Optical Physical Layer SDN [Invited]

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***Abstract*—Optical system management software has been migrating toward software-defined networking (SDN) methods and interfaces. The increased programmability of SDN promises greater flexibility, dynamic operation, and multivendor compatibility for optical systems. However, physical layer control systems are complicated by transmission engineering requirements, including quality of transmission, optical power stability, and multidomain service guarantees. These challenges and recent commercial and research efforts to address them are examined.**

***Index Terms*—Multidomain service guarantees; Optical physical layer control; Optical power stability; Quality of transmission; Software-defined networking (SDN).**

I. Introduction

Software-defined networking (SDN) has become an important control and management framework for communication networks. It has found widespread applications in electrical circuit and packet switching systems. More recently, it has been used in optical system network management software [1]. Common SDN protocols such as OpenFlow have recently been expanded to include optical system compatibility [2]. In fact, SDN has the potential to provide a unified control and management solution, bringing together IP, Ethernet, and optical, which has been pursued but never realized for close to two decades.

While the use of SDN in optical network management provides the potential for greater automation and standardization, it falls short of the flexibility and real-time programmability that comes from an SDN control plane implementation. The control plane for commercial optical systems today, which we refer to here as the physical layer control plane, is proprietary. Certain components of these proprietary controls have been heavily studied such as path computation elements or engineering tools that perform impairment aware routing and wavelength assignment to determine the lightpaths prior to provisioning [3–6]. However, the actual control plane operations that set up the lightpath and tune the amplifiers, switches, and power settings along the path have not been well documented. These operations are critical for determining the speed at which wavelengths can be switched and the efficacy of an autonomous control plane. In fact, studies have shown that, if such a control plane is not carefully managed, then the system can become unstable, creating large optical power fluctuations with the potential to severely disrupt traffic [7]. Furthermore, optical systems go through heavy testing and evaluation of their control plane operation and its compatibility with the system transceivers [8,9].

This operating complexity of optical systems is hidden from the user through the network management software. Because optical systems do not expose their control planes to the operator, they cannot be operated dynamically and thus network management system (NMS) or element management system (EMS) solutions are suitable. Optical networks are operated as “set and forget” with wavelengths fixed in place for the life of the system, except in the case of a failure. Thus, the physical layer control plane is primarily used to provision channels, recover from failures, and maintain stable and reliable operation. Note that the last of these three functions is often ignored but remains important as optical system performance varies with age, temperature, and through effects such as polarization dependent loss (PDL) induced power fluctuations [10].

The use of coherent receivers and the overall maturation of optical device performance and control have provided considerable simplification of the engineering requirements. Although, higher data rates and more advanced modulation techniques tend to increase the complexity. Nevertheless, the potential to develop stable, reliable optical control planes that can be exposed to external operation exists and in fact recent efforts in industry and academia are making progress. In particular, as white box optical hardware becomes available, this creates a commercial incentive and a platform for the research and development of physical layer control systems. Increasing interest in small metro systems also creates opportunity for open control systems because smaller systems greatly ease the engineering complexity. In fact, much research on SDN control of optical systems has focused on such small systems for which the physical layer control is not needed and is typically ignored. Going to small systems, however, is not a solution and even metro systems, although short in reach, can have dozens or even hundreds of nodes. The engineering complexity scales with the number of nodes, not the transmission reach.

In this work, we extend a recent analysis and review on physical layer control using SDN [11]. We first review the role of NMS and EMS systems, which form the main interface for optical systems with SDN controllers. We also look at the automatically switched optical network (ASON) and

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generalized multiprotocol label switching (GMPLS) control planes, which are top-down and bottom-up approaches to introduce control plane functionality in the physical layer. GMPLS has found widespread use in layer 2 and for the management of data flowing through optical systems, but not for real time control of the optical signals themselves. We describe basic SDN control in relation to optical systems and review implementations in the literature. Next we describe progress on SDN interfaces and device controls for optical systems that can be used to form the basis for an SDN control plane. We examine the three main challenges facing physical layer SDN control: optical power dynamics, transmission performance guarantees, and multidomain operation. Finally, we describe recent activities in the commercial sector that are advancing the use of SDN in optical systems and for physical layer control, including white box and bright box platforms.

II. Optical Network Control and Management

Optical network control and management has evolved from NMS/EMS to ASON/GMPLS-based control plane architectures to SDN, continuously expanding network intelligence in physical layer control to support greater network functionality and upper layer services.

A. Network Management System and Element Management System

The design focus of telecommunication networks transitioned away from switched voice traffic, and this transition brought up the issue of handling a variety of complex technologies forming an integrated transport network to facilitate high-speed data and video traffic. In order to address the complexity of different physical layer technologies, EMSs are used to control and configure the diverse physical technologies and provide abstracted information to the NMS through its northbound interface for high-level management.

An EMS typically manages a group of elements of the same type or system of telecommunications network equipment [12], which forms a domain. The complete management information of all the network elements (NEs) within each domain can only be exposed to its EMS, which acts as the sole mediator of control and management between the NEs and network management layer. The goal of the EMS is to control and manage all the aspects of the domain and make the most use of the physical layer resources. Its key functions can be divided into five categories: fault, configuration, accounting, performance, and security management. An EMS manages the functions and capabilities within each NE but does not manage the traffic between different NEs in the network. While in the management layer, a NMS is a set of software tools that allows an IT professional to supervise the individual components of a network and support management of the traffic between NEs. Standard EMS/NMS interfaces have been investigated and developed to enable EMS-NMS communications, such as common object request broker architecture [13], simple network management protocol (SNMP) [14] and transaction language 1 (TL1) [15].

In the EMS/NMS control and management architecture, telecommunications network management can be performed, but network control can only be configured with operator inputs. Its shortcomings include manual or offline automated error-prone provisioning, long provisioning times, inefficient resource utilization, difficult interoperability between the packet client networks and optical networks or between networks belonging to different operators, and complex network management. These issues all create strong incentives to introduce intelligence into optical network control and management architectures.

B. Control Plane-Based Intelligent Network Control and Management

In order to achieve fast dynamic provisioning, easier network operation, higher network reliability, scalability, and simpler planning and design [16], control-plane-based intelligent network control and management architectures for optical networks have been proposed. By moving the configuration management from NMS to distributed control planes, and introducing distributed database and intelligence at NEs, the key functions of signaling, routing, and discovery can be realized.

When designing an optical network control plane, several fundamental architecture principles should be taken into consideration: 1) decoupling of services from service delivery mechanisms; 2) decoupling of quality of service (QoS) from realization mechanisms; 3) providing boundaries of policy and information sharing; 4) providing for various distributions of control functionality among physical platforms; 5) decoupling of topology of the controlled network from that of the network supporting control plane communications (SCN) [17]. Based on those principles, much work on global standardization for distributed control planes has been done. The telecommunication standardization sector of the International Telecommunications Union (ITU-T) [18] proposed a reference architecture for an ASON [19], while IETF [20] extended the multiprotocol label switching (MPLS) protocol [21] to GMPLS [22] to support distributed optical network control plane functionalities.

1) ASON: ASON is a top-down approach that aims at producing protocols to meet well-defined architecture requirements for synchronous digital hierarchy (SDH)/ synchronous optical networks and wavelength-division multiplexing (WDM) optical networks. It considers business and operational aspects of real-world deployments and involves both a service (*call*) and a connection (*connection*) perspective. A *call* supports the end-to-end service provisioning without violating the independence requirement of the various businesses involved, and a *connection* can automatically provision network connection(s) spanning one or more managerial/administrative domains, in support of a service [17]. There are three types of

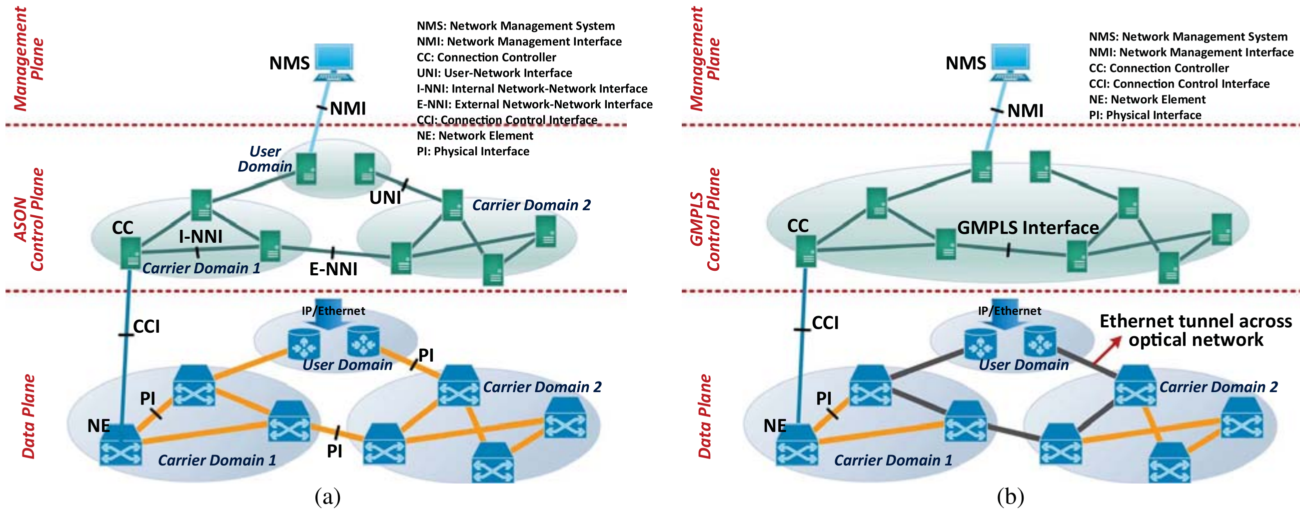

Fig. 1. (a) ASON-based optical network control architecture. (b) GMPLS-based optical network control architecture.

connections, i.e., permanent, soft permanent, and switched connections. A permanent connection is the connection whose provisioning is triggered by the management system, while a switched connection is established on demand by the communicating end points using a dynamic protocol message exchange. A soft permanent connection is a combination of permanent connections at the user-to-network and network-to-user sides and a switched connection within the network. These three types of connections all together support providing agile service provisioning under various requirements.

Figure 1(a) illustrates the ASON-based optical network control architecture. The ASON control plane is divided into different domains corresponding to those in the data plane. The internal network-to-network interface (I-NNI) is used for communication between connection controllers (CC) in the same domain, while the external network-to-network interface (E-NNI) [23] is designed for inter-domain information exchange. The client and server relationship between a user domain and a carrier domain requires a specified interface to invoke services, which is referred to as the user network interface (UNI) [24]. Physical layer control is executed through the connection control interface (CCI), and the control plane elements are managed by the NMS through the network management interface (NMI).

2) GMPLS-Based Optical Network Control Plane: Opposite to the ASON, the GMPLS-based optical network control plane is a bottom-up approach, which makes use of existing protocols in response to industry requirements. The evolution of the protocol starts from MPLS, which is treated as a layer 2.5 protocol to provide a unified data-carrying service for both circuit-based clients and packet-switching clients. Then traffic engineering (TE) was introduced to form MPLS-TE. MPLS control was applied on optical channels (wavelengths/lambdas) and optical interior gateway protocol (IGP) TE extensions were first made in multiprotocol lambda switching (MPλS). GMPLS is an application of MPLS control on layer 2 (ATM/Ethernet), TDM circuits (SDH/SONET), and optical channel (wavelength/fiber), and its IGP extensions include open shortest path first (OSPF) and intermediate system to intermediate system (IS-IS). More extensions were added to GMPLS to make it compatible with G.707 SDH [25], G.709 OTN [26] standards, and enable hitless restart and recovery functionalities. The typical protocols in GMPLS include resource reservation protocol (RSVP)-TE for signaling, OSPF-TE for intra-domain routing, ISIS-TE for inter-domain routing, and link management protocol (LMP) for link management.

The GMPLS-based optical network control architecture is shown in Fig. 1(b). Compared with ASON control planes, the GMPLS control plane aims to act as a unified control plane, which can interoperate across different domains and different layers enabled by the GMPLS protocols. Because it evolves from MPLS, the GMPLS-controlled optical networks are treated as pipes for Ethernet tunnels. The CCI is also used for physical layer controls in GMPLS-controlled optical networks.

GMPLS has been widely deployed in many operator's networks and makes use of the label switching capabilities to better manage aggregated data at layer 2 and basic wavelength provisioning functions in optical networks but falls short of a unified control plane solution in real-life deployment [27].

3) Compare ASON and GMPLS: ASON is a network architecture designed to facilitate intelligent optical networking, while the GMPLS is a protocol suite that can potentially be used to implement the general control plane architecture of the ASON or other architectures. The GMPLS suite explicitly considers data and transport networks and specifically addresses the I-NNI interface at the control plane level. However, several issues have hampered widespread commercial use of the optical functionality, including the lack of a standardized inter-domain routing architecture and no integration across non-GMPLS enabled networks. Furthermore, neither approach addresses the physical layer transmission and control challenges associated with optical switching. GMPLS has found application in layer 2 and for managing optical connections but not for real-time or automated optical signal switching operations in the physical layer.

C. Software-Defined Networking Architectures for Optical Networks

Starting with the higher network layers, Ethernet, and IP switching, software-defined networking (SDN) has more recently been proposed and adopted for optical networks. It aims to solve the issue of control plane complexity, providing common map-abstraction of network resources and enabling a gradual adoption path for new control planes [28]. SDN has been widely explored as a valuable tool to enable greater control and customization of network operation.

SDN, which has been defined as a networking paradigm to enable network programmability through centralized control [29], decouples the control plane from the data plane, recognizes the control plane as an operating system and abstracts the applications from the hardware. It allows for fast technology innovation in the control plane, and its centralized control characteristic can address some inevitable issues of control and management complexity in distributed network control architectures. Those give it potential capabilities for handling networks as a single entity and to enhance network flexibility, interoperability, and intelligence.

As illustrated in Fig. 2, SDN architectures can be coarsely divided into three layers: infrastructure layer, control layer, and application layer. The communication between these layers are enabled by an SDN controller's northbound interfaces (to application layer) and southbound interfaces (to physical infrastructure layer).

1) Infrastructure Layer: The infrastructure layer contains both network physical layer elements and virtual resources, which can be exposed to the control layer for network control and management. Traditionally, network infrastructure and elements are integrated with

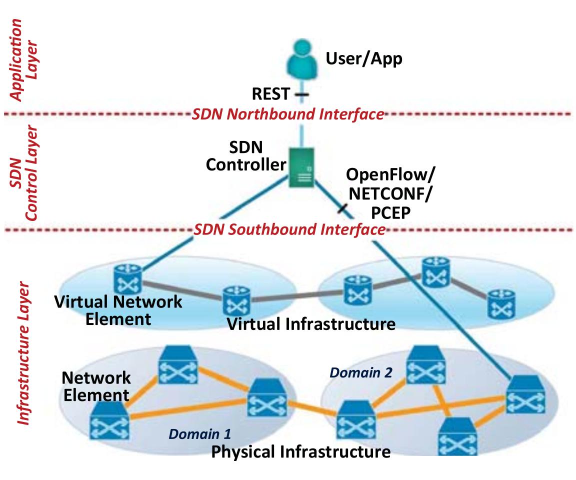

Fig. 2. SDN-based optical network control architecture.

vendor-specified decision-making and control capabilities to automatically perform network actions, such as routing and wavelength path provisioning. In SDN, the autonomous control functionalities are decoupled from physical layer elements, letting the physical layer just act purely based on control instructions from the control plane, thus reducing its complexity and improving its programmability.

2) Control Layer: The control layer is a centralized logic entity that typically has visibility into the entire network. It is responsible for programming the network elements in the infrastructure layer according to requirements from the application layer. The control layer is highly flexible and equipped with various control and management-related functionalities, serving as the key component of SDN.

3) Application Layer: The application layer is used to facilitate network applications, which make use of the control layer to execute basic network functions over the physical and virtual infrastructures. The operations of the application layer rely on abstracted network information provided from the control layer and include control-related actions such as network topology discovery and traffic provisioning as well as higher-level network management functions such as network data analysis.

4) SDN Interfaces: SDN interfaces include the northbound interface and the southbound interface. Representational state transfer (REST) [30] is a typical northbound interface for flexible communication between the control layer and the application layer, and is usually designed as an API [31]. The southbound interface is a logic connection linking SDN controllers to physical layer network elements. Multiple protocols can be used to realize the southbound interface, such as OpenFlow [32], network configuration protocol (NETCONF) [33], and path computation element protocol (PCEP) [34].

5) Integration of SDN/GMPLS: Path computation elements (PCEs), which were originally designed for path computation in optical networks with GMPLS, can also be extended to act as an SDN controller with some functional and signaling extensions. Together with a GMPLS control plane, the integrated PCE/GMPLS control architecture can perform on-demand dynamic optical network control and management functions. Intelligent inter-domain connection provisioning for multidomain multivendor optical networks enabled by a distributed stateful PCE and GMPLS control architecture has been experimentally realized [35], and a field trial was conducted using PCE-based optical signal-to-noise ratio (OSNR)-aware dynamic restoration in multidomain GMPLS translucent networks [36]. Recently, PCEP was also used to implement the southbound interface (SBI) in the SDN architecture for configuring optical network elements [37].

D. SDN Implementations in Optical Networks

Optical networks are widely used today in data center, access, metro, and long-haul networks. Much work has focused on software-defined control for optical networks in various network environments to improve network control capabilities and push toward the convergence of heterogeneous networks, which are enabled by the intrinsic SDN features of flexibility and interoperability.

Research has shown that applying SDN control to upgraded optical line terminals (OLTs) and optical network units (ONUs) [38,39] can improve control capability and possibly reduce network energy consumption in passive optical networks (PONs). Different types of networks, i.e., optical metro and wireless access networks, can be converged through SDN to support cloud and mobile cloud computing services [40,41]. Different transport technologies, such as WDM, flexi-grid, and packet switched, can also be uniformly controlled by SDN [42]. Furthermore, different optical switching platforms, i.e., optical circuit switching (OCS) and optical burst switching (OBS) [43], and different multiplexing technologies, i.e., spatial-division multiplexing (SDM), time-division multiplexing (TDM) and WDM [44], were experimentally coordinated by introducing SDN control. In addition, a converged intra- and inter-data center network was studied in which SDN control provides multirate, flexible bandwidth allocation in the optical layer for virtual machine migration [45].

III. Basis: Software-Defined Control Capability of Optical Physical Layer Components

In order for the higher-layer software-defined control and management functions to utilize the physical layer, they require control over the physical layer infrastructure, which must reliably carry out physical layer operational controls. In order to be compatible with the SDN architecture, a new portfolio of optical network equipment and devices integrated with SDN control capability is needed, such as wavelength selective switches (WSSs), optical channel monitors, optical amplifiers (OAs), and bandwidth-variable transceivers (BVTs). For the purposes of smooth network upgrades and convergence of heterogeneous networks, existing network physical layer components can be upgraded by using retro-fitting methods to turn non-SDN optical devices into SDN controllable ones. In this section, SDN investigation into two main optical physical layer components, i.e., transceivers and switching elements, will be described, and an introduction on retro-fitting methods for non-SDN network devices will be provided.

A. SDN Controlled Transceivers

SDN controlled transceivers can provide flexible transmission characteristics based on network states for different traffic demands with full programmability. The transmission characteristics include channel bandwidth, modulation format, coding type, and subcarriers.

SDN was used in a flexible bandwidth network enabled by adaptive modulation, i.e., switching between binary phase-shift keying (BPSK) and quadrature phase shift keying (QPSK), and spectrum-positioning in real time [46]. A flexible SDN transmitter supporting more modulation formats ranging from BPSK, QPSK to 8QAM and 16QAM without hardware modifications, as well as various transmission rates, was also experimentally demonstrated [47,48]. Adaptive modulation is achieved by adjusting the electrical binary drive signals of the Mach–Zehnder modulator to generate different symbol rates and modulation formats. The flexible receiver is also able to automatically detect various modulation formats and symbol rates and measure the bit-error rate (BER) which serves as a trigger for modulation format switching at the transmitter. The control feedback for these transceivers was realized through SDN controllers and OpenFlow extensions were proposed to enable the control of the transceivers.

Apart from adaptive modulation, more dimensions of flexibility can be introduced to SDN controlled transceivers, such as subcarrier and coding type. An SDN programmable bandwidth-variable multiflow transmitter (as well as its corresponding receiver) with various low-density parity-check (LDPC) coding types has been investigated [49,50]. The SDN controlled flexible transmitter and receiver allows for the setting the number of subcarriers, the subcarrier bitrate, and the LDPC coding rate.

A virtualized BVT architecture [51,52] consists of an optical subcarrier pool and an optical modulator pool, which can generate various combinations based on the service requirements. The optical subcarrier pool contains multiple optical carriers, in which channel spacing and central frequency can be independently selected. And the optical modulator pool contains multiple modulation formats that can be selected independently from the subcarriers. A virtual transceiver is a combination of a particular set of subcarriers and a particular modulation format generated by a virtualization algorithm.

B. SDN Controlled Switching Elements

Switching elements form the basic function module for switching and adding/dropping wavelength channels carrying optical signals without optical-electrical-optical (OEO) conversion. Optical switches provide transparent optical switching entirely in the optical layer with high bandwidth, low latency and high energy efficiency. Traditionally in commercial systems, switching elements are pre-configured in a “set and forget” mode of operation such that changes of a wavelength channel (including routing path and wavelength assignment) cannot be done dynamically without interruption of other channels. SDN controllable switching elements provide a promising solution for dynamic, flexible optical network reconfiguration.

The reconfigurable optical add-drop multiplexer (ROADM) is a typical switching element in optical networks. Colorless, directionless ROADM architectures [53] use WSSs and provide SDN controlled wavelength channel cross-connection capabilities. Contentionless, colorless, and directionless ROADM architectures have been proposed that can maximize switching capability [54,55].

A function programmable add/drop on demand architecture for ROADMs which leverages high port-count optical cross-connects at the add/drop bank was also proposed and experimentally evaluated [56].

A notable industry effort for SDN controlled switching elements is Open ROADM [57], which decouples software from conventional proprietary systems to increase the pace of innovation and competition in hardware, as well as enabling SDN software control and abstraction through open interface definitions. The multisource agreement (MSA) for Open ROADM creates the device, network, and service models for interoperability specifications of open hardware and SDN control, described in YANG data models. A "learning living network" built on Open ROADM was demonstrated, and the margin allocation of this network was evaluated by estimating the wavelength path's performance based on the pre-tested and the measured BERs of spared and existing paths, respectively [58].

C. Retro-Fitting Methods

The interoperability between SDN-controllable networks and non-SDN networks can be enhanced through retro-fitting methods that turn non-SDN network elements into SDN-compatible ones. This usually involves adding network elements or a virtual layer as the interpreters between SDN standardized protocols and device specified control interfaces. An agent was used for this purpose to create abstracted models of network elements [59–61], with the northbound SDN interface supporting the OpenFlow protocol. The southbound interface of the retro-fitting elements depends on the optical physical layer device control interfaces. If the devices are equipped with a native management system, the control may be through SNMP, TL1, or proprietary (vendor-specific) APIs. Otherwise, the network devices can be controlled by the retro-fitting elements directly through its hardware control interfaces, such as Ethernet, USB, and RS232.

IV. Goal: Software-Defined Optical Networking With Guaranteed Transmission System Performance

Though much progress in developing programmable optical infrastructure and SDN control functionality for optical systems and devices has been achieved, including both SDN control plane implementations mentioned in Section II.D, and SDN compatible network elements and devices described in Section III, the provisioning of optical circuits through these networks still requires extensive simulation and testing of engineering rules in order to guarantee transmission quality and system stability. However, most of the prior work is focused on SDN control functionality demonstrations that are independent of optical transmission system research considerations, in which the physics of optical transmission and the design of optical transmission systems must be addressed [62]. It is feasible for research in small networks to neglect the transmission effects and issues or artfully avoid them through elaborately designed configurations. In real-life commercial systems, the complexity of transmission system design must be taken into consideration so that the system can stay reliable and perform to specification [63]. A SDN function which enables dynamic on-demand optical network control and management will not be viable if it may render the system unstable. Even temporarily disrupting traffic or degrading performance would not be acceptable. Large international research projects have addressed control software for on-demand functionality in optical systems, but the physical layer system control, e.g., how to tune the amplifiers and/or switches to maintain error free performance, remains the missing step. On the other hand, though many SDN studies include PCE or quality of transmission (QoT) estimators in their control operations, they often only perform software simulations or small-scale implementations that may not reflect the real-world challenges of optical transmission control [64].

In this section, optical power control methods and impairment-aware path computation for transmission performance guarantees enabled by software-defined control will be introduced. An extended discussion on multidomain network environments will also be presented.

A. Optical Power Control

When switching or adding/dropping wavelength channels in optical transmission systems, the variable optical powers of different channels interact with each other through optical amplifiers, fiber nonlinearities, and power control elements (e.g., WSSs). This may cause optical channel power instability and result in transmission-quality degradation. These phenomena can become much more severe in a network environment, in which the propagation of optical channel power fluctuations can form a closed loop. The worst case corresponds to an entire optical channel forming a closed loop, which can result in optical lasing [65]. Therefore, this condition is carefully guarded against during control operations, including leakage of optical power at filter edges. Even when channels are prevented from forming closed loops, the interactions between channels in different parts of a mesh network can generate fluctuations to form closed loops and create disruptions.

Based on the response timescale, optical power instability can be categorized into two groups: optical power transients [66,67] and optical power excursions [68,69], both of which are examples of optical power dynamics. Optical power transients occur on short timescales (typically <1 ms) and are caused by the optical amplifier response. They can be largely mitigated through fast feedforward and/or feedback control to the EDFA pump power [70,71]. Optical power excursions persist over much longer timescales and are caused by channel power interactions occurring from a wide variety of sources, including amplifiers, and can be addressed through individual channel power corrections in specific network elements, such as WSSs.

The optical power control stability problem for optical systems was first defined in two early landmark papers [72,73], and was first experimentally observed for constant power controlled amplifiers [74] and later for constant gain controlled amplifiers [75]. The study of these optical power dynamic effects, particularly their evolution over long distances, has been complicated by limited experimental methods. Traditionally, optical transmission is studied using recirculating loop experiments, which in general do not allow for transmission control because the "recirculation" provides a feedback path that can impact control. In order to minimize the impact on the constant gain control of the amplifiers, a technique for keeping the total number of channels constant to study the impact of channel reconfiguration in a recirculating loop was developed [76,77]. However, its complexity and limitations make it problematic for many applications.

Other research methods have been introduced into optical power stability control studies. Experiments have shown that stable power control can be achieved by sequencing channel power tuning on each node in a 3-ROADM ring network. While sequencing is time consuming, a distributed node scheduling algorithm that dynamically defines domains for independent node control allows for simultaneous sequenced control operations in a network was demonstrated through network simulations [7]. The impact of topology, traffic, and amplifier physics on node-to-node channel-power coupling effects was also investigated, and a control strategy for scheduling the adjustment of control elements was evaluated through simulations [78]. A global power control algorithm, which uses live optical performance monitor (OPM) measurements to enable dynamic optical networking, was proposed and evaluated through simulations and experiments [79]. Recently, machine learning algorithms have been introduced for wavelength selection of dynamic channel add/drop [80] and power preadjustment [81] with the objective of minimizing the channel power divergence on provisioning. Our recent study shows that using fast tunable lasers can provide a new level of control, which can be used to enhance WDM network power stability [82].

An example of a commercial software system for transmission quality control is software control of transmission (SCOT) [83], which can control both total and per-channel power through built-in optical spectrum analyzers and photodetectors located at each node. Novel Raman pump control algorithms were utilized [84], and fault isolation was facilitated by using optical supervisory channels (OSCs). The transmission of the channels that are added by the upstream ROADMs can be automatically established by SCOT, which is enabled by node-to-node communications.

B. QoT Guarantee With IA RWA/RSA

The transparence of optical lightpaths allows the accumulation of physical layer impairments through long-distance propagation, which may deteriorate the quality of transmission (QoT) resulting in unacceptable network performance. Physical layer impairments in optical networks include signal power attenuation, amplified spontaneous emission (ASE) noise, polarization mode dispersion (PMD), PDL, chromatic dispersion (CD), group velocity dispersion (GVD), etc., which are complicated to address. PCEs are designed to execute physical layer impairment-aware (IA) routing and wavelength assignment (RWA) or routing and spectrum allocation (RSA) in flex-grid networks for QoT guarantees. The IA path computation usually requires RWA/RSA to meet some physical layer impairment goals, such as a BER or an OSNR threshold at the receiving end, which requires the knowledge of physical layer impairment parameters and the adoption of QoT models. IA RWA that considers the OSNR at the receiver was experimentally demonstrated [3], and IA RSA schemes for dynamic elastic optical networks were also proposed [4,5]. Strategies that either avoid or minimize the extensive computation of physical layer nonlinearities in IA RSA, with minimal trade-offs on network blocking performance, were proposed for transport SDN [85]. IA RWA for multidomain optical networks under the backward recursive path computation (BRPC) framework was also investigated, in which k end-to-end shortest paths are considered, and their BERs are checked [6].

The EU DICONET Project [86] is aimed at considering the impact of physical layer impairments in the planning and operation of all-optical networks, and its main outcome is the impairment-aware dynamic network planning and operation tool (NPOT) [87,88]. Its key modules consist of the physical layer performance evaluator and the IA-RWA engines, whose performance over a nation-wide core network was evaluated through experiments. NPOT predates SDN but incorporates many of the elements found in recent optical SDN controllers.

In industry, an engineering and planning tool (EPT) for an ultra-long-haul optical mesh transport system was developed and commercially deployed by Lucent Technologies [63]. The EPT can handle the planning of complex networks with numerous highly nonuniform long wavelength paths. This can be done by computing the expected system margin based on a Monte Carlo analysis of the statistical variations in various physical layer impairments and attempting to find the least-cost design providing necessary performance.

C. Multidomain Dilemma

A key benefit of SDN resides in the logically centralized control and management entity. With holistic knowledge and a global view of the network, efficient and optimized routing, and resource allocation, as well as network operational controls, can be conducted. However, the multidomain dilemma is inevitable in SDN-controlled optical networks because optical networks are divided into multiple domains according to geographic location, different carrier ownership, and network equipment manufacturers. The complexity of physical layer control and its proprietary implementation in optical systems can lead to unpredictable or unstable behavior when connecting optical systems across domains. One is left with either giving up on end-to-end control for optical networks or dealing with the complexity of multidomain transmission and control.

At present, the network inter-domain exchange is performed in layer 3, which involves OEO at each

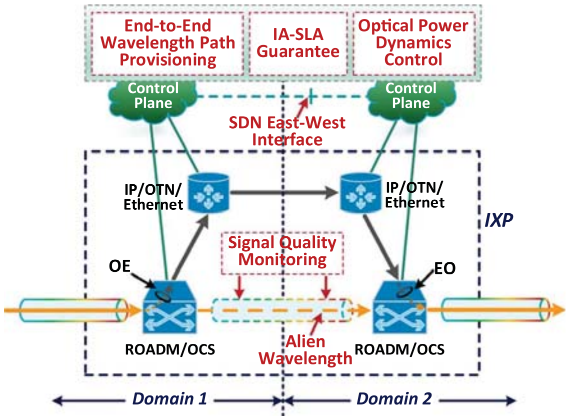

Fig. 3. Inter-domain exchange in multidomain optical networks.

Internet exchange point (IXP). All-optical inter-domain exchange has the potential to provide higher bandwidth, lower latency, and higher energy efficiency. In recent years, optical systems have added support for alien wavelengths, which are signals from transceivers that were not designed and tested for the system. For transparent IXPs, alien wavelength support needs to be extended to midstream introduction, and optical signal monitoring mechanisms need to be introduced for service-level agreement (SLA) enforcement (as shown in Fig. 3). The end-to-end QoT guarantee requirement also brings challenges in effective information exchange through the east–west interfaces between different SDN controllers, with the goal of enabling software-defined inter-domain peering without sacrificing confidentiality inside each domain. The collaborative behaviors between different SDN controllers needed for end-to-end wavelength path provisioning, along with IA-SLA guarantees and optical power dynamics control, also needs to be addressed.

IA end-to-end inter-domain path computation algorithms leveraging BRPC were proposed for multidomain wavelength switched optical networks [6,89]. Recently, our group presented a transparent software-defined exchange (tSDX) [61], in which all-optical inter-domain exchange at IXPs with real-time signal quality monitoring for SLA guarantees is realized. In conventional inter-domain exchanges, optical signals are converted to electrical and then go to another domain through routers peered with border gateway protocol (BGP) sessions. tSDX introduces optical express connections (OECs) to let the signals be transmitted entirely in the optical layer to other domains. OPM, together with an SDN control system, is used for real-time in-band continuous signal quality (more specifically, OSNR) monitoring on each wavelength channel for multidomain transmission system performance guarantee.

V. Enabling Physical Layer Programmability Through Open Control Systems

The research and evaluation of physical-layer SDN to enable optical network programmability requires an effective way to investigate potential solutions against common reference platforms. Opening optical system control (referred to as open control in the following) to research is a promising direction, in which different solutions can be developed, tested, and compared. In this section, two approaches to open control systems for optical networks will be introduced as well as several representative efforts.

A. White Box and Bright Box

When introducing SDN control into optical networks, especially the optical physical layer, two main directions can be considered. The first is the bare metal white box approach [shown in Fig. 4(a)], in which all the network functionalities and physical layer control capabilities are moved from network elements to SDN control planes, except for some drivers for hardware-related operations and device controls such as automatic gain control in amplifiers. In this approach, the SDN control planes or the SDN controllers have full view and control of the network and are responsible for performing all the physical layer operational functions, even the basic ones inside each node, such as setting amplifier gain targets or controlling WSS channel switch settings. There is generally no communication channel for control message exchange directly between network nodes, all the communication and coordination between different nodes must be carried out through SDN controllers. In this way, each node can be treated independently and sourced from different vendors on a component-by-component basis. However, the white box approach loses the benefits of in-band communication for multinode control operation and coordination, which can be faster and more scalable. A potential way to compensate this is to build standards for in-band communication or other node to node capabilities, in order to let network nodes from different vendors talk in the same language.

The second approach is referred to as the bright box model [shown in Fig. 4(b)]. Similar to the traditional optical system, the optical system in the bright box model also includes a control or operating system, which in this case is SDN control-compatible. Physical layer control complexity can be fully handled by this control or operating system and hidden from upper layers. Effectively, the proprietary network control system can be turned into an SDN controller and make use of abstraction to communicate and work with other SDN controllers or network operating systems. Different controllers or control modules and algorithms can be implemented, taking advantage of the controls available and unique performance characteristics of each optical system. This approach also creates a hierarchy or effective layering, similar to current systems, which may be more scalable given the complexity of physical layer control. The exact composition of the layering and its impact on the control performance is a subject of research.

B. Representative Efforts for Open Control Systems

There are many ongoing efforts on open control systems to extend and adopt SDN into optical networks.

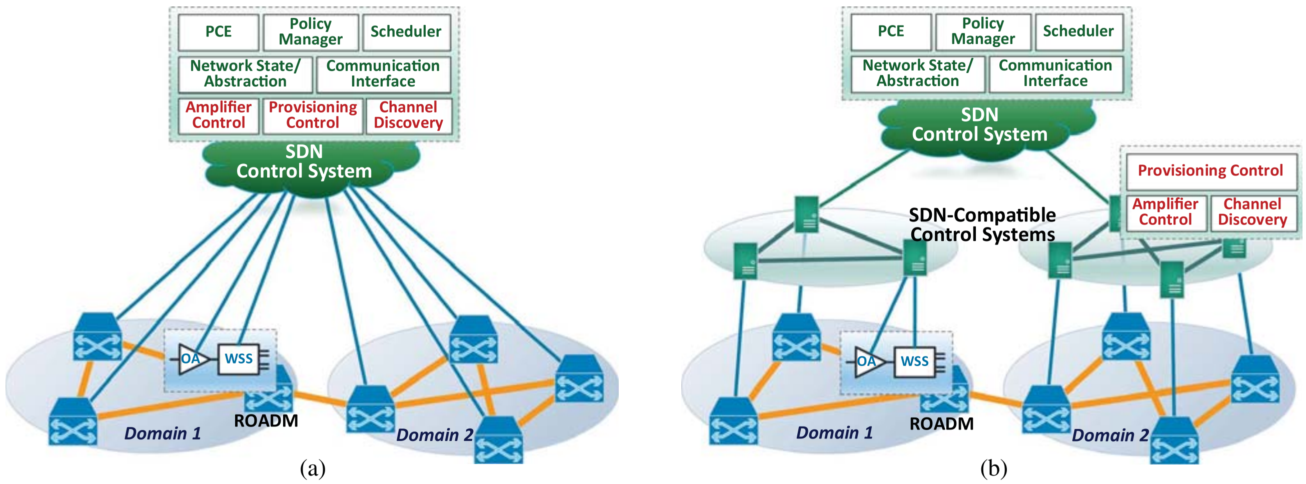

Fig. 4. Optical network open control approaches: (a) white box; (b) bright box.

Open ROADM [57], a new industry multisource agreement initiative, and Facebook Voyager [90] are examples of the white box approach, which decouples software from conventional proprietary systems to enhance innovation and competition in the hardware as well as optical layer flexibility and software controllability. OpenConfig [91] aims at moving networks toward a more dynamic, programmable infrastructure by adopting SDN principles such as declarative configuration and model-driven management and operation. It can be thought of as a standard for EMS and NMS systems that interface with an SDN architecture.

Many SDN open control platforms are developed and shared for building SDN controllers or control systems compatible with standardized protocols to enhance network interoperability. NOX [92] is the first OpenFlow control platform initially developed at Nicira Networks in C++ and was donated to the research community in 2008, thus making it the basis for many and various research projects during the early exploration of SDN. The Floodlight Open SDN Controller [93] is an enterprise-class, Apache-licensed, Java-based OpenFlow controller supported by a community of developers, including Big Switch Networks. It supports a broad range of virtual and physical OpenFlow switches with some high-performance designs. OpenDaylight [94] is currently the largest open-source SDN control platform, which gathers a community of solution providers, individual developers, and users to deliver interoperable and programmable networks to service providers, enterprises, universities, and a variety of organizations around the world. A component-based software-defined networking framework called Ryu [95] can provide an easy way for developers to create new network management and control applications through its software components with well-defined APIs. The Open Network Operating System (ONOS) [96] is an SDN operating system for service providers to easily create apps and services with scalability, high availability, high performance and abstractions. It is a fast-growing platform with a community, including over 50 partners and collaborators, and has quickly matured to be feature-rich and production-ready. The adoption of those SDN open-control platforms for optical networks requires extensions to the open-control platforms in order to support optical network operations. Different open-control platforms have advantages on different aspects, which may have an impact on the optical extensions. For example, traffic engineering is partially supported by all the aforementioned SDN control platforms except for OpenDaylight, in which it is fully supported. This makes OpenDaylight superior in handling traffic engineering-related optical extensions. Multilayer network optimization is partially supported by OpenDaylight and ONOS among the aforementioned platforms, which gives them the advantage in handling optical networks in a multilayer environment.

VI. Conclusion

SDN is finding application in management software for optical systems. It holds the promise as a unified network control plane solution, and numerous studies have shown its use across multiple technologies and network domains. The physical layer control for optical systems, however, remains a barrier to implementing a real-time, open optical control plane. Transmission engineering complexity, optical power control, and multidomain transmission control all need to be addressed. Different architectures, including hierarchical controllers and white box or bright box approaches, are all promising directions that need further research. Opening up the physical layer control software is an important step that is currently underway and has the potential to enable a new generation of research and development in optical systems and networks.

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