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Service Provisioning in Multi-Domain SD-EONs

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(Invited Paper)

***Abstract*—This work investigates the service provisioning in multi-domain software-defined elastic optical networks (SD-EONs) by taking advantage of the centralized network control and management (NC&M) provided by OpenFlow (OF). We design two control plane frameworks, and discuss the corresponding service provisioning schemes in them. The frameworks are also implemented and experimentally demonstrated in a multi-national control plane testbed that consists of two SD-EON domains in China and USA, respectively.**

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

I. Introduction

Recently, the flexible-grid elastic optical networks (EONs) have attracted intensive research attentions [1]. Combined with the software-defined networking (SDN), EONs become software defined EONs (SD-EONs), which can support centralized network control and management (NC&M). SD-EONs bring enhanced flexibility and programmability into the optical networks, and provide network operators more flexibility to customize their infrastructure dynamically and shorten the time needed for adapting to new services. Considering worldwide deployment of EONs, we expect there will be an increasing demand to incorporate multi-domain scenarios to enhance network scalability and extend service reach. Specifically, multi-domain SD-EONs can handle the situation in which the optical networks are geographically-distributed and/or operated by different carriers [2]. Recently, OpenFlow (OF) has become a standard SDN protocol and provides us a powerful method to implement SD-EONs for multiple domain scenarios. As utilizing spectrum resources efficiently is essential in EONs, we can leverage OF to realize cooperative routing and spectrum allocation (RSA) for intelligent multi-domain service provisioning. In this work, we investigate service provisioning in multi-domain SD-EONs.

The rest of the paper is organized as follows. Section II discusses the network architectures for multi-domain SD-EONs. The service provisioning schemes for multi-domain SD-EONs are designed in Section III, and we show the experimental demonstrations in Section IV. Finally, Section V summarizes the paper.

II. OF-based Multi-Domain SD-EONs

A. Network Architectures

For an OF-based multi-domain SD-EON, we consider two possible network architectures as in Figs. 1(a) and 1(b).

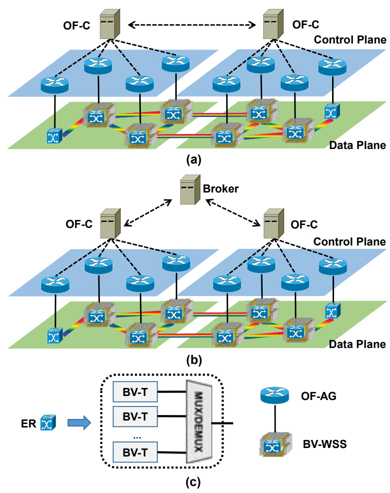

Fig. 1. Network architectures of multi-domain SD-EONs using the control plane (a) without a broker and (b) with a broker, and (c) network elements in the data plane.

Specifically, the control plane in Fig. 1(a) has a flat structure without a broker, while the network in Fig. 1(b) leverages a hierarchical control plane structure and introduces a broker to coordinate the operations of multiple OpenFlow controllers (OF-Cs). In each SD-EON domain, the data plane is built up with edge routers (ERs) and bandwidth-variable wavelength-selective switches (BV-WSS'). Fig. 1(c) shows the detailed configuration of an ER that consists of several bandwidth-variable transponders (BV-Ts) and a wavelength multiplexer/de-multiplexer (MUX/DEMUX). Above the data plane, the control plane consists of a few OpenFlow agents (OF-AGs) that each locally attaches to a network element (*i.e.*, ER or BV-WSS) directly, and one centralized OF-C that controls all the OF-AGs in each domain. Each OF-AG talks with its OF-C using an extended OF protocol [3]. OF-Cs function as the "brains" of their domains. To handle multi-domain tasks, they can either talk with each other directly through an inter-domain protocol (IDP) [3] as in Fig. 1(a), or connect to a broker that coordinates them as in Fig. 1(b).

B. Functional Design of Control Plane

The functional design of the OF-C and OF-AG in multi-domain SD-EONs is illustrated in Fig. 2. Basically, OF-Cs as well as the broker decide the service provisioning schemes, then each OF-C distributes the corresponding cross-connection entries, which are extended based on the original flow-entries

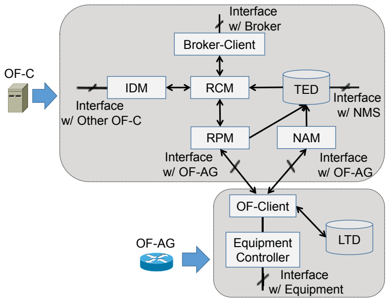

Fig. 2. Functional design of the control plane in multi-domain SD-EONs.

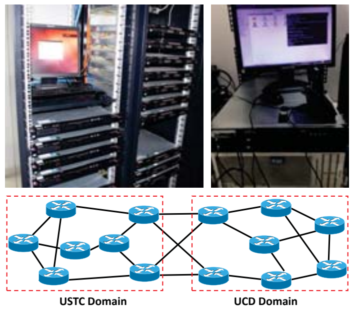

Fig. 3. Multi-national control plane testbed.

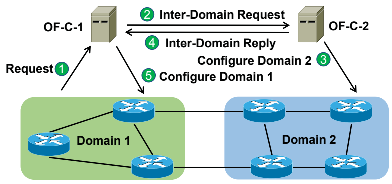

Fig. 4. Service provisioning in multi-domain SD-EONs without a broker.

defined in OF, to the related OF-AGs in its domain. The OF-Client in an OF-AG is responsible for communicating with OF-C, while the local traffic database (LTD) stores active cross-connection entries that have been used by the equipment controller to configure the network element.

In an OF-C, the inter-domain module (IDM) interacts with other OF-Cs through IDP to handle inter-domain messages for multi-domain tasks. The resource provision module (RPM) is used to process OF messages from/to OF-AGs. For instance, upon receiving a *Packet_In* message that represents a request from an OF-AG, RPM instructs the resource computation module (RCM) to calculate the service provisioning scheme. When the calculation is done, it is instructed by the RCM to build corresponding cross-connection entries and send them to all the related OF-AGs for setting up the lightpath. RPM is also responsible for updating the information of in-service lightpaths' in the traffic engineering database (TED) in real time. Hence, TED stores a domain's most updated network status, *e.g.*, the frequency slot (FS) usage on each link. The network abstraction module (NAM) is used to abstract network elements, and collect the network topology for TED. When the broker is introduced for multi-domain service provisioning, it interacts with OF-Cs using Broker messages.

C. Implementation of Control Plane Testbed

We implement the control plane frameworks discussed above in a multi-domain SD-EON testbed. The testbed includes two domains. When it comes to the scenario with the broker, we make it reside in the higher control level above both the SD-EON domains. Each OF-AG is programmed based on OpenvSwitch, while the OF-Cs and the broker are implemented with the POX platform. All the control plane elements, *e.g.*, the broker, OF-Cs and OF-AGs, run on high-performance Linux servers as in Fig. 3. The topology of the testbed is also shown in Fig. 3, where each domain includes 7 OF-AGs and there are four inter-domain links to connect the two domains. Note that the domains are located in the University of Science and Technology of China (USTC) and the University of California, Davis (UCD), respectively, and we have the broker placed in USTC.

III. Multi-Domain Service Provisioning

A. Multi-domain Service Provisioning without a Broker

Fig. 4 shows the procedure of service provisioning in multi-domain SD-EON without a broker.

- **Step 1**: When a client traffic request $LR(s, d, B, \Delta t)$ comes in *Domain-1* (where s and d are the source and destination addresses, B is the bandwidth requirement in Gb/s, and Δt is the required holding time), the OF-AG on the source node encodes a *Packet_In* message and forwards it to *OF-C-1* to inform the arrival of the request.
- **Step 2**: With the *Packet_In*, *OF-C-1* checks d and finds out that LR is for a multi-domain lightpath. For each inter-domain link, RCM in *OF-C-1* calculates the shortest path from s to the corresponding egress node as the path segment in *Domain-1*. Then it obtains the FS usages on that path segment, and randomly chooses some FS-blocks that each can accommodate B. The path segments and the selected FS-blocks on them are treated as R-SA candidates in *Domain-1*, which are encoded in an *Inter_Domain_Request* message to OF-C-2.
- **Step 3**: For each RSA candidate in the *Inter_Domain _Request*, *OF-C-2* calculates the shortest path from the related ingress node to d, finds the available FS-blocks on it as the RSA candidates in *Domain-2*. Then, *OF-C-2* tries to merge the two domains' RSA candidates and checks whether LR can be set up all-optically end-to-end. The requirement on Quality-of-Transmission (QoT) is also considered here, *i.e.*, if the signal's QoT would be too low for the all-optical transmission, an O/E/O conversion will be performed at the ingress node for signal regeneration. If a feasible solution can be obtained, *OF-C-2* instructs the related OF-AGs to assemble LR's portion in *Domain-2* by distributing the corresponding cross-connection entries with *Flow_Mod* messages.
- **Step 4**: If an RSA solution can be found in **Step 3**, *OF-C-2* encodes the selected RSA in *Domain-1* in an *Inter_Domain_Reply* message to *OF-C-1*. The message includes all the necessary information for assembling LR's portion in *Domain-1*. Otherwise, *OF-C-2* uses an *Inter_Domain_Reply* message to inform *OF-C-1* of the failure of the multi-domain service provisioning.

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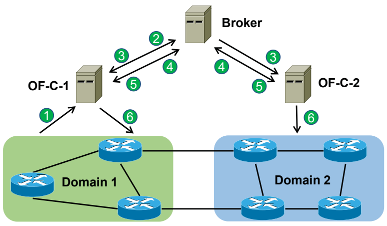

Fig. 5. Service provisioning in multi-domain SD-EONs with a broker.

- **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.

B. Multi-domain Service Provisioning with a Broker

Fig. 5 shows the procedure of the service provisioning in multi-domain SD-EON with a broker.

- **Step 1**: When a request $LR(s, d, B, \Delta t)$ arrives in *Domain-1*, the OF-AG on s inform *OF-C-1* about it by sending a *Packet_In* message.
- **Step 2**: *OF-C-1* finds out that LR is for multi-domain and encodes a *Broker_Request* message to the broker.
- **Step 3**: The broker requests necessary intra-domain network status in both *Domain-1* and *Domain-2* by sending *Status_Request* messages to *OF-C-1* and *OF-C-2*.
- **Step 4**: OF-Cs abstract the intra-domain path segments from s to the egress nodes in *Domain-1*, and from the ingress nodes in *Domain-2* to d as virtual links. OF-Cs provide intra-domain information (*i.e.*, virtual links and the FS usages on them) to the broker with *Status_Reply* messages. Note that when reporting the intra-domain information, an OF-C can only disclose partial information if the service contract permits.
- **Step 5**: The broker constructs a virtual topology based on the intra-domain information provided by the OF-Cs and performs path computations. It then merges the path segments in the two domains, selects proper FS-blocks, and sends the multi-domain RSA result to the OF-Cs using *Broker_Reply* messages.
- **Step 6**: OF-Cs receive the *Broker_Reply* messages, if LR can be provisioned, they instruct the related OF-AGs to assemble the path segments by distributing cross-connection entries using *Flow_Mod* messages.

IV. Experimental Results

We conduct experiments on multi-domain lightpath provisioning with the aforementioned schemes in the control plane testbed illustrated in Fig. 4. Fig. 6 shows the results from the multi-domain service provisioning without a broker. Figs. 6(a) and 6(b) show the Wireshark captures for the messages on the OF-Cs in USTC and UCD domains. Fig. 7 shows the results from the multi-domain service provisioning with a broker. Fig. 7(a) shows the Wireshark captures for the messages exchanged between the broker and the OF-Cs, while the Wireshark captures for the messages on *OF-C-1* of USTC domain are in Fig. 7(b).

No.	Time	Source	Destination	Protocol	Length	Info
562	12.112979	OVS-6	OF-C-1(USTC)	Extended-OF	196	50201 > 6655 [Type:PacketIn]
567	12.359287	OF-C-1(USTC)	OF-C-2(UCD)	Inter-Domain	169	35518 > 2334 [Type:Request]
585	12.631108	OF-C-2(UCD)	OF-C-1(USTC)	Inter-Domain	83	33797 > 2334 [Type:Reply]
587	12.631835	OF-C-1(USTC)	OVS-7	Extended-OF	162	6655 > 48678 [Type:FlowMod]
589	12.632043	OF-C-1(USTC)	OVS-7	Extended-OF	74	6655 > 48678 [Type:Barrier_Request]
591	12.632180	OF-C-1(USTC)	OVS-6	Extended-OF	178	6655 > 50201 [Type:FlowMod]
593	12.632353	OF-C-1(USTC)	OVS-6	Extended-OF	74	6655 > 50201 [Type:Barrier_Request]
594	12.632409	OVS-7	OF-C-1(USTC)	Extended-OF	74	48678 > 6655 [Type:Barrier_Reply]
597	12.632742	OVS-6	OF-C-1(USTC)	Extended-OF	74	50201 > 6655 [Type:Barrier_Reply]

(a) Wireshark captures of OF-C-1 in USTC domain.

No.	Time	Source	Destination	Protocol	Length	Info
277	4.979523	OF-C-1(USTC)	OF-C-2(UCD)	Inter-Domain	169	35518 > 2334 [Type:Request]
281	4.983435	OF-C-2(UCD)	OVS-9	Extended-OF	162	6655 > 39165 [Type:FlowMod]
282	4.983770	OF-C-2(UCD)	OVS-10	Extended-OF	162	6655 > 33674 [Type:FlowMod]
284	4.983837	OF-C-2(UCD)	OVS-9	Extended-OF	74	6655 > 39165 [Type:Barrier_Request]
288	4.984082	OF-C-2(UCD)	OVS-10	Extended-OF	74	6655 > 33674 [Type:Barrier_Request]
289	4.984093	OVS-9	OF-C-2(UCD)	Extended-OF	74	39165 > 6655 [Type:Barrier_Reply]
291	4.984122	OF-C-2(UCD)	OF-C-1(USTC)	Inter-Domain	83	33797 > 2334 [Type:Reply]
293	4.984294	OVS-10	OF-C-2(UCD)	Extended-OF	74	33674 > 6655 [Type:Barrier_Reply]

(b) Wireshark captures of OF-C-2 in UCD domain.

Fig. 6. Messages captured for multi-domain service provisioning without broker in the control plane testbed across multiple nations.

No.	Time	Source	Destination	Protocol	Length	Info
472	13.700886	OF-C-1(USTC)	Broker	Broker	90	45827 > 2333 [Type:Broker_Request]
474	13.701335	Broker	OF-C-2(UCD)	Broker	121	2333 > 59745 [Type:Status_Request]
475	13.701508	Broker	OF-C-1(USTC)	Broker	109	2333 > 45827 [Type:Status_Request]
478	13.703372	OF-C-1(USTC)	Broker	Broker	220	45827 > 2333 [Type:Status_Reply]
501	13.887531	OF-C-2(UCD)	Broker	Broker	269	59745 > 2333 [Type:Status_Reply]
503	13.929922	Broker	OF-C-2(UCD)	Broker	93	2333 > 59745 [Type:Broker_Reply]
504	13.930044	Broker	OF-C-1(USTC)	Broker	93	2333 > 45827 [Type:Broker_Reply]

(a) Wireshark captures of the broker.

No.	Time	Source	Destination	Protocol	Length	Info
1181	14.226861	OVS-1	OF-C-1(USTC)	Extended-OF	196	41367 > 6633 [Type:PacketIn]
1183	14.320970	OF-C-1(USTC)	Broker	Broker	90	45827 > 2333 [Type:Broker_Request]
1186	14.321745	Broker	OF-C-1(USTC)	Broker	109	2333 > 45827 [Type:Status_Request]
1188	14.323440	OF-C-1(USTC)	Broker	Broker	220	45827 > 2333 [Type:Status_Reply]
1214	14.550545	Broker	OF-C-1(USTC)	Broker	93	2333 > 45827 [Type:Broker_Reply]
1215	14.551068	OF-C-1(USTC)	OVS-6	Extended-OF	162	6633 > 39721 [Type:FlowMod]
1216	14.551393	OF-C-1(USTC)	OVS-1	Extended-OF	178	6633 > 41367 [Type:FlowMod]
1218	14.551457	OF-C-1(USTC)	OVS-6	Extended-OF	74	6633 > 39721 [Type:Barrier_Request]
1222	14.551801	OF-C-1(USTC)	OVS-1	Extended-OF	74	6633 > 41367 [Type:Barrier_Request]
1223	14.551808	OVS-6	OF-C-1(USTC)	Extended-OF	74	39721 > 6633 [Type:Barrier_Reply]
1226	14.551979	OVS-1	OF-C-1(USTC)	Extended-OF	74	41367 > 6633 [Type:Barrier_Reply]

(b) Wireshark captures of OF-C-1 in the USTC domain.

Fig. 7. Messages captured for multi-domain service provisioning with broker in the control plane testbed across multiple nations.

V. Conclusion

This paper investigated the OF-based service provisioning in multi-domain SD-EONs. Our proposals were implemented and experimentally demonstrated in a multi-national SD-EON control plane testbed that consists of two domains located in China and USA, respectively.

Acknowledgments

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