First Field Trial of OLS Network Testbed with All-Optical Contention Resolution of Asynchronous, Variable-Length Optical Packets

Bo Xiang[1], Zuqing Zhu[1], Haijun Yang[1], Wei Jiang[1], David. L. Harris[2], Katsuya Ikezawa[3], Ryuji Umeda[3], and S. J. Ben Yoo[1]

1: Department of Electrical and Computer Engineering, University of California, Davis, California 95616, USA
Phone: (530)-752-7063, Fax: (530)-752-8428, Email: yoo@ece.ucdavis.edu
2: Advanced Technology Labs, Sprint Nextel, Burlingame, CA 94010, USA
3: Photonics Business Division, Yokogawa Electric Corporation, Tokyo, Japan

Abstract: We demonstrate field trial of asynchronous, variable-length packet contention resolution at data-rate of 10-Gb/s in an OLS network testbed built with in-ground field fiber. Both the lab-test and the field trial results indicate error-free operation.

OCIS codes: (060.4250) Networks, (060.4510) Optical Communications

1. Introduction

Optical-label switching (OLS) is a promising technology for integration of data and optical networking. The immense bandwidth provided by the optical networking and the capabilities to switch packets directly at the optical layer make OLS attractive for the Future Photonic Internet [1,5]. In OLS networks, especially for variable-length packet switching, the key challenge lies in resolving contentions between multiple packets wanting to be forwarded on the same wavelength, on the same output port, at the same time. While there is no viable optical buffering technology available today, all-optical contention resolution has been proved to be very effective in the wavelength, time, and space domains [2,3]. In particular, the wavelength domain contention resolution, not available in conventional electronic routers, is capable of resolving contention with no additional latency or jitter by forwarding the contenting packet to different wavelengths on the same output port fiber. Previous work investigated optical packet-by-packet contention resolution in a controlled environment without fiber transmission [1,4]. Chromatic dispersion, polarization-mode dispersion, and other signal impairment mechanisms in realistic network environments are concerns at 10 Gb/s and above. We demonstrate, for the first time to our knowledge, the variable-length and asynchronous packet contention resolution at 10 Gb/s using a 5-node OLS network testbed with the field fiber plant.

2. Lab Test Experiment

In preparation for the field trial, the experiment was first set up with lab fiber spans. Figure 1(a) shows the experimental setup. At OLS Node 1 and 2, two subcarrier-multiplexed transmitters (SCM-Tx's) generate variable-length, OLS packets with 10 Gb/s payloads at the baseband and 155 Mb/s labels on a 14 GHz subcarrier. These packets will be sent to Node 4 and 5 through Node 3. This will create contention at Node 3 when different input packets are trying to reach the same output port on the same output fiber at the same time. The OLS packets reach Node 3 after lab fiber transmissions, which consist of 60 km large-effective-area fiber (LEAF) and Erbium-doped fiber amplifiers (EDFA's). The chromatic dispersion (CD) of the fiber transmission is compensated with dispersion compensation fiber (DCF). At the input interfaces of Node 3, the label extractors use fiber Bragg gratings (FBG's) to separate the SCM labels and the payloads all-optically. [5] The label burst-mode receivers recover the labels and send them to the switch controller for routing decisions. The switch controller, which is realized by the Field Programmable Gate Array (FPGA), makes contention resolution, arbitration, and forwarding decisions according to the label contents and the internal look-up table, and instructs the tunable lasers (TLD's) to change their wavelengths accordingly [2]. Together with a semiconductor optical amplifier based Mach-Zehnder interferometer (SOA-MZI), the TLD constructs a tunable wavelength converter that can copy the payloads onto wavelengths corresponding to the designated output ports of the arrayed waveguide grating router (AWGR). Meanwhile, the SOA-MZI will introduce all-optical 2R regeneration effect on the payload [1, 4]. Here, $(m,n)_{in}$ in Figure 1(a) represents the nth wavelength on the mth input fiber and the similar definition applies to $(m,n)_{out}$. In the experiment, Node 1 and Node 2 are sending P1 P2 P3 and P1' P2' P3', respectively. The packet lengths of them are: 9216 bits for P1 and P1', 8192 bits for P2 and P2', and 5120 bits for P3 and P3'. For each incoming

©OSA 1-55752-830-6

packet, the switching controller examines the packet length field of the label and occupies the destination output port for the corresponding amount of time. The optical receivers at Node 4 and 5 recover the switched payloads for bit-error-rate (BER) measurements. Figure 1(b) explains the details of the modules in the experimental setup.

Figure 2(a) illustrates packet sequence designed for the lab test. The 1st input fiber connects to node 1 and the 2nd input fiber connects to node 2, while the 1st output fiber connects to node 4 and the 2nd output fiber connects to node 5. P1 from $(1,1)_{in}$ occupies $(1,1)_{out}$ when P1' from $(2,1)_{in}$ arrives. As a result, P1' cannot access $(1,1)_{out}$. The router forwards P1' to $(1,2)_{out}$ instead. When P1 has been forwarded, $(1,1)_{out}$ is released since P2 targets $(2,1)_{out}$. Therefore, P2' is forwarded to $(1,1)_{out}$. When P3 arrives, it also occupies the $(1,1)_{out}$ and then P3' is forwarded to $(1,2)_{out}$ again. Figure 2(a) also shows in the oscilloscope screens measured during the experiment. The router produces the expected results, and the packet contention is successfully resolved with wavelength conversion.

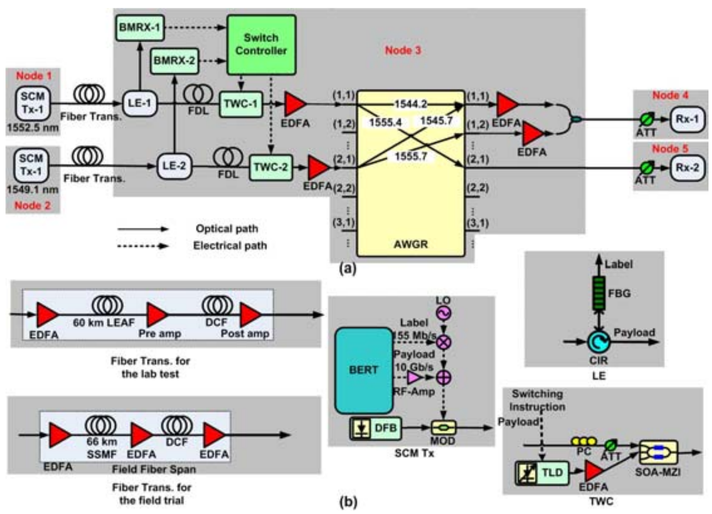

Figure 1 Simplified experimental setup (a) Optical-label switching router setup. (b) Details of the composing modules: TLD: tunable laser diode; SCM Tx: subcarrier multiplexing transmitter; LE: label extractor; EDFA: Erbium doped fiber amplifier; BMRX: burst-mode receiver; LO: local oscillator; DFB: DFB laser diode; BERT: bit-error-rate tester; RF-amp: RF amplifier; MOD: $LiNbO_3$ modulator; TWC: tunable wavelength converter; FDL: fiber delay line; AWGR: arrayed waveguide grating router; Pre amp: pre amplifier; Post amp: post amplifier; ATT: attenuator; SOA-MZI: semiconductor optical amplifier based on Mach-Zehnder interferometer; SSMF: standard single mode fiber; PC: polarization controller; DCF: dispersion compensation fiber; CIR: circulator; FBG: fiber Bragg gratings; RX: optical receiver.

Figure 2(b) and (c) show the BER curves and the eye diagrams for the packets generated at Node 1 and 2, respectively. With $2^{23}-1$ pseudorandom binary sequence (PRBS), all the BER curves reach 10^{-9} and achieve error-free after receiving 10^{12} bits. The power penalties are within 0.5 dB and the receiver sensitivity is –14dBm on average. The wavelength converters achieve optical 2R regeneration therefore the eye diagrams at the output port have cleaner mark- and space-levels relative to the signals just after the fiber transmission.

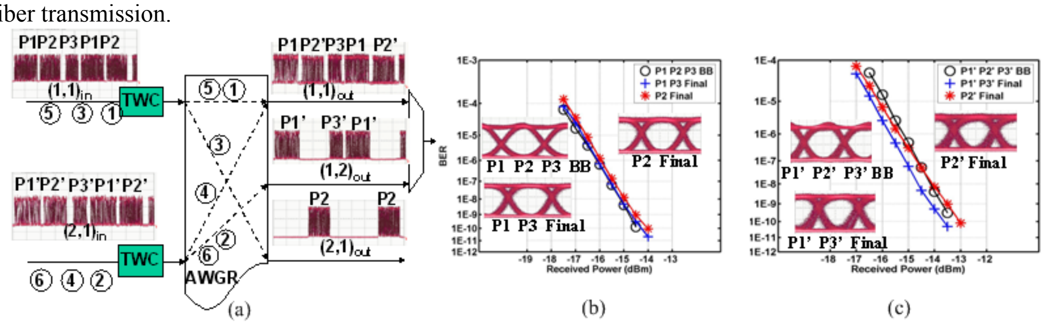

Figure 2 (a) Packet Sequence at the input and output ports (b) BER curves and eye diagrams for the P1 P2 P3 generated at Node 1 (c) BER curves and eye diagrams of the P1' P2' P3' generated at Node 2

3. Field Trial Experiment

A field trial experiment is then set up with a similar configuration, but replaces the lab fiber spans with in-ground field fiber spans and also replaces a standard optoelectronic converter with a 10 Gb/s burst-mode receiver. Figure 3 shows the characteristics of the field fiber. The building block of the field fiber transmission is defined as one field fiber span. As shown in Figure 3(a), each field fiber span, which is consisted of 66 km (2 × 33 km) SSMF (standard single mode fiber), runs from Burlingame to Palo Alto and loops back. Figure 3(b) illustrates the setup of each field fiber span. There is a two-stage EDFA and DCF located at Burlingame to compensate for the loss and the CD of the field fiber transmission, but unable to compensate for polarization mode dispersion at ~7 psec. Figure 3(c) shows the OSNR evolution through multiple field fiber spans. Node 1 and 2 are connected to Node 3 by 132 km (2 spans) and 66 km (1 span), respectively.

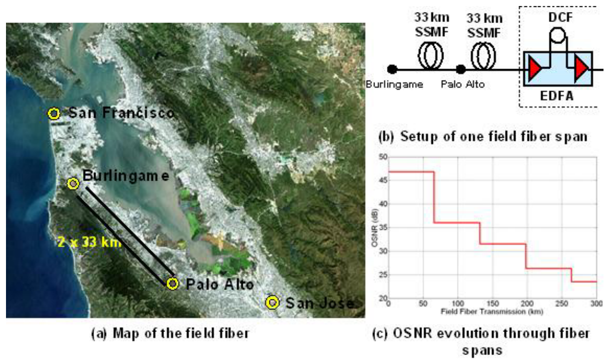

Figure 3 Characteristics of the field fiber plant (a) Map of the field fiber (b) setup of one of the field fiber span, SSMF: standard single-mode-fiber; DCF: dispersion compensated fiber; EDFA: Erbium doped fiber amplifier

Figure 4(a) shows the packet sequence at the input and output ports of the OLS router with expected results. A commercially available 10 Gb/s burst-mode receiver (Yokogawa 10Gbps Burst-mode CDR) helps recover the packetized payload data for BER measurements. The BER curves and eye diagrams of the packets generated at Node 1 and 2 are in Figure 4(b) and (c), respectively. Similar to the lab test results, we achieve error-free operation when use $2^{23} - 1$ PRBS in the BER measurements. The BER power penalties are within 1 dB.

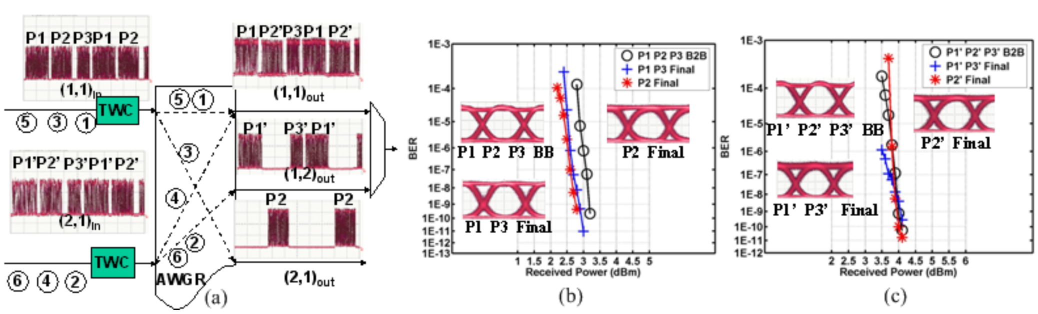

Figure 4 results of field trial experiment (a) packet sequence at the input and output ports (b) BER curves and eye diagrams of packets generated at Node 1 (c) BER curves and eye diagrams of packets generated at Node 2

4. Summary

This paper demonstrated asynchronous, variable-length packet switching at the data rate of 10 Gb/s with contention resolution in an OLS network testbed. For the first time, the 10 Gb/s OLS experimental demonstration incorporated in-ground field fiber, and both the lab test and the field trial results indicated error-free operation of the variable-length packet contention resolution.

5. References

[1] Z. Pan, et al., *IEEE Photon. Technol. Lett.*, vol. 16, pp. 1772-1774, Jul. 2004
[2] F. Xue, et al., *J. Lightwave Technol.*, vol. 22, pp. 2570-2581, Nov. 2004
[3] S. Yao, et al., *J. Lightwave Technol.,* vol. 21, pp. 672-683, Mar. 2003
[4] Z. Pan, et al., *IEEE Photon. Technol. Lett.*, vol. 15, pp 1312-1314 Sept. 2003
[5] H. J. Lee, et al., *IEEE Photon. Technol. Lett.,* vol. 13, pp 635- 637, 2001
[6] B. Hui, et al., *Tech. Dig. OFC/IOOC'99*, vol. 3, pp. 231-233, Feb. 1999