Demonstration of Variable-Length Packet Contention Resolution and Packet Forwarding in an Optical-Label Switching Router

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***Abstract*—This letter presents experimental demonstrations of variable-length optical packet switching with all-optical contention resolution "on the fly" on a packet-by-packet basis by incorporating an optical router controller that examines a packet length field in the optical label. The experimental results show the effectiveness of the contention resolution and indicate error-free operation.**

***Index Terms*—Contention resolution, optical label switching, optical packet switching, optical router, variable-length packet switching.**

I. Introduction

OPTICAL-PACKET switching is an attractive technology geared toward the integration of data and optical networking. The immense bandwidth provided by the optical networking and the capability to switch packets directly at the optical layer make a powerful combination for the next-generation Internet [1] where scalability, agility, and performance are critically important. The early optical-packet switching technologies investigated bit-synchronous, fixed-size packet switching [2]. More recently, Internet protocol (IP)-over-optical has emerged as a novel concept that targets the seamless integration of data and optical networking. The accommodation of variable-length optical packets on all-optical packet switching routers allows IP packets on an all-optical network while avoiding the repeated packet segmentations and reassemblies that are commonly seen in conventional routers. Such unnecessary processing increases not only latency but also router complexity and cost, especially for routers with the switching capacity beyond terabits per second. Previous experimental demonstrations of variable-length optical-packet switching did not engage contention resolution [3], [4]. Contending conditions arise when more than one packet attempts to access the same wavelength of the same output port at overlapping times. For a given traffic matrix on a router, asynchronous, variable-length packet switching causes far more frequent packet-contending conditions than synchronous fixed-length packet switching [5]. To address this issue, a novel contention resolution algorithm that employs wavelength, time, and space domains was designed and simulated for variable-length packet switching and demonstrated for fixed-length packets [6]. This letter demonstrates the optical router controller implementation

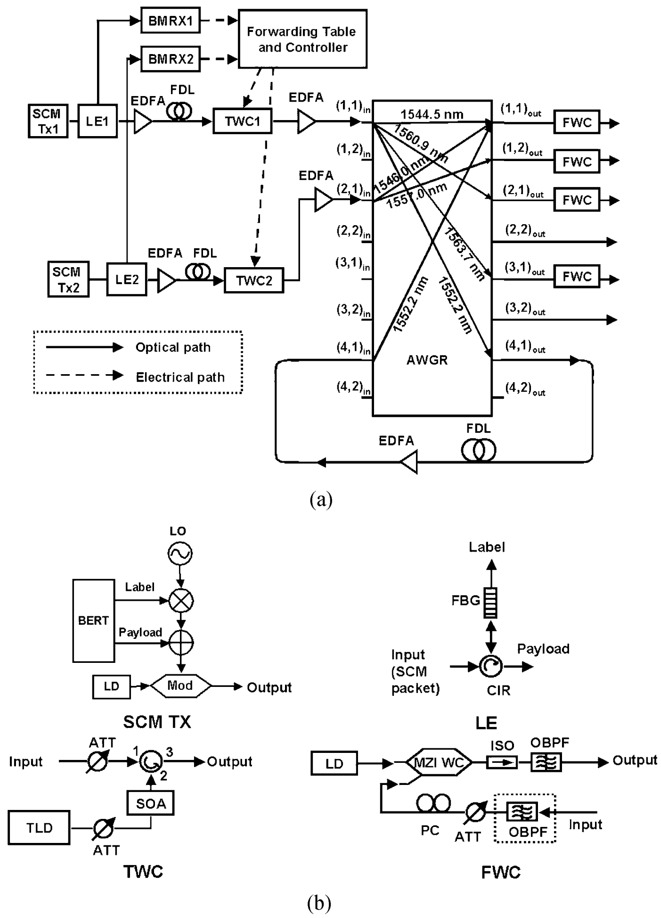

Fig. 1. Simplified experimental setup. (a) OLS router setup. (b) Details of composing modules. LD: laser diode. SCM TX: subcarrier multiplexing transmitter. EDFA: Erbium-doped fiber amplifier. BMRX: burst-mode receiver. FDL: fiber delay line. BERT: BER tester. LO: local oscillator. Mod: modulator. FBG: fiber Bragg grating. CIR: circulator. TLD: tunable laser diode. ATT: attenuator. SOA: semiconductor optical amplifier. MZI WC: Mach–Zehnder interferometer wavelength converter. ISO: isolator. OBPF: optical band-pass filter. PC: polarization controller. In the AWGR, the wavelength values for switching from a certain input to a certain output are shown.

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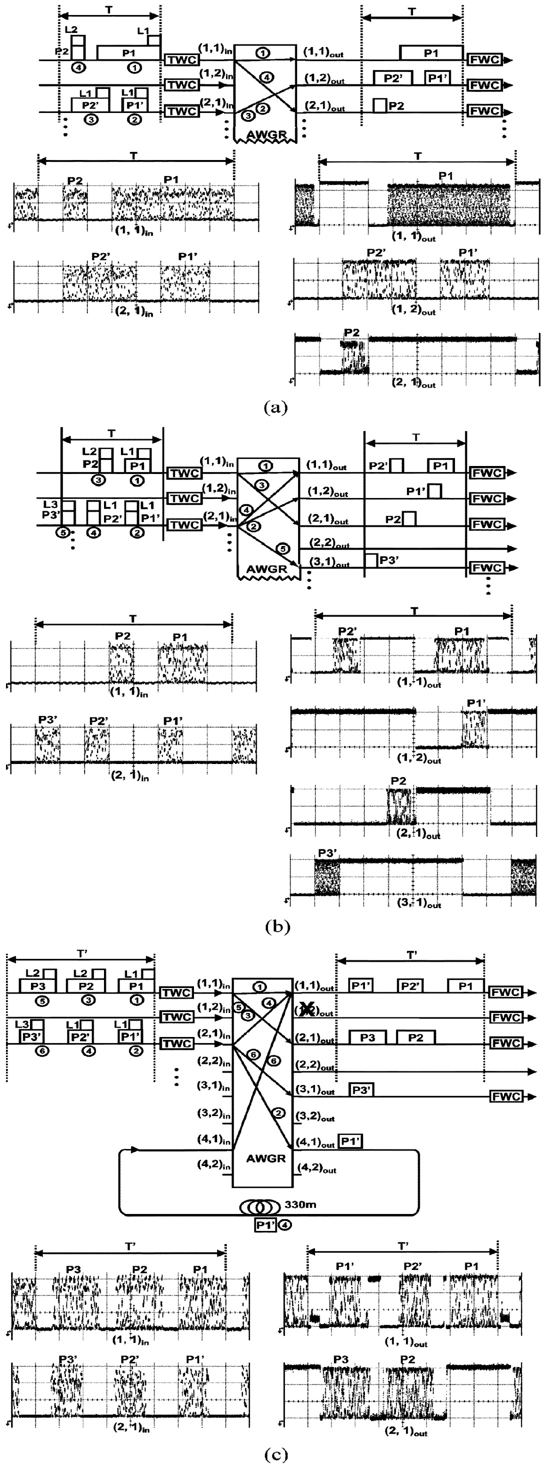

Fig. 2. Timing diagrams and scope traces of packets. (a) Case A. (b) Case B. (c) Case C. The numbers in circles show the order of the packet arrivals as well as the sequence of TWC switching. $T = 1.65\ \mu$s. $T' = 2.48\ \mu$s. In the scope traces, the time axes are pointing to the left. In (a) and (b), the time scale is 206.45 ns/div. In (c), the time scale is 275.27 ns/div. Due to the two inverting wavelength conversions and the switching in between, some sections of guard time appear as artificial one-levels in the scope traces.

and experimental optical packet switching with contention resolution of variable-length packets arriving asynchronously. The technique adopts the optical-label-switching (OLS) technology [7], [8] that provides true interoperability between circuit, packet, and burst switching at the optical layer.

II. Experiment Description

This experiment uses an OLS router test bed to demonstrate contention resolution in the wavelength and time domains. The space domain case is not addressed, as its results would be synonymous with those of the wavelength domain. Fig. 1 illustrates the experimental setup. The switching fabric has four input fibers and four output fibers, each bearing two wavelength channels. For simplicity, multiplexers and demultiplexers are omitted. One of the output channels is looped back to input as a fixed length buffer. $(m, n)_{\rm in}$ and $(m, n)_{\rm out}$ stands for the nth wavelength channel on the mth input and output fiber, respectively. In Fig. 1(a), the subcarrier multiplexing transmitter generates optical packets with 2.5-Gb/s payloads in the baseband and 155-Mb/s labels on the 14-GHz subcarrier. The label extractor (LE) utilizes a fiber Bragg grating as a narrow-band (0.1 nm) filter to separate the label and the payload [9]. The burst-mode receiver recovers the label. The forwarding table and controller makes routing decisions according to the label content and the forwarding table. The worst-case label processing time is approximately 400 ns. The tunable wavelength converter (TWC) converts the payload onto a wavelength that carries it to the designated output port of the arrayed waveguide grating router (AWGR) [10], where it is converted to the wavelength supported on the output fiber by the fixed wavelength converter (FWC). The setting time of 2 ns has been measured for the tunable laser in the TWC switching between two adjacent super modes. We are working on fast switching among all useful wavelength channels. Label rewriting that normally takes place in the final stage [11] is omitted here for simplicity. Fig. 1(b) shows the details of the modules.

The experiment tests three cases: Cases A and B with contention resolution in the wavelength domain, and Case C in the time domain. Fig. 2 shows the timing diagrams as well as scope traces of the packets. Label L_i indicates that the packet desires to reach output fiber i. In Case A, packet P1 from $(1, 1)_{\rm in}$ occupies $(1, 1)_{\rm out}$ while P1' and P2' from $(2, 1)_{\rm in}$ arrive. P1' and P2' cannot access $(1, 1)_{\rm out}$. Instead they reach $(1, 2)_{\rm out}$. This is contention resolution in the wavelength domain, because contending packets are converted to another wavelength on the same output fiber. In Case B, P1 from $(1, 1)_{\rm in}$ is shorter, so contention only occurs with P1'. In Case C, $(1, 2)_{\rm out}$ is occupied at the time of contention, so P1' is switched to $(4, 1)_{\rm out}$, travels through the fixed length buffer, and rejoins the traffic without further contention. This is contention resolution in the time domain, because the contending packet is delayed in time. To facilitate bit-error-rate (BER) measurements, in Cases A and B, the packet sequences repeat with a period of $T = 1.65\ \mu$s; in Case C, the period is $T' = 2.48\ \mu$s.

In the experiment, a field programmable gate array realizes the forwarding table and controller. A previously reported algorithm implements contention resolution in the wavelength, time, and space domains [6]. It is modified to examine the packet length field in the label and to occupy the destination output channel for the corresponding amount of time. The packet length field is a 4-bit value supporting 16 different lengths, four of which are employed here: 512, 1024, 1536, and 2560 bits. The real network may adopt a higher resolution

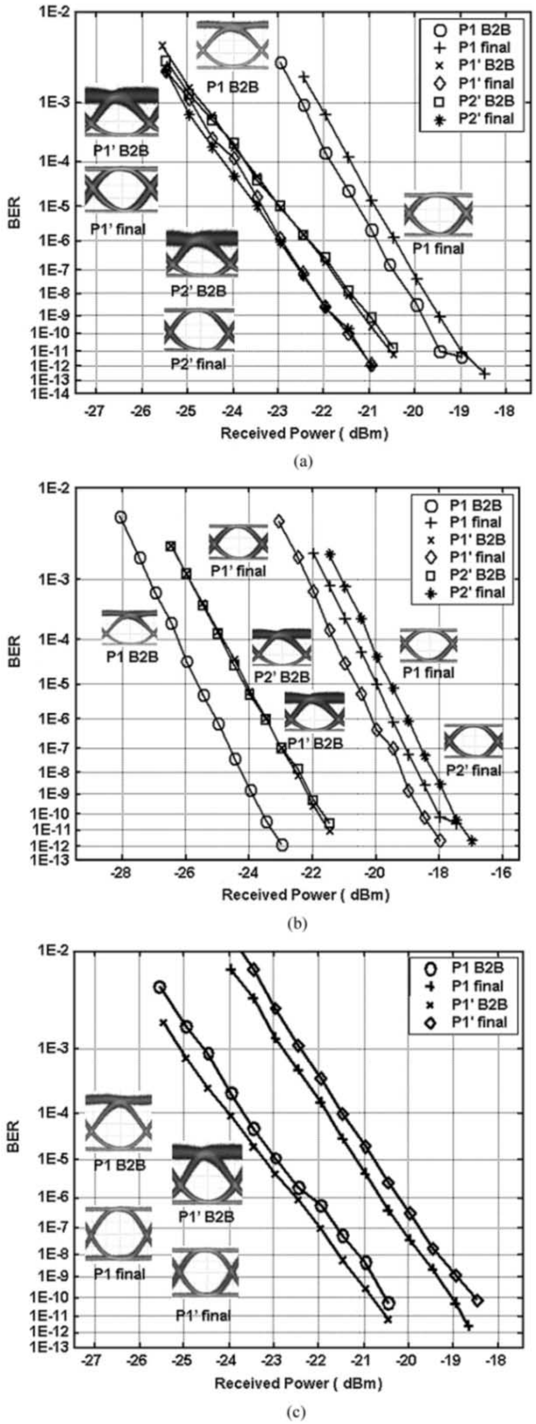

Fig. 3. Experimental results. (a) BER curves and eye diagrams, case A. (b) BER curves and eye diagrams, case B. (c) BER curves and eye diagrams, case C. B2B: back-to-back. The time scale is 100 ps/div for the eye diagrams.

packet length field (e.g., 8 bits) to directly address more diverse packet lengths.

III. Experimental Results

Fig. 3 shows the BER test results and eye diagrams. With $2^{31}-1$ pseudorandom binary sequence, the results show error-free operation. The apparent power penalties are mostly positive. However, they include both the effects of packet switching and of inverting wavelength conversion. Such effects change the average output power even without changing the signal quality. The packet sequence at $(1,1)_{\rm in}$ in Fig. 2(a) provides an example. After an inverting wavelength conversion in the TWC, P2 is switched away. After another inverting wavelength conversion in the FWC, the packet sequence at $(1,1)_{\rm out}$ exhibits "high" power where P2 used to exist. Even if the system does not change the signal quality, the average power of the packet sequence is increased. By including only the power within the packet under investigation for both the back-to-back and the final output, we can obtain the "true power penalties" for the eight packets in the three cases. They range from -1.6 to 1.5 dB, mostly negative. The negative power penalty is a result of the 2R regeneration of the payload in the Mach–Zehnder interferometer wavelength converter, which improves the signal quality [12] and reduces the crosstalk from the residual label imposed on the payload after the LE. The regeneration effects are evident in the eye diagrams in Fig. 3.

IV. Summary

This letter has demonstrated variable-length packet switching with contention resolution in an OLS router. Successful programming of the router controller and switching fabric implementation with 2R regeneration resulted in the experimental demonstration of error-free operation.

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