Error-free 31-hop cascaded operation of an optical packet switching router with all-optical 3R regeneration

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Abstract: This paper demonstrates 31-hop cascaded operation of an optical-label switching router. The all-optical 3R regeneration enables error-free 31-hop cascaded packet switching with no additional penalty beyond 3 hops up to 31 hops.

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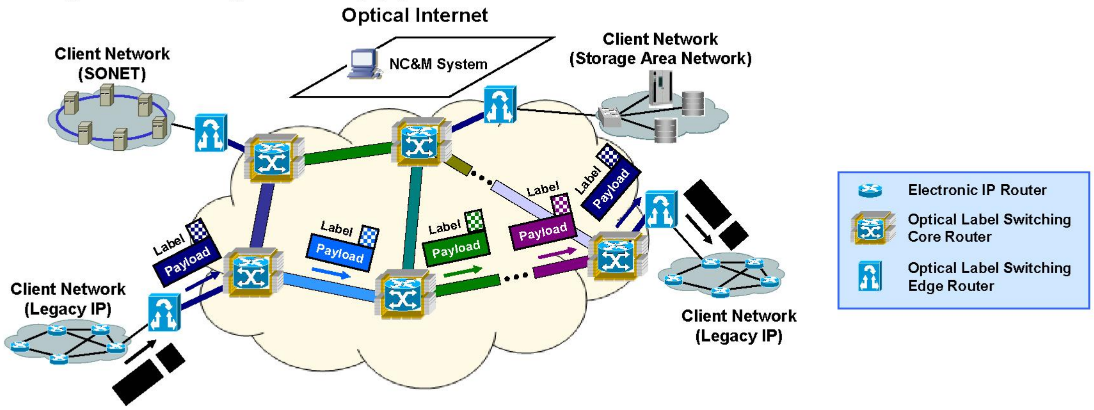
1. Introduction

Optical-label switching (OLS) effectively combines the large bandwidth of the optical technology and the functional flexibility of the electrical technology to enable high-capacity and agile networking with interoperability between packet, burst, and circuit switching [1]. Scalability of the OLS technology is an important consideration for its applicability in the next generation optical Internet. OLS routers must maintain high-quality signals after a reasonably large (>17 hops) number of cascaded multi-hop packet forwarding [2]. While optical 3R regeneration (re-amplification, reshaping, and retiming) can partly limit the accumulation of signal impairments caused by, for instance, optical loss, spontaneous emission noise, optical crosstalk, dispersion, and nonlinear effects, its applicability in all-optical routers has not been tested, especially for cascaded optical packet switching operation. Thus, it would be important to study the application of the optical 3R regeneration method in the OLS network, focusing on multi-hop operations, which are challenging due to the burstiness inherent to packet switching. This paper demonstrates significant progress compared to the previous 11-hop operation with 2R regeneration at 2.5 Gb/s [3]. It achieves error-free 31-hop operation with 3R regeneration at 10 Gb/s, where the retiming function clearly proves to be important in optical packet switching.

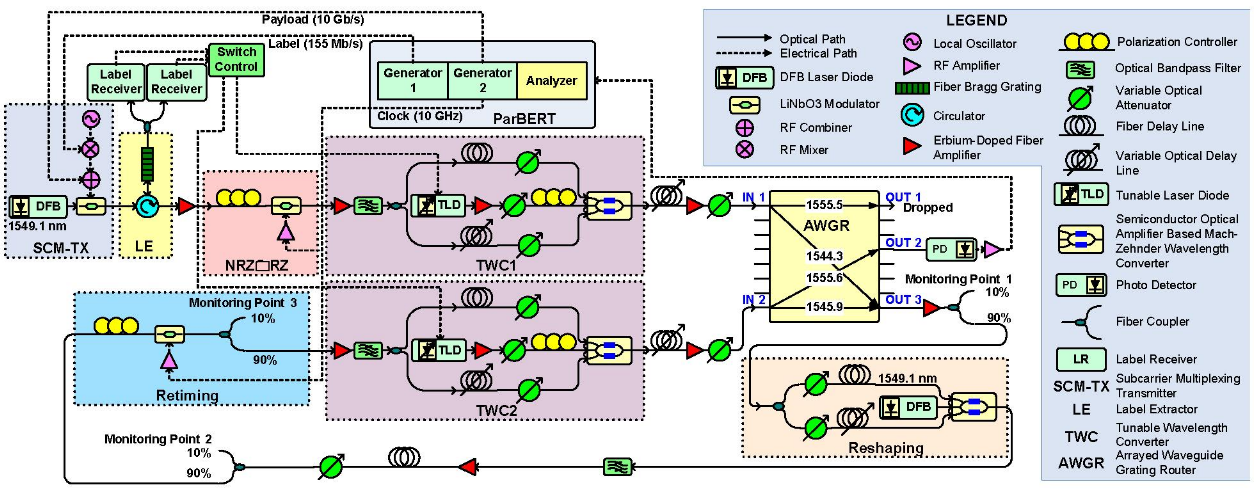
2. Experimental description

Fig. 1(a) shows an example OLS network to be emulated. The ingress edge router aggregates the legacy network packets and converts them into OLS packets by attaching an optical label to the payload. At each hop in the OLS network, the OLS router extracts the routing information from the optical label and performs packet forwarding while keeping the payload in the optical domain. At the egress after multiple OLS router hops, the egress edge router converts the packet back to the legacy network format of the client network. In order to experimentally emulate multi-hop packet switching using a single OLS router testbed, this demonstration directs the packet through the same router multiple times until it reaches the desired hop count, at which point the packet exits the optical router for measurements.

Fig. 1(b) shows the experimental setup. The subcarrier-multiplexing transmitter generates optical packets with 10 Gb/s non-return-to-zero (NRZ) payload on the baseband and 155 Mb/s NRZ label on the 14 GHz subcarrier. The label extractor separates the label and the payload [4]. A 10 GHz clock drives a $LiNbO_3$ modulator to convert the payload from NRZ to return-to-zero (RZ), which allows differential mode operation of semiconductor-optical-amplifier based Mach-Zehnder interferometer wavelength converters (SOA-MZI) [5]. The label receiver receives the label and the switch control makes a decision according to the label content and the forwarding table. The switch control then instructs the tunable wavelength converter (TWC) to duplicate the payload on a corresponding wavelength that directs the payload from port IN 1 to a desired output port of the arrayed waveguide grating router (AWGR). Those packets labeled for assisting the hop counting will travel to the drop port (OUT 1), while those packets labeled for multi-hop operation will travel to OUT 3 and pass the reshaping functional block that cleans up the amplitude-domain noise on the space and mark levels by cross-phase modulation [6]. Then they will pass the retiming functional block with a 10 GHz clock driving a $LiNbO_3$ modulator to perform synchronous modulation to suppress the time-domain noise [7]. The reshaping and retiming blocks form the 3R regenerator for optical packets. The packets continue to travel to another TWC at IN 2 that switches them either back to the router again (OUT 3) or to the final output (OUT 2) when the packets has completed the designed maximum number of hops. For simplicity, the switch control keeps track of the hop count by accurate timing rather than by updating the time-to-live field in the label using label rewriting at each hop [3].



(a)



(b)

Fig. 1. (a) Optical-label switching network with multi-hop packet switching. NC&M: network control and management. (b) Experimental setup. In the AWGR the numbers with arrows show the wavelength values for switching from a certain input to a certain output.

3. Experimental results

Fig. 2(a)-(f) show the packet sequences and corresponding eye diagrams observed at OUT 2 for different maximum number of hops. The back-to-back data shows the packets after the NRZ-to-RZ modulator. Starting from 3 hops, the packet sequence has (N-2) "empty slots" following each packet, during which time the packet is traveling through the hops. Here N is the maximum hop count. Fig. 2(g)-(i) show the packet sequences observed at the Monitoring Point 1 (MP1) that captures a copy of the packet traveling through each hop. The power level of the packet stabilizes after a few hops. Fig. 3 shows the bit-error rate (BER) test result at OUT 2. Fig. 3(a) shows BER curves against measured optical power. The power penalties in this plot do not automatically reflect actual signal quality degradations since the average power at OUT 2 would vary with the total number of hops due to the change in the duty cycle (or filling factor). This is evident from Fig. 2(a)-(f). Multiplying the measured power by (N-1) will provide the power for the packet. For back-to-back, N=2 is used. Fig. 3(b) shows the results based on the calibrated optical packet power. The curves indicate that for BER level of 10^{-9}, the first 2 hops introduce a penalty of 0.63 dB, while the 3rd hop introduces an additional penalty of 0.99 dB. After 3 hops and up to 31 hops, there is no further penalty thanks to the 3R regeneration. Similarly, the eye shape stabilizes after 3 hops and remains the same for up to 31 hops. The root-mean-square jitter measured from the eye remains approximately 2~3 ps. All the BER curves are error-free (BER <1E-12), and all the eyes are open and clear. Although the demonstration stops at 31 hops, the trend indicates that the system can support more hops with stable performance.

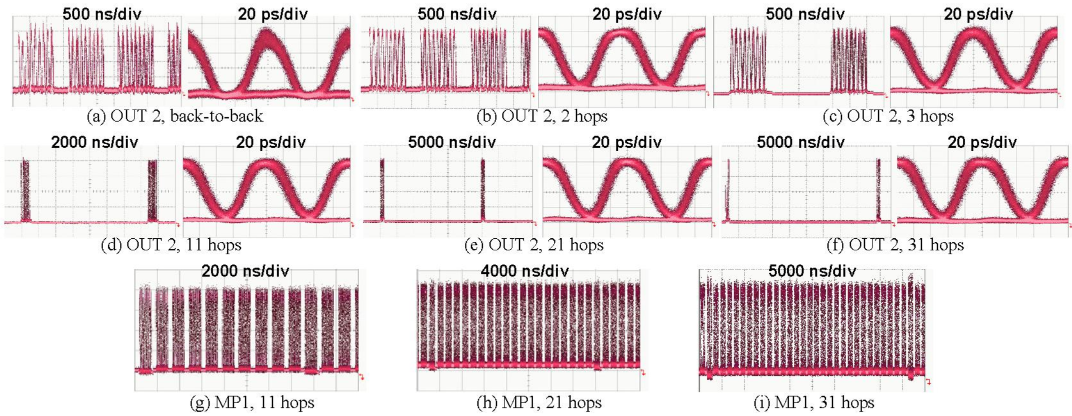
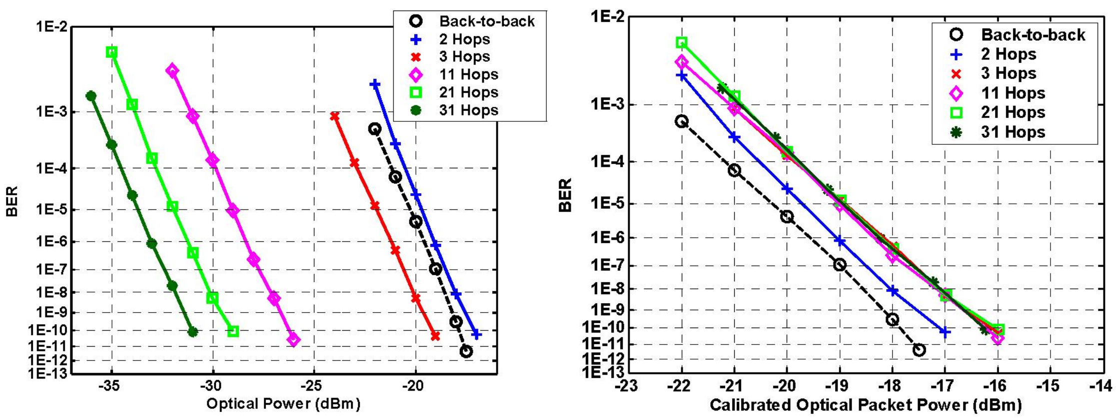


Fig. 2. Packet sequences and eye diagrams observed at OUT 2 for (a) back-to-back, (b) N=2, (c) N=3; (d) N=11; (e) N=21, and (f) N=31; and packet sequences observed at MP1 for (g) N=11, (h) N=21; (i) N=31. N is the maximum hop count.



(a) (b)

Fig. 3. Bit-error rate measurement results v.s. (a) directly measured optical power. (b) calibrated optical packet power.

4. Summary

This paper demonstrates the multi-hop operation of an optical-label switching router. The optical 3R regeneration scheme using wavelength conversion and synchronous modulation enables error-free 31-hop 10 Gb/s packet switching with no hop-to-hop penalty beyond 3 hops. The results indicate that the optical 3R regeneration is suitable for multi-hop packet switching application.

5. References

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