Time-Stacked Optical Labels: An Alternative to Label-Swapping

Pegah Seddighian[1], Yousra BenM'Sallem[1], Alberto Leon-Garcia[2], and Leslie A. Rusch[1]
[1]*Centre d'Optique Photonique et Laser (COPL), ECE Dept., Université Laval, Québec, QC G1V 0A6, Canada*
[2]*Department of Electrical and Computer Engineering, University of Toronto, Toronto, Canada*
rusch@gel.ulaval.ca

Abstract: We propose a simple, practical approach to eliminate complex label-swapping in label-switched networks: time-stacked multi-wavelength labels. We demonstrate experimentally a two-hop optical network and measure BER performance. Label processing is achieved with low-complexity, off-the-shelf commercial components.

OCIS codes: (060.4250) Networks; (060.4510) Optical communications

1. Introduction

Optical packet switching has emerged recently to reduce the number of layers of the current protocol stack to two levels: IP over optical. High speed packet transmission over the optical domain can be achieved by label switching techniques; a short label decreases the header recognition latency [1]. At each node the label is replaced with a new value to be used for forwarding at the next hop, a process called label-swapping. Optical label-swapping for various label formats has been reported in the literature [2,3,4]. For instance, we have recently demonstrated all-optical label-swapping of multi-wavelength labels using semiconductor fiber ring lasers [4]. However, *tunable* label swappers, as well as the optical processing to determine the appropriate new label are complex.

In this paper, we propose to avoid label-swapping, and instead transmit all the labels required for the entire optical route end-to-end. Our objective is to move the complex table-look-up processing toward the smart electrical edge nodes, and benefit from a simple, practical, economical, and ultra-fast optical backbone. In our scheme, the path from the source to the destination on the optical domain is determined at the edge nodes, and accordingly, all the labels required for the intermediate hops are attached to the packets in non-overlapping time slots (Fig. 1a). At each hop, the leading label in the stack is used for forwarding and is removed when leaving the node; the remaining labels are pushed ahead one label interval (Fig. 1b,c).

We use multi-wavelength labels due to their potential for high-speed packet forwarding with low-complexity hardware [5]. One advantages of this technique is fixed label power loss at each node, as opposed to the correlation based techniques where the loss scales with the number of labels [6]. Furthermore, the network is scalable due to the rich set of labels and also the structure of the forwarding module using a multi-stage switch. The label processing requires only simple and low-speed electronic hardware for forwarding multi-rate and variable-length payloads.

We demonstrate the proof of the concept by routing optical packets with two time-stacked labels over a 2-hop network. A 1×4 two-stage switch with tree-like connectivity has been implemented. The payload data rate is 10 Gbps, due to the availability of test equipment, and can be easily scaled up to 40 Gbps or higher. Low-cost and commercially-available components are used to implement the system. The error free transmission confirms the outstanding performance of the proposed structure.

2. Packet format and network structure

In our proposed scheme, the packets arriving from legacy electrical networks are processed at the edge nodes where a routing algorithm determines the path through the optical domain. At the same node, the electrical packet is

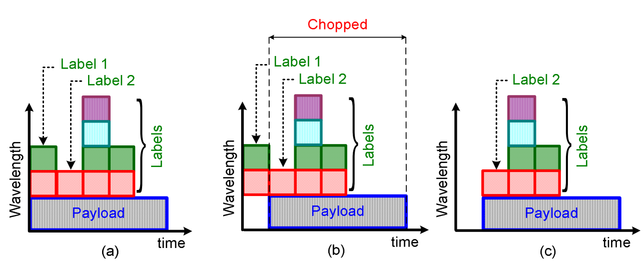

Fig 1. Optical packet (a) with time-stacked multi-wavelength labels, (b) in the first transit node where the payload is time aligned with label 2, and (c) at the output of the first transit node where label 1 is removed and label 2 leads the label stack.

converted to the payload of the optical packet, and all the labels required for forwarding throughout the transit nodes are added to the payload. We use orthogonal wavebands for the labels and payload; therefore, no time-overhead is added to the packets for the labels. The labels are transmitted in fixed-length time slots in chronological order; that is, the first label is used at the first hop and so on. The packet duration is greater than or equal to the number of labels in a stack times the slot interval. At each hop the corresponding label is removed from the stack and is used for routing; the rest of the labels are pushed ahead one time-slot. This is achieved by separating the payload and labels, delaying the payload for one time slot, adding the labels to the payload (Fig. 1b), and finally time gating the recoupled signal over the payload interval (Fig. 1c).

The labels are encoded using bit-parallel multi-wavelength approach where 1/0 state of a bit turns on/off the related wavelength channels [5]. In this approach L wavelengths are required for a label with L bits; 2^L different labels can be composed.

At the intermediate node of the optical network, the payload is switched without being processed. Therefore, the system is transparent to the bit rate and the format of the payload. The switch fabric has a self-routing multistage architecture with tree interconnections. An $N \times N$ switch is constructed from $N(N-1)$ 1×2 switching elements. The multistage switch has the advantage of scalability, i.e., the switch dimension can be easily enlarged by increasing the number of stages. Label extraction is accomplished by passive optical filtering. An arrayed waveguide grating (AWG) separates the label wavelengths, each controlling one switch stage, and automatically directs the packet to the proper output port [5].

3. Experimental setup

The experimental setup consists of a packet generator and a forwarding node as illustrated in Fig. 2. The optical packets contain two time-stacked labels, each label has two bits, i.e., two wavelengths. The first label contains routing information for the first hop. After successful routing, our setup recirculates the packet back to the input of the node. At this point, the second label will be processed to route the packet through its second hop. The bit error rate (BER) is measured after the packet generator, hop 1 and hop 2 to evaluate the performance of the switching structure.

In Fig. 2, we generate packets of length 150 ns every 750 ns. Two directly modulated DFB lasers at λ_1=1549.43 nm and λ_2=1549.85 nm are used for the labels. The lasers are driven by programmable waveform generators to form time-stacked labels of length 50 ns. Label 1 and label 2 are [λ_2, λ_1]=[1,1] and [λ_2, λ_1]=[1,0] respectively, which correspond to output 4 and 3 of the switch (Fig. 3a). The payload contains 1500 bits of 2^{11}-1 PRBS data at 10 Gbps, generated by externally modulating a laser at 1552.25 nm. At the forwarding node, the labels and payload are separated by a band-reject filter which reflects the labels and transmits the payload. The band-reject filter is implemented by a fiber Bragg grating (FBG) with insertion loss of 2 dB, 3 dB bandwidth of 3.6 nm, and reflectivity of ~99.9%. The payload is delayed (FDL1) for a label interval (50 ns) and is split by coupler 3; the signal on the upper arm is sent to an envelope detector (ED) and the signal on the lower arm, now delayed by one label time slot, is re-coupled with the labels (see Fig. 1b). The envelope detector output is used as a control signal to drive a 1×2 optical switch (SW 1). The delay following coupler 4 is selected to ensure that the ED control signal cleanly slices the top-of-the-stack label and switches it to output 1 of SW 1, while the payload and newly shifted stack is switched to output 2. The label (output 1 of SW 1) is sent to an AWG to separate the label bits. The AWG has 16

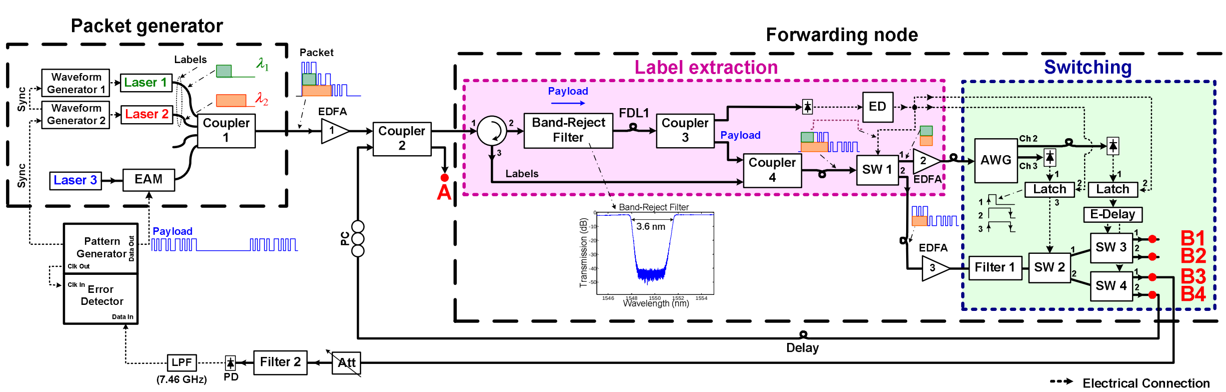

Fig. 2. Experimental setup of the packet switching network with time-stacked multi-wavelength labels; EAM: electro absorption modulator, EDFA: Erbium doped fiber amplifier, FDL: fiber delay line, ED: envelope detector, SW: 1×2 switch, AWG: arrayed waveguide grating, PC: polarization controller, Att: variable attenuator, PD: photodiode, LPF: low-pass filter.

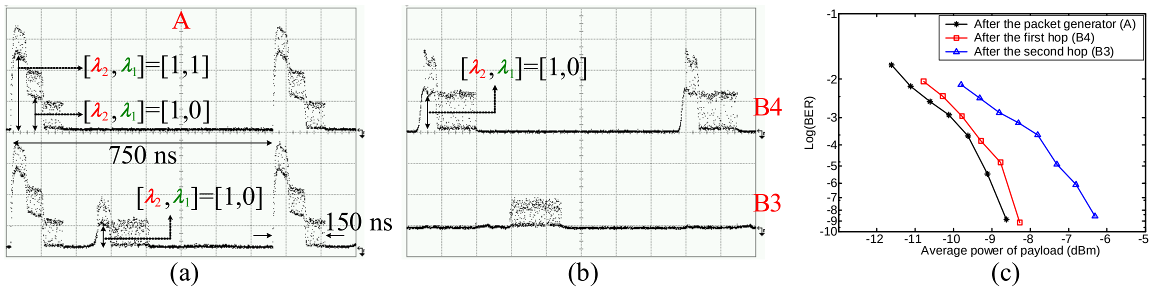

Fig. 3. Oscilloscope traces of (a) point A and (b) point B3 and B4 of Fig. 2. (c) BER versus the average power of payload for points A, B3, and B4 of Fig. 2.

channels with 50 GHz channel spacing and 8 dB insertion loss. The label channels trigger an electronic latch whose other input is connected to the ED control signal. The latch is triggered by the rising edge of the label and holds until the falling edge of the envelope (Fig. 2). Therefore, the latch generates a control signal with the same width as the packet, whenever the label bit is present. This signal sets the state of the switching elements. Three 1×2 switching elements (SW 2, 3, and 4) form a 1×4 tree switch. The switching elements direct the input to the upper/lower output when the control signal is OFF/ON. The time alignment between the incoming packet and the control signals is achieved by fiber delay lines and a fixed electronic delay (E-Delay). Filter 1 (1.2 nm) is used to remove the amplified spontaneous emission (ASE) of the optical amplifiers.

The packet is self-routed to output 4 by label 1 ([1,1]) and is recirculated to the input for the second hop. Next, label 2 ([1,0]) forwards the packet to output 3. We measure the BER of 1280 bits in the middle of the payload, after the packet generator, the first and the second hop. Filter 2 (0.2 nm) is used to remove the ASE of the optical amplifiers. An electrical low-pass filter (7.46 GHz) after the photodiode removes out-of-band noise.

4. Results and discussion

The oscilloscope traces of the packets at different points of the setup (Fig. 2) are illustrated in Fig. 3a and 3b. The upper trace in Fig. 3a shows the packets after the packet generator (point A of the setup), i.e., when the lower arm of coupler 2 is disconnected; the packets contain two time-stacked labels. In the lower trace, the lower arm of coupler 2 recirculates the successfully routed packets for the second hop. Label 1 is removed from the routed packet, and label 2 is moved up in the stack. The upper (lower) trace of Fig. 3b demonstrates the packets after being switched for the first (second) time, that is, point B4 (B3) of the setup. The upper packet contains label 2, which is used for the second hop and is ultimately removed from the stack, as shown in the lower trace.

We measure the BER versus the average optical received power of the payload at points A, B3 and B4 of the setup. As illustrated in Fig. 3c, the performance degradation after switching is low, confirmed with the low power penalty between point A and B4. The 2 dB power penalty between hop 1 (B4) and hop 2 (B3) is due to the recirculating loop, which accumulates intensity noise between the first routed payload and the leakage from the electro-absorption modulator (EAM with 11 dB extinction ratio) during the silent period between packets. The polarization controller before coupler 2 is used to reduce the intensity noise.

5. Conclusions

We demonstrated time-stacking of multi-wavelength labels which can be used as an alternative to label swapping, alleviating node hardware complexity. We verified the performance of the proposal architecture by implementing a 1×4 forwarding node and 2-hop network that routed optical packets with two time-stacked labels. Label processing is achieved with low-complexity, off-the-shelf commercial components.

6. References

[1] S. J. Ben Yoo, "Optical packet and burst switching technologies for the future photonic Internet," *J. Lightwave Technol.*, **24**, 4468-4492, (2006).

[2] Z. Zhu, Z. Pan, and S. J. B. Yoo, "A compact all-optical subcarrier label-swapping system using an integrated EML for 10-Gb/s optical label-switching networks," *Photon. Technol. Lett.*, **17**, 426-428, (2005).

[3] K. Kitayama, N. Wada, and H. Sotobayashi, "Architectural considerations of photonic IP router based upon optical code correlation," *J. Lightwave Tech.*, **18**, 183-1844, (2000).

[4] P. Seddighian, *et al.,* "All-optical swapping of spectral amplitude code labels for packet switching," *Photonics in Switching Conference*, (2007).

[5] P. Seddighian, *et al*, "Low-cost, scalable optical packet switching networks with multi-wavelength labels," *OFC'07,* (2007).

[6] P. Seddighian, *et al*, "Label stacking in photonic packet switched networks with spectral amplitude code labels," *J. Lightwave Technol.*, **25**, 463-471, (2007).