Experimental demonstration of packet-rate 10-Gb/s OOK OSNR monitoring for QoS-aware cross-layer packet protection

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Abstract: A cross-layer network platform may enable introspective access to the physical layer, allowing optical performance monitoring measurements to feedback to higher layers for packet rerouting and protection. We experimentally demonstrate quality-of-service-aware packet protection that leverages cross-layer signaling based on the monitoring of packets’ optical-signal-to-noise ratio. In order to detect degraded data streams, the monitoring system is based on a delay-line Mach-Zehnder interferometer and a field-programmable gate array. The system is realized in an experimental cross-layer enabled optical packet switched fabric, measuring the optical-signal-to-noise ratio for 10-Gb/s OOK streams. The packet protection scheme uses the dynamic performance measurements to actuate a rerouting of high-quality-of-service packets. 8 × 10-Gb/s wavelength-striped optical messages are rerouted through the fabric error-free (bit-error rates less than 10^{-12}).

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References and links
1. Introduction

In order to support the exponential growth in network traffic and use of high-bandwidth applications, the design of next-generation communication infrastructures may feature all-optical transmission at high modulation bit rates. To ensure reliable, robust high-speed data links, future data-centric networks will require advanced optical performance monitoring (OPM) to dynamically measure optical signal degradations in real-time [1,2]. This comprises a potentially essential functionality for high-capacity networks and will enable the monitoring and isolation of physical-layer impairments, in addition to the fast evaluation of the optical quality-of-transmission (QoT) of the transmitted data signals. These metrics can then provide a means of feedback to higher network layers or a control plane to optimize global routing and network performance [3,4]. Several optical parameters can be monitoring, including signal power, wavelength, optical-signal-to-noise ratio (OSNR) [5–7], chromatic dispersion (CD) [8], and polarization-mode dispersion (PMD) [9].

We propose a bidirectional cross-layer packet-level signaling design (Fig. 1) that allows optical performance monitoring measurements to affect network routing algorithms, as well as enable a packet protection scheme. IP-layer quality-of-service (QoS) attributes can flow down the network stack and become encoded directly in the optical packets to influence optical switching, and OPM measurements can be transmitted upward. The ability to realize fast, real-time performance monitoring of the physical layer allows for these integrated packet-timescale OPM subsystems to efficiently execute routing. Using the proposed cross-layer optimized networking environment, accounting for applications’ QoS will help create QoS-aware protocols within a dynamically adaptable network.

In this work, we demonstrate a QoS-aware cross-layer proactive optical packet protection scheme [10,11] that uses packet-level OSNR performance monitoring to actuate a rerouting of high-QoS/priority optical messages upon measuring a degraded OSNR [12]. The scheme aims to reduce the penalty associated with packet retransmission of critical, high-priority data flows. The OSNR is monitored using a 1/4-bit Mach-Zehnder (MZ) delay-line interferometer (DLI) implemented in conjunction with power meters and a field-programmable gate array (FPGA). The fast OSNR monitoring is realized in an implemented optical packet switching (OPS) fabric test-bed to allow the packet protection mechanism to dynamically detect and reroute degraded high-QoS optical messages. Alternatively, degraded messages can be dropped and regenerated to be forwarded to subsequent network nodes.

OPS [13] comprises a potential technology for future Internet routers to support high-throughput traffic with characteristically low power consumption. It can realize a flexible, high-bandwidth switching fabric with a high level of programmability to transparently switch multiwavelength optical messages. The OPS fabric design here seamlessly supports a wavelength-striped packet structure, wherein control signals (such as frame, address, and QoS header bits) are encoded on a subset of allotted wavelengths, and the payload information is fragmented and modulated at a high data rate (here, at 10 Gb/s per wavelength) on several other wavelengths in the available band. The headers are set constant for the message length, comprising a single bit per timeslot per wavelength.

Optical performance monitoring within OPS fabrics enables an agile network that can independently and holistically isolate degradations and reroute optical messages accounting for impairments [7,14,15]. Specifically, OSNR monitors that exhibit fast responses and can measure the OSNR on a packet-by-packet basis may be a valuable tool for OPS fabrics to ensure reliable links [7]. Here, we experimentally evaluate the QoS-aware protection scheme enabled by the fast, packet-by-packet OSNR monitor. 8 × 10-Gb/s multi-wavelength packets are shown routed through the implemented OPS fabric, detected and assessed by the OSNR monitoring system, and rerouted based on the packet-encoded priority and OSNR measurement signals. Messages that egress from the output of the test-bed attain error-free performance with bit-error rates (BERs) less than 10^{-12}. A power penalty less than 2 dB is obtained using a three-stage optical switching fabric and the packet-timescale optical performance monitoring system.

2. Cross-layer packet protection scheme

As in [16], the proactive packet protection switching scheme uses OPM measurements as an indication of degraded data streams. The switching mechanism is also triggered by the QoS class encoded in the optical packet. A degraded signal quality is detected (here, a low OSNR is measured) and the protocol sets a predefined performance threshold below which rerouting is actuated to prevent the loss of important data streams. The degraded optical packets making up a high-QoS data flow are discarded. A cross-layer control signal is propagated backwards to the source node if transmission is successful; the lack of the control signal notifies the source to proactively change the flow’s path, rerouting the data stream on a parallel protection
path. The QoS-aware nature of the protocol allows data flows with high-QoS, low-OSNR optical packets to be proactively identified and rerouted on the protection path, while low-QoS (regardless of OSNR) and high-QoS, high-OSNR messages are forwarded to the destination.

The packet protection mechanism may be experimentally implemented in several ways. The OPS switching fabric itself could accept feedback signals from a control plane and/or directly from the OPM devices, or a separate custom switch could be used at the receiving end to forward or discard the high-QoS messages; Fig. 2 provides a diagram of a potential network node architecture for the physical layer. Here, we use a custom switch design to realize a new cross-layer receiving node (Fig. 3), which uses a dedicated OPM subsystem that measures the optical signal quality in real-time. At the output of the switching fabric, the optical packets are sent to the cross-layer node such that the optical signal’s QoT can be calculated on a packet-by-packet basis. Thus, both the message-level signal impairments and packet-encoded QoS classes can act as inputs in the network routing decision and enable impairment-aware packet switching protocols.

### 3. Packet-rate OSNR monitoring system

The OPM is realized as a fast OSNR monitor (Fig. 3), which measures the OSNR on a message basis to ultimately allow packet-level control and rerouting of a data stream using the packet protection switching protocol. The OSNR is assessed using a ¼-bit Mach-Zehnder DLI, designed to support several modulation formats at 10 Gb/s [5]. The OSNR monitoring method is independent of other physical-layer impairments, such as CD and PMD. The two discrete ports of the DLI provide constructive \( P_{\text{const}} \) and destructive \( P_{\text{dest}} \) interference, respectively. At the output of the ¼-bit DLI, the constant phase relationship during a single bit yields constructive interference over \( \frac{3}{4} \) of the bit period. The signal’s OSNR is proportional to the ratio of \( P_{\text{const}} \) divided by \( P_{\text{dest}} \). Since the phase relationship between consecutive bits is not crucial to this monitoring method, multiple modulation formats can be supported; here, we use non-return-to-zero (NRZ) on-off-keying (OOK). The ¼-bit DLI has a free spectral range (FSR) that is four times the bit rate (here, 10 Gb/s), thus the majority of the power is transmitted to the constructive port. The noise signal is evenly distributed between the two output ports. With a decreasing measured OSNR value, \( P_{\text{dest}} \) increases greater than \( P_{\text{const}} \) as a result of the random noise.

In order to monitor the OSNR at a packet timescale, the OSNR monitor uses the DLI in conjunction with a high-speed FPGA. At the output of the switching fabric, the custom cross-layer receiving node filters a portion of one 10-Gb/s payload channel comprising the egressing wavelength-striped optical packet and transmits the filtered signal to the DLI. The values of
$P_{\text{const}}$ and $P_{\text{dest}}$ are then determined from the two output ports of the DLI, each of which is connected to a power meter. The FPGA obtains the two power values at the packet rate and the high-speed logic performs the online processing to evaluate the $P_{\text{const}} / P_{\text{dest}}$ ratio to determine the packet’s OSNR on a packet timescale. Within the FPGA, the calculated OSNR value is then compared to a performance threshold. If the minimum value is met, the FPGA generates an electronic gating signal that is the length of the packet and transmits the pulse to a semiconductor optical amplifier (SOA) based cross-layer switch that is controlled by a complex programmable logic device (CPLD). The switch simultaneously extracts the QoS from the wavelength-striped packet’s header using a fixed wavelength filter and optical receiver. Using both the packet’s QoS (i.e. the designated high or low priority) and OPM-based QoT signal from the FPGA, the CPLD ultimately makes a routing decision to switch or discard packets as per the proactive protection scheme; Table 1 summarizes the implemented routing logic. This is accomplished by either gating on or off the separate cross-layer SOA. Optical packets may be forwarded to the final destination port, or discarded and rerouted on the parallel path.

Fig. 3. Cross-layer receiver node designed and used in this experimental demonstration; insets show photographs of the major realized hardware components, including (a) the OSNR monitor and (b) the cross-layer SOA-based switch.

Table 1. Truth Table for Cross-Layer Proactive Packet Protection Scheme

<table>
<thead>
<tr>
<th>QoS Level</th>
<th>Measured OSNR Level</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td>Transmit to output as desired</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>Transmit to output as desired</td>
</tr>
<tr>
<td>High</td>
<td>Low</td>
<td>Actuate rerouting so that transmitter can retransmit along alternative path</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
<td>Transmit to output as desired</td>
</tr>
</tbody>
</table>

4. Optical switching fabric architecture

To demonstrate the packet protection switching scheme, the OSNR monitoring system is implemented on a multi-terabit capacity 4 × 4 cross-layer enabled OPS fabric test-bed [17]. The test-bed is based on a multistage Banyan design, using two parallel OPS fabric entities to allow a path diversity of two between the source and destination nodes [18]. The basic
element is a 2 × 2 non-blocking photonic switching element (PSE); each building block PSE routes the optical messages using four SOA packet gates to provide broadband operation and bit-rate transparency. The PSEs' routing control logic is implemented distributedly and is programmable by using CPLDs located within each PSE.

As outlined above, the 2 × 2 PSE supports wavelength-striped optical packets, comprised of both packet-rate control headers and high-speed modulated payload information. As shown in Fig. 4, the control signals, which are either set high or low for the entire packet duration, are used to denote the presence of a packet (via the frame signal), as well as for routing through the switching fabric (via the address signals) and for QoS encoding (via the QoS signals). Here, the eight payload wavelength channels are modulated at 10 Gb/s (per wavelength), in order to support 8 × 10-Gb/s wavelength-striped packet streams.

![Fig. 4. Structure of the wavelength-striped optical packet format, showing the temporal shape of the packets (y-axis: wavelength, x-axis: time). This representative timing diagram shows three different packets with varying QoS levels and OSNR levels, with varying number of address bits and payload channels.](image)

Packets that are routed through the PSE create transparent lightpaths that extend across the fabric. At each of the PSEs, the control headers are received and decoded instantaneously upon the packets' leading edge using a fixed filter and optical receiver. The detected control bits are processed by high-speed electronics and the CPLD to create a routing decision. The corresponding SOA is then gated on to switch the optical packet to the appropriate output port. Contending messages are dropped and a short physical-layer control acknowledgment (ack) pulse is sent in the opposite direction to notify the source of successful reception. Transmitting sources that do not receive these control ack pulses can then retransmit at the next timeslot, switching the data stream to an alternate, parallel protection path. The aforementioned cross-layer receiver design is realized at the output of the switching fabric, incorporating the OSNR monitoring system. Depending on the encoded QoS class, packets with degraded measured OSNRs are intentionally discarded by the cross-layer receiver to suppress the ack pulse and thus trigger packet rerouting. When a packet is discarded, the latency associated with packet retransmission is related to the propagation delay of the fabric; we have studied this packet protection mechanism in simulation and shown a relationship between the packet loss rates of the switching scheme and the size of the switching fabric. This protection technique provides the most gain for small-size fabrics.
5. Experimental setup and results

5.1. Experimental demonstration

The proactive packet protection mechanism is experimentally validated using the described cross-layer receiver and fast OSNR monitor realized at the output of a $4 \times 4$ optical switching fabric test-bed. The fabric design is based on a multicast-capable packet-splitter-and-delivery architecture [18] that offers two distinct and independent paths between any of the source ports to any of the destination output ports. The test-bed here uses two parallel optical packet switches (a three-stage switch in conjunction with a two-stage switch) to provide this two-fold path diversity, yielding a main routing lightpath and an alternate protection route. Messages are routed across each optical packet switch entity based on the wavelength headers encoded in the individual packet’s structure. The fabric test-bed is comprised of ten $2 \times 2$ photonic switching elements that are composed of discrete, individually-packaged optical and electrical components. Each PSE is constructed using four Kamelian SOAs, four low-speed 155-Mb/s p-i-n photodetectors, four fixed wavelength filters, several passive optical devices, and high-speed digital electrical circuit components. Within each PSE, the routing control logic is synthesized in one Xilinx CPLD, which facilitates a distributed routing scheme within the complete test-bed. The round-trip latency of the implemented test-bed is on the order of hundreds of nanoseconds, with the PSEs having equivalent propagation times of approximately 40 ns.

To demonstrate the packet routing and protection functionalities, a predetermined experimental pattern of $8 \times 10$-Gb/s wavelength-striped optical packets is generated and injected into one port of the implemented fabric (Fig. 5); the packets have differing high and low OSNR values. At the input of the test-bed, the wavelength-striped optical packets are generated as per the following setup. The payload wavelength channels are created using eight discrete continuous-wave (CW) distributed feedback (DFB) lasers. The DFB lasers range from 1540.1 nm to 1558.3 nm, to explicitly showcase the broadband transparency of the optical switching design. The minimum spacing between two adjacent payload channels is 100 GHz, to show that no crosstalk is shown between neighboring channels.

All eight channels are passively multiplexed onto a single-mode fiber using an optical coupler and are concurrently modulated using a single LiNbO$_3$ amplitude modulator that is electrically driven by a high-speed pulse pattern generator (PPG). The PPG generates a 10-Gb/s $2^7-1$ pseudo-random bit sequence (PRBS) in a NRZ-OOK format, modulating the eight channels simultaneously. The resulting multiwavelength payload information is then decorrelated using 25 km of single-mode optical fiber (SMF-28) and passively multiplexed into two identical streams to create the dedicated high-OSNR and low-OSNR data streams that will be required for experimentally monitoring the OSNR at the output of the fabric. As in Fig. 5, the low-OSNR data streams in the input pattern are generated by degrading the OSNR of the low-OSNR stream using an optical attenuator (set to attenuate by 8 dB), followed by a separate SOA from Kamelian. The SOA amplifies the signal to the original value while concurrently providing a certain amount of amplified spontaneous emission (ASE) to yield sufficiently degraded OSNR streams. The dedicated high-OSNR data stream is not transmitted through this OSNR-degradation setup (of an optical attenuator and SOA), thus resulting in sufficiently high OSNR for this flow. In this demonstration, the threshold for the high and low OSNR classes is 5 dB.

The control header signals are generated separately using six other CW-DFB lasers at the required frame, address, and QoS wavelengths for routing. The frame signal is located at 1555.75 nm and the five address signals range from 1531.12 nm to 1550.92 nm. Each of the control header bits, as well as the high-OSNR and low-OSNR payload data streams, are then transmitted to separate external SOA devices which gate the continuous streams into discrete wavelength-striped optical packets for the experimental demonstration.

As shown in Fig. 5, the gating SOAs are driven by a fast FPGA that is synchronized to the PPG and acts as an electrical pulse generator to manage the experimental test-bed addressing
Fig. 5. Experimental setup, depicting the generation of the high- and low-OSNR optical packets, photographs of the optical switching fabric, and the setup of the packet-analysis system. The setup requires one FPGA device that is used both to implement the logic in the cross-layer node and to act as a high-speed electronic signal generator creating the optical packet sequence. The ‘Cross-Layer Receiving Node’ is depicted by the red box/region and represents the setup as in Fig. 3.

and packet gating. The experimental setup requires one FPGA, that serves two important roles: (1) to realize the cross-layer logic and OSNR calculation within the ‘Cross-Layer Receiving Node,’ and (2) to generate the optical packet sequence (i.e. to act as the high-speed electronic signal generator connected to the gating SOAs). Using one FPGA ensures that all the electronic signals and components are synchronized to a common clock throughout the experiment. The source for the optical ack pulses is a separate DFB laser at 1541.1 nm, which is transmitted to a SOA for gating by the FPGA; in an ideal implementation, an additional circulator and low-speed receiver would be used on the transmitter side to read the ack pulse and then affect the ingressing packets. Here, the electrical outputs of the FPGA denote a pre-programmed sequence of optical packets that were chosen explicitly for this experiment. The appropriate gating SOAs’ outputs are then multiplexed together using a passive optical coupler. Thus, the created sequence of $8 \times 10\text{-Gb/s}$ wavelength-striped optical packets contains: a constant one-bit frame signal; the appropriate optical address encoding to route the optical messages transparently end-to-end on the test-bed using both parallel packet switches; a QoS control header denoting the high or low QoS class designated to the optical packet; and a combination of high and low OSNR multiwavelength payloads, with the data modulated at $10\text{-Gb/s}$ NRZ-OOK on each of the eight frequency channels.

Regarding the OSNR streams, the high- or low-OSNR metric is set on a packet-by-packet basis. The external SOAs corresponding to the high-OSNR and low-OSNR streams are gated by the FPGA in such a way that a single pattern of packets will have two differing OSNRs. This is realized by ensuring that the gating pulses for the high-OSNR and low-OSNR data streams do not overlap (i.e. only one of the OSNR SOAs is gated on at a single time). This yields a pattern sequence of both high-OSNR messages and low-OSNR messages, with two different QoS classes, which is injected in one active port of the switching fabric test-bed to demonstrate the protection scheme. Similar to [19], the QoS class is directly encoded as one of the control headers, and is set constant over the length of the packet; a high-QoS class is denoted by a high control bit, while a low-QoS class is represented by a low control bit.

The packet durations are determined by the recovery times of this initial, discrete-component experimental implementation of the fast OSNR monitor and are limited primarily
by the processing speeds of the power meter equipment and of its communication interface. In the first implementation of this packet-rate OSNR monitoring scheme [12], the speed of the performance monitoring was not optimized (i.e. not minimized to the fastest sampling time possible given the hardware limitations). The first demonstration thus utilized 1.2-s long timeslots with 1-s long optical packets. Here, in this enhanced experimental demonstration, the speed of the OSNR monitoring technique was optimized to the extent supported by the realized hardware. This allows the FPGA to poll the power meters at a much faster rate than previously demonstrated, giving rise to the fast packet-rate speed of the OSNR monitor. To accommodate the sampling timescales required by the cross-layer receiver, OSNR measurement, and FPGA processing, the system here supports 18-ms packet lengths within 20-ms duration timeslots. Future integrated setups will allow for even more rapid OSNR measurements; ideally, we would aim to realize a monitoring system with sampling times (i.e. packet lengths) on the order of hundreds of nanoseconds.

To realize the packet-rate monitoring of the messages’ OSNR, we implement the cross-layer receiving node at the output of the fabric in our test-bed using the setup in Fig. 3 (i.e. the experimental setup in Fig. 3 is represented in Fig. 5 as the red region). The cross-layer node allows for a packet-level OSNR monitor that can dynamically monitor fabric-egressing messages and can initiate a rerouting of degraded-OSNR high-QoS packets. Here, the cross-layer receiver is realized at one of the test-bed ports for demonstration purposes; in future scale implementations, we envision a similar design at each output port to fully exploit the protection routing functionalities for all egressing optical packets. The receiver uses the interferometric-based OSNR monitor, implemented with a high-speed FPGA and SOA-based switch. At the receiving end of the fabric test-bed, a portion of the wavelength-striped packet is filtered using a JDSU TB9 tunable grating filter with an optical bandwidth of 0.22 nm. The tunable filter is set to select any of the 10-Gb/s payload channels in the egressing optical packet. The OSNR is directly dependent on the effective bandwidth of the wavelength filter [5], as it determines the noise equivalent bandwidth of the monitored 10-Gb/s channel [15]. The system here monitors 10-Gb/s NRZ-OOK signals; with the above filter bandwidth and supported modulation format, a $P_{\text{const}}/P_{\text{dest}}$ ratio of 7 dB corresponds to a 5 dB OSNR.

As shown in Fig. 3, the extracted 10-Gb/s payload channel is then transmitted to the ¼-bit Mach-Zehnder DLI. The DLI used here is an off-the-shelf differential phase-shift keying (DPSK) demodulator that is commercially-available from Optoplex. The DLI supports C-band frequencies and is experimentally phase-tuned for maximum and minimum power, respectively, in the two output ports. The Optoplex DLI has a tunable FSR is highly stable, with less than 1% of FSR error. The DLI then feeds a fiber switch device from Polatis with integrated power meter capabilities and an interfacing RS232 serial port. The power information ($P_{\text{const}}$ and $P_{\text{dest}}$) resulting from the DLI interference is obtained by the power meters and sent using the serial interface to a high-speed Xilinx Virtex-5 FPGA. The FPGA acquires the power values every timeslot (20 ms) (once per packet) and processes the information online to calculate the packet’s OSNR on a packet-by-packet basis. If the measured OSNR is greater than a predetermined threshold (here, set to 5 dB), the FPGA generates an electrical gating pulse which is transmitted to a SOA-based switch. In this experiment, the switch is controlled by a CPLD, which uses this FPGA-generated signal as an indication that the minimum performance threshold has been satisfied. If the measured OSNR is less than the threshold, the FPGA does not generate the pulse for the CPLD. Simultaneous to the OSNR measurement system, the switch uses a fixed wavelength filter and low-speed optical receiver (similar to the photonic switching elements that comprise the fabric in our test-bed) to extract the QoS header bit from the wavelength-striped packet. The QoS acts as a contributing factor in triggering protection routing.

The CPLD in the SOA-based cross-layer switch contains the synthesized routing logic that makes the packet protection decision, using both the measured OSNR signal from the FPGA (denoting the packet’s QoT) as well as the packet’s extracted QoS class as inputs. According to these metrics, the CPLD makes the decision either: to electrically drive the SOA to forward low-QoS (irrespective of the OSNR) and high-QoS, low-OSNR messages to the final
destination port; or to proactively discard high-QoS, low-OSNR optical messages so that the packet protection mechanism can actuate the rerouting of these messages on a protection path. Table 1 summarizes the overall rerouting scheme. The degraded, high-priority messages are discarded by the CPLD (by not gating the SOA), such that no ack is backward propagated to the source to trigger rerouting on an alternate path. This system allows the packets emerging from the switching fabric to be dynamically monitored by the cross-layer receiving node, which the fast OSNR monitor can signal to proactively reroute the degraded packets in a high-priority data stream.

Optical packets that are passed by the cross-layer node logic at the output of the switching fabric are experimentally analyzed (as depicted in Fig. 5) using an optical spectrum analyzer (OSA) and high-speed communications signal analyzer (CSA). The packet examination setup incorporates a tunable grating filter to select one 10-Gb/s payload channel of the packet for system analysis and verification, which is sent to an erbium-doped fiber amplifier (EDFA), a second optical tunable filter, and then to a variable optical attenuator (VOA). The packet is then transmitted to a DC-coupled 10-Gb/s p-i-n photodiode and transimpedance amplifier, followed by a limiting amplifier (RX). The electrical signals are transmitted to a bit-error-rate tester (BERT) that is synchronized with the PPG and the fast pattern-generating FPGA; no clock recovery is performed in this experiment. The FPGA also generates an electronic gating signal that allows the BERT to be gating for BER testing over the length of the packets. The packets were gated for over 85% of their duration.

5.2. Results and discussion

In this experiment, a pattern of 8 × 10-Gb/s NRZ-OOK wavelength-striped optical packets with high and low OSNRs is injected into the test-bed (as created by the above experimental setup). As shown in Fig. 6, the multiwavelength optical messages are injected in the switching fabric and then propagate to the “Cross-Layer Receiving Node.” Figure 6 depicts the primary (red) and alternate protection (blue) paths through both parts of the switching fabric, showing the lightpaths taken by the optical packets in the overall system. One should note that the primary path uses the upper, three-stage optical packet switch (with three SOA hops), while the alternate path uses the lower, two-stage optical packet switch (with two SOA hops). When a degraded OSNR is measured after a packet takes the primary path, the message can then be retransmitted on the secondary path. By allowing the packet to propagate through one fewer SOA device, improved OSNR performance may be achievable at the output.

The per-packet OSNR monitoring and packet protection method is shown using the Virtex-5 FPGA and SOA switch to accurately discard optical messages. The modified cross-layer receiving design measures the packets’ OSNR and proactively detects (and discards) the high-priority packets with OSNR values that are specifically degraded below the performance threshold. Packets are shown to be correctly routed by the switching fabric to their desired destinations, using the DLI-based monitoring system, based on the encoded QoS level and OSNR measurement signal. The cross-layer node identifies the messages on a packet-by-packet timescale, initiating a rerouting to the degraded stream using the fabric’s ack signal. The packets can then be rerouted on an alternate protection path. Several payload wavelength channels in the egressing packets are selected by the TB9 filter, exhibiting similar results.

Using the BERT and packet-analysis system outlined above, we confirm error-free transmission of all packets at the output of the fabric and cross-layer node. The BER measurements verify that BERs less than 10^{-12} are obtained on all eight payload channels. Thus, the system here achieves error-free operation without needing to use any forward error correction (FEC) techniques. The power penalty performance for the experimental system is evaluated for the optical packets egressing from the three-stage switch (i.e. the worst-case path). Figure 7 provides the 10-Gb/s sensitivity curves for one typical payload wavelength channel (λ = 1556.5 nm). The back-to-back measurements correspond to the optical packet prior to injection in the fabric. The experimental system is seen to incur a 2-dB power penalty (taken at a BER of 10^{-9}), which includes the three-stage switch and the cross-layer node. The
10-Gb/s input and output optical eye diagrams corresponding to the fabric input and output are provided as insets in Fig. 7.

Fig. 6. Block schematic showing the transparent lightpaths taken by the wavelength-striped optical packets as they propagate through the switching fabric and cross-layer node. The primary routing path (red) and the alternate routing path (blue) are provided.

Fig. 7. Sensitivity curves for the experiment; dashed line/unfilled points refer to the back-to-back measurements and solid line/filled points correspond to the through measurements. Insets show the 10-Gb/s optical eye diagrams.

6. Conclusion

The growing demand on data traffic is driving the design for a dynamic future Internet that features a cross-layer optimized network stack. The cross-layer platform evaluates optical signal degradations and packets’ quality-of-transmission in order to provide a real-time feedback to higher routing layers and enable proactive packet protection for critical data flows. The fast OPM measurements provide the means to detect and actuate dynamic rerouting of degraded, high-QoS streams. We show the message-level monitoring of optical packets’ OSNR at the output of an implemented OPS fabric using a Mach-Zehnder-interferometric-based approach, leveraging the dynamic measurements as a physical-layer performance indicator within a QoS-aware packet protection mechanism. The switching scheme discards degraded 8 × 10-Gb/s wavelength-striped optical messages based on the encoded priority and actuates packet rerouting on an alternate route as required. Error-free transmission of the routed high-bandwidth messages is obtained with BERs less than 10^{-12}. This work explores developing cross-layer designs and routing control algorithms for future networks based on emerging optical devices, real-time physical-layer measurements, and...
incorporating varying QoS protocols. These schemes can dynamically optimize physical-layer switching, enabling a deeper exposure of the physical-layer substrate.

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