Demonstration of Edge Interoperability, Re-Shaping and Re-Timing using Hybrid Mode-Locking within a 40Gb/s Optical Packet Router

John M. Garcia, Kimchau N. Nguyen, Taran Huffman, Michael Belt, Jonathan S. Barton, Henrik N. Poulsen, and Daniel J. Blumenthal

Optical Communications and Photonic Networks Group
Department of Electrical and Computer Engineering
University of California, Santa Barbara, CA 93106-9560, USA
johngarcia@ece.ucsb.edu

Abstract: We demonstrate a regenerative optical router node showing 2R and 3R regeneration on 40Gb/s labeled optical packets. Successfully achieved >5dB increase in received power sensitivity and obtained >99% edge-to-edge Ethernet frame recovery.

OCIS codes: (060.6719) Switching, packet; (200.6015) Signal regeneration; (060.4259) Networks, packet-switched

1. Introduction

Optical label switching (OLS) and all-optical data routers (ODR) are currently being investigated as a possible solution to scale the bandwidth and routing capacity of today's networks [1]. Signal amplification (1R), re-shaping (2R), and re-timing (3R) are keys to extending the reach of OLS by enabling multi-hop operation [2]. As future optical networks become feasibly deployable interoperability with legacy networks will be crucial.

Previous work in this field has demonstrated impressive regenerative, multi-hop ODR operation [3, 4], but it has been demonstrated at relatively low bit rates and without edge interoperability. In this paper we demonstrate a 2R and 3R regeneration scheme for 40Gb/s labeled switched optical packets that is amenable to multi-hop operation. The focus of this paper is also to demonstrate signal regeneration functionality in tandem with edge adaptation layers to enable edge-to-edge, multi-hop operation.

2. Optical Router Architecture

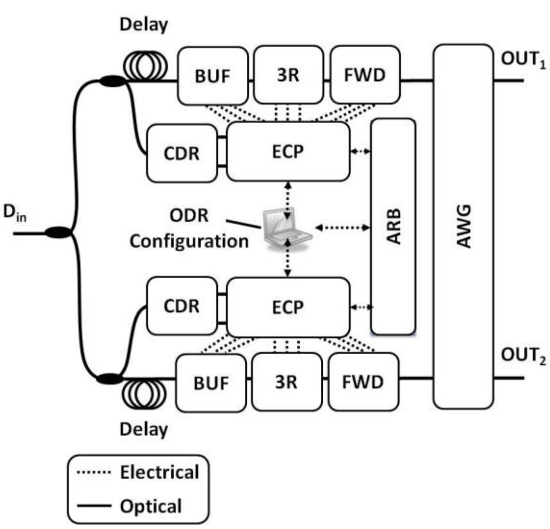

Fig. 1(a). 2x2 optical Data Router

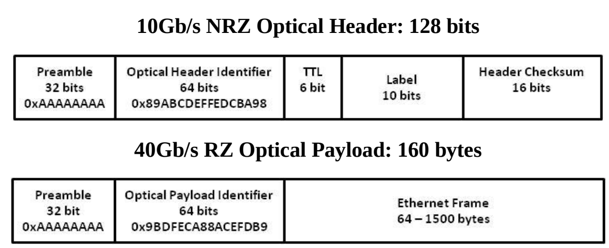

Figure 1(b). Labeled optical packet structure.

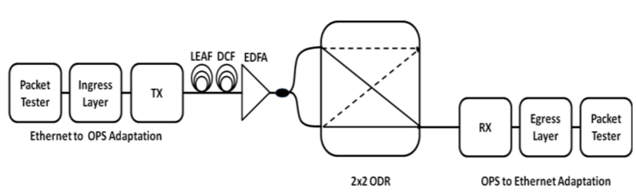

Fig. 1(c). Experimental setup.

A schematic representation of our proposed 2x2 label switched optical routed is illustrated in Fig. 1(a), while the packet structure used in our router architecture is shown in Fig. 1(b). The labeled optical packets consist of a 40Gb/s RZ payload that encapsulates an Ethernet frame within a 64-bit payload identifier. This payload is preceded by a 10Gb/s NRZ header that contains a unique 64-bit identifier and a 10-bit label used for forwarding purposes. Each arm of the ODR consists of an optical data path and an electronic control path where the payload and the header are respectively processed. The optical path contains a packet buffer (BUF) for contention resolution, a 3R stage for signal regeneration, and a packet forwarding plane (FWD) that performs the core routing functionality. The electronic control plane performs clock and data recovery (CDR) on the header and extracts the forwarding information in order to provide the appropriate control signals to the optical plane.

3. Experimental Setup

The experimental setup used to evaluate the regenerative ODR node is schematically shown in Fig. 1(c). Edge interoperability is demonstrated by utilizing a commercially available packet tester to generate a100MbE stream of 64-byte frames. The Ethernet frames are converted to and from the labeled 40Gb/s OPS format using a set of custom, FPGA-based adaptation layers [6]. The optical packets are amplified using an Erbium doped fiber amplifier (EDFA) and are sent through 20km of large effective area fiber (LEAF) that is compensated using dispersion compensating fiber (DCF). Packets are evenly split between the each arm of the 2x2 ODR using an optical 3dB coupler. An optical receiver is placed at the second output of the ODR to evaluate the signal quality of the packets traversing the optical datapaths.

Each major ODR subsystem is described in detail within Fig. 2. The optical packet buffer design consists of a re-circulating 64ns external fiber delay design. Packets are switched in and out of the buffer via a 2x2 cross-bar switch based on InP semiconductor optical amplifiers (SOA). An SOA is placed within the fiber delay to compensate for any losses incurred within the loop. A polarization controller (PC) is also placed in the loop delay to maintain a TE polarization.

Optical 3R regeneration is performed using the optical circuit shown in Fig. 2(b). Data from the optical buffer is evenly divided between the optical clock recovery (OCR) and the 2R regenerator. Optical clock recovery is achieved by performing hybrid locking of a mode-locked laser (MLL). The MLL has a repetition rate of f_0=39.8182GHz and 5nm frequency comb centered about 1552nm. A slight forward bias of 0.3V is placed across the saturable absorber (SA) of the MLL and is modulated by an RF signal that is the result of the electro-optic conversion of the buffer output. The recovered optical clock is amplified and filtered by an EDFA and a 5nm optical band-pass filter (OBPF) respectively. The filtered clock is then used as the pump input to a Mach-Zehnder interferometer wavelength converter (MZI-WC). Additionally, the buffered packets are forwarded to the probe inputs of the MZI-WC to be used in a push/pull configuration for 40Gb/s operation. Finally, a 5nm OBPF is used to filter out the push/pull inputs from the encoded clock pulses that are forwarded to the optical receiver.

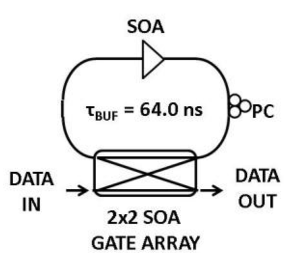

Fig. 2(a). Re-circulating optical packet buffer.

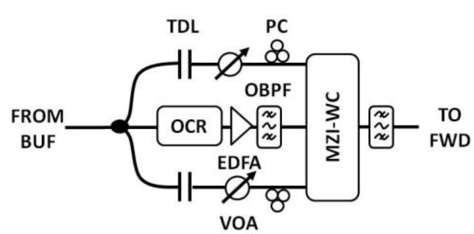

Fig. 2(b). Optical regeneration, reshaping, and retiming.TDL: tunable delay line, VOA: optical variable attenuator, OBPF: optical band-pass filter.

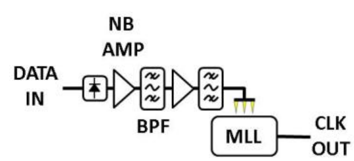

Fig.2(c). Hybrid mode-locking circuit. NB AMP: narrow-band amplifier, BPF: bandpass filter, MLL: mode-locked laser.

The transmitter data rate was set to 39.95455GHz to match the MLL repetition rate while the wavelength was set to 1560nm to maximize the gain provided by the buffer switch. For simplicity, the packet buffer was hardwired to a state that allows packet so bypass the fiber delay. Also, the packet forwarding plane was omitted from the experimental setup. Regenerated packets were forwarded to the optical receiver and then to the Egress Adaptation where Layer-II measurements were performed via recovery of the 64-bit payload identifier. The Egress Layer then converts the OPS packets back to a conforming Ethernet format and forwards the converted frames to the packet tester to perform Layer-III measurements by calculating a 32-bit cyclic redundancy check (CRC) over the entire frame. A performance comparison between the MLL-based 3R stage was carried out against a 2R implementation where the MLL was replaced by a CW laser operating at λ = 1552nm.

3. Experimental Results and discussion

The oscilloscope traces in Fig. 3(b) show the signal quality of a 2^7-1 pseudo random bit sequence (PRBS) through different stages of signal regeneration. The top trace shows the input signal after having traveled through 20km of delay. One can see that the modulation amplitude has degraded to a value close to 1mW while the extinction ratio is about 11.68dB. The middle trace presents the clock that was recovered from the input signal using the hybrid mode locking circuit. The clock pulses have increased to a modulation depth of about 2mW while the extinction ratio has decreased to 6dB. Finally, the bottom trace shows the output of the MZI-WC. It is clear that the increase in eye height is maintained through the wavelength conversion while trading off extinction ratio. The extinction ratio penalty is caused by not being able provide enough swing in RF power when driving the SA. However, the 3R stage clearly provides a re-shaping functionality.

Single side band phase noise measurements were performed on the signals from 3(a) to quantify the jitter reduction and effectively verify re-timing. Fig. 3(b) shows us that the phase noise for all three signals is relatively similar for lower offset frequencies yielding a jitter transfer bandwidth of about 1MHz. Adding to that, the reader will note that the 3R stage reduces phase noise for the higher offset frequencies. Integrating over the phase noise produces an RMS jitter value of 1.077ps and 0.8273ps for the degraded and regenerated signals respectively.

Fig. 2(c) shows the Layer-II (top) and Layer-III (bottom) measurements as a function of receiver power where the back-to-back (B2B) result was obtained by removing the buffer and the 3R stages from the link. Evaluating the power penalty at the 90% recovery rate, we see that there exists a power penalty of ~20dB between the 2R and the B2B curves with respect to payload identifier recovery. On the other hand, the 3R curve exhibits a 15dB penalty. When considering the Ethernet packet recovery rates, the 3R curve demonstrates about 5dB in increased performance relative to the 2R curve.

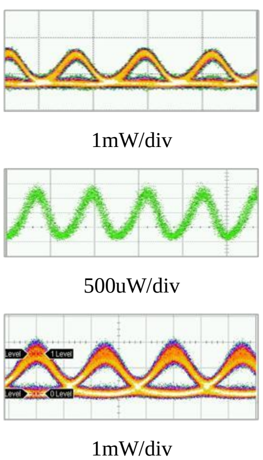

Fig. 3(b). Input signal (top), recovered clock (middle), and reshaped pulses (bottom).

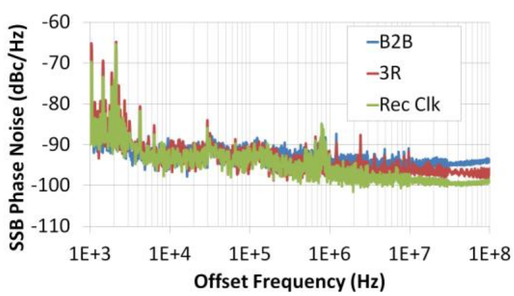

Fig. 2(c). Single side band phase noise measurement results of the back-to-back, regenerated, and recovered clock signals.

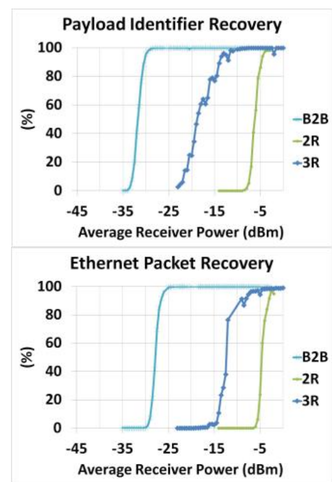

Fig. 2(c).End-to-end payload and packet recovery measurement results

4. Conclusion

We demonstrate regenerative optical router node showing 2R and 3R regeneration on 40Gb/s labeled optical packets. Additionally, we Obtained >99% edge-to-edge Ethernet frame recovery showing an increase received power sensitivity greater than 5dB.

This work is supported by DARPA/MTO and ARL under LASOR award #W911NF-04-9-0001.

5. References

[1] S. J. Yoo, “Optical Packet and Burst Switching Technologies for the Future Photonic Internet,” J. Lightwave Thec. **24,** 4468-4496 (2006).
[2] J. D. Guyton and M. F. Schwartz, “Locating nearby copies of replicated internet servers,” ACM Comp. Comm., Rev., vol. 25, no. 4, pp. 288-298, 1995.
[3] Z. Pan, "All-Optical Label Swapping, Clock Recovery, and 3R Regeneration in 101-Hop Cascaded Optical-Label Switching Router Networks," in Photonic Tech. Letters, vol. 18, no. 24, 2629-2631 (2006).

[4] T. Nakahara *et al*, “Enhanced multi-hop operation using hybrid optoelectronic router with time-to-live-based selective forward error correction,” Opt. Express, 16(226):B301-7, Dec. 12, 2011.
[5] J.M. Garcia *et al*, " Demonstration of End-to-End Interoperability between Legacy 100MbE and a 40Gb/s Optical Label Switched Network Layer," in *ECOC 2011*, Paper T h.12.B.4.