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Software Defined Optical Networks and Its Innovation Environment

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Abstract

Software defined optical networks (SDONs) integrate software defined technology with optical communication networks and represent the promising development trend of future optical networks. The key technologies for SDONs include software-defined optical transmission, switching, and networking. The main features include control and transport separation, hardware universalization, protocol standardization, controllable optical network, and flexible optical network applications. This paper introduces software defined optical networks and its innovation environment, in terms of network architecture, protocol extension solution, experiment platform and typical applications. Batch testing has been conducted to evaluate the performance of this SDON testbed. The results show that the SDON testbed has good scalability in different sizes. Meanwhile, we notice that controller output bandwidth has great influence on lightpath setup delay.

Keywords

optical networks; software defined networking; innovation environment

1 Introduction

With the emerging of new network services, the interaction of all kinds of information grows day by day. It is an eternal theme for optical networks to satisfy the transmission demands for high speed, wide broadband, large capacity, and long-distance transmission. The changes of servics properties brings a new challenge: intelligence of optical networks. For example, high burst services require optical networks to have dynamic adaptability; large-scale networking requires optical networks to be scalable; and variable bandwidth provisioning requires optical networks to be flexible. To realize the intelligent optical network, the industry has carried out a long-term research and exploration. So far, the intelligent optical network has gone through three important stages of development.

1) Automatic Switching Optical Networks (ASON)

An ASON is divided into three planes: the transmission plane, control plane and management plane. With the control plane based on Generalized Multi-Protocol Label Switching (GMPLS) protocol, ASON adopts distributed signaling and routing to solve the connection control problem and satisfy the function demands of automatic switching [1]–[4]. However, ASON has obvious limitations in many aspects, including large-scale connection control, complex path calculation, network openness, devices interworking, and cost reduction. Besides, the GMPLS standard is very complex, which greatly affects the application and promotion of ASON.

2) Path Computation Element (PCE) Architecture for ASON

In order to better adapt to the characteristics of multi-layer multi-domain large-scale optical networks, the Internet Engineering Task Force (IETF) separates the path calculation function from the control layer and develops an independent unit, i.e., PCE [5]–[8]. In order to satisfy the function demands of large-scale multi-layer/domain, PCE adopts the distributed signaling and centralized routing to solve the problem of path selection and calculation for inter-layer and inter-domain path. However, with unitary function of path calculation, PCE needs to cooperate with other technology in applications.

3) Software Defined Optical Networks (SDONs)

SDONs can offer a unified schedule and control for various kinds of optical layer resources according to the requirements of users or operators. With programmable software and dynamic customization, the SDON solves the problem of function extension and therefore realizes rapid response to requests, efficient utilization of resources and flexible service provisioning. The SDON well supports service processing, control strategy and programmable transmission device, which achieves programmable tuning of optical network elements [9]. Therefore, the SDON is more suitable for multi-layer/domain and multi-constraint optical networks, and it can effectively improve operational efficiency and reduce cost.

The article introduces the SDON innovation environment from the perspectives of architecture, protocol extension, experimental platform and typical applications. Section 2 describes the hierarchical control architecture and the process of cross-

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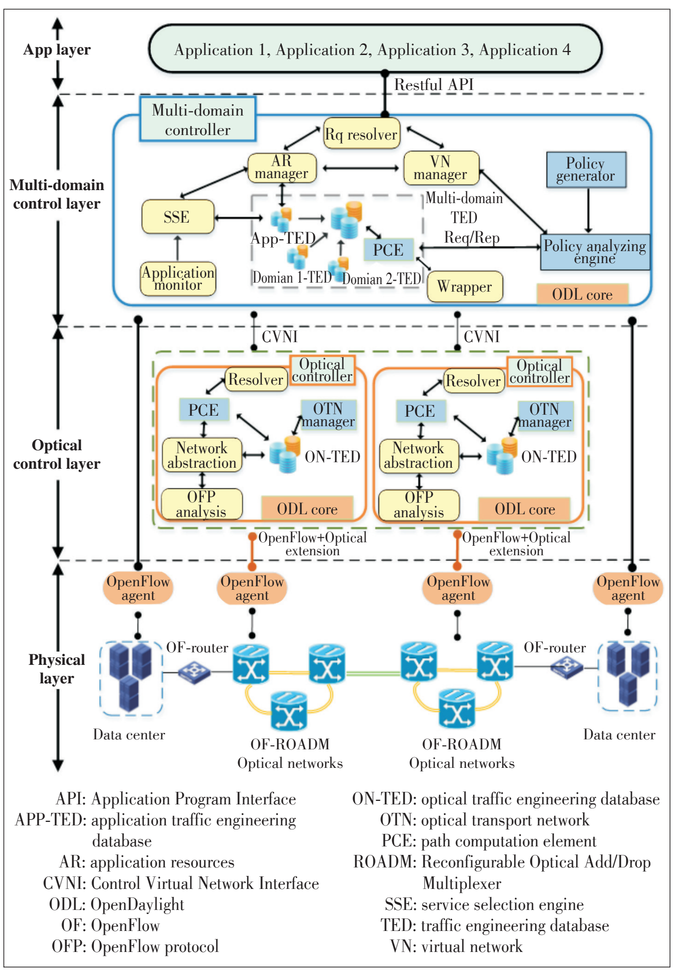
domain connection provisioning in detail. Section 3 depicts the workflow of connection provisioning in multi-domain optical networks. Section 4 shows the necessary extension work of OpenFlow 1.3 protocol for optical networks. The experimental environment and typical applications of SDON are respectively discussed in section 5 and section 6. Section 7 is performance evaluation of the SDON testbed and the last section summarizes the paper.

2 Hierarchical Architecture for SDON

As shown in **Fig. 1**, considering the cross-layer distribution of multi-domain optical network resources, this paper proposes an OpenFlow enabled hierarchical control architecture in order to solve the problem of programmable control in optical network. With the advantage of software-defined networking, the architecture uniformly abstracts optical transmission network resources and content resources, and provides them with the multi-domain controller through the northbound interface. In this way, the uniform control of cross-layer resources is realized. The hierarchical architecture consists of three layers: the physical layer, control layer and application layer.



▲**Figure 1. Hierarchical network architecture.**

1) The physical layer mainly includes data-center and inter-data-center optical transmission networks. OpenFlow-enabled IP Routers (OF-Router) and optical transmission equipment with OpenFlow agents (OF-ROADM) are deployed in the network.

2) The application layer mainly includes various applications such as dynamic migration of virtual machines, virtual network provisioning, and spectrum defragmentation. It is connected with the control layer through the Restful API interface. All the service requests are triggered from this layer.

3) The control layer is mainly composed of optical controllers and multi-domain controller.

In the optical controller, the protocol analysis module analyzes the underlying optical transmission equipment via the OpenFlow protocol extended for optical transmission devices. It collects the status of OF-ROADM in the optical network and abstracts the network topology information. Then the abstracted topology information is sent to the network abstraction module and stored in the optical database (ON-TED). The OTN manager manage the optical transmission equipment, such as lightpath setup and deletion, and resources allocation. The optical network controller packages the network status and topology information via the protocol encapsulation module and makes a notification to the multi-domain controller.

The multi-domain controller integrates the network information collected by the optical controller through the southbound Control Virtual Network Interface (CVNI) interface and monitors the network status. With the northbound Restful-API, it parses the application requests sent by the application layer. It consists of nine function modules and one resource integration module. Resource integration is completed by the heterogeneous network database (Het-TED). The application database (App-TED) and ON-TED in network are set into the same database, with the purpose of supplying the network resources information for the corresponding module in the network. The nine function modules are respectively described as follows.

1) Application monitor: It monitors the computing resources in the network and reports the information of computing resources to service selection engine.

2) Service selection engine (SSE): According to the status of application resources and network resources requests, it selects the most appropriate application resources to meet the virtual requests.

3) Application resource manager: It manages the application resources in the network, and keeps real-time synchronous update with the resources information in the application resources database (App-TED).

4) Request resolver: It parses the requests sent by the application layer and forward them to the corresponding module for processing.

5) Virtual network manager: It manages the virtual network requests sent by the application layer according to the status of application resources and network resources, and selects the

most appropriate network links to meet the virtual network requests with the corresponding strategy.

6) Policy generator: According to the network requests from the application layer, it generates the corresponding strategy information of resource provisioning for the heterogeneous network controller.

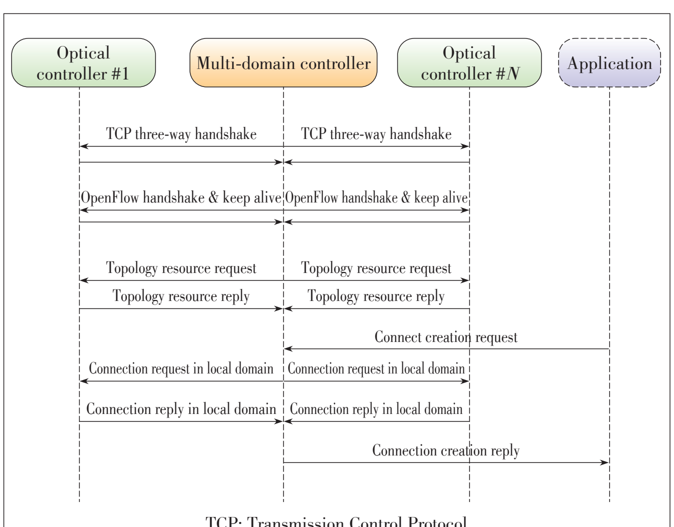
7) Policy analyzing engine: It parses the strategy generated by the strategy generator module, and sends it to the corresponding module for network resource allocation.

8) PCE: As a core component of the multi-domain controller, PCE is used in response to the request of path computation. The calculation is based on the input path information, strategy information and request information, etc. It may return two kinds of calculation results, the appropriate path information computed by multi-domain or the failure information.

9) Wrapper: It packages the resource allocation information with the CVNI protocol and sends it to the optical controller via the CVNI interface.

3 Workflow of Connection Provisioning

Fig. 2 shows the workflow of providing an end-to-end connection in the multi-domain optical networks. After a Transmission Control Protocol (TCP) connection is established, the multi-domain controller completes the handshake with the optical controller by using OpenFlow messages, then periodically sends packages to keep the connection alive. The multi-domain controller requests the abstract topology as well as the detailed port information. After receiving a request for connection setup the optical controller completes the path computation and resource allocation in the local domain via the domain-specified protocol. Once the process is finished, the optical controller sends a "success" reply to the multi-domain controller. When the multi-domain controller collects all the "success" messages from optical domains, a "success" notification will be sent to the application layer. At this point, a connection or lightpath is considered to be established successfully.



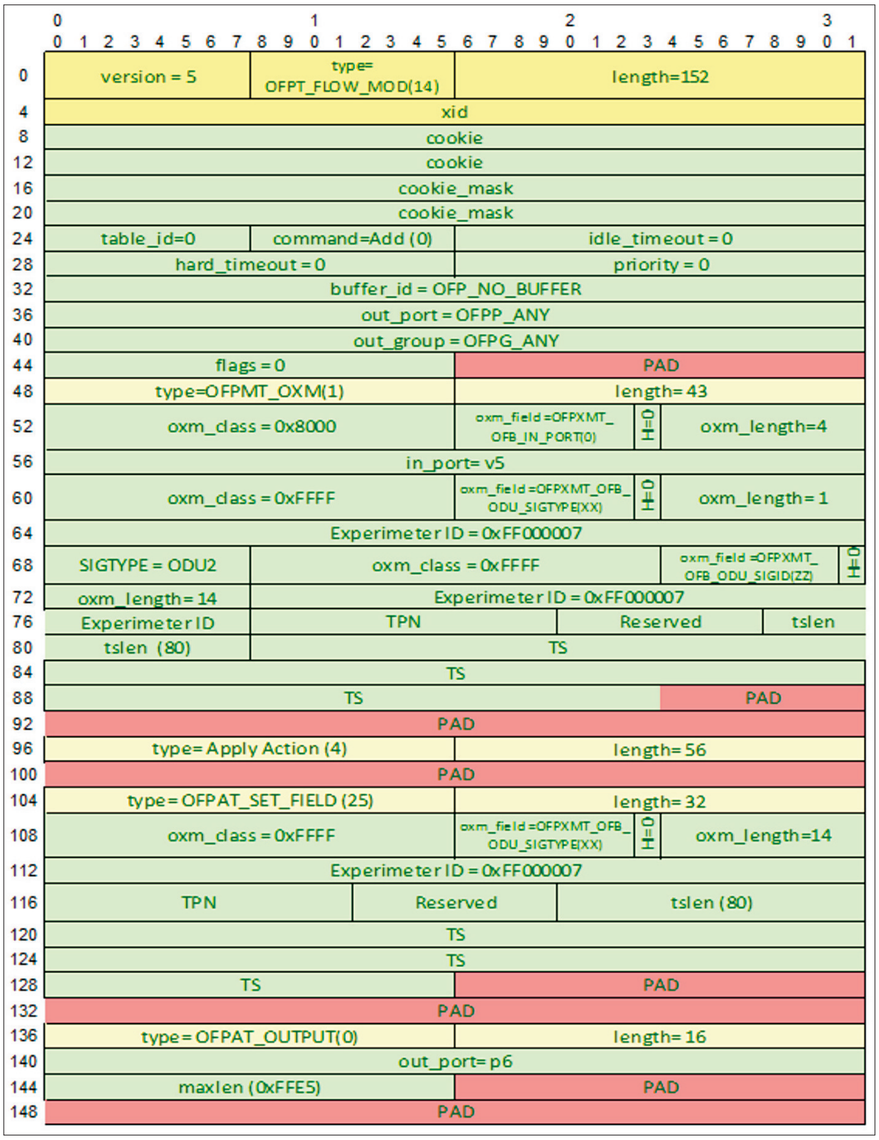
▲**Figure 2. Workflow of connection provisioning in multi-domain optical networks.**

4 Protocol Extensions for SDON

Based on OpenFlow 1.3 protocol, CVNI is an interface protocol between the multi-domain controller and optical layer controller. Several OpenFlow messages in CVNI have been extended to satisfy the requirements of optical networks. The multi-domain controller sends a GET_CONFIG_REQUEST message to the optical controller to get the location of network nodes and the optical controller replies a GET_CONFIG_REPLY message. The MULTIPART_REQUET messages is used by the multi-domain controller to obtain topology resources including ports and links information. The MULTIPART_REPLY message carries topology information from the optical controller to the multi-domain controller. The multi-domain controller employs FLOW_MOD messages to complete connection setup and deletion. The match field and action field in an extended FLOW_MOD message respectively represent the input optical port and output optical port. Note that the multi-domain controller sends a BARRIER_REQUEST message to the single-domain controller in order to verify whether the optical cross connection is deployed successfully. The single-domain controller then sends a BARRIER_REPLY message to notify the multi-domain controller that the connection is created or deleted successfully. Due to space limitation, only FLOW_MOD message extension is illustrated in **Fig. 3**.

5 Experimental Platform for SDON

As shown in **Fig. 4**, an all-optical network innovation (AONI) experimental platform for SDON is distributed in three geography locations connected by optical fiber links. Two of them are located in Room 342 and Room 423 in the Science&Research building of Beijing University of Posts and Telecommunications (BUPT), and the third location is at 21Vianet Company in Jiuxianqiao, Beijing. Two data centers are respectively deployed in Room 342 and 21Vianet Company, and Room 423 serves as the access network for users, which composes a typical network environment with the application of data center. The AONI platform supports three typical network scenarios, i.e., the inter-data center network, user access to data center network and intra-data center network. The AONI platform focuses on how to embody the advantages of optical switching network in these three scenarios. The platform supports both optical burst switching and optical circuit switching, and supports both flexible grid high-speed optical transmission and fixed grid transmission. Therefore, the AONI platform not only provides efficient transmission and switching in the future but also remains compatible with traditional networks. The high capacity optical burst switching (OBS) is mainly used for



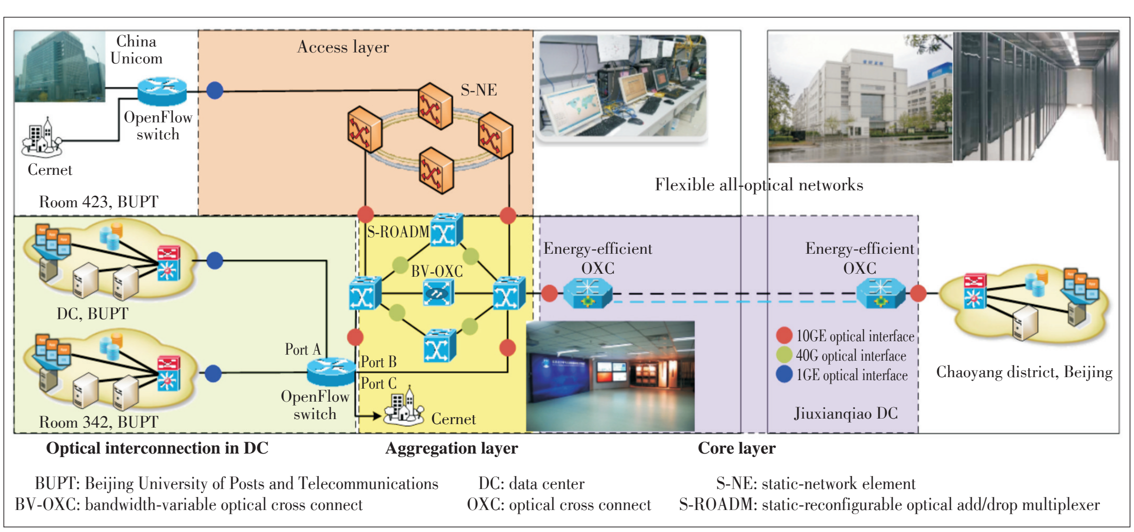
▲**Figure 3. FLOW_MOD message extension of CVNI protocol.**

the adaption to the high burstiness characteristic of intra-data center services. The flexible grid high-speed optical transmission andoptical circuit switching are mainly applied to the inter-data center to realize large-grained variable bandwidth switching. The all-optical access and convergence layer uses fixed grid transmission and switching to achieve flexible access of broadband services. Thus the architecture of AONI includes intra-data center all-optical interconnection, all-optical access layer, all-optical convergence layer and all-optical core layer. Such a platform can highly simulate real scenarios of all-optical switching wide area network (WAN) in the future.

6 Typical Applications of SDON

The SDON is a promising solution to high intelligence of next generation optical network and has broad application prospects. The typical applications include bandwidth on demand (BoD) provisioning, virtual machine (VM) online migration, spectrum defragmentation, and virtual optical networks (VON) provisioning. The homepage of AONI applications is shown in **Fig. 5**.

BoD applications and VM migration are implemented based on the physical topology shown in Fig. 4. For lack of flexible-grid optical devices, a multi-domain logical topology (**Fig. 6**) is designed for VON provisioning and spectrum defragmentation. Both the physical topology and the logical topology are under control of the SDN controller. Each domain in-



◀**Figure 4. AONI: all optical network innovation environment.**

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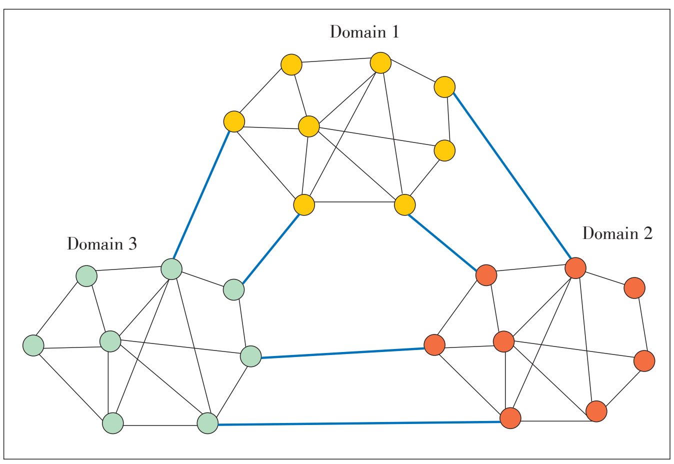
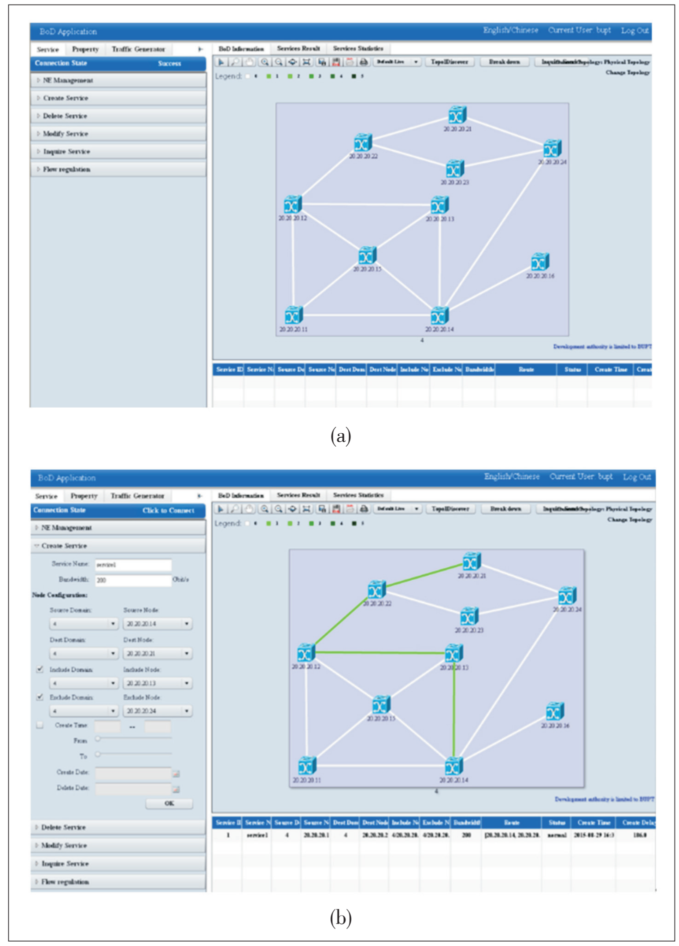
▲Figure 5. Homepage of AONI applications.



▲Figure 6. Multi-domain logical topology.



▲Figure 7. Web view of BoD application: (a) before connection setup; (b) after connection setup.

cludes eight standalone OpenFlow-Agents (OF-AGs). Running on high-performance Linux servers, each OF-AG is programmed based on Open-vSwitch.

6.1 BoD Applications

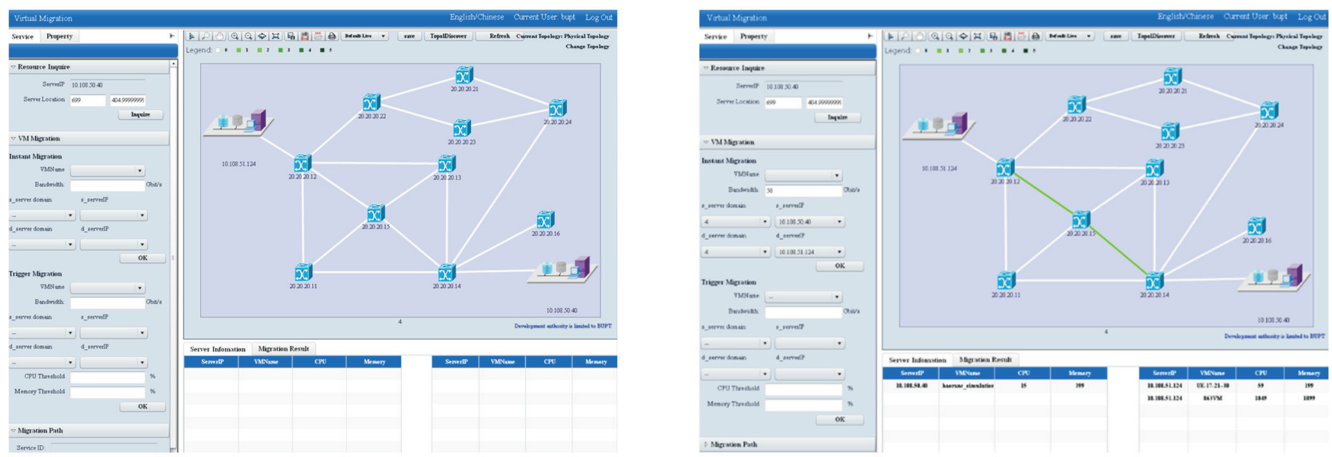
BoD applications help users have a global understanding of underlying optical networks and accomplish a series of operations in optical networks, including connection setup, connection deletion, connection query, connection modification and so on. A lightpath connection is built and on-demand bandwidth is allocated according to users requirements. Besides the instant operation, users are able to make an appointment to carry out above operations by setting starting and ending time. **Fig. 7** shows a connection named "service 1" is created from node 20.20.20.14 to node 20.20.20.21 with required bandwidth. The detailed information about this connection is listed in the lower part of Fig. 7b, including routing, current status, creation delay and so on.

6.2 VM Online Migration

VM migration plays an important role in data backup and load balance of data centers. A VM migration application enables online migration of virtual machines among different data centers. With transmission advantages of optical networks, it just takes a short time to complete the migration process. In addition, the online migration pattern has no impact on users' access to resources in the migrating virtual machine. In **Fig. 8**, a VM, 863VM, is migrated from server 10.108.50.40 to server 10.108.51.124 and the migration path is 20.20.20.14 - 20.20.20.15 - 20.20.20.12. Meanwhile, users can query resource utilization information of the selected servers, such as CPU and memory status.

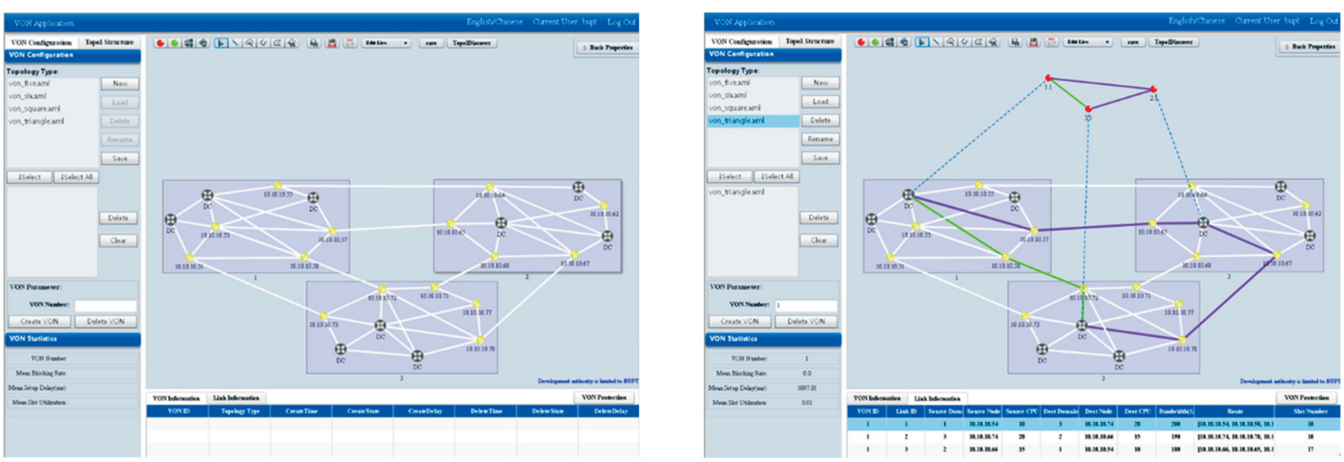
6.3 VON application

Optical network virtualization technologies support the dynamic provisioning of VONs in the same network infrastructure and achieve high-efficiency utilization of network resources. Because of its centralized control manner, software-defined networking (SDN) is regarded as a promising technology for realizing VON provisioning. In the AONI testbed, network operators can provide virtual optical networks for different customers. The topology of VON can either be pre-configured by oper-



(a) (b)

▲Figure 8. Web view of VM migration: (a) before the migration; (b) after the migration.



(a) (b)

▲Figure 9. Web view of VON provisioning: (a) before the process; (b) after the process.

ators or be customized by users. In **Fig. 9**, a triangle VON topology is successfully mapped to multi-domain networks. Meanwhile, 1+1 protection is available for services deployed in the VON. The green path in Fig. 9b stands for the working route of the service while the purple path represents the protection path.

6.4 Spectrum Defragmentation

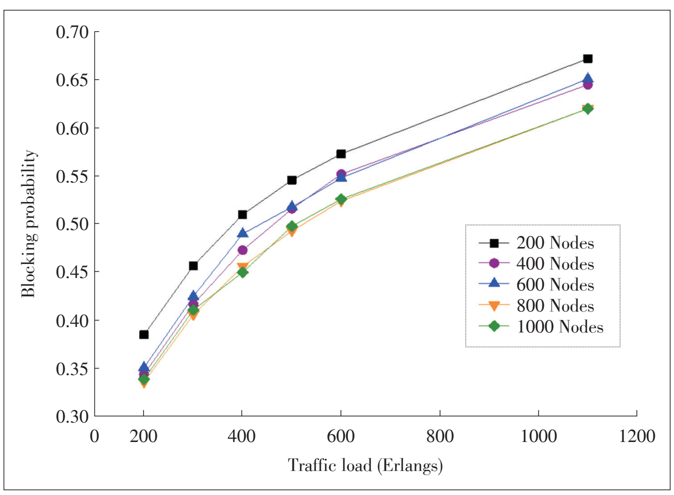
The frequent setup and release of lightpaths in a dynamic network scenario will fragment the optical spectrum into non-aligned, isolated and small-sized spectrum segments. Spectrum fragments result in low spectrum utilization and high blocking probability since these fragments could hardly be occupied for new incoming requests. With the application of spectrum defragmentation, users can have a good knowledge of spectrum utilization and trigger spectrum defragmentation if necessary to optimize spectrum resources. In **Fig. 10**, there are 50 connections or lightpaths deployed in the multi-domain network shown in Fig. 6. It is obvious that the spectrum utilization is effectively improved with the implementation of spectrum defragmentation

7 Performance Evaluation of SDON Testbed

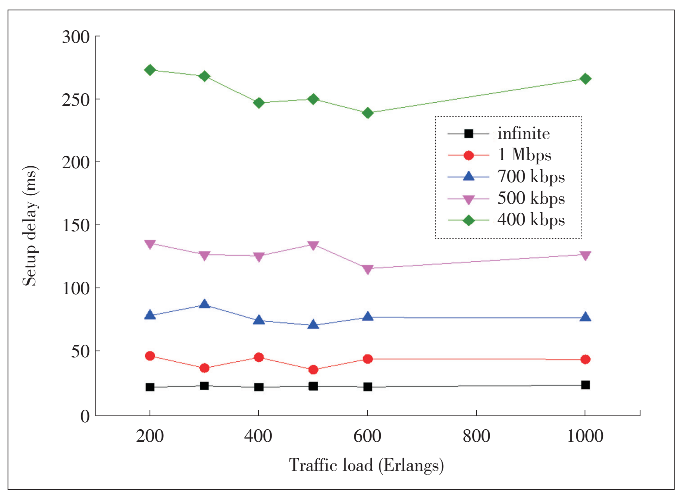
Batch testing has been conducted to evaluate the performance of this SDON testbed. Ten thousands lightpath requests are generated following Poisson distribution, and their source-destination pairs per execution are randomly chosen. The holding time of lightpath requests follows exponential distribution.

To verify the scalability of the SDON testbed, we compare the blocking probabilities of different network sizes. As shown in **Fig. 11**, the number of network nodes ranges from 200 to

▲Figure 10. Web view of spectrum defragmentation: (a) before defragmentation; (b) after DFefragmentation.



▲Figure 11. Blocking probabilities of different network sizes.



▲Figure 12. Lightpath setup delay of different output bandwidth.

1000. For each network size, the blocking probability increases with traffic load. With the same traffic load, 1000-nodes network has the lowest blocking probability since it has the highest network capacity.

In addition, the relationship between the controller output bandwidth and the lightpath setup delay is studied. The controller output bandwidth can be adjusted by the VMware Ethernet bandwidth modulator. As shown in **Fig. 12**, the output bandwidth of controller is set to five different values, including 400 kbps, 500 kbps, 700 kbps, and 1 Mbps. The average delay of lightpath setup is calculated for each case. We can see that the output bandwidth of controller has great influence on lightpath setup delay. With the growth of output bandwidth, the average setup delay decreases significantly from 300 ms to 50 ms.

8 Conclusions

With the advantage of programmable network elements, the SDON realizes service customization, adaptive modulation format, flexible bandwidth allocation and dynamic provisioning of virtual network resources with centralized control manner. This paper introduces SDON and its innovation environment—AONI in terms of network architecture, protocol extension solution, experiment platform, typical applications and performance evaluation. The SDON represents the development direction of optical networks and has broad application prospects in the future.

References

[1] *Requirements for Generalized Multi-Protocol Label Switching (GMPLS) Routing for the Automatically Switched Optical Network (ASON)*, IETF RFC4258, Nov. 2005.

[2] *Requirements for Generalized MPLS (GMPLS) Signaling Usage and Extenstions for Automatically Switched Optical Network (ASON)*, IETF RFC4139, Jul. 2005.
[3] *Requirements for GMPLS-Based Multi-Region and Multi-Layer Networks (MRN/MLN)*, IETF RFC5212, Jul. 2008.
[4] Y. Ji, D. Ren, H. Li, X. Liu, and Z. Wang, "Analysis and experimentation of key technologies in service-oriented optical internet," *Science China Information Sciences*, vol. 54 no. 2, pp. 215–226, Feb. 2011. doi: 10.1007/s11432-010-4168-5.
[5] *A Path Computation Element (PCE)-Based Architecture*, IETF RFC4655, Aug. 2006.
[6] *Path Computation Element (PCE) Communication Protocol Generic Requirements*, IETF RFC4657, Sept. 2006.
[7] *Requirements for Path Computation Element (PCE) Discovery*, IETF RFC4674, Oct. 2006.
[8] *Path Computation Element Communication Protocol (PCECP) Specific Requirements for Inter-Area MPLS and GMPLS Traffic Engineering*, IETF RFC4927, Jun. 2007.
[9] J. Zhang, H. Yang, Y. Zhao, et al., "Experimental demonstration of elastic optical networks based on enhanced software defined networking (eSDN) for data center application," *Optics Express*, vol. 21, no. 22, pp. 26990–27002, Nov. 2013. doi:10.1364/OE.21.026990.

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Dr. SONG Wenzhan is the Georgia Power Mickey A. Brown Professor of Engineering in the University of Georgia, USA. Dr. Song is a distinguished scientist and educator on cyber-physical systems informatics and security in energy, environment and health applications, where decentralized sensing, computing, communication and security play a critical role and need a transformative study. He has an outstanding record of leading large multidisciplinary research projects on those issues with multi-million grant support from NSF, NASA, USGS, and industry, and his research was featured in *MIT Technology Review*, *Network World*, *Scientific America*, *New Scientist*, *National Geographic*, etc. Dr. Song is a recipient of NSF CAREER Award (2010), Outstanding Research Contribution Award (2012) at GSU, Chancellor Research Excellence Award (2010) at WSU. He was also a recipient of 2004 National Outstanding Oversea Student Scholarship by China (only 40 in USA) during PhD study. Dr. Song also has a outstanding publication record and serves many premium conferences and journals as editor, chair or TPC member. He is also an inaugural member of OpenFog consortium involving industry and academic leaders.