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Article

Unified Multi-Layer among Software Defined Multi-Domain Optical Networks (Invited)

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Abstract: The software defined networking (SDN) enabled by OpenFlow protocol has gained popularity which can enable the network to be programmable and accommodate both fixed and flexible bandwidth services. In this paper, we present a unified multi-layer (UML) architecture with multiple controllers and a dynamic orchestra plane (DOP) for software defined multi-domain optical networks. The proposed architecture can shield the differences among various optical devices from multi-vendors and the details of connecting heterogeneous networks. The cross-domain services with on-demand bandwidth can be deployed via unified interfaces provided by the dynamic orchestra plane. Additionally, the globalization strategy and practical capture of signal processing are presented based on the architecture. The overall feasibility and efficiency of the proposed architecture is experimentally verified on the control plane of our OpenFlow-based testbed. The performance of globalization strategy under heavy traffic load scenario is also quantitatively evaluated based on UML architecture compared with other strategies in terms of blocking probability, average hops, and average resource consumption.

Keywords: OpenFlow; multi-domain optical networks; software defined network; multi-layer architecture

1. Introduction

As a promising centralized control architecture, the software defined networking (SDN) enabled by OpenFlow protocol has gained popularity by supporting programmability of data center and IP network functionalities [1,2], which has become the miniature of future network for its great advantages of separating the control plane from the data plane [3]. From the data plane's perspective, in order to accommodate the traffic demands, the elastic optical network has been proposed and experimentally demonstrated [4,5] to better utilize the frequency resource and accommodate super-wavelength traffic effectively. It supports channels operating at heterogeneous line rates [6] by allocating spectral resources tailored for a variety of connection demands in a flexible and dynamic manner [7]. When applied to the elastic optical networks which provide the services accommodation with end-to-end connects, the software defined optical network (SDON) can provide maximum flexibility for the operators [8], make a unified control over various resources and abstract them as unified interface for the joint optimization of functions and services with a global view [9]. To meet the demand of the increasingly larger scale of networks and service requirements, multi-domain optical networks with multi-controller have been introduced to SDON, with its standard protocol, OpenFlow, extended into different versions [10–14].

In order to improve the multi-domain network performance, the researchers tend to focus on the optimization within one domain [15,16], while the resources between domains are barely arranged, especially for the cross-domain services, which leads to the increase of blocking rate across the whole network. The problem has been ignored to solve partly due to the fact that current network architecture has few effective mechanism to achieve the effective control over the resources between domains. Some works have researched about GMPLS/PCE multi-domain optical network using hierarchical PCE architecture [17–19]. Some excellent works focus on the issues of routing and management in multi-domain IP networks of electrical domain [20–22] or interconnect for data centers [23]. In [21], the authors present a management architecture for wide area software defined networks using multiple controllers. Aimed at multi-tenant services in data center network, the hierarchical network manager can provide redundant, vendor agnostic zone control deployed software defined networking [22]. In [23], the authors perform software defined control of both IP and WAN from one controller has been shown in a 100 km network between three data centers. However, the unified control architecture among multi-layer multi-domain optical networks has not been researched well. On the other hand, several venders have developed their own OpenFlow devices, which arises the problem of interconnection between multi-vendor products via private control protocols. Obviously, the problem can be the obstacle in improving the network efficiency, especially when the service quantity increases quite fast. The service request can only be exchanged across the user-network interface (UNI) between different networks [24].

The cross stratum optimization (CSO) between optical network and application stratum resources that allows us to accommodate the services has been discussed in our previous works [9,10]. To solve the problems described above, we propose a unified multi-layer (UML) architecture with dynamic orchestra plane (DOP) in multi-domain network with multi-controller based on SDON. One hand, the proposed UML architecture can shield the differences among various optical devices from multi-vendors and the details of connecting heterogeneous networks. On the other hand, the dynamic orchestra plane can also unify control various controllers (e.g., Opendaylight, Floodlight, ONOS, NOX, *etc.*), and provide the users with unified and integrated resources. Based on the architecture, the IP network, data center and other network types can be extended into integration, and perform the global optimization of resources utilization. Additionally, the globalization strategy and practical capture of signal processing are presented based on the proposed architecture. The overall feasibility and efficiency of the proposed architecture is experimentally verified on the control plane of our OpenFlow-based testbed. We use the Wireshark capture inserted in the dynamic orchestra plane to demonstrate the feasibility of the proposed architecture, while the simulation of large-scale network is used to explain and analyze its efficiency. The performance of globalization strategy under heavy traffic load scenario is also quantitatively evaluated based on UML architecture compared with other strategies in terms of blocking probability, average hops, and average resource consumption.

The rest of this paper is organized as follows. Section 2 proposes the novel UML architecture and builds functional models of UML. The globalization strategy and interworking procedure of signaling processes is introduced in Section 3. Finally, we describe the demonstration environment and present the numeric results and analysis in Section 4 and conclude the paper in Section 5.

2. UML Functional Architecture

The UML architecture for software defined multi-domain optical network is illustrated in Figure 1. There are four planes in the proposed architecture. The data plane consists of all the physical networks, including kinds of optical hardware devices in the network. To control the heterogeneous networks with OpenFlow protocol, OpenFlow-enabled optical device nodes with OpenFlow agent software are required. The content of the control plane is series of network controllers from different vendors. Each controller should consist of the path computation element (PCE) and unified interfaces to the higher plane. In each controller, the protocol analyzer is used for vendor-specialized protocols (e.g., OpenFlow protocol), and performs the lighpath provisioning to control the optical devices intra-domain. The resource pool manager can monitor and manage the traffic engineering database (TED) [25]. Note that the dynamic orchestra plane (DOP) is the core orchestration of the whole architecture, which mainly has three responsibilities. (1) It responses to the requests from the application plane; (2) It reads and stores the network information reported by the control plane, including the whole network topology, resources intra- and inter-domains, which is the basis of global optimization; (3) It provides the unified interface to the control plane with being aware of the controller vendor and the vendor-specialized protocol between the controller and the switches.

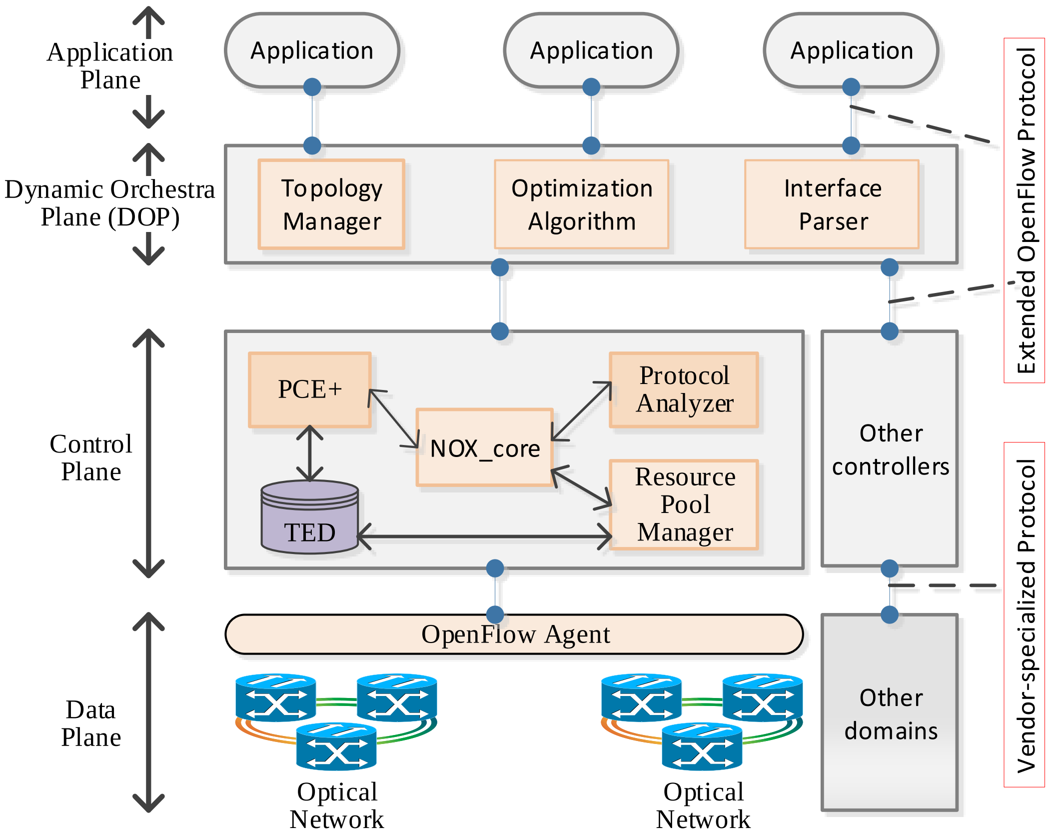


Figure 1. The architecture of UML.

Besides running the optimization algorithm for arranging the network resources to meet the different demands of users, it can also help the controllers to deal with the collaboration and interoperability in heterogeneous networks. The application plane provides users with the network resources for various kinds of operations. This layer triggers the whole network behavior.

When dealing with cross-domain services, the motivations for DOP are mainly twofold. Firstly, it can modify the service requests into adaptive requests to different controller in different domains, according to the vendor and topology information. Secondly, when building the service, the DOP will take the resource between domains into consideration along with resource within the domains and achieve the global optimization. Therefore, the controllers do not need to formulate specific protocols for communications when cooperating for cross-domain services, and thus the blocking rate can decrease due to the management by the DOP.

3. Globalization Strategy and Signaling Processes for the UML Architecture

Based on the proposed architecture, we propose the globalization strategy in the DOP to accommodate the cross-domain service request optimally. We use G (*V*, *E*, *W*) to describe the network architecture, where $V = \{v_1, v_1, \ldots, v_n\}$ denotes the set of OpenFlow-enabled optical switching nodes, $E = \{E_1, E_1, \ldots, E_n\}$ indicates the set of bi-directional fiber links between nodes in *V*. $W = \{w_1, w_1, \ldots, w_n\}$ is the set of spectrum slots on each fiber link, while *N*, *L* and *W* represent the number of network nodes, links and spectrum slots respectively. We also define *C* as the collection of all the inter-domain links. Here, *H* means the average hops of each successful deployed service, while *R* stands for the average resource consumption. Aimed at the cross-domain service request, the proposed strategy can first calculate the paths which meet the request among multi-domain and intra-domain. Note that some standardized algorithms are presented in IETF RFC [26], and we have adopted the backward-recursive PCE-based computation (BRPC) as the cross-domain computation. Then it can reserve enough spectrum resources for the service through the selected paths. The general steps of the proposed globalization strategy are described as follows.

Algorithm 1: Globalization Strategy

for every cross-domain service request

1 for every link K ϵ C
2 **Compute** all the paths that meet the request among multi-domain using BRPC, and put them in a priority queue
3 **Select** the path that has the minimum H
4 for every selected path
5 If cannot **reserve** the needed resource
6 **Jump** to step 3 for no more than 3 times
7 If cannot reserve the resource successfully, then the service is dropped

We also illustrate the signaling process using the globalization strategy within the UML architecture, as show in Figure 2.The vendor-specialized protocols are performed between the resource plane and the control plane, which can notify the controller with the intra-domain information. Then the controllers should report the vendor-specialized interfaces, protocols, inter-domain topology information, as well as the information of itself to the DOP. From the view of the DOP, the topology contains the controller information within different domains and the inter-domain nodes.

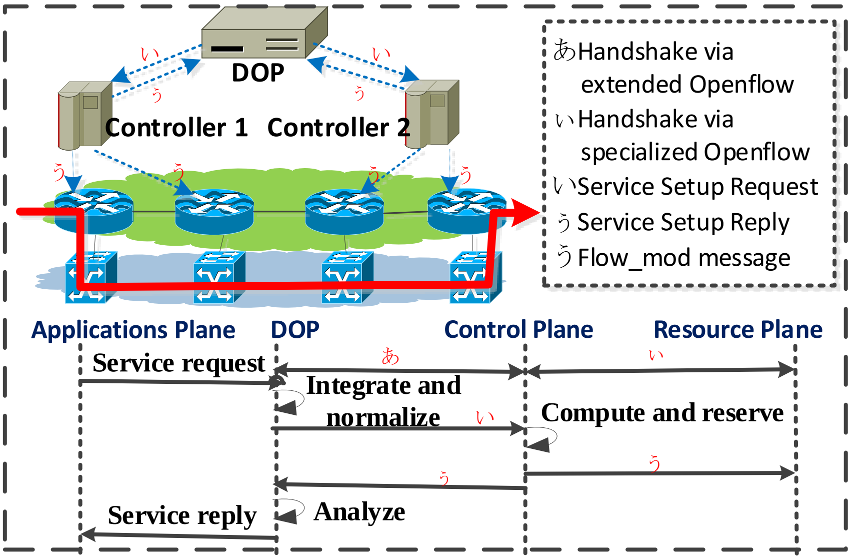
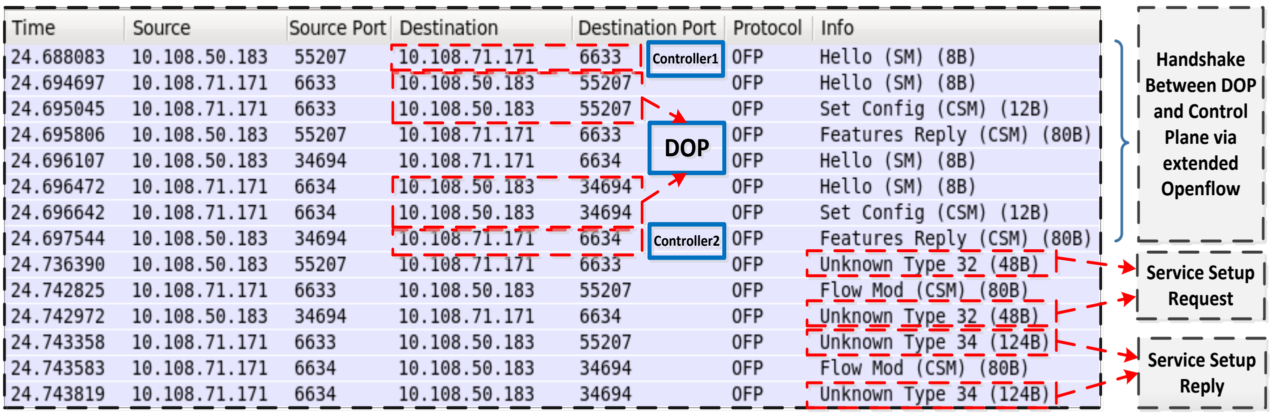


Figure 2. The demonstration for signal process of unified multi-layer (UML).

When received a cross-domain service request, the DOP is supposed to have a pre-computing about the service-related domains and inter-domain nodes, with its purpose of optimizing inter-domain link resources, then send specialized requests to the controllers. When a controller receives the intra-domain request from the DOP, it computes a path and reserves the needed resource to meet the requirement, and send *flow_mod* message to the nodes and service reply to the DOP. Having received intra-domain replies from controllers, the DOP will form the full path route and send a unified reply to application plane, which is used for presenting results to the users.

4. Experimental Demonstration and Emulation Results

To experimentally evaluate of the proposed UML architecture, we set up an OpenFlow-based unified multi-layer testbed with control plane. Due to the lack of hardware, we develop a software OpenFlow protocol agent to emulate the device of data plane. The data plane nodes are implemented on an array of virtual machines created by VMware ESXi V5.1 running at embedded Linux platform on IBM X3650 servers. Since each virtual machine has an operating system, its own CPU, and storage resource, it can be considered as a real node. Therefore, system virtualization technology makes it easy to set up experiment topology based on the backbone of NSFNet which comprises 14 nodes and 21 links. For OpenFlow-based UML control plane, each domain is controlled by a controller, which is assigned to support the proposed architecture and deployed in three servers for protocol analysis, PCE computation and resource management, while the database management servers are responsible for maintaining traffic engineering database, management information base, connection status and the configuration of the database. The dynamic orchestra plane server is used for resources optimization, topology management and interface with various controllers and users. The application plane is deployed in a server and deploys the service information generator to implement batch services for the experiments. Note that various controllers (e.g., Opendaylight, Floodlight, ONOS, NOX, *etc.*) can be used for each domain in the proposed architecture, while we develop the controller based on NOX for the realization simplicity. We have designed and verified cross-domain lightpath provisioning in the testbed for the demonstration. The experimental results are shown in Figure 3. Figure 3 presents the whole signaling procedure for UML by using OFP through a Wireshark capture inserted in the dynamic orchestra plane, which are the same as the procedures we depicted in Figure 2.



Time	Source	Source Port	Destination	Destination Port	Protocol	Info
24.688083	10.108.50.183	55207	10.108.71.171	6633	OFP	Hello (SM) (8B)
24.694697	10.108.71.171	6633	10.108.50.183	55207	OFP	Hello (SM) (8B)
24.695045	10.108.71.171	6633	10.108.50.183	55207	OFP	Set Config (CSM) (12B)
24.695806	10.108.50.183	55207	10.108.71.171	6633	OFP	Features Reply (CSM) (80B)
24.696107	10.108.50.183	34694	10.108.71.171	6634	OFP	Hello (SM) (8B)
24.696472	10.108.71.171	6634	10.108.50.183	34694	OFP	Hello (SM) (8B)
24.696642	10.108.71.171	6634	10.108.50.183	34694	OFP	Set Config (CSM) (12B)
24.697544	10.108.50.183	34694	10.108.71.171	6634	OFP	Features Reply (CSM) (80B)
24.736390	10.108.50.183	55207	10.108.71.171	6633	OFP	Unknown Type 32 (48B)
24.742825	10.108.71.171	6633	10.108.50.183	55207	OFP	Flow Mod (CSM) (80B)
24.742972	10.108.50.183	34694	10.108.71.171	6634	OFP	Unknown Type 32 (48B)
24.743358	10.108.71.171	6633	10.108.50.183	55207	OFP	Unknown Type 34 (124B)
24.743583	10.108.71.171	6634	10.108.50.183	34694	OFP	Flow Mod (CSM) (80B)
24.743819	10.108.71.171	6634	10.108.50.183	34694	OFP	Unknown Type 34 (124B)

Figure 3. Wireshark capture of the signal processing for the UML architecture.

We also adopt the backbone topology of NSFNet to evaluate the performance and scalability of UML based on globalization strategy under heavy traffic load scenario and compare it with the traditional randomization strategy in terms of blocking probability, average hops and average resource consumption. Note that, only in the proposed architecture, the globalization strategy using global resources optimization can be performed successfully in multi-vendor scenario. More than 10,000 services have been performed following a Poisson process with the proper control strategy among multi-domains (2 and 3 domains are emulated in this paper), which are referred to as 3 domain_randomization, 3 domain_globalzation, 2 domain_randomization, and 2 domain_globalzation respectively.

The emulation results can give a clear measurement of the benefit that the proposed architecture can bring to the network. Figure 4a shows that when comparing the blocking probability of the network, the strategies within two domains perform better than three domains. The reason is that inter-domain resource is the key constrains of inter-domain services, so the blocking probability is surely increased as the growing of the number of domains. When the network has the stationary number of domains, the globalization strategy handled by the DOP archived less blocking probability than the randomization one, clearly present the great benefit brought by the DOP to the network. While the average hops of the services have nothing to do with Poisson parameter, in Figure 4b they almost stay the same as the growing lambda. As to Figure 4c, the average resource consumption declines a little because, with the growing of services quantity, the larger services are always blocked.

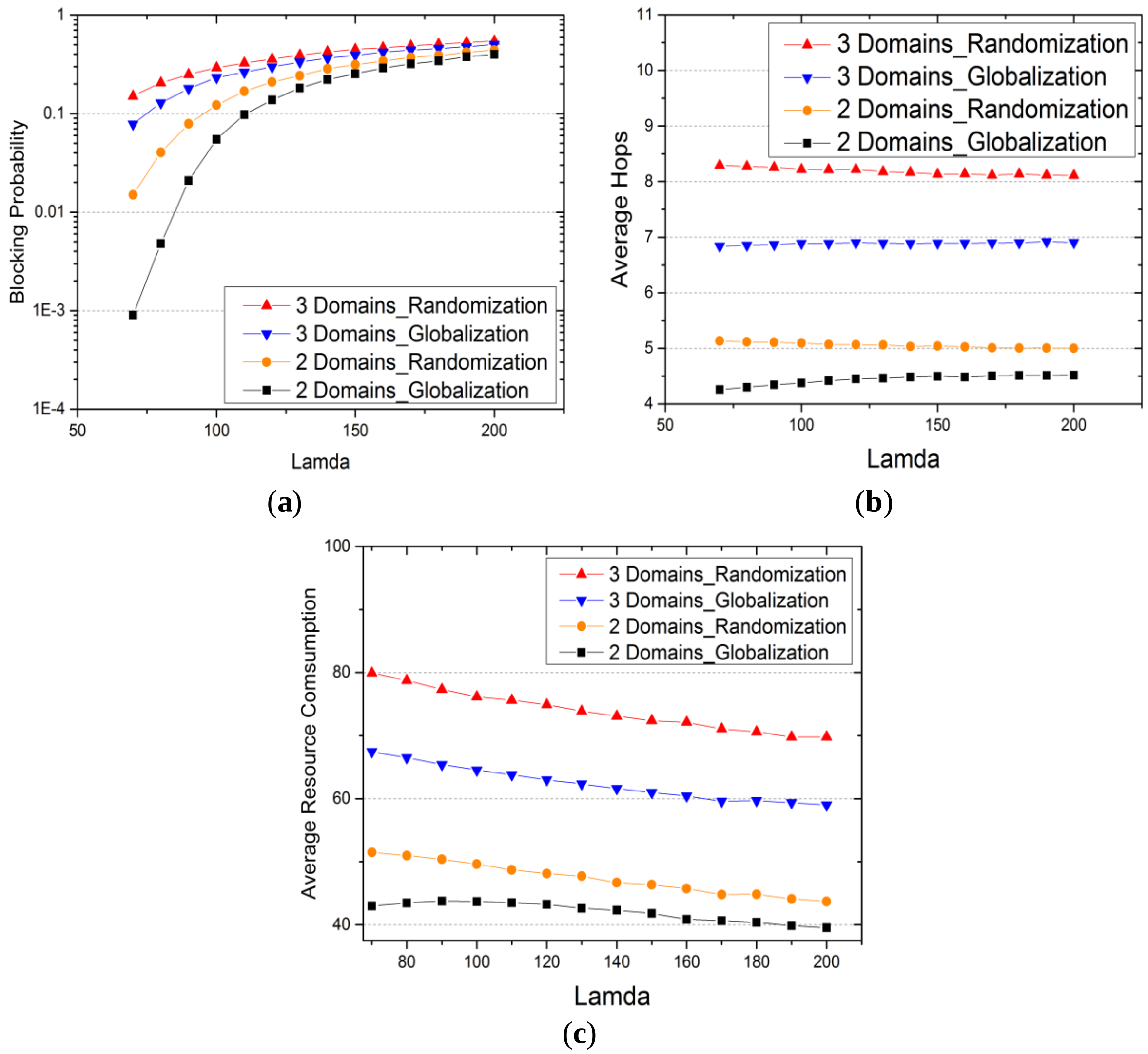


Figure 4. (**a**) Blocking probability; (**b**) average hops; (**c**) average resource consumption among various strategies under heavy traffic load scenario.

5. Conclusions

In order to overcome various problems against the control of multi-domain optical network, this paper proposes a unified multi-layer (UML) architecture to improve the interconnection between domains and unified managements among multiple controllers in multi-domain optical networks based on SDON. Capture results present the signal process of the proposed architecture. The emulation results show that it can enhance the network performance significantly in terms of blocking probability, average hops, and average resource consumption. Obviously, if a proper load balancing algorithm is added to the optimization algorithm module in DOP, the network resource can get higher utilization, which thus shows the great prospect of the proposed scheme.

Our future works for unified multi-layer architecture include two aspects. One is to improve the performances through the proposed architecture and extend the simulation to a large scale network topology. The other is to research the realization of virtualization for multiple domain, and conduct theoretical study and algorithm design in the elastic data center optical network.

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Author Contributions

Hui Yang, Yadi Cui and Jie Zhang conceived and designed the experiments; Hui Yang and Yadi Cui performed the experiments; Hui Yang and Yadi Cui analyzed the data; Hui Yang wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

References and Notes

1. Liu, L.; Tsuritani, T.; Morita, I.; Guo, H.; Wu, J. Experimental validation and performance evaluation of OpenFlow-based wavelength path control in transparent optical networks. *Opt. Express* **2011**, *19*, 26578–26593.
2. Amaya, N.; Yan, S.; Channegowda, M.; Rofoee, B.R.; Shu, Y.; Rashidi, M.; Ou, Y.; Hugues-Salas, E.; Zervas, G.; Nejabati, R.; *et al*. Software defined networking (SDN) over space division multiplexing (SDM) optical networks: Features, benefits and experimental demonstration. *Opt. Express* **2014**, *22*, 3638–3647.
3. Szyrkowiec, T.; Autenrieth, A.; Gunning, P.; Wright, P.; Lord, A.; Elbers, J.; Lumb, A. First field demonstration of cloud datacenter workflow automation employing dynamic optical transport

network resources under OpenStack and OpenFlow orchestration. *Opt. Express* **2014**, *22*, 2595–2602.

4. Liu, L.; Peng, W.; Casellas, R.; Tsuritani, T.; Morita, I.; Martínez, R.; Muñoz, R.; Yoo, S.J.B. Design and performance evaluation of an OpenFlow-based control plane for software defined elastic optical networks with directdetection optical OFDM (DDO-OFDM) transmission. *Opt. Express* **2014**, *22*, 30–40.
5. Paolucci, F.; Cugini, F.; Hussain, N.; Fresi, F.; Poti, L. OpenFlow-based flexible optical networks with enhanced monitoring functionalities. In Proceedings of the 2012 38th European Conference and Exhibition on Optical Communications (ECOC), Amsterdam, The Netherlands, 16–20 September 2012; pp. 1–3.
6. Shen, G.; Yang, Q. From coarse grid to mini-grid to gridless: How much can gridless help contentionless. In Proceedings of the 2011 and the National Fiber Optic Engineers Conference Optical Fiber Communication Conference and Exposition (OFC/NFOEC), Los Angeles, CA, USA, 6–10 March 2011; pp. 1–3.
7. Channegowda, M.; Nejabati, R.; Rashidifard, M.; Peng, S.; Amaya, N.; Zervas, G.; Simeonidou, D.; Vilalta, R.; Casellas, R.; Martínez, R.; *et al*. Experimental demonstration of an OpenFlow based software-defined optical network employing packet, fixed and flexible DWDM grid technologies on an international multi-domain testbed. *Opt. Express* **2013**, *21*, 5487–5498.
8. Kozicki, B.; Takara, H.; Yoshimatsu, T.; Yonenaga, K.; Jinno, M. Filtering Characteristics of Highly-spectrum Efficient Spectrum-sliced Elastic Optical Path (SLICE) Network. In Proceedings of the OFC 2009 Conference on Optical Fiber Communication–Incudes Post Deadline Papers, San Diego, CA, USA; 22–26 March 2009; pp. 1–3.
9. Yang, H.; Zhao, Y.; Zhang, J.; Wang, S.; Gu, W.; Ji, Y.; Han, J.; Lin, Y.; Lee, Y. Multi-Stratum Resources Integration for OpenFlow based Data Center Interconnect [Invited]. *J. Opt. Commun. Netw*. **2013**, *5*, A240–A248.
10. Yang, H.; Zhang, J.; Zhao, Y.; Ji, Y.; Li, H.; Lin, Y.; Li, G.; Han, J.; Lee, Y.; Ma, T. Performance evaluation of time-aware enhanced software defined networking (TeSDN) for elastic data center optical interconnection. *Opt. Express* **2014**, *22*, 17630–17643.
11. Jinno, M.; Kozicki, B.; Takara, H.; Watanabe, A.; Sone, Y.; Tanaka, T.; Hirano, A. Distance-adaptive spectrum resource allocation in spectrum-sliced elastic optical path network. *IEEE Commun. Mag*. **2010**, *48*, 138–145.
12. Sun, W.; Li, P.; Li, C.; Hu, W. Seamlessly transformable hybrid packet and circuit switching for efficient optical networks. *Chin. Opt. Lett*. **2013**, *11*, 010601.
13. Yu, Y.; Zhang, J.; Zhao, Y.; Wang, S. Open Virtual Infrastructure: Implementation Framework for Integrated Provisioning of Virtualized Network and Application Resources based on Software Defined Networking (SDN). In Proceedings of the 39th European Conference and Exhibition on Optical Communication (ECOC 2013), London, UK, 22–26 September 2013; pp. 1–3.
14. Liu, L.; Zhang, D.; Tsuritani,, T.; Vilalta, R. Field Trial of an Openflow-Based Unified Control Plane for Multilayer Multi-granularity Optical Switching Networks. *J. Lightwave Technol*. **2013**, *31*, 506–514.
15. Chatterjee, B.; Sarma, N.; Sahu, P.P. Priority Based Routing and Wavelength Assignment With Traffic Grooming for Optical Networks. *IEEE/OSA J. Opt. Commun. Netw*. **2012**, *4*, 480–489.

16. Yang, H.; Zhao, Y.; Zhang, J.; Wang, S.; Gu, W.; Han, J. Multi-Stratum Resources Integration for Data Center Application Based on Multiple OpenFlow Controllers Cooperation. In Proceedings of the Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC), Anaheim, CA, USA, 17–21 March 2013.
17. King, D.; Farrel, A. The Application of the Path Computation Element Architecture to the Determination of a Sequence of Domains in MPLS and GMPLS, IETF RFC 6805.
18. Giorgetti, A.; Paolucci, F.; Cugini, F.; Castoldi, P. Proactive Hierarchical PCE based on BGP-LS for Elastic Optical Networks. In Proceedings of the Optical Fiber Communication Conference (OFC), Los Angeles, CA, USA, 22–26 March 2015.
19. De Dios Gonzalez, O.; Casellas, R.; Morro, R.; Paolucci, F.; Lopez, V.; Martínez, R.; Munoz, R.; Vilalta, R.; Castoldi, P. First Multi-partner Demonstration of BGP-LS enabled Inter-domain EON control with H-PCE. In Proceedings of the OFC 2015, Los Angeles, CA, USA, 22–26 March 2015.
20. López, V.; De Dios Gonzalez, O.; Miguel, L.; Joshua, F.; Silva, H.; Blair, L.; Marsella, J.; Szyrkowiec, T.; Autenrieth, A.; Liou, C.; *et al*. Demonstration of SDN Orchestration in Optical Multi-Vendor Scenarios. In Proceedings of the Optical Fiber Communication Conference (OFC), Los Angeles, CA, USA, 22–26 March 2015
21. Ahmed, R.; Boutaba, R. Design Considerations for Managing Wide Area Software Defined Networks. *IEEE Commun. Mag*. **2014**, *52*, pp. 116–123.
22. DeCusatis, C.; Cannistra, R.; Hazard, L. Managing multi-tenant services for software-defined cloud data center networks. In Proceedings of the 2014 6th International Conference on Adaptive Science & Technology (ICAST), Ota, Nigeria, 29–31 October 2014; pp. 1–5.
23. DeCusatis, C.; Carranza, A.; Sher-DeCusatis, C.J. Dynamic Software Defined Network Provisioning for Resilient Cloud Service Provider Optical Network. In Proceedings of the International Conference on Computer and Information Science and Technology, Ottawa, Canada, 11–12 May 2015; pp. 1–9.
24. Das, S.; Parulkar, G.; McKeown, N. Why OpenFlow/SDN can succeed where GMPLS failed. In Proceedings of 2012 38th European Conference and Exhibition on Optical Communications (ECOC), Amsterdam, Netherlands, 16–20 September 2012; pp. 1–3.
25. Casellas, R.; Martinez, R.; Munoz, R.; Liu, L. An Integrated Stateful PCE/Openflow controller for the Control and Management of Flexi-Grid Optical Networks. In Proceedings of the Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC), Anaheim, CA, USA, 17–21 March 2013; pp. 1–3.
26. Vasseur, J.P. (Ed.). A Backward-Recursive PCE-Based Computation (BRPC) Procedure to Compute Shortest Constrained Inter-Domain Traffic Engineering Label Switched Paths, IETF RFC. Available online: https://tools.ietf.org/html/rfc5441 (accessed on April 2009).