All-Optical Label Swapping of 160 Gb/s Data Packets Employing Optical Processing of Scalable In-Band Address Labels

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ABSTRACT
Scalability of packet switched cross-connects that utilize all-optical signal processing is a crucial issue that eventually determines the future role of photonic signal processing in optical networks. We present a 1x4 all-optical packet switch based on label swapping technique that utilizes a scalable and asynchronous label processor and label rewriter. The packet address information is encoded by in-band labels. With this we mean that the wavelengths of the labels are chosen within the bandwidth of the payload. We encode addresses by combining different labels. Thus, by using $N$ in-band label wavelengths, $2^N$ possible addresses can be encoded, which makes this labelling technique highly scalable within a limited bandwidth. Experimental results showed error-free packet switching operation at 160 Gb/s, while the label erasing and new label insertion operation introduces only 0.5 dB of power penalty. Those results indicate a potential utilization of the presented technique in a multi-hops packet switched network.

Keywords: optical packet switching, optical signal processing, label processor, wavelength converter, semiconductor optical amplifier.

1. INTRODUCTION
Boosted by the high capacity request of the emerging FTTx technology, future all-optical metro and core networks should be capable to handle Tb/s data traffic. Current networks are based on electronic circuit switching technology that has fundamental limits due to the scalability of multi-racks electronic switching fabrics and power consumption required by the optoelectronic conversions [1, 2].

All-optical packet switching has been proposed as a technology to solve the bottleneck between the fibre bandwidth and the electronic router capacity by exploiting ultra-high speed and parallel operation of all-optical signal processing. Moreover, photonic integration of the optical sub-systems potentially allows a reduction of volume and power consumption. In an all-optical packet switch the packets are routed based on address information that is encoded by attached labels. In [3] a 1x2 all-optical packet switch is demonstrated, that employs a single in-band optical label. The processed label is stored by an optical flip-flop and the packet is routed by a wavelength converter. However, a key-issue is the implementation of a highly scalable label processing technique. Here, we present a 1x4 optical packet switch that employs a label processor that is highly scalable.

For a practical implementation of a packet switched cross-connect node, a key issue is that building up a large optical packet switched cross-connect out of 1x2 optical packet switches requires a large number of packet switches. For instance, in a WDM switching node that has 16 input and 16 output fibres that each carry 16 wavelength channels one needs 16x16 = 256 1x2 packet switches per input fibre. This brings the total number of 1x2 packet switches for the entire switching node to 4096. If the node however contains 32 input fibres and 32 output fibres carrying each 32 wavelength channels, the number of packet switches increases to 32768. If one succeeds however to realize a 1xN optical packet switch, the number of switches required in a node can be drastically reduced. Suppose that a 1x16 optical packet switch exists, a node that consists out of 16 input and 16 output fibres that carry each 16 wavelengths can be built-up out of 256 packet switches. To realize a 1xN optical packet switch, it is essential to process N labels in parallel. Moreover, to further improve the scalability and power consumption of the OPS node by decreasing the amount of active components, label swapping technique should be implemented in the packet switch configuration [1]. This will ask for a label erasing/rewriting function. Furthermore, it is highly desirable that the label swapping operation could be asynchronous, so that the packet switch does not require any additional external synchronization of packets.

Here, we present an all-optical 1x4 packet switch including the label erasing/processing and a label rewriting function to accomplish the label swapping. Moreover, cascadability of the packet switch is investigated in two-cascaded nodes configuration.

2. SYSTEM OPERATION
Figure 1 shows the two cascaded node system to investigate the label erasing/re-inserting performance. Node 1 contains the 1x4 packet switch based on label swapping technique, while in Node2 the inserted label is extracted by the label extractor and the switched payload is evaluated. The input packets consist of a 160 Gb/s payload at
\( \lambda_p = 1553.8 \text{ nm} \), with bit duration of 1.6 ps making the 20 dB bandwidth of the payload to be 5 nm. The packet has duration of 250 ns and the guard time is 10 ns. The packet address information is encoded by in-band labels. With this we mean that the wavelengths of the labels are chosen within the bandwidth of the payload. We encode addresses by combining different labels. Thus, by using \( N \) in-band label wavelengths, \( 2^N \) possible addresses can be encoded, which makes this labeling technique highly scalable within a limited bandwidth.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Experimental set-up. At the bottom, the label swapping table and corresponding wavelengths.}
\end{figure}

The advantage of the in-band labeling is that the labels can be extracted by passive wavelength filtering, and using a label that has the same time-duration as the payload makes the use of optical flip-flops redundant. In the experiment, we encode 4 addresses by using two in-band labels at \( \lambda_{L_1} = 1551.9 \text{ nm} \) and \( \lambda_{L_2} = 1552.5 \text{ nm} \). The labels are within the 20-dB optical bandwidth of the packet-payload spectrum. The 1x4 all-optical packet switch based on wavelength routing technique consists of a label extractor/eraser, a label processor, a label rewriter and a wavelength converter. The input packet is firstly processed by the label extractor/eraser, which consists of two fiber Bragg gratings (FBG) with a 3 dB bandwidth of 0.12 nm and 0.43 nm at \( \lambda_{L_1} \) and \( \lambda_{L_2} \), respectively. While the data payload passes through the label extractor/eraser, the labels are taken (reflected) out by the FBGs. The separated packet-payload enters the wavelength converter and is converted at the control signal wavelength provided by the label processor.

The optical power of the extracted labels are split and fed into the label processor and the label rewriter. The label processor was demonstrated in [4]. In brief, the label processor is made of two MZI-SOAs, which act as fast wavelength selective switches that are optically controlled by the value of the labels. As shown in Figure 1, CW signals at (\( \lambda_1, \lambda_2 \)) and (\( \lambda_3, \lambda_4 \)) are applied to port 1 and 2 of the MZI-SOA1, respectively. If no label at \( \lambda_{L_1} \) is present, signals (\( \lambda_3, \lambda_4 \)) appear at the MZI-SOA1 output. However, if there is the label (\( \lambda_{L_1} \)), signals (\( \lambda_1, \lambda_2 \)) exit MZI-SOA1. The AWG and the 2x1 couplers are used to separate the pair of CW-signals and coupled them into different input ports of MZI-SOA2. Thus, according to the label value (\( \lambda_{L_2} \)) only one signal at distinct wavelength is selected by the label processor. This signal represents the control signal to which the payload will be converted.

The label rewriter is based on the same principle of operation of the label processor. In this case the CW-signals represent the new labels. The wavelengths of the CW-signals are set to be in-band with the switched payload (the central wavelength of the payload is set by the label processor). In this case the old labels select a couple of new labels. Thus, for a given old labels combination, the control signal is provided by the label processor, and the new labels are provided by the label rewriter. In Figure 1, the label swapping table and the corresponding wavelengths are reported. As an example, if packet with labels ‘0 1’ enters the packet switch, the label processor produces a signal at 1560.6 nm (at which the payload is converted) and the label rewriter provides the new labels ‘1 0’, which is represented by the CW-signal at 1558.9 nm. The new labels are coupled to the converted payload, so that at the 1x4 packet switch output, the switched packet contains the new in-band label information. The switched packet enters Node 2, where is processed by the label extractor/eraser, and the resulting 160 Gb/s payload is evaluated.
3. EXPERIMENTS AND RESULTS

The experimental setup of the 1×4 packet switch based on label swapping technique is shown in Figure 1. We processed four packets each contains two labels. The extracted labels are shown in Figure 2 (a-b). The optical power of label 1 and label 2 at the MZI-SOA of the label processor and rewriter were 1.5 dBm and 0.3 dBm, respectively. The optical power per channel of the CW-signals was -2.5 dBm. The measured OSNR at the SOA-MZI output was 32 dB, and the dynamic extinction ratio was 13 dB. The wavelength converter is based on ultra-fast chirp dynamics in a single SOA [5]. We set the CW-signals according to the label swapping table (see figure1). The label processor output traces are shown in Figure 2 (c-f), while in Figure 3 (c-f) it is shown the output traces of the label-rewriter. The new labels were then combined with the 160Gb/s wavelength converted payload.

![Figure 2. a-b) Extracted labels. c-f) Output traces of the label processor.](image1)

To study the cascadability of the proposed packet switch, the switched packet at Node 1 output was fed into Node 2. At Node 2 the packet was processed by the label extractor/eraser, and the resulting 160 Gb/s payload was evaluated. Figure 4 and 5 show the optical spectra and BER measurements at different position of the two nodes system, respectively. The BER measurements were performed in a static operation by using a 160 Gb/s PRBS $2^{23}-1$ data payload and fixing one address (old label (0 1)).

Figure 4b shows the spectrum of the payload signal after label extraction at Node 1. As compared with Figure 4a, the label was erased. Figure 5 reports also the eye diagrams in different point of the setup. Small degradation and broadening of the pulses is observed after the label extraction with respect to the 160 Gb/s back-to-back payload pulses. The label extractor in Node 1 causes a penalty of less than 0.5 dB compared to the payload. After the wavelength conversion, error-free operation was obtained with 5.5 dB of penalty. As reference we also reported the 160 Gb/s back-to-back wavelength converted, which has 4 dB of penalty. The additional 1.5 dB penalty compared with 160 Gb/s back-to-back wavelength conversion can be ascribed to the pulse broadening by the label extractor which affects the wavelength conversion performance. The optical spectrum of the switched packet including the new label is shown in Figure 4c. The switched packet was then fed into Node 2. The performance of the label erasing and re-inserting operation is evaluated by BER measurement of the data payload after the label extractor in Node 2. Figure 4d shows the optical spectrum of the data payload after the label extractor/eraser at Node 2. The measured power-penalty is 0.5 dB. This result indicates that the extraction/insertion of the new labels causes only a limited power penalty.
4. CONCLUSIONS

We demonstrated an all-optical 1×4 packet switch based on label swapping technique for in-band labels addresses. The employed label processor and label rewriter functions scale as \( \log_2 N \), with \( N \) the number of addresses. Moreover, the label swapping technique operates in asynchronous fashion and therefore it does not require any external synchronization of packets. This is very important since packets synchronization operation requires a packet based clock-recovery circuit which is not trivial to realize at data rate above 10 Gb/s. Experimental results validate the proposed technique in two-cascaded nodes configuration. BER measurements show error-free packet switching operation at 160 Gb/s, while the label erasing and new label insertion operation introduces only 0.5 dB of power penalty. Those results indicate a potential utilization of the presented technique in a multi-hops packet switched network.

REFERENCES