All-Optical Signal Processing in Photonic Label Switching Routers

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Abstract: This paper proposes and demonstrates an optical-label switching router with all-optical time-to-live, performance monitoring, label swapping, and 2R regeneration. Experimental results of unicast and multicast packet forwarding with contention resolution of asynchronously arriving variable-length packets.

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1. Introduction

Optical-label switching (OLS) is a promising technology for meeting the challenge posed by the rapidly increasing Internet traffic [1]. The processing of optical-label allows new optical signal processing technologies to be implemented to facilitate high-performance packet routing and networking. These include all-optical time-to-live (TTL), all-optical label swapping, all-optical regeneration, and performance monitoring. Fig. 1 shows a the main packet switching fabric of a recently integrated all-optical label switching router. Routing loop is a serious problem in packet-switching networks, which can cause severe overload and congestion in the network. The IP protocol employs a loop mitigation based on TTL, where each hop will reduce the value of the TTL field in the IP header and will discard the packet when the packet's TTL value reaches zero. For optical packet switching networks, recent works [2, 3] have demonstrated optical TTL using ultrashort pulse bursts and non-linear effects. Because there is no effective all-optical logic processing capability, these TTL methods are complex and difficult. A preferred method of optical TTL would mitigate routing loop and at the same time discard errant packets caused by transmission errors. By utilizing a strong correlation in the BER between the labels and the payloads, it is possible to estimate the error rates in the packets by checking the errors in the label. Fig. 2 shows intentional packet dropping by checking the errors in the optical labels, demonstrated in an optical label switching router including the switch control where the errors in the labels get detected.

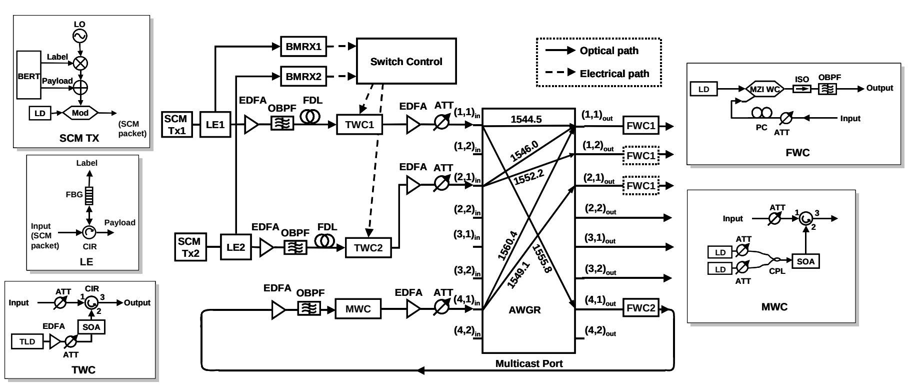

Fig. 1. Experimental setup. The insets show the details of the composing modules. In the AWGR the wavelength values for switching from a certain input to a certain output are shown. SCM TX: subcarrier-multiplexing transmitter; LD: laser diode; LO: local oscillator; MOD: modulator; LE: label extractor; FBG: fiber-Bragg grating; CIR: circulator; BMRX: burst-mode receiver; EDFA: Erbium-doped fiber amplifier; OBPF: optical bandpass filter; FDL: fiber delay line; TWC: tunable wavelength converter; ATT: variable attenuator; SOA: semiconductor optical amplifier; TLD: tunable laser diode; AWGR: arrayed waveguide grating router; FWC: fixed wavelength converter; MZI-WC: Mach-Zehnder interferometric wavelength converter; ISO: isolator; MWC: multi-wavelength converter; CPL: coupler.

The optical label switching router effectively combines the unicast and multicast-capable linecards to achieve packet forwarding with scalable multicast and optical regeneration. While various architectures have been proposed for optical-layer multicasting, scalability is still an issue. Optical switching fabrics based on broadcast-and-select suffer excessive losses and require a large number of switching elements (typically N^2) [4]. While introducing one-to-many (multi-) wavelength conversion solves the first problem, a non-blocking multicast switching architecture is still complicated due to the large number of active components required [5].

We propose a limited multicast switching architecture by modifying our previously reported OLS router architecture 6. Fig. 1 is a simplified illustration, in which the OLS router has 4 input fibers and 4 output fibers. Each fiber carries 2 wavelengths. The third fiber acts as a fixed length buffer to support the contention resolution scheme [6]. The fourth fiber acts as a multicast port. When a packet that requires multicast arrives at the OLS router, the switch control forwards the payload to the multicast port and instructs the multi-wavelength converter (MWC) to copy the payload onto multiple wavelengths that successively forward the payload to multiple output ports of the AWGR. The limitation of this scheme lies in the fact that a multicast packet must go through contention resolution if other multicast packets are occupying the multicast port. In other words, the architecture is not designed to support 100% multicast packets. However the proposed architecture can effectively support both unicast and multicast packets without relying on bulky and lossy multicast router architectures that require broadcast-and-select on all ports. If the multicast service demand increases, the proposed architecture can also upgrade unicast linecards (unicast wavelength converters) to multicast linecards (MWC) without affecting every linecard.

2. Experimental description

Fig. 2 shows the experimental setup that realizes two input wavelength channels and one multicast port. For simplicity the setup does not include the multiplexers, demultiplexers, the fixed length buffer and the label rewriters, and the MWC only demonstrates two-wavelength conversion with the output wavelengths fixed instead of controlled by the switch control. The subcarrier-multiplexing transmitter (SCM TX) generates optical packets with 2.5 Gb/s payload on the baseband and 155 Mb/s label on the 14 GHz subcarrier. The label extractor (LE) separates the label and payload [8]. The burst-mode receiver (BMRX) receives the label and forwards it to the switch control that makes a decision according to the label content and forwarding table. The switch control then instructs the tunable wavelength converter (TWC) to copy the payload onto a new wavelength that can direct the payload to the desired arrayed waveguide grating router (AWGR) output port. After the AWGR, the fixed-wavelength converter (FWC) converts the payload to the wavelength that the packet desires to take. For a multicast packet, however, the switch control will direct the payload to the multicast port. The MWC will copy the payload onto two wavelengths that direct the payload through the AWGR to two desired ports. The MWC utilizes the cross-gain modulation (XGM) effect in a semiconductor optical amplifier (SOA) with multiple probe lights.

Fig. 3 shows the timing diagram and the oscilloscope traces of the packets, demonstrating the multicast function and a simple all-optical contention resolution scenario. $(m,n)_{in}$ and $(m,n)_{out}$ represent the *n*th wavelength channel on the *m*th input and output fiber, respectively. There are three types of labels. The packets with L1 desire to go to output fiber 1, preferably $(1,1)_{out}$. The packets with L2 desire to go to output fiber 2, preferably $(2,1)_{out}$. The packets with L3, which are multicast packets, desire to go to both output fiber 1 and 2. Packet P1 with label L3 arrives at $(1,1)_{in}$ first. The switch control sends the payload to the multicast port, which replicates the payload and forwards the two copies to $(1,1)_{out}$ and $(2,1)_{out}$. P1' with L1 arrives at $(2,1)_{in}$ later and travels to $(1,1)_{out}$ with no contention. Another multicast packet P2 with L3 arrives at $(1,1)_{in}$ and travels to $(1,1)_{out}$ and $(2,1)_{out}$. When P2' with L1 arrives at $(2,1)_{in}$, the port $(1,1)_{out}$ is still occupied. Thus, P2' has to go through contention resolution in wavelength domain and travel to $(1,2)_{out}$ [7]. The packet sequences repeat from here to facilitate the bit-error rate (BER) measurement.

The oscilloscope traces show that the router produces the expected results. The traces show inverted-logic packets purposely chosen to facilitate the switching experiment including power-inverting TWCs and FWCs in the switching fabric.

3. Experimental results

Fig. 4 shows the packet-by-packet BER measurement results including eye diagrams. Since P1 and P2 always go through the same switching paths leading to identical BER performance, the BER curves for P2 are ignored. All the BER curves can reach below 1E-10, indicating that the router is functioning correctly. As a byproduct of the negative-logic payload, although the back-to-back payloads after the LE are error-free down to 1E-10, they show clear crosstalk from the label. Probably due to this crosstalk, at the BER of 1E-9, the back-to-back P1' and P2' curve shows a sensitivity of -18.6 dBm, and the P2' final output at $(1,2)_{out}$ curve shows a sensitivity of -19.8 dBm, while most BER curves have a sensitivity between –20.7 to –21.1 dBm. The wavelength conversion by cross-phase modulation in the FWCs performs 2R regeneration that improves the signal quality by increasing the extinction ratio and removing amplitude noises [7], thus producing a better final output quality than the back-to-back signal.

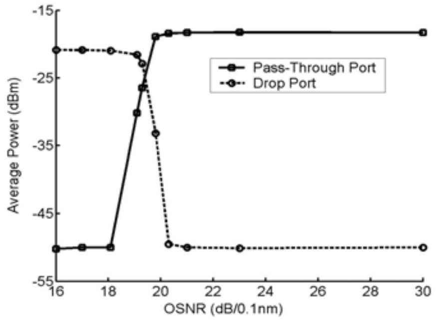

Fig. 2 Packet dropping effect as OSNR decreases

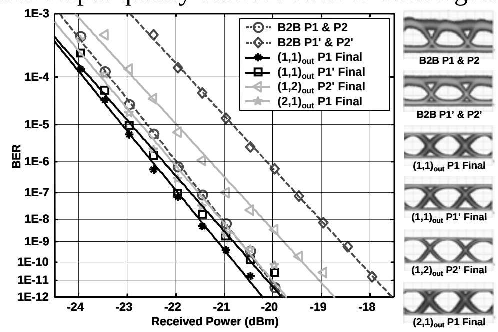

Fig. 4. Bit-error rate measurement results and eye diagrams. B2B: back-to-back. The time scale of the eye diagrams: 100 ps/div.

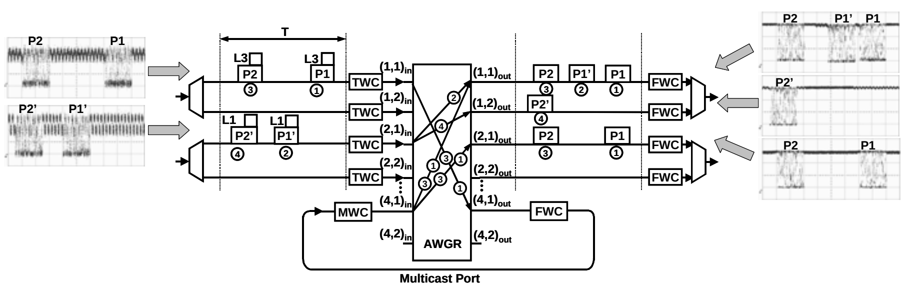

Fig. 3. Timing diagram and oscilloscope traces. T = 2.06 μs. The time axes of the oscilloscope traces are pointing to left; the time scale is 206.4 ns/div. The numbers in circles show the order of packet arrival and switching. TWC: tunable wavelength converter; AWGR: arrayed waveguide grating router; FWC: fixed wavelength converter; MWC: multi-wavelength converter.

4. Summary

We demonstrated an all-optical label switching router with all-optical TTL based performance monitoring, all-optical label swapping, all-optical signal regeneration, and multicast/unicast routing capability. In particular, the architecture provides a simple and scalable OLS router architecture capable of limited multicast with efficient support of both unicast and multicast traffic. It can scale effectively by upgrading individual unicast linecards to multicast ones without affecting each linecard. The experiment demonstrates the multicast function and a simple contention resolution scenario, proving that the router is functioning correctly with the BER lower than 1E-10.

References

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