Error-free 1,001-hop Cascaded Operation of an Optical-label Switching Router with Optical 3R Regeneration

Zhong Pan (1), Zuqing Zhu (1), Masaki Funabashi (1), Haijun Yang (1), S. J. B. Yoo (1)
1 : Department of Electrical and Computer Engineering, University of California, Davis, California 95616, USA, yoo@ece.ucdavis.edu

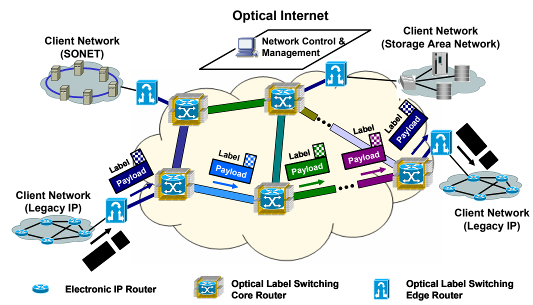
Abstract *This paper demonstrates cascaded 1,001-hop operation of an optical-label switching router. The optical 3R regeneration using wavelength conversion and synchronous modulation leads to negligible hop-to-hop penalty and stabilized Q-factor towards large hop numbers.*

Introduction

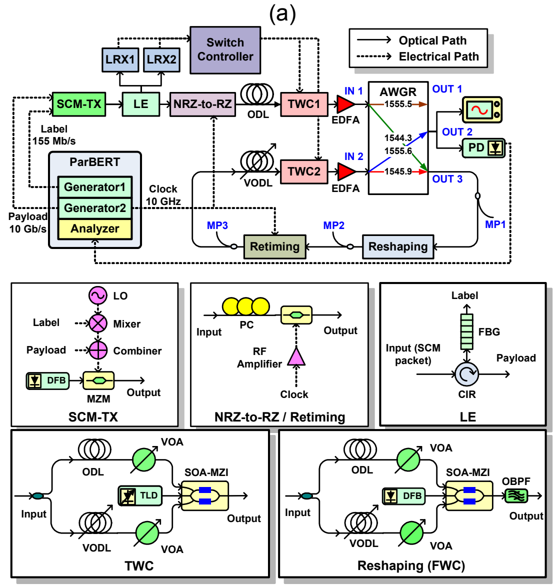
Optical-label switching (OLS) is a promising technology for high-capacity data networking supporting packet, burst, and circuit switching with full interoperability [1]. For the future photonic Internet, scalable OLS networking is desired. The OLS routers must maintain high signal quality beyond a very large number of cascaded stages of multi-hop packet forwarding [2]. While optical 3R regeneration (re-amplification, reshaping, and retiming) has demonstrated its effectiveness in mitigating accumulation of signal impairments caused by a number of mechanisms (e.g. optical loss, spontaneous emission noise, optical crosstalk, dispersion, and nonlinear effects), its applicability in all-optical routers has not been fully tested for a very large scale OLS networking. Optical 3R regeneration in OLS packet switching networks with multi-hop operations is challenging due to its requirement for supporting bursty optical packets. This paper demonstrates, for the first time, error-free 1,001-hop operation of an OLS router with 3R regeneration at 10 Gb/s. This is a significant progress compared to the previous 11-hop operation with 2R regeneration at 2.5 Gb/s [3], and it clearly proves the importance of the retiming function in scalable optical packet switching OLS networks.

Experimental description

Fig. 1(a) depicts an OLS network with multi-hop packet forwarding. The packets from a client network will acquire corresponding optical labels at the OLS edge router at the ingress, and will go through a number of OLS core routers in cascade until it egresses through another OLS edge router where the optical label will be detached. Within the OLS network, each OLS router reads the label via O/E conversion, makes a forwarding decision based on the label content and the forwarding table, and forwards the packet all-optically to the desired next hop. We have successfully prototyped an OLS router system capable of optical 3R packet regeneration, and the setup in Fig. 1(b) emulates a large-scale OLS network with the OLS router by forwarding the packet to itself repeatedly up to a preset hop count.



(a)



ParBERT: parallel bit-error rate tester (Agilent 81250); SCM-TX: sub-carrier multiplexing transmitter; LE: label extractor; LRX: label receiver; ODL: optical delay line; VODL: variable optical delay line; TWC: tunable wavelength converter; EDFA: Erbium-doped fiber amplifier; AWGR: arrayed waveguide grating router; PD: photo detector; MP: monitoring point; DFB: distributed feedback laser; LO: local oscillator; MZM: Mach-Zehnder modulator; PC: polarization controller; CIR: circulator; FBG: fiber Bragg grating; TLD: tunable laser diode; VOA: variable optical attenuator; SOA-MZI: semiconductor optical amplifier based Mach-Zehnder interferometer wavelength converter; FWC: fixed-wavelength converter; OBPF: optical bandpass filter.

(b)

Fig. 1. (a) Optical-label switching network with multi-hop packet forwarding. (b) Experimental setup. In the AWGR the numbers show the wavelength values for switching from a certain input to a certain output.

In Fig. 1(b), the subcarrier multiplexing transmitter generates optical packets with 10-Gb/s payload on the baseband and 155-Mb/s label on a 14-GHz subcarrier. The label extractor extracts the label using optical filtering [4]. A clock-driven Mach-Zehnder modulator (MZM) converts the non-return-to-zero (NRZ) payload into the return-to-zero (RZ) format, which facilitates the differential operation of the semiconductor optical amplifier based Mach-Zehnder interferometer (SOA-MZI) wavelength converters [5]. Based on the label content and the forwarding table, the switch controller determines where to forward the packet, and instructs the tunable laser diode inside the tunable wavelength converter (TWC) to tune to the corresponding wavelength. The TWC duplicates the payload information onto this wavelength, which in turn carries the payload through the arrayed waveguide grating router (AWGR) to the destination output. In this manner, a packet labeled for multi-hop operation will travel from IN1 to OUT3, and go through the router multiple times following the OUT3→IN2→OUT3→IN2… path. At the same time, packets labeled for immediate drop will continue to arrive periodically at IN1 and travel to OUT1. The switch controller uses the periodically arriving packets to count the hops. When it registers the preset hop count, the switch controller will direct the packet that has gone through multiple hops from IN2 to OUT2 for measurements.

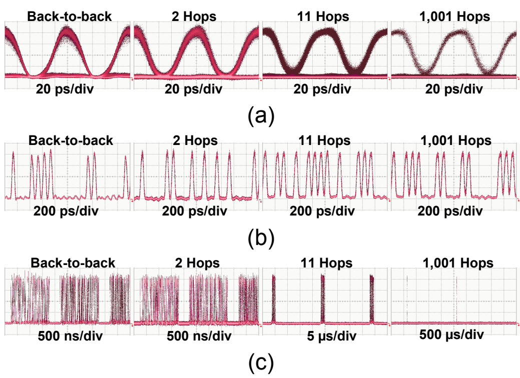
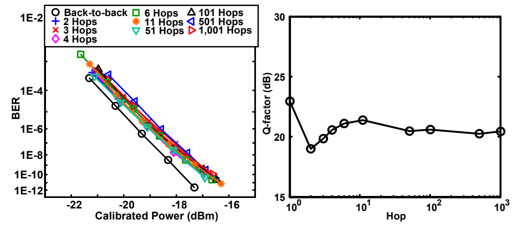


Fig. 2. (a) Eye diagrams, (b) bit patterns, and (c) packet sequences observed at OUT 2 for different hop counts.

Between every two hops, the packet travels through a reshaping block that performs 2R regeneration and a retiming block that performs the 3rd R. The reshaping block consists of a fixed-wavelength SOA-MZI wavelength converter. Utilizing the nonlinear transfer function of the cross-phase modulation wavelength conversion, the SOA-MZI suppresses amplitude noise on the space and mark levels [6]. The retiming block consists of an MZM driven by a synchronous 10-GHz clock, which suppresses jitter accumulation and pulse width expansion [7].

Experimental results

Each packet contains 15,616-bit PRBS 2^{31}-1 sequence. There is one packet arriving at the router every 1.9712 µs. Fig. 2(a)-(c) show the eye diagrams, bit patterns, and packet sequences observed at OUT2 for different preset hop counts. The eyes and



(a) (b)

Fig. 3. (a) BER v.s. calibrated optical packet power. (b) Q-factor evolution for calibrated power of -12 dBm.

bit patterns quickly stabilize and remain clear, showing no amplitude noise or time jitter accumulation. The packet sequences prove the proper switching of the router. Fig. 3(a) shows the BER test results versus the calibrated optical power. The average optical power received at OUT2 decreases when the preset hop count increases even if the power contained in a packet remains approximately the same. Thus a careful calculation is necessary to calibrate the received power in order to reveal the true power penalty relevant to the signal quality. The power penalties for 2, 3, 4, 6, 11, 51, 101, 501, and 1,001 hops at BER = 10^{-9} are 0.9, 1.0, 0.6, 0.8, 0.9, 0.7, 0.9, 1.0, and 1.0 dB, respectively. The hop-to-hop penalty beyond 2 hops is negligible. The BER curves show no error floor at 10^{-10}. Fig. 3(b) shows the Q-factor calculated by fitting the BER versus decision level curves for a calibrated power of -12 dBm. The Q-factor initially drops during the first 2 hops, and then stabilizes with a value above 20 dB even for large hop counts due to effective 3R regeneration. It is expected that this trend will go on well beyond 1,001 hops.

Summary

This paper experimentally demonstrated error-free 1,001-hop packet forwarding with negligible hop-to-hop penalty and stabilized Q-factor in the cascaded operation of an OLS router at 10 Gb/s. The optical 3R regeneration scheme using wavelength conversion and synchronous modulation proved effective for multi-hop packet switching application.

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