Transport Network Orchestration for End-to-End Multi-layer Provisioning Across Heterogeneous SDN/OpenFlow and GMPLS/PCE Control Domains

Raul Muñoz, *Senior Member, IEEE,* Ricard Vilalta, *Member, IEEE,* Ramon Casellas, *Senior Member, IEEE,* Ricardo Martínez, *Member, IEEE,* Frederic Francois, Mayur Channegowda, Ali Hammad, Shuping Peng, Reza Nejabati, *Member, IEEE,* Dimitra Simeonidou, *Member, IEEE,* Noboru Yoshikane, Takehiro Tsuritani, *Member, IEEE,* Victor López, *Member, IEEE,* and Achim Autenrieth

(Invited Paper)

***Abstract*— A multi-domain optical transport network composed of heterogeneous optical transport technologies (e.g., flexi/fixed-grid Optical Circuit Switching and Optical Packet Switching) and control plane technologies (e.g. centralized OpenFlow or distributed GMPLS) does not naturally interoperate, and a network orchestration mechanism is required. A network orchestrator allows the composition of end-to-end network service provisioning across multi-domain optical networks comprising different transport and control plane technologies. Software Defined Networking (SDN) is a key technology to address this requirement, since the separation of control and data planes makes the SDN a suitable candidate for end-to-end provisioning service orchestration across multiple domains with heterogeneous control and transport technologies. This paper presents two different network orchestration's architectures based on the Application-Based Network Operations (ABNO) which is being defined by IETF based on standard building blocks. Then, we experimentally assesses in the international testbed of the STRAUSS project an ABNO-based network orchestrator for end-to-end multi-layer (OPS and Flexi-grid OCS) and multi-domain provisioning across heterogeneous control domains (SDN/OpenFlow and GMPLS/Stateful PCE) employing dynamic domain abstraction based on virtual node aggregation.**

***Index Terms*— Path Computation Element (PCE), control plane, Generalized Multiprotocol Label Switching (GMPLS), Software Defined Network (SDN), stateful PCE, stateless PCE, OpenFlow, Flexi-grid optical networks.**

I. Introduction

The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7/2007-2013 under grant agreement n^{o} 608528 and by the Japanese Ministry of Internal Affairs and Communications (MIC) and National Institute of Information and Communications Technology (NICT) through the EU-Japan coordinated project STRAUSS, and the Spanish Ministry of Economy and Competitiveness (MINECO) through the project FARO (TEC2012-38119).

R. Muñoz, R. Vilalta, R. Casellas, and R. Martínez are with Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Av. Carl Friedrich Gauss 7, 08860 Castelldefels (Barcelona), Spain, e-mail: {raul.munoz, ramon.casellas, ricard.vilalta, ricardo.martinez}@cttc.es.

F. Francois, M. Channegowda, A. Hammad, S. Peng, R. Nejabati and D. Simeonidou are with the High-Performance Networks Group, University of Bristol, United Kingdom, e-mail: {f.francois, mayur.channegowda, shuping.peng, reza.nejabati, dimitra.simeonidou}@bristol.ac.uk

N. Yoshikane, T. Tsuritani are with KDDI R&D Laboratories, 2-1-15 Ohara, Fujimino, Saitama, 356-8502 Japan, e-mail:{yoshikane, tsuri}@kddilabs.jp

V. López is with Telefónica I+D, Don Ramon de la Cruz 84, Madrid, Spain, e-mail: {victor.lopezalvarez}@telefonica.com

A. Autenrieth is with ADVA Optical Networking, Martinsried (Munich), Germany, e-mail: {AAutenrieth}@advaoptical.com

In recent years, new high-performance Internet applications such as Cloud Computing and high-definition video streaming are emerging. These applications have a common requirement for a high capacity network infrastructure, which can only be provided efficiently by optical transport networks. Networks based on Dense Wavelength Division Multiplexing (DWDM) supporting Optical Circuit Switching (OCS) do offer a mature and robust high-bandwidth infrastructure. In order to support flexible and efficient transmission technologies and enable advanced functionalities in the core network, optical networks are evolving towards a flexible DWDM grid [1], in which the optical spectrum is dynamically and adaptively allocated by assigning the necessary number of fixed sized slices of spectrum. On the other hand, new switching and aggregation technologies at sub-wavelength granularity are required to reduce the cost and energy per bit, to increase scalability and maintain a high throughput in terms of packets per second. These stringent requirements can only be met by adopting optical aggregation and switching technology based on Optical Packet Switching (OPS) [2].

Moreover, it is common practice for network operators to fragment their optical transport networks into multiple domains to cope with administrative and regional organizations. The fragmentation of a network into several domains can result in each domain being provided by a different vendor with a different control plane for the provisioning of dynamic, adaptive and fault-tolerant connectivity services. Two control plane architectures are active subjects of research, namely Generalized Multi Protocol Label Switching (GMPLS) and OpenFlow. The GMPLS architecture is based on a distributed control plane (signaling, routing and link management), and has been extended to support delegating the path computation function to a Path Computation Element (PCE) [3]. More recently, an active stateful PCE architecture has been proposed whereby the capability of dynamically setting up and releasing new connections (i.e., Label Switched Paths; LSPs-), is exposed to external applications [4]. By contrast, OpenFlow is an open protocol which allows the configuration of several network devices remotely through the use of applications running on a logically centralized controller [5].

When a physical infrastructure comprises heterogeneous optical transport (e.g., flexi/fixed-grid OCS and OPS) and control plane technologies (e.g. centralized OpenFlow and distributed GMPLS), which are not interoperable, an orchestration mechanism is required. Thereby, the orchestration mechanism allows the composition of end-to-end service provisioning and recovery across multiple optical networks comprising different transport and control plane technologies. Software Defined Networking (SDN) is a key technology to address this requirement since it advocates the separation of control and data planes, which eases the end-to-end provisioning and recovery service orchestration across multiple domains with heterogeneous control and transport technologies. The ICT STRAUSS project [6] is developing a network orchestration layer by using a SDN orchestrator based on the Application-Based Network Operations (ABNO) [7] [8], which is based on standard building blocks that are currently being defined by Internet Engineering Task Force (IETF). The ABNO-based network orchestrator enables the seamless interworking between GMPLS/PCE and SDN/OpenFlow control plane entities for end-to-end provisioning and recovery of dynamic connectivity services across the targeted multi-layer (OPS and Flexi-grid OCS) and multi-domain network.

The first proof-of-concept prototype of an ABNO-based orchestration for multiple SDN/OpenFlow controllers was presented in [9] and [10]. In that work, the ABNO-based orchestrator had a full view of the physical topology (i.e., node and links) of each domain. Since this approach lacks of scalability (for a very large number of nodes) and confidentiality (SDN/OpenFlow controllers may not disclose internal topology within a domain), in this paper we extend the ABNO-based orchestrator to deal with abstracted views of the topology of each domain. In addition, we also consider, for the first time, the orchestration of end-to-end connectivity provisioning services across not only multiple SDN/OpenFlow controllers but also with GMPLS-controlled domains with active stateful PCE. Failure recovery is out of the scope of this work and we leave this as future work. This paper is organized as follows. In Section II, we present the considered ABNO architecture for the network orchestrator. Section III presents the proposed network orchestration's architectures, analyzing the benefits and drawbacks of each of them. Finally, in section IV, we present the developed proof-of-concept prototype and section V concludes the paper.

II. ABNO Architecture

This section presents the selected ABNO architecture for the orchestration of multi-technology optical transport networks (e.g., flexi/fixed-grid OCS and OPS) with heterogeneous control plane paradigms (e.g., GMPLS/PCE and OpenFlow). The orchestrator is a parent controller which handles the automation of the end-to-end connectivity provisioning by controlling the controller of each domain under its control. The orchestrator works at a higher (and abstracted) level and covers only the inter-domain aspects of the connectivity provisioning across different domains.

Fig.1 presents the six building blocks of the ABNO architecture that are required to support the multi-domain and multi-layer network orchestration considered in this paper. The

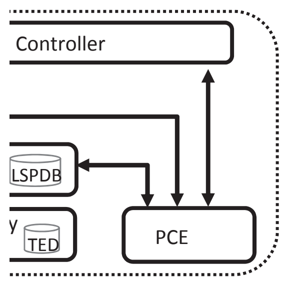


Fig. 1: ABNO-based Orchestrator Architecture.

Orchestration Controller runs the different workflows and can interwork with the different blocks. The Topology Server (TS) gathers the domain topology of each SDN/OpenFlow domain controller exposed by the North-Bound Interface (NBI) and/or the GMPLS/PCE domain through new protocols such as BGP-LS [11] to obtain the Traffic Engineering Database (TED) by BGP peering. The TED stores the global network topology, which is composed of the intra-domain topologies with the inter-domain links connecting them. The PCE handles the path computation across the network graph provided by the Topology Server and it has been extended to deal with OpenFlow datapath identifiers [12]. The Provisioning Manager (PM) is responsible for the actual flow establishment request to the OpenFlow domain controllers through each specific controller's NBI, and to the active stateful PCE of the GMPLS domains. The Flow Server is responsible for storing the state of the provisioned flows in the Label Switch Path Database (LSPDB). Finally, the Virtual Network Topology Manager (VNTM) is responsible to coordinate the path provisioning in multi-layer networks by performing the layered establishment of connections in the server layer (e.g., OCS connections) and its promotion as logical link in the client layer (i.e., OPS). It is worth mentioning that the NBI of the SDN/OpenFlow or GMPLS/PCE Controllers are typically technology and vendor dependent. Thus, the Network Orchestrator shall implement different plugins for each of the controller's NBI.

III. ABNO-based Network Orchestration Architectures

In the next subsections, two different architectures of the ABNO-based orchestrator are presented along with the analysis of the benefits and drawbacks of each of them. The two different architectures differ by the level of network topology abstraction and the hierarchy of the path computation responsibilities performed.

A. Physical network topology orchestration and centralized Path Computation

Fig.2 shows the first proposed network orchestration architecture, which centralizes the management of the complete multi-layer physical network topology and the full end-to-end path computation in the ABNO-based orchestrator. It differs from our previous work in [9], [10] because it considers both OpenFlow and GMPLS domains at the same time. The topology server receives the complete physical network

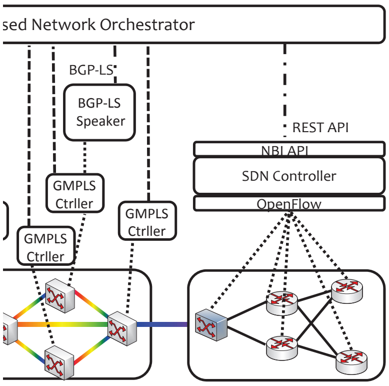


Fig. 2: ABNO-based network orchestrator with physical network topology and centralized path computation

topology information from each domain through the specific NBIs exposed by each control plane for all involved switching layers. Thus, the PCE can perform complete end-to-end path computations (i.e., specifying a complete and explicit strict hop list within each domain involving all switching layers) across the whole multi-domain network topology. Once the end-to-end path is calculated, the PCE sends it to the Orchestration controller which in turn sends it to the PM that is responsible for identifying the involved domains and sending customized/specific flow provisioning request messages for each one of the involved domain network controllers through their specific NBIs. These flow provisioning requests must specify the complete and strict hop list computed by the PCE for each domain. Thus, it can be considered that the OpenFlow and/or GMPLS domains have no path-computation capabilities. In order to identify the corresponding domain controller to forward the flow provisioning requests, the PM needs to ask the TS for the association between network node and network domain.

In terms of scalability (i.e., large number of network controllers, large number of physical nodes), this architecture has serious disadvantages because performing path computations in large networks by a single centralized entity will become a computationally intensive and complex operation. The large computational times may result in a higher blocking probability of the multiple concurrent requests made to the path computation' service. Moreover, it is highly probable that the Orchestrator's TED information will not be synchronized with the actual network state under dynamic network scenarios since the TS must process large volumes of network state changes generated by each domain. It is worth noting that this information can be generated both asynchronously from the domain controller to the TS (e.g., using BGP-LS) and through synchronous polling from the TS to the domain controller (e.g., using a REST API). In addition, individual domain controllers may not want to disclose their internal topology information outside its network domain due to confidentiality policies and commercial competitiveness. From this analysis of the drawbacks of the first architecture of the ABNO-based orchestrator, we defined a second architecture of the orchestrator which can delegate part of the orchestration functionalities to the distributed domain network controllers and thereby alleviate the problems linked with having an orchestrator working on the complete view of the multiple domains.

B. Abstracted network topology and Distributed Path Computation

Fig.3 shows the second proposed architecture of the network orchestrator. The main architectural change introduced in this approach is the delegation of some of the topology management and path computation tasks to the individual domain controllers. In order to achieve this delegation, the second architecture includes three new modules inside each SDN/OpenFlow controller, namely: Flow Provisioning Manager (FPM), Abstract Topology Manager (ATM), and Path Segment Expansion (PSE) and an Active Stateful PCE (AS-PCE) in the GMPLS domain. The TS builds an abstracted multi-domain and multi-layer topology based either on the virtual node or abstract link aggregation mechanisms. The virtual node aggregation mechanism abstracts internal connectivity by representing each domain as a virtual node. This abstraction results in the border nodes of each domain being seen as ports of the virtual nodes, which are connected with other virtual nodes through inter-domain links. For the abstract link aggregation mechanism, the network domain's internal connectivity can be dynamically mapped to a mesh of virtual links. Each domain controller computes a path between the border nodes of the domain and exposes these virtual links, together with the border nodes, to the TS. Each SDN/OpenFlow controller's ATM module or the BGP-LS speaker in the GMPLS domain is responsible for computing the abstract network topology and performing the actual mapping of the virtual nodes/ports with the real nodes/ports. They are responsible for the exposure of the domain abstract topology (either based on virtual node or abstract link aggregation mechanisms) to the orchestrator's TS.

As for the path computation, it is performed in two stages.In the first stage, the PCE of the ABNO-based orchestrator calculates a path through the abstracted multi-layer and multi-domain topology. The PCE then performs the domain sequence selection by identifying the domains and border nodes involved in the calculated path. The actual computation of the strict paths within each domain between two border nodes (known as path segment expansion) is performed in parallel by either each SDN/OpenFlow controller through the PSE module or the AS-PCE in the GMPLS domain through the use of the complete intra-domain TED and regular algorithms available within each domain. Specifically, the PM requests the expansion of the path segment and the provisioning of the flow to either the FPM module in the SDN/OpenFlow domain or the AS-PCE in the GMPLS domain once the PCE of the orchestrator performs the domain sequence selection. In the case of the AS-PCE, it can perform both the expansion of the path segment and the provisioning of the flow while for the FPM module in the SDN/OpenFlow domain, it must send a path computation request to the PSE to expand the path segment and, once computed, the FPM requests to the

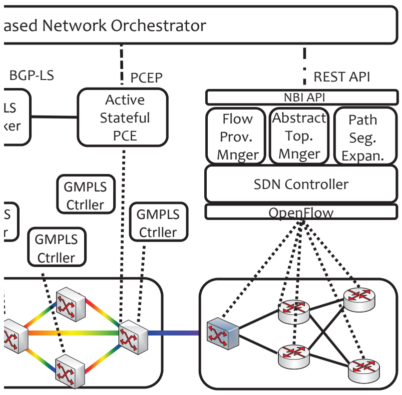
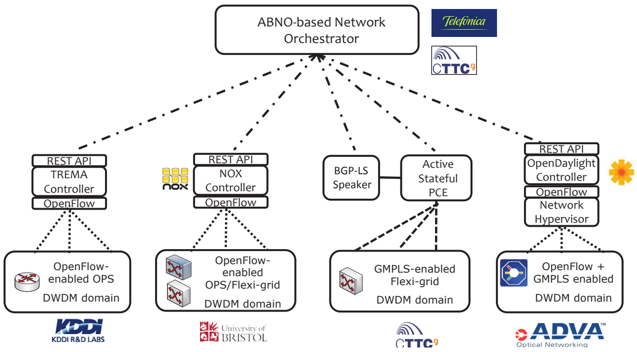
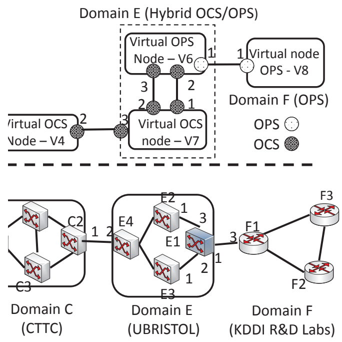


Fig. 3: ABNO-based network orchestrator with abstracted network topology and distributed path computation



(a) International Testbed of the STRAUSS project



(b) Abstract and physical network view

Fig. 4: Experimental network scenario

SDN/OpenFlow controller the provisioning of the computed complete intra-domain path. In this approach, the scalability and confidentiality problems are solved but new considerations must be taken into account such as insufficient knowledge of the intra-domain resources availability by the orchestration layer. This may lead to a suboptimal domain sequence selection.

IV. Experimental Assessment of the ABNO-based Network Orchestration

A. Experimental scenario

Fig.4.a shows the available transport and control plane technologies of each partner's network domain involved in the international testbed of the ICT STRAUSS project. Fig.4.b depicts the network scenario deployed in order to experimentally assess the end-to-end multi- layer and multi-domain provisioning across heterogeneous SDN/OpenFlow and GMPLS/PCE controlled domains at the control plane level (i.e., no hardware configuration is performed at the domains). The physical network scenario consists of two SDN/OpenFlow-controlled OPS domains (A and F) at KDDI R&D Labs in Japan, two SDN/OpenFlow-controlled hybrid OPS/OCS domains (B and E) at University of Bristol in UK, one GMPLS/PCE-controlled OCS domain (C) at CTTC in Spain, and the ABNO-based orchestrator located also at CTTC premises. The OpenFlow controllers of the KDDI R&D Labs and University of Bristol domains are connected to the controller of the CTTC domain using OpenVPN tunnels for the exchange of control messages. Each domain is seen as a virtual node by the ABNO-based Orchestrator with the exception of the two hybrid OPS/OCS domains (Domain B and E) where each domain is represented with two virtual nodes, one for each switching technology. Hence, the border nodes of each domain are seen as ports of the virtual nodes which are inter-connected through inter-domain links. Each SDN/OpenFlow controller or BGP-LS speaker (in the case of the GMPLS domain) is responsible for performing the actual mapping of the virtual node/ports with the real nodes/ports and to expose the virtual topology information such as node_id, port_id, port_type, supported range of OPS Labels or flexi-grid nominal central frequencies to the Network Orchestrator.

Architecture and implementation details of the GMPLS control plane and Active Stateful PCE are reported in [13] and [14].The OPS controller has been implemented in TREMA and it has been reported in [15]. As for the hybrid OPS/OCS SDN controller, it is based on NOX. Fig.5 shows the implemented architecture. The description of each functional component of the controller is given below:

- Northbound RESTful API: this component provides the RESTful API through which the ABNO orchestrator can interact with the OpenFlow controller.
- OpenFlow Drivers: the OpenFlow Drivers can populate the "Physical Switches + Peering Links" database whenever new switches connect to the OpenFlow controller and send OpenFlow Features Reply messages. In addition, the OpenFlow Drivers have the ability to interpret the abstract switch configuration messages from the Switch Configurator to the suitable OpenFlow messages for the switches.
- Physical Switches + Peering Links Database: the "Physical Switches + Peering Links" database keeps a record of all the switches currently connected to the OpenFlow controller. The database has also information about the ports of each physical switch in it. For example, it can have details on which port of a given switch is connected to which other peer port of another switch. Moreover, the database can have information about the port type such as packet, OCS and OPS.
- Physical to Virtual Entity Mapper: the Physical to Virtual Entity Mapper is a component which can create virtual

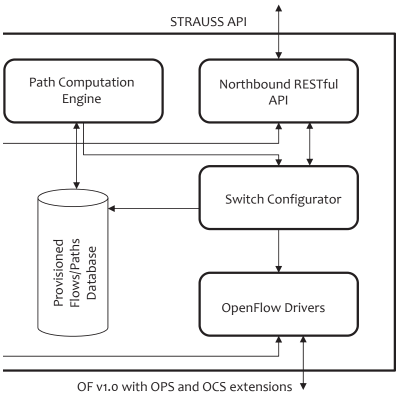


Fig. 5: OpenFlow Controller for hybrid OPS-OCS domains

representations of one or more physical switches. In the context of this work, it was configured so that all switches of a particular technology in a domain are represented by one single virtual switch.

- Virtual Switches + Peering Links Database: the "Virtual Switches + Peering Links" database stores the different virtual switches which were created by the Physical to Virtual Entity Mapper. In the context of this work, the peering links (the cross-technology and inter-domain links) are also stored in this database together with the logical ports that are created to connect to new flows being created.
- Path Computation Engine: the Path Computation Engine is a component that can take requests to set up flows between two virtual ports in the domain from the Northbound RESTful API and calculate the appropriate path that needs to be installed in the physical topology of the hybrid domain. When the Path Computation Engine has calculated successfully a path, instructions are sent to the Switch Configurator for the configuration of the physical switches.
- Switch Configurator: the Path Computation Engine is a component that can take requests to set up flows between two virtual ports in the domain from the Northbound RESTful API and calculate the appropriate path that needs to be installed in the physical topology of the hybrid domain. When the Path Computation Engine has calculated successfully a path, instructions are sent to the Switch Configurator for the configuration of the physical switches.
- Provisioned Flows/Paths Database: the "Provisioned Flows/Paths" database stores all the successful computed flows/paths that have been successfully configured into the switches. Each flow has an identifier which links the flow in the database with the logical ports that can be created through the Northbound RESTful APIs.

B. OpenFlow-controlled OPS node architecture

In the ideal case, the OPS nodes are able to support the OpenFlow protocol and communicate with OpenFlow controllers directly, so that each OPS node can send packet-in message to the controller and the controller can modify the Flowtable in the OPS node in turn. Unfortunately, such an OpenFlow-supportive OPS node is still not available at this moment. However, with the introduction of an additional OpenFlow Agent (OFA) between the OpenFlow controller and the regular OPS node, an OPS network can still be controlled via OpenFlow. The OFA is an extended OpenFlow switch that acts as a proxy for the southbound OPS node. The OFA virtualizes the resources of the OPS node (ports, available wavelengths and links, etc.) for the Controller, and translates the OpenFlow protocol messages into commands that can be understood by the OPS node, thus enabling the communication between the Controller and the OPS node through message exchange and protocol translation in the OFA. The OPS node switches packets according to a unique label called OP-ID pre-assigned at the edge node. The optical packet transponder (OP-TP) has a label mapping table that maps the destination IP address of incoming packet to a designated OP-ID, according to which the node attaches this OP-ID to each packet for later switching. Each OPS node holds another Forwarding table, according to which the switch is configured to forward the packet with a certain OP-ID from an input port to the appropriate output port.

C. Active Stateful PCE architecture

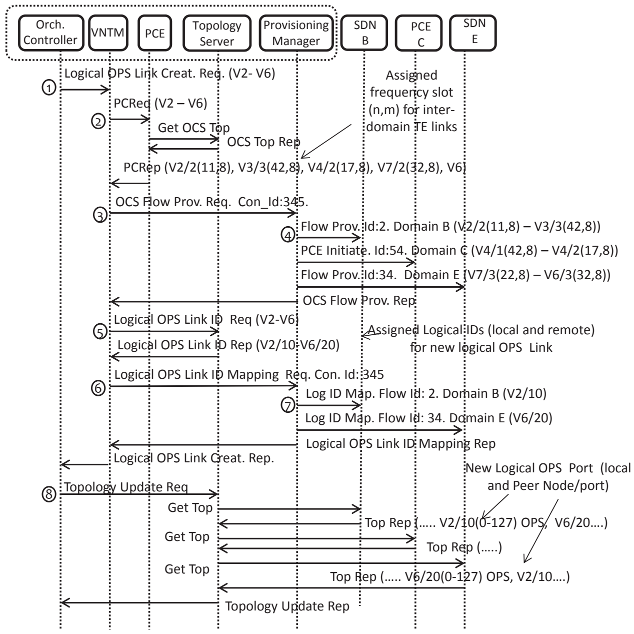
A Stateful Path Computation Element (PCE) is a key element for the introduction of dynamics and adaptation in a GMPLS-based distributed control plane for flexi-grid DWDM networks, as well as for enabling the standardized deployment of the GMPLS control plane in the Software Defined Networking (SDN) control architecture

D. Logical OPS link creation

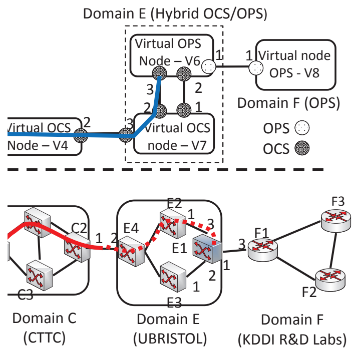
Let us consider the scenario where we need to provision an OPS connection between a pair of OPS nodes from Domain A and F. Since there is no OPS connectivity between Domain B (V2) and Domain E (V6), the orchestration controller requests to the VNTM the creation of a new logical OPS link between virtual nodes V2 and V6 (step 1 in Fig.6.a). In the step 1, the VNTM requests to the PCE of the orchestrator a Flexi-grid OCS path from V2 to V6 for a defined bandwidth based on the ABNO's policy (step 2). If the PCE can find a path solution across Domains B, C and E (Fig.6.b), it replies with the spatial path (i.e., virtual nodes and links). In addition, the PCE assigns a frequency slot to each virtual link corresponding to inter-domain links.

In this experiment, we have made the assumption that each domain border node is equipped with full 3R regeneration and therefore, no spectrum continuity constraint must be satisfied from end-to-end. In the following step 3, the orchestration controller requests to the Provisioning Manager the setup of the end-to-end OCS flow for the computed path. The first action performed by the Provisioning Manager is to identify the domains that will be involved in the actual provisioning of the end-to-end OCS flow. Subsequently, the second action is to segment the received path into the corresponding domains. For each domain segment, the Provisioning Manager must also identify the input virtual node/port and the output virtual node/port as illustrated in Fig.6.b. Finally, the Provisioning Manager requests the actual provisioning of the domain segments using either each specific SDN controller's Restful API NBI or the PCEP interface for the instantiation of LSPs through an active stateful PCE in the GMPLS domain (step 4). Each domain must then map the received virtual nodes/ports into real nodes/ports (e.g., V2/2 - V3/3 in Domain B to B1/3 - B4/2) and expand the received segment by computing an explicit path based on the physical topology information of the domain. In addition, each domain must assign the required frequency slot(s) to satisfy the bandwidth requirements.

Once all domain segments have been successfully provisioned, the established OCS flow can then be used as a data link for the OPS layer. To create a logical OPS link associated to the OCS flow that can be used by the PCE when computing paths and performing traffic grooming (i.e., multiple OPS flows may be grouped over a single OCS flow), the VNTM requests to the Topology Server (TS) an available port identifier for node V2 and V6 (step 5). These logical identifiers will be used to unambiguously identify the created logical OPS link. In step 6, the VNTM requests to the Provisioning Manager the mapping of the provisioned Flexi-grid OCS flow and the logical OPS link by specifying the assigned port identifiers (i.e, V2/10 and V6/20). In step 7, the Provisioning Manager identifies the domains associated to each virtual node and sends a request to map the assigned logical port to the established OCS flow at the specified node. In order to achieve this, it was required to extend the RestFul API of the SDN controller located in Domains B and E with a new command: add_port(dpath, port, flow_id, type, peer_dpath, peer_port). Once the mapping has been performed successfully, the VNTM notifies the orchestration controller so that it requests the Topology Server to update its topology databases (step 8) to learn about the new logical OPS link. This trigger is required because the current RestFul API interface of the SDN controller do not support asynchronous notification of changes in the network topology, unlike BGP-LS or OSPF-TE routing protocols



(a) Workflow for a Logical OPS Link creation (V2 and V6)



(b) Abstract and physical network view

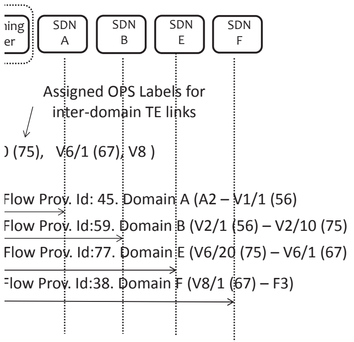
Fig. 6: Logical OPS link creation

E. OPS flow provisioning

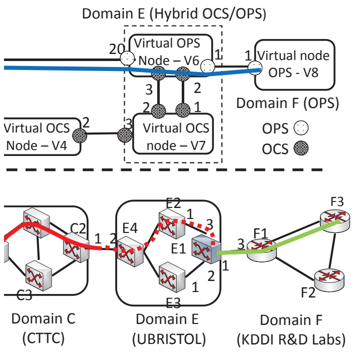
The orchestration controller requests to the PCE the computation of a path between the OPS nodes A2 and F3 (Fig.7.a). Now, the PCE can compute a path through virtual nodes V1, V2, V6 and V8 using the new logical OPS link (V2/10-V6/20), as observed in Fig.7.b (blue line). After the PCE successfully finishes the path computation, it replies with the spatial and the assigned OPS labels to each inter-domain link. As mentioned before, the assignment of either the frequency slot or the OPS labels for the virtual links corresponding to inter-domain links is responsibility of the ABNO-based orchestrator. Afterward, the orchestration controller requests the provisioning of the computed OPS path to the Provisioning Manager as in step 3 described previously.

F. Experimental assessment

In this experimentation, all the modules of the ABNO-based orchestrator, with the exception of the PCE (IP:10.0.34.34), have been implemented in a single server (IP:10.0.34.30). The five control domains involved in the experimentation are the following: two OpenFlow-controlled OPS domains from KDDI R&D Labs (IP: 10.0.34.10 and 10.0.34.26), two OpenFlow-controlled OPS/OCS domains from BRISTOL (IP: 10.0.34.6 with port 8080 and 8081) and a GMPLS-controlled OCS domain with active stateful PCE from CTTC (10.0.34.14). First, we request to provision an OPS flow from Domain A to Domain F. Since there is no OPS connectivity between V2 and V6, it requires the creation of a logical OPS link between these pair of virtual nodes following the steps described in the previous example. Fig.8 shows the abstract network topology seen by the ABNO-based orchestrator's PCE before and after establishing the OPS link between V2 and V6. Fig.9 shows a Wireshark capture at the orchestration controller with the involved workflow: OCS path computation to the PCE (step 2 in Fig.6.a), OCS flow provisioning for each domain (step 4), Logical OPS link ID mapping (step 7), OPS path computation to PCE (step 9 in Fig.7.a), and



(a) Workflow for an OPS flow provisioning (A2-F3)



(b) Abstract and physical network view

Fig. 7: OPS flow provisioning

OPS flow provisioning per domain (step 10). The provisioning time is above 7 seconds in average. We have also test the provisioning of multi-layer and multi-domain connections that reuse the provisioned OCS flow (i.e., traffic grooming), and the provisioning time is reduced to 3 seconds in average.

V. Conclusions

This paper has presented two SDN-based ABNO architectures to perform the orchestration of end-to-end multi-layer provisioning services in a multi-vendor environment, where each domain may have different optical transport technologies with its own control plane technology. In the first architecture, the ABNO-based orchestrator had a full view of the physical topology (i.e., node and links) of each domain. Since this approach lacks scalability (for a very large number of nodes) and confidentiality (SDN/OpenFlow and GMPLS/PCE controllers may not disclose internal topology within a domain), in the second proposed architecture, we have extended the ABNO-based orchestrator to deal with abstracted views of the topology of each domain in the second proposed architecture. In addition, we have also experimentally assessed in an international testbed composed of CTTC, University of Bristol, and KDDI R&d Labs, an ABNO-based network orchestrator for end-to-end multi-layer (OPS and Flexi-grid OCS) and multi-domain provisioning across heterogeneous control domains (SDN/OpenFlow and GMPLS/Stateful PCE) employing dynamic domain abstraction based on virtual node aggregation.

References

[1] "Itu-t recommendation g.694.1: Spectral grids for wdm applications: Dwdm frequency grid," 2012.

[2] S. Yoo, "Energy efficiency in the future internet: the role of optical packet switching and optical-label switching," *Selected Topics in Quantum Electronics, IEEE Journal of*, vol. 17, no. 2, pp. 406–418, 2011.

[3] R. Muñoz, R. Casellas, R. Martínez, and R. Vilalta, "Pce: What is it, how does it work and what are its limitations?" *Journal of Lightwave Technology*, vol. 32, no. 4, pp. 528–543, 2014.

[4] E. Crabbe, I. Minei, S. Sivabalan, and R. Varga, "Pcep extensions for pce-initiated lsp setup in a stateful pce model," IETF draft-ietf-pce-pce-initiated-lsp (work in progress), December 2013.

[5] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker, and J. Turner, "Openflow: enabling innovation in campus networks," *ACM SIGCOMM Computer Communication Review*, vol. 38, no. 2, pp. 69–74, 2008.

[6] R. Munoz, R. Vilalta, R. Casellas, R. Martinez, X. Cao, N. Yoshikane, T. Tsuritani, L. Contreras, V. Lopez, J. Fernandez-Palacios *et al.*, "Network virtualization, control plane and service orchestration of the ict strauss project," in *Networks and Communications (EuCNC), 2014 European Conference on*. IEEE, 2014, pp. 1–5.

[7] D. King and A. Farrel, "A pce-based architecture for application-based network operations," 2015.

[8] A. Aguado, V. Lopez, J. Marhuenda, J.-P. Fernández-Palacios *et al.*, "Abno: a feasible sdn approach for multi-vendor ip and optical networks," in *Optical Fiber Communication Conference*. Optical Society of America, 2014, pp. Th3I–5.

[9] Y. Yoshida, A. Maruta, K.-i. Kitayama, M. Nishihara, T. Tanaka, T. Takahara, J. Rasmussen, N. Yoshikane, T. Tsuritani, I. Morita *et al.*, "First international sdn-based network orchestration of variable-capacity ops over programmable flexi-grid eon," in *Optical Fiber Communication Conference*. Optical Society of America, 2014, pp. Th5A–2.

[10] Y. Yoshida, A. Maruta, K. Kitayama, M. Nishihara, T. Takahara, T. Tanaka, J. Rasmussen, N. Yoshikane, T. Tsuritani, I. Morita *et al.*, "Sdn-based network orchestration of variable-capacity optical packet switching network over programmable flexi-grid elastic optical path network," p. 10.1109/JLT.2014.2351852, 2014.

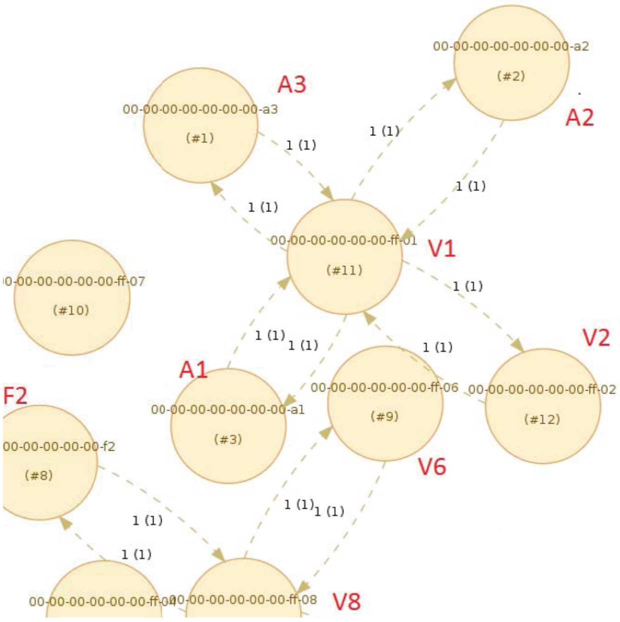
[11] M. Cuaresma, F. M. del Nuevo, S. Martinez, A. Mayoral, O. G. de Dios, V. Lopez, and J. P. Fernandez-Palacios, "Experimental demonstration of h-pce with bpg-ls in elastic optical networks," *ECOC, Sep*, 2013.

[12] R. Casellas, R. Martínez, R. Muñoz, L. Liu, T. Tsuritani, and I. Morita, "An integrated stateful pce/openflow controller for the control and management of flexi-grid optical networks," in *Optical Fiber Communication Conference*. Optical Society of America, 2013.

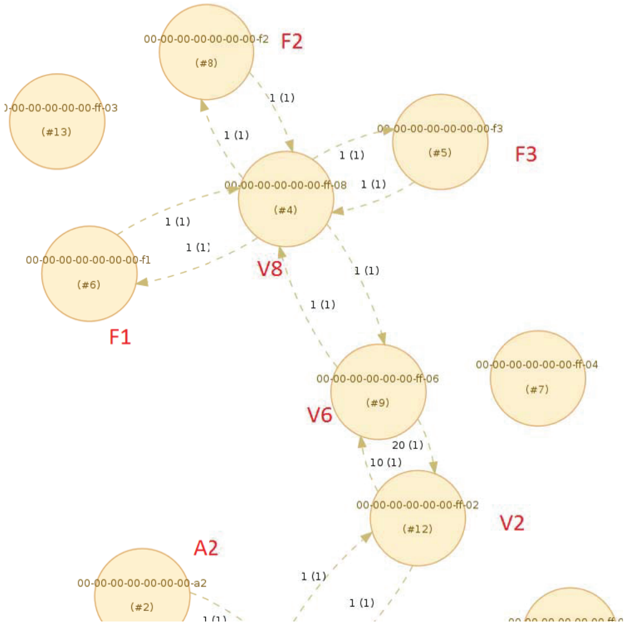
[13] R. Munoz, R. Casellas, R. Vilalta, and R. Martínez, "Dynamic and adaptive control plane solutions for flexi-grid optical networks based on stateful pce," *Journal of Lightwave Technology*, vol. 32, no. 16, pp. 2703–2715, 2014.

[14] A. Mayoral, R. Vilalta, R. Munoz, R. Casellas, and R. Martinez, "Experimental validation of automatic lightpath establishment integrating opendaylight sdn controller and active stateful pce within the adrenaline testbed," in *Transparent Optical Networks (ICTON), 2014 16th International Conference on*. IEEE, 2014, pp. 1–4.

[15] X. Cao, N. Yoshikane, T. Tsuritani, I. Morita, T. Miyazawa, and N. Wada, "Openflow-controlled optical packet switching network with advanced handling of network dynamics," in *Optical Communication (ECOC), 2014 European Conference on*. IEEE, 2014, pp. 1–3.



(a) Before the provisioning of the OPS Link between V2 and V6



(b) After the provisioning of the OPS Link between V2 and V6

Fig. 8: Abstract OPS Network Topology seen by the ABNO-based orchestrator's PCE drawn as a directed graph.

No.	Time	Source	Destination	Protocol	Info
1	0.000000	10.0.34.30	10.0.34.34	PCEP	PATH COMPUTATION REQUEST MESSAGE
2	1.748137	10.0.34.34	10.0.34.30	PCEP	PATH COMPUTATION REPLY MESSAGE
3	1.798084	10.0.34.30	10.0.34.6	HTTP	GET /set_flow/?dpath_src=00-00-00-00-00-00-FF-02&
4	1.864323	10.0.34.30	10.0.34.14	PCEP	PATH COMPUTATION INITIATE MESSAGE
5	3.667313	10.0.34.30	10.0.34.6	HTTP	GET /set_flow/?dpath_src=00-00-00-00-00-00-FF-07&
6	3.760976	10.0.34.30	10.0.34.6	HTTP	GET /add_port/?dpath_src=00-00-00-00-00-00-FF-02&
7	3.854475	10.0.34.30	10.0.34.6	HTTP	GET /add_port/?dpath_src=00-00-00-00-00-00-FF-06&
8	3.917795	10.0.34.30	10.0.34.34	PCEP	PATH COMPUTATION REQUEST MESSAGE
9	5.674728	10.0.34.34	10.0.34.30	PCEP	PATH COMPUTATION REPLY MESSAGE
10	6.032277	10.0.34.30	10.0.34.10	HTTP	GET /set_flow_action/?%7B%22flow_id%22:%221%22,%2
11	6.755098	10.0.34.30	10.0.34.26	HTTP	GET /set_flow_action/?%7B%22flow_id%22:%221%22,%2
12	7.165105	10.0.34.30	10.0.34.6	HTTP	GET /set_flow/?dpath_src=00-00-00-00-00-00-FF-02&
13	7.261782	10.0.34.30	10.0.34.6	HTTP	GET /set_flow/?dpath_src=00-00-00-00-00-00-FF-06&

Fig. 9: Wireshark capture at the orchestration controller

PLACE PHOTO HERE

Raül Munoz (SM'12) graduated in telecommunications engineering in 2001 and received a Ph.D. degree in telecommunications in 2005, both from the Universitat Politècnica de Catalunya (UPC), Spain. After working as undergraduate researcher at Telecom Italia Lab (Turin, Italy) in 2000, and as assistant professor at the UPC in 2001, he joined the Centre Tecnològic de Telecomunicacions de Catalunya (CTTC) in 2002. Currently, he is Senior Researcher at CTTC. Since 2000, he has participated in several R&D projects funded by the European Commission's Framework Programmes (FP7, FP6 and FP5) and the Spanish Ministries, as well as technology transfer projects. He leads the European Consortium of the EU-Japan project STRAUSS, and the Spanish project FARO. His research interests include control and service management architectures, protocols and traffic engineering algorithms for future optical networks.

PLACE PHOTO HERE

Ricard Vilalta graduated in telecommunications engineering in 2007 and received a Ph.D. degree in telecommunications in 2013, both from the Universitat Politècnica de Catalunya (UPC), Spain. He also has studied Audiovisual Communication at UOC (Open University of Catalonia) and is a master degree on Technology-based business innovation and administration at Barcelona University (UB). Since 2010, Ricard Vilalta is a researcher at CTTC, in the Optical Networks and Systems Department. His research is focussed on Optical Network Virtualization and Optical Openflow. He is currently a Research Associate at Open Networking Foundation.

PLACE PHOTO HERE

Ramon Casellas (SM'12) graduated in telecommunications engineering in 1999 by both the UPC-BarcelonaTech university and ENST Telecom Paristech, within an Erasmus/Socrates double degree program. After working as an undergraduate researcher at both France Telecom R&D and British Telecom Labs, he completed a Ph.D. degree in 2002. He worked as an associate professor at the networks and computer science deptartment of the ENST (Paris) and joined the CTTC Optical Networking Area in 2006, with a Torres Quevedo research grant. He currently is a research associate and the coordinator of the ADRENALINE testbed. He has been involved in several international R&D and technology transfer projects. His research interests include the GMPLS/PCE architecture and protocols, software defined networking and traffic engineering mechanisms. He contributes to IETF standardization within the CCAMP and PCE working groups. He is a member of the IEEE Communications Society and a member of the Internet Society.

PLACE PHOTO HERE

Ricardo Martínez graduated in telecommunications engineering 2002 and received a Ph.D. degree in telecommunications in 2007, both from the Technical University of Catalonia, Spain. Since June 2007 he has been a research associate in the CTTC Optical Networking Area. He has participated in several Spanish, EU-funded (EU FP6, FP7 and CELTIC) and Industrial projects in the context of optical networking. His research interests include GMPLS architecture, distributed control schemes, packet and optical transport networks. He has published over 80 scientific conferences and peer reviewed journal papers.

PLACE PHOTO HERE

Frederic Francois is currently a researcher with the High Performance Networks Group at Bristol University where he is involved mainly in the integration of the OFELIA testbed at Bristol into the Federation of Future Internet and Research Experimentation (Fed4FIRE). He obtained his PhD on "Energy-aware Traffic Engineering" from the University of Surrey (UK) in 2013 and an MEng in Electronic and Communications Engineering at The University of Sheffield (UK) in 2010. He has authored several conference and journal papers on internet traffic engineering and has won Best Student Award at the IEEE/IFIP conference on Network Operations and Management Symposium.

PLACE PHOTO HERE

Mayur Channegowda received a M.Sc. degree from the University Of Essex in 2010 and presently holds a Research Officer role at the High Performance Networks Group (HPNG) at University of Bristol. Previous industry experience involved working at IBM & TechMahindra Ltd on Routing & Switching technologies. His current research interest is on Software Defined Networks (SDN) particularly on its implications on the optical networks. From 2011 he is actively participating in the SDN/OpenFlow based FP7 ICT projects mainly OFELIA, ALIEN & FIBRE and has authored/co-authored papers on optical SDN.

PLACE PHOTO HERE

Ali Hammad received the B.Sc. in Informatics Engineering from Damascus university, Syria, in 2006. He received the M.Sc. degree with distinction in Communication and Information Networks from University of Essex, UK, in 2010. He is currently working towards the Ph.D. degree at university of Essex. His main interests are network virtualization for both IP and optical networks, cross layer IP over optical network virtualization, and Software Defined Networks (SDN). He is currently a researcher in the High Performance Networks group at University of Bristol.

PLACE PHOTO HERE

Shuping Peng received her B.S. in Physics, and Ph.D. in Communications from Peking University. She is a Research Fellow in High Performance Networks group at the University of Bristol. She is involved in multiple international and national (UK) projects. Her research interests include network virtualization, network modeling, and algorithm design. She is author and co-author of over 50 papers.

PLACE PHOTO HERE

Reza Nejabati is a Senior Lecturer (associated professor) in High Performance Networks Group, Senior Member of IEEE and Fellow of UK Higher Education Academy at University of Bristol. He has over 15 years of academic and industrial experience in the field of telecommunication and computer science. His current area of research is in the filed of disruptive new Internet technologies with focus on application of high-speed network technologies, software defined network, network virtualization, service-oriented and programmable network, cross layer network design and architecture as well as network architecture and technologies for e-science, data centres and cloud computing. He has written or co-authored over 150 peer reviewed papers and three standardisation documents.

PLACE PHOTO HERE

Dimitra Simeonidou is Professor of High Performance Networks group at University of Bristol. Dimitra is a leading academic in Optical Networks, Future Internet Research and Experimentation (FIRE), Grid and Cloud Computing, and a founder of Transport Software Defined Networking. She has chaired a number of international conferences and committees across these technical fields. She is the author and co-author of over 350 publications of which many have received best paper awards, 11 patents and standards.

PLACE PHOTO HERE

Noboru Yoshikane joined KDD Corporation (currently KDDI Corporation), Tokyo, Japan in 1999, and since 2001 has been working at their Research and Development Laboratories. He has been engaged in research on the design of submarine cable systems, highly spectrally efficient optical communication systems utilizing wavelength division multiplexing transmission, and designing and modeling of photonic networks. Dr. Yoshikane is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

PLACE
PHOTO
HERE

Takehiro Tsuritani joined Kokusai Denshin Denwa (KDD) Company Ltd. (currently KDDI Corporation), Tokyo, Japan in 1997 and since 1998 he has been working at their Research and Development Laboratories. He has been engaged in research on long-distance optical communication systems using wavelength division multiplexing transmission and designing and modeling of photonic networks. Dr. Tsuritani is a member of the Institute of Electronics, Information and Communication Engineers (IEICE).

PLACE
PHOTO
HERE

Victor López received the M.Sc. (Hons.) degree in telecommunications engineering from Universidad de Alcalá de Henares, Spain, in 2005 and the Ph.D. (Hons.) degree in computer science and telecommunications engineering from Universidad Autónoma de Madrid (UAM), Madrid, Spain, in 2009. In 2004, he joined Telefónica I+D as a Researcher. In 2006, he joined the High-Performance Computing and Networking Research Group (UAM) as a Researcher in the ePhoton/One+ Network of Excellence. He worked as an Assistant Professor at UAM. In 2011, he joined Telefonica I+D as Technology specialist. He has co-authored more than 100 publications and contributed to IETF drafts. His research interests include the integration of Internet services over IP/MPLS and optical networks and control plane technologies (PCE, SDN, GMPLS).

PLACE
PHOTO
HERE

Achim Autenrieth is currently Principle Research Engineer Advanced Technology in the CTO Office at ADVA Optical Networking, where he is working on the design and evaluation of multilayer networks, control plane, and SDN concepts. He received his Dipl.-Ing. and Dr.-Ing. degree in Electrical Engineering and Information Technology from the Munich University of Technology, Germany, in 1996 and 2003. Achim is a member of IEEE and VDE/ITG, he authored or co-authored more than 75 reviewed and invited scientific publications and he is technical program committee member of ECOC, DRCN, and RNDM.