Experiment of Transparent QoT-Aware Cross-Layer Wavelength Assignment Switching

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Abstract—**Transparent quality-of-transmission-aware cross-layer wavelength assignment switching is experimentally described in this paper. The wavelength assignment switching occurs based on the cross-layer information exchange. An inline optical performance monitoring module is implemented to measure real-time optical signal to noise ratio in optical domain. Intelligent network control and management software is developed to control the network nodes bandwidth status and the wavelength provisioning. Various multi-rate heterogeneous traffic flows with different quality-of-service classes (i.e., traffic prioritization) are aggregated over a 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 bandwidth profile according to qualities of transmission, (ii) to intelligently reconfigure wavelengths 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, optical performance monitoring, quality-of-transmission, wavelength assignment.**

I. INTRODUCTION

THE inefficient electronic switching within optical networks is seen as a bottleneck. In “opaque” or “translucent” networks, the optical signal undergoes expensive OEO conversions at every switching node or strategic locations respectively. It is believed that the dynamic optical switching of wavelengths or fractions of wavelengths can be a promising solution for efficient bandwidth assignment [1, 2]. However optically switched networks provide transparency to data-rate, protocol and data formats (modulation), they also complicate the process of determining an optimum bandwidth through the network owing to the different physical layer impairments imposed by the transmission links and optical switching nodes. Considering the physical impairment as extensions to traditional routing and wavelength assignment algorithms have already been proposed [3]. The data-rate, modulation format and electronic processing capabilities, such as electronic equalization and/or forward error correction, of the transponders interfacing to the “transparent” (all-optical) network impact the Bit-Error Rate (BER) penalty due to physical impairments [4]. Attractively a common optical transport platform for heterogeneous optical services is offered by visionary all-optical networks. This is particularly significant when considering bit-rate capacity upgrades. Since these services will have widely varying optical performance criteria, the importance of a Quality-of-Service (QoS) and impairment-aware wavelength assignment has been shown to be even more pronounced in such network scenarios [5, 6]. On the other hand, when connection holding times get very short, the signaling and path computation times could become a significant overhead. This is further exacerbated if complex impairment-aware wavelength assignment algorithms are also considered. Since these algorithms are typically executed in software in a sequential fashion, it is difficult to improve upon their convergence times and ultimately this may limit the rate at which short-lived connection requests can be delivered. Here, we have also experimented our concept through a network control and management software; however, some research are also considering the hardware-assisted schemes to enhance the processing time [2, 7] as it is ongoing work for us too.

In an effort to overcome these shortcomings a concept, so-called Wavelength Assignment Provisioning (WAP) in this paper, proposes: (i) to monitor the physical impairments at wavelength level and bridge the results with higher layers, then (ii) re-assign the services with different qualities to next available wavelengths within the network according to the Optical Performance Monitoring (OPM) results. The fundamental approach is to maintain the optical performance parameters for every wavelength in the node and the next hop link as a node integrity vector and link integrity vector of each node respectively. As part of a control header in the packet frame (in-band or out-of-band like wavelength-striped concept [8]), a path integrity vector carries the required metric thresholds and a running total of the current optical parameters for each available wavelength on the path or payload, according to the mode of network node operation. The vectors are updated by the vector arithmetic analysis as they traverse through the network hop by hop.

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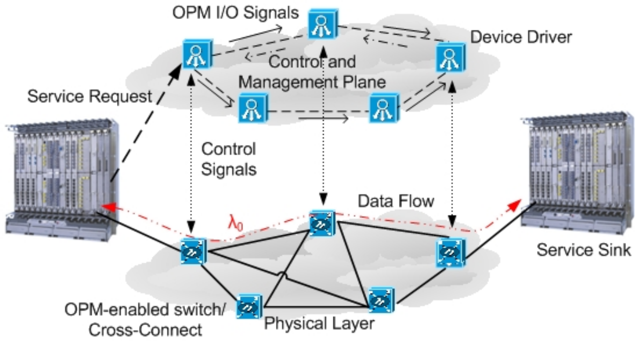


Fig. 1. Cross-layer-enabled control plane for heterogeneous services

The principle of operation for a cross-layer information exchange between physical layer and control plane is shown in Figure 1 in which a control and management plane monitor the quality of services and transmissions for heterogeneous traffics. In our reservation scheme the path integrity vector is real-time measured as the optical performance parameter i.e., Optical Signal to Noise Ratio (OSNR). The different optical parameters will have different weightings and different thresholds based on the destination receiver sensitivity and current network conditions.

Here for this experiment, Network Control and Management Software (NCMS) is developed to monitor and control the wavelengths to determine whether the services should be reassigned ‘on-the-fly’ i.e., if a wavelength provisioning is required for the payload (burst or packet). This paper focuses on a WAP scheme based on the performance monitoring of the physical layer to handle heterogeneous optical services. Future optical transport networks will have to provide connectivity between heterogeneous service interfaces with different operating bandwidths, protocols and sensitivities to optical impairments (due to advances in modulation formats, electronic equalization and error correction coding). For short holding times of these services, the key to efficient network utilization is to provision just enough network resources that satisfy the service request within a relatively short period of time (assuming connection requests arrive in real time). This is a particularly difficult problem if optical constraints are also to be considered. Wavelength assignment algorithm that considers both the OSNR and residual dispersion values of a signal in both the routing and wavelength assignment has already been numerically simulated in [5]. It is shown that high data-rate signals are remarkably more affected by residual dispersion due to the mismatches between the transmission and the dispersion compensating fibers. The algorithm reserves wavelengths with lower end-to-end residual dispersion for the higher data-rates signals. However, here we experimentally demonstrate the cross-layer-based real-time WAP.

On the other hand, today’s network elements are restricted to specific network layers and communication, while associated optimization across those layers is not supported. This leads to large energy consumption, because traffic cannot be flexibly allocated to the optical layer that consumes the least power. It also limits the amount of traffic that can be supported by a given capacity, because traffic engineering only occurs in layers. This results in reduced bandwidth utilization and efficiency, where increases network cost. Therefore, a fresh architectural design of the network protocol stack could be an essential target for the next generation Internet and access networks to support flexible network routing and wavelength assignment. 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 [9, 10]. This cross-layer architectural design features profound introspective access into the physical layer that can expose the OPM measurements to greatly enhance and optimize overall network performance. The protocol stack of today’s networks is generally not aware of the impairments affecting the physical layer; thus, the ultimate endeavor is to develop a bidirectional networking protocol and communications environment such that the physical layer state can be taken into account, e.g. to reconfigure and optimize packet routing [10].

The embedded devices directly into existing network infrastructures may monitor the physical layer performance such as BERs denoted using Forward Error Correction (FEC) [11], or dedicated OPM devices. These measurements could be acquired packet-by-packet to provide a packet-level control and wavelength assignment. As an example of cross-layer information exchange, a previously proposed packet protection switching scheme [7, 12] 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 dedicated real-time performance measurement then interact with network aggregation nodes and inline components to reassign the wavelength provisioning to the data stream on an alternate clean wavelength. In this way, packet-level changing QoS classes and physical impairments may affect wavelength-routed networks and help realize QoS- and QoT-aware protocols.

As one of the recent efforts toward this goal, a Testbed for Optical Aggregation Networks (TOAN) has been implemented addressing the challenges of aggregation of heterogeneous and service-oriented (i.e., variable QoS) architecture [13]. The intelligent NNCMS has been developed considering the impact of physical layer impairments in optical networking. Here, we experimentally demonstrate the concept of Wavelength Assignment Provisioning (WAP) scheme using a dedicated OPM device that monitors real-time OSNR within an Optical Packet Switching (OPS) platform.

II. INFRASTRUCTURE: TESTBED FOR OPTICAL AGGREGATION NETWORKS (TOAN)

A testbed is developed to host 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 such as delivering cost effective efficient bandwidth and guaranteed QoS in a dynamic environment where dealing with multiprotocol requirements. The testbed for optical aggregation networks (TOAN) at the College of Optical Sciences in the University of Arizona takes advantages of academic and industry collaborations [13]. As such collaborations, TOAN enjoys two Fujitsu FlashWave 9500 (FW) [14] network nodes which apply time-tested optical networking heritage to deliver a general-purpose aggregation and transport infrastructure for the emerging packet-centric services. This platform can take an optical network into upcoming bandwidth-aggressive applications while preserving existing technology assets. The FW 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 software across a variety of configurations and traffic capacities. The 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. The TOAN OPS elements 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 explain the cross-layer-based QoS and impairment-aware WAP switching mechanism, performance monitoring (i.e., OPM), control plane (i.e., NCMS) and experiment validations.

A. *Experiment Procedure*

The cross-layer-based WAP scheme is demonstrated on a single WDM link between two aggregation nodes (Flashwave 9500 [14]). Figure 2 illustrates the aggregation ring toward access networks with complete (optical) heterogeneous packet switched network architecture.

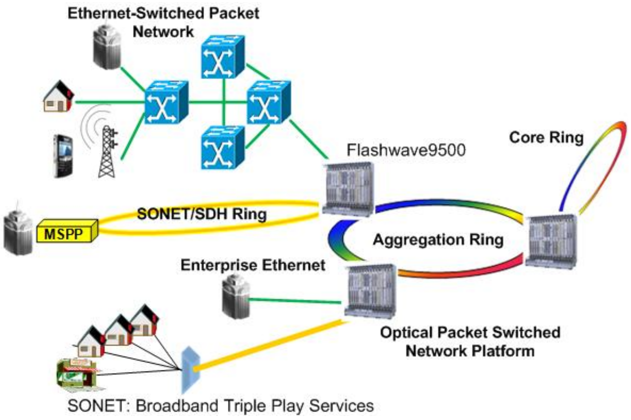


Fig. 2. Optical packet-switched platform

The fiber link is monitored and controlled at wavelength level by developed 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). 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 wavelength, with the payload segmented and modulated at a high data rate of 10 Gbps.

To simulate the real-world concept of this experiment, real traffics have been fed into the network nodes and routed correctly to their destinations, including pre-recorded packets from real Ethernet traffics [15], data from wireless sensor networks testbed, full-HD (i.e., 1080p) video streaming, emulated OC-12 frames and Ethernet-over-SONET packets at OC-3 frames. Then, all the various traffics with different data-rates and QoSs are aggregated to a single WDM link through the Wavelength-Selective Switch (WSS) and ROADM configuration at 1550.12 nm. 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.

In [7], an experimental cross-layer communications infrastructure necessary to realize the packet protection scheme using a generated pseudo-BER has been reported. 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 [16, 17] 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 ($P_{\text{Cons.}}$) and

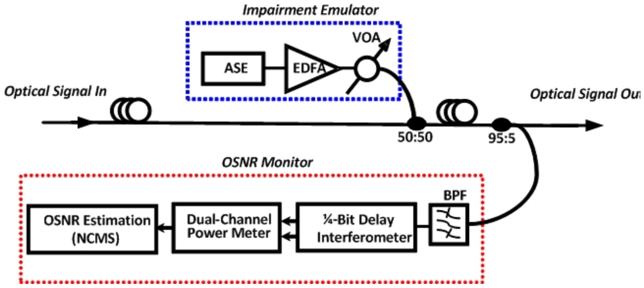


Fig. 3. Circuit diagram of transparent OPM module in the lightpath

destructive ($P_{\text{Dest.}}$) 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 $P_{\text{Cons.}}/P_{\text{Dest.}}$ [7]; while with decreasing OSNR, $P_{\text{Dest.}}$ increases more than $P_{\text{Cons.}}$ 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.

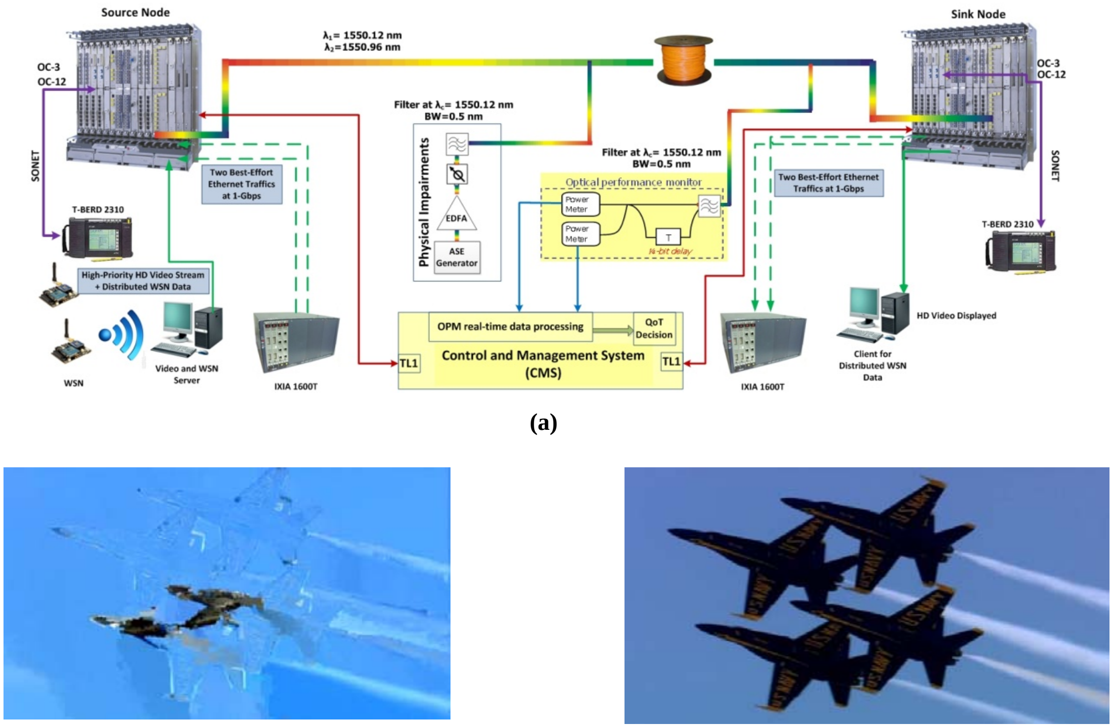
Using a ¼-bit delay Mach-Zehnder Interferometer (MZI) and NNCMS software interface, the OSNR of a single channel WDM optical packet is measured real-time at the output of the power meters. Intelligent NNCMS will read the OSNR from the OPM module to decide whether the quality is below a certain threshold (compared with minimum BER requirements for FWs) to reassign the wavelength provisioning; meaning to move the heterogeneous services from one wavelength to the next available one in band. OPM has been offered as a means for enabling robust future optical networks [18]. Although the potential and benefits of using OPM for real-time measurements within a live fiber network are clear [19], limited works as of yet have shown an integrated cross-layer communications platform using real-time OPM measurements for wavelength assignment and provisioning within an optical networking testbed. To realize this, performance monitoring must become integrated into the cross-layer platform, thus unifying the QoS-aware protocols with advanced measurements will provide a deeper exposure of the network management.

B. *Experiment Outcome*

To emulate the heterogeneous services, two Ethernet packet streams are generated and replayed through IXIA 1600T traffic generator at 1 Gbps each. Ethernet traffics are classified as best-effort representing the low priority as layer 2 impairment to simulate the congestion (i.e., QoS-aware). 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. TOAN also leverages the wireless sensors networks built for border surveillance [20] as part of its aggregation mechanism and interfaces. For this experiment, four sensors (Waspmote nodes with temperature, vibration, tilt, impact sensors onboard) and one multimedia sensor (Imote2node with battery-powered camera) have been used to feed the network nodes. The entire TOAN experiment block diagram including wireless interface to the node is shown in Figure 4(a). These traffics have been set as high priority streams between two nodes to consider the importance and delay-sensitivity of the sensed data (high QoS requirement). And finally, the high priority traffics are devoted to 1080p HD video and WSN streams over the optical gigabit Ethernet link at 30 Mbps using user datagram protocol (UDP), a suitable protocol for media streaming. Then, all the traffics as seen in Figure 4(a) are aggregated over a single WDM channel at $\lambda_1 = 1550.12\,\text{nm}$. 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 (right at the edge of all traffics) through reconfigurable bandwidth profile, used for provisioning and configuring the FW nodes. 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 video on intentionally impaired wavelength to enable the OSNR monitoring (Figures 3 and 4). The mechanism leverages signal introspection measurements to provide a means of detecting data stream degradation has been proposed in [7, 10, 16]. The scheme detects a degrading signal (i.e., low OSNR) at wavelength level by configuring the optical filters (see Figures 3 and 4(a)) at center wavelength $1550.12\text{ nm} \mp 0.25\text{ nm}$. Accordingly, the specific lambda will be impaired and monitored. As a result of OSNR monitoring, NCMS sets a threshold (compared with minimum BER requirements for FWs) as a performance integrity factor for which wavelength assignment provisioning (WAP) is triggered to prevent packet loss. NCMS software is used to command the source and destination nodes to reprovision their wavelength to next available one in band (i.e., $\lambda_2 = 1550.96\,\text{nm}$ in this experiment). The loss of a degraded optical message is improved by a cross-layer control signal and later transmission over clean wavelength (see Figures 4(b), 4(c)). The WAP switching mechanism is triggered by link performance measurements and QoS. Data streams with high priority (i.e., HD video and WSN streams) are delivered properly and the packet drop occurs on other low priority traffics seen in T-BERD and IXIA traffic analyzers.

The OSNR is intentionally degraded using an ASE noise generator cascaded with EDFA and variable optical attenuator (see Figure 3). The ¼-bit DLI is a commercially-available optical differential phase-shift keying (DPSK) demodulator from Optoplex that should be phase-tuned for maximum power and minimum power in the two 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., $P_{\text{Cons.}}$ and $P_{\text{Dest.}}$) is then sent to NCMS control plane to calculate the OSNR and control the FWs and lightpath switches. There is no buffering scheme implemented in this experiment, thus packet-loss occurs during the WAP switching. However, there is built-in buffering mechanism in FW to protect the data-loss during the link power balancing and connection establishment process.



(a)

(b) (c)

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

The OPM data is thus used to detect the degraded streams and act upon that through cross-layer communications. As an initial step towards all-optical OSNR monitoring within a network test-bed, we show that the OSNR degradation of a high-QoS packet streams can be proactively monitored and transferred to higher layers. Correct network routing is validated by accurately receiving the desired data at destinations end with remarkable BER of 10^{-12} reported at FW nodes. The control and management latencies by the current experimental setup are limited by the transmission and processing latencies of the system. Thus far, we have realized the real-time OSNR measurement to monitor the signal quality at optical layer with future plans to implement other OPM capabilities with compensation methods and more cross-layer interactions.

IV. SUMMARY

QoT and impairment-aware cross-layer wavelength assignment provisioning mechanism is experimentally demonstrated. Transparent OSNR monitoring at wavelength level was implemented in testbed for optical aggregation networks. The optical performance monitoring (OPM) module is based on a ¼-bit Mach-Zehnder DLI-based OSNR measurement and NCMS software incorporated at the network nodes allowing for a degraded data stream to be proactively detected and reprovisioned to another available wavelength according to the WAP scheme. This work demonstrates that a real-time OPM can be realized in a wavelength-routed network to achieve advanced cross-layer communications and network management based on varying QoS 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.

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