Cross-Layer Communications for High-Bandwidth Optical Networks

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ABSTRACT
A major challenge in meeting the enhanced performance requirements of next-generation optical networks is overcoming the rigid limitations due to network layering. Our work addresses this issue by creating a bidirectional cross-layer communications infrastructure that can leverage knowledge of the optical-layer performance to improve network performance. The goal is to create an intelligent, dynamic, and programmable optical substrate where optical performance monitoring measurement data can be used for cross-layer communications, specifically for network routing and packet protection. Ns-2 simulations show that a cross-layer proactive packet protection scheme using physical-layer bit-error rate measurements performs better than a fast-reroute mechanism in terms of packet loss rates. Further experimental demonstrations of the cross-layer communications infrastructure on an optical packet-switching fabric test-bed can also incorporate the optical packet's signal degradation and quality-of-service class to switch and reroute messages. We can then realize a quality-of-service-aware cross-layer network control framework that is based on emerging optical performance monitoring devices for next-generation optical networks.
Keywords: optical communication, cross-layer optimized network design, optical performance monitoring, quality-of-service, optical packet switching

1. INTRODUCTION

Achieving the advanced performance required by next-generation optical networks will require overcoming the challenges presented by network layering. The performance of the current Internet architecture is constrained by the rigid limitations imposed by the different network layers, with each layer's functionality previously optimized independently. Furthermore, in order to address the exploding bandwidth demands and to efficiently support today's vast variety of user services and applications, the physical layer will be required to incorporate novel optical technologies and devices. This will allow the transparent physical-layer lightpaths to scale to high bandwidths with greater dynamic programmability. The proposed clean-slate design will facilitate next-generation optical networks to have the ability to provide dynamic bandwidth allocation and support flexible packet routing with higher data rates. Ultimately, the future design of optical networks should allow for a bidirectional cross-layer communications infrastructure that can leverage knowledge of the optical layer's performance to optimize overall network operation and reliability. Our goal is to create an intelligent and programmable optical substrate into which packet-level optical performance monitoring (OPM) devices can be directly embedded. Measurement data from these OPM systems, indicating physical-layer impairments and characteristics, can then be used by higher network layers in a cross-layer communication platform, specifically for network routing and optical packet protection. These optical cross-layer (OCL) routing protocols must also invoke quality-of-service (QoS) classes from the application layer's requirements on the optical layer. Figure 1 shows the envisioned bidirectional OCL-optimized stack.

The technique of cross-layer optimization was previously proposed for wireless networks to increase energy efficiency based on resource allocation [1], [2]; other researchers have also investigated the notion of impairment-aware networking for the planning of optical networks [3], [4]. Our work focuses on the design of

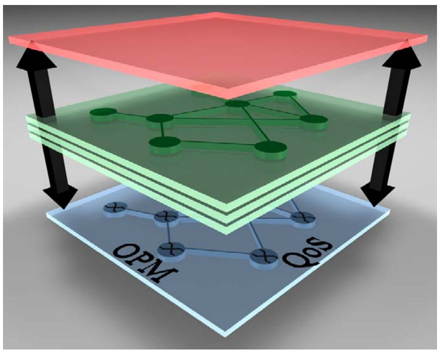

Figure 1. Envisioned cross-layer-optimized network stack, with OPM devices embedded in the physical layer.

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a bidirectional cross-layer infrastructure for next-generation transparent optical networks that can use dynamic real-time OPM measurements with a fine data packet granularity and an awareness of the optical QoS [5]-[8]. Within this scope, we focus on a proactive packet protection scheme that can be triggered on both OPM measurement data and the optical packet's QoS. Our work is twofold: first, we perform a simulation exploration [5], [6] in the ns-2 environment, showing the advantages of cross-layer communications. We show that the packet protection scheme using physical-layer bit-error rate (BER) measurements performs better than a traditional fast-reroute mechanism. Second, the focus of this paper, we design and experimentally demonstrate a cross-layer communications infrastructure [7], [8] on an optical packet-switching (OPS) test-bed, where packet-level signal performance and QoS requirements can be used in the protection scheme to switch and reroute high-bandwidth optical messages. This design provides the potential for dynamic bandwidth scaling on a packet-level granularity with physical-layer impairment awareness and the support for varying levels of QoS.

2. NS-2 SIMULATIONS

Future optical networks will be engineered to account for physical-layer performance variations; however, current packet simulators do not consider the effects of fast optical impairments. Thus, we have incorporated physical-layer BER variations in the ns-2 environment to support an approach where this information can act as input to higher-layer packet routing in a cross-layer way [5], [6]. We focus on both packet-by-packet BER variations as well as intra-packet variations.

Through discrete-event network simulations, we also provide an application of these numerical modules by comparing two fast packet protection schemes. The first is a fast-reroute scheme that switches packets to a protection path when the received BER exceeds the correction threshold BER_E of the underlying forward-error correction (FEC); here, $BER_E = 2\times10^{-3}$. Our proposed proactive packet protection is triggered at a lower BER threshold, $BER_T = 10^{-4}$, such that packets with a higher slope of BER degradation can be proactively switched to the protection path earlier. We assume a step change in the BER and study the number of lost packets (Fig. 2 from [5]). We see that the proposed proactive protection scheme provides no packet loss until the BER step increases such that the time span between BER_E and BER_T is shorter than the round-trip time (RTT), the minimum time for the protection mechanism to be activated. Additional details and results on this simulation study can be found in [5]. The cross-layer network simulations show that knowledge of the physical-layer BER

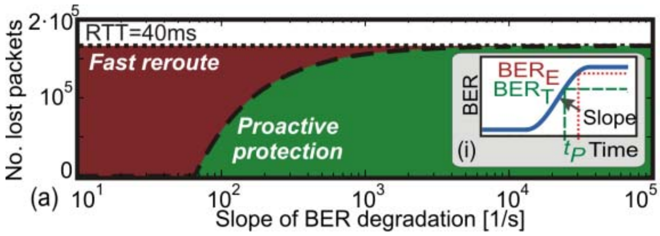

Figure 2. Simulated comparison of packet loss performance between fast-reroute and proactive packet protection mechanisms [5].

variations can be used to improve the packet loss performance by providing an efficient means for packet rerouting.

3. EXPERIMENTAL DEMONSTRATIONS

Monitoring the optical signal performance and incorporating the resulting measurement data in the overall network operation is the key aim for creating an OCL-optimized platform for future networks. We experimentally implement a cross-layer-enabled optical network test-bed that realizes the envisioned packet protection scheme. Dedicated OPM devices can be deployed within the optical network to account for dynamic physical-layer characteristics. Thus far, we have realized a real-time optical-signal-to-noise-ratio (OSNR) monitor to measure the optical packet quality with future plans to implement other OPM units.

3.1 Optical Network Test-Bed

A QoS-aware packet protection scheme is implemented on an optical fabric test-bed, where the degradation of high-QoS/priority packets can be proactively detected at the receiver using the read-out from OPMs [7], [8]. The customized cross-layer receiver monitors the optical packets egressing from the network and makes rerouting decisions on a packet-by-packet scale depending on the QoS and BER. A short optical control signal is then sent to the transmitting port to allow the data stream to be switched and rerouted to a protection path. The packet routing decision can thus be optimized dynamically considering the applications' QoS requirements and optical signal degradation with a message granularity.

The implemented 4×4 optical fabric test-bed is composed of two fabric nodes placed in parallel (Fig. 3). This topology provides greater protection path diversity and packet multicasting capabilities. The network test-bed supports multi-wavelength optical packets with 8×10-Gb/s wavelength-striped payload channels, where control

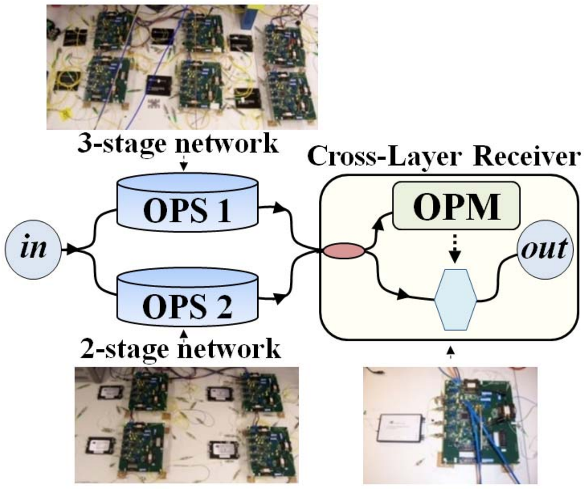

Figure 3. Diagram and photographs of the optical network test-bed with customized cross-layer enabled receiver design [7].

signals (such as frame, address, and priority) are encoded on a subset of allocated wavelengths at a single bit per packet, and the payload is fragmented on the rest of the band and modulated at a high data rate (such as 10 Gb/s per wavelength channel). The network is organized in a multistage fashion and composed of non-blocking 2×2 photonic switches, setting up transparent lightpaths among the network ports. Each photonic switch uses four semiconductor optical amplifier (SOA) gates that offer data rate transparency and message granular switching. The electronic routing control logic is distributed among the switches and is synthesized in high-speed complex programmable logic devices (CPLDs) located within each switch, providing a high level of flexibility. The switches filter and extract the control information instantaneously at the optical packets' leading edge using fixed wavelength filters and low-speed optical receivers. Based on the headers, the corresponding SOA is gated on and the optical messages are routed to their appropriate destination. A physical-layer acknowledgement (ack) mechanism is implemented where short optical pulses are sent to the transmitting node to indicate successful transmission. In this experimental demonstration of the proactive packet protection scheme, contending messages are dropped. According to the QoS class, packets with high BER are intentionally discarded after reception, with the aim of suppressing the ack and triggering rerouting.

The proposed packet protection scheme uses signal introspection offered by a real-time OPM to realize packet rerouting on a protection path. We can then use the two independent paths that exist between the network input and output ports. The modified receiver design monitors optical packets and the switching scheme is based on both the per-packet QoS and the measured BER. Data streams with high-QoS/high-BER optical messages are rerouted on an alternate protection path, while low-QoS (regardless of BER) and high-QoS/low-BER messages are forwarded.

3.2 Cross-Layer Experimental Results

The switching fabric is implemented with discrete, commercially-available electronic and optical components, such as Xilinx CPLDs, Kamelian SOA devices, low-speed p-i-n photodetectors, passive optics, and electronic circuitry. The system supports 115.2-ns duration packets with 10-Gb/s pseudo-random binary sequence (PRBS) modulated data on eight payload wavelength channels [7]. A sequence of optical packets is injected in the test-bed with two differing QoS classes. The cross-layer receiver node monitors the packets' QoS and signal quality. In this initial exploration, a pseudo-BER is generated offline in place of an OPM device. Figure 4a shows the optical waveform traces associated with the experimental demonstration, validating the packet protection scheme. Proactively protected packets (such as packet C) are rerouted. We confirm no packet loss and error-free transmission of all received packets. BERs less than 10^{-12} are obtained for all eight payload wavelengths; Fig. 4b gives the 10-Gb/s input and output eye diagrams. This experimental demonstration shows the envisioned cross-layer infrastructure whereby novel real-time OPM devices can be leveraged to provide a feedback to higher layers for packet rerouting.

3.3 Implementing a Real-Time OSNR Monitor

Previously, a pseudo-BER was generated in lieu of an OPM device. In recent work [8], we report on realizing a real-time OSNR monitor [9] in the aforementioned optical network test-bed. OSNR monitoring is a novel optical technology that may ultimately lead to BER extrapolation for real-time physical-layer performance assessment. The OSNR monitor is based on a ¼-bit Mach-Zehnder delay-line interferometer (DLI), which may support multiple modulation formats and is insensitive to the effects of other impairments (such as chromatic dispersion and polarization mode dispersion). The two ports of the DLI provide constructive (P_{const}) and destructive (P_{dest}) interference, respectively, and the resulting ratio of P_{const}/P_{dest} correlates to the OSNR as in [9]. By using fast power monitors and a high-speed field-programmable gate array (FPGA), the OSNR can be measured on a message timescale. The packet-level OSNR monitor dynamically and simultaneously monitors packets egressing from the network test-bed and signals the rerouting of degraded high-QoS wavelength-striped

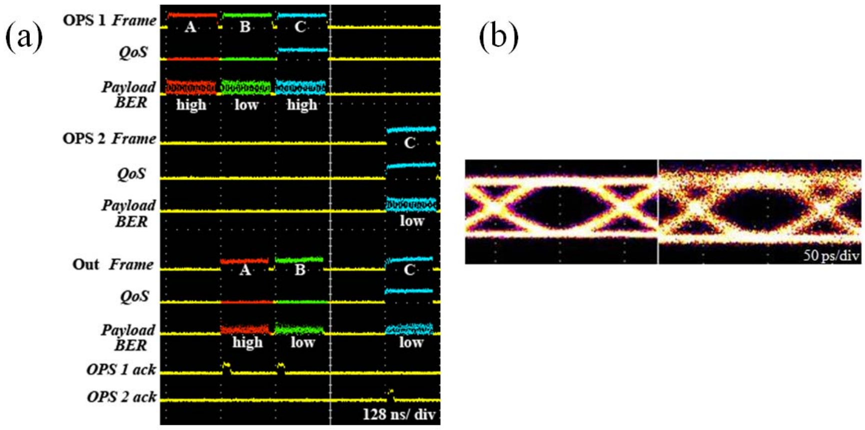

Figure 4. (a) Optical waveforms, with colours pertaining to the different time-multiplexed packet streams; (b) 10-Gb/s input (left) and output (right) eye diagrams [7].

packets, as per the proactive packet protection scheme above. The FPGA contains the scheme's decision logic and calculates the signal's OSNR on a packet-by-packet basis.

4. CONCLUSIONS

Our goal is to leverage novel OPM devices and other emerging optical technologies to create a cross-layer communications platform to optimize network operation and performance. Within the scope of cross-layer optimization, we focus on a proactive packet protection routing mechanism whereby degraded messages can be detected at the receiver and rerouted on an alternate path. Optical packet network simulations in ns-2 show that a cross-layer packet protection scheme performs better than a FEC-based fast-reroute mechanism. An experimental demonstration of an implemented cross-layer infrastructure on an optical network test-bed shows the benefits of the proactive packet protection routing, accounting for the optical packet's signal quality and QoS class. As large-scale optical networks evolve towards a more packet-based infrastructure with a high level of required performance, it is important to demonstrate that a cross-layer framework can be realized in which emerging OPM devices can achieve QoS-aware cross-layer network control.

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