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Hardware-programmable optical networks

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Abstract For future multi-dimensional optical networks, vast network resources provided by space division multiplexing and wavelength division multiplexing technologies, require new network architectures to scale up current network functions. The huge switch-granularity range requires a more dynamic way to deploy network resources. In this paper, we proposed a hardware-programmable optical network which deploys network resources according to incoming traffic requests. The proposed network supports node function programmability and node architecture adaptability, which are critical for dynamic function and resources deployments. Architecture-on-Demand based node architecture adapts node architectures and also enables network function programmability by incorporating with several flexible node functions. Other enabling technologies, such as ubiquitous power monitoring and dynamic optical power management, assures the programmable optical node work properly. Based on all these technologies, we established a hardware-programmable optical network testbed. Several use cases were demonstrated successfully, such as dynamic power equalization and optical debugging. These work verified the feasibility of hardware-programmable optical network, which dynamically allocate network resources for service provision. The proposed hardware programmable optical network will lead to a better hardware utilization and provide a possible solution for the future multi-dimensional optical network.

Keywords optical networks, flexibility, network function programmability

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1 Introduction

Driven by emerging bandwidth-hungry internet applications, the total network traffic has increased dramatically in the past two decades. The recent traffic forecasts from Cisco indicate the global IP traffic will reach 511 Tbps in 2019, which triples the size in 2014 [1]. In addition to the high traffic volume, network traffic has become more dynamic and far less predictable both in traffic size and traffic patterns. A mix of devices and connections contributes to the complex traffic patterns and link requests in optical networks. The "mouse" flow and "elephant" flow will coexist with a wide dynamic range. Thus, optical networks need to evolve continuously to not only satisfy the increasing bandwidth requests but also provide differentiated services for diverse applications upon the same network infrastructures. Meanwhile, network

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convergence is another trend observed between Metro and access networks or other network regions [2], which simplifies network architectures and provides a unified interface for various applications. Network convergence further blurs the separation of different technology regions. In order to provide end-to-end service establishment throughout different network domains (e.g., LET and OPS), network convergence should enable the versatile interfacing among these domains with different technologies. Thus, optical devices at edge nodes are required to provide diverse network functions for different network domains.

Several technologies have been developed to handle the increased network traffic. On one side, deployment of spectrally efficient high-order-modulation optical signals increases optical capacity without adopting wider-bandwidth electronic devices. The advanced optical signals, such as QPSK and 16QAM [3], provide more capacity by encoding several bits in a single symbol. On the other side, channel spacing can be reduced by exploring orthogonality between different WDM channels, either in the frequency domain (OFDM) [4], or in the time domain (Nyquist-WDM) [5], to packet the signal into a symbol-rate-spaced channels. By combing advanced modulation and spectral shaping technologies, a spectral efficiency up to 10 bit/s/Hz can be achieved, which will lead to a total fiber capacity up to several tens of TBit/s over C- and L-band in a single fiber/core.

Recently, space division multiplexing (SDM) technology is attracting researchers' interest. SDM technology can provide more paralleled channels by employing multi-core fibers (MCF) or multi-mode fibers (MMF). MCFs provide several tens of paralleled fiber cores with a similar physical dimension as that of the typical single mode fibers (SMF) [6]. In MMFs, multiple transmission modes are used to increase the total fiber capacity [7]. Furthermore, the combing of WDM and SDM technologies would lead to a huge optical capacity [8]. However, SDM technologies are currently only used for point-to-point transmission. SDM-based network is still limited due to the unavailability of key network functions, such as spatial switching.

In addition to the bandwidth provisioning, the effective fiber capacity can be increased by optimizing the utilization efficiency of the available optical bandwidth. Elastic optical networks (EON) promise to remove the grid limitation in the fixed grid DWDM network and to provide variable optical bandwidths for different link requests [9]. The dynamic bandwidth provisioning helps improve network spectral utilization and also improve network performance in blocking probability and spectrum saving [10]. To enable flexgrid EONs, two key technologies are required: (1) flexgrid wavelength selective switches (WSS) or spectrum selective switches (SSS) which support a fine bandwidth granularity (12.5 GHz or less); (2) elastic transponders with variable baud rate (corresponding to the occupied optical spectrum) and adaptable modulation formats (variable spectral efficiencies for different transmission coverage). Thus, the spectrum flexibility in flexgrid EON enables a more effective fiber bandwidth utilization.

Regarding the control plane, software defined networks (SDN) aim to develop a more dynamic control plane by decoupling data plane and control plane for distributed network hardware [11]. The centralized control plane in SDN offers many advantages including easier network abstraction, management, configuration, and scalability, global view of network state and better traffic engineering. The decoupling of data plane and control plane also enables both planes to evolve independently without one restricting the growth of other. On top of SDN control layer, optical network virtualization can virtually slice (separate) optical networks to provide infrastructure as a service [12]. With same network infrastructure, network virtualization can provide differentiate and isolated virtualized optical networks (VON) to satisfy the special requests from variable network applications. Thus, network resources can be programmed or scheduled for dynamic traffic or VN requests. The freedom in the network resource provision will also lead to better network utilization.

Spectrally efficient DWDM technologies and SDM technologies promise a large optical bandwidth for future network traffic. On the other side, EONs and SDN technologies are developed to improve network utilization efficiency both in infrastructure and network resources. However, availability of bandwidth resources is not enough for the dynamic feature of future traffic requests. Furthermore, huge bandwidth resource offered by SDM and WDM technologies will stimulate new applications which will require large network resources. The enlarged dynamic range of the bandwidth demands challenges the current network architecture, which is static and supposed to grow steadily with traffic demands or change according to

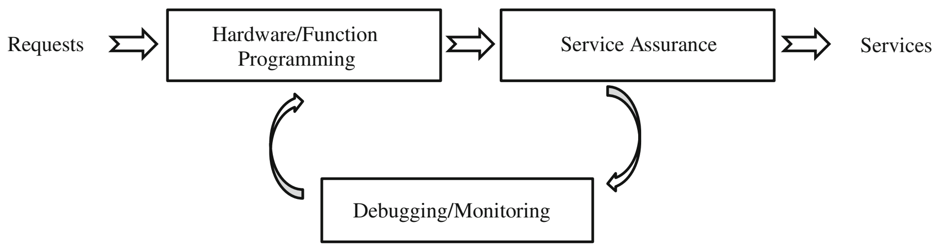

Figure 1 Service/function deployment in hardware-programmable optical network.

pre-planned protection/restoration schemes [13]. The traditional static architecture will limit the final performance of the networks in supporting the emerging applications. The dynamic nature of the network traffic require a new network architecture to support future network applications, for example, a short timescale bandwidth demand with the order of multiple Gb/s will be served in a more economical way with a dynamic optical network. In addition, future SDM/WDM based multi-dimensional optical networks also need a dynamic architecture due to its vast resource. Thus, an optical network with a flexible architecture and possible infrastructure programming will provide services for the dynamic traffic request and use network resources efficiently.

In this paper, a hardware-programmable optical network is proposed based on the Architecture-on-Demand (AoD) concept [14] and variable monitoring technologies. The proposed hardware-programmable optical network deploys network functions at each node according to traffic requests. The whole network can be programmed and debugged like a programmer do on a computer. To achieve this, key node functions are modularized as function modules or subsystems. The common components, such as EDFAs, wavelength selective switches (WSS), are also viewed as function modules for possible device reuse. The node inventory, which consists of these function modules, serves as a function library for network programming. Variable monitoring technologies, such as ubiquitous power monitoring and OSNR monitoring, enable characterization of function modules and also provide feedbacks to network programming. The monitoring information will further enable optical network debugging. The hardware-programmable optical network with capabilities to be programmed, debugged, and diagnosed, will introduce ultra-flexibility in node architecture and function deployment in optical networks. Through function aggregation and device reuse, the hardware-programmable optical network will also improve hardware utilization and possible lead to a cost-effective and power-efficient optical network.

The rest of paper is organized as follows. Section 2 presents the proposed hardware-programmable optical network. The key enabling technologies are presented in Section 3. In Section 4, several application scenarios are demonstrated the proposed hardware-programmable optical network. Section 5 concludes the paper.

2 Hardware-programmable optical networks

Figure 1 shows the general workflow for service deployments in the proposed hardware-programmable optical network. Traffic requests are mapping to hardwares or node functions through hardware/function programming, which is referred as node function composition. The node function composition programs devices and functions in each node. The device/function programming is achieved based on the AoD concept. During the process, requests will be aggregated to share the same device or functions to improve hardware utilization. After function composition, service assurance will work to check the deployed functions with monitoring technologies. If the services are assured, requests will be provided with services. Then the monitors will monitor the services continuously. In addition, variable monitoring technologies also enable network debugging, if network issues or failure are detected. The request-based function composition would reduce the complexity of the node composition algorithm, and leads to a short response time.

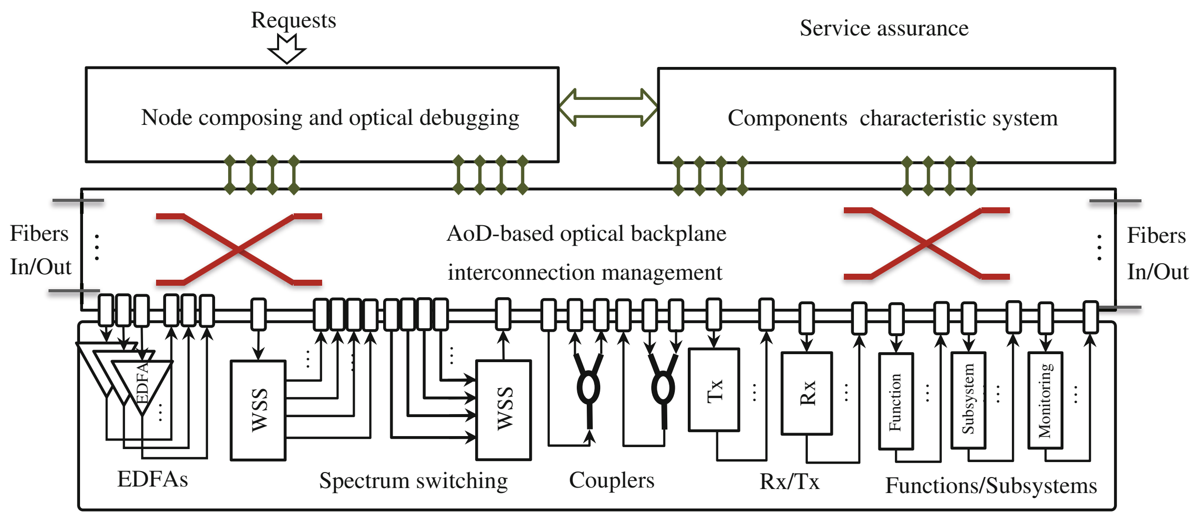

Figure 2 (Color online) Architecture-on-Demand (AoD) based optical node with node function composition module and function inventory.

2.1 AoD-based node function composition in optical nodes

The architecture of the AoD-based optical node is shown in Figure 2. To achieve function programmability, each node function should be modularized as a standalone block. Some node functions, such as ROADM, whose scale depends on traffic requests, are separated into several parts to control the scale of the node function easily. Such design also enables device reuse during node composition. As shown in Figure 2, functions, subsystems, and other common devices are all connected to a large-port-count fiber switch (LPFS). Both input and output ports are managed by the LPFS. The LPFS configures optical interconnections between these modules and functions to synthesize node functions and achieve node function programmability. On top of the LPFS, node composing algorithms response the network requests from the control plane, including node functions, wavelength allocation, and bandwidth requirements. Then the algorithm will transfer network requests to a switch matrix of the LPFS to synthesize an optical node. The node composing algorithms will balance the payload of the optical node to use the network hardware efficiently. The components characteristic system will control all the available monitors to monitor the provided services for service assurance. In addition, the components characteristic system will also provide components characterization function using monitoring technologies. The in-node function characterization could monitor the performance of the devices, functions, and subsystems to optimize the node composing process.

The node composing and optical debugging module configures the optical node architecture dynamically, according to the incoming traffic requests. Between any pairs of connections, the node functions or subsystems will be deployed only when the traffic requests need these functions. For variable traffic patterns, the node can provide optimum services with minimum optical devices. In addition, the optical node adapts its node architecture to better serve the incoming traffic requests. Hardware optimization will be carried on during the node composition process. Variable traffic requests will be firstly aggregated together to share the same function modules for a better hardware utilization efficiency. Compared with the constant architecture of the optical node, the AoD-based flexible/adaptable optical node reconfigures its architecture when traffic change occurs. The dynamic and programmable feature of the AoD based node enables optical network only need to deploy network functions when needed. The improved hardware utilization will lead to a cost-efficient and low power consumption optical node.

2.2 Requirements for node functions

Adaptability in node architecture can be achieved by the AoD-based adaptable node. However, to handle the dynamic traffic requests, more flexibility are required for node functions. The requirements for node functions are summarized as follows:

• Flexible bandwidth provision. Deployment of dynamic services in Hardware-programmable optical networks is achieved through flexible bandwidth provision. In a multi-dimensional optical network, flexible bandwidth provision consists of flexibility in resource allocation, including optical spectra, cores or modes, and time slots. The flexible bandwidth provision requires flexible designs in optical transponders, switching devices, etc.

• Multi-layer optimization. Flexibility in physical layer alone is not enough for future optical networks. The multi-layer information would benefit optical network optimization. Transponders, which connects to different layers, could provide a capability for cross-layer optimization.

• Visibility. The dynamic feature of the hardware-programmable optical network requires more information about the status of programmable functions. The status will be used to assure the required services are successfully delivered. In addition, these information can be fed back to the node composing algorithm for network optimization.

2.3 Other enabling technologies for AoD-based adaptable node

In hardware-programmable optical networks, node functions are deployed according to the traffic requests. Compared with the traditional static node, node reconfigurations occur more frequently. Furthermore, internal connections in optical nodes cannot be predicted due to the node programmability. Thus, dynamic power and connection managements are required for the proposed hardware-programmable optical networks. To support these managements, some node functions should be developed for practical use of AoD-based programmable optical nodes.

(1) Ubiquitous power monitoring. The core device in the AoD-based optical node is the LPFS, which connects both input and output ports of all the components and devices. The LPFS integrated power monitors at all the input and output ports. Thus for each connected device, both the input and output power can be monitored. The power monitor information indicates the operation status of the device. For example, the power difference between input and output ports of EDFA is proportional to the gain of EDFA. The power monitor provides an efficient way to monitor each component and the whole optical node. Combining with the control plane, the whole optical link over different optical nodes can be monitored with the power monitors. Compared with the tradition power monitoring in a static optical node, the optical power monitoring system in AoD-based optical node provide power monitor at all the input and output ports of all the components or subsystem modules. The detailed monitoring information can not only indicate the failure of the link but also provide a tool to analyze each component of the whole link.

(2) Dynamic optical power management. Hardware-programmable optical node needs to reconfigure internal interconnections of the AoD-based adaptable node. The reconfiguration would combine several signals together. However, the dynamic feature of the AoD-based node means a big power variety may exist among these signals. The combining signals from signals with huge power variety will experience signal degradation after further amplifications or other operations. Beam-steering LPFS supports power attenuations at output ports. The integrated power attenuator provides a wide range of power attenuation. Combining with the aforementioned ubiquitous power monitoring, dynamic power management can be achieved for internal connections.

(3) Quick Reconfiguration time. Node programmability is achieved through configurations of the LPFS. Thus, the switch time of the LPFS will limit the response time of node reconfiguration. To achieve dynamic operation, power monitors are integrated at both the input and output ports of the LPFS. The monitors monitor signal powers and will tigger a link reconfiguration when signal power drops below a power threshold. We measured the response time of a monitoring-trigger reconfiguration. Figure 3 shows the measured response time about 10 ms, which includes the response time of the integrated power monitor and the switching time of the LPFS.

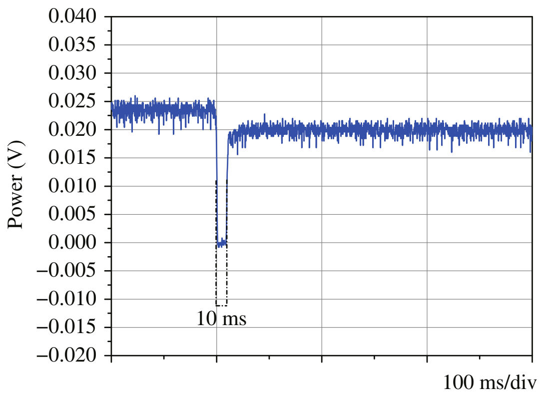

Figure 3 (Color online) Restoration time (10 ms) triggered by a integrated power monitor at the input port.

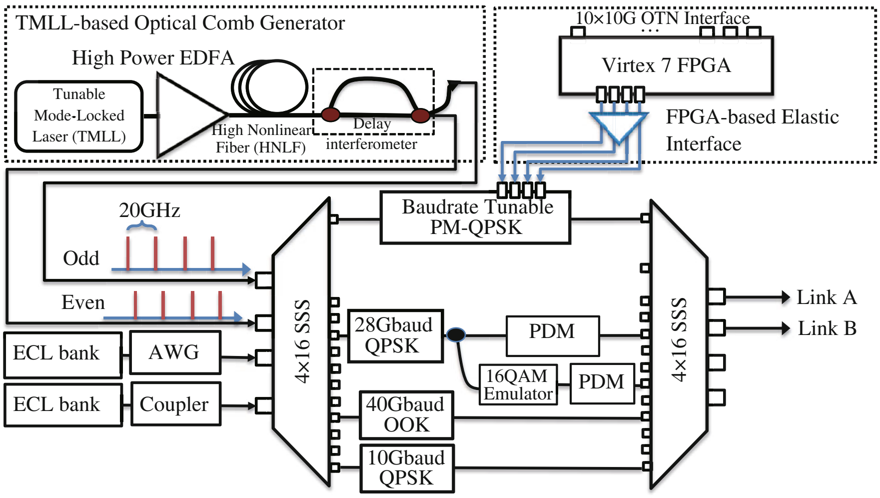

Figure 4 (Color online) Experimental setup of the programmable superchannel transmitter.

3 Enabling technologies for hardware-programmable optical networks

3.1 Programmable superchannel transmitter

To support future bandwidth-hungry applications, optical capacity up to Tbit/s is required. Such a big capacity cannot be provided by a single carrier-signal. Thus, superchannel signal, which assembles several optical carriers together, is introduced into the flexigrid optical network to satisfy the huge bandwidth requirement of the aggregated data from other network domains [15]. To enable hardware-programmability in optical networks, superchannel transmitter also needs to provide flexibility in variable ways. Thus, we propose a fully programmable optical superchannel transmitter, which can generate multiple superchannel signals with dynamic setting of carriers' central wavelength, bandwidth, modulation format, and total quantity of carriers.

Experimental setup of the programmable superchannel transmitter is shown in Figure 4. A large number of high-quality optical carriers is provided by a tunable mode-locked laser (TMLL) based optical comb generator. The experimental setup is shown in the inset of Figure 4. A 10 GHz optical pulse with pulsewidth about 1.8 ps from the TMLL is amplified to 30 dBm with a high power EDFA. Then the optical pulses are sent to a 50 m long highly nonlinear optical fiber (HNLF). The optical spectrum will get broader due to self-phase modulation and cross-phase modulation effects. The broadened spectrum can provide plenty of optical carriers with a frequency interval of 10 GHz. Then a delay interferometer is used to separate the odd and the even channels for further processing in a spectrum selective switch (SSS). The separated carriers with 20 GHz frequency interval are all fed into a 4×16 SSS. Figure 5

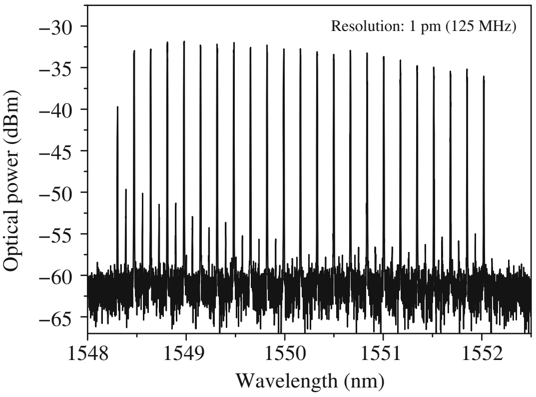

Figure 5 Generated optical carriers with TMLL-based optical comb generator.

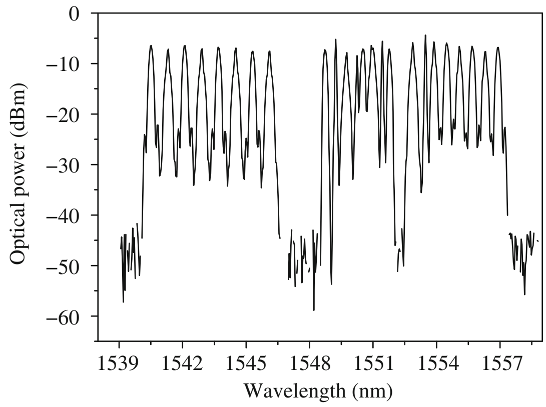

Figure 6 Optical spectrum of the generated optical signals by the programmable superchannel transmitter.

presents the obtained optical comb with 20 GHz frequency interval. The wide frequency interval enables efficient management by the SSS. In addition, the multiple port SSS also manages two ECL banks, to provide optical carriers with linewidth less than 100 KHz.

The first SSS equalizes optical carriers and forwards optical carriers to modulators. In our setup, 40 Gbaud OOK modulator, 10 Gbaud PM-QPSK modulator, 28 Gbaud PM-QPSK/16QAM modulator, and an elastic interface driven PM-QPSK modulator are connected to the SSS. The PM-QPSK transmitter driven by an elastic interface aggregates the incoming OTN tributaries onto a just-enough optical transported data rate [16]. The operation baud rate can vary between 2.67 Gbaud and 26.7 Gbaud with a step of about 2.67 Gbaud, to deliver a corresponding variable bit rate from 10.7 Gbit/s to 107 Gbit/s on a PDM-QPSK optical modulation format. The elastic interface is developed based on a Virtex-7 FPGA, which enables the transmitter to handle cross-layer information, such as OTN in this setup. By combining the above modulators, various values of optical capacity can be provided. In the last stage, another 4×16 SSS is used to multiplex all the optical signals. The second SSS also equalizes the signals for further fiber transmission in an extended network scenario. The multiple ports SSS can additionally provide several superchannel signals towards different destinations and enables multicasting function in optical networks.

Figure 6 shows the optical spectrum of a generated superchannel signal. Each carrier in the superchannel can be configured by its modulation format, occupied optical bandwidth, baud rate, and output ports. Thus, the flexibility of the superchannel signal provides a method to optimize optical connections based on link conditions and traffic requests, to achieve spectrally-efficient and bandwidth variable optical connections. Compared to the fixed connections, the first SSS in the setup can switch optical carriers to realize wavelength reconfiguration. The SSS can also forward several optical carriers to a single modulator for optical multicasting. By forwarding another optical carrier to the modulator, the signal can be easily duplicate to another wavelength. The new capability makes hitless optical fragmentation possible in elastic optical networks.

3.2 AoD-based multi-dimensional ROADM

Reconfigurable optical add/drop multiplexer (ROADM) is one of the key functions in optical networks. To support flexible optical bandwidth provision, SSSs will be used in ROADMs with either "Route and Select" (R&S) or "Broadcast and Select" (B&S) architectures [17]. We first adopted the AoD-based adaptability in add/drop banks (ADB) of ROADM [18]. The AoD-based ADB provides a better flexibility with contentionless, routing alternatives or architectural options. In particular, we observed improvements in flexibility for ADBs which offer contentionless, routing alternatives or architectural options respectively.

Regarding main ROADM function, AoD-based architecture is introduced as shown in Figure 7 for a 4-degree ROADM. All the input and output ports of the SSSs and splitters are managed by an LPFS.

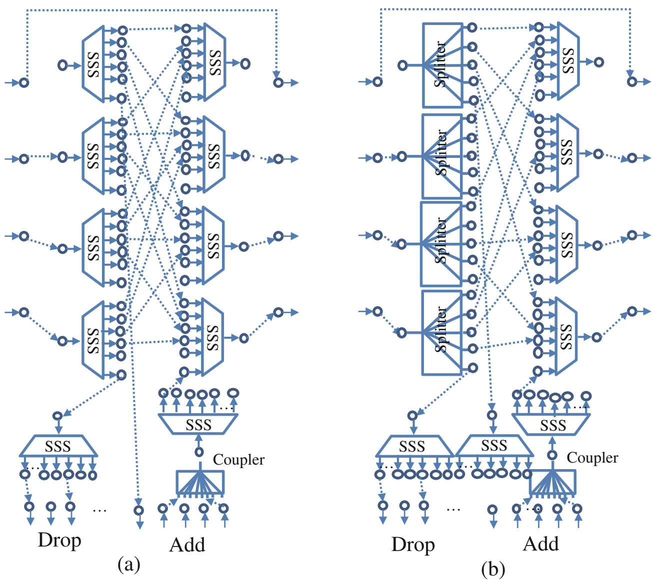

Figure 7 (Color online) AoD-based flexible ROADM. (a) Route and select; (b) broadcast and select.

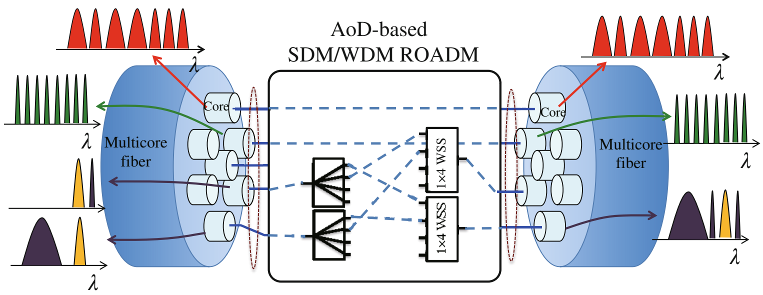

Figure 8 (Color online) AoD-based flexible ROADM for SDM/WDM networks.

According to the incoming traffic, the AoD-based ROADM is dynamically configured, which provides flexibilities as follows:

(1) For a high-degree ROADM, bypass operations are supported. Thus, optical signals in a fiber can be directed forward to the output fiber without passing through the lossy ROADM. When bypass operation happens, the ROADM can reduce the degree of the ROADM.

(2) The ROADM architecture is adaptable. Figure 7(a) shows a R&S ROADM. Figure 7(b) shows a B&S ROADM. Both ROADM architectures can be achieved by programming the LPFS. The architecture adaptability could offer optimized services for different traffic pattern.

(3) Device reuse. A lot of SSSs are required to achieve a high-degree flexible ROADM. In AoD-based ROADM, all SSSs are shared among by optical cross connection and Add/drop bank. Thus, when traffic requests are low, AoD-based ROADM will use less network resource.

For future SDM/WDM multi-dimensional networks, design of multi-dimensional ROADM faces big challenges. The huge bandwidth resources in SDM/WDM networks will require core-to-core switching and wavelength-level switching. On the other side, the big number of cores require SSSs with a big number of ports to scale up current typical static ROADM. The flexibility of the AoD-based ROADM makes it a potential choice for SDM/WDM networks. Figure 8 shows the principle of the AoD-based SDM/WDM ROADM. The AoD-based ROADM enables the core-to-core switch and also traffic-tailored ROADM architecture for WDM ROADM. All the fiber cores are managed by a LPFS. The spacing switch capability of the LPFS enables core-to-core switching. For the wavelength-level switching, the aforementioned AoD-based ROADM will synthesize the ROADM according to the traffic requests. The flexibility of the AoD-based ROADM can change the scales, degrees of the wavelength-level ROADM.

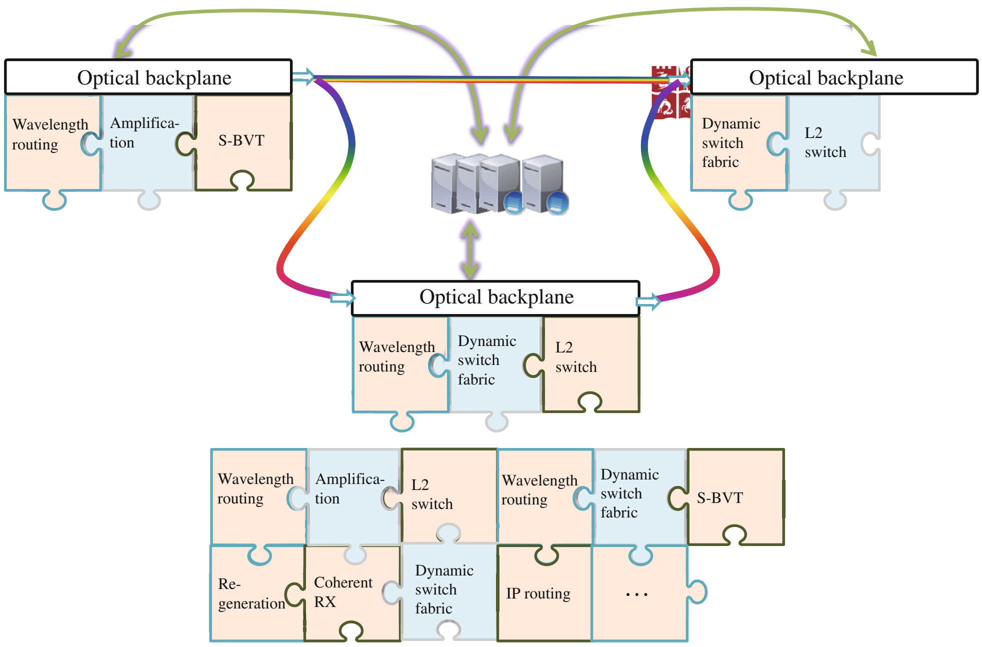

Figure 9 (Color online) Principle of hardware-programmable optical network.

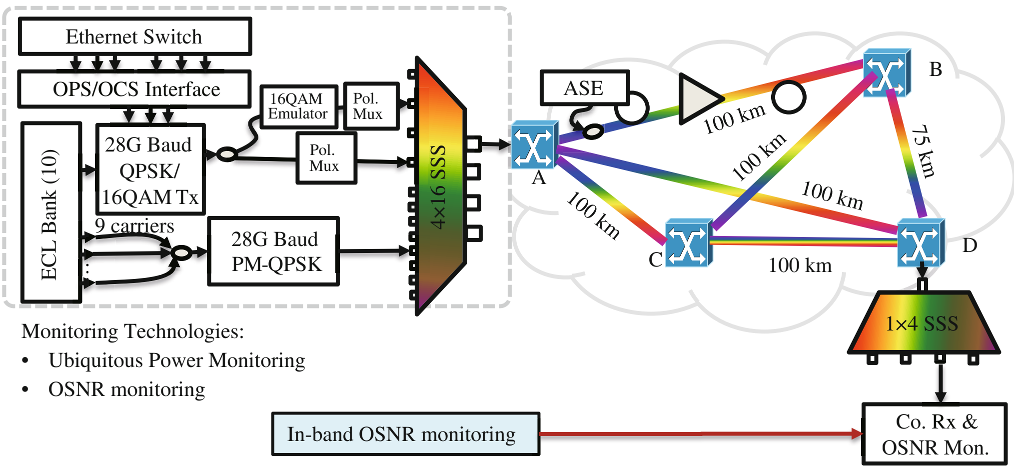

Figure 10 (Color online) Programmable optical testbed.

4 Demonstration of hardware-programmable optical networks

With the aforementioned technologies, programmable optical nodes with dynamic function deployment can be setup. Furthermore, a fully programmable optical network can be setup with programmable optical nodes. Figure 9 shows the principle of the programmable optical network. A centralized controller will manage and control all programmable optical nodes in the optical network. Each AoD-based programmable node consists of a function inventory. According to incoming traffic requests, the centralized controller will configure each node to deploy network functions. Thus, functions will be deployed only when they are needed. The scale and architecture of the node will also be adjusted based on the traffic requests. In addition to the centralized control, some node management functions will run locally, such as dynamic power management, node monitoring, and optimization.

Based on the principle of the programmable optical network, a programmable network testbed is established successfully. All the subsystems, function modules are registered into an inventory and managed by a 192 $\times$ 192 beam steering fiber switch (Polatis, inc.). According to the incoming traffic request, node composing algorithm will synthesize node architecture. Figure 10 show the programmable

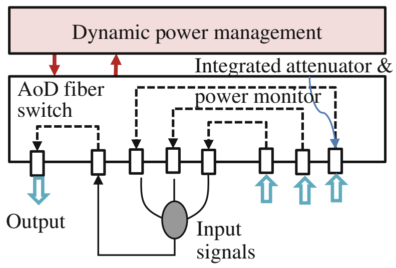

Figure 11 (Color online) Experimental setup of dynamic power management.

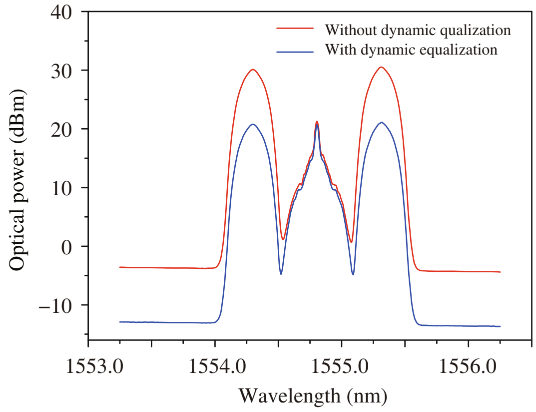

Figure 12 (Color online) Optical spectrum of combined signals with/without power management.

testbed.

A programmable superchannel transmitter is deployed at Node A. The superchannel transmitter can configure its carriers by modulation formats, baudrate, wavelength, and occupied optical bandwidth. At node D, signals will be dropped and received by a coherent receiver. The coherent receiver also provides an in-band OSNR monitoring function based on error-vector-magnitude. Four AoD-based programmable nodes are connected together with different lengths of fibers. The network topology is shown in Figure 10. Other node functions and devices are omitted for simplicity.

The AoD based node can provide ubiquitous power monitoring with integrated power monitors at all ports of the LPFS. Thus, both input and output powers of all the devices and functions, which are connected to and managed by the LPFS, can be monitored. In addition, wide-range optical power attenuators are integrated at all the output ports, which enable dynamic power management in dynamic optical nodes. These functions make the programmable optical network more practical.

4.1 Dynamic power management

Due to the dynamic feature of the AoD-based programmable node, efficient optical power management is critical for successful deployment of dynamic network functions. When signals need to be combined together, optical powers of the input signals should be managed to avoid big power variation. For our proposed AoD-based programmable node, dynamic power managements are operated during all the combining operations, such as wavelength multiplexing, optical coupling.

As shown in Figure 11, power equalization was achieved at an optical coupler. Three signals with different optical powers are combined together with a 1×3 coupler. The monitored power values are feedback to the power management algorithm. Then the power algorithm will configure the integrated attenuators to equalize the signal in advance. The optical spectra of the combined signals with/without power equalization are shown in Figure 12. For multiple channel signals, the power deviation should also consider the channel occupations. Without resorting to the last-stage SSS (spectrum selective switch), the power equalization at all the combing device will improve energy consumption and node reliability.

4.2 Enabling optical debugging and auto-restoration in programmable optical networks

Ubiquitous power monitoring provides input and output powers of all the components in the link. These power values can be used to characterize the connected devices, such as insertion loss, gain, or other performance. In addition, these values can be used for optical debugging in the proposed programmable optical networks. For each end-to-end connection in nodes, the optical power of the signal can be monitored and analyzed for all used components or functions. When signal loss occurs, optical debugging can be triggered to locate the failed device.

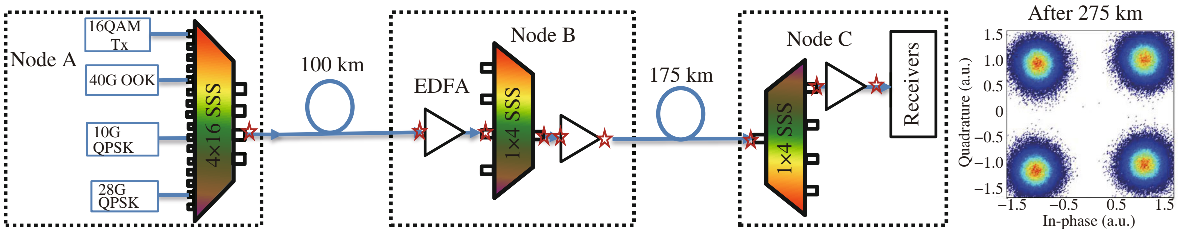

Figure 13 (Color online) Experimental setup of network debugging and auto-restoration.

As shown in Figure 13, an optical channel is setup through three AoD-based programmable optical nodes. The LPFSs at each node are omitted for simplicity. The link passes several SSSs, EDFAs, and optical links. All the connection points, indicated with star symbols, are monitored and managed by the LPFSs. In our demonstration, a network failure occurs when the last EDFA is broken. The detecting signal loss will trigger the debugging application to check the insertion loss of all the connected components in the link. By comparing to the reference value, the debugging application located the broken component, as indicated the last EDFA in the link is down. Then the AoD based node checks the optical component inventory to find another available EDFA and replaced the broken EDFA by changing the AoD configuration. After the replacement, the network failure is restored. The constellation for the 28 GBaud PM-QPSK signal after transmitting over 275 km is shown in the inset of Figure 13. The auto-restoration feature will improve the robustness of optical network and also decrease the network operation cost.

In addition to current use cases for core networks, the hardware-programmable optical network can also be used in Metro or Data center network (DCN) applications. Our previous work indicated dynamic network programmability gave more flexibility in a flat-structured DCN [19].

5 Conclusion

In this paper, a hardware-programmable optical network was proposed and demonstrated based on architecture-on-demand optical node and variable monitoring technologies. At each node, node composing function mapped instant traffic requests to variable node functions. Several key technologies, such as dynamic power management and ubiquitous power monitoring, were developed to assure the dynamic features of the programmable node. The proposed hardware-programmable optical network suits for future SDM/WDM multi-dimensional optical networks, where the traditional static node architecture could not scale up to provide the required node functions. Several programmable node functions were developed, which leveraged the programmability of the proposed network. The developed functions included several key node functions, such as programmable superchannel transmitter and SDM/WDM ROADM. Based on AoD-based programmable nodes, a testbed of the hardware-programmable optical network was setup. Several use cases for the hardware-programmable network were demonstrated successfully. Hardware-programmable optical network enables ultra-flexibility for future large-scale networks. Dynamic deployment of the node functions and network resources will improve hardware utilization efficiency and leads to a cost and power consumption efficient optical network. The proposed hardware-programmable optical network can also be used in Metro or data center network for efficient network resource allocation.

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

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