# An All-Optical Bufferless Multiwavelength Sorter for 40 Gb/s Asynchronous Variable-Length Optical Packets

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**Abstract:** We present a new all-optical multiwavelength sorter designed for asynchronous, variable-length packets. We demonstrate experimentally that the scheme can efficiently implement sorting function without contention for 40 Gb/s variable packets at a BER of less than $10^{-9}$ without an error floor.



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## 1. Introduction

Packet switched optical networks require methods to handle contention when multiple packets compete for the same resources at e.g. switch output ports. However, there has not been an efficient contention resolution technique to handle contention between Internet Protocol (IP) packets that are inherently variable in length and arrive at a switch asynchronously with respect to each other [1][2].

In this paper we present a new unbuffered multiwavelength sorter (multi-λ sorter) that supports very high bit-rate, variable-length packets arriving asynchronously. We demonstrate experimentally that the scheme can implement sorting function without contention at error free operation between multiple input-ports asynchronously loaded with 40Gb/s variable-length packets. To the best of our knowledge, this is the first time an all-optical sorter for asynchronous and variable length packets has been demonstrated. The multi-λ sorter, which is based on the 2x2 λ-contention resolution switch (λ-switch) constructed from latching optical cross-coupled λ-decision circuits, converts incoming packets to new wavelengths ($\lambda_1$, $\lambda_2$ ,…,$\lambda_n$) according to the order of arrival time. The packets are re-ordered at the output ports according to wavelength dependent priority without contention. The sorter is inherently latching and maintains packet switching state for the whole duration of the packet or overlapping contending packets, without fragmentation while enabling operation with any length packet arriving asynchronously at multiple input ports.

## 2. Principle of Operation

The architecture of the all-optical multi-λ sorter is shown schematically in Figure 1 can be used as front end of an optical switch stage. The packet sorter consists of multiple 2x2 λ-contention resolution switches arranged as a multistage asynchronous switch.. The function of sorter is to sort the incoming packets on original wavelength $\lambda_s$ so that first-in packets arrive at the top outputs with $\lambda_1$ and last in packets at the bottom outputs with $\lambda_n$. The 2x2 λ-switches operate asynchronously and are latching so that packets that arrive first or overlapping packets arriving in the 2x2 switch at the same time, will be completely switched to the correct port without fragmentation. All packets with different wavelengths are switched simultaneously to desired links using an optical switch.

Variable-length packets $P^{(m)}_n$ where packet 'n' arrives at the input port 'm': $P_1^{(1)}$, $P_2^{(1)}$, …, $P_n^{(1)}$ and $P_1^{(2)}$, …, $P_n^{(2)}$, …, and $P_1^{(n)}$ …, and $P_n^{(n)}$, arrive asynchronously at the input-ports on $\lambda_s$. Increasing length fiber delay lines are used to provide fixed processing time delays between switches. $P_1^{(1)}$ and $P_1^{(2)}$ are processed by the first 2x2 λ-switch ($S_1$) according to the following rule: (i) if $P_1^{(1)}$ arrives first it is converted to $\lambda_1$ and $P_1^{(2)}$ is converted to $\lambda_2$; (ii) if $P_1^{(2)}$ arrives first it is converted to $\lambda_1$ and $P_1^{(1)}$ to $\lambda_2$; (iii) when any one of two packets is absent, the switch outputs a packet with $\lambda_1$. Considering possible case that $P_1^{(3)}$ comes first among $P_1^{(1)}$, $P_1^{(2)}$ and $P_1^{(3)}$, second ($S_2$) and third 2×2 λ-switches ($S_3$) are used to further process $P_1^{(3)}$, $P_1^{(2)}$ and $P_1^{(1)}$ then assign $\lambda_1$, $\lambda_2$ and $\lambda_3$ to them according to the same above rules. This process continues for $P_1^{(4)}$, $P_1^{(6)}$,…, $P_1^{(n)}$ until all packets are sorted at the first stage according to the rule described above. In order to handle all $n$ incoming packets, $n(n-1)/2$ cascaded 2x2 λ-switches need to be used.

It is important to emphasize the mechanism by which asynchronous, variable-length packet are switched using the latching function in order to keep the λ- switches in a fixed state until the longest packet and all overlapping shorter packets at both inputs have exited the switch. The state of the switch is then reset and will set its new state based on the next packet arrival at its input-ports once both ports are clean for a certain time (switching time). An additional feature of this design is that a packet can be erased at any time by turning off the corresponding wavelength. These two features, reading and erasure of packets are important to allow priority queuing for applications where a variety of differentiated services are carried by the packets (e.g. voice, video).

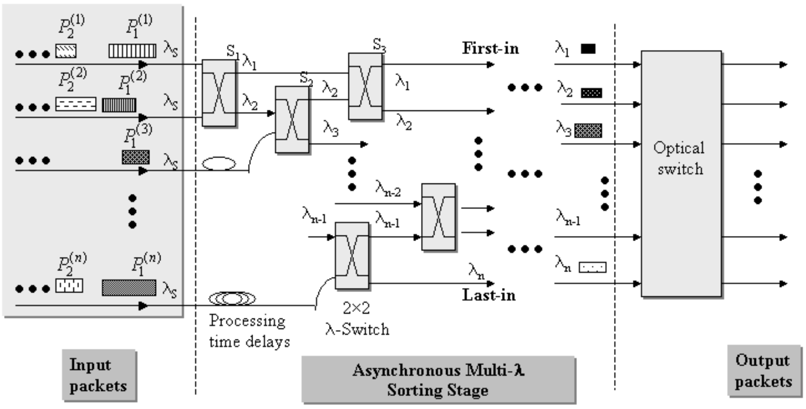


Fig. 1 Proposed all-optical sorting scheme for multiple packets.

The 2x2 λ-Contention Resolution Switch is shown in Figure 2(a). Packets entering input-port 1 and input-port 2 namely, $P^{(1)}$ and $P^{(2)}$ are fed to the switch. The packet λ-decision blocks generate the desired probe CW signal to wavelength converters based on the priority of the incoming packets. The probe signals of the packet λ-decision blocks are generated by cross coupled probe signal circuits for each λ as shown in the inset of Fig 2(a). The packet streams $P^{(1)}$ and $P^{(2)}$ serve as input parameters for the λ probe control circuit. Setting one probe signal automatically resets the other λ probe signal to prevent transmission of the packet on both the priority channels, thereby making the λ probe control signals mutually exclusive. Fig 3 shows the physical implementation details that provide the logic for the probe control circuit. The output probe signal, generated on a per packet basis is then fed to a wavelength converter along with the corresponding data line to switch the packet to the desired priority access port. Fig 2(b) shows the timing diagram for the signals generated for the different cases of possible incoming variable and asynchronous packets in particular reference to $P^{(2)}$ packet λ- decision block detailed in the inset.

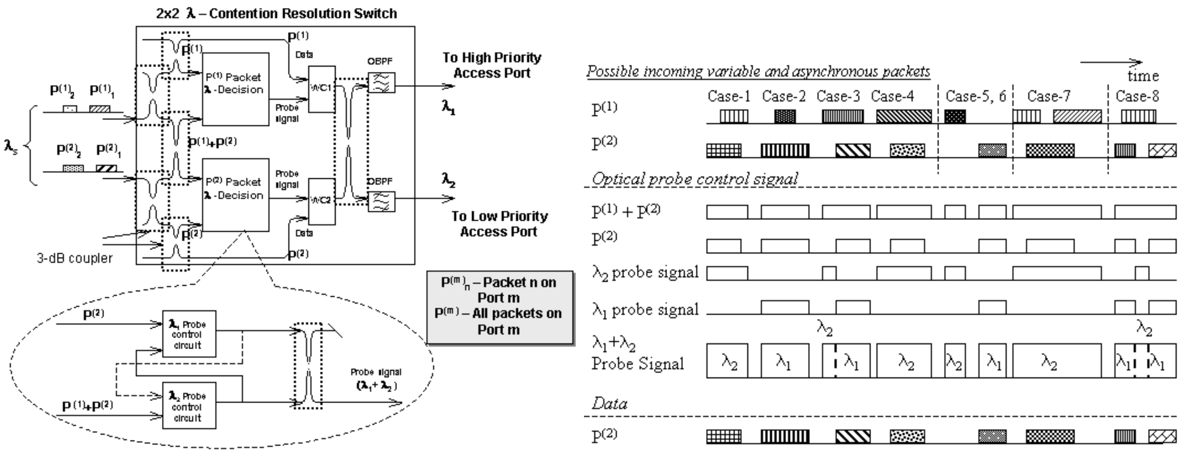


Fig. 2 (a) Structure and operation principle of 2×2 λ-switch (b) Timing diagram for probe signals generated

## 3. Experiment Setup and Results

The experimental setup for demonstrating operation of $P^{(2)}$ packet λ-decision in a 2×2 contention resolution switch is shown in Fig.3. A 10GHz fiber ring laser is used to generate pulses at 1555nm ($\lambda_s$). Its output was modulated with a variable length (PRBS $2^{31}$-1) packet source (BERT), and then multiplexed from 10Gb/s to 40Gb/s. To demonstrate asynchronous and variable length packets, the 40Gb/s data output was split into two parts by a splitter: one part was regarded as input packets of $P_1^{(2)}$, …, $P_n^{(2)}$ at input-port 1and the other part went through a fiber spool (~11.2μs delay) as packets of $P_1^{(1)}$, $P_2^{(1)}$, …, $P_n^{(1)}$ at input-port 2. Considering the delay time of the fiber spool, we generated four packet lengths, 4.7μs, 4.5μs, 4.7μs and 4.9μs in duration and interval time is 0.8μs, which is shown as the inset waveform in Fig.3.

In the first experiment, we demonstrated that $\lambda_2$ optical probe signal was produced basing on packet arrival sequence at input-port 2. The probe circuit consists of two parts: one part is constructed from CW fiber ring laser structure. When packets present, packets suppressed the lasing in the CW ring laser; the other part is a cross gain modulation (XGM) function to invert the CW ring laser output signal to the same polarity as the existence of packets using another SOA. A new wavelength 1547nm ($\lambda_2$) was simultaneously issued during this processing step.

We used an acousto-optical modulator (AOM) to simulate $\lambda_1$ optical probe signal. The signal from AOM has the wavelength 1558nm ($\lambda_1$) and was split into two parts: one part feedbacks to control the $\lambda_2$ probe signal; the other part was delayed to combine with $\lambda_2$ probe signal to form desired $\lambda_1$+$\lambda_2$ probe signal as the input probe signal for wavelength conversion of the packets at input-port 2. Corresponding timing diagram was recorded as shown as the inset waveform in Fig. 3. Then, the $\lambda_1$+$\lambda_2$ probe signal was coupled with the packets at input-port 2 to enter a fiber wavelength converter [3]. As shown as the inset waveform in Fig.3, three wavelengths are present simultaneously in the input signal for the wavelength converter, which are $\lambda_s$:1555nm, $\lambda_1$:1558nm, $\lambda_2$:1547nm, respectively.

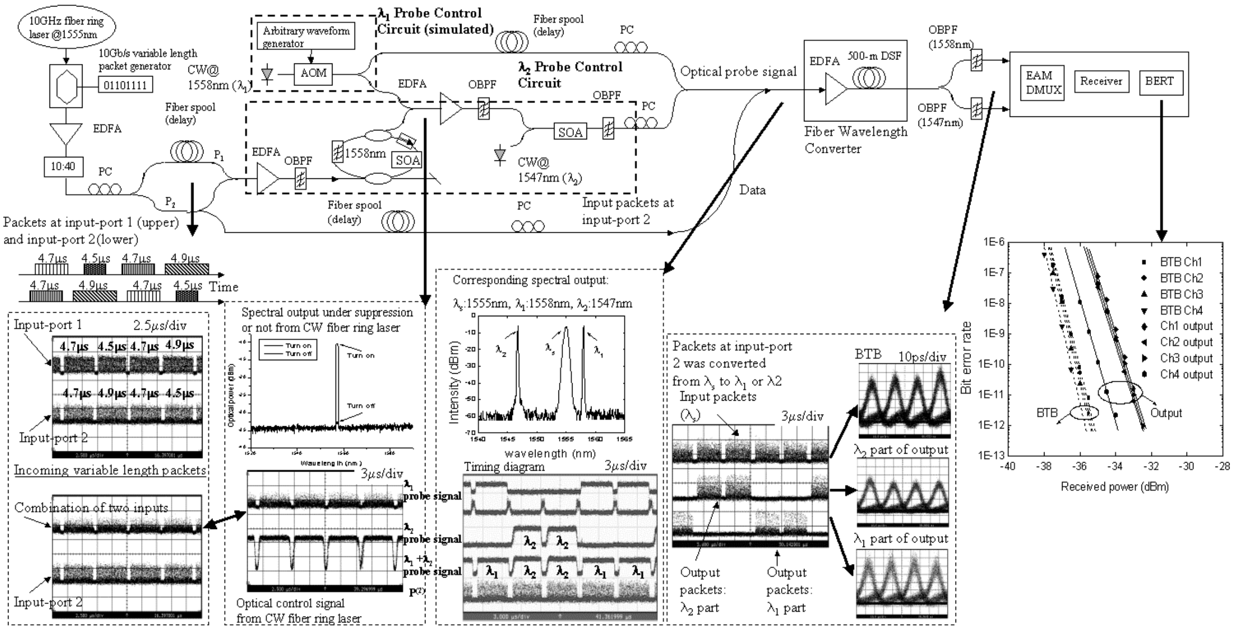


Fig. 3 Experimental setup. MOD: Modulator. PC: Polarization Controller. OBPF: Optical Bandwidth-pass Filter

In the second experiment, we demonstrated that the packets at input-port 2 were converted from $\lambda_s$ to $\lambda_1$ or $\lambda_2$ depending on the different arrival time, which is shown as the inset waveform in Fig.3. The corresponding eye diagrams are clean and open well. Since $\lambda_1$ part signal was directly produced by AOM (simulation signal), only BER of $\lambda_2$ part was measured and plotted as a function of the received optical power, which is also shown in Fig. 3. The dashed lines are the BER curves for back-to-back (BTB) and the solid lines are the BER curves for $\lambda_2$ (1547nm) part of output packets. The maximum power penalty for any channel is less than 3-dB at BER of $10^{-9}$ compared with the input packets. The power penalty was mainly caused by the relatively low optical probe signals.

## 4. Summary and Conclusion

We have presented a new all-optical bufferless multiwavelength sorter for asynchronous variable length packets without contention. BER results show that it is error free operation for 40Gb/s variable length packets. The maximum power penalty for any channel is less than 3-dB compared with back-to-back. The priority strategy used in the multi-λ sorter can easily be modified to accommodate other schemes.


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