Experimental Demonstration of Transparent QoT-Aware Cross-Layer Lightpath Protection Switching

M. M. Karbassian, J. He, W. Duncan, D. Carothers, N. Zhu, J. Wissinger and N. Peyghambarian

Abstract—**This paper describes an experiment demonstrating quality-of-transmission-aware transparent lightpath protection switching. The lightpath protection switching occurs in the optical domain and is based on cross-layer information exchange. An inline interferometer-based optical performance monitoring module is implemented to measure the real-time optical signal to noise ratio in the optical domain. Intelligent network control and management software is developed to dynamically control the network nodes and the lightpath switching. Various multi-rate heterogeneous traffic flows with different quality-of-service classes (i.e., traffic prioritization) are aggregated over a single wavelength division multiplexing (WDM) link and correctly routed at the destinations within a testbed. The testbed features commercially deployed optical network elements. This experiment highlights the potential for optical performance monitoring (i) to dynamically control and manage optical networks according to qualities of transmission, (ii) to intelligently reconfigure lightpaths according to impairments, and (iii) to optimize the transmission reliability in a real-time automatic cross-layer regime.**

***Index Terms*—aggregation node, cross-layer optimization, impairment-aware switching, optical performance monitoring, quality of transmission.**

I. Introduction

THE impact of physical layer impairments in the planning and operation of all-optical networks (as an ultimate vision) plays a significant role in the current industry and research trends on optical networking. A key trend of optical networks is toward high-capacity and cost-effective optical aggregation/access networks [1, 2]. In "opaque" networks, the optical signal undergoes expensive OEO conversions at every switching node. One approach to reduce the cost is the employment of sparsely placed electrical or optical regenerators so-called "translucent" networks [3]. In translucent networks, a set of sparsely but strategically located regenerators based on OEO conversion is used to maintain the acceptable level of signal quality from the source to its destination. On the other hand, in all-optical networks so-called "transparent", the signal remains entirely in optical domain as it propagates through a lightpath from source to destination. Future optical networks promise more optical processing and the elimination of a significant amount of electronic processing to lower the power consumption, capital and operational expenditures, as well as enhanced capabilities, such as transport any type of data format (modulation and bit rate independence) through the network and support for dynamic demands, programmability and re-configurability [4].

The communications networks are driven by the extreme growth in traffic originating from the recent expansion of bandwidth-hunger applications. Today's network elements are restricted to specific network layers and communication, while associated optimization across those layers is not supported. This leads to excessive energy consumption, because traffic cannot be flexibly allocated to the layer that consumes the least power. It also limits the amount of traffic that can be supported within a given capacity, because traffic engineering only occurs within layers. This results in reduced bandwidth utilization and increased network cost. Therefore, a fresh architectural design of the network protocol stack is an essential target for the next generation Internet and access networks to support flexible network routing applications. To successfully provide variable path integrity vectors and accordingly accommodate dynamic network routing, novel cross-layer network designs need to engage emerging physical layer technologies and devices with higher layers [5]. This cross-layer architectural design should feature profound introspective access into the physical layer that can expose so-called Optical Performance Monitoring (OPM) measurements to greatly enhance and optimize overall network performance. The protocol stack of today's optical networks is generally not aware of the impairments affecting the optical physical layer; thus, the ultimate endeavor is to develop a bidirectional networking protocol and communications environment such that the physical layer status can be taken into account, e.g. to reconfigure and optimize packet routing [6] or to provide impairment-aware lightpath routing [7]. The embedded devices directly into existing network infrastructures may monitor the physical layer performance such as Bit Error Rates (BERs) [8], or dedicated OPM devices. These measurements could be acquired packet-by-packet to provide a packet-level control and rerouting functionality [6]. As an example of Quality of Service (QoS)-aware cross-layer optimization, a previously proposed packet protection

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switching scheme [9, 10] demonstrated the high-priority optical packets are proactively identified at the receiving port using a dedicated OPM module.

Here in this paper, a cross-layer control signal is generated based on feedback from OPM module to a Network Control and Management Software (NCMS) to dynamically manage and control the aggregation network nodes and inline components to monitor and reroute the data stream on an alternate protection lightpath. In this experiment, physical impairments as part of the measure of the Quality of Transmission (QoT) affect the network lightpath switching in real-time.

As one of the recent efforts addressing the dynamic aggregation network management, a Testbed for Optical Aggregation Networks (TOAN) has been implemented that addresses the challenges of aggregation of heterogeneous and service-oriented (i.e., variable QoS) traffic flows [1]. The intelligent NCMS has been developed considering the impact of physical layer impairments within optical networking. Here, we experimentally demonstrate a protection scheme using a dedicated OPM device that monitors real-time Optical Signal to Noise Ratio (OSNR) within an optical packet switching platform.

II. Infrastructure: Testbed for Optical Aggregation Networks (TOAN)

A testbed is developed based on optical packet-switched aggregation networking platform as a cutting-edge infrastructure for evolving packet-centric optical networks. The desire for experiencing the connected-world drives significant new requirements onto service provider networks. Requirements such as delivering cost effective efficient bandwidth and guaranteed QoS in a dynamic multiprotocol environment are essential. The TOAN testbed at the College of Optical Sciences in the University of Arizona is fully funded by National Science Foundation (NSF) fostering the academic and industry collaborations. The TOAN tackles with efficient bandwidth management at the heterogeneous traffic aggregation from core to access and vice versa mainly driven by promising high-bandwidth applications. Deriving from industrial and academic collaborations, TOAN enjoys two Fujitsu FlashWave 9500 (FW) network nodes [11]. Figure 1 illustrates the testbed network nodes, traffic generation station, network control and management console, and modular workstation. This platform can take an optical network into upcoming bandwidth-aggressive applications while preserving existing technology assets. The FW's unique hardware and software architecture integrates 1 and 10 Gigabit Ethernet, Reconfigurable Optical Add/Drop Multiplexer (ROADM) and SONET/SDH technologies in a single shelf, reducing management and cost in the metropolitan area networks. Accordingly, TOAN provides a modular, chassis-level fusion of connection-oriented Ethernet, ROADM-on-a-card and SONET/SDH transport on a single addressable optical networking element.

TOAN consists of common interface cards and system

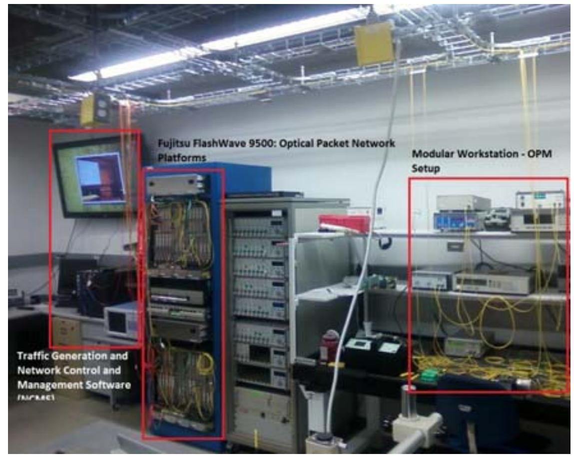

Fig. 1. Testbed for optical aggregation networks (TOAN) infrastructure in the College of Optical Sciences at the University of Arizona

software across a variety of configurations and traffic capacities. TOAN reconfigurable topology allows optimizing the cost, architecture, performance, algorithm, as well as scalability from top to bottom layers of networking perspectives in a real-size network. TOAN, considering the emerging aggregation network architectures, provides distributed aggregation and transport layers. This approach allows highly optimized service elements like routers to provide specialized feature-rich functions in a less widely distributed topologies. TOAN optical packet-switched platform can reduce the cost of real-world network experiments since the operation is similar to dedicated scalable Ethernet, SONET/SDH and ROADM network elements. TOAN is capable of generating and handling various services such as multi-rate QoS-supported Ethernet, wireless, SONET and WDM at 10 Gbps per wavelength. Also, there are three modular workstations used for external subsystem and device insertions depending on the experiment concepts and purposes.

III. Experiment Procedure and Outcomes

In this section, we describe the cross-layer-based QoT-aware lightpath protection switching mechanism, the OPM, and the NCMS as well as the outcomes obtained from this experiment.

A. *Experiment Procedure*

The cross-layer-based lightpath protection scheme is demonstrated on a single WDM link between two aggregation nodes (Flashwave 9500) over two fiber-runs of various lengths, as will be discussed in details in experiment results section. Figure 2(a) illustrates the aggregation ring toward access networks with complete (optical) heterogeneous packet-switched network architecture, while Figure 2(b) shows the cross-layer interaction between physical and networking layer through control and management plane.

Figure 2(b) illustrates how the connectivity between two network nodes is established from a service request of a

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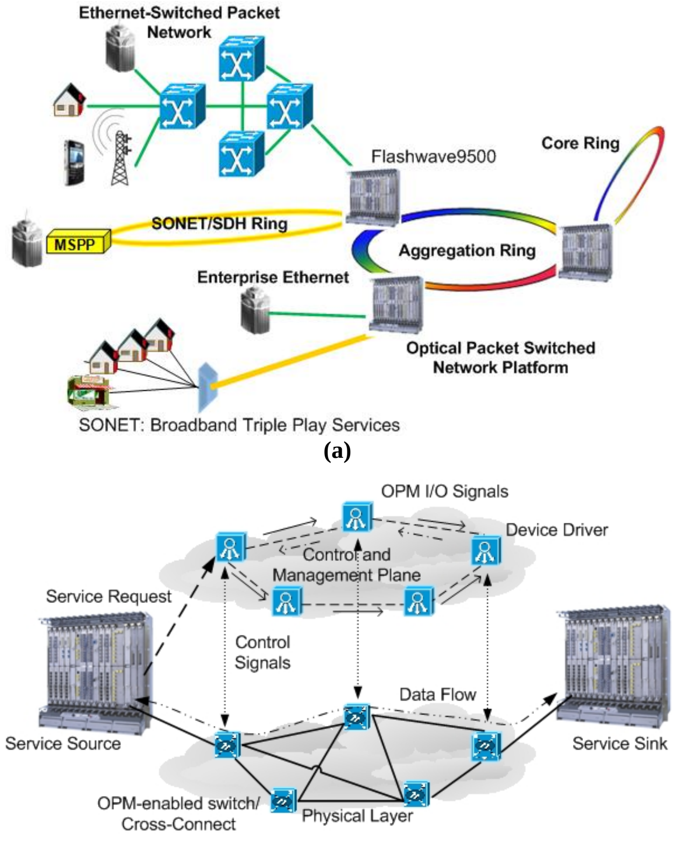

Fig. 2. a) Heterogeneous optical packet-switched platform b) cross-layer OPM-enabled control and management mechanism

service source (i.e., network node) to control and management plane. There is a mesh cross-connects at the optical physical layer via Optical Cross-Connects (OXC). The lightpath is then established based on the control signals coming from control plane driving the OXCs. It is also shown that the OXCs could have power monitoring capability to report to the control plane.

Here in this experiment, we only focus on a link between two network nodes and two OXCs to demonstrate the concept of QoT-aware cross-layer optimization. Two fiber paths are routed through two 1×2 switches controlled by NCMS. The switch fabric is supported by fully programmable FW ASIC technology featuring universal STS, packet, OTN and high density ROADM (up to 8-degree with 88-channel at C-band) up to 480 Gbps aggregation capacity. The fabric is comprised of two parallel packet-switched entities providing increased protection path diversity. The nodes' control logic is distributed and provides a high level of programmability. Optical payloads are switched within each node using the internal cross-connects to the switch fabric which are provisioned at the network planning phase. The supported optical packet format includes control header information (e.g., frame, address, QoS) encoded on dedicated wavelengths, with the payload segmented and modulated at a high data rate of 10 Gbps/wavelength.

To emulate the real-world relevance of this experiment, real

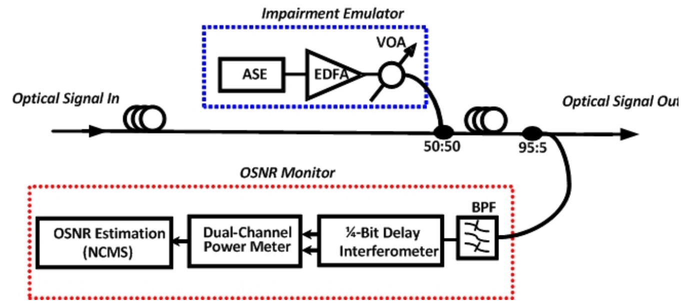

Fig. 3. Circuit diagram of transparent OPM module in the lightpath

traffic has been fed into the network nodes and routed correctly to their destinations, including pre-recorded packets from real Ethernet traffic flows [12], data from wireless sensor network nodes, full-HD (i.e., 1080p) video streaming, emulated OC-12 frames and Ethernet-over-SONET packets at OC-3 frames. Then, all the various traffic streams with different data-rates and QoS are aggregated to a single WDM link through the Wavelength-Selective Switch (WSS) and ROADM configuration. Based on the provisioned logic interfaces, flow points and transport service groups generated at the aggregation nodes, the switch fabric routes the right packets to the desired output and/or dropped on contention or priority. For this experimental implementation, depending on the QoS class, packets with lower priority will be dropped at their destination port when congested.

For OPM monitoring, an experimental cross-layer communications infrastructure necessary to realize the packet protection scheme using a generated pseudo-BER has been reported [10]. Here, we implemented the OPM device by realizing an OSNR performance monitor. OSNR monitoring may help lead to BER extrapolation for real-time systems-level physical layer performance assessment. The OSNR monitor [13, 14] as shown in Figure 3 is based on a ¼-bit Mach-Zehnder Delay-Line Interferometer (DLI) which can support multiple modulation formats and is insensitive to other impairments (i.e. chromatic dispersion and polarization mode dispersion).

The two ports of the DLI provide constructive ($P_{Cons.}$) and destructive ($P_{Dest.}$) interferences. The phase relationship in a single bit results in constant constructive interference over ¾ of the bit period at the output of a ¼-bit DLI. The OSNR is given by the ratio $P_{Cons.}/P_{Dest.}$ [10]; while with decreasing OSNR, $P_{Dest.}$ increases more than $P_{Cons.}$ due to noise's random phase. Here, the OSNR is monitored on a message timescale and the data used as a physical layer performance indicator within the network's protection scheme.

Using a delay interferometer and NCMS interface, the OSNR of a single channel WDM link is measured real-time at the output of the power meters. Intelligent NCMS will read the OSNR from the OPM module to decide whether the quality is below a certain threshold (compared with minimum BER requirements for FWs) to trigger the switches to a protection lightpath. OPM has been offered as a means for enabling robust future optical networks [15]. Although the potential and benefits of using OPM for real-time measurements within a

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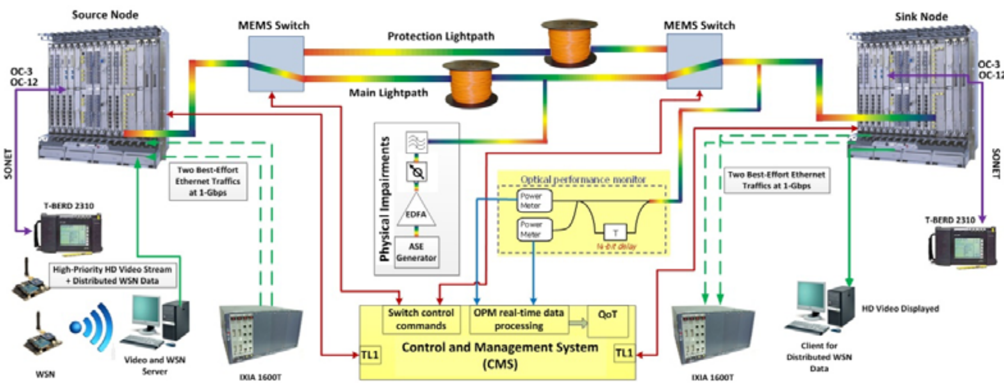

(a)

(b)

(c)

Fig. 4. (a) Experimental setup for cross-layer protection lightpath switching, including heterogeneous traffic, (b) impaired video (c) video after lightpath protection switching

live fiber network are clear [16], limited works as of yet have shown an integrated cross-layer optimization platform using real-time OPM measurements within an optical networking testbed. To demonstrate this limit, performance monitoring became integrated into the cross-layer platform within this experiment, thus unifying the QoT-aware protocol with advanced measurements provided a deeper exposure of the network substrate status in contrast to existing protocol and infrastructures.

B. Experiment Outcomes

To emulate the heterogeneous traffic, two Ethernet packet streams are generated and replayed through IXIA 1600T traffic generator at 1 Gbps each. Ethernet traffic streams are classified as best-effort representing the low priority as layer 2 impairment to simulate the congestion (i.e., QoS). We had one OC-12 SONET (622 Mbps) and two OC-3 Ethernet-over-SONET packets (2×155 Mbps) generated via T-BERD 2310 traffic analyzer and FW itself respectively. A wireless sensors network developed for the border surveillance [17] is also integrated to the TOAN infrastructure as part of aggregation mechanism and interfaces. The wireless sensor network consists of four sensors (Waspmote nodes with temperature, vibration, tilt, impact sensors onboard) and one multimedia sensor (Imote2node with battery-powered camera). The entire TOAN experiment block diagram including wireless sensor network is shown in Figure 4(a). The traffic from wireless sensors network is configured to be high priority (i.e. high QoS requirement) to consider the importance and delay-sensitivity of the sensed data. And finally, another high priority traffic is devoted to 1080p HD video stream over one optical gigabit Ethernet link at 30 Mbps using user datagram protocol (UDP), a suitable protocol for media streaming. Then, all the traffic flows as seen in Figure 4(a) are aggregated over a single WDM channel at 1550.12 nm. Since the system capacity is 10 Gbps NRZ per wavelength and to demonstrate the actual data congestion and QoS-aware mechanism, the channel has been rate limited to 2.7 Gbps through reconfigurable bandwidth profile by the system provisioning software Netsmart 500 and TL1 commands (a unique provisioning software used to configure FW nodes provided by Fujitsu). To accommodate the enough bandwidth and appropriate congestion, the IXIA ports have also been rate-limited to 90% of total transmission rate.

Figure 4(b) shows the impaired video as a result of intentionally impaired lightpath to enable the OSNR monitoring (Figure 3). The mechanism leveraging signal introspection measurements to provide a means of detecting data stream degradation has been proposed in [6, 9, 14]. The scheme detects a degrading signal (i.e., low OSNR) and sets a predefined threshold (compared with minimum BER requirements for FWs) for which packet rerouting is triggered to prevent packet loss. The loss of a degraded optical message is improved by a cross-layer control signal and later transmission along a protection path. The switching mechanism is triggered by link performance measurements and QoT. Data streams with high priority (i.e., HD video and WSN) are delivered properly and the packet drop occurs on other low priority traffic seen in T-BERD and IXIA traffic

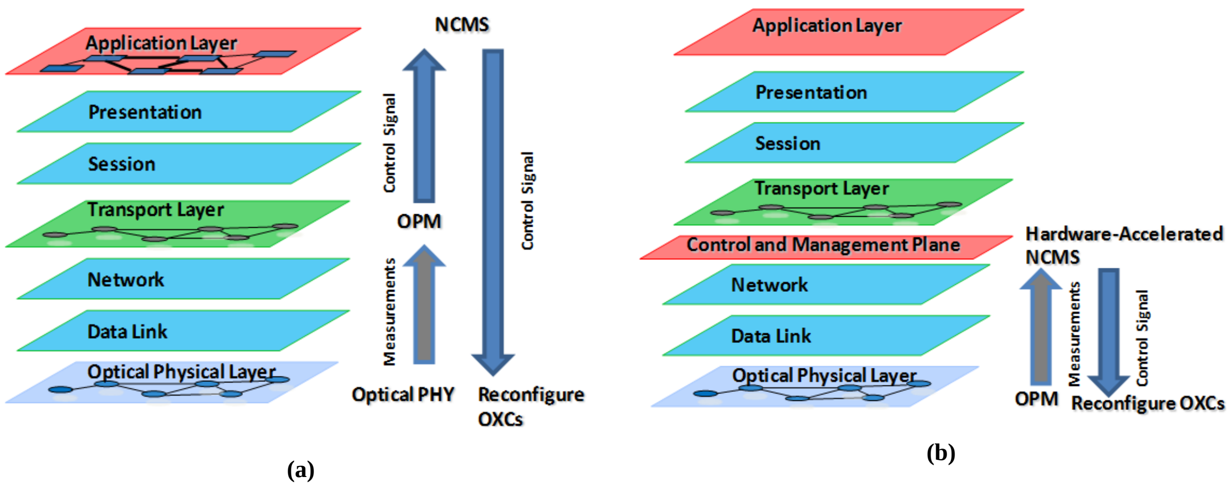

Fig. 5. Cross-layer optimization approach, (a) implemented cross-layer prototype in this experiment as a proof of concept, (b) more realistic approach in our future work

analyzers.

The OSNR is intentionally degraded using an ASE noise generator cascaded with EDFA and variable optical attenuator (see Figure 4(a)). The ¼-bit DLI is a commercially-available optical Differential Phase-Shift Keying (DPSK) demodulator from Optoplex that should be phase-tuned for maximum and minimum power at its two output ports. The DLI exhibits flexible tunability and high stability of phase tuning. The DLI feeds to an optical dual power meter and the power information (i.e., $P_{Cons.}$ and $P_{Dest.}$) is then sent to NCMS control plane to calculate the OSNR and control the FWs and lightpath switches similar to Figure 2(b). Lightpath switches are commercially available ThorLabs MEMS switches at µs-switching speed with maximum 2.5 dB port-to-port insertion-losses. There is no buffering scheme implemented in this experiment, thus packet-loss occurs during the switching. However, there is built-in buffering mechanism in FW to protect the data-loss during the link power balancing and connection establishment process. Since the FW recognizes the signal degradation much faster than OPM and NCMS do, it starts buffering packets as soon as its BER drops below a certain threshold ($BER \leq 10^{-6}$); therefore the packet loss is extremely minimized. However, since the link speed at 10 Gbps, 10 µs switching speed and packet length of 1504 bytes are realized then we reached to a very low number of packet drop (≈ 10 packet) during the switching action. On the other hand, new fiber route needs power balancing through both FW network nodes which may takes a few seconds depending on the fiber lengths. The packet loss does not count these few seconds as the data has been buffered beforehand.

The OPM data is thus used to detect the degraded signal quality and act upon that accordingly through cross-layer communications as shown in Figure 5. Figure 5(a) illustrates the classic OSI layered network architecture in which the cross-layer approach exceeds the processing time and reduces the processing load by bypassing the classic layer-by-layer communications. As seen in Figure 5(a), layers are directly communicating through independent measure of request. Since the developed NCMS (emulating the control plane) sits in application layer in this approach it takes a great deal of processing time to make its configuration decision. A better realistic approach, as seen in Figure 5(b), will be using the hardware-accelerated NCMS sitting on top of networking layer, so-called control plane, dynamically automatically real-time controlling and managing the reliable data transmission.

As an initial step towards all-optical OSNR monitoring within a network test-bed, we showed that the OSNR degradation of a high-QoS packet streams can be proactively monitored (at transport layer) and transferred to application layer where the NCMS sits to directly control the physical layer OXCs. This approach, as opposed to existing static network configuration, can bring the intelligence to the optical network enabling it to dynamically reconfigure its architecture on-demand based on impairment-aware or even service-oriented.

The future of this work will be (i) to implement other OPM capabilities with automatic compensation and correction, (ii) to consider higher data rates of up to 100 Gbps in aggregation node with advanced modulation formats, and (iii) more cross-layer interactions with actual contention resolution in mind. The network stability in terms of power, security and resource management comes to attention when the number of aggregation network nodes grows. Therefore, network stability as an important parameter is in the horizon as well as an expansion of TOAN.

IV. Summary

QoT and impairment-aware cross-layer optimized lightpath protection switching mechanism has been experimentally demonstrated. Transparent OSNR monitoring was implemented in an optical packet-switched network testbed. The OPM module is interferometer-based monitoring technique using DLI to measure real-time OSNR. NCMS software incorporated at the network nodes allows a degraded data stream to be proactively detected and rerouted according to the protection mechanism. This work demonstrates that a real-time OPM can be realized in a network to achieve advanced cross-layer communications and network management based on varying QoT and imposed physical impairments This represents a key step toward realizing next generation optical networks that can engage emerging physical layer technologies in a cross-layer regime. The outcome suggests existing architecture should benefit a dynamic reconfiguration of optical network's physical layer in addition to automatic real-time monitoring of the lightpath.

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References

[1] Engineering Research Center for Integrated Access Networks (CIAN) www.cian-erc.org.
[2] Globat Environments for Neworks Innovations (GENI) www.geni.net.
[3] B. Ramamurthy, et al. Transparent versus opaque versus translucent wavelength-routed optical networks. in OFC. 1999.
[4] J. Berthold, et al., Optical networking: past, present, and future. J. Lightw. Technol., 2008. 26(9): p. 1104-1118.
[5] C. P. Lai, H. Wang, and K. Bergman, Cross-layer communication with an optical packet switched network via a message injection control interface. IEEE Photonics Tech. Letters, 2008. 20(12): p. 967-969.
[6] C. P. Lai, et al. Demonstration of QoS-aware packet protection via cross-layer OSNR signaling. in OFC 2010.
[7] J. He, et al. QoT-aware routing in impairments-constraint optical networks. in IEEE GlobeCom. 2007.
[8] O. Gerstel, et al. Near-hitless protection in IPoDWDM networks. in OFC. 2008.
[9] F. Fidler, et al. Cross-layer simulations of fast packet protection mechanisms. in ECOC. 2009.
[10] C. P. Lai, F. Fidler, and K. Bergman. Experimental demonstration of QoS-aware cross-layer packet protection switching. in ECOC. 2009.
[11] Fujitsu FlashWave 9500 Packet Optical Networks Platform (P-ONP) http://www.fujitsu.com/downloads/TEL/fnc/datasheets/flashwave9500.pdf.
[12] The Cooperative Association for Internet Data Analysis (CAIDA) www.caida.org.
[13] Z. Pan, C. Yu, and A.E. Willner, Optical performance monitoring for the next generation optical communication networks. Optical Fiber Techonlogy, 2010. 16(1): p. 20-45.
[14] Y. K. Lizé, et al. Simultaneous and independent monitoring of OSNR, chromatic and polarization mode dispersion for NRZ-OOK, DPSK and Duobinary. in OFC. 2007.
[15] C. C. K. Chan, Optical performance monitoring: advance techniques for next generation photonic networks. 2010: Academic Press.
[16] T. Anderson, et al. Optical Performance Monitoring for Intelligent Networks. in ECOC. 2009.
[17] J. He, et al. Smart border: ad-hoc wireless sensor networks for border surveillance. in SPIE Defense, Security, and Sensing. 2011.