that can leverage advanced transmission techniques such as optical orthogonal frequency-division multiplexing (O-OFDM) for flexible resource allocation have attracted intensive research attention [1]. Different from traditional fixed-grid wavelength division multiplexing (WDM) networks, EONs set up lightpaths with bandwidth-variable transponders (BV-Ts) and switches (BV-WSSs) that operate on a series of spectrally contiguous frequency slots (FSs) with fine granularity (i.e., 6.25 GHz) and adaptive

modulation formats. However, as the spectrum allocation granularity becomes smaller, spectrum fragmentation, which refers to the accumulation of nonaligned, isolated, and small-sized unused FS blocks [2], can be worse and arise as a major factor to restrict the effectiveness of spectrum utilization in EONs.

In order to deal with spectrum fragmentation, researchers have proposed a few defragmentation (DF) algorithms that reoptimize in-service lightpaths with routing and spectrum assignment (RSA) reconfigurations [2–7]. All of these works reoptimize lightpaths based on the knowledge of global resource utilization, and thus imply centralized network control and management (NC&M) for system implementation. It is known that software-defined networking (SDN) with OpenFlow (OF) [8] can improve the programmability of optical networks by leveraging flow-based switching and using a centralized controller [9–12]. The combination of SDN and EON leads to software-defined EONs (SD-EONs) and can further improve the flexibility and programmability of EONs [13–18]. Therefore, SD-EONs provide new opportunities for implementing DF effectively, and the centralized NC&M in them fits well with the requirement of DF. In line with this, in [18], we have designed and experimentally demonstrated online DF in a single-domain SD-EON testbed by utilizing periodic OF-assisted RSA reconfigurations.

In this paper, we extend our work in [18] and study online DF in both single- and multi-domain SD-EONs. We first elaborate on the overall system design and OF protocol extensions that we proposed to support efficient online DF, and discuss the DF experiments that incorporate RSA reconfigurations in a single-domain SD-EON in detail. Then, we investigate how to realize fragmentation-aware RSA (FA-RSA) in multi-domain SD-EONs with the cooperation of multiple OF controllers (OF-Cs). In order to provision inter-domain lightpaths with restricted domain visibility on intra-domain resource utilization and optical–electrical–optical (O/E/O) conversion capability, we design an inter-domain protocol (IDP) and implement it to facilitate FA-RSA in a five-domain SD-EON testbed for controlling the spectrum fragmentation on inter-domain links (i.e., realizing proactive online DF [7]).

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The rest of the paper is organized as follows. Section II discusses the overall network architecture, system functional design, and OF extensions for SD-EONs that enable online DF. Then, the OF-assisted online DF in single-domain SD-EONs is studied in Section III, including the system implementation and experimental demonstration. In Section IV, we investigate OF-assisted FA-RSA in a multi-domain SD-EON testbed with IDP and show the experimental results. Finally, Section V summarizes the paper.

II. SOFTWARE-DEFINED ELASTIC OPTICAL NETWORKS

In this section, we present the SD-EON framework that facilitates online DF in both the proactive (i.e., through FA-RSA) and reactive (i.e., through RSA reconfigurations) manners. We first show the overall network architecture, system functional design, and related OF extensions. Then, online lightpath provisioning is demonstrated with the SD-EON framework.

A. Network Architecture

Figure 1 shows the network architecture of an SD-EON. The lightpaths are established in the data-plane, which is built with edge routers (ERs) and BV-WSSs. The ERs are responsible for sending/receiving optical signals for lightpaths that carry client traffic, and thus each consist of several BV-Ts and a wavelength multiplexer/demultiplexer (MUX/DEMUX). Each BV-T can set up a lightpath by tuning its optical signal onto appropriate FSs and using a suitable modulation format, while the BV-WSSs along the lightpath switch the optical signal correctly to its destination. Note that the bandwidth and spectral location of each FS is defined in the ITU-T G.694.1 recommendation [19].

The SD-EON's control-plane is based on the extended OF protocol [8], and it consists of a centralized OF-C and several OF agents (OF-AGs). The OF-C achieves centralized NC&M for efficient resource management, while each OF-AG is locally attached to data-plane equipment (i.e., ER or BV-WSS) for controlling its operation according

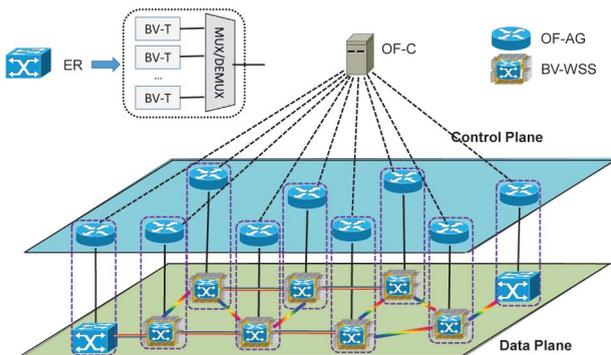


Fig. 1. Network architecture of SD-EON. OF-C, OF controller; OF-AG, OF agent; ER, edge router; BV-WSS, bandwidth-variable wavelength-selective switch; BV-T, bandwidth-variable transponder; MUX/DEMUX, wavelength multiplexer/demultiplexer.

to the instructions from the OF-C. During network operation, the OF-C communicates with each OF-AG to collect and analyze the spectrum utilization in the network, and when a lightpath request comes in, it calculates a proper RSA based on the global information and instructs related OF-AGs to configure their data-plane equipment for installing the lightpath.

B. System Functional Design

The system functional design of the OF-AG and OF-C for realizing online DF is illustrated in Fig. 2. In an OF-AG, the OF client communicates with the OF-C with an extended OF protocol, and the local traffic database (LTD) stores the flow entries that are used by the equipment controller to configure its data-plane equipment.

The OF-C has a more complicated architecture. The resource provision module (RPM) interacts with OF-AGs or peer OF-Cs in an inter-domain scenario for handling lightpath provision related OF messages. Upon receiving a provision request, the RPM instructs the resource computation module (RCM) to perform corresponding RSA calculation. It also tells the traffic engineering database (TED) to update spectrum availability in the network, when the request is successfully provisioned. The RCM is responsible for RSA calculations, and it serves both the RPM and the DF agent in ways that the former forwards lightpath information for the initial setup while the latter invokes RSA calculations for in-service lightpath reconfigurations. The DF agent monitors the network status in the TED and invokes DF operations accordingly, i.e., selecting in-service lightpaths to reconfigure. Meanwhile, the network operator can control the DF agent and trigger DF operations manually through an external network management system (NMS). Finally, the network abstraction module (NAM) talks with OF-AGs, collects the

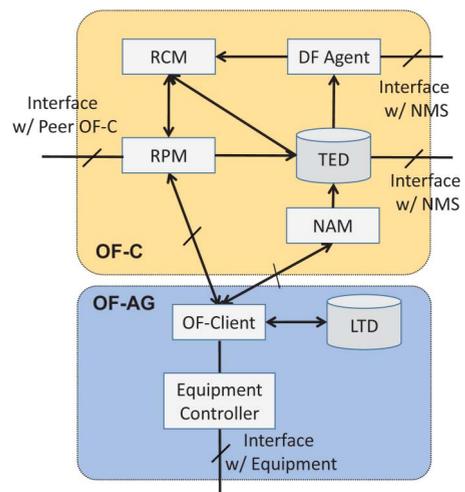


Fig. 2. System functional design for the OF-AG and OF-C to realize online DF. LTD, local traffic database; DF agent, defragmentation agent; NMS, network management system; RCM, resource computation module; TED, traffic engineering database; RPM, resource provisioning module; NAM, network abstraction module.

network's topology information, and abstracts the data-plane equipment for the TED.

C. OpenFlow Protocol and Proposed Extensions

According to the working principle of OF, we identify each lightpath in SD-EON with a flow entry that contains information such as matching fields, actions, and related counters. We implement the SD-EON's control-plane based on OpenFlow v1.0 [8], since it is a stable version and can be widely supported by various OF systems. Figure 3 shows the flow-table matching fields and the associated actions for the source/destination ERs and intermediate BV-WSSs of a lightpath. The key fields are explained as follows:

- *FS_Bandwidth*: bandwidth of an FS, which is $f_{grid} = 12.5$ GHz according to ITU-T G.694.1 [19].
- *Starting_Frequency*: the starting frequency of the FS block for the lightpath. Here, the field contains an integer, and we calculate the real starting frequency in gigahertz as $(193,100 + Starting_Frequency \times 12.5)$.
- *Number_of_FS*: bandwidth of the lightpath, which is represented as the number of f_{grid} .

In order to establish the lightpath correctly, the flow-matching actions are different for the source/destination ERs and intermediate BV-WSSs. For the source ER, the flow-matching actions are "Output Port" and "Set FS'," which means that it should instruct a BV-T to operate on a specific FS block with the selected modulation format and then send the optical signal to the assigned output port. In the intermediate BV-WSSs, the flow-matching action is to switch the optical signal from input to output correctly. Finally, at the destination ER, the flow-matching action is to drop the lightpath locally (i.e., configure a BV-T to receive the optical signal).

D. Implementation of SD-EON Testbed

We implement the control-plane of the aforementioned SD-EON system in a testbed that consists of 14 standalone OF-AGs and an OF-C. The OF-AGs are connected according to the NSFNET topology in Fig. 4 to mimic a wide-area optical network. OF-AGs and the OF-C are both implemented on high-performance Linux servers (ThinkServer RD530), as shown in Fig. 5. Each OF-AG is programmed based on Open-vSwitch [20], while the OF-C is implemented with the POX platform [21]. Note that we focus

on the control-plane implementation in this work, and the data-plane is emulated in the experiments.

With the SD-EON testbed, we first perform a simple experiment on establishing lightpaths with online RSA and use it to verify the basic functionalities of the system. The procedure of OF-assisted online RSA is as follows.

- **Step 1:** A lightpath request $LR(d, C, \Delta t)$ for client traffic (e.g., IP) arrives at the source ER, where d is the destination address, C is the bandwidth requirement, and Δt is the requested service duration.
- **Step 2:** The OF-AG on the source ER generates a *Packet-In* message to include $\{s, d, C, \Delta t\}$ and sends it to the OF-C, where s is the address of the source ER.
- **Step 3:** The RPM in the OF-C receives the *Packet-In* message and instructs the RCM to perform RSA calculation.
- **Step 4:** The RCM obtains the network status from the TED and calculates the RSA for the request. Here, the RCM performs quality-of-transmission (QoT)-aware RSA and selects the modulation format adaptively based on the routing path's physical distance [22]. If a feasible solution can be obtained, the RCM instructs the RPM to build corresponding flow entries for the source/destination ERs and intermediate BV-WSSs. Otherwise, the

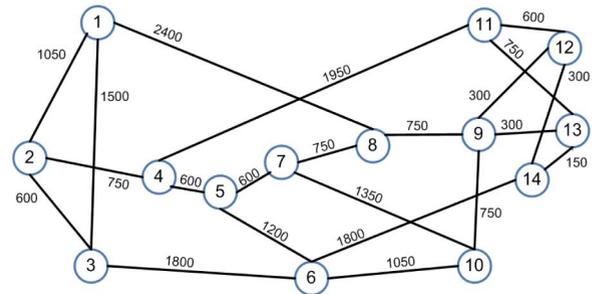


Fig. 4. NSFNET topology for single-domain SD-EON testbed (link lengths in kilometers).

Flow-Matching Fields					Action	
Input Port	FS Bandwidth	Destination Address	Capacity Requirement	Expiring Time	Output Port, Set FS'	Source ER
Input Port	FS Bandwidth	Destination Address	Starting Frequency	Number of FS'	Output Port, Set FS'	Intermediate WSS
Input Port	FS Bandwidth	Destination Address	Starting Frequency	Number of FS'	Local Drop, Set FS'	Destination ER

Fig. 3. Flow-matching fields and associated actions.



Fig. 5. SD-EON control-plane testbed built with Linux servers.

RCM tells the RPM to communicate with the source ER's OF-AG for blocking the request.

- **Step 5:** The RPM distributes the flow entries to all the related OF-AGs along the routing path with *Flow-Mod* messages.
- **Step 6:** Each OF-AG parses the flow entry and configures its data-plane equipment accordingly. Then, it updates its LTD to include the new lightpath and send the configuration result to the OF-C using a *Barrier-Reply* message.
- **Step 7:** If all the configurations are successful, the RPM updates the TED. Otherwise, it invokes error recovery.
- **Step 8:** When a lightpath expires, the OF-C updates its TED and removes the related flow entries on the OF-AGs.

Figure 6 shows the wireshark capture for setting up a lightpath that has two hops with the OF-assisted online RSA, which includes all the related OF messages in time order. It can be seen that it takes the SD-EON system around 11 ms to set up the lightpath in the control-plane. Note that with the increase of hop counts, the lightpath setup latency can be increased accordingly. We also use wireshark to capture and parse the *Flow-Mod* message, and the result is shown in Fig. 7. We observe that the online RSA decides to allocate six FSs that use QPSK modulation to carry the bandwidth requirement of the lightpath.

Time	Source	Destination	Protocol	Length	Info
5.039504	192.168.102.217	192.168.102.205	OF-Extension	196	44049 > 6655 [Type:PacketIn]
5.049767	192.168.102.205	192.168.102.218	OF-Extension	162	6655 > 50683 [Type:FlowMod]
5.049981	192.168.102.205	192.168.102.218	OF-Extension	74	6655 > 50683 [Type:Barrier_Request]
5.050054	192.168.102.205	192.168.102.217	OF-Extension	178	6655 > 44049 [Type:FlowMod]
5.050168	192.168.102.218	192.168.102.205	OF-Extension	74	50683 > 6655 [Type:Barrier_Reply]
5.050361	192.168.102.205	192.168.102.217	OF-Extension	74	6655 > 44049 [Type:Barrier_Request]
5.050688	192.168.102.217	192.168.102.205	OF-Extension	74	44049 > 6655 [Type:Barrier_Reply]
5.052984	192.168.102.205	192.168.102.217	OF-Extension	90	6655 > 44049 [Type:Packet Out]

Fig. 6. Wireshark capture for setting up a lightpath with online RSA.

Match	
Inport:	1
Match Type	
Destination:	Node_3 (3)
Starting_Frequency:	289
Frequency_Slot_Bandwidth:	12.5GHz (0)
Number_of_Frequency_Slots:	6
Modulation_Format:	QPSK (2)
Defragmentation_Flag:	Normal (0)
Command:	Set_Up_New_Connection (0)
IdleTimeout:	45
HardTimeout:	0
Priority:	32768
BufferId:	4294967295
OutPort:	Any (65535)
Flags:	0
Actions	
action_type:	OUTPUT (0)
Output_Port:	3

Fig. 7. Wireshark capture of a *Flow-Mod* message in online RSA.

III. OPENFLOW-ASSISTED ONLINE DEFRAGMENTATION IN SINGLE-DOMAIN SD-EONS

In this section, we discuss the implementation of OF-assisted online DF in single-domain SD-EONS and demonstrate the proposed system experimentally. Note that here we design the DF to reoptimize the spectrum utilization in an SD-EON with RSA reconfigurations, which generally belongs to the category of reactive DF, based on the analysis in [7].

A. Defragmentation Procedure

Figure 8 shows the procedure of the proposed OF-assisted online DF, whose details are as follows.

- **Step 1:** The DF agent in the OF-C invokes a DF operation, selects lightpaths in the TED to be reconfigured, and instructs the RCM to calculate the new RSAs for them.
- **Step 2:** The RCM obtains the network status from the TED and recalculates RSAs for the selected lightpaths with the objective of minimizing spectrum fragmentation [23].
- **Step 3:** Based on the new RSA solutions, the RCM instructs the RPM to build new flow entries.
- **Step 4:** For each selected lightpath, the RPM uses *Flow-Mod* messages to distribute the flow entries to the OF-AGs on the original and new routing paths.
- **Step 5:** Each related OF-AG parses the flow entries, configures its data-plane equipment accordingly, and returns the result to the OF-C using a *Barrier-Reply* message.
- **Step 6:** The RPM updates the TED accordingly when all the *Barrier-Reply* messages have been received.

B. Experimental Demonstration

We conduct the OF-assisted online DF experiments still in the testbed with the NSFNET topology. Figure 9 shows

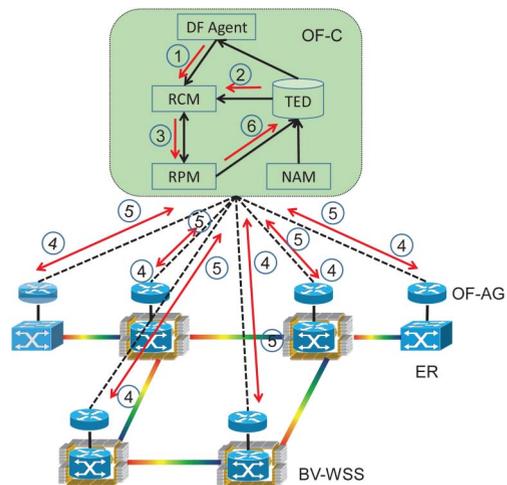


Fig. 8. Working principle of OF-assisted online DF.

Time	Source	Destination	Protocol	Length	Info
6.151367	192.168.102.205	192.168.102.218	OF-Extension	162	6655 > 38923 [Type:FlowMod]
6.151509	192.168.102.205	192.168.102.218	OF-Extension	162	6655 > 38923 [Type:FlowMod]
6.151862	192.168.102.205	192.168.102.218	OF-Extension	162	6655 > 38923 [Type:FlowMod]
6.152048	192.168.102.205	192.168.102.218	OF-Extension	74	6655 > 38923 [Type:Barrier_Request]
6.152147	192.168.102.205	192.168.102.217	OF-Extension	178	6655 > 60500 [Type:FlowMod]
6.152414	192.168.102.205	192.168.102.217	OF-Extension	74	6655 > 60500 [Type:Barrier_Request]
6.152424	192.168.102.218	192.168.102.205	OF-Extension	74	38923 > 6655 [Type:Barrier_Reply]
6.152762	192.168.102.217	192.168.102.205	OF-Extension	74	60500 > 6655 [Type:Barrier_Reply]

Fig. 9. Wireshark capture for reconfiguring a lightpath in online DF.

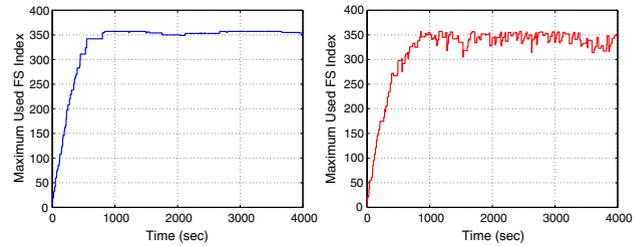
the Wireshark capture for reconfiguring a lightpath in the online DF, and the related OF messages are listed. The Wireshark capture of the *Flow-Mod* message is illustrated in Fig. 10, where we observe that the *Defragmentation_Flag* is turned on to indicate that the message is actually for a RSA reconfiguration in DF. Then, we perform online DF experiments with dynamic lightpath requests to study the performance of the proposed DF framework further. We assume that each fiber link can accommodate 358 FSs. Each OF-AG generates dynamic lightpath requests according to the Poisson process and selects their destinations randomly. The bandwidth requirement of each request (i.e., C) is uniformly distributed within [25,500] Gb/s. In the experiments, we consider the case in which the OF-C triggers the DF operations automatically based on the network status. More specifically, a DF operation is triggered when the number of expired requests exceeds 80. In each DF, the OF-C selects 50% of all the in-service lightpaths for reconfiguration.

Figure 11 compares the network spectrum utilizations for the cases with and without online DF. Here, we look at the maximum used FS index on all the fiber links in the SD-EON, and the results are obtained by examining the memory dumps of the TED on the fly. In Fig. 11(a), we observe that when there is no online DF, the maximum used FS index reaches its maximum value (i.e., 358) rapidly and stays around that value as time goes on. This means that the spectra of the SD-EON can easily become fragmented as there are no common available FS blocks on all the fiber links. On the contrary, after we implement the

```

▼ Match
  Inport: 2
  Match_Type
  Destination: Node_3 (3)
  Starting_Frequency: 134
  Frequency_Slot_Bandwidth: 12.5GHz (0)
  Number_of_Frequency_Slots: 6
  Modulation_Format: QPSK (2)
  Defragmentation_Flag: Defragmentation (1)
  Command: Set_Up_New_Connection (0)
  IdleTimeout: 23
  HardTimeout: 0
  Priority: 32768
  BufferId: 4294967295
  OutPort: Any (65535)
  Flags: 0
▼ Actions
  action_type: OUTPUT (0)
  Output_Port: 65534

```

Fig. 10. Wireshark capture of a *Flow-Mod* message in online DF.

(a) Without online DF.

(b) With online DF.

Fig. 11. Results on the maximum used FS index on all the fiber links.

online DF, the maximum used FS index decreases periodically in Fig. 11(b). This indicates that the DF can effectively consolidate the spectrum utilization in SD-EONs with the “push-to-the-wall” scheme.

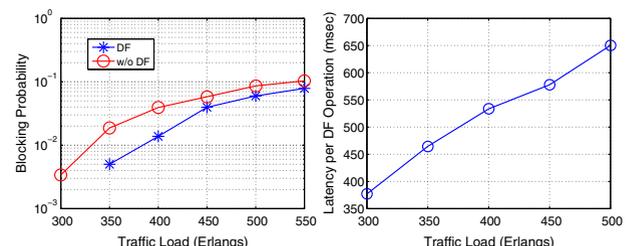
Figure 12 shows more experimental results, where the results on requests’ blocking probability are plotted in Fig. 12(a), and Fig. 12(b) provides the average control-plane latency per DF operation for reconfiguring all the selected lightpaths. It can be seen that the OF-assisted online DF can effectively improve the SD-EON’s blocking performance. For the average control-plane latency, its value is around 650 ms when the traffic load is as high as 500 E. Since, when the traffic load becomes higher in the experiments, the number of in-service lightpaths to reconfigure in each DF is also larger, the latency increases with traffic load in Fig. 12(b). Note that in order to obtain each data point in Fig. 12, the OF-C serves 14,000 incoming requests from the 14 OF-AGs in the SD-EON testbed.

IV. OPENFLOW-ASSISTED FRAGMENTATION-AWARE RSA IN MULTI-DOMAIN SD-EONs

In this section, we discuss the implementation of OF-assisted FA-RSA in multi-domain SD-EONs and show experimental demonstrations. FA-RSA tries to consolidate the spectrum utilization on inter-domain links when setting up the lightpaths initially. Hence, it tries to avoid spectrum fragmentation in a proactive manner [7].

A. Service Provisioning Framework

Figure 13 shows an example of multi-domain SD-EON, where the control-plane of each domain consists of an



(a) Blocking probability.

(b) Control-plane latency per DF.

Fig. 12. Experimental results for online DF.

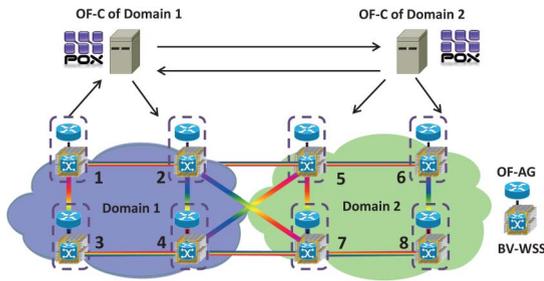
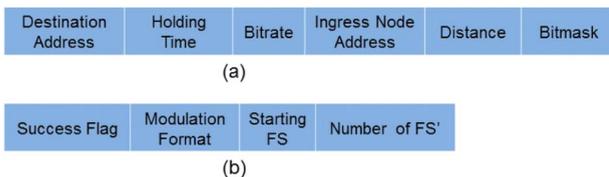


Fig. 13. Example of multi-domain SD-EON.

OF-C and a few OF-AGs. Each OF-AG talks with its own OF-C using the extended OF protocol discussed in Subsection II.C, while the OF-Cs communicate with each other for establishing an inter-domain lightpath with FA-RSA. We assume that all the border nodes (e.g., nodes 2, 4, 5, and 7) can perform O/E/O conversions for the inter-domain lightpaths. In order to facilitate efficient communication among the OF-Cs, we design an IDP that uses the *Inter-Domain Request* and *Inter-Domain Reply* messages in Fig. 14. With the IDP, the OF-Cs can set up the inter-domain lightpaths collaboratively with FA-RSA. More specifically, during the provisioning of an inter-domain lightpath, the source domain's OF-C sends an *Inter-Domain Request* message to the OF-C in the destination domain (or an intermediate domain) for initializing FA-RSA, while its peer OF-C replies with an *Inter-Domain Reply* message to finalize the service provisioning.

In the *Inter-Domain Request* in Fig. 14(a), the *Ingress_Node_Address* field indicates the ingress node in the next domain, while the *Bitmask* and *Distance* fields provide information on available FSs and the physical length of the current path segment (i.e., the path from the source to the egress node of the domain), respectively. Note that in order to protect the privacy of each domain, the *Bitmask* field will not disclose the whole FS usage on the intra-domain path segment, and it will randomly hide several available FSs by turning off the corresponding bits in the bitmask. The *Distance* field helps us to accomplish impairment-aware modulation-level selection for the lightpaths [22], and if the end-to-end inter-domain path is too long for all-optical transmission, we either try to use a lower modulation level or perform an O/E/O conversion at the border nodes. For the *Inter-Domain Reply* in Fig. 14(b), the *Success_flag* field indicates whether a feasible RSA solution can be found for the inter-domain lightpath end to end. If there is a feasible RSA, the *Modulation_Format*, *Starting_Frequency*, and *Number_of_FS*' fields represent the spectrum assignment.

Fig. 14. Messages for the inter-domain protocol: (a) *Inter-Domain Request* and (b) *Inter-Domain Reply*.

B. Fragmentation-Aware RSA in Multi-Domain SD-EONs

For an inter-domain lightpath request from s to d , where s and d reside in different domains, we use the procedure in Algorithm 1 to accomplish FA-RSA for it. In line 1, the domain sequence \mathbb{D} for routing the lightpath from s to d is calculated based on a simple virtual node abstraction. Specifically, as shown in Fig. 15, for the global SD-EON topology that contains five domains, we abstract all the nodes in a domain as a virtual node and keep the inter-domain links. Note that this virtual topology should be stored in every OF-C in the multi-domain SD-EON. Then, the OF-C in the source domain uses the shortest-path routing to obtain \mathbb{D} . Lines 2–6 are for initialization. Basically, we number the domains from low to high starting from the source.

Algorithm 1 FA-RSA in Multi-Domain SD-EONs

```

1 calculate domain sequence  $\mathbb{D}$  based on  $s-d$ ;
2  $v_{in} = s, i = 1, flag = 0$ ;
3 for each domain in  $\mathbb{D}$  from source do
4   mark the domain as  $D_i; i = i + 1$ ;
5 end
6 for  $i = 1$  to  $|\mathbb{D}|$  do
7   if  $D_i$  is the destination domain then
8      $v_{out} = d, flag = 1$ ;
9   else
10    set  $v_{out}$  as the ingress node of  $D_{i+1}$ ;
11  end
12  calculate a path  $p_i$  from  $v_{in}$  to  $v_{out}$  with the FA
13  method in [6];
14  if  $p_i$  cannot be found then
15    encode an Inter-Domain Reply message with
16    Success_flag turned off;
17    send the message to peer OF-Cs;
18    break;
19  else
20    if  $flag = 0$  then
21       $v_{in} = v_{out}$ ;
22      encode the information on current path
23      segment in Inter-Domain Request;
24      send the message to the OF-C in  $D_{i+1}$ ;
25    else
26      for  $j = |\mathbb{D}|$  to 1 do
27        select modulation level for the path
28        segment in  $D_j$ ;
29        assign an FS block in  $D_j$ ;
30        send flow entries to related OF-AGs;
31      if  $j > 1$  then
32        reply an Inter-Domain Reply
33        message to the OF-C in  $D_{j-1}$ ;
34    end
35  end
36  end
37  end

```

The “for” loop in lines 7–34 is for path computation and domain status collection in the forward direction. Specifically, we process the domains in \mathbb{D} in the sequence from

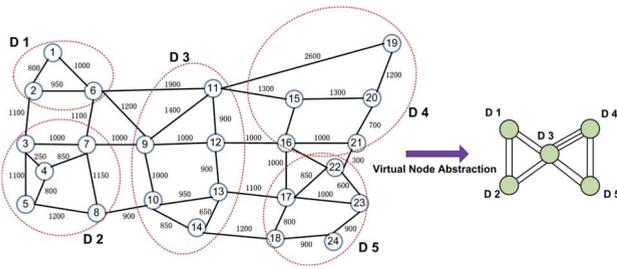


Fig. 15. Virtual node abstraction for the global SD-EON topology that contains five domains (link lengths in kilometers).

source to destination. As shown in *line 13*, each domain calculates a path segment from its ingress node (i.e., v_{in}) to the ingress node of the next domain (i.e., v_{out}) with the fragmentation-aware method proposed in [6]. Basically, the domain's OF-C calculates K shortest paths from v_{in} to v_{out} , and selects the one that has sufficient available FSs, and the spectrum allocation on it will bring the least spectrum cuts [6] on the inter-domain link. When performing the path computation, we take account of the FS usage bit-mask received from the previous domain. If such a path cannot be found, *lines 14–17* instruct the peer OF-Cs to block the request. Otherwise, we proceed to *lines 19–32*, where two situations are considered. *Lines 19–22* handle the situation in which the domain is not the destination domain, and the information on the current path segment is encoded in an *Inter-Domain Request* message and sent to the next domain. Otherwise, if the destination domain is reached, *lines 24–31* perform resource allocations in the backward direction. Basically, we finalize the modulation-level and spectrum assignment in each domain, instruct related OF-AGs to configure the data-plane equipment accordingly, and send the resource allocation result to the previous domain with an *Inter-Domain Reply* message. Note that, in this work, we assume that O/E/O conversion(s) can be used at the border nodes, if there are no available FS blocks across the domains or the overall path length is too long for all-optical transmission.

C. Experimental Demonstration

We perform the inter-domain FA-RSA experiments in a multi-domain SD-EON testbed that contains five domains with the topology in Fig. 15. The experimental setup of each domain is the same as that in Subsection III.B, which consists of a centralized OF-C and a few OF-AGs that each attach to data-plane equipment. The OF-Cs of different domains communicate with each other with the IDP proposed in Subsection IV.A. Figure 16 shows the messages captured by Wireshark for setting up an inter-domain lightpath from D_1 to D_2 . The messages captured in both domains are listed in time order, and we observe that the control-plane latency for setting up the lightpath is around 28 ms. The related *Inter-Domain-Request* and *Inter-Domain-Reply* messages are also captured and shown in Figs. 17 and 18, respectively.

We then perform online FA-RSA experiments with dynamic inter-domain lightpath requests, and the experiment

Time	Source	Destination	Protocol	Length	Info
14.406764	192.168.102.217	192.168.102.205	OF-Extension	196	44822 > 6655 [Type:PacketIn]
14.431539	192.168.102.205	192.168.102.221	InterDomain	139	56256 > 2334 [Type:Request]
14.434007	192.168.102.221	192.168.102.205	InterDomain	82	41294 > 2334 [Type:Reply]
14.434380	192.168.102.205	192.168.102.218	OF-Extension	162	6655 > 51477 [Type:FlowMod]
14.434536	192.168.102.205	192.168.102.217	OF-Extension	178	6655 > 44822 [Type:FlowMod]
14.434559	192.168.102.205	192.168.102.218	OF-Extension	74	6655 > 51477 [Type:Barrier_Request]
14.434767	192.168.102.205	192.168.102.217	OF-Extension	74	6655 > 44822 [Type:Barrier_Request]
14.434831	192.168.102.218	192.168.102.205	OF-Extension	74	51477 > 6655 [Type:Barrier_Reply]
14.435113	192.168.102.217	192.168.102.205	OF-Extension	74	44822 > 6655 [Type:Barrier_Reply]

(a)

Time	Source	Destination	Protocol	Length	Info
10.475185	192.168.102.205	192.168.102.221	InterDomain	139	56256 > 2334 [Type:Request]
10.477044	192.168.102.221	192.168.102.220	OF-Extension	162	6655 > 57129 [Type:FlowMod]
10.477281	192.168.102.221	192.168.102.220	OF-Extension	74	6655 > 57129 [Type:Barrier_Request]
10.477310	192.168.102.221	192.168.102.219	OF-Extension	162	6655 > 53550 [Type:FlowMod]
10.477467	192.168.102.221	192.168.102.205	InterDomain	82	41294 > 2334 [Type:Reply]
10.477455	192.168.102.221	192.168.102.219	OF-Extension	74	6655 > 53550 [Type:Barrier_Request]
10.477612	192.168.102.220	192.168.102.221	OF-Extension	74	57129 > 6655 [Type:Barrier_Reply]
10.477777	192.168.102.219	192.168.102.221	OF-Extension	74	53550 > 6655 [Type:Barrier_Reply]

(b)

Fig. 16. Wireshark captures in (a) domain D_1 and (b) domain D_2 for setting up an inter-domain lightpath with FA-RSA.

```

InterDomain Protocol, Type: Request (1)
  Header
    Type: Request (1)
    length: 73
    xid: 0
    Destination_Addr_dpId: 272744415148566
    Holding_Time_in_sec: 100
    Bitrate_in_Gbps: 128
    Ingress_Addr_dpId: 272744414982424
    Distance_in_km: 3750
    Bitmask: 00808f1fff1ffe03f8ff3f0000ffff0700e0ffffff...
```

Fig. 17. Wireshark capture of an *Inter-Domain-Request* message.

```

InterDomain Protocol, Type: Reply (2)
  Header
    Type: Reply (2)
    length: 16
    xid: 0
    Success_Flag: Success (0)
    Modulation_Format: BPSK (1)
    Starting_Frequency: 32
    Number_of_FS: 11
```

Fig. 18. Wireshark capture of an *Inter-Domain-Reply* message.

parameters are the same as those in Subsection III.B. In the experiments, we compare FA-RSA with a traditional RSA algorithm that uses shortest-path routing and first-fit spectrum assignment (SP-FF). Figure 19 shows the experimental results. The results on blocking probability in Fig. 19(a) indicate that the proposed inter-domain FA-RSA always achieves lower blocking probability. This is because FA-RSA can reduce the spectrum fragmentation on inter-domain links. In order to verify that the reduction on blocking probability is not due to more O/E/O consumption in FA-RSA, we plot the results on the average number of O/E/O conversions per inter-domain lightpath in Fig. 19(b). It can be seen that the two resource allocation schemes use a comparable number of O/E/O conversions per lightpath. Actually, when the traffic load is lower than 300 E, FA-RSA uses slightly fewer O/E/O conversions than SP-FF. When the traffic load keeps increasing, FA-RSA can require

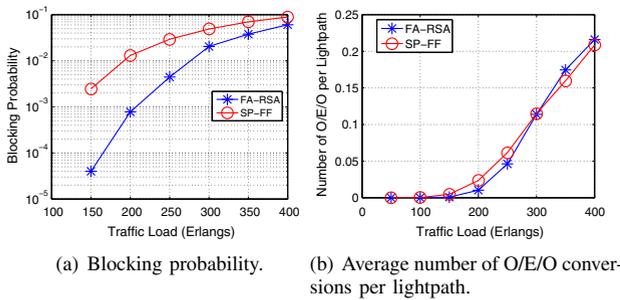


Fig. 19. Experimental results for online FA-RSA in multi-domain SD-EON.

slightly more O/E/O conversions than SP-FF. This is because when the multi-domain SD-EON is very crowded, FA-RSA can provision some inter-domain lightpaths with relatively long paths, which increases O/E/O consumption due to the QoS constraint.

V. CONCLUSION

This paper investigated OF-based implementations for realizing online DF in both single- and multi-domain SD-EONs. We first discussed the overall system design and OF protocol extensions to support efficient online DF, and conducted DF experiments with RSA reconfigurations in a single-domain SD-EON. Then, we studied how to realize FA-RSA in multi-domain SD-EONs with the cooperation of multiple OF-Cs. We designed and implemented an IDP to facilitate FA-RSA in multi-domain SD-EONs, and demonstrated controlling the spectrum fragmentation on inter-domain links with FA-RSA. Our experimental results indicated that the proposed DF systems performed well and could improve the performance of SD-EONs effectively.

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