Demonstration of QoS-Aware Packet Protection via Cross-Layer OSNR Signaling

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Abstract: Quality-of-service aware packet protection is demonstrated using cross-layer signaling from a delay-line-interferometer-assisted optical-signal-to-noise-ratio monitor. 8×10 Gb/s wavelength-striped optical messages are successfully rerouted based on performance monitoring measurements communicated between the physical and networking layers.

OCIS Codes: (060.4250) Networks; (060.4261) Networks, protection and restoration; (060.4510) Optical communications

1. Introduction

The rapid design of the next generation networks is driven by the intense growth in traffic originating from the recent explosive expansion of high-bandwidth applications. These vastly increasing bandwidth demands and the associated traffic diversity require highly agile networks that are dynamically adaptable and can efficiently accommodate the wide variety of applications. To meet these growing demands and enable more efficient traffic engineering, next generation networks will likely employ bidirectional information flows between the layers of the network protocol stack [1,2]. A clean-slate 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 bandwidth allocation and accommodate dynamic network routing, network designs will need to further engage and drive emerging physical layer technologies and devices [2,3]. This challenge may be addressed by creating an integrated packet-level cross-layer signaling communication infrastructure that can support flexible, broadband bidirectional information flow across the otherwise strictly layered networking environment (Fig. 1). This cross-layer architectural design facilitates introspective access deep into the physical layer which can then extract optical performance monitoring (OPM) measurements to greatly improve 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. This holistic, cross-layer approach that includes explicit information exchange with the physical layer can enable more flexible and dynamically adaptable network architectures.

The physical layer performance may be monitored by devices directly embedded in existing networking equipment, e.g. bit-error rates (BERs) denoted using forward error correction (FEC) [4], or dedicated OPM devices. These measurements may be acquired message-by-message to provide a packet-level control and rerouting functionality. As an example of cross-layer information exchange, we have previously proposed a proactive packet protection switching scheme [5,6]. Degraded, high-priority optical packets are proactively identified at the receiving port using a dedicated OPM. A cross-layer control signal is then sent to the transmitting node, which can switch and reroute the data stream on an alternate protection path. In this way, packet-level changing quality-of-service (QoS) classes and signal impairments may affect network routing and help realize impairment-aware protocols.

Here, we experimentally demonstrate the aforementioned protection scheme using a dedicated packet-level OPM device that monitors real-time optical-signal-to-noise-ratio (OSNR) within an optical packet switching (OPS) test-bed. Using a ¼-bit delay Mach-Zehnder interferometer (MZI) and field-programmable gate array (FPGA), the OSNR of a wavelength-striped optical packet is measured at the output. Depending on its QoS class (i.e. high/low priority), the packet may be forwarded to the receiving port, or discarded and rerouted on alternate path. 8×10 Gb/s multi-wavelength optical messages are shown correctly routed and detected by a cross-layer receiver. OPM has been offered as a means for enabling robust future optical networks [7,8]. Although the potential and benefits of using OPM for real-time measurements within a live fiber network are clear [9], no work as of yet has shown an integrated cross-layer communications platform using real-time per-packet OPM measurements within a networking test-bed.

To realize this, performance monitoring must become integrated into the cross-layer platform, thus unifying the QoS-aware protocols with advanced measurements that provide a deeper exposure of the substrate.

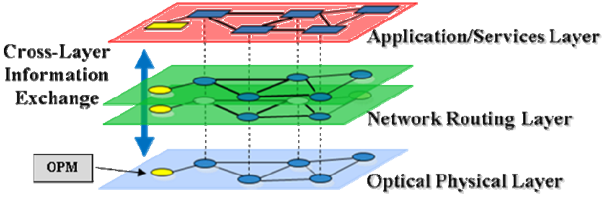

Fig. 1. Cross-layer enabled network protocol stack allowing for bidirectional information exchange between network layers; the physical layer is envisioned to incorporate OPM capabilities

2. Optical Switching Fabric Architecture

The packet protection scheme is demonstrated on a 4×4 optical switching fabric test-bed [5,10]. Based on the SPINet topology, the fabric is comprised of two parallel OPS network entities providing increased protection path diversity. The fabric's basic building block is a wideband 2×2 programmable photonic switching node. The nodes' routing control logic is distributed and provides a high level of programmability. Optical messages are switched within each node using four semiconductor optical amplifier (SOA) gates. The supported wavelength-striped 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 on the rest of the band (e.g. 10 Gb/s per wavelength) (Fig. 2a). The 2×2 photonic switching nodes extract the control signals instantly at the messages' leading edge low-speed optical receivers. Based on the headers, the electronic routing control logic gate the appropriate SOAs and the messages are either routed to their desired output or dropped on contention. An optical layer acknowledgement (ack) protocol is realized via short optical pulses sent in the reverse direction to inform the source of successful reception. Sources that are missing an ack can retransmit at the next timeslot and/or switch and reroute the data stream on a parallel protection path. For this experimental implementation, depending on the QoS class, packets with degraded OSNR are intentionally discarded after reception in order to suppress the ack and trigger rerouting.

3. Cross-Layer Packet Protection Switching Mechanism

As previously proposed in [5], the packet protection mechanism leverages signal introspection measurements to provide a means of detecting a data stream degradation. The scheme detects a degrading signal (here, a degrading OSNR) and sets a predefined threshold for which packet rerouting is triggered to prevent packet loss. The loss of a degraded optical message is alleviated by a cross-layer control signal and later transmission along a protection path. The switching mechanism is triggered by per-packet performance measurements and QoS. Data streams with high-priority/low-OSNR optical messages are rerouted on a protection path, while low-priority (irrespective of OSNR) and high-priority/high-OSNR messages are forwarded.

In [5], we have demonstrated an experimental cross-layer communications infrastructure necessary to realize the packet protection scheme using a generated pseudo-BER. Here, we implement 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 [7] 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_{const}) and destructive (P_{dest}) interference. 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_{const}/ P_{dest}; with decreasing OSNR, P_{dest} increases more than P_{const} 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.

4. Experimental Test-bed Validation

The test-bed is comprised of ten 2×2 wideband photonic switching nodes. The distributed electronic logic is synthesized in high-speed Xilinx complex programmable logic devices (CPLDs). Each node is realized with discrete components including a CPLD, SOAs, 155-Mb/s p-i-n photodetectors, electronic circuitry, and passive optics. To accommodate the timescales required by the OSNR measurements, the system supports 1.2-s timeslots with 1-s length packets with 10-Gb/s modulated data on eight payload wavelength channels; a $LiNbO_3$ modulator is used to create a 2^{15}-1 non-return-to-zero (NRZ) pseudorandom bit sequence (PRBS). At the network input, the OSNR is degraded for a subset of packets using an optical attenuator followed by a SOA, creating the low-OSNR packets.

To exemplify the scheme, a modified cross-layer receiver design is used at the network output incorporating a packet-level OSNR monitor to dynamically and simultaneously monitor egressing packets (Fig. 2b) and to signal rerouting of degraded high-QoS packets. The ¼-bit DLI is a commercially-available optical differential phase-shift keying (DPSK) demodulator from Optoplex that is 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 a fiber switch tray from Polatis that has integrated power monitors and supports a RS232 serial interface. The power information (P_{const} and P_{dest}) is then sent via the RS232 port to a Xilinx Virtex-5 FPGA, which calculates the OSNR on a message-by-message timescale and contains the scheme's decision logic. The OPM data is thus used to detect degraded streams.

As an initial step towards per-packet OSNR monitoring within a network test-bed, we show that the OSNR degradation of a high-QoS wavelength-striped packet stream can be proactively detected. Correct network routing is validated and the modified receiver correctly detects the high-priority/low-OSNR messages on a packet-by-packet basis; the scheme then initiates a rerouting of the degraded packet stream. The packet lengths supported by the current experimental system are limited by the transmission and processing latencies of RS232. The packets are received at the test-bed's output by a 10 Gb/s p-i-n photodiode with transimpedance amplifier and limited amplifier pair. BER measurements confirm error-free transmission with BERs less than 10^{-12} at the output of network test-bed.

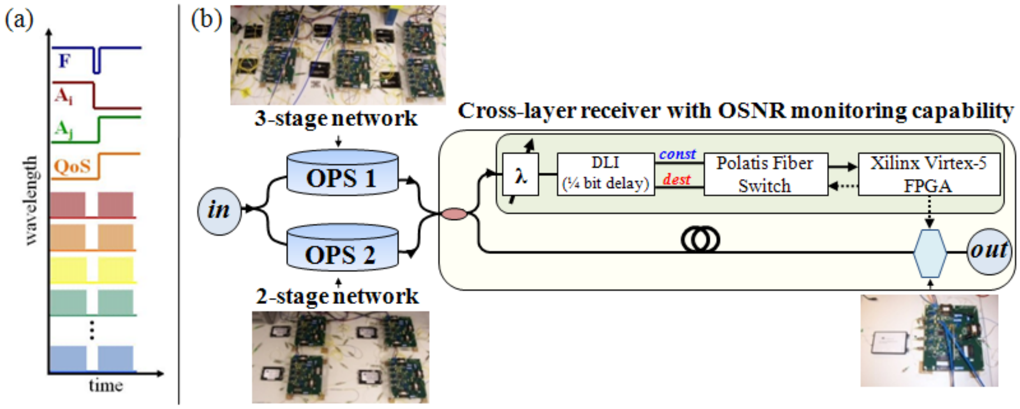

Fig. 2. (a) Wavelength-striped optical packet format; (b) Schematic of experimental setup incorporating the OSNR monitoring device

5. Conclusions

A packet-level OSNR monitor is implemented for a network test-bed and leveraged in a packet protection switching scheme. The OSNR monitoring is based on a ¼-bit Mach-Zehnder DLI and FPGA incorporated at the network's receiving end, allowing for a degraded data stream to be proactively detected and rerouted according to the protection scheme. High-bandwidth 8×10 Gb/s optical messages are correctly routed through the test-bed. This work demonstrates that a real-time packet-level optical performance monitor can be realized in a network to achieve advanced cross-layer communications and network management based on varying QoS protocols. This represents a key step toward realizing next generation optical access networks that can engage emerging physical layer technologies in a cross-layer way.

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6. References

[1] CIAN (Center for Integrated Access Networks), http://cian-erc.org
[2] GENI (Global Environment for Network Innovations), http://www.geni.net
[3] 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 Technology Letters* **20** (12) 967-969 (Jun 2008).
[4] O. Gerstel, I. Leung, G. Nicholl, H. Sohel, W. Wakim, and K. Wollenweber, "Near-Hitless Protection in IPoDWDM Networks," in *Opt. Fiber Commun. Conf. (OFC 2008)*, San Diego, CA, Feb 2008, Paper NWD4.
[5] C. P. Lai, F. Fidler, and K. Bergman, "Experimental Demonstration of QoS-Aware Cross-Layer Packet Protection Switching," in *Eur. Conf. Opt. Commun. (ECOC 2009)*, Vienna, Austria, Sep 2009, Paper 2.5.3.
[6] F. Fidler, P. J. Winzer, C. P. Lai, M. K. Thottan, and K. Bergman, "Cross-Layer Simulations of Fast Packet Protection Mechanisms," in *Eur. Conf. Opt. Commun. (ECOC 2009)*, Vienna, Austria, Sep 2009, Paper 2.5.2.
[7] Y. K. Lizé, J.-Y. Yang, L.C. Christen, X.-X. Wu, S. Nuccio, T. Wu, A. E. Willner, R. Kashyap, and F.Séguin, "Simultaneous and Independent Monitoring of OSNR, Chromatic and Polarization Mode Dispersion for NRZ-OOK, DPSK and Duobinary," in *Opt. Fiber Commun. Conf. (OFC 2007)*, Anaheim, CA, Mar 2007, Paper OThN2.
[8] A. E. Willner, Z. Pan, and C. Yu, "Optical performance monitoring," *Optical Fiber Telecommunications VB*, Ch. 7, Ivan P. Kaminow, T. Li, and A. E. Willner, eds (Elsevier Publishers, Academic Press, San Diego, Feb 2008).
[9] T. Anderson, J. C. Li, D. Hewitt, and O. Jerphagnon, "Optical Performance Monitoring for Intelligent Networks," in *Eur. Conf. Opt. Commun. (ECOC 2009)*, Vienna, Austria, Sep 2009, Paper 9.3.3.
[10] A. Shacham and K. Bergman, "An Experimental Validation of a Wavelength-Striped, Packet Switched, Optical Interconnection Network," *Journal of Lightwave Technology* **27** (7) 841-850 (Apr 1, 2009).