All-Optical Contention Resolution With Wavelength Conversion for Asynchronous Variable-Length 40 Gb/s Optical Packets

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***Abstract*—We present a new all-optical technique for resolving contention between asynchronous variable length packets. The approach utilizes a novel all-optical asynchronous latching switch based on cross-coupled injection-locked wavelength converters. We experimentally demonstrate that the scheme resolves contention between variable-length, asynchronous 40 Gb/s packets with a measured bit error rate of better than 10^{-9}, without an error floor.**

***Index Terms*—Contention resolution, optical buffers, optical packet switching, optical routing.**

I. Introduction

PACKET-SWITCHED optical networks must support routing of variable-length packets that can arrive asynchronously at packet-routing nodes. Contention occurs when multiple packets compete for the same resource such as switch output port, an optical buffer, or a wavelength. Future optical routers must be able to rapidly resolve packet contentions [1], [2]. All-optical techniques promise to rapidly resolve packet contentions, however, optical buffers that exhibit the access properties of electronic buffers do not exist today. The options are to use fixed delay-line buffering, which has utilization tradeoffs, or real-time approaches. An all-optical contention method was described in [3] that handled the case where two packets arrive at exactly the same time (synchronized). However, this previously demonstrated method assumed that one packet must have higher priority and that the packet with lower priority must be longer than the higher priority packet in order to prevent the lower priority packet from being fragmented into multiple wavelengths.

In this paper, we present a novel all-optical approach that, to our knowledge, demonstrates for the first time real-time contention resolution between asynchronous variable-length packets without restrictions on the packet length, ordering or resulting in packet fragmentation. The technique utilizes an asynchronous latching switch constructed with cross-coupled optical injection-locked wavelength converters. We have experimentally demonstrated that this scheme resolves the contentions between 40 Gb/s asynchronous variable length packets with better than 10^{-9} bit error rate (BER). To the best of our knowledge, this is the first time that all-optical contention resolution for asynchronous variable length packets has been demonstrated.

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II. Wavelength-Routing Contention Resolution Architecture

Contention occurs in a packet-switched network when two or more packets request to utilize the same resource (e.g., switch output port, wavelength) within an overlapping time interval. For asynchronous Internet Protocol-like networks where packets can be of random length over a wide dynamic range (e.g., 40–9000 B), one of the most challenging issues is resolving contention between randomly arriving packets. In electronic systems, this problem is handled using electronic elastic buffers that can hold multiples of the longest length packets at a time. However, a practical elastic optical buffer does not exist today and fixed optical delay-line buffers result in severe tradeoffs in capacity, utilization, and latency when operated with variable-length packets.

An alternative to elastic buffering is to make real-time decisions as to which packet should be routed to the desired resource and which packet should be assigned to another resource (e.g., wavelength, fiber). However, in order to accommodate the fact that packets of variable-lengths can arrive at any input at any time, the decision element must perform some form of latching or event driven memory function similar to that of a flip-flop.

In this paper, we demonstrate contention resolution using a mechanism to assign an outgoing wavelength each packet based on the arrival of its envelope relative to other incoming packets on a first-come-first-serve priority basis. Fig. 1 shows the contention resolution scheme demonstrated for input packet port-1 $\mathrm{P}^{(1)}$ and port-2 $\mathrm{P}^{(2)}$. A fixed fiber delay provides the fixed processing time of packet envelope detection and processing. Packet streams P_1, P_2 and the composite packet stream $(\mathrm{P}_1 + \mathrm{P}_2)$ are first sent through a packet envelope detector. The envelope of all packet streams are then compared with that of $(\mathrm{P}_1 + \mathrm{P}_2)$ at the latching optical logic (LOL) and a λ control signal appropriate to the packet priority is generated. The packet stream and the λ control signal are then input to a wavelength converter for translation of the bits of the packet to the priority-assignment wavelength on a per packet basis. While the priority assignment decision is made on the packet envelope, translation of the packet to the assigned priority level using wavelength conversion is done at the bit level. The logical function of the latching optical logic is shown in the inset of Fig. 1.

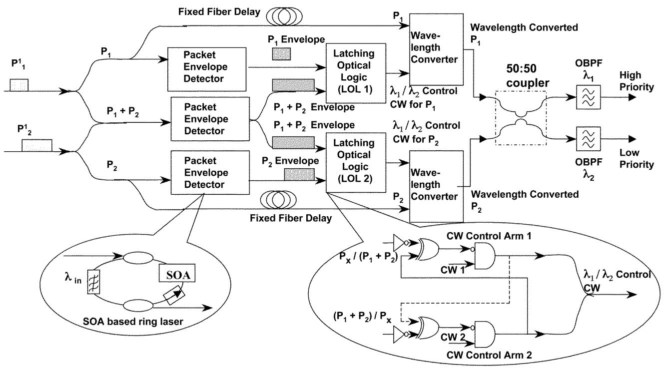

Fig. 1. All-optical contention resolution technique.

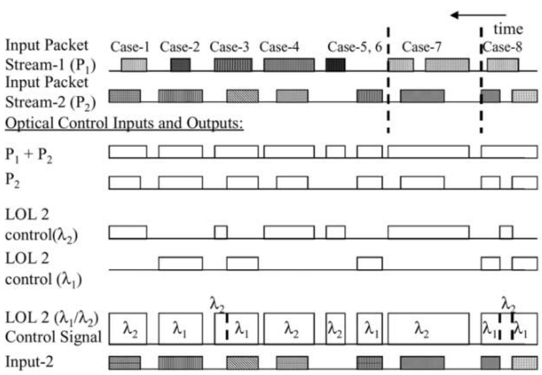

Fig. 2. Timing diagram for latching optical logic (LOL) 2.

The latching operation between the two arms of the optical logic ensures that enabling the continuous wave (CW) wavelength sources (λ_1/λ_2) on either arm are complementary, guaranteeing that no packet is transmitted on both priority ports. Each packet stream envelope is compared to that of the composite packet envelope of $(P_1 + P_2)$. If a packet is already present on the composite envelope, the lower priority CW (λ_2) is enabled for that packet in the data stream. The state of the latching optical logic is held until the packet envelope ends on both input streams. This ensures that packets are not fragmented. The output of the wavelength converter for each packet stream is then combined and fed to the output priority ports. A set of filters ensure that only packets assigned to that priority wavelength get transmitted out that port. When two packets arrive at the node simultaneously, although this probability is very small, only one of the packets will randomly receive priority based on multiple noise mechanisms and the state of the latching circuits. This technique can be scaled to handle multiple packets by constructing multistage circuits of this basic 2×2 to sort packets on N inputs to different wavelengths. Fig. 2. shows the different possible packet input conditions and the control signals. The control signal decisions are made for the P_2 packet stream at the LOL 2.

1) Cases 1 and 4: Since packet at input-1 arrives first, packet at input-2 is assigned to λ_2 and input-1 to λ_1.
2) Cases 2 and 3: Since packet at input-2 arrives first, packet at input-2 is assigned to λ_1 and input 1 to λ_2.
3) Cases 5 and 6: Packet only present at input-1 or at input-2, thus, the packet is switched to λ_1 in either case.
4) Case 7: Packet at input-1 arrives first. Packet at input-2 arrives next and is switched to λ_2. Before packet at input-2 ends, another packet at input-1 arrives; switching is held until the packet envelope ends on both input streams.
5) Case 8: Packet at input-2 arrives first and is switched to λ_1. Packet at input-1 then arrives and is switched to λ_2. Before packet at input-1 ends, another packet at input-2 arrives; switching is held until the packet envelope ends on both input streams.

III. Experiments and Results

The experimental setup for demonstrating the operation of the $P^{(2)}$ latching optical logic (LOL 2) is shown in Fig. 3. A 10-GHz optical fiber-ring laser (FRL) is used to generate pulses at 1555 nm. The FRL output is modulated with a variable length (PRBS $2^{31} - 1$) packet source (BERT). We generate packets of duration 4.7, 4.5, 4.7, and 4.9 μs, with an interpacket time interval of 0.8 μs. A 1:4 passive interleaved multiplexer was used to generate 40 Gb/s RZ variable length packets from the 10-Gb/s packets. To simulate contention cases $1 \sim 4$ shown in Fig. 2, the 40-Gb/s packets are split into two copies and one copy is delayed by ~ 11.2-μs using a fiber delay line. The inset waveform A in Fig. 3 shows the input packet streams.

In the first experiment, we demonstrate that the appropriate λ control signal is generated on one of the CW control arms of the LOL 2 based on the packet arrival sequence. The inverted packet envelope detector is implemented using a CW fiber ring laser with a cavity length of 8 m, made up of a semiconductor optical amplifier (SOA) as the gain medium, an optical band-pass filter (OBPF) and an optical isolator (OI). The presence (absence) of incoming packets will (will not) suppress the lasing in the CW ring laser realizing an optical gate signal corresponding to the incoming packet envelopes. The logical operation of CW (λ_1) control arm is identical to that of the CW(λ_2) arm. Its output is simulated using an acoustooptical switch and is based on the packet arrival conditions and control outputs seen in Fig. 2. Cross-gain modulation (XGM) is used to invert the optical gate signal inside a second SOA. This SOA also acts as a switch for CW (λ_2). The output of this switch is the λ_2 part of the control CW for packet stream P_2. This output gated CW (λ_2) is then combined with appropriately delayed simulated gated CW (λ_1) to form the composite λ_1/λ_2 control CW out of LOL2 for packet stream P_2. The timing diagrams corresponding to contention cases-1 ~ 4 were recorded in Fig. 4.

The rise/fall times of the packet envelope detector are less than 300 ns, and mainly depend on the cavity length of the CW fiber ring laser [4]. The packet-envelope detector can be constructed using a monolithic, integrated-ring laser or other injection-locked structure or by making modifications to the current FRL to reduce the rise/fall times to a few nanoseconds, thereby making it possible to handle packet lengths and interpacket gaps as narrow as several nanoseconds. The LOL output λ switching is limited by the rise and fall times of the CW ring laser (packet envelope detector). Consequently, the SOA operation bias point was chosen such that the CW switching took place before the start of the packet and after the end of the packet. This ensures that the whole packet gets switched based on the contention decision. This also limits the interpacket gap to a minimum of 300 ns. Improving the CW fiber ring laser switching time can bring down this limit. Also, a high-speed semiconductor laser, instead of the CW FRL, could improve the switching time. Inset B in Fig. 3 shows the spectrum of the input to the fiber wavelength converter [5]. The wavelengths for the composite control CW: λ_1:1560-nm, λ_2:1550-nm and the input packet stream P_2: λ_s: 1555-nm can be seen.

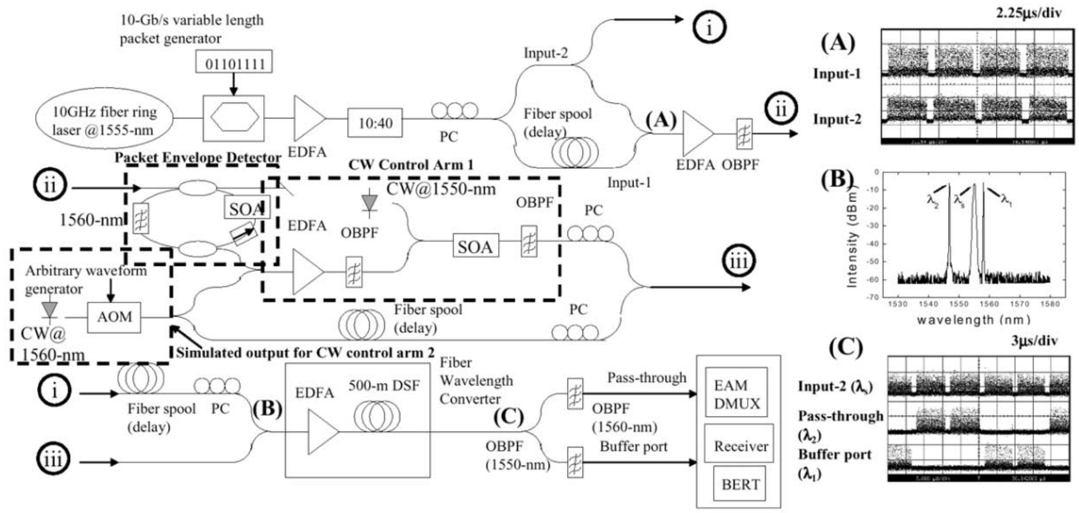

Fig. 3. Experimental setup. (i) Input packet stream $\mathrm{P}^{(2)}$ (ii) Composite packet stream $\mathrm{P}^{(1)} + \mathrm{P}^{(2)}$ (iii) Composite control CW (λ_1/λ_2) output from LOL 2. MOD: Modulator. PC: Polarization Controller.

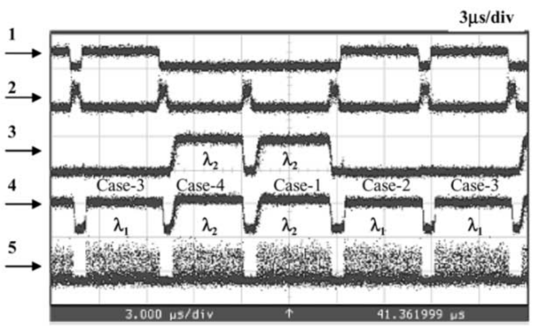

Fig. 4. The recorded timing diagram of the packets at input Port-2 ($\mathrm{P}^{(2)}$) and the LOL outputs (1) Simulated CW (λ_1) output from control arm 2 obtained from an acoustooptic switch; (2) Output from CW ring laser; (3) The CW (λ_2) output from control arm 1 experimentally obtained; (4) λ_1/λ_2 control CW for P_2 from LOL 2; (5) Input Packet stream 2 $\mathrm{P}^{(2)}$.

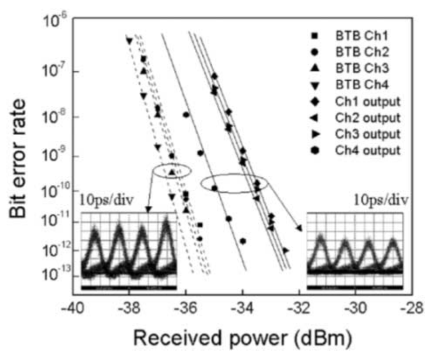

Fig. 5. Measured packet BER results.

In the second experiment, we demonstrate wavelength routing on a per packet basis based on the composite control CW output from LOL 2. The inset waveform C in Fig. 3 shows that input-2 was converted from λ_s to λ_1 or λ_2 depending on the priority assigned to the packet by the LOL module. The measured BER for the packet stream is plotted as a function of the received optical power in Fig. 5. The dashed lines are the BER curves for back-to-back and the solid lines are the BER curves for λ_2 (1550 nm) part of $\mathrm{P}^{(2)}$. The inset waveforms in Fig. 5 show the corresponding eye diagrams. The eye diagram of output packets wavelength converted from the packet stream $\mathrm{P}^{(2)}$ to wavelength λ_2 is clean and well open. The maximum power penalty for all channels is less than 3 dB at BER of 10^{-9}, compared with the input packets. The power penalties were mainly caused by the relatively low power level of the composite control CW that can be handled by the switching SOA.

IV. Conclusion

We have demonstrated real-time contention resolution for asynchronous 40 Gb/s variable length packets using a new all-optical contention resolution technique based on cross-coupled injection-locked wavelength converters. The technique exploits an important latching function that prevents fragmentation and enables asynchronous operation with variable length packets. The technique is transparent to packet format and bit-rate out to a maximum determined by the wavelength conversion technology used. Packet BER measurements show error free operation for 40 Gb/s variable length packets for better than 10^{-9}. Furthermore, the technique can be extended to efficiently resolve the multiple packet collisions by using a cascaded contention resolution system.

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