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Prospects and research issues in multi-dimensional all optical networks

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Abstract Research into all optical network (AON) technology has been ongoing over the past decade, and new features are constantly being developed. The advantages of AON include large-bandwidth provisioning, low-latency transmission and low energy consumption. The basic concept underlying AON is transmission of data signals entirely through the optical domain from source to destination nodes, with no optical-electrical-optical (O-E-O) conversion at intermediate nodes. The technologies used to implement AON have undergone a series of evolutions, which encompass time division multiplexing (TDM), frequency division multiplexing (FDM), and space division multiplexing (SDM). Multi-dimensional AON (MD-AON), which leads the trend of AON's future architecture, provides a vibrant state for emerging applications such as cloud computing and Internet of Things (IoT). In this article, we review the evolution of AON architectures based on the different all optical switching and multiplexing technologies (i.e., TDM, FDM, and SDM), which is one of the main areas of focus in this article. The other main area is detailed discussion of implementations such as data plane and control plane technologies as well as resource optimization technologies for realizing AON. We also introduce several AON testbeds with their compositions and functions, and some potential application scenarios that can be implemented based on these testbeds

Keywords all optical network, multi-dimensional optical switching, software-defined optical network, optical network virtualization, all optical network innovation

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1 Introduction

Emerging applications such as high-definition video, intense social networking, and real-time gaming are significantly changing human life and behaviors. According to a recent Cisco visual networking index report [1], there will be 11.6 billion mobile-connected devices by 2020, which will lead to a significant bandwidth requirement low latency and reduced cost requirements. All optical network (AON) is considered an important information infrastructure for meeting the requirements of future Internet as it has the potential to support the continued demands for bandwidth. The basic concept underlying all optical switching is transmission of data signals entirely in the optical domain from source to destination to eliminate so-called electronic bottlenecks, and allow transmission of arbitrary signal formats, bit rates,

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and protocols. Theoretically, optical-electrical-optical (O-E-O) conversions are only processed at the edge nodes (gateways), while intermediate nodes only perform optical signal switching and multiplexing. AON has lower latency and higher energy efficiency than electrical switching networks as the data signals are operated in the optical domain.

The development of AON can in general be classified in terms of various optical transmission and multiplexing technologies. One scope of AON is based on the time domain, in which data signals access the optical network via different time slots. Classical TDM-based all optical switching technologies include optical burst switching (OBS) and optical packet switching (OPS) [2,3]. However, owing to their lack of optical buffering and caching, OBS and OPS are not used in current optical networks. Another scope of AON is based on the frequency domain, in which the data signals are multiplexed by different spectrum slots. Wavelength division multiplexing (WDM) network is a well-studied and commercialized AON paradigm based on the frequency domain [4]. Recently, elastic optical network (EON), which uses optical orthogonal frequency division multiplexing (OOFDM) or Nyquist WDM technology, has been proposed as a promising AON architecture in the frequency domain [5,6]. Finer frequency granularity can be provided by EON, which enables flexible optical layer switching and networking. The latest scope of AON is based on the space domain, where data signals are multiplexed into different spatial channels (specifically, cores and modes) [7]. SDM-based all optical network can significantly improve network capacity through extension of available spatial channels. However, it also brings extra challenges as associated with SDM routing and resource allocation which are more complex than those associated with FDM/TDM.

1.1 Contributions of this article

This article provides an integrated review that covers various aspects of multi-dimensional AON (MD-AON). We begin with the evolution of AON and its unique characteristics under different dimensions, and then the requirements of MD-AON from three planes (another view of multiple dimensions), specifically, data plane, control plane, and application plane are discussed in detail. Then, we discuss data plane enabling technologies such as MD-AON transponder, MD-AON switching node, and evaluate their functionality. Subsequently, we present some promising control plane technologies including general multiple protocol label switching (GMPLS), path computing element (PCE) and software defined networking (SDN), and discuss their characteristics and performances. Based on the MD-AON architecture, multi-dimensional optical resource allocation schemes (e.g., routing, spectrum, core allocation) and network virtualization solutions are discussed. As regards the application plane, some innovative applications are introduced based on the reported AON testbeds.

1.2 Organization

The remainder of this article is organized as follows. Section 2 presents an overview of the evolution of AON from TDM to SDM. Section 3 describes data plane technologies of MD-AON. Section 4 evaluates three kinds of control plane technologies for MD-AON. Section 5 discusses the routing and multi-dimensional resource allocation problem, as well as network virtualization technology. Section 6 presents several innovative applications based on AON testbeds. Section 7 concludes the article.

2 AON evolution

The purpose of AON is to transmit and switch data signals in the optical domain. Signals can be multiplexed and switched in many different ways. In general, a communication system can multiplex signals in three domains: time domain, frequency domain, and space domain. The continual evolution of AON depends on advanced optical processing technologies in the different domains. In this section, we review some typical cases in different AON evolutional stages.

2.1 All optical switching in the time domain

Optical time division multiplexing (OTDM) is similar to electrical time multiplexing (ETDM), but the signal transmission and switching are entirely in the optical domain [8]. OPS has been proposed as an AON solution in the time domain [9]. Similar to electronic packet networks, the user data are transmitted as optical packets that are switched by optical packet switches according to the header of the optical packet. OPS can take advantage of statistical multiplexing gain, but it needs an optical buffer to store the payload while processing the packet header. An alternative solution is optical burst switching (OBS), in which bursts of traffic are transmitted through an optical slot by establishing a connection and reserving resources end-to-end for the duration of each burst [10]. OBS combines the advantages of circuit switching and packet switching without the need for any type of buffering at intermediate nodes. However, signaling for optical time slot reservation has to be considered [11]. Another AON solution based on time multiplexing is optical flow switching (OFS) which aims to address optical switching and routing for large dynamic transactions [12]. OFS is an end-to-end, all optical transport service that provides end users with cost-effective access to bandwidth by exploiting the complementary strengths of optics and electronics [13]. All the AON solutions mentioned above are characterized by effective transmission of burst and variable IP traffic.

2.2 All optical switching in the frequency domain

By the 1990s, channels comprising multiple wavelengths could be multiplexed together onto a single fiber, giving rise to WDM. WDM techniques offer very effective utilization of the fiber bandwidth directly in the frequency domain, rather than in the time domain. In addition, wavelength can be used to perform functions such as routing and switching [14], which has become an important consideration for realization of an all optical transparent network. A WDM network is a highly commercialized optical network that is widely used in current core networks. However, the fixed and coarse granularity of WDM technology (e.g., 50 GHz or 100 GHz) restricts the optical network with tight bandwidth provisioning, inefficient capacity utilization, and high cost. Consequently, EON, which has flexible-grid technology, was proposed to overcome the drawbacks of WDM [15,16]. In EON, spectrum is further divided into finer granularity (e.g., 6.25 GHz or 12.5 GHz) called spectrum slots, and the combination of multiple spectrum slots can achieve supper-wavelength transmission. The enabling technologies of EON from component level to networking level are well studied. They include bandwidth-variable optical transponder and switch, all optical control and management, as well as resource allocation schemes [17]. In contrast of OPS/PBS, EON is considered a near-term AON solution.

2.3 All optical switching in the space domain

For single-mode/-core fiber, the total achievable capacity has almost reached its limit. One approach to increase the link capacity further is to use spatial transmission. Space division multiplexing (SDM) exploits the physical dimension “space” in terms of modes or cores to transmit data signals [18,19]. The introduction of SDM provides flexibility in the assignment of an optical channel to have spatial attributes. For example, data signals can be associated with a “label” named after different propagation modes, different fiber cores, or different strands of fiber in a fiber bundle. SDM can significantly increase the capacity of AON, but it also introduces some new challenges. The most important physical constraint is the inter-core (inter-mode) crosstalk, in which the amount of optical signal power leaking from adjacent cores (modes) to a specific one causes interference for the signal already propagating there [20]. In addition, SDM networking devices (such as optical multiplexer and de-multiplexer, SDM transponder and switch) are still in a very early stage [21,22], and associated application scope and multi-dimensional resource allocation are still under research.

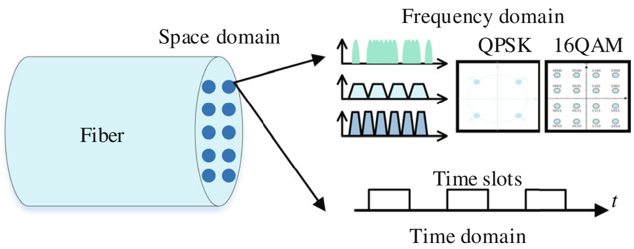

Figure 1 (Color online) Illustration of multi-dimensional optical resources integration.

2.4 AON architecture with multi-dimensional resources

MD-AON is a multiple resource integration environment that consists of time slots (time domain), spectrum slots (frequency domain), and multi-cores or modes (space domain) as shown in Figure 1. MD-AON provides the necessary building blocks and technologies to establish a flexible and scalable AON, but also brings new challenges to the optical network architecture.

For the data plane, MD-AON needs to be equipped with multi-function devices and sub-systems to support multi-dimensional resource switching (SDM-WDM-TDM). For example, multi-dimensional reconfigurable optical add/drop multiplexer (MD-ROADM) has to be designed to add and drop data signals from any spectrum slot of a core. It also has to support migration from the current WDM network or EON to the emerging SDM network. Architecture on demand (AoD) optical systems can support wide and flexible spatial as well as spectral switching [23–25].

For the control plane, MD-AON needs to coordinate multiple resources to perform routing, spectrum, time slot, and core allocation. The abstraction of multi-dimensional resources is a key point for resource allocation and optimization. In addition, MD-AON needs to support an open networking environment, where physical layer resources are programmable by upper-layer users. Software defined optical network (SDON) is considered a promising technology for exploiting multi-dimensional optical resources [26,27]. The centralized controller in SDON performs resource optimization schemes and controls the physical nodes (e.g., MD-ROADM) through a southbound interface.

With the rapid proliferation of large-bandwidth applications, optical networks are being widely developed to carry the corresponding client traffic flow. The application plane is an emerging framework for optical network, which can be accessed by end users to customize various services, such as spectrum on demand (SoD) and virtual optical network provisioning (VON). The application plane has an open northbound interface to realize programmable control through application software. The purpose of MD-AON is to provide a multi-granularity transmission infrastructure for the emerging services, and the application plane is an important tool for end users to access the optical network efficiently.

3 All optical switching fabric with multi-dimensional resources

The flexible and scalable all optical switching fabric is an important element of the data plane to build MD-AON, additional necessary building blocks for space switching need to be developed in the current time/frequency-based optical switching nodes. MD-AON can offer significant switching capabilities in all three optical domains. Large amounts of traffic can be switched using not only spatial multiplexed channels, but also wavelength/band (e.g., WDM) and sub-wavelength (e.g., TDM). Figure 2 depicts a multi-level switching architecture for MD-AON.

3.1 Sub-wavelength switching

For fine granularity switching (e.g., sub-wavelength), special and spectral resources are flexibly divided into time slots for different bandwidth requirements. The TDM switching fabric is usually equipped at the user side for sub-wavelength access and switching. It is based on high-speed optical switches such as plumbum lanthanum zirconate titanate (PLZT) [28] for rapid switching of the optical time slots (e.g.,

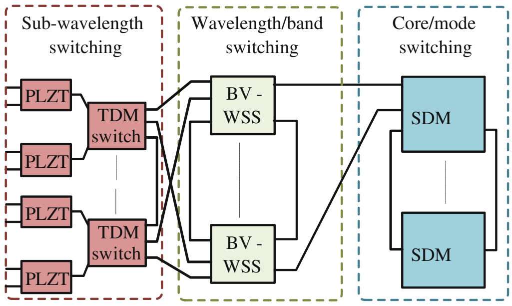

Figure 2 (Color online) Switching fabric for MD-AON.

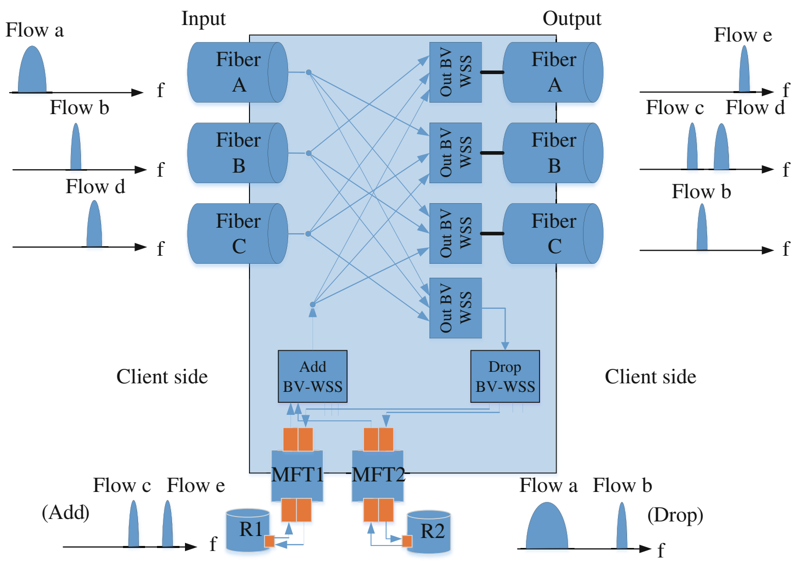

Figure 3 (Color online) Elastic spectrum switching enabled by BV-WSS and MFT.

optical packets). Optical buffers such as fiber delay lines (FDLs) are required when the switch fabric processes optical headers.

3.2 Spectrum switching

Spectrum switching has a coarser granularity than optical TDM switching. Bandwidth-variable wavelength-selective switch (BV-WSS) is a key component that can filter optical signals according to the spectral width of the incoming signals [29,30]. In general, a BV-WSS performs spectrum demultiplexing/multiplexing and optical switching functions using integrated spatial optics. The light from an input fiber is split into constituent spectral components using a dispersive element. Sliceable bandwidth variable transponder (S-BVT) also called multi-flow transponder (MFT), which is integrated into BV-WSS, can generate multiple independent optical flows for different traffic requirements [31–34]. Figure 3 shows the elastic spectrum switching enabled by BV-WSS and MFT.

3.3 Multi-core/mode switching

SDM utilizing multicore fiber has recently been proposed and demonstrated to increase the switching capacity of one fiber [7,22]. In order to apply SDM in optical mesh networks, flexible space switching and adding/dropping has to be taken into account. Because the SDM provides a coarse granularity, the combination of SDM and EON is a promising solution for future AON. Much work has been conducted on spectral and spatial EON and switching nodes [35–40]. Figure 4 shows the SDM based ROADM architecture. Another approach towards SDM based ROADMs that supports spatial super-channel routing and switching has also been proposed by Nelson et al. [35]. In order to support add/drop/express switching functions for multiple granularities, several BV-WSSs have to be cascaded for cores/modes and

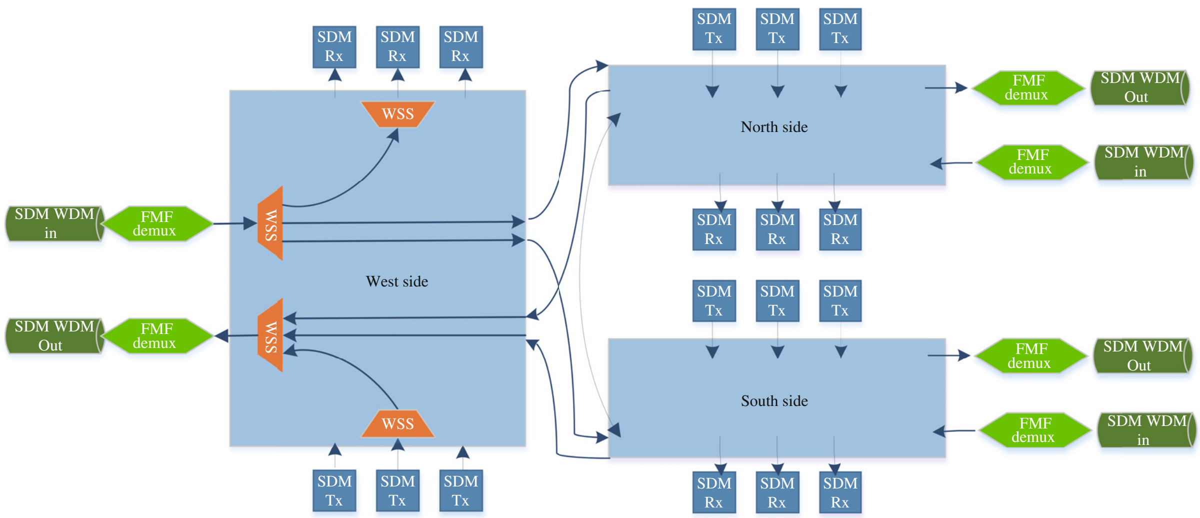

Figure 4 (Color online) SDM switching node architecture.

wavelengths switching, which might result in a scalability issue in the future owing to the port number limitation of BV-WSS. SDM-WDM switching node is the key component to realize multi-dimensional switching in a flexible manner.

Research and development of the MD-AON switching fabric is still ongoing under the ever-changing optical networking requirements. The integration of time, spectrum and space switching function in a MD-AON node is a promising solution for multiple granularities switching. Supporting AoD according to different traffic loads and properties is a potential challenge for future AON.

4 Moving from static to dynamic with intelligent control plane

With the growing bandwidth demand and proliferation of various broadband services, such as cloud computing and virtual reality (VR), the demand for a promptly responsive network is increasing. Consequently, it is necessary for intelligent control technology to be implemented in future AON. On the other hand, the rapid development of configurable photonic components and modules, such as wavelength-selective-switch (WSS) and flexible transponder, is also making dynamic light path provisioning and tuning achievable in AON [29]. Automatically switched optical network (ASON) has been introduced to fulfill the intelligent requirements of optical networks, such as dynamic setup of connections, automatic end-to-end service provisioning, and fast re-routing[1)]. Control plane is designed in ASON along with transport and management planes to accomplish the actual resource assignment and connection management[2)]. Various control plane technologies have appeared at different stages, as shown in Figure 5.

4.1 GMPLS/ASON

Generalized Multi-Protocol Label Switching (GMPLS) is tightly coupled with ASON. GMPLS is a protocol suite that has been extended from MPLS to different kinds of interfaces and switching technologies, such as packet interfaces and switching, time division multiplexing, layer-2 switching, wavelength switching, and fiber switching[3)]. As shown in Figure 5(a), a series of control plane (CP) software are distributed at each transport node and interconnected through Network to Network Interfaces (NNIs). Various functions including resource discovery, signaling, routing, connection setup and tear-down, connection protection and restoration, and wavelength assignment, are implemented through cooperation among different control nodes.

1) G.807/Y.1302. Requirements for automatic switched transport networks (ASTN) call and connection management.
2) G.8080/Y.1304. Architecture for the automatically switched optical network (ASON).
3) Mannie E. Generalized multi-protocol label switching (GMPLS) architecture. RFC 3945, 2004. IETF.

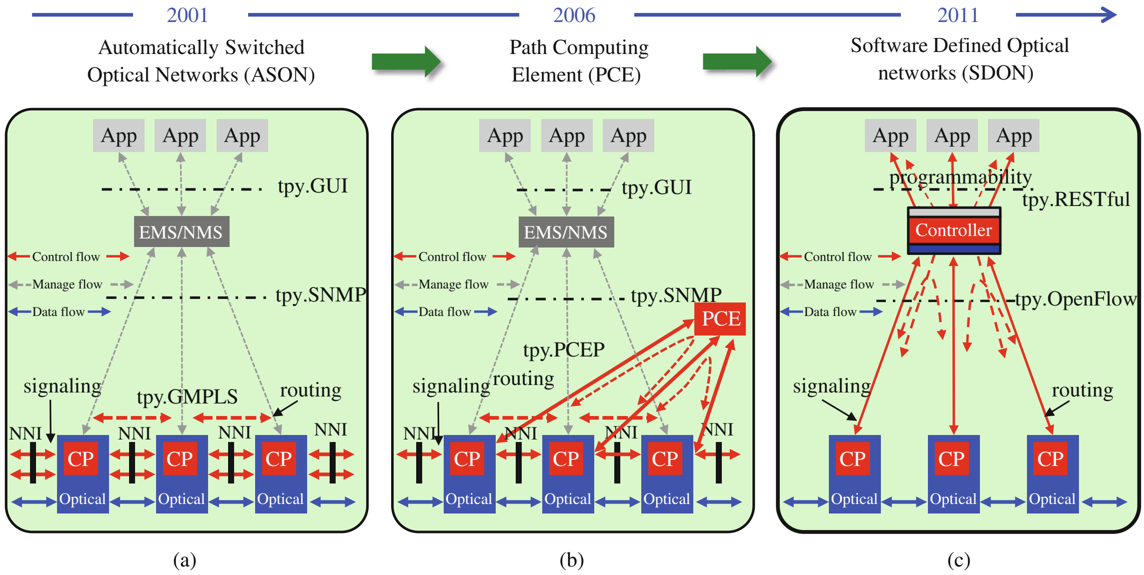

Figure 5 (Color online) Various optical network control plane technologies. (a) GMPLS/ASON; (b) PCE; (c) OpenFlow/SDON.

4.2 PCE

Path computation in large-scale multi-layer and multi-domain networks is actually complex and may require special computational components and cooperation between different domains. Then, Internet Engineering Task Force (IETF) has summarized the requirements for GMPLS-based multi-layer and multi-domain networks and has proposed a PCE framework[4)] to serve the path computation request through the PCE protocol (PCEP), as shown in Figure 5(b). As with PCE, remote routing controller (RC) has been introduced into the ASON/GMPLS control plane[5)] to provide path computation capability. To acquire the best path computation performance in both centralized and distributed routing schemes, a novel scalable framework called Dual Routing Engine Architecture in triple M scenarios (DREAM) has been proposed by Zhao et al. [41]. DREAM takes advantage of both the distributed control nodes and centralized PCE, which can carry out both fast routing and path establishment.

4.3 SDON

In recent years, SDN has attracted much attention from industry and academia because it can support programmability of network functions and protocols by decoupling the control plane from the data plane. OpenFlow (OF) is a southbound protocol of SDN that was first proposed by Stanford University to enable the flow table application in switches [42]. Extending SDN principles to include optical networks can provide a new framework, i.e., SDON, for evolving carrier grade and cloud networks [43]. SDON can potentially facilitate application-specific network slicing at the optical layer, coordination and orchestration of higher network layers, and applications with optical layers.

With the evolution of enabling technologies in the physical layer, the spectral and spatial resources in MD-AON can be exploited effectively. SDON has been implemented in EON for datacenter service migration [44]. A cognitive SDN orchestration was demonstrated over 400-Gbps OPS and Tbps-class Flexi-WDM networks [45]. The first demonstration of an SDN-enabled control plane has also been presented fully controlling node architecture configuration and bandwidth provisioning, over an SDM network consisting of three AoD nodes linked by two multi-core fibers (MCFs) [46]. However, a reasonable multi-dimensional node model and practical implementation protocols need to be designed. In addition, more SDN functions have to be developed in MD-AON to exploit multi-dimensional resources and support innovative applications in the future.

4) Farrel A, Vasseur J-P, Ash J. A path computation element (PCE)-based architecture. RFC4655, 2006.
5) Cheng D. ASON routing architecture and requirements for remote route query. ITU-T G.7715.2. 2007.

5 Routing and multi-dimensional resources allocation

5.1 Traditional routing and spectrum allocation (RSA)

A series of research works have been conducted on RSA in EON [47–50]. Static routing and the spectrum assignment problem in co-existing fixed/flex grid optical networks has been addressed [47]. This was achieved with the stated objective of minimizing the utilized spectrum when serving all the connections in a traffic matrix. Wang et al. [48] proposed an ant-based RSA approach and performed simulation experiments to evaluate their solution. Cai et al. [49] developed anode-arc ILP that led to an algorithm that jointly found routes and allocated spectrum resources. In addition, owing to the computational difficulty in solving ILP models for a large network, efficient heuristic algorithms were provided based on the multi-iteration optimization technique and three request-shuffling strategies. Yin et al. [50] investigated the spectrum fragmentation problem in EON in both the spectral and the spatial dimensions and proposed two fragmentation-aware RSA algorithms to proactively prevent fragmentation when routing and assigning the spectrum to incoming requests.

5.2 RSA with flexible transponder selection/modulation format

The transponder selection and modulation format are two important factors in the process of RSA. However, there are problems associated with routing, modulation, and spectrum allocation (RMSA) and routing, spectrum, and transponder allocation (RSTA). Fukuda et al. [51] proposed a fully distributed control plane for EON exploiting the protocol extensions of GMPLS RSVP-TE. The conventional GMPLS-based solution for RMSA problems suffers from large control plane overhead arising from OSPF-TE dissemination and the collision among requests caused by signaling latency. To address the fragmentations in EON, Yin et al. [52] investigated how service provisioning fragmented the spectral resources on links along a path, and subsequently proposed several corresponding fragmentation-aware RMSA algorithms to alleviate the fragmentation.Further, an effective routing, wavelength, and spectrum allocation (RWSA) algorithm has been proposed specifically for wavelength-convertible flexible optical WDM (WC-FWDM) networks [53].

In another approach, a two-dimensional network resource model that divides spectrum resources into fine granularity spectrum blocks over time was first constructed by Wang and Jue [54]. Then, on the basis of this model, a dynamic RMSA algorithm that considers different modulation formats for each request was designed. Tornatore et al. [55] analyzed the complexity trade-offs in the design of optical flexi-grid ring networks supporting electronic traffic grooming, regeneration, modulation format, and baud rate assignment. Subsequently, they adapted integer linear programs exploiting two different modeling approaches (slice-based and channel-based) to multiple network settings. Dallaglio et al. [56] integrated transponder selection with the RSA and proposed a resulting dynamic RSTA scheme that supports both ML-SBVT and MW-SBVT technologies.

5.3 Routing, spectrum and core allocation (RSCA) algorithm

To establish an elastic optical path in SDM networks, traditional RSA algorithms are no longer directly applicable; thus, new RSCA algorithms are needed. Some research has been conducted on RSCA algorithms for various optimization objectives [57–60]. Fujii et al. [57] proposed a novel spectrum and core allocation method that constructs spectrum regions based on the AoD concept. In their proposed method, each spectrum region respectively accommodates connections requiring the same bandwidth and the signals in the spectrum region are multiplexed and de-multiplexed with MUX/DEMUX. Fujii et al. [58] also proposed an "on demand" spectrum and core allocation method that reduces the crosstalk in MCFs from the perspective of networking. Two predefined policies were introduced to reduce not only the crosstalk in MCFs but also the blocking probability of total networks.

5.4 Multi-dimensional optical network virtualization

Optical network virtualization enables network operators to operate different virtual optical networks that share a common physical network, simplify optical layer resource management, provide flexibility in spectrum allocation, and offer secure application services. There are many types of virtualization including node virtualization, resource virtualization, and network function virtualization.

(1) Optical node virtualization. Many studies have been conducted on optical node virtualization Dzanko et al. [61] studied the benefits of AoD ROADM node structures supporting spectrum and fiber switching to overall network availability. In order to support multi-dimensional resources such as TDM sub-wavelength, wavelength, super-channel, and fiber switching, Garrich et al. [62] studied the power consumption and backplane cross-connection scalability of AoD Further, in order to reduce the number of required optical modules compared to a static ROADM design. Muhammad et al. [63] presented a cost-efficient design for non-contiguity and contiguity constrained networks with OXCs that exploits the flexibility offered by AoD. The proposed virtualization AoD node made it possible to preserve fully flexible MCF-EONs with less flexible SSSs and some fixed-grid MUXs/DEMUXs. Spectrum and core allocation methods suitable for AoD node architecture were also proposed focusing on non-uniform required bandwidths in EONs.

(2) Optical resource virtualization. Both optical nodes and optical resources can be virtualized. Chen et al. [64] investigated several cost-effective virtual optical network mapping approaches in EON. Further, an extended auxiliary graph was constructed by coordinating both the virtual optical network and the physical network to simplify virtual resource mapping, and several energy aware and spectrum resource aware mapping approaches with dedicated-path protection that minimize energy and spectrum consumption have been developed [65]. Minimum-submatrix-based energy and spectrum schemes that map the virtual links for each VON to the physical optical network by largest-smallest mapping have also been proposed. Meanwhile, Wang et al. [66] proposed an MP-based VON provisioning procedure for distance-aware flexible-grid optical networks, and investigated the impact of flexible virtual node-to-physical-node mapping on network resource utilization. Xie et al. [67] focused on the problem of impairment-constrained virtual optical network resource mapping in flexible-grid optical networks with the aim of minimizing the combined cost of working and backup optical network equipment, including transponders, regenerators, and shared infrastructure.

(3) Network function virtualization. Network function virtualization (NFV) facilitates efficient resource utilization by dynamically spinning up/down virtual network functions. There are many research efforts involved in NFV studies. Nejabati et al. [68] leveraged the flexibility and capability of optical devices, i.e., their programmability and computational power and combined these capabilities with SDN and NFV technologies. For datacenter scenarios, Muñoz et al. [69] virtualized the SDN control functions moved them to the cloud, and experimentally assessed and evaluated them in a multi-partner experimental setup for multi-tenant transport networks to dynamically deploy VONs and their corresponding virtual SDN controllers as Virtual Network Functions (VNF). Vilalta et al. [70] also presented an NFV architecture for deploying different VNFs on optical transport networks. Thus, the concept of NFV does not only apply to data plane functions (i.e., packet processing and forwarding), but also to control plane functions such as path computation.

6 Innovative applications based on AON testbeds

6.1 AON testbeds

Various AON testbeds have been built in recent years to verify the performance of novel network frameworks and enabling technologies.

(1) Application-Based Network Operations (ABNO) testbed. An ABNO-based network orchestrator has been developed for end-to-end multi-layer (OPS and Flexi-grid OCS) and multi-domain provisioning across heterogeneous control domains employing dynamic domain abstraction based on virtual node

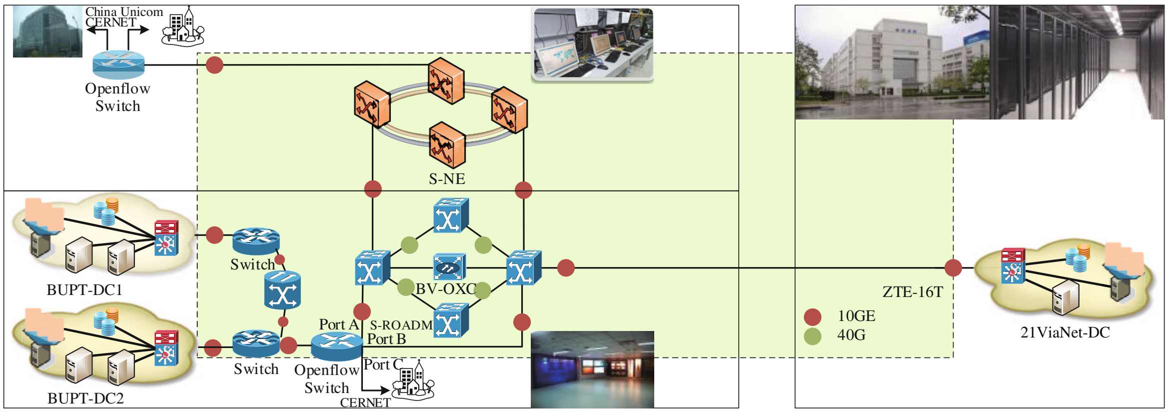

Figure 6 (Color online) AONI testbed environment.

aggregation. Details of the available transport and control plane technologies in the international testbed of the ICT STRAUSS project can be found in [71]. In the testbed, each domain has its own control plane, and the ABNO-based network orchestrator takes charge of the orchestration of different domains.

(2) SDN over SDM testbed. A testbed of fully integrated SDN-controlled bandwidth-flexible and programmable SDM optical networks has been built utilizing sliceable self-homodyne spatial super-channels to support dynamic bandwidth and Quality of Transmission (QoT) provisioning, infrastructure slicing and isolation. The experimental setup comprises three transmitters and three programmable nodes. The details of the testbed can be found in [72]. SDN-controlled automatic bandwidth and QoT provisioning over the SDM infrastructure, AoD node configuration, and self-homodyne spatial super-channel slicing, routing and switching can be demonstrated on the testbed with good end-to-end performance according to user requirements.

(3) All Optical Network Innovation (AONI) testbed. An AONI testbed has been built, as shown in Figure 6, and deployed over two main geographically distributed locations: Beijing University of Posts and Telecommunications (BUPT) and Chaoyang District in Beijing, China [73]. The testbed consists of several domains, such as IP domain, optical edge network (consisting of software defined network elements, i.e., S-NE), optical core network (consisting of software defined ROADM, i.e., S-ROADM, and bandwidth-variable OXC, i.e., BV-OXC), and datacenters. As the key component of the architecture, the control plane consists of two types of controllers: domain controllers and father controllers. Both of the controllers are extensions from the OpenDayLight project. RESTful application programming interfaces (APIs) are available in the architecture to support various applications. Based on the AONI testbed, a flexible mobile optical fronthaul network enabled by SDN has also been developed to support digital and analog radio access [74].

6.2 Innovative applications

Various innovative applications can be developed within the AON testbeds using a variety of dimensional resources, such as spectrum defragmentation, SoD, and virtual resource migration, which are explained below.

(1) Spectrum defragmentation. With agile spectrum management, EON improves spectral efficiency and brings intelligence into the optical layer. However, the twin processes of setting up and tearing down connections with mixed bandwidth sizes turn the spectral resources into non-contiguous fragments, and result in high blocking rates and low utilization of network capacity. To solve this issue, network operators need to periodically re-optimize the network and return it to its optimal state, which is defined as spectrum defragmentation [75]. Spectrum defragmentation is necessary in multi-dimensional AON. Figure 7 illustrates the occupation situation of the spectrum resources before and after the defragmentation operations, from which it is clear that the utilization of spectrum resources is significantly improved.

(2) Time-aware SoD. Various datacenter applications (e.g., service migration and backup) require a

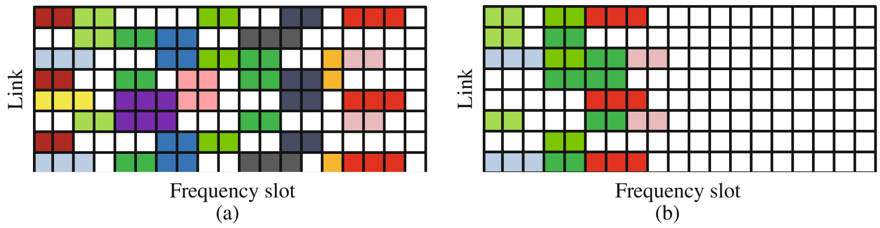

Figure 7 (Color online) (a) Before spectrum defragmentation; (b) after spectrum defragmentation.

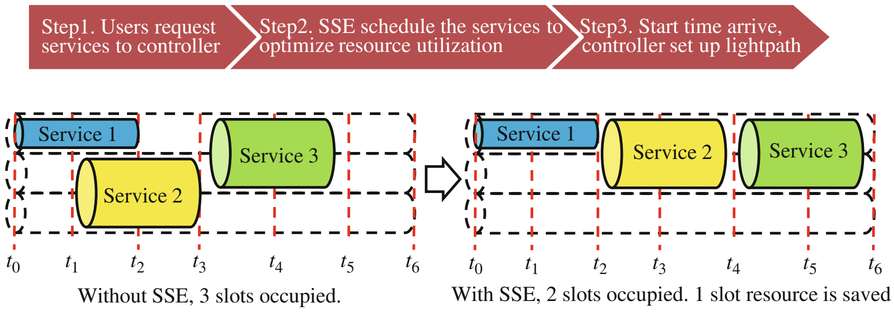

Figure 8 (Color online) Time-aware SoD.

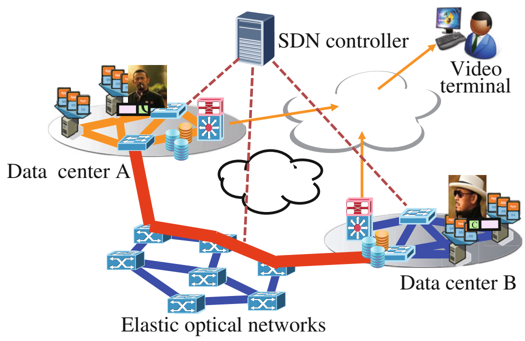

Figure 9 (Color online) Virtual resource migration between DC.

specific delay and higher availability with corresponding level end-to-end guaranteed quality of service (QoS). Because SDN architecture provides maximum flexibility for operators and facilitates unified control over various resources, the SDN/OpenFlow technique can be applied globally to control network and application resources in optical intra-datacenter networks. For example, the time-aware SoD function can be deployed to arrange and accommodate users' requests with a required QoS considering the time factor. This would improve the utilization of spectrum resources in intra-datacenter networks. A time-aware SoD provisioning algorithm based on service schedule expert (SSE) is shown in Figure 8. First, user request services are sent to the controller, and the SSE module schedules these request services to optimize the spectrum resources utilization. Finally, the controller sends a message to the optical nodes to set up lightpaths once the start time of the services has arrived.

(3) Virtual resource migration. With the rapid development of cloud computing, datacenters are now widely deployed in various areas. Connected by optical networks, these datacenters are always distributed unbalanced according to the service requirement of different regions. For uncontrollable and random requests from large numbers of clients, more tasks might focus on a small number of datacenters, which would cause partial network server paralysis. Upgrading the hardware processing power is not a fundamental solution as it would invariably rapidly increase the cost of equipment. Therefore, services focusing on some datacenters have to be dispatched to other idle datacenters by dynamically migrating the virtual machines. These operations increase the utilization of datacenter resources, improve the quality of user services, and prolong the life of physical host computers. During virtual resource migration, an effective software defined control mechanism, as well as a monitor that determines when and where to operate the migration are highly needed. A virtual resource migration architecture is shown in Figure 9.

7 Conclusion

Multi-dimensional AON exploits the network resources in time, spectrum, and space dimensions to accommodate more traffic. This article surveyed research issues in MD-AON by first reviewing the AON evolution process. Then, the architecture and switching fabric of MD-AON were summarized. Three kinds of control plane technologies, specifically, GMPLS/ASON, PCE, and SDON, were analyzed along with their features, principles, and protocols. Subsequently, routing and resource assignment issues and network virtualization issues were discussed in detail with some typical paradigms. Several testbeds of associated with AON were introduced with their composition and functions, and some potential applications scenarios. From the analysis above, we can conclude that MD-AON will be an overwhelming trend in the future. However, the question of how to exploit the multi-dimensional resources effectively and flexibly will become increasingly significant, especially with the emergence of new drivers, such as 5G, IoT, and Fog computing. End-to-end resource provisioning considering global resources will also be actualized.

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Conflict of interest The authors declare that they have no conflict of interest.

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