

# Experimental demonstration of variable-size packet contention resolution and switching in an optical-label switching router

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**Abstract:** This paper discusses experimental demonstrations of variable-size optical packet switching with optical contention resolution, utilizing a packet length field in the optical label. The experiment achieves error-free operation and negative power penalty.

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## 1. Introduction

Optical-packet switching is an attractive technology geared towards 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 are a powerful combination for the Next Generation Internet where scalability, agility and performance are important considerations. The early optical-packet switching technologies investigated bit-synchronous, fixed-size packet switching. More recently, IP-over-optical emerged as a novel concept targeting seamless integration of data and optical networking [1]. Accommodating variable-size optical packets on all-optical packet switching routers allows natural IP packets on an all-optical network without repeated packet segmentations and reassemblies commonly seen in conventional routers today. Such unnecessary processing increases not only the latency but also the complexity and the cost of the router, especially when the switching capacity beyond terabits-per-second is considered. In the optical-packet switching, the main challenge, especially for variable-packet-size switching, lies in contention resolution, which occurs when more than one packet attempts to access the same output port on the same wavelength at the same time. For a given traffic matrix, asynchronous and variable-size packet switching in routers cause far more frequent packet-contending conditions than synchronous and fixed-size packet switching [2]. A novel contention resolution algorithm employing wavelength, time, and space domain has been designed and simulated for variable size packet switching and demonstrated for fixed size packets [3]. This paper demonstrates the optical router controller implementation and experimental optical packet switching with contention resolution of variable-size packets arriving asynchronously. The technique adopts the optical-label switching (OLS) technology [4,5] that provides true interoperability between circuit, packet, and burst switching at the optical layer.

## 2. Experiment description

In this demonstration the OLS router resolves contention resolution in the wavelength domain. Fig. 1 shows the experimental setup. The router has four input fibers and four output fibers. Each fiber has two wavelength channels.  $(m, n)_m$  stands for the  $m$ th wavelength channel on the  $m$ th input fiber. A similar definition applies for the output  $(m, n)_{out}$ . 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) separates the label and the payload utilizing a fiber Bragg grating as a narrow-band (0.1 nm) filter [6]. The burst-mode receiver recovers the label. The forwarding table and controller makes routing decisions according to the label content and the forwarding table. It controls the tunable wavelength converter (TWC) to convert the payload onto a wavelength that carries the payload to the designated output port of the arrayed-grating waveguide router (AWGR) [7]. The fixed wavelength converter (FWC) at the output of the AWGR converts the payload back to the wavelength supported on the output fiber. Label rewriting that occurs at the final stage is ignored for simplicity in this experiment. Fig. 1(b) shows the details of the modules.

The experiment tests two cases. Fig. 2 shows the timing diagrams. A packet with label  $L_i$  desires to reach output fiber  $i$ . In case A packet  $P_1$  from  $(1, 1)_m$  occupies  $(1, 1)_{out}$  while  $P_1'$  and  $P_2'$  from  $(2, 1)_m$  arrive. As a result,  $P_1'$  and  $P_2'$  can not access  $(1, 1)_{out}$ . Instead they reach  $(1, 2)_{out}$  on the same output fiber. This is called contention resolution in the wavelength domain because the contending packets are converted to another wavelength on the

same output fiber. In case B, as a comparison, P1 from  $(1, 1)_{in}$  is shorter, so contention only happens to P1'. In both cases the designed packet sequences repeat with a period of  $T = 1.65 \mu s$  to facilitate bit error rate (BER) measurements.

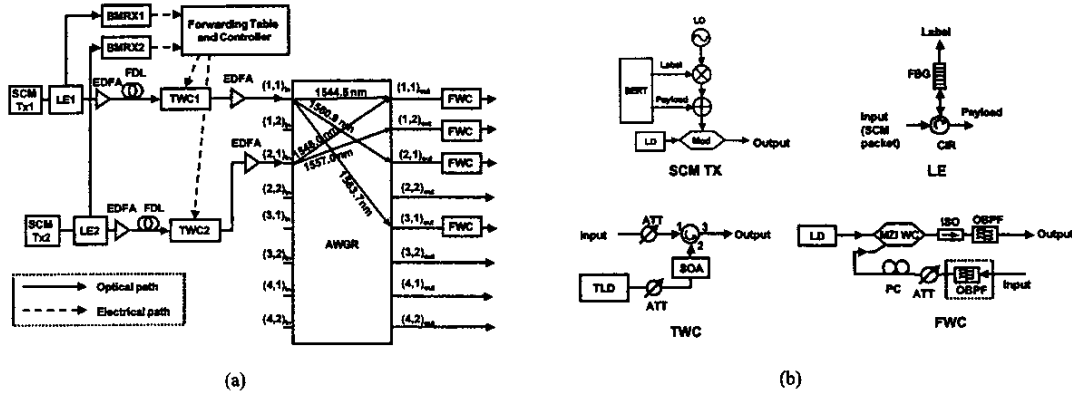


Fig. 1. Simplified experimental setup. (a) Optical-label switching router setup. (b) Details of composing modules. LD: laser diode; SCM TX: subcarrier multiplexing transmitter; LE: label extractor; EDFA: Erbium doped fiber amplifier; BMRX: burst-mode receiver; FDL: fiber delay line; TWC: tunable wavelength converter; AWGR: arrayed waveguide grating router; FWC: fixed wavelength converter; BERT: bit-error rate 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 to switch from a certain input to a certain output are shown.

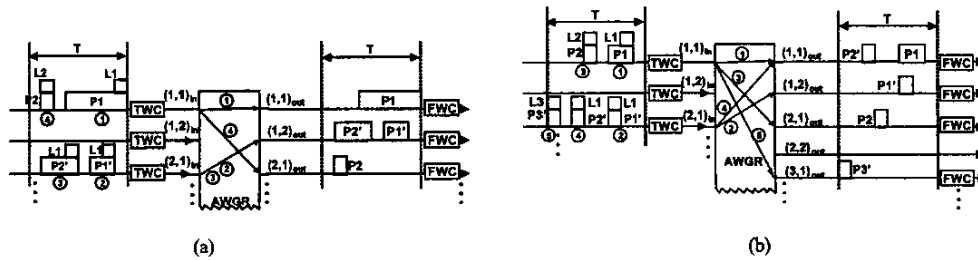


Fig. 2. Timing diagrams. (a) Case A. (b) Case B. TWC: tunable wavelength converter; FWC: fixed wavelength converter; AWGR: arrayed waveguide grating router. The numbers in circles show the order of the packet arrivals as well as the sequence of TWC switching.  $T = 1.65 \mu s$ . Processing and propagation delays are ignored.

In the experiment a Field Programmable Gate Array realizes the function of the forwarding table and controller. A previously reported algorithm implements contention resolution in the wavelength, time and space domain [3]. The algorithm examines the packet length field in the label, and occupies the destination output channel for the corresponding amount of time. The packet length field is a 4-bit value supporting 16 different lengths. This experiment employs 4 of them: 512 bits, 1024 bits, 1536 bits and 2560 bits.

### 3. Experimental results

Fig. 3 shows the experimental results. Fig. 3(a) and (b) show the packet sequences at the input and output ports. Due to the two inverting wavelength conversions in the TWC and FWC and the switching in the AWGR, some sections of guard time appear as an artifact 1-level in the oscilloscope traces. Fig. 3(c) and (d) show the BER test results and eye diagrams. The bit sequence is  $2^{31}-1$  PRBS. The result shows error-free operation. For case A, the apparent power penalty measured at the BER of  $10^{-9}$  is 0.4 dB, -0.7 dB and -0.8 dB for P1, P1' and P2', respectively. In case B, the apparent power penalty is 5.6 dB, 3.4 dB and 4.4 dB for P1, P1' and P2', respectively. The apparent power penalty includes effects due to switching and logic inversions by the wavelength conversion that give rise to changes in the measured average power not related to signal impairments or improvements. By excluding such influences, an approximate calculation shows the corrected "true system penalty" ranging from -0.5 to -2 dB for each case. The negative power penalty is a combined result of two counteracting effects. One is the crosstalk from the label that degrades the back-to-back payload measured after the LE, and the other the 2R regeneration of the

payload by cross-phase modulation in Mach-Zehnder interferometer wavelength converter, which improves the signal quality of the final outputs [8]. This is also evident from the eye diagrams in Fig. 3(c) and (d).

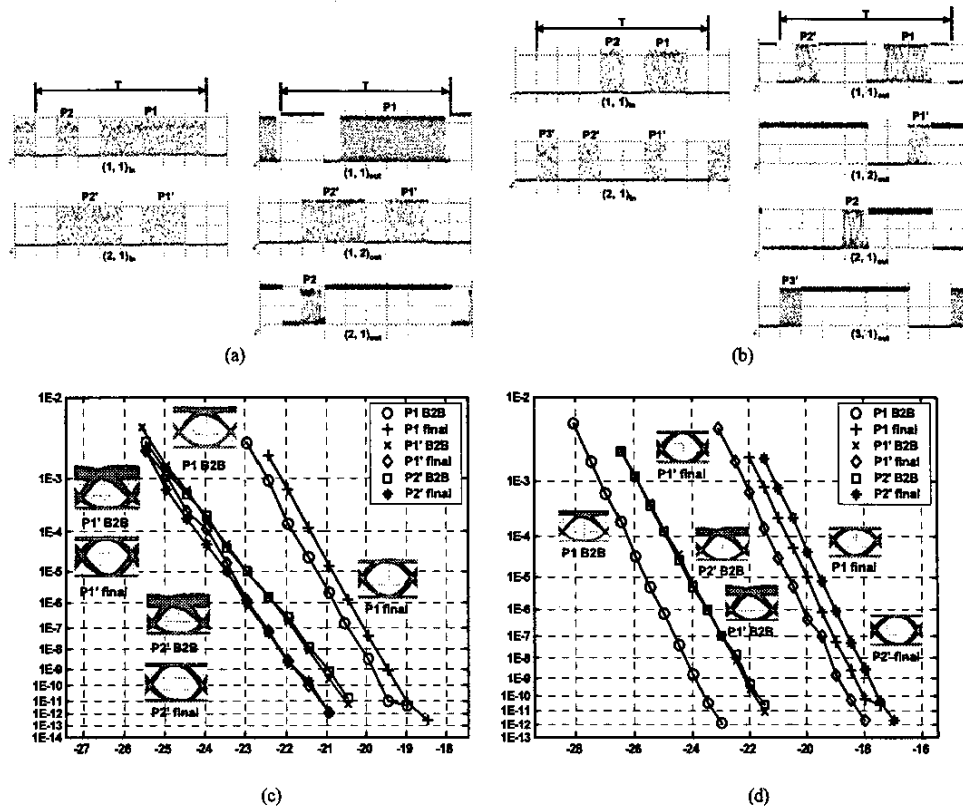


Fig. 3 Experimental results. (a) Packet sequences on oscilloscope, case A. (b) Packet sequences on oscilloscope, case B. (c) BER curves and eye diagrams, case A. (d) BER curves and eye diagrams, case B. B2B: back-to-back. To facilitate the comparison with Fig. 2, the time axes in (a) and (b) are pointing to the left. The time scale is 206.45 ns/div in (a) and (b), and 100 ps/div for the eye diagrams in (c) and (d).

#### 4. Summary

This paper demonstrated variable-size packet switching with contention resolution in an optical-label switching router. Successful programming of the router controller and switching fabric implementation with 2R regeneration resulted in experimental demonstration of error-free operation with negative power penalty.

#### 5. References

- [1] DARPA BAA 98-02 Next generation internet, [http://www.darpa.mil/ipto/Solicitations/CBD\\_9802.html](http://www.darpa.mil/ipto/Solicitations/CBD_9802.html)
- [2] S. Yao, *et al.*, "Electrical ingress buffering and traffic aggregation for optical packet switching and their effect on TCP-level performance in optical mesh networks," *IEEE Commun. Mag.*, vol. 40, no. 9, pp. 66-72 (2002).
- [3] S.J.B. Yoo, *et al.*, "Optical-label based packet routing system with contention resolution in wavelength, time and space domains," *Optical Fiber Communication Conference*, Anaheim, California, paper WO2 (2002).
- [4] S.J.B. Yoo, G.K. Chang, *High-Throughput, Low-Latency Next Generation Internet Using Optical Tag Switching*, in *U. S. Patent 6,111,673*. 1997, Bellcore: U. S. A.
- [5] B. Meagher, *et al.*, "Design and implementation of ultra-low latency optical label switching for packet-switched WDM networks," *J. of Light. Tech.*, vol. 18, no. 12, pp. 1978-87 (2000).
- [6] Hyuek Jae Lee, *et al.*, "A simple all-optical label detection and swapping technique incorporating a fiber Bragg grating filter," *IEEE Phot. Tech. Lett.*, vol. 13, no. 6, pp. 635-7 (2001).
- [7] S. J. B. Yoo, *et al.*, "Optical-label switching and routing by rapidly tunable wavelength conversion and uniform loss cyclic frequency array-waveguide grating," *Optical Fiber Communication Conference*, Anaheim, California, paper WDD49 (2001).
- [8] T. Gyselings, G. Morthier and R. Baets, "Strong improvement in optical signal regeneration and noise reduction through asymmetric biasing of Mach-Zehnder interferometer all optical wavelength converters", in *Proceeding of ECOC'97*, pp. 188-191 (1997).

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