Error-free multi-hop cascaded operation of optical label switching routers with all-optical label swapping

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Abstract: This paper discusses multi-hop routing, all-optical label swapping operation of optical label switching routers that make real-time decisions based on the label and the forwarding table. The switching fabric conducts data regeneration and label rewriting.

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1. Introduction
Optical-label switching technology has made key progress in providing the low-latency and transparent switching desired for the next generation Internet [1-2]. For practical network applications, the optical routing system must be cascadable. Recent demonstrations have been limited to single-hop operations with label swapping [3], multi-hop operations without label or data regeneration [4]. High-performance optical-label switching routers are expected to include data and label regeneration with label swapping capabilities. This paper discusses an experimental demonstration of a cascaded multi-hop optical packet routing system with optical-label switching. The system includes tunable lasers, wavelength converters, arrayed waveguide grating routers, burst mode receivers, a switch controller with a forwarding table, and an all-optical label-swapping module.

2. Experiments
The experiment emulates a network with multiple optical-label switching routers, each providing label-based packet forwarding. Fig 1(a) shows an emulated optical-label switching network consisting of several optical-label switching routers (OLSR). Three types of packets, P1, P2, and P3 with labels L1, L2, and L3 respectively, ingress into the optical label switching networks. The first OLS router (OLSR1) performs the optical-label based forwarding of all three packets. OLSR1 forwards P3 north to a neighboring OLS router (OLSR2) and forwards P1 and P2 east to another neighboring OLS router (OLSR3). The OLSR3 in turn forwards P1 and P2 to two different output ports. For multi-hop scalable OLSR operations, data payload regeneration and label swapping/regeneration are beneficial. Fig 1(b) shows the detailed structure of OLSR and setup for this network emulation. As Fig 1(b) shows, the actual experiment places OLSR1 and OLSR3 on the same optical router system with multiple line cards and replaces OLSR2 with a drop port. The OLSR system consists of an optical-subcarrier multiplexing transmitter (SCM Tx), two optical label/data separators, two burst mode receivers (BMRx1 and BMRx2) for label detection, a field programmable gate array (FPGA) that implements the forwarding table and switching control, two tunable wavelength converters consisting of tunable lasers and semiconductor optical amplifiers (SOAs), a uniform-loss-cyclic frequency (ULCF) arrayed waveguide grating router (AWGR), a label rewriting module [5] and data receivers. The Parallel Bit Error Rate Tester/Pattern generator (ParBERT) synchronously generates the electrical label and payload signals. The LiNbO3 external modulator modulates the continuous wave (CW) light from the distributed feedback laser diode (DFB LD) using a subcarrier multiplexed signal consisting of a baseband 2.5 Gb/s data payload and a 155 Mb/s label modulated onto a 14 GHz subcarrier. Hence, the modulated signal includes a double-sideband subcarrier label 14 GHz away from the center optical carrier frequency. The combination of a fiber Bragg grating and an optical circulator achieves all-optical label extraction [6]. The BMRx asynchronously recovers the label contents from optical domain to electrical domain. The recovered label signal induces the forwarding decision inside the switch controller according to the routing algorithm in the FPGA. Based on the forwarding decision, the switch controller sends a control signal to the tunable laser (TLD) to switch to the designated wavelength [7]. The TLD generates a tunable probe light for the SOA1, which modulates the payload signals onto the new wavelength by cross-gain modulation. Payloads with different labels are converted onto different wavelengths corresponding to the desired output ports of the AWGR.
The ParBERT generates repeated patterns of packet 1 (P1), packet 2 (P2), and packet 3 (P3) with different labels (L1, L2, L3). Fig 2(a) shows the three packets. The optical labels L1, L2 and L3 cause the wavelength of the TLD1 to be switched to $\lambda_1$ (1552nm), $\lambda_1$ (1552nm), and $\lambda_2$ (1546 nm) respectively according to the forwarding table. The tunable wavelength converter will convert P1 and P2 to wavelength 1552 nm and P3 to 1546 nm according to the optical-label based forwarding decision. After routing through the AWGR, P3 will be dropped and P1 and P2 go to the label-swapping module as shown in Fig 2 (b). This represents the OLSR1 in the emulated network. The switch controller generates new labels for payload P1 and P2 and drives the modulator inside the label-rewriting module with a 14 GHz carrier frequency. At the same time, payload P1 and P2 will be regenerated to the fixed wavelength (1555.7nm) in the SOA Mach-Zehnder Interferometer wavelength converter (SOA-MZI WC). The packets with the regenerated label and payload transmit to label / data separator 2. The BMRx2 recovers the new label contents and sends them to the switch controller. Again, according to the label contents, the switch controller sends control signals to the TLD2 to switch to the correct wavelengths. The new labels L1’ and L2’ cause the wavelength of the
TLD2 to be switched to $\lambda_1$ (1546nm) and $\lambda_2$ (1542nm) respectively. TLD2 drives the SOA2 that converts the payload signal onto the desired wavelength by cross-gain modulation. P1 converted to 1546 nm will be routed to the destination port. Fig 2(c) shows P1 on the destination port. P2 converted to 1542 nm will be dropped after AWGR. The switched data payload P1 goes to the data receiver for BER measurements. Here, the switching with new labels L1’ and L2’ emulates the OLSR3 in Fig 1 (a).

Fig. 2. Scope traces showing (a) the incoming P1, P2 and P3, (b) P1 and P2 sent to the second hop after dropping P3, and (c) P1 at the final destination output after two-hop OLSR.

Packet by packet bit-error-rate measurements took place on the P1 at each hop. Fig. 3 shows the measured data. Each packet is 600ns long with a 200ns guard time, thus each packet period is 800ns. The bit pattern was $2^{15} - 1$ PRBS truncated into the packets. The three curves in Fig. 3 are for the optical baseband back-to-back and the payload signals after one and two hop OLSR, respectively. The signal after one hop shows about 0.7 dB power penalty compared to the baseband payload signal. However, a negative power penalty about 0.2 dB at BER=1e-9 appears after 2 hop OLSR, which is mainly due to the 2R regeneration in the SOA-based MZI WC and the decrease of the received average power after two packet-droppings. The eye diagrams of the switched payload are shown as the insets in Fig. 3. All eye diagrams show clear openings. The signal-to-noise ratio was higher for the second hop compared to the first hop due to the 2R regeneration of MZI WC. Also the XGM based SOA wavelength converters invert the logic of the signal which leads to the change of the average power of signal. This results in a higher average power for the first hop. For the second hop the second XGM wavelength converter will invert the logic back to normal. For these reasons, the power received by the date receiver corresponds to different ratios of the real packet power for the 1-hop operations and the 2-hop operations. The combination of the 2R regeneration and the optical power change leads to the negative power penalty for the 2-hop operation.

Fig. 3. BER test results of the cascaded OLSR

(Insets: eye diagrams of the baseband payload and signals after OLSR)
3. Summary

We have demonstrated for the first time, to our knowledge, the error-free multi-hop cascaded operation of an all-optical label routing system with optical label swapping. The experiment emulated optical packet switching through 2 hops in the network. Experiment results show regenerating optical label switching with label swapping and 2R packet regeneration. The two-hop routing OLSR system demonstrates negative power penalty of 0.2dB at BER=1e-9 for data packets.

4. References


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