# Demonstration of an Optical-Label Switching Router with Multicast and Contention Resolution at Mixed Data Rates

Zhong Pan, *Student Member, IEEE*, Haijun Yang, *Student Member, IEEE*, Zuqing Zhu, *Student Member, IEEE*, and S. J. Ben Yoo, *Senior Member, IEEE*

***Abstract*—This letter experimentally demonstrates a scalable optical-label switching router architecture that supports a limited multicast function. A semiconductor-optical-amplifier-based Mach–Zehnder interferometer wavelength converter performs multiwavelength conversion for multicast at 10 Gb/s by cross-phase modulation. With a 2.5-Gb/s unicast channel, the experiment also demonstrates contention resolution in the wavelength domain at mixed data rates.**

***Index Terms*—Contention resolution, multicast, optical-label switching (OLS), optical packet switching.**

## I. Introduction

The modern Internet demands versatile functionality in addition to ever-increasing bandwidth to deliver new services. Optical-label switching (OLS) meets this demand by combining the vast bandwidth of the optical technology with the functional flexibility of the control-plane electronic technology. OLS keeps the high-data-rate payload in the optical domain while converting the low-data-rate label into the electrical domain for processing [1]–[4]. Routing and forwarding processes are transparent to the bit rate, the format, and the length of the data payload. Contention resolution happens all-optically in wavelength, time, or space domains [4]. Through the label, the router can support network layer functions such as quality of service, class of service, optical time-to-live, and multicast [4]–[6].

To efficiently utilize the network resources, current multimedia streaming and conferencing applications call for multicast functions in IP routers and in future optical routers. Various methods have been proposed and demonstrated for optical-layer multicast, a challenge due to the lack of a practical optical memory. The broadcast-and-select method induces unnecessary loss and requires a large number of switching (selecting) elements, typically on the order of $N^2$ where $N$ is the number of multicast destinations [7]. The one-to-many (multi-) wavelength conversion (MWC) method removes the excessive loss but still requires a large number of active components such as lasers and switches [8]–[11].

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The authors are with the Department of Electrical and Computer Engineering, University of California, Davis, CA 95616 USA (e-mail: yoo@ece.ucdavis.edu).

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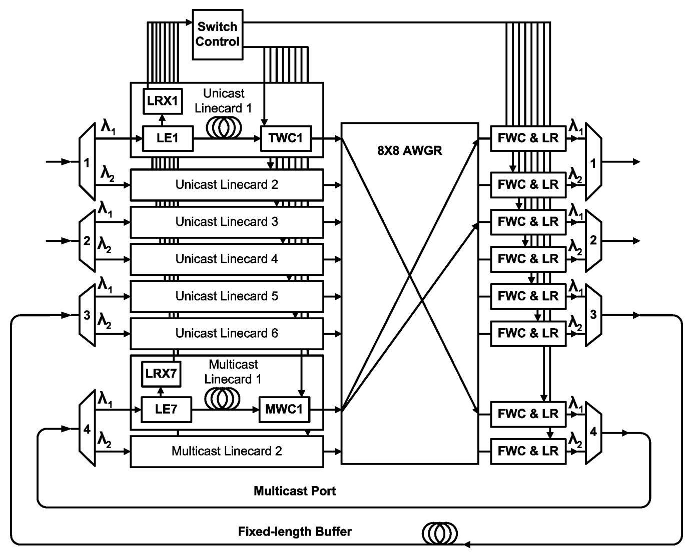



Fig. 1. Architecture of an OLS router supporting limited multicast function.

We have proposed an OLS architecture that supports limited multicast function and demonstrated its performance at 2.5 Gb/s using cross-gain modulation (XGM) in a semiconductor optical amplifier (SOA) as the MWC method [6]. This letter demonstrates OLS multicast at 10 Gb/s using cross-phase modulation (XPM) in an SOA-based Mach–Zehnder interferometer wavelength converter (SOA-MZI WC) as the MWC. Contention between 2.5-Gb/s unicast packets and the 10-Gb/s multicast packets spurs wavelength-domain all-optical contention resolution for mixed-rate variable-length packets.

## II. System Architecture

Fig. 1 shows the architecture of an OLS router supporting limited multicast function. It has four input fibers and four output fibers, each carrying two wavelengths. For each input wavelength, there is a unicast linecard that includes a label extractor (LE), a label receiver (LRX), a fiber delay line, and a tunable wavelength converter (TWC) that performs wavelength switching. The arrayed waveguide grating router (AWGR) routes packets to appropriate output ports according to their wavelengths. For each output port there is a fixed wavelength converter and a label rewriter (FWC & LR) to convert the payload to a transmission wavelength and to attach a new label. The TWC and the FWC, and thus the optical router, are data-rate transparent up to 10 Gb/s (limited by the

SOA-MZI) and they regenerate signals degraded from dispersion, polarization-mode dispersion, and nonlinear effects in fiber transmission. An incoming packet would travel through a unicast linecard, the AWGR, and the FWC & LR to arrive at the appropriate output port. A unicast packet then travels to the next hop. A multicast packet, on the other hand, would go through a multicast port to a multicast linecard where an MWC duplicates the payload onto multiple output wavelengths that will reach multiple desired output ports through the AWGR. A fiber-delay line loops back as a fixed length buffer [4].

This architecture is modularly scalable in that, by including only a few multicast linecards, the OLS router is capable of both unicast and multicast. If the increase of the multicast traffic causes a high contention level, some of the unicast linecards can be upgraded to multicast linecards to support more multicast traffic. Hence, the router can gradually upgrade to eventually support all-multicast traffic if necessary.

## III. Experimental Description

Fig. 2 shows the experimental setup that includes two unicast linecards and one multicast linecard. For simplicity, the setup uses a two-wavelength converter with fixed wavelengths as the MWC; it does not include the multiplexers, demultiplexers, fixed length buffer, and the FWC & LR. The Agilent ParBERT system and the subcarrier-multiplexing transmitters (SCM-TX) generate the optical packets with 10- or 2.5-Gb/s payload on the baseband and 155-Mb/s label on the 14-GHz subcarrier. The 5120-bit 10-Gb/s payload is 514.5 ns long, while the 1024-bit 2.5-Gb/s payload is 411.6 ns long. The label carries the information pertaining to routing and forwarding including the destination and the multicast requirement. When a packet arrives at a unicast linecard, the LE separates the label and the payload utilizing a fiber Bragg grating as a narrow (0.1 nm) optical filter [12]. The burst-mode LRX converts the label to an electrical signal and sends it to the forwarding table and controller that is implemented on a field-programmable gate array (FPGA). The controller makes the routing decision in approximately 300 ns and instructs the tunable laser diode in the TWC to tune to the corresponding target wavelength. Measurements indicated that the tunable laser switching between the two adjacent laser modes settles to within 20 GHz in less than 2 ns and to within 200 GHz in less than 1 ns. This settling time mainly determines the minimum guard time between packets. We are investigating fast tuning among all useful wavelength channels. The optical payload travels through a 60-m fiber delay line to approximately match the 300-ns label processing delay before it is copied onto the new target wavelength by the TWC. The TWC in the 10-Gb/s channel utilizes XPM in an SOA-MZI WC, while that in the 2.5-Gb/s channel uses XGM in an SOA. The converted payload then travels through the AWGR and reaches the desired output port determined by the target wavelength. If this packet is a multicast packet, the router forwards it to the multicast linecard where it is duplicated onto multiple target wavelengths by the MWC. These copies pass through the "pulse carver" (a synchronous modulator that reshapes a pulse in time domain) for retiming-regeneration and travel to multiple output ports that correspond to the multicast tree branches at this network node.

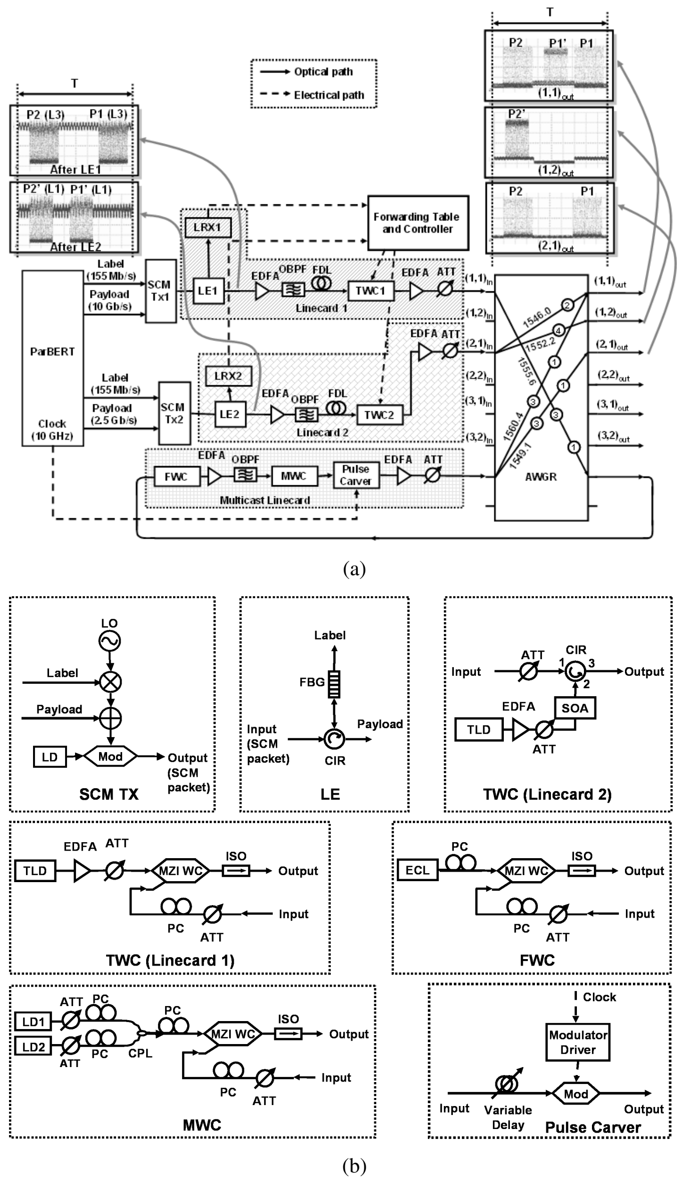
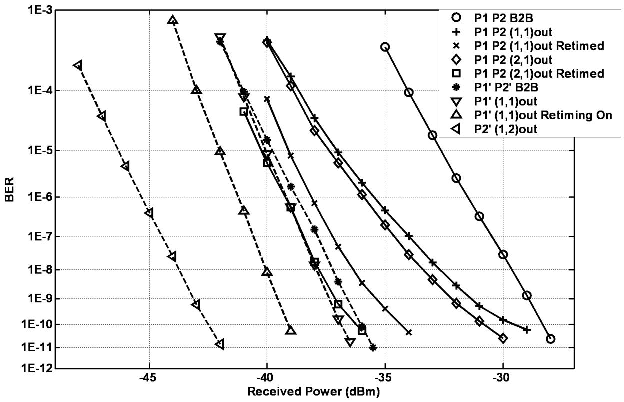
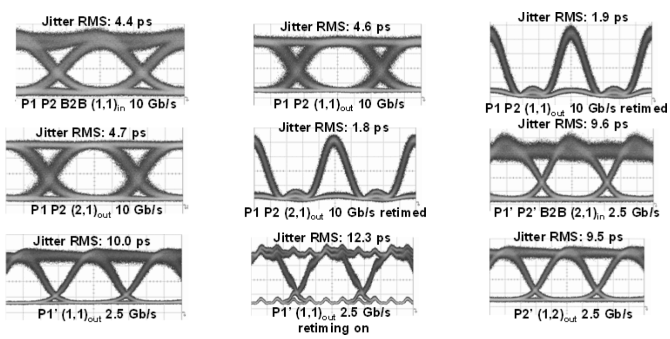



Fig. 2. Experimental setup and oscilloscope traces of packet sequences. (a) The modular setup and packet sequences. (b) The details of the modules in (a). Oscilloscope traces are taken with the pulse carver and show payloads only. For input packets, the corresponding labels are noted in the parentheses. The time axis points to the left and the time scale is 206.4 ns/div. $T = 2.06$ $\mu$s. In the AWGR, the wavelength values for switching from a certain input to a certain output are shown. The numbers in circles indicate the order of switching. ATT: Attenuator. CIR: Circulator. CPL: Coupler. ECL: External cavity laser. EDFA: Erbium-doped fiber amplifier. FBG: Fiber Bragg grating. ISO: Isolator. LD: Laser diode. LO: Local oscillator. Mod: $LiNbO_3$ modulator. PC: Polarization controller. TLD: Tunable laser diode.

Fig. 2 shows the packet sequences used in the demonstration. Packets with label L1 are unicast packets which need to travel to output fiber 1, whereas packets with label L3 are multicast packets which need to travel to both output fibers 1 and 2. $(m,n)_{\rm in}$ and $(m,n)_{\rm out}$ in Figs. 2 and 3 denote the $n$th wavelength on the $m$th input and output fiber, respectively. Multicast packet P1 with L3 comes to $(1,1)_{\rm in}$ first and travels to $(1,1)_{\rm out}$ and $(2,1)_{\rm out}$. After P1 passes unicast packet P1$'$ with L1 arrives at $(2,1)_{\rm in}$ and travels to $(1,1)_{\rm out}$. P2 with L3 is also a multicast packet and travels to $(1,1)_{\rm out}$ and $(2,1)_{\rm out}$. Then P2$'$ with L1 finds the output $(1,1)_{\rm out}$ to be occupied by P2, so P2$'$ goes




(a)




(b)

Fig. 3. Experimental results. (a) BER curves. Left: 10-Gb/s payload; right: 2.5-Gb/s payload. (b) Input and output payload eye diagrams. Time scale: 20 ps/div for 10 Gb/s and 100 ps/div for 2.5 Gb/s.

through contention resolution in the wavelength domain and instead travels to $(1,2)_{\rm out}$, a different wavelength on the same output fiber [4]. The packet sequence then repeats to assist the bit-error rate (BER) measurement.

## IV. Experimental Results and Discussion

Fig. 2 shows the oscilloscope traces of the packet sequences. The outputs are the same as expected indicating that the unicast, multicast, and wavelength-domain contention resolution of the OLS router are working as designed. To ensure that the all-"0" guard time has a low power level at the AWGR output ports after the logic-inverting TWC, the modulators inside the SCM-TXs are biased in the inverting mode. Since the data payloads pass through an odd number of logic-inverting wavelength converters, the final output becomes inverted compared to the input, which is evident from Fig. 2(a). Employing high-performance noninverting mode wavelength converters can solve this problem.

Fig. 3 shows the BER measurement results and the payload eye diagrams. Without retiming, the timing jitter after the router is apparent and the BER curves have a smaller slope with an error floor. A $LiNbO_3$ modulator synchronously driven by a 10-GHz clock serves to carve and to retime the 10-Gb/s signal so that only the center portion of each bit passes [13]. Since the clock has low intrinsic jitter, this method reduces the RMS jitter by about 60%. This demonstration uses a local clock while transparent asynchronous-bit-packet-switching applications will require variable-bit-rate burst-mode clock recovery. The BER curves confirm steeper slopes and lower error floors. Due to the logic inverting wavelength conversion, the switching, and the nonreturn-to-zero–return-to-zero (RZ) format conversion, the measured average signal power level changes even for comparable signal quality. The power penalty directly measured from the BER curves needs corrections. A calculation that takes into account the packet and guard time length assuming infinite extinction ratio and 50% duty cycle for the RZ pulses indicates that the corrected power penalty for P1 and P2 at $(1,1)_{\rm out}$ is $-1.13$ dB, at $(2,1)_{\rm out}$ is $-0.23$ dB; for P1$'$ at $(1,1)_{\rm out}$ is 2.52 dB, P2$'$ at $(1,2)_{\rm out}$ is 2.52 dB. The small or slightly negative power penalty is due to the regeneration effect of the SOA-MZI WC that helps reduce the crosstalk from the label in the original back-to-back signal [14].

## V. Summary

This letter experimentally demonstrates an OLS router architecture that supports limited multicast function at 10 Gb/s. The multicast function employs XPM in an SOA-MZI WC as an MWC. Synchronous modulation in a $LiNbO_3$ modulator provides retiming function to improve output signal quality. The demonstration also shows contention resolution between packets of different packet lengths, data rates, and unicast/multicast requirements.

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