Field Trial of Broker-based Multi-domain Software-Defined Heterogeneous Wireline-Wireless-Optical Networks

Lei Liu[1], Zuqing Zhu[2], Xiong Wang[1, 3], Guanghua Song[1, 4], Cen Chen[2], Xiaoliang Chen[2], Shoujiang Ma[2], Xiaotao Feng[1], Roberto Proietti[1], S. J. B. Yoo[1]

[1]*University of California, Davis (UC Davis), One Shields Ave, Davis CA 95616, USA.*
[2]*University of Science and Technology of China (USTC), Hefei, Anhui 230027, China*
[3]*University of Electronic Science and Technology of China, Chengdu 610054, China*
[4]*Zhejiang University, Hangzhou, Zhejiang 310027, China*
**Author e-mail address: liulei@ieee.org, sbyoo@ucdavis.edu*

Abstract: Driven by a broker-based OpenFlow control plane, we report the first field trial of software-defined heterogeneous wireline-wireless-optical multi-domain networks connecting UC Davis Campus, USTC, California OpenFlow Testbed Network (COTN) and Energy Sciences Network (ESNet).

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1. Introduction

Software-defined Networking (SDN), in particular, the OpenFlow (OF) architecture and its associated protocol has been widely studied in recent years due to its open interface and flexibility for network programming. Most of the works have focused on a single domain scenario, and some recent studies have started to extend SDN/OF to support multi-domain networks [1-4]. However, to the best of our knowledge, there has not been an experimental demonstration for a multi-domain software-defined heterogeneous network where wireline, wireless and optical domains co-exist, especially through a field trial using practical network testbeds including real data plane hardware and in-ground field fibers. In this paper, we report the first field trial of software-defined heterogeneous wireline-wireless-optical (including both fixed-grid and flexi-grid) multi-domain networks, which connect UC Davis Campus Network, USTC, California OpenFlow Testbed Network (COTN) [5] and Energy Sciences Network (ESNet) [6]. A market-driven broker-based [2] OF control plane is deployed to dynamically program and control the multi-domain heterogeneous network for end-to-end resource management and service provisioning.

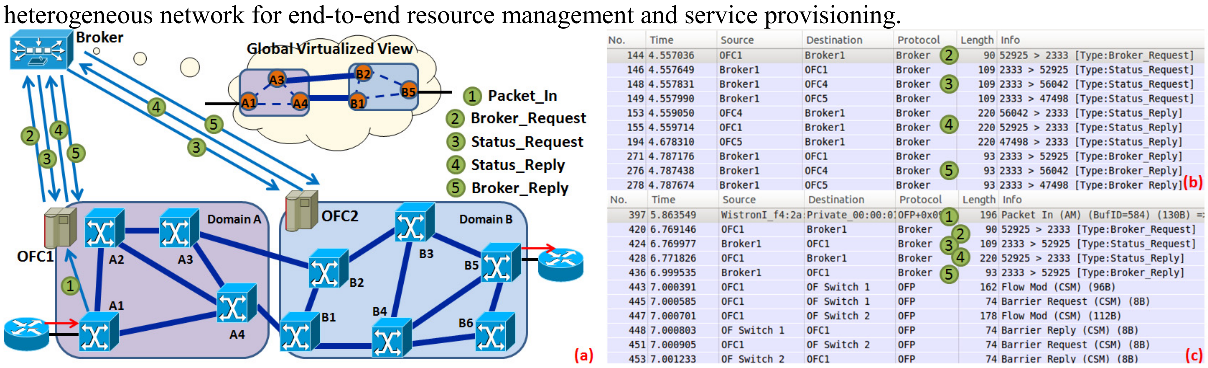

Fig. 1: (a) Broker-based OF control plane for multi-domain networks; (b) Wireshark capture of Broker 1 for dynamic path provisioning from UC Davis to COTN to ESNet; (c) Wireshark capture of OFC1 for dynamic path provisioning from UC Davis to COTN to ESNet.

2. Market-driven broker-based [2] OpenFlow control plane for multi-domain heterogeneous networks

Fig. 1(a) illustrates the concept behind the broker-based OF control plane for multi-domain heterogeneous networking. In each domain, an OF Controller (OFC) is deployed, which manages the entire intra-domain information and can control the wireline, wireless and/or optical switches in its domain through the OF (or extended OF) protocol. Due to the security and confidentiality requirements, each OFC has no visibility of other domains. On top of OFCs, at least one broker agent is deployed which has a virtualized global view of domains, including full information of the inter-domain links and virtualized network status in intra-domains. An inter domain broker protocol is proposed, as the southbound interface, for the broker to communicate with OFCs, as the detailed procedure for end-to-end path provisioning is shown in Fig. 1(a). If a flow arrives at a domain ingress node (A1), and if this flow doesn't match any existing flow entry in A1, A1 forwards the first packet of this flow, as the *Packet_In* message to the controller OFC1 (step 1 in Fig. 1(a)). If the destination of this flow is in another domain, OFC1 sends this request to the broker, by using the *Broker_Request* message (step 2). Then the broker requests the intra-domain network status from OFC1 and OFC2 using the *Status_Request* messages (step 3), and in turn, each OFC provides the virtual intra-domain information to the broker with the *Status_Reply* messages (step 4). Here, OFCs abstract the related intra-domain path segments, including the source node to egress nodes in the source domain, ingress nodes to egress nodes in the intermediate domains, and ingress nodes to the destination node in the destination domain, respectively, as virtual links. The virtual links represent the segments' information, which can include the aggregated information such as resource availability and link distances, or even more, depending on the service agreement between the broker and OFCs. Once the broker receives all the *Status_Reply* messages, a virtual topology with the inter-domain links and virtual intra-domain links can be constructed, as shown in Fig. 1(a), and then the broker can perform path computation and send the results to the corresponding OFCs through the *Broker_Reply* messages (step 5). After that, each OFC parses the *Broker_Reply* message, maps the selected virtual link to the physical path segment in its domain, and then configures the data plane switches accordingly to set up the path by using the *Flow_Mod* messages. Note that the messages in the above steps 2-5 are newly proposed in the inter domain broker protocol, whereas the *Packet_In* and *Flow_Mod* are OF messages, and extensions to them are needed in order to support fixed-grid or flexi-grid optical networks [7, 8].

Macroscopically, from the control plane architecture point of view, the proposed broker-based approach adopts an hierarchical model, which is similar with the Hierarchical Path Computation Element (H-PCE) [9] or SDN orchestration [3, 4]. However, the brokered approach can be naturally applied to the future multi-domain heterogeneous networks, in particular in a multi-carrier scenario, as the relationship between the broker services and domains are through market-driven incentives [2]. Multiple broker agents can be deployed, which compete freely with each other to provide attractive inter-networking services to domains, while the domains choose service plans from one or multiple brokers that are valuable for their inter-networking needs.

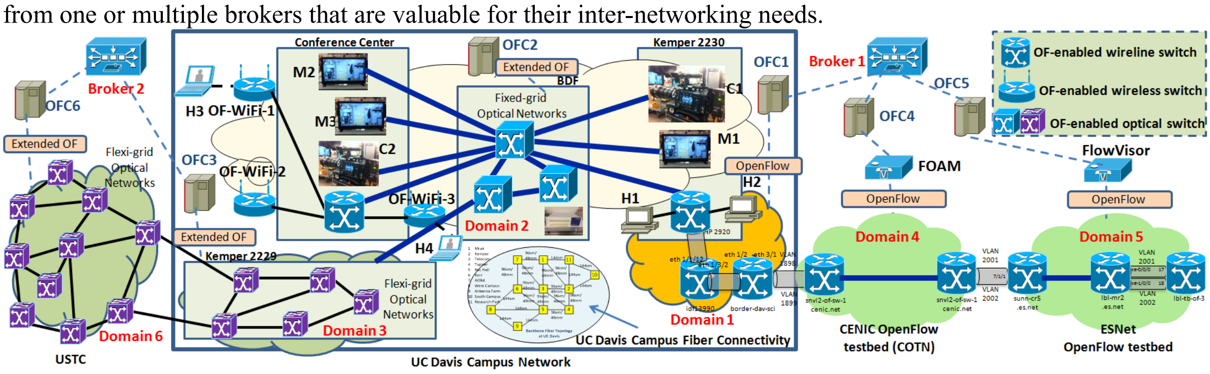

Fig. 2: Field trial setup: a software-defined heterogeneous wireline-wireless-optical multi-domain networks.

3. Field trial setup, results and discussion

As Fig. 2 illustrates, we set up the field trial with 6 domains with optical, wireline, and wireless networking gears. The control plane involves 6 OFCs and 2 brokers, which are connected through the public Internet. Domains 1-3 are deployed based on UC Davis campus networks, which exploit the infrastructure of 144 strands of fibers and 11 major nodes interconnecting nearly 200 buildings on campus. As Fig. 2 shows, domain 1 is a wireline domain which comprises 3 OF switches from 3 different vendors and deployed in 3 different buildings in campus. Domain 2 includes OF-enabled wireline, wireless and fixed-grid optical networks, spanned across three buildings in campus. Two 4k cameras and three 4k monitors are placed in different buildings, which represent a high bandwidth, real-time, interactive multi-media conference system for latency-sensitive applications since no video compression and decompression are involved. The bandwidth of the 4k signals from the cameras used in the field trial is 12 Gb/s, which are dynamically switched to different monitors by controlling the fixed-grid optical switches via extended OF for cross-connection. In addition, three wireless WiFi routers are deployed around the conference center of UC Davis, and are connected to a wireline OF switch. We upgrade the WiFi routers' firmware to OpenWRT, and modify some modules and services of OpenWRT to support the OF protocol. Two hosts (H3 and H4) connect to WiFi for communication with each other, and we demonstrate that, with the movement of H3 around the conference center, the service between H3 and H4 is not interrupted by dynamically switching the WiFi access points. This dynamic, seamless handover is coordinated by an OF controller using the similar method presented in [10]. Domain 1 is connected to COTN (domain 4) and ESNet (domain 5) through 100GE, which are controlled by OFC1, OFC4 and OFC5 respectively. Specifically, OFC4 is connected to COTN via FOAM [11], which is an OpenFlow aggregate manager to allocate OpenFlow resources. For the ESNet domain, a FlowVisor is deployed for the OFC5 to use the flow space. The Broker 1 is deployed to achieve coordinated resource management and end-to-end service provisioning across domains 1, 4, and 5. In this experiment, a bi-directional path is dynamically provisioned from domain 1 to domain 4 to domain 5 to accommodate the flow traffic between hosts H1 and H2. Fig. 1(b) and (c) show the Wireshark capture of the Broker 1 and OFC1 during this end-to-end path provisioning procedure. Note that in addition to the OF switches depicted in Fig. 2, there are also several non-OF switches along the path from domain

1 to domain 4 to domain 5. To facilitate the end-to-end service delivery, a VLAN stitching technique is adopted. When inserting flow entries in the OF switches, in addition to the input and output ports, we also identify the input VLAN ID in the MATCH field and set the output VLAN ID in the ACTION field, as the Wireshark capture shown in Fig. 3(a). By using this approach, a VLAN tag is added to the flows, so that the non-OF switches can route the flow to the correct destination according the VLAN tag. Fig. 3(d) shows the data plane round trip time (RTT) for the traffic during the path provisioning. Due to the configuration delay and packet inspection at some border devices along the path, the RTT at the beginning is very long (around ~3200ms). Once the created path is stable, the RTT is sharply reduced to ~11.5ms and is kept at this value during the flow transmission. Domains 3 and 6 are emulated flexi-grid optical networks with control planes only, which are deployed in UC Davis and USTC respectively. The Broker 2, OFC3 and OFC6, with the capability to support routing and spectrum assignment and related protocol extensions, are deployed to control domains 3 and 6. Fig. 3(b) shows the Wireshark capture of a *Broker_Reply* message for path provisioning from domain 6 to domain 3. This message includes selected virtual link, frequency slots and modulation formats calculated by Broker 2, and is sent to OFC3 to control the flexi-grid optical domain. Fig. 3(c) summarizes the control plane processing latencies for different scenarios reported in this field trial.

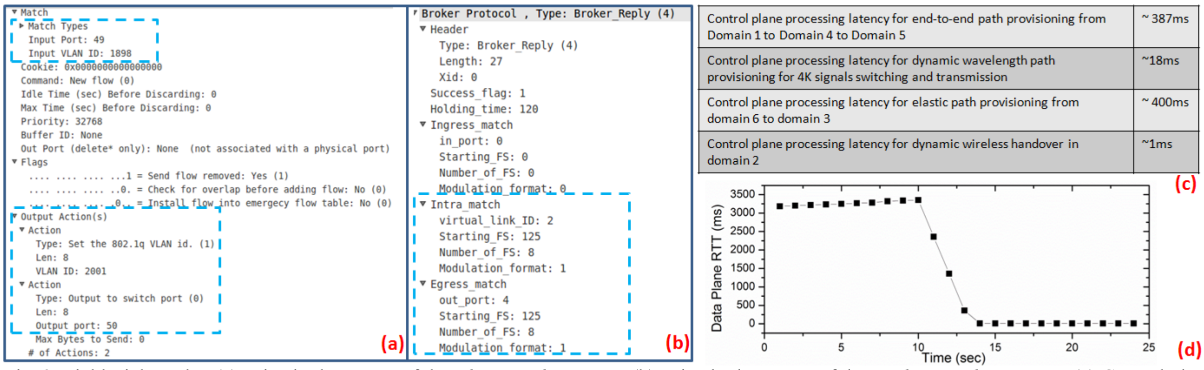

Fig. 3: Field trial results: (a) Wireshark capture of the *Flow_Mod* message; (b) Wireshark capture of the *Broker_Reply* message; (c) Control plane processing latencies for different scenarios; (d) Data plane RTT during the path provisioning from UC Davis to COTN to ESNet.

4. Conclusions

In this paper, we report the first field trial of software-defined heterogeneous wireline-wireless-optical (including both fixed-grid and flexi-grid) multi-domain networks, which connect the UC Davis campus network, USTC, COTN and ESNet. By using the proposed market-driven brokers with OF protocol extensions, we successfully demonstrate various services such as end-to-end dynamic path provisioning across multiple domains, high-bandwidth and low latency 4K signal switching and seamless wireless handover, validating the overall feasibility and efficiency of the proposed solutions for future multi-domain, multi-carrier, multi-vendor heterogeneous networks.

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