Implementing an Optical QoS Encoding Scheme in an Optical Packet Switching Fabric Test-Bed

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***Abstract*—The next-generation Internet may be required to invoke quality-of-service classes directly on the optical layer to optimize global network routing, as well as exploit optical packet switched architectures as a solution to switch high-bandwidth optical messages. In this work, the functionality of optical networks is enhanced to implement different service classes directly on the optical layer. A physical-layer quality-of-service encoding scheme is introduced for an optical switching fabric test-bed that allows for the prioritized transmission of broadband wavelength-striped messages. Contention is resolved by dropping low-priority messages. Packets with 8 $\times$ 10-Gb/s payloads are shown correctly routed error-free, with verified bit-error rates less than 10^{-12}. A power penalty of 1.2 dB for the three-stage network test-bed is demonstrated.**

***Index Terms*—Optical communication, packet switching, photonic switching systems.**

I. Introduction

INNOVATIVE architectures will be essential to address the explosive bandwidth growth in the next-generation Internet. The conventional approach of regarding the physical layer as static presents several limitations. Recent optical technology innovations allow for the integration of novel optical devices within the physical layer, yielding new network optimization possibilities [1]. We envision a dynamic, programmable optical layer that interacts with higher network layers to create a platform for optical cross-layer (OCL) communications.

Future OCL designs will allow quality-of-service (QoS) classes to be invoked directly on the optical layer that can then be leveraged by higher layer applications to optimize end-to-end network routing. Guaranteeing QoS directly on the optical layer may comprise an important service that can yield improved network performance. The mechanisms for QoS provisioning must account for the physical-layer impairments. An OCL algorithm should be aware of a packet's optical QoS (OQoS) during message transmission and routing [2], [3].

Further, optical packet switching (OPS) is a novel photonic technology to enable a bandwidth-efficient Internet [4]. OPS has been shown as a scalable approach for routing high-bandwidth wavelength-division-multiplexed (WDM) traffic with characteristically low power and low latency [5]. The practical realization of OPS faces significant challenges, particularly with contention resolution which may be required as multiple packets attempt to egress simultaneously on the same link. Contention resolution is not easily managed, owing to the infeasible realization of optical buffers. Current schemes use packet-dropping and retransmission, which may be costly for important messages. Implementing QoS classes on the optical layer may mitigate the expensive issue of contention resolution in OPS networks [6].

OPS networks may offer several higher quality or higher priority connection-oriented services [7]. The optical network should support user-differentiated protocols embedded on the physical layer through varying levels of QoS and priority. QoS-aware routing schemes for optical networks have been presented for optical burst-switched (OBS) networks [8] and the loss performance of a multi-QoS scheme has been studied in simulation for OPS networks [9]. OPS network performance may be significantly improved by realizing service classes through different packet priority levels and by the routing of prioritized optical messages. In order to adequately implement these service-aware routing schemes, an optimal coding mechanism must be experimentally demonstrated to show the feasibility of creating QoS-aware optical messages.

In this letter, we show an OQoS encoding scheme for an experimental, programmable OPS fabric test-bed that allows for packet switching to account for a diverse set of OQoS classes that are encoded directly within the optical messages. The OQoS priority encoding mechanism specifically addresses contention resolution in future OPS fabrics [10], [11]. Contending messages are dropped and retransmitted in a subsequent timeslot. Our OQoS-aware routing scheme prevents high-priority packets from being dropped, allowing for an overall reduction in packet retransmission penalty for critical data streams. The 8 $\times$ 10-Gb/s wavelength-striped messages are shown correctly routed error-free, with verified bit-error rates (BERs) less than 10^{-12}.

II. Switching Fabric Architecture

The design of the OPS network test-bed is based on a multistage Omega network. Messages create transparent lightpaths that extend across the network endpoints. The switch, the fundamental building block, is a 2 $\times$ 2 nonblocking wideband photonic switching node; two independent optical messages can be routed concurrently through the node. Semiconductor optical amplifier (SOA) gates switch the optical messages, resulting in wideband transmission, data format transparency, and packet-level granularity. The architecture supports a wavelength-striped packet format (Fig. 1) that takes advantage of the high aggregated message bandwidth offered by WDM. The

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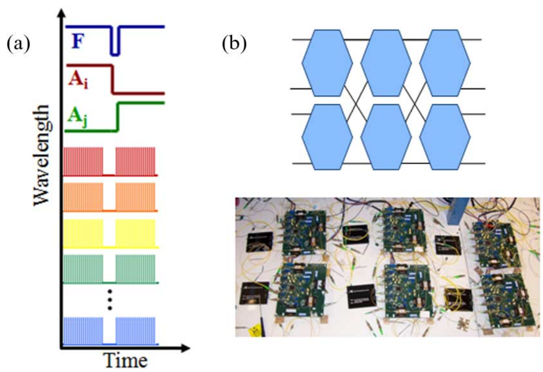

Fig. 1. (a) Wavelength-striped optical message structure, depicting the optical packet header signals, such as the frame (F) and address bits (A_i, A_j), and modulated payload wavelength channels; (b) three-stage switching fabric network topology and test-bed photograph.

packet is comprised of control header information (the frame and destination address) that is encoded on a subset of dedicated wavelengths, as well as the payload data that is fragmented and modulated at a high data rate (here, 10 Gb/s per wavelength) on numerous other wavelengths in the available frequency band.

The switching node detects and decodes the header information instantaneously at the packets' leading edge using a fixed wavelength filter and low-speed receiver. The nodes' switching elements consist of four SOAs that are organized in a gate-matrix structure: two input ports are connected to the two output ports using separate paths. The SOA gains are set to exactly compensate for the losses in each node, yielding no net gain/loss per stage. The control signals are recovered from the incoming optical message, and processed by high-speed electronic circuitry. Routing is performed by gating on the appropriate SOAs, and optical messages are either routed to their preferred port or dropped upon contention. An optical acknowledgement (ack) protocol is used to signal message dropping. Short optical pulses are sent from the receiver to sending port upon successful transmission using the messages' lightpaths. Sources whose messages were dropped do not receive acks and retransmit at a later time.

III. OQoS Encoding Scheme

Due to the reprogrammable capability of the photonic switching nodes' control logic, the implemented OPS network test-bed can be straightforwardly adapted to support OQoS priority-encoded packet transmission [11]. The packet encoding mechanism is offered through a simple modification of the switching node's electronic routing control logic, in addition to the fabric's supported optical message format. According to the high or low class of service assigned to the packet, the corresponding priority class is encoded directly in the optical header signals.

A low-duty electronic pseudoclock signal is experimentally distributed among all the switching nodes. The clock consists of two short pulses per timeslot (i.e., per message duration). The frame and address header signals (labeled F and A_i/A_j in Fig. 1) are experimentally modified to incorporate a one-bit priority (Fig. 2). The implemented routing control is based on sequential logic that samples the frame on the two pulses of the pseudoclock. The first sampled bit determines the presence of

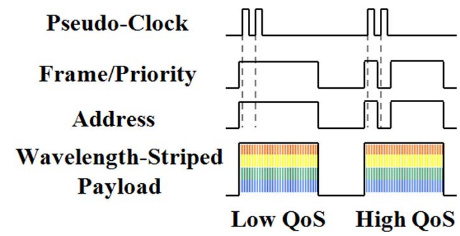

Fig. 2. Diagram depicting the implemented OQoS encoding scheme for the supported wavelength-striped optical packet.

the optical packet, while the second bit denotes the packet's OQoS class. In the case of a low-priority packet, both of the sampled bit signals will be high; for a high-priority packet, the first sampled bit will be high and the second bit will be low. The subsequent message routing decision at each switching node can then be made according to the two high/low levels detected by the control logic. In the situation of contention between two wavelength-striped packets, the new adapted routing logic and circuitry gates on the SOA associated with the high-OQoS/priority packet, while dropping the contending low-OQoS/priority packet.

IV. Experimental Results

The experimental 4 × 4 three-stage fabric test-bed is constructed using individually-packaged components, including SOAs, passive optical elements, optical receivers, and digital electronics. The electronic control logic for the OQoS encoding scheme is synthesized in complex programmable logic devices (CPLDs) within the photonic switching nodes. A one-bit, two-level OQoS routing is implemented here as an initial demonstration of the feasibility of our approach; by using a pseudoclock with multiple pulses, a multilevel QoS implementation could also be achieved. To experimentally demonstrate the OQoS-encoded packet routing, a set pattern of wavelength-striped packets is injected in the OPS fabric with a combination of high and low priority encoded packets. This demonstration supports 57.6-ns timeslots, containing 51.2-ns duration packets with data modulated at 10 Gb/s on eight payload wavelengths (ranging from 1540.1 to 1558.3 nm). The pseudoclock thus uses two pulses within the 51.2-ns packet duration to sample the packet's OQoS level. Optical packets are created using a $LiNbO_3$ modulator with a $2^7 - 1$ nonreturn-to-zero (NRZ) pseudorandom bit sequence (PRBS) and gated into packets using external SOAs. The optical header of each packet has a frame signal encoding a one-bit OQoS, one-bit distribution address (selecting one of two possible paths through the test-bed), and two-bit routing address. Fig. 3 provides the input and output waveform traces of the optical packets and pseudoclock, and confirms correct routing. The figure shows the packets' frame with encoded priority, address, and one sample wavelength channel of the 8 × 10-Gb/s payload. The faded waveforms in Fig. 3 refer to the contending low-OQoS packets that are initially dropped due to the control logic's encoding scheme.

The experimental packet sequence exemplifies the functionality of the OQos encoding. This exploration shows one high-OQoS source (in1), one low-OQoS source (in2), and one source whose retransmitted packets are given higher OQoS

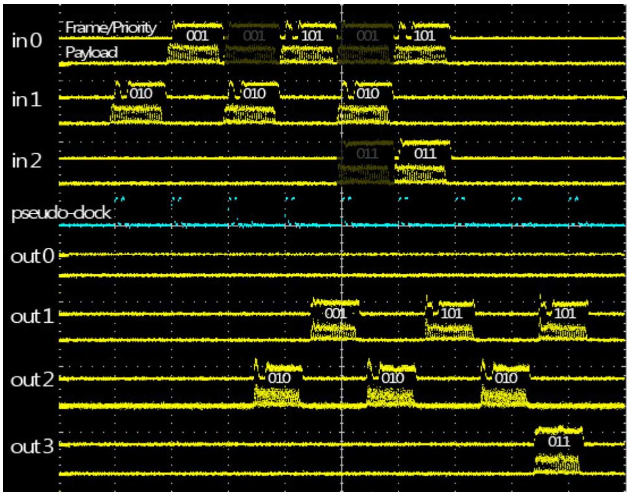

Fig. 3. Experimental optical input and output waveforms validating the correct routing of the encoding scheme; the pseudoclock trace is also provided. Packets are injected using three input ports, with the three address bits labeled above the waveforms, and emerge from four output ports.

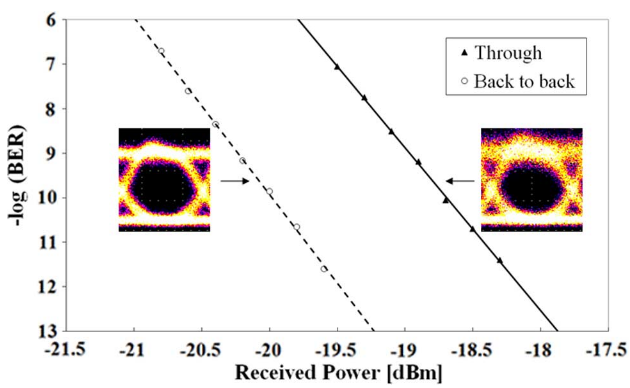

Fig. 4. Sensitivity curves for one typical payload channel (dashed line refers to the back-to-back measurements, solid line refers to the output data); insets give the 10-Gb/s eye diagrams of the input and output ($\lambda = 1558.3$ nm).

(in0) (Fig. 3). When two messages contend at a given switching node, the lower priority packet is dropped and no ack pulse is received at its sending port. If the sending port does not obtain an ack, it can retransmit on a different path in the next timeslot by modifying the distribution bit. The retransmitted packet can have an equivalent or higher priority class. Here, the acks are not implemented due to the large round-trip time of the realized test-bed compared to the envisioned integrated one; instead, packets are assumed to be received (or not) within the timeslot.

Error-free transmission of all egressing packets is verified with a 10-Gb/s direct-coupled p-i-n receiver with transimpedance amplifier (TIA). A bit-error-rate tester (BERT) is synchronized with the packet gating signals and is gated over 80% of the packet. BERs less than 10^{-12} are obtained for each of the eight payload wavelengths. Fig. 4 shows the sensitivity curves for one typical payload channel, with the 10-Gb/s eye diagrams; all payload wavelengths performed similarly. The three-stage test-bed exhibits a power penalty of 1.2 dB (0.4 dB/SOA hop), which is consistent with previously shown power penalty values at 10 Gb/s; the performance of the test-bed is not negatively affected by the realization of the encoding scheme. This verifies the functionality of the proposed OQoS-encoding routing scheme.

V. Conclusion

Next-generation Internet and packet routing applications will likely provide a prerequisite allowing for the priority of end users to be taken into account to ensure sufficiently high QoS for users with higher priority. The physical layer switching fabric should thus be designed to give transmission priority to high-QoS packets and data paths. Our work addresses this concept by providing an OQoS encoding scheme for routing wavelength-striped optical messages through an OPS fabric test-bed. The priority encoding mechanism is effectively shown, demonstrating two distinct classes of frame-encoded packet priority. The scheme offers high and low priority levels, as well as prioritized routing in the case of message-dropping. Correctly routed wavelength-striped packets with $8 \times$ 10-Gb/s payloads are transmitted error-free through the test-bed (BERs $< 10^{-12}$). Our exploration examines the potential and reaffirms the feasibility of realizing OQoS-aware protocols in the future Internet infrastructure.

References

[1] A. E. Willner, "The optical network of the future: Can optical performance monitoring enable automated, intelligent and robust systems?," *Opt. Photon. News*, vol. 17, no. 3, pp. 30–35, Mar. 2006.

[2] C. P. Lai, F. Fidler, and K. Bergman, "Experimental demonstration of QoS-aware cross-layer packet protection switching," presented at the Eur. Conf. Opt. Commun. (ECOC 2009), Vienna, Austria, Sep. 2009, Paper 2.5.3.

[3] I. Baldine, "Unique optical networking facilities and cross-layer networking," presented at the IEEE Lasers Electro-Optics Soc. Summer Topical (LEOSST 2009), Newport Beach, CA, Jul. 2009, Paper TuD4.2.

[4] G. N. Rouskas and L. Xu, "Optical packet switching," in *Emerging Optical Network Technologies: Architectures, Protocols and Performance*, K. Sivalingam and S. Subramaniam, Eds. New York: Springer, 2004, ch. 5, pp. 111–127.

[5] O. Liboiron-Ladouceur, A. Shacham, B. A. Small, B. G. Lee, H. Wang, C. P. Lai, A. Biberman, and K. Bergman, "The data vortex optical packet switched interconnection network," *J. Lightw. Technol.*, vol. 26, no. 13, pp. 1777–1789, Jul. 1, 2008.

[6] A. G. P. Rahbar and O. Yang, "Prioritized retransmission in slotted all-optical packet-switched networks," *J. Opt. Netw.*, vol. 5, no. 12, pp. 1056–1070, Dec. 2006.

[7] S. Yao and B. Mukherjee, "A comparison study between slotted and unslotted all-optical packet-switched network with priority-based routing," presented at the Opt. Fiber Commun. Conf. (OFC 2001), Anaheim, CA, Mar. 2001, Paper TuK2.

[8] B. G. Bathula and V. M. Vokkarane, "QoS-based manycasting over optical burst-switched (OBS) networks," *IEEE/ACM Trans. Netw.*, vol. 18, no. 1, pp. 271–283, Feb. 2010.

[9] A. Cianfrani, V. Eramo, A. Germoni, C. Raffaelli, and M. Savi, "Loss analysis of multiple service classes in shared-per-wavelength optical packet switches," *J. Opt. Commun. Netw.*, vol. 1, no. 2, pp. A69–A80, Jul. 2009.

[10] A. Shacham and K. Bergman, "An experimental validation of a wavelength-striped, packet switched, optical interconnection network," *J. Lightw. Technol.*, vol. 27, no. 7, pp. 841–850, Apr. 1, 2009.

[11] C. P. Lai, H. Wang, A. Shacham, and K. Bergman, "Priority encoding scheme for contention resolution in optical packet-switched networks," presented at the Eur. Conf. Opt. Commun. (ECOC 2008), Brussels, Belgium, Sep. 2008, Paper P.5.7.