All-Optical Label Swapping, Clock Recovery, and 3R Regeneration in 101-Hop Cascaded Optical-Label Switching Router Networks

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***Abstract*—This paper experimentally demonstrates the cascaded operation of an optical-label switching router for up to 101 hops, with optical label swapping, optical clock recovery, and 3R regeneration (re-amplification, reshaping, and retiming) at each hop. The optical label swapping utilizes all-optical payload/label separation and label rewriting with subcarrier label. An interferometer wavelength converter enables the reshaping function, while the synchronous modulation driven by the optically recovered packet clock performs the retiming function. The optical label swapping and 3R regeneration enable the packets to traverse a large number of hops while maintaining the signal quality to support the scalability of the optical-label switching network.**

***Index Terms*—Clock recovery, optical label swapping, optical-label switching, optical packet switching, 3R regeneration.**

I. INTRODUCTION

THE rapidly growing Internet demands larger bandwidth and more sophisticated network functions. Optical-label switching (OLS) can meet this demand through the effective combination of the large bandwidth of optical technology and the functional flexibility of electrical technology. This combination also provides interoperability between packet, burst, and circuit switching [1], [2].

The next generation optical mesh network imposes requirements on the scalability of the OLS technology. In particular, the OLS routers must support multihop packet forwarding (>17 hops) [3]. Optical-label swapping allows the updating and complete regeneration of the optical label at each hop. Optical 3R regeneration (re-amplification, reshaping, and retiming) can partly limit the accumulation of signal impairments and extend the reach of the signal without repeated high-speed optical-electrical-optical (O/E/O) conversions. It is important to investigate the multihop operation of OLS networks through testbed demonstrations. Previous work has demonstrated OLS with label swapping and 2R regeneration for up to 11 hops [4], 1001-hop cascaded OLS using 3R regeneration with local clock [5], and 101-hop cascaded OLS with optical clock recovery and 3R regeneration but no label swapping [6]. Based on the referenced work, this paper experimentally demonstrates an OLS router testbed with label swapping, optical clock recovery, and 3R regeneration at each hop for multihop operation.

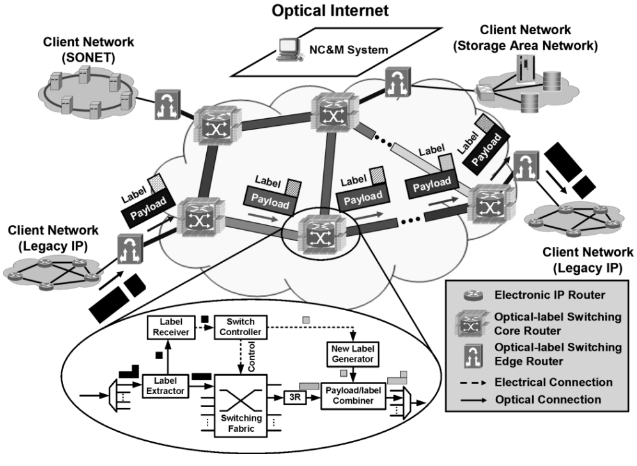

Fig. 1. A multihop optical-label switching network. The inset shows the simplified router architecture for label swapping, switching, and 3R regeneration functions, focusing on one packet traveling from a certain input port to a certain output port.

II. EXPERIMENTAL DESCRIPTION

Fig. 1 depicts a multihop OLS network. The ingress edge router aggregates client network packets, generates labels, and constructs OLS packets. An intermediate OLS router performs label swapping and switching operations, which extract the original label, optically switch the payload to an appropriate output based on the label content and forwarding table, and rewrites a new label. The egress edge router reconverts the OLS packets to the legacy client network format.

Fig. 2 shows the experimental setup emulating the multihop OLS network. In the setup, the packets travel through the same OLS router testbed for a predesigned number of hops. Being switched by the router once counts as one hop.

The subcarrier-multiplexing transmitter (SCM-TX) generates the OLS packets by optically combining the 10-Gb/s return-to-zero (RZ) payload and the 155-Mb/s nonreturn-to-zero (NRZ) label that resides on the 14-GHz subcarrier. The packet length is 2.0 μs and the guard time is 100 ns. The payload contains pseudo-random bit sequence (PRBS) $2^{31} - 1$ data with a 24-bit preamble (“111111111111111101010101”) and a 16-bit all-“1” suffix. The preamble allows a fast lock-in of the optical clock recovery while avoiding strong pattern-dependent effect on the data; the suffix extends the coverage of the recovered clock. Label extractor 1 (LE1) extracts the label using a

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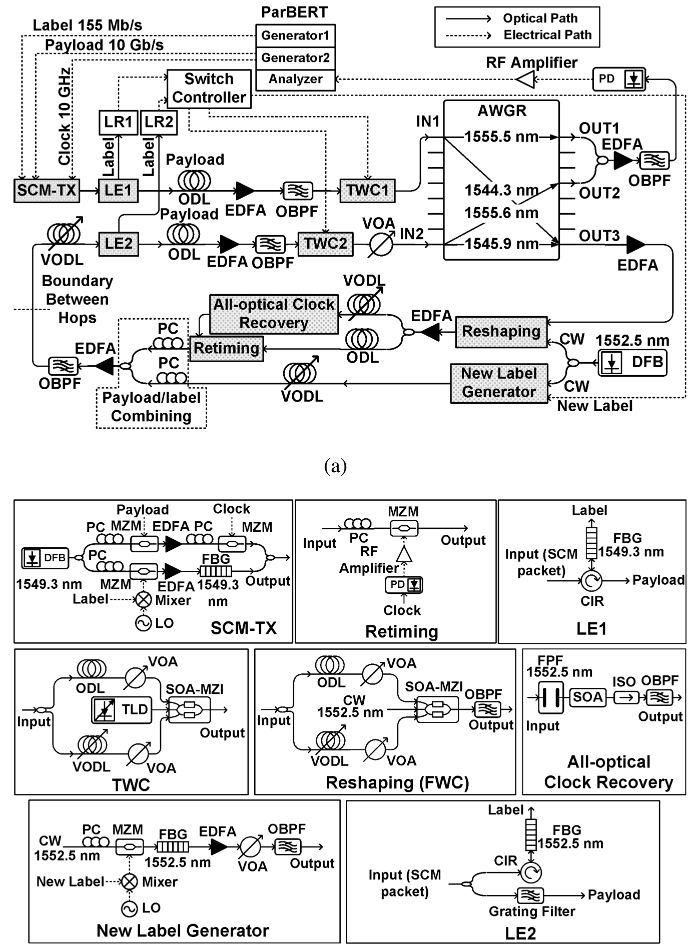
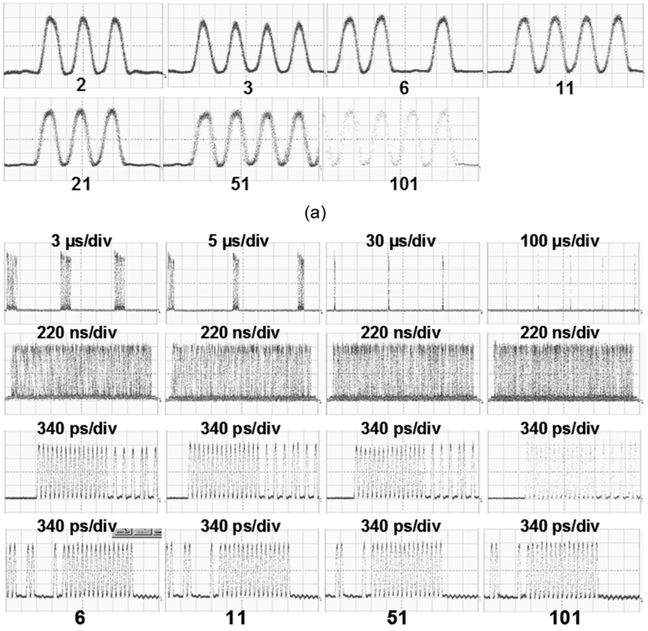


(a)

(b)

Fig. 2. (a) Experimental setup. The numbers in the AWGR indicate the wavelengths for switching from certain inputs to certain outputs. (b) The functional blocks in (a). AWGR: arrayed-waveguide grating router; CIR: circulator; CW: continuous wave; DFB: distributed feed-back laser; EDFA: Erbium-doped fiber amplifier; FBG: fiber Bragg grating; FPF: Fabry–Pérot filter; FWC: fixed wavelength converter; LE: label extractor; LO: local oscillator; LR: label receiver; MZI: Mach-Zehnder interferometer; MZM: Mach-Zehnder modulator; NRZ: nonreturn-to-zero; OBPF: optical band-pass filter; ODL: optical delay line; ParBERT: parallel bit-error rate tester; PC: polarization controller; PD: photo-detector; RZ: return-to-zero; SCM: subcarrier-multiplexing; SOA: semiconductor optical amplifier; TLD: tunable laser diode; TWC: tunable wavelength converter; TX: transmitter; VOA: variable optical attenuator; VODL: variable optical delay line.



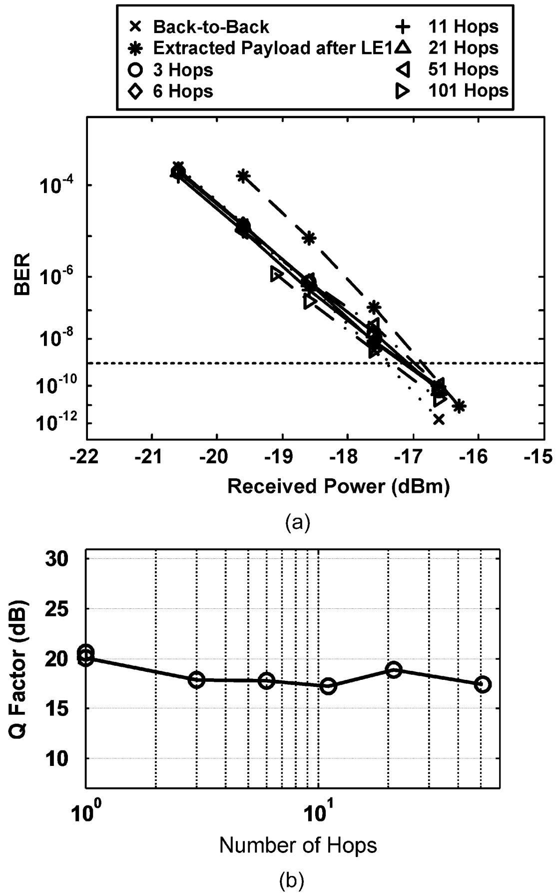
(a)

(b)

Fig. 3. Oscilloscope traces at OUT2, the final output. The bold number below the figures indicate the different number of hops traveled. (a) Bit patterns, 50 ps/div; (b) Row 1: packet sequences; row 2: packet; row 3: the leading bits of the packet; row 4: the ending bits of the packet.

fiber Bragg grating (FBG) with a full-width at half-maximum (FWHM) bandwidth of 0.16 nm [7]. The label receiver 1 (LR1) receives the label into the electrical domain, and the switch controller makes a switching decision based on the label and the forwarding table. Instructed by the switch controller, the tunable laser diode 1 (TLD1) inside the tunable wavelength converter 1 (TWC1) tunes to a target wavelength, and the TWC1 copies the payload onto this target wavelength through cross-phase modulation in a semiconductor optical amplifier (SOA) based Mach-Zehnder interferometer wavelength (MZI) converter. The payload then travels through the arrayed waveguide grating router (AWGR) to an appropriate output port determined by the wavelength.

One among every N packets has label L1 and goes to OUT3; the other $(N-1)$ packets have labels L2 and go to OUT1. N is the predesigned hop number less one. The time-to-live (TTL) field in L1 contains an initial value N. The payload arriving at OUT3 then travels through the reshaping functional block, where an SOA-MZI utilizes the nonlinear transfer function to clean the amplitude noise on the space and mark levels [8]. Then 50% of the payload travels to the all-optical clock recovery block, where a combination of a Fabry–Pérot filter (FPF) and an SOA performs burst-mode clock recovery with post amplitude equalization [9]–[11]. The free spectrum range of the FPF is 10 GHz, while the finesse is 100 [6]. The 10%–90% rise time of the clock envelope is approximately 3 ns while the fall time is approximately 10 ns measured after the optical bandpass filter (OBPF) following the SOA. The retiming block synchronously modulates the other 50% of the payload with the recovered clock to limit pulse expansion and reduce time jitter [12]. As the payload is going through the 3R regeneration, the switch controller calculates a new label by decreasing the TTL field of the received label by 1. The new label generator block generates the new optical label through subcarrier modulation. A fiber coupler combines the payload and the new label to re-form the OLS packet, which then travels across the boundary between two hops. The packet enters LE2, which extracts the label using an FBG identical to that discussed above. However, the payload passes a grating filter with an FWHM bandwidth of 0.2 nm instead, alleviating the distortion of the RZ pulses through repeated narrow filtering. Using an FBG with more rectangular spectral passband can simplify the structure of LE2 to that of LE1. The switch controller will switch the payload to OUT3 again if the label has a TTL larger than 0. When the packet has traveled through the predesigned $(N+1)$ hops, the TTL decreases to 0, so the switch controller will send the payload to



(a)

(b)

Fig. 4. (a) BER measurement results. The dotted line indicates $\mathrm{BER} = 10^{-9}$. (b) Q-factors at a receiver power of -13.6 dBm for back-to-back, extracted payload after LE1, 3, 6, 11, 21, and 51 hops.

OUT1 for measurement. All of the SOA-MZIs operate in the differential mode [13].

III. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 3 shows the oscilloscope traces of the final output observed at OUT2 for different numbers of hops. Fig. 3(a) shows the bit patterns. Fig. 3(b) shows the output packet sequence, one output packet, the leading bits of the output packet, and the ending bits of the output packet.

Fig. 4 shows the packet bit-error rate (BER) measurement results. The measurement excludes the preamble and the suffix. Environmental fluctuations cause random fiber length changes, which in turn induce low frequency jitter that is not removed by the burst-mode clock recovery and retiming. As a result, when the hop count is large (51 and 101), the BER measurements must use the electrical clock recovery internal to the Agilent 81250 Parallel BER Tester to recover the clock from the combined output of OUT1 and OUT2. The packets from OUT1 fill in the long gap at OUT2 to form a semi-continuous packet stream, which facilitates the electrical clock recovery. However, the BER test only measures the packets from OUT2. The 51-hop BER test excludes the first half of each packet to provide sufficient time for the nonburst-mode electrical clock recovery to lock; the 101-hop BER test measures only the center 5120 bits so that it can further tolerate the large timing fluctuation. All BER curves can reach below 10^{-10}. The power penalties at $\mathrm{BER} = 10^{-9}$ for the payload after LE1, 3-, 6-, 11-, 21-, 51-, and 101-hops are 0.57, 0.35, 0.31, 0.31, 0.35, 0.46, and 0.11 dB, respectively. The negative power penalty between the payload after LE1 and the payload after multiple hops is an effect of retiming-induced pulse narrowing rather than signal quality improvement. The curves for hop counts larger than 3 fall in a narrow power range of 0.35 dB. Fig. 4(b) shows the Q-factor evolution calculated by curve-fitting the BER-versus-threshold measurements at a receiver power of -13.6 dBm. The Q-factor remains above 17.2 dB, indicating that the BER floor is lower than 2.17×10^{-13}. The BER and Q measurements show that the signal quality stabilizes as the result of the 3R regeneration.

IV. SUMMARY

This paper experimentally demonstrated the 10-Gb/s, cascaded operation of an OLS router for up to 101 hops, including optical subcarrier label swapping and optical 3R regeneration using burst-mode optical clock recovery at each hop. The results showed stabilized signal quality for the multihop operation, indicating that the demonstrated schemes are suitable for scalable OLS network applications.

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REFERENCES

[1] B. Meagher, G. K. Chang, G. Ellinas, Y. M. Lin, W. Xin, T. F. Chen, X. Yang, A. Chowdhury, J. Young, S. J. Yoo, C. Lee, M. Z. Iqbal, T. Robe, H. Dai, Y. J. Chen, and W. I. Way, "Design and implementation of ultra-low latency optical label switching for packet-switched WDM networks," *J. Lightw. Technol.*, vol. 18, no. 12, pp. 1978–1987, Dec. 2000.

[2] S. J. B. Yoo, "Optical-label switching, MPLS, MPLambdaS, and GMPLS," *Opt. Netw. Mag.*, vol. 4, no. 3, pp. 17–31, May/Jun. 2003.

[3] J. D. Guyton and M. F. Schwartz, "Locating nearby copies of replicated internet servers," *ACM Comput. Commun. Rev.*, vol. 25, no. 4, pp. 288–298, 1995.

[4] J. Cao *et al.*, "11-hop operation of optical-label switching system with all-optical label swapping," presented at the ECOC'03, 2003, Paper Th3.2.

[5] Z. Pan *et al.*, "Error-free 1,001-hop cascaded operation of an optical-label switching router with optical 3R regeneration," presented at the ECOC'06, Cannes, France, Sep. 2006.

[6] Z. Pan, Z. Zhu, M. Funabashi, H. Yang, and S.J.B. Yoo, "101-hop cascaded operation of an optical-label switching router with all-optical clock recovery and 3R regeneration," *IEEE Photon. Technol. Lett.*, vol. 18, no. 15, pp. 1654–1656, Aug. 1, 2006.

[7] H. J. Lee *et al.*, "Simple, polarisation-independent, and dispersion-insensitive SCM signal extraction technique for optical switching systems applications," *Electron. Lett.*, vol. 37, no. 20, pp. 1240–1241, Sep. 2001.

[8] T. Gyselings *et al.*, "Strong improvement in optical signal regeneration and noise reduction through asymmetric biasing of Mach-Zehnder interferometric all optical wavelength converters," in *Proc. IOOC-ECOC'97*, 1997, vol. 2, pp. 188–191.

[9] M. Jinno and T. Matsumoto, "Optical tank-circuits used for all-optical timing recovery," *IEEE J. Quantum Electron.*, vol. 28, no. 4, pp. 895–900, Apr. 1992.

[10] C. Bintjas, K. Yiannopoulos, N. Pleros, G. Theophilopoulos, M. Kalyvas, H. Avramopoulos, and G. Guekos, "Clock recovery circuit for optical packets," *IEEE Photon. Technol. Lett.*, vol. 14, no. 9, pp. 1363–1365, Sep. 2002.

[11] G. Contestabile, A. D'Errico, M. Presi, and E. Ciaramella, "40-GHz all-optical clock extraction using a semiconductor-assisted Fabry–Pérot filter," *IEEE Photon. Technol. Lett.*, vol. 16, no. 11, pp. 2523–2525, Nov. 2004.

[12] M. Nakazawa *et al.*, "10 Gbit/s soliton data-transmission over one million kilometers," *Electron. Lett.*, vol. 27, no. 14, pp. 1270–1272, Jul. 1991.

[13] K. Tajima *et al.*, "Ultrafast all-optical signal processing with symmetric Mach-Zehnder type all-optical switches," *Opt. Quantum Electron.*, vol. 33, no. 7–10, pp. 875–897, Jul. 2001.