Demonstration of Cooperative Resource Allocation in an OpenFlow-Controlled Multidomain and Multinational SD-EON Testbed

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(Invited Paper)

***Abstract*—The combination of elastic optical networks (EONs) and software-defined networking (SDN) leads to SD-EONs, which bring a new opportunity for enhancing programmability and flexibility of optical networks with more freedom for network operators to customize their infrastructure dynamically. In this paper, we investigate how to apply multidomain scenarios to SD-EONs. We design the functionalities in the control plane to facilitate multidomain tasks, and propose an interdomain protocol to enable OpenFlow controllers in different SD-EON domains to operate cooperatively for multidomain routing and spectrum assignment. The proposed system is implemented and experimentally demonstrated in a multinational SD-EON control plane testbed that consists of two geographically distributed domains located in China and USA, respectively. Experimental results indicate that the proposed system performs well for resource allocation across multiple SD-EON domains.**

***Index Terms*—Multi-domain networking, openFlow (OF), software-defined elastic optical networks (SD-EONs).**

I. Introduction

The recent emergence of the spectrum-sliced Elastic Optical Networks (EONs) [1], [2] allows management of the optical layer more flexible without being constrained by the fixed spectral grids or modulation formats. By taking advantage of advanced optical transmission and switching techniques, EONs can provide a bandwidth allocation granularity at 12.5 GHz or less and support a super-channel at 400 GHz and beyond as well. Hence, compared with the traditional fixed-grid Wavelength Division Multiplexing networks, EONs achieve improved spectral efficiency and more agile resource allocation.

When EONs have to support highly-dynamic traffic by provisioning lightpaths frequently, an efficient network control and management (NC&M) mechanism is highly desired. Previous works have investigated NC&M methods for EONs incorporating the distributed generalized multi-protocol label switching (GMPLS) or hybrid GMPLS and path computation element (PCE) architectures [3]–[5]. Meanwhile, by decoupling the control and data planes of a network, software-defined networking (SDN) enables the network to be programmable, adaptive and application-aware [6]. As a promising implementation of SDN, OpenFlow (OF) [7] has been developed as a standard protocol. The combination of SDN and EONs leads to software-defined EONs (SD-EONs), which also support efficient NC&M and bring new opportunities for enhancing the programmability of optical networks. Specifically, SD-EONs can provide network operators more freedom to customize their infrastructure dynamically and shorten the time needed for introducing new services [8].

Previous studies have pursued new experiments on SD-EONs [9]–[11]. However, most of them only focused on single-domain SD-EONs. If and when world-wide deployment of EONs takes place, there will be an increasing demand to incorporate multi-domain scenarios. Moreover, in practical network operations, considering multi-domain service provisioning is very relevant. For instance, the multi-domain scenarios can accommodate the inter-operability issues when deploying network elements from different vendors, enhance network scalability and extend service reach, and handle the situation where the optical switches are geographically-distributed and/or operated by different carriers. Recent studies have also demonstrated a few network orchestration schemes for multi-domain SD-EONs [12]–[14]. Casellas *et al.* demonstrated the NC&M of a multi-domain EON with an integrated PCE and OF controllers (OF-Cs) in [12]. Datacenter service migration in multi-domain SD-EONs has been experimentally investigated in [13]. The authors of [14] proposed a framework to realize load-balancing in multi-domain SD-EONs. However, the protocol design and experimental demonstration of cooperative routing and spectrum

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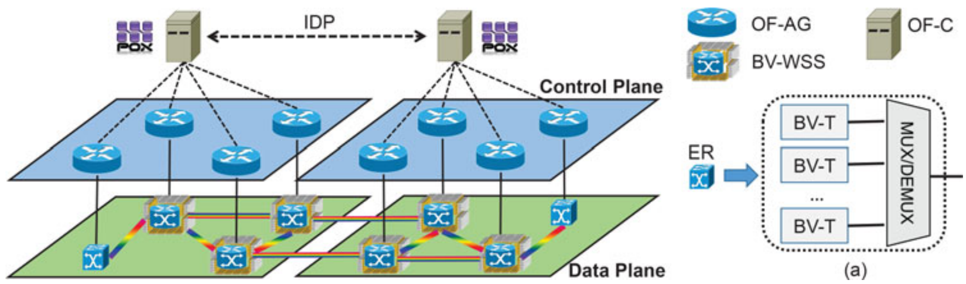

Fig. 1. Network architecture of a multi-domain SD-EON (OF-C: OpenFlow controller, OF-AG: OpenFlow agent, BV-WSS: Bandwidth-variable wavelength-selective switch, ER: Edge router, BV-T: Bandwidth-variable transponder, MUX/DEMUX: Wavelength multiplexer/de-Multiplexer).

assignment (RSA) for multi-domain service provisioning in SD-EONs have not been fully explored yet.

In this paper, we study cooperative RSA for multi-domain service provisioning in SD-EONs. Specifically, in order to realize the proof-of-concept demonstration, we design an inter-domain protocol (IDP) to enable OF-Cs in different SD-EON domains to operate cooperatively for multi-domain RSA. The multi-domain RSA realizes impairment-aware lightpath provisioning by considering both the transparent (i.e., the lightpaths are provisioned all-optically across multiple domains) and translucent (i.e., the lightpaths can go through optical-to-electrical-to-optical (O/E/O) conversions in between domains) schemes. Furthermore, since the IDP can hide the intra-domain resource utilization to other domains, intra-domain privacy can be maintained when the domains are operated by independent domain managers. We implement the proposed IDP and demonstrate it in a multinational SD-EON control plane testbed that consists of two geographically-distributed domains (in China and in USA). The contributions of this work can be summarized as follows,

- We design the functional modules for the control plane in SD-EONs to facilitate cooperative multi-domain RSA.
- We design an IDP to realize impairment-aware lightpath provisioning in multi-domain SD-EONs.
- We implement and experimentally demonstrate the proposed system in a multi-domain and multinational SD-EON control plane testbed.

The rest of the paper is organized as follows. Section II describes the architecture of multi-domain SD-EONs and elaborates on our functional design for realizing cooperative multi-domain RSA. The proposed IDP and the procedure of multi-domain lightpath provisioning with it are discussed in Section III. Then, we show the experimental demonstrations in Section IV. Finally, Section V summarizes this paper.

II. Multi-Domain SD-EONs

A. Network Architecture

Fig. 1 illustrates the network architecture of a multi-domain SD-EON. In each domain, the data plane includes edge routers (ERs) and bandwidth-variable wavelength selective switches (BV-WSS'). As shown in Fig. 1(a), an ER consists of a wavelength multiplexer/de-multiplexer (MUX/DEMUX) and a set of Bandwidth-Variable Transponders (BV-Ts). The control plane is based on OF and each domain has a centralized OF-C. To control network elements in the data plane (i.e., ERs or BV-WSS'), an OF agent (OF-AG) is locally attached to each of them. Each OF-C communicates with the OF-AGs in its domain using an extended OF protocol [15], while the OF-Cs use the proposed IDP to talk with each other. Note that the design of the IDP is inspired by the PCE communication protocol (PCEP) [16], which was defined for PCE cooperation in the control plane architecture that uses hybrid GMPLS and PCE. Therefore, we expect that it can be treated as the new extensions of PCEP for multi-domain RSA, when we integrate PCE with OF-C in SD-EONs [12].

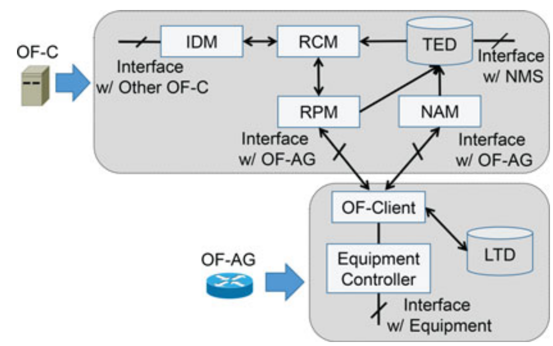

Fig. 2. Functional design of control plane components for multi-domain SD-EONs (IDM: Inter-domain module, RCM: Resource computation module, RPM: Resource provisioning module, TED: Traffic engineering database, NAM: Network abstraction module, NMS: Network management system, OF-Client: OpenFlow client, LTD: Local traffic database).

B. System Functional Design

Fig. 2 shows the functional design of the control plane components (i.e., OF-AG and OF-C). Basically, the OF-Cs calculate the service provisioning schemes and distribute the corresponding cross-connection entries, which are extended based on the flow-entries in the original OF protocol [15], [17], to the OF-AGs in their domains. The OF-AGs configure the network elements according to the cross-connection entries for lightpath provisioning. The detailed component designs to realize the functionality are as follows.

- *IDM:* It resides in an OF-C and interacts with other OF-Cs using IDP to handle inter-domain messages for multi-domain tasks. Note that the details of IDP will be discussed in Section III-C.
- *Resource Provision Module (RPM)*: OF-C uses it to process the OF messages from/to OF-AGs. For instance, upon

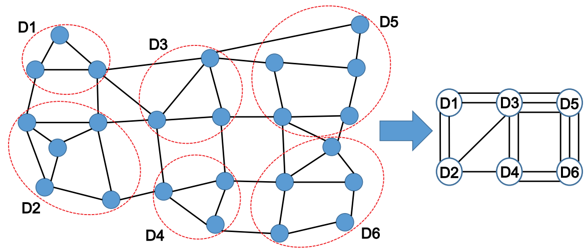

Fig. 3. Managing domain connectivity with virtual topology abstraction.

receiving an extended *Packet_In* message (i.e., a client traffic request) from an OF-AG, RPM instructs the resource calculation module (RCM) to calculate the service provisioning scheme. It is also the responsibility of RPM to update the information of in-service lightpaths in the traffic engineering database (TED) in real time.

- *RCM:* It receives calculation tasks from RPM or IDM and determines the service provisioning schemes (i.e., RSA) for both single- and multi-domain lightpaths. When the calculation is done, RCM instructs the RPM in its OF-C or other OF-Cs to build corresponding cross-connection entries for the related OF-AGs.
- *TED:* It stores the network status of an OF-C's domain, including the frequency flot (FS) usage on each link and the information of each in-service lightpath. TED is updated in real time to include the most-updated information.
- *Network Abstraction Module (NAM):* It abstracts network elements, and collects the domain's topology for the TED in its OF-C.
- *OF-C:* It resides in an OF-AG, talks with OF-C through an extended OF protocol, parses OF messages, and configures the data plane equipment accordingly through the equipment controller.
- *Local Traffic Database (LTD)*: It stores the active cross-connection entries for an OF-AG locally.

III. Multi-Domain Service Provisioning

A. Lightpath Provisioning Procedure

For the multi-domain SD-EON, we assume that its domain connectivity is either administratively predetermined or determined by certain neighbor discovery methods when the domains are connected initially. More specifically, the example in Fig. 3 explains how the domain connectivity (i.e., the border nodes and inter-domain links) is managed. For the topology that contains six domains, we abstract each domain as a virtual node and record the information of the border nodes and inter-domain links. Then, the virtual topology is stored in every OF-C and will be managed dynamically based on the spectrum usages on the inter-domain links. Hence, during network operation, the OF-C in the source domain can apply the shortest path routing in it to get the sequence of domains to be traversed for each request. We also assume that the nodes in each domain are associated with a specified address range and this information is also available to all the OF-Cs. Hence, by looking at the destination address, the OF-C in the source domain can figure out the location of the destination node.

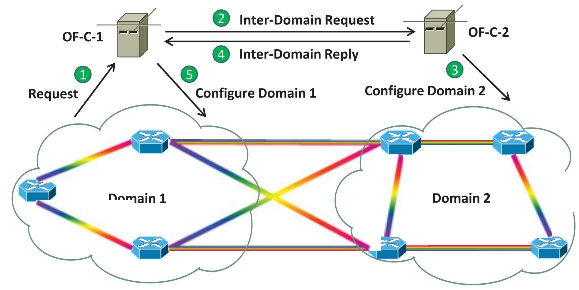

Fig. 4. Detailed procedure for multi-domain lightpath provisioning.

Next, we use the example in Fig. 4 to show the procedure for provisioning a multi-domain lightpath. Here, for simplicity, we assume that the SD-EON only consists of two domains, but note that the scheme proposed in this work can also be applied to the SD-EONs that include more than two domains. The details of the operations are explained as follows, and we denote the OF-C in *Domain-x* as *OF-C-x*.

- *Step 1:* When a request $LR(s, d, B, \Delta t)$ for client traffic comes in *Domain-1* (where s and d are the source and destination addresses, respectively, B is the bandwidth requirement in gigabit per second, and Δt is the required service duration), the OF-AG on the source ER sends a *Packet_In* message to *OF-C-1* to inform the arrival of the request.
- *Step 2:* Based on the *Packet_In* message, *OF-C-1* finds out that LR is a multi-domain one. Then, for each inter-domain link between the two domains, the RCM in *OF-C-1* obtains the K pre-calculated shortest paths, each of which goes from s to the egress node of *Domain-1* that it uses, merges each of them with the inter-domain link as an inter-domain path segment. Next, *OF-C-1* checks the spectrum usages on the path segments to select the least-loaded one, and randomly chooses a few usable FS-blocks on it, each of which is large enough to accommodate B. Specifically, we have an upper limit (i.e., N) on the number of usable FS-blocks that can be selected as the RSA candidates on an inter-domain path segment. If the number of usable FS-blocks on a path segment is larger than N, we randomly select N out of them. Otherwise, all the usable FS-blocks will be selected. At this point, for each inter-domain link, we obtain a path segment and N or less usable FS-blocks. Then, the path segments and the FS-blocks are treated as the RSA candidates for LR in *Domain-1*, and the IDM in *OF-C-1* encodes them in an *Inter-Domain-Request* message and sends it to *OF-C-2*. In the implementation, we set $K = 3$ and $N = 3$.
- *Step 3:* For each RSA candidate in the *Inter-Domain-Request* message, *OF-C-2* calculates the shortest path from the corresponding ingress node to d, and finds the available FS-blocks on it as the RSA candidates in *Domain-2*. After processing all the RSA candidates from *Domain-1*, *OF-C-2* tries to merge the two domains' RSA candidates and checks whether LR can be set up all-optically end-to-end. Note that the requirement on quality-of-transmission (QoT) is also considered here, i.e., if the signal's QoT would be too low for end-to-end all-optical transmission,

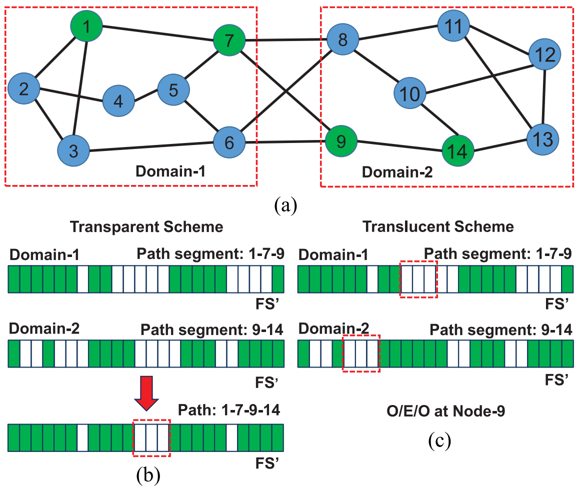

Fig. 5. Example of transparent and translucent schemes for multi-domain lightpath provisioning.

the lightpath will experience an O/E/O conversion in between the domains for signal regeneration. If LR can be served all-optically, *OF-C-2* finalizes its provisioning scheme by merging the corresponding RSA candidates. Otherwise, *OF-C-2* turns to the translucent option, randomly selects an RSA candidate in *Domain-1* from the *Inter-Domain-Request* message, makes sure that the lightpath experiences an O/E/O conversion on the ingress node of *Domain-2*, and determines a feasible RSA solution within *Domain-2*. If a transparent or translucent solution can be found, *OF-C-2* instructs the related OF-AGs in *Domain-2* to set up LR by distributing the corresponding cross-connection entries with *Flow_Mod* messages.

- *Step 4:* If the RSA solution in *Step 3* can be obtained, *OF-C-2* encodes the selected RSA in *Domain-1* with an *Inter-Domain-Reply* message and sends it *OF-C-1*. The message consists all the necessary information for assembling LR's portion in *Domain-1*. Otherwise, *OF-C-2* uses an *Inter-Domain-Reply* message to tell *OF-C-1* that the multi-domain provisioning for LR is failed.
- *Step 5: OF-C-1* receives the *Inter-Domain-Reply* message. If LR can be provisioned, it instructs the related OF-AGs to assemble LR's portion in *Domain-1* accordingly. Otherwise, it blocks LR.

Note that in *Steps 2 and 3*, we partially protect the intra-domain privacy by randomly selecting a portion of the intra-domain RSA candidates to inform peer domains. Basically, we do not disclose all the intra-domain spectrum usages, since in the situation where the domains are operated by different carriers, each carrier may not want to expose too much intra-domain information to the others. Meanwhile, more effective mechanisms for confidentiality such as the path key [18] are being investigated to be included in the IDP.

Fig. 5 shows the examples of the transparent and translucent schemes for multi-domain lightpath provisioning. With the two-domain EON in Fig. 5(a), we establish a lightpath from *Node-1* in *Domain-1* to *Node-14* in *Domain-2*, and the routing path is 1→7→9→14. Apparently, if the FS usages on path segments 1→7→9 and 9→14 are like those in Fig. 5(b), we can find a common available FS-block on the whole path across the two domains. Consequently, the lightpath can be provisioned with the transparent scheme if the QoT requirement is also satisfied. On the other hand, if the FS usages on the path segments are like those in Fig. 5(c), the lightpath has to go through an O/E/O conversion at *Node-9* for changing spectrum location, i.e., using the translucent scheme. Note that in this work, we will always use the transparent scheme to set up the lightpaths if it is possible, i.e., the all-optical reach of a lightpath is kept as long as possible. Meanwhile, it will be interesting to compare the performance of the transparent and translucent schemes in multi-domain SD-EONs in future studies.

B. Multi-Domain RSA Algorithm

Algorithm 1 shows the details of the multi-domain RSA algorithm for a generic multi-domain SD-EON, i.e., the SD-EON can consist of more than two domains. In *Line* 1, we obtain the domain sequence $\mathbb{D}$ for the end-to-end routing based on s and d of the multi-domain request, while *Lines* 2–6 are for initialization. The for-loop in *Lines* 7–44 is for the multi-domain RSA calculation across all the domains in $\mathbb{D}$. As shown in *Lines* 8–25, the OF-C of each domain calculates several RSA solutions. More specifically, the OF-C in the source domain calculates the RSA candidates for the path segments from s to all possible ingress nodes of the next domain. While in the destination domain, the OF-C obtains the RSA solutions for the path segments from the ingress node to d based on the RSA candidates encoded in the *Inter-Domain-Request* message from its previous domain. For all the intermediate domains, each OF-C gets the RSA candidates for the path segments from its ingress node to the ingress node of the next domain based on the *Inter-Domain-Request* from its previous domain. Note that in each domain, we pre-calculate K shortest paths between each node pair and use them to obtain the RSA candidates. In the implementation, we have $K = 3$. *Lines* 26–29 are for blocking the multi-domain request, when no feasible RSA solution can be found in one domain. *Lines* 31-42 perform resource allocation in the reversed order of the domains in $\mathbb{D}$. It can be seen that in order to simply the control plane procedure, path computation and service provisioning are coupled in our proposed IDP.

C. Inter-Domain Protocol

The detailed structures of the two IDP messages, i.e., *Inter-Domain-Request* and *Inter-Domain-Reply*, are shown in Fig. 6. In Fig. 6(a), the first three fields of *Inter-Domain-Request* include the basic information of the request, while the rest ones are for the RSA candidates in the current domain. The field structure of each RSA candidate is also shown in Fig. 6(a). The first sub-field stores the address of the ingress node of the next domain, the second one is for the all-optical transmission distance from the last-known BV-T (i.e., in s or an intermediate O/E/O converter) to the ingress node, and the rest ones store the available FS-blocks on the path segment.

The first field of the *Inter-Domain-Reply* message in Fig. 6(b) indicates whether a feasible RSA solution can be found in the current domain. Specifically, if there is no feasible RSA solution in the current domain, the *Blocking_Flag* is 1, and otherwise,

Algorithm 1: Multi-Domain RSA in SD-EON

obtain domain sequence $\mathbb{D}$ based on s-d;
$v_{in} = s$, $i = 1$;
for *each domain in* $\mathbb{D}$ *from source domain* **do**
  mark the domain as D_i;
  $i = i + 1$;
end
for $i = 1$ *to* $|\mathbb{D}|$ **do**
  if $i \neq |\mathbb{D}|$ **then**
    for *each link* e *between* D_i *and* D_{i+1} **do**
      set v_{out} as the egress node of e;
      if $i > 1$ **then**
        select an RSA candidate c from the *Inter-Domain-Request* from D_{i-1};
        set v_{in} as the ingress node in c;
      end
      calculate a path p from v_{in} to v_{out};
      if p *is not found* **then**
        continue;
      else
        get several available FS-blocks on p;
      end
    end
  else
    select an RSA candidate c from the *Inter-Domain-Request* from D_{i-1};
    get an RSA solution in D_i based on c;
  end
  if *no RSA solution in* D_i *can be found* **then**
    set *Blocking_Flag*=1 in *Inter-Domain-Reply*;
    send the message to the OF-Cs in $\{D_j,\ j < i\}$;
    break;
  else
    if $i \neq |\mathbb{D}|$ **then**
      encode the RSA solutions in D_i as RSA candidates in *Inter-Domain-Request*;
      send the message to OF-C in D_{i+1};
    else
      for $k = |\mathbb{D}|$ *to* 1 **do**
        select modulation-level for the path segment in D_k;
        send cross-connection entries to related OF-AGs;
        if $k > 1$ **then**
          send an *Inter-Domain-Reply* to OF-C in D_{k-1};
        end
      end
    end
  end
end

it is 0. The second field stores the identification of the RSA candidate that the OF-C in the current domain chooses from the *Inter-Domain-Request* message, and the rest ones are for the detailed information of resource allocation, i.e., the selected modulation format and FS-block. Note that the OF-Cs determine the modulation format for intra-domain path segments according to the total all-optical transmission distance. Therefore, with

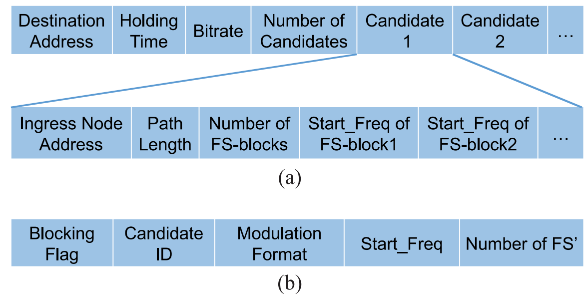

Fig. 6. Messages defined for the IDP, (a) *Inter-Domain-Request*, (b) *Inter-Domain-Reply*.

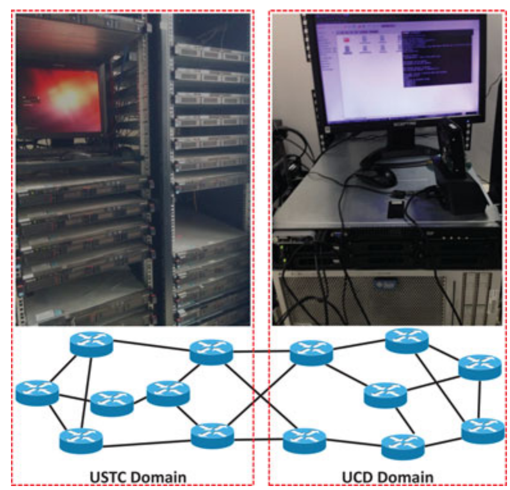

Fig. 7. Multi-domain SD-EON control plane testbed built with high performance Linux servers.

the *Inter-Domain-Reply* message, any individual OF-C cannot figure out whether the multi-domain request is provisioned all-optically or not, and it only knows the selected modulation format and FS-block from the last-known BV-T to the ingress node of the next domain. While how the request is handled outside that path segment is hidden from it. By doing so, we protect the privacy of the domains.

IV. Experimental Demonstrations

A. Experimental Setup

We demonstrate the system in a multi-domain SD-EON control plane testbed as shown in Fig. 7. The testbed consists of two domains each of which includes seven OF-AGs, and there are four inter-domain links. Note that one of the domains is located in the University of Science and Technology of China (USTC), while the other is in the University of California, Davis (UCD), USA. In each domain, the OF-C is implemented with the POX platform [19], and the OF-AGs are programmed based on OpenvSwitch [20]. All the OF-Cs and OF-AGs are running on independent high-performance Linux servers. Since we focus on the control plane operation in multi-domain SD-EONs, the data plane is emulated in this work. In other words, each OF-AG configures a virtual software-emulated network element but not a real ER or BV-WSS. Each fiber link in the multi-domain

```
▽ Interdomain Protocol    , Type: Request (1)
  ▽ Request_Header
    ▽ Header
        Type: Request (1)
        length: 103
        xid: 0
      Destination_Address_dpid: 125792405173064
      Holding_Time_in_sec: 100
      Bitrate_in_Gbps: 108
      Number_of_Candidates: 4
  ▽ Source_Candidates
    ▽ Candidate
        Ingress_Node_Address_dpid: 59449695647552
        Path_Length_in_km: 2700
      ▽ Frequency_Info
          Number_of_FS_Blocks: 3
          Start_Freq_in_THz: 191.3125THz (36)
          Start_Freq_in_THz: 192.3000THz (115)
          Start_Freq_in_THz: 193.9625THz (248)
    ▽ Candidate
        Ingress_Node_Address_dpid: 266192938945099
        Path_Length_in_km: 3300
      ▽ Frequency_Info
          Number_of_FS_Blocks: 1
          Start_Freq_in_THz: 191.3250THz (37)
    ▽ Candidate
        Ingress_Node_Address_dpid: 59449695647552
        Path_Length_in_km: 4050
      ▽ Frequency_Info
          Number_of_FS_Blocks: 2
          Start_Freq_in_THz: 191.2250THz (29)
          Start_Freq_in_THz: 192.0250THz (93)
    ▽ Candidate
        Ingress_Node_Address_dpid: 266192938945099
        Path_Length_in_km: 3300
      ▽ Frequency_Info
          Number_of_FS_Blocks: 3
          Start_Freq_in_THz: 191.3250THz (37)
          Start_Freq_in_THz: 192.1125THz (100)
          Start_Freq_in_THz: 194.6125THz (300)
```

(a)

```
▽ Inter Protocol    , Type: Reply (2)
  ▽ Header
      Type: Reply (2)
      length: 17
      xid: 0
    Blocking_Flag: Success (0)
    Candidate_ID: 0
    Modulation_Format: BPSK (1)
    Start_Freq_in_THz: 191.3125THz (36)
    Number_of_FS: 9
```

(b)

Fig. 8. IDP messages from the experiments. (a) *Inter-Domain-Request* message. (b) *Inter-Domain-Reply* message.

Time	Source	Destination	Protocol	Length	Info
12.112979	192.168.102.216	192.168.102.205	OF-Extension	196	50201 > 6655 [Type:PacketIn]
12.359287	192.168.102.205	169.237.74.17	InterDomain	169	35518 > 2334 [Type:Request]
12.631108	169.237.74.17	192.168.102.205	InterDomain	83	33797 > 2334 [Type:Reply]
12.631835	192.168.102.205	192.168.102.217	OF-Extension	162	6655 > 48678 [Type:FlowMod]
12.632043	192.168.102.205	192.168.102.217	OF-Extension	74	6655 > 48678 [Type:Barrier_Request]
12.632180	192.168.102.205	192.168.102.216	OF-Extension	178	6655 > 50201 [Type:FlowMod]
12.632353	192.168.102.205	192.168.102.216	OF-Extension	74	6655 > 50201 [Type:Barrier_Request]
12.632409	192.168.102.217	192.168.102.205	OF-Extension	74	48678 > 6655 [Type:Barrier_Reply]
12.632742	192.168.102.216	192.168.102.205	OF-Extension	74	50201 > 6655 [Type:Barrier_Reply]

(a)

Time	Source	Destination	Protocol	Length	Info
4.979523	222.195.92.10	169.237.74.17	InterDomain	169	35518 > 2334 [Type:Request]
4.983435	169.237.74.17	169.237.74.247	OF-Extension	162	6655 > 39165 [Type:FlowMod]
4.983770	169.237.74.17	169.237.74.246	OF-Extension	162	6655 > 33674 [Type:FlowMod]
4.983837	169.237.74.17	169.237.74.247	OF-Extension	74	6655 > 39165 [Type:Barrier_Request]
4.984082	169.237.74.17	169.237.74.246	OF-Extension	74	6655 > 33674 [Type:Barrier_Request]
4.984093	169.237.74.247	169.237.74.17	OF-Extension	74	39165 > 6655 [Type:Barrier_Reply]
4.984122	169.237.74.17	222.195.92.10	InterDomain	83	33797 > 2334 [Type:Reply]
4.984294	169.237.74.246	169.237.74.17	OF-Extension	74	33674 > 6655 [Type:Barrier_Reply]

(b)

Fig. 9. Messages captured in the multi-domain SD-EON testbed across multiple nations. (a) Wireshark captures in USTC domain. (b) Wireshark captures in UCD domain.

SD-EON is set to accommodate 358 FS' that each has a bandwidth of 12.5 GHz. Each OF-AG in the testbed generates dynamic requests according to the Poisson traffic model. For each request, the destination address d is randomly selected, and the bandwidth requirement B is uniformly distributed within $[25, 500]$ Gb/s.

B. Experimental Results

Fig. 8 shows the *Inter-Domain-Request* and *Inter-Domain-Reply* messages that are captured with Wireshark in the experiments. The *Inter-Domain-Request* in Fig. 8(a) includes four feasible path segments to the next domain, each of which carries one or more available FS-blocks. For instance, the length of the first path candidate is 2700 km, and it has three available FS-blocks that can be used to provision the lightpath.

Note that in this work, we consider the QoT of fiber transmission and determine the modulation format that is used for a request on an all-optical path segment (i.e., the path segment between two adjacent BV-Ts on the lightpath) based on its transmission distance. More specifically, with B as the bandwidth requirement, the number of contiguous FS' to be assigned is $n = \lceil \frac{B}{m \cdot C_{\text{FS}}^{\text{BPSK}}} \rceil$, where $C_{\text{FS}}^{\text{BPSK}}$ is the capacity that a 12.5-GHz FS can provide with BPSK, and m is the modulation-level, where $m = 1$, 2, 3 and 4 represent modulation formats BPSK, QPSK, 8-QAM and 16-QAM, respectively. Each modulation-level can support a maximum transmission reach based on QoT. Hence, when selecting the available FS-blocks for an RSA candidate in a domain, we consider the worst case, assume that BPSK is used, and ensure that the size of each FS-block is larger than $n = \lceil \frac{B}{C_{\text{FS}}^{\text{BPSK}}} \rceil$ FS'. While the actual modulation format that is used on an all-optical path segment is determined when it is finalized and the total all-optical transmission distance is known. With the *Inter-Domain-Request* in Fig. 8(a), the OF-C reports nine RSA candidates to its peer in the next domain. The *Inter-Domain-Reply* message in Fig. 8(b) indicates that the next domain uses the shortest-path and first-fit scheme to choose the first RSA candidate as it reports the shortest all-optical transmission distance. Since a feasible RSA solution is obtained, *Blocking_Flag* is turned OFF. Also, the modulation format and FS-block for the lightpath are confirmed.

Fig. 9 illustrates the Wireshark captures for the whole procedure of provisioning a multi-domain lightpath in the experiment. The messages in Fig. 9(a) and (b) are from the OF-Cs in USTC and UCD domains, respectively. We observe that the control plane latency for the OF-Cs to exchange IDP messages is 272 ms, while the total latency for setting up the multi-domain lightpath is 520 ms.

We also conduct experiments for dynamic network operation. In each experiment, the 14 OF-AGs in the multi-domain testbed use the Poisson traffic model to generate 4000 dynamic requests within certain time period, and the OF-Cs try to serve them with the proposed scheme and count all the blocked requests. By changing the parameters of the Poisson traffic model, i.e., the arrival rate of the requests and their average hold-time, we

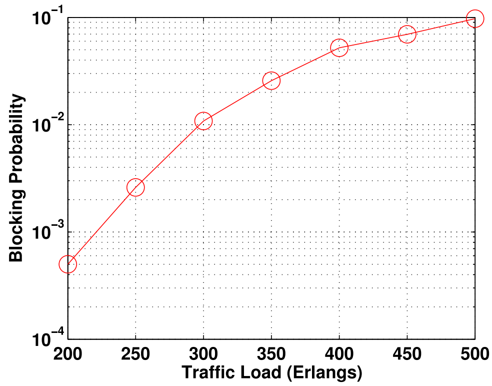

Fig. 10. Experimental results on blocking probability of connection requests.

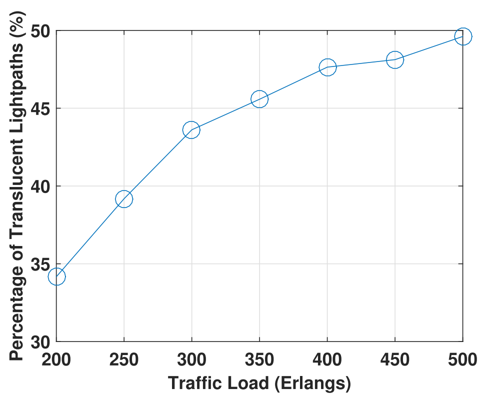

Fig. 11. Experimental results on percentage of translucent lightpaths.

conduct different experiments and obtain the request blocking probabilities for different traffic loads. The experimental results on blocking probability are shown in Fig. 10. Fig. 11 plots the results on percentage of translucent lightpaths in the multi-domain service provisioning. We can see that the percentage of translucent lightpaths increases with the traffic load. This is because when the traffic load increases, it will be more difficult for the OF-Cs to serve the requests with the transparent scheme.

V. Conclusion

This paper investigated how to accomplish multi-domain RSA in an SD-EON that consists of multiple domains. We proposed an IDP to enable OF-Cs in different SD-EON domains to operate cooperatively for the multi-domain RSA, which realized impairment-aware lightpath provisioning by considering both the transparent and translucent schemes. We implemented the proposed system, demonstrated its functionality in a multinational SD-EON control plane testbed that consisted of two geographically-distributed domains located in China and USA, respectively, and quantitatively measured the network performance in terms of lightpath provisioning latency and blocking probability.

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Authors' photographs and biographies not available at the time of publication.