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Multi-Layer Network Analytics with SDN-based Monitoring Framework [Invited]

Shuangyi Yan, Alejandro Aguado, Yanni Ou, Rui Wang, Reza Nejabati, and Dimitra Simeonidou

***Abstract*—Optical transport networks with expanding variety and volume of network data services challenge network provider's ability to provide high-quality service assurance and network managements. Software-defined networks (SDN) decouple the data plane and control plane and enable network programmability in optical networks with a centralized network controller. The optical network would become more dynamic in network architecture and require frequent network reconfigurations. The dynamic optical networks require all kinds of visibility into application data types, traffic flows and end-to-end connections. Thus, we propose an SDN-based monitoring framework that expands network analytics to a converged packet and optical network. With a designated monitoring hub, monitoring information from multiple layers are collected and processed in a centralized server. Several monitoring technologies are provided as network services with the architecture-on-demand optical node architecture. The developed network applications on top of SDN controller process all the collected monitoring information and enables multi-layer network analytics based the SDN-based monitoring framework. We demonstrate the proposed multi-layer network analytics successfully in several use cases. In the demonstrations, the multi-layer network analytics enables QoS recovery to avoid network disruption, optical power equalization at any combining device and network debugging and restoration in optical networks. The developed multi-layer network analytics provides powerful tools for network re-planning and optimization dynamically.**

***Index Terms*—Software defined networking; Optical fiber networks; Ethernet networks; Next generation networking**

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I. Introduction

Network analytics have been widely used in network management/monitoring systems (NMS), operational support systems (OSS) and operations, administration and maintenance handlers (OAM handler) by service providers to plan and manage network resources (e.g., capacity), and to deliver superior service to customers. These traditional network analytics technologies focus on customer services which lack the whole network information, especially optical networks. However, the emerging bandwidth-hungry internet applications with the soaring internet users and facilities, contributes to the exponential growth of optical networks that occurs in network scale, network elements, service platforms and connected devices. Network traffics go to more dynamic with the expanding variety and volume [2]. On the other side, the emerging 5G networks depend on optical networks for back-hauling and front-hauling solutions [3], and also rely on innovations in optical access, metro, and core networks for ever-increasing demand for greater flexibility in all parts of the network [4]. Large-scale internet applications need end-to-end services over multiple network technology domains [5]. In addition, dedicated networks (e.g., internet of things) are beginning rollout, which means optical networks need to be tailored for special applications to improve network utilization and efficiency [6]. Traditional network analytics technologies that focus on customer's side services face big challenges to handle the dramatic changes in network traffic pattern and their QoS requirements [7].

On the other hand, optical networks also have been becoming more dynamic to support various network services. Recent developments of software-defined optical networks (SDON) that decouple the data plane and control plane with a centralized SDN controller [8] promise a programmable optical network with a global view of network state and better traffic engineering. To achieve this, dynamic network planning and analysis are required to provide the dimensioning and analysis of a network within an "event-based" short-time scale [9]. The programmable optical network also requires a better network service/function assurance for the dynamic network reconfigurations.

Thus, network analytics tools or applications are needed to be extended to optical networks to enable end-to-end network analytics capability, which could support better capacity planning, traffic management as well as more effective service assurance. The dynamic optical network also requires instant/real-time feedbacks to understand network performance. Thanks to variable optical performance monitoring technologies, lots of information about physical layer can be obtained, such as link transmission performance, power information, link impairment, and pre-FEC bit error rate. In addition, Architecture-on-Demand (AoD) programmable optical nodes, which enable network function programmability [10], can potentially provide ubiquitous power monitoring to optical networks with large-port-count fiber switches (LPFS) [1], which provides power information for all the input and output ports of all the used function modules or subsystems. However, currently, all optical performance monitors are equipped for local applications. On the other hand, existing OAM services (Operations, Administration, and Maintenance) provides the service assurance in different layers [11]. The detection, resiliency, and monitoring capabilities in different protocol layers enabled auto-provisioning of equipment and made end-to-end deployment easy through connectivity fault management and link-level protection. However, OAM isolates network problem to its layer, thus network troubleshooting, as an example, can be only done on the same layer. Just as SDN has done in control layer, a unified monitoring hub that integrates all the monitoring technologies or resources from both physical layer and control layer, could provide a powerful tool for network analytics and cross-layer troubleshooting.

In this paper, we propose a novel SDN-based monitoring analytics framework for multi-layer network analytics in converged packet and optical networks. The developed SDN framework aggregates all the monitoring information from different network layers to a centralized monitoring hub. The collected information includes current states and the history information of the whole network. The optical network analytics applications will process and analyze the collected monitoring information in combining with the current network configurations. Through these optical network analytics applications, the collected multi-layer monitoring information could facilitate network operations in the following ways. 1) Monitoring information could provide a precise and up-to-date description of network link states for network abstraction, for example, OSNR penalty of an optical channel could be deduced by monitoring OSNR at different parts of an established optical link. Up-to-date network abstraction could benefit SDN applications for better network planning. 2) Continuous network assurance and pre-recovery. Multi-layer network analytics applications process the real-time monitoring information of the established links and could trigger network reconfigurations when link performance degrades to a certain level, then network reconfiguration will be executed through SDN controller to avoid network outages. 3) Active network diagnosis when network failure happens. The monitors from different network layers could be used to analyze the failed connections in different perspectives. Furtherly, AoD-based optical nodes could provide optical power information of the key components and subsystems to locate the failed components. By deploying optical performance monitors in AoD node, network diagnostic applications could program the monitoring resource to check different parts of the AoD-based nodes, which makes "debugging" of optical network possible.

The integrated monitoring hub makes real-time multiple-layer monitoring information, especially optical performance monitoring information, be accessible to network applications. On top of the integrated monitoring hub, many network analytics applications could be developed to process the monitoring information and trigger new network configuration based on the current and history network status through SDN controller. With the proposed multi-layer network analytics, we demonstrate various network scenarios supported by monitoring enabled network analytics tools, including network optimization, network re-planning and network debugging and restoration. The experimental demonstrations confirmed that the integrated monitoring information with multi-layer network analytics applications would help the control plane to configure the network in a hardware-efficient way and improve the network reliability.

The rest of paper is organized as follows. Section 2 reviews key technologies enabling multi-layer network analytics. Section 3 introduces the proposed SDN-based monitoring framework for multi-layer network analytics. In Section 4, three application scenarios are demonstrated for the network analytics. Section 5 concludes the paper.

I. Review of Related Research

Network analytics was developed for service providers to improve the customer experience and optimize network investments. Network analytics tool could provide real-time insights into network traffic, support better network service assurance, instant network action and optimization. With minutes of use and data volumes, network analytics can provide statistical models to anticipate network bottlenecks in a more granular and precise way, which would help to plan network expansions properly [6]. The rapid development of SDN technologies leverages legacy networks to a converged SDN platform, which could measure, monitor, and automate important network functions. Network analytics is becoming more critical for network applications. Furtherly, network analytics could analyze both history and current data with big data related technologies, to improve network performance, including on-demand analytics and rapid response [12]. However, current network analytics are still limited at the packet level and focused on network services close to the customers. The hardware, especially optical transportation infrastructure, is not considered in network analytics.

On the other side, optical networks have been becoming increasingly dynamic and even programmable both in network functions [13] and node architectures [10], [14]. SDON platform makes optical networks interoperable, flexible and programmable. Researchers start to use optical monitoring information for better network management. A. Di Giglio explored monitoring information for cross-layer optimization and active-control functions in optical networks [15]. With BER monitoring, a network can learn from its path-level performance for small-margin network operation [16]. Optical performance monitoring techniques could also support cognitive optical networking [17], and benefit cognitive SDN orchestration [18] and on-demand control plane functions [19]. However, all these monitoring-support network operations focused on some use cases and lacked a general operation framework to expose related monitoring information to SDN applications for better network management and diagnosis. In addition, a huge amount of monitoring information needs specific applications rather than current SDN application to process both the instant monitoring information and the historic monitoring information. As the traditional network analytics does in packet networks, optical network analytics could provide better network function assurances to the dynamic optical networks and offer a set of powerful network tools to analyze, automate, and optimize networks.

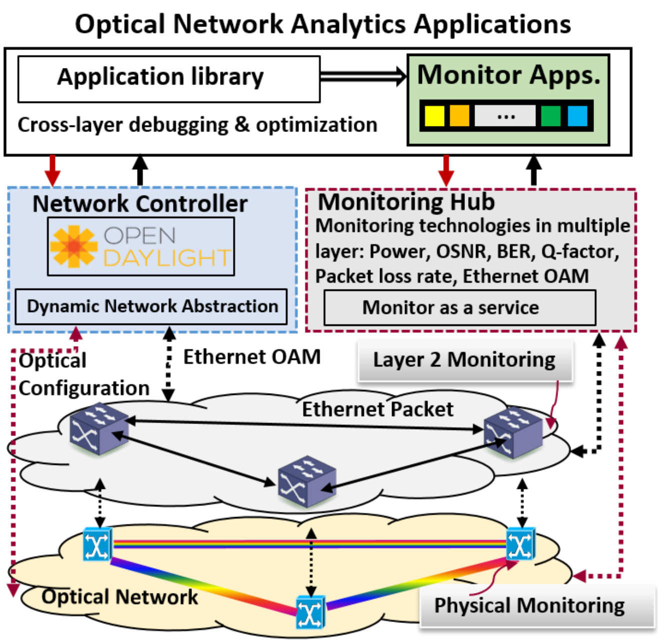


Fig. 1. Architecture of SDN-based optical network analytics

II. Architecture of SDN-based Optical Network Analytics Framework

Figure 1 presents the proposed framework for optical network analytics based on SDN principles. The physical infrastructure of the optical network is implemented with AoD-based programmable optical nodes. Variable optical performance monitoring techniques are used in the physical layer to estimate and acquire various physical parameters of transmitted signals, link conditions, and components' performance, including OSNR monitoring, ubiquitous power monitoring, BER estimation, chromatic dispersion, polarization mode dispersion, fiber nonlinearity. On top of the optical network, the Ethernet packet layer is also shown in Figure 1, as the extended optical network analytics also includes traditional network analytics in packet layer. The networks are controlled by the extended OpenDaylight SDN controller. All the monitoring information from the physical layer and Ethernet layer are collected by a centralized monitoring hub. In the monitoring hub, multi-layer monitoring information is processed according to current network configurations. On top of the SDN controller and monitoring hub, optical network analytics applications are developed. Optical network analytics applications would process monitoring information for specific network application and triggers network reconfiguration through SDN controller.

The architecture provides a generic methodology that enables network diagnostic tool with multilayer monitoring technologies. With this optical network analytics framework, network analytics applications could improve network planning with history link information, response to link performance degradation by replanning, and diagnose optical network from multiple perspectives.

To implement optical network analytics functions in the dynamic optical networks, several key technologies should be developed as follows:

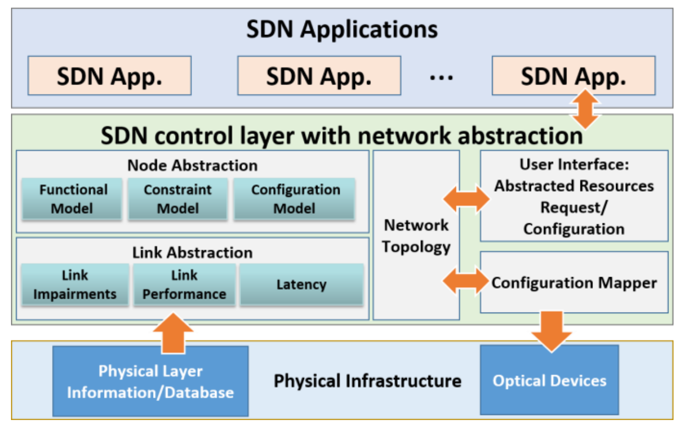


Fig. 2. Control plane architecture for software-defined optical networks

A. *Optical software defined networking*

SDN technology decouples data plane and control plane, thus enables fully programmable and fast reconfigurable optical networks. In the proposed architecture, SDN controller configures physical infrastructure according to SDN applications. Figure 2 shows the SDN control plane for SDN-enabled optical networks with a dynamic abstraction of optical networks. By extending OpenFlow to support optical nodes, SDN controller, such as OpenDaylight (ODL), can make forwarding decisions based on wavelength/space on OXC and/or ROADM, regardless of device vendors. High-level network abstractions could provide a global network view of the network through node and link abstractions. With the abstracted information, the centralized integrated SDN controller can configure the underlying optical networks more intelligently and reconfigure or re-plan the optical networks. In our proposed architecture, multi-layer monitoring information is exposed to SDN applications, such as dynamic link abstraction and node abstraction. Thus, network state abstraction could be performed also based on real-time or history monitoring information. Via the SDN controller developed network analytics applications will trigger network reconfiguration when monitors observe a rapid change of links or networks.

B. Integrated monitoring hub and monitor as a service (MaaS)

Optical performance monitoring (OPM) estimates and acquires various physical parameters of transmitted signals, link conditions, and components' performance [20]. By exploring OPM in frequency, time, and polarization domain, variable physical parameters can be monitored with the available technologies. Traditional monitoring information is used only for local applications. In the context of SDN, exposing the monitoring information to the SDN controller has been becoming very straightforward. In the proposed optical network analytics, monitoring information are collected together by a centralized server, which is referred as monitoring hub. All network performance monitors will be connected to the monitoring hub either through dedicated links or SDN control links. Table I lists all the monitorable optical parameters in optical networks. The monitoring information from layer 2 or layer 3 is also collected to the monitoring hub through the links to the SDN controller.

TABLE I
MONITORING PARAMETERS FOR OPTICAL NETWORKS

Components	PARAMETERS
Transmitter	Laser linewidth Laser wavelength drift Laser relative intensity noise Electrical-driving signal parameters
Link	Fiber attenuation loss Fiber linear distortion (CD, PMD, PDL) Fiber nonlinear distortion (SPM, XPM, FWM, Brillouin and Raman scattering) Inter symbol interference Multipath interference (MPI) Cross-talk of MCF Optical amplifier noise figure Optical amplifier gain fluctuation and power saturation Optical signal noise ratio (OSNR)
Node	Sub-functions monitoring Optical power monitoring Spectrum variance after equalization
Receiver	Receiver noise Receiver saturation Timing jitter Signal power
Network	Network topology Network capability

In addition to tradition monitoring technologies, the AoD-based optical nodes based on an LPFS enables a new monitoring capability, i.e., ubiquitous power monitoring. As shown in Fig. 3, several devices are deployed between the input and output fiber, including an EDFA, a WSS, and a Splitter. The devices or components can be dynamically deployed by programming the LPFS. As all the ports of LPFS are integrated with power monitors, both input and output power of all the devices and components can be obtained. Compared to the traditional power monitoring, ubiquitous power monitoring provides more detailed information of all the connected devices and fibers in the optical nodes, which is a powerful tool for optical network analytics.

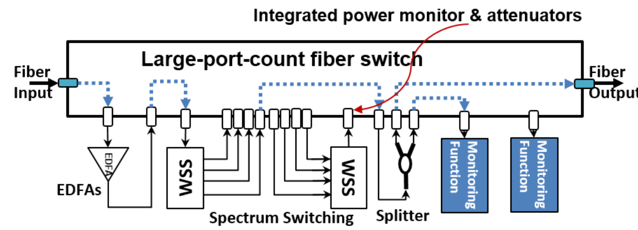


Fig. 3. Architecture-on-Demand (AoD) based optical node with ubiquitous power monitoring and monitor-as-service capability

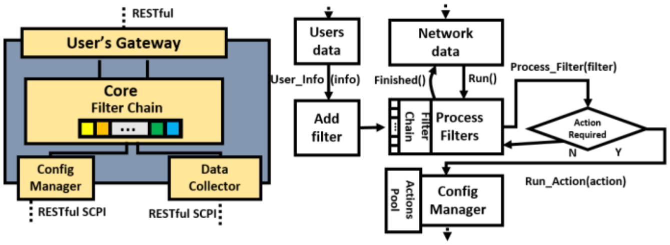
Furthermore, the programmability of the AoD-based optical nodes can deploy standalone monitoring functions according to requests. Figure 3 shows the monitoring functions can be deployed at any network points by configuring the LPFS. Thus, some monitoring functions that are targeted for slow changing parameters (e.g., OSNR monitoring) can be shared by several monitoring requests, by programming the OSNR monitor to different monitoring ports. Most importantly, programmable deployment of monitoring functions enables monitor-as-a-service in optical nodes, which leverages monitoring functions to general network services. The monitoring based network analytics application could deploy monitoring service based on their interests for active network diagnosis.

In addition to the physical layer monitoring, there are also a lot of monitoring features from other layers. OAM in different layers provides a lot of tool to monitoring and diagnose connectivity issues. Besides, network administration software also could provide network monitoring and analysis tools as the traditional network analytics does. With optical performance monitoring in physical layer, multiple-layer monitor technologies could monitor and diagnose networks from different perspectives.

All this collected monitoring information will be stored in the monitoring hub and processed based on network configurations at that time. For each link, monitoring information from all the used components and device could be linked together. Regarding each component, the current information and history information will be stored together. The structured monitoring information shows the history and current information about the whole physical infrastructure. This information could be retrieved and accessed by SDN applications for further processing. For example, dynamic network abstraction application could be improved with previous information about link performance, assuming optical links keep stable for a period. In addition, specific applications could be developed to analyze all the collected monitoring information. The history information, in combing with network configuration information, could possibly be used for network traffic predictions. Through data mining, much useful information could be abstracted from a vast amount of monitoring information.

In some case, monitoring information requires optical network response quickly to avoid network disruption. These applications run on top of the collected monitoring information and are referred as optical network analytics application.

C. Optical network analytics applications



(a) (b)

Fig. 4. (a)Architecture for optical network analytics application; (b) Flowchart of the defined optical network analytics application

On top of an SDN controller, multi-layer network analytics applications are developed. Through the SDN controller, the applications would deploy the monitoring service to the physical layer or other network layers, to enable network analytics functions, such as cross-layer troubleshooting, traffic analysis, and function stability analysis. Furthermore, these optical network analytics applications would use network analytics results to optimize the optical networks. All these multi-layer network analytics applications comprise a network analytics tool library for network operation and administration.

The architecture of optical network analytics application (see Fig. 4(a)) is composed of a monitoring data analytics core, the users' gateway to handle users' requests, a monitoring data collector and a configuration manager. The optical network analytics framework operates based on the concepts of the filter chain and actions pool. Some examples of filter chains are shown in Table II. A set of configurable monitoring data filters is defined by the user and appended into a chain which is run regularly by the core based on a predefined timer. A monitoring data filter is defined in this test as a set of attributes: filter (power, OSNR, data rate, etc.), thresholds (numerical number), types (maximum or minimum), ids or resources (eg. list of ports) and action.

TABLE II
EXAMPLE OF FILTER CHAINS

Technology	Filter	Threshold	Type	Ports	Action
Optical	Power	-10	Max	196, 351, 353	Attenuate
Optical	Power	-15	Min	All	Recover
Packet	Rate	1G	Max	5,6	Allocate
OSNR	Value	22.67	Value	n/a	Re-plan
…	…	…	…	…	…

Figure 4(b) shows the flowchart associated with the defined monitoring application. Based on the users' data (filters enabled) coming to the gateway and the network data retrieved by the collector, the core process the filters that run the different configuration actions into the network, such as attenuate the signal, perform a local reconfiguration or send a trigger to a higher-level controller or orchestrator to initiate an end-to-end re-planning [21], [22].

III. DEMONSTRATION OF NETWORK OPTIMIZATION WITH MULTI-LAYER NETWORK ANALYTICS

With the developed key technologies, we demonstrated multi-layer network analytics based on the proposed network analytics framework with the following use cases.

A. QoS recovery enabled by multi-layer network analytics with layer-2 monitoring and OSNR monitoring

In this use case, we demonstrated a border node that converts Ethernet traffic to spectrally efficient high-order modulation format signals in a converged optical and packet network. In this demonstration, the developed multi-layer

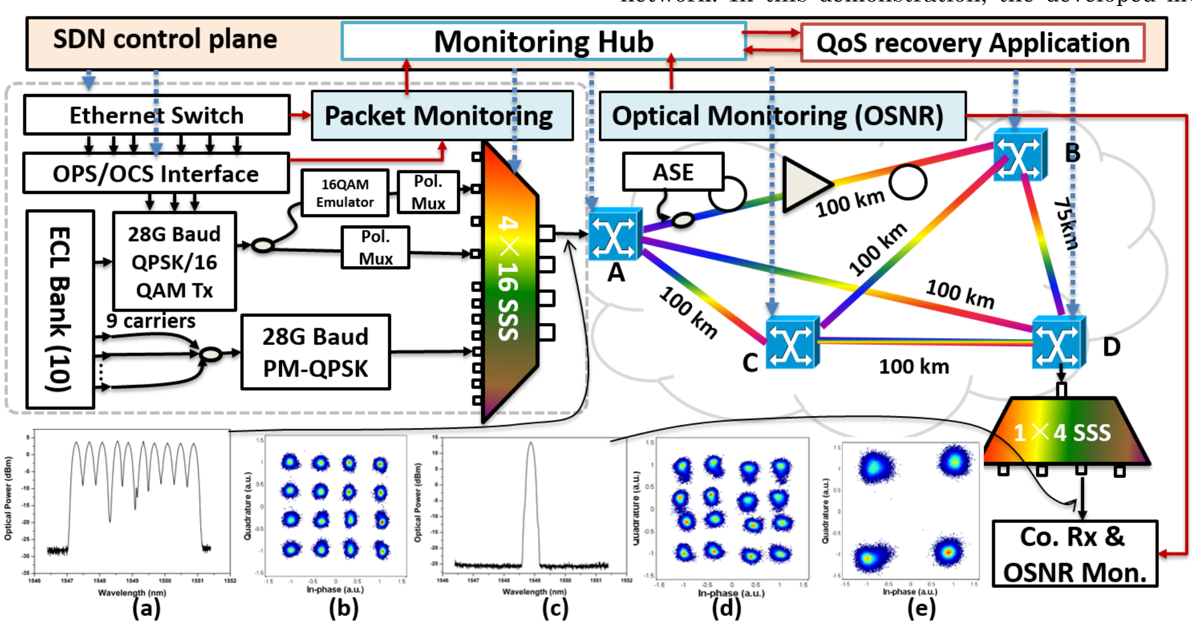


Fig. 5. Experimental demonstration of QoS recovery with packet and optical monitoring information

network analytics application optimized the converged optical and packet network according to the incoming client traffic and characteristics of the transmission link with an optical network analytics application. With several monitoring technologies, QoS recovery is achieved by re-planning the optical network to handle the increased OSNR penalty in an existed link.

Figure 5 shows the experimental setup of QoS-recovery demonstration. An FPGA-based OPS/OCS interface converts Ethernet traffic to OCS traffic [23]. The packet monitoring information is used to estimate the traffic capacity request and further choose the required modulation format of the QPSK/16QAM multi-format transmitter based on estimated information. To dynamic allocate bandwidth, a network analytics application is developed to process the collected network throughput information of the Ethernet switch and configure the FPGA-based OPS/OCS interface for bandwidth allocation. The network analytics application uses the generation architecture introduced in Fig.4 and would filter the packet rate (Table II) to trigger reconfiguration of the FPGA-based OPS/OCS interface.

For the OCS domain, as shown in Fig. 5, ten carriers with either QPSK or 16QAM signals are launched into the optical network at node A. The 28Gbaud QPSK/16QAM transmitter with a central wavelength of 1548.9nm is connected to the packet domain with an integrated OPS/OCS interface. The transmitter can be configured to provide either 28Gbaud PM-16QAM (224Gbit/s) or 28Gbaud PM-QPSK (112Gbit/s) signals. Different modulation formats accommodate different transmission distances. By changing modulation formats, signals could offer different required OSNR for same link performance. Figure 6 shows the back-to-back results of the modulation-adaptable transmitter. It can be observed that the required OSNR for 16QAM signal is 22.67dB for a BER of 3.8E-3 (Pre-FEC Threshold). Regarding QPSK signals, the required OSNR for same BER performance drops to 13.8 dB.

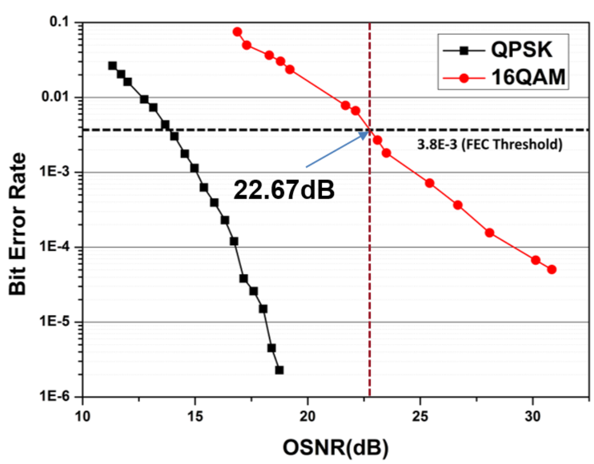


Fig. 6. OSNR vs. BER for the multiple-format transmitter adopting either QPSK or 16QAM signal format

The signal is multiplexed with other 9×28 Gbaud PM-QPSK signals by a 4×16 spectrum selective switching (SSS). Then the signals are transmitted 175km from node A, through node B, then to node D, and demultiplexed at node D for the coherent detection. In the coherent receiver, an EVM-based OSNR monitor [24] is deployed to collect in-band OSNR of the received signal. The collected OSNR information is stored in a chronological order. As OSNR change occurs slowly, the collected OSNR information could be analyzed to predict possible network disruption.

We developed a network analytics application to process the collected OSNR information for each link. The monitoring application processes the two-layer monitoring information to detect OSNR degradation or incoming traffic change and then triggers the SDN control plane to reconfigure optical link to adopt a lower order modulation format, or to choose another link if links or components failure occurs. The multi-layer monitoring information from both the optical link and layer-2 switch is used to optimize the end-to-end link.

To emulate the OSNR degradation of the link, extra ASE noise is added into the link between node A and B. The initial modulation format of the link is 16QAM at 28Gbaud. By adding more ASE noise in the link, the monitored OSNR will decrease to a threshold of 23dB. Then the monitor application notifies the SDN Controller to reconfigure the link. In scenario 1, the QPSK/16QAM TX reconfigures its modulation format from 16QAM to QPSK, to provide a guaranteed bitrate with only half of original bitrate. Recovered constellation diagrams are shown in Fig. 5(d) for the 16QAM and Fig. 5(e) for the QPSK signal. In scenario 2, the SDN controller reconfigures the optical path to node A to node D directly with a reduced distance link.

B. *Enable power equalization at any combing device*

Based on AoD-based optical nodes, Network function programmability is firstly introduced to optical networks [10]. The unprecedented levels of flexibility and modularity enable optical node synthesis its node functions based on the traffic requests. Compared to the traditional static optical nodes, the internal connections of the AoD-based node reconfigure frequently and the lightpaths become unpredictable. The dynamic node reconfiguration raises a lot of challenges, one of which is the power equalizations. When several signals with different signal powers are combined at couplers or multiplexers, the unequalized signal will suffer signal degradation in the following amplification and other operations. The un-equalization couldn't be compensated as lightpaths change dynamically. Thus, we developed a network analytics application to enable power equalization at any combing device.

The developed network analytics application uses ubiquitous power monitoring to obtain the optical powers of the input signals in the combing device. The LPFS also embeds power attenuation function at all the output ports. During optical node synthesis, signal combining will use the developed network analytics application to perform signal equalization coarsely. When signal combining happens, the network analytics application would check the input power of all the signals and query the SDN controller the configured information to obtain the occupied spectra of signals. With optical power and occupied spectrum information, the network analytics application could perform signal equalization at any combing device.

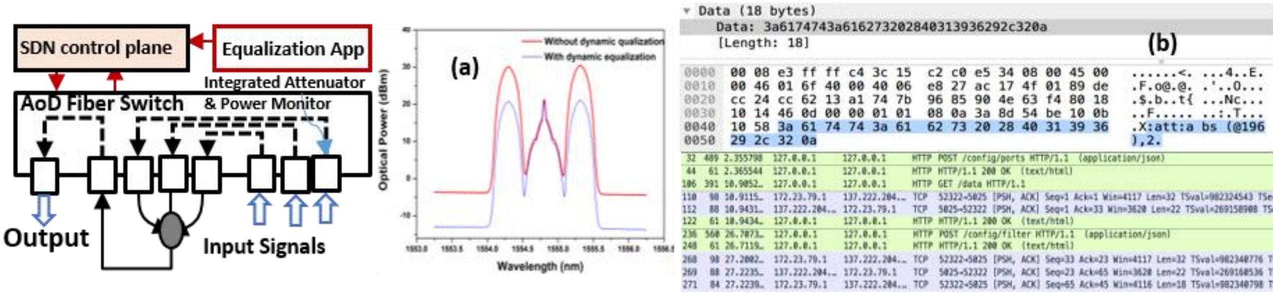


Fig.7 (a) Power equalization enabled by ubiquitous optical power monitoring. (b)Captured SDN messages.

As shown in Fig.7, power equalization can be achieved at any combing device in optical node, with integrated attenuators and power monitors in the AoD fiber switch. The equalization application processed the power monitoring information and configurations and triggered the SDN controller to configure the integrated attenuators at the input ports if power deviation exceeded a threshold of 2 dB. The optical spectra of the combined signal with/without power equalization are shown in Fig.7(a). The captured SDN configuration messages are shown in Fig.7 (b).

Without resorting to the last-stage SSS (spectrum selective switch), power equalization at any combing device will improve energy consumption and node reliability.

C. *Optical network debugging and auto-restoration*

Network administration and operation fee make a large proportion of the total network cost. Especially, when network hardware failure occurs, a technician should be sent out to diagnose the hardware on site and restore the network by replacing the failed device or subsystem. The labor-intensive network maintenance usually causes high operation expenses with the soaring labour cost.

In this case, we demonstrated optical network analytics application could debug and restore optical networks as a programmer does for a program. The optical network analytics application uses a database to store all network functions and related performance. The database stores all the used components of the established link and available inventory for all the key network functions or subsystems. For example, the database would save all the available EDFAs and current used EDFAs with their performance

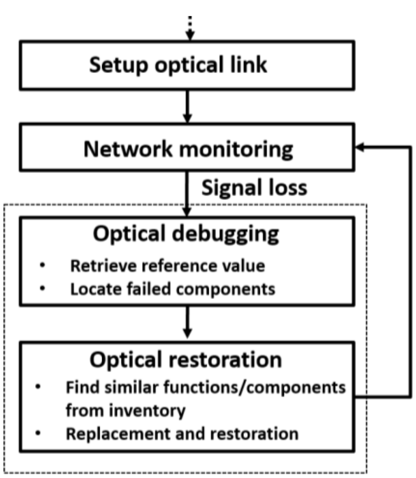


Fig. 8. Workflow for optical network debugging and auto-restoration

(gain). The database is referred as network function abstraction. Then, the programmable optical network will deploy network functions based on network function abstraction.

Optical debugging and auto-restoration application (ODA) relies on ubiquitous power monitoring technology that provides input and output powers of all the components in the link and AoD-based programmable optical network. Optical power could indicate a lot of information about links and components. It's very easy to obtain the insertion loss or gain of all the connected components. With the ubiquitous power monitoring technology, detailed network analysis can be achieved. For an established link, ODA could analyze insertion loss of all the used optical components. Comparing with all the stored refered value, ODA could locate the failed subsystem or component and replace it with another same function components.

Fig. 8 shows the workflow of ODA. If a network failure occurs, signal loss will trigger the running of the ODA application. The ODA will check the insertion loss of all the connected components in the failed traffic flow. By comparing the insert loss with the reference value, a failed network device could be located. Then the ODA will check the current network function inventory to find same function or components with similar performance. Through SDN controller, ODA would replace the failed function and restore the failed link.

Figure 9 shows the experimental demonstration of ODA in an optical network testbed. An optical channel is established through three AoD-based optical nodes. The AoD fiber switch is 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 AoD fiber switch. 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 28GBaud PM-QPSK signal after transmitting over 275km is shown in the inset of Fig. 9.

The network debugging and auto-restoration can be achieved in a short time after a network failure. Without

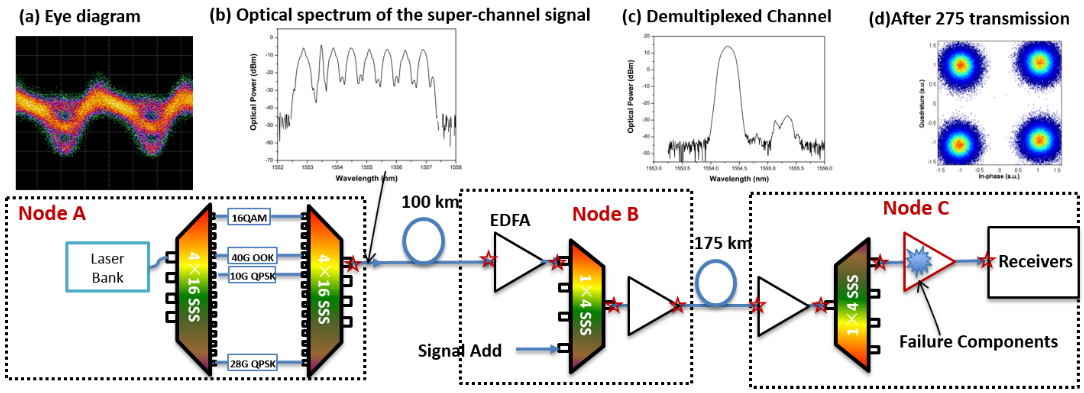


Fig. 9. Experimental setup of optical network debugging and auto-restoration

human intervention, network operation cost could be dropped dramatically.

IV. Conclusion

In this paper, we propose a network analytics framework for future programmable and dynamic optical networks based on SDN and variable monitoring technologies. The multi-layer network analytics uses various monitoring technologies in different network layers obtain network status, then diagnoses and analyzes optical networks for further network re-planning and optimization. With the developed optical/packet analytics applications, we demonstrated network optimization in a converged packet and optical network. QoS recovery can be performed before network disruption occurs with history OSNR monitoring information. Optical power equalization can be achieved in any combining devices in an AoD-based optical node, which improves the performance for programmable optical nodes. Also, network debugging and restoration were demonstrated that the debugging and restoration application could help to improve network reliability and reduce network administration cost. The SDN-based framework for optical network analytics gives network operators powerful tools to optimize the future dynamic optical networks.

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