First Demonstration of Multihop All-Optical Packet Switching

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***Abstract*—Experimental demonstration of all-optical multihop routing through 2 × 2 photonic packet switches is described for the first time. As each packet traverses a switch, the functions of routing, contention resolution, header regeneration, and header reinsertion are performed. Three all-optical hops are demonstrated for the payload without optical amplification. The number of hops is currently limited by −13 dB optical loss per switch pass. Each packet is coded using six discrete optical wavelengths, making this the widest bit-parallel photonic switch reported to date.**

I. Introduction

All-optical packet switch networks are gaining increasing attention in high bandwidth applications such as telecommunications and computer communications due to their data and format transparency. In all-optical multihop networks, packets traverse multiple link/switch pairs with the payload remaining optical from the source to destination. The control, however, may be processed electronically and regenerated at each node. A 2 × 2 photonic packet switch is a basic building block for all-optical packet networks. Each switch must have the capability to route packets, resolve output-port contention, regenerate new headers, and reinsert them with outgoing payloads. Header regeneration/reinsertion is required in switches that completely remove the header for processing, or in cases where the header is changed (e.g., ATM switching, priority based routing). In multihop networks, packets typically traverse an unknown number of switches. Therefore, header regeneration/reinsertion must be independent of the lifetime of the packet in the network.

Previously, self-routing and contention resolution in 2 × 2 switches has been reported [1], [7]. Demonstrations of header reinsertion, capable of supporting only a single switch pass in a 1 × 2 switch [4] is not suitable for multihop networks. Cascaded switching in $1 \times N$ photonic switches has also been demonstrated [3], [5] and did not handle the important case of contention.

In this paper we report the first experimental demonstration of all-optical packet routing through multiple 2 × 2 photonic switches. This work advances the state-of-the-art by performing the functions of routing, contention resolution, and header regeneration/reinsertion at every switch pass with both input ports active. This level of functionality is required to construct larger all-optical packet switched networks. The primary challenge in this experiment was to actually route packets through multiple switches with both input ports active such that contention occurs at each pass while performing the functions described above. Header regeneration/reinsertion is accomplished by impressing new information on lasers in the switch control processor and merging the optical signals with payloads exiting the switch output ports. The switch uses deflection routing, a simple routing protocol, to arbitrate output port contention.

Manuscript received May 20, 1993; revised December 23, 1993.

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IEEE Log Number 9400076.

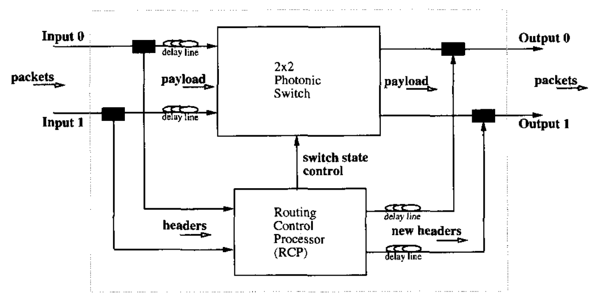

Fig. 1. A 2 × 2 photonic switch building block.

II. Switch Architecture

A block diagram of the packet switch is shown in Fig. 1. The primary components are a 2 × 2 photonic switch fabric and an optoelectronic routing control processor (RCP). This building block can be used to construct larger $N \times N$ centralized switches or distributed switches with local host access [6]. Header information is coded out-of-band on a separate optical wavelength. This technique simplifies header extraction and reinsertion over comparable time division multiplexing techniques. While the header and payload can separate due to fiber dispersion, interswitch distances are generally known in advance, and the optoelectronically regenerated header is retimed at each pass. At the switch input, the payload is temporarily delayed in fiber delay lines to compensate for RCP latency. The RCP generates a switch control signal and new header based on the routing requests and priority information of current packets entering the switch. The all-optical payload and updated header are aligned at the switch output using fiber optic delay lines. A 2 × 2 $LiNbO_3$ photonic switch is used for the switching fabric.

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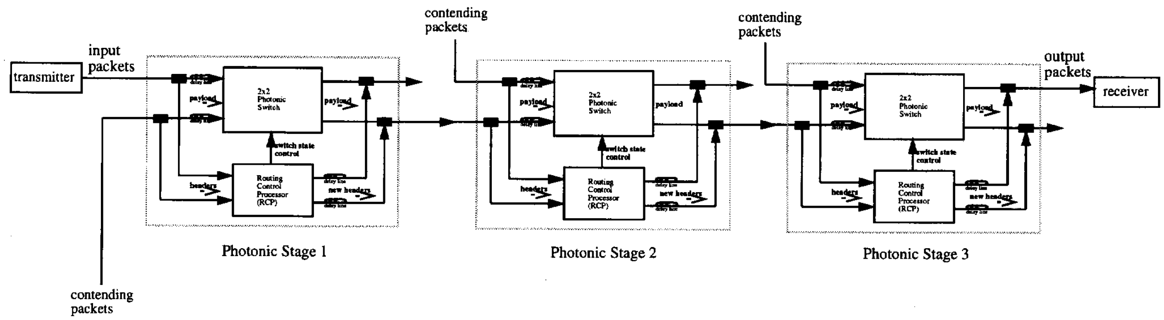

Fig. 2. Block diagram of multihop all-optical routing through three photonic packet switches.

Contention for switch output-ports is handled using deflection routing [1]. Routing decisions are based on destination addresses and priority bits. Packets entering the switch at both input ports, destined for the same output-port, are routed based on priority. The packet with higher priority is directed to the desired output-port and the other packet is deflected to the remaining output-port. It is assumed that the network topology is multipath and recirculating so that packets can reach the destination via an alternate path [6]. Deflected packets may have their priority increased in order to decrease the probability of deflection at the next switch.

The case of contention with equal priority requires fair arbitration. This condition is resolved by maintaining priority states from packets entering the switch during the previous clock cycle. In [1], the switch was maintained in the previous state under this condition. While the latter technique yields a random allocation between input-ports, the former technique will grant priority to one input for bursty periods of time, yet is able to change between the two inputs over time.

III. All-Optical Multihop Routing Demonstration

Multihop routing for three switch passes is illustrated in Fig. 2. Optical packets are injected into the first stage with contending packets at the other input port. Routing, contention resolution, and header regeneration/reinsertion are performed, with the updated optical packet exiting the first switch. The all optical packet is routed to a second and third switch, with the same functions performed at each stage and contending packets at the other inputs.

This functionality is demonstrated using the experimental setup shown in Fig. 3. An optical packet generator injects packets at input port 0. Output port 1 is fed back to input port 1 to demonstrate multihop operation and provide packets at both input ports. Output port 0 is monitored to verify switch operation. The feedback fiber length is equal to the packet generator rate plus the RCP latency. Regenerated optical headers, consisting of updated address and priority bits, are reinserted with payloads exiting output port 1. For this experiment, an electronic clock is distributed from the transmitter to the RCP. In an actual network, optical clock distribution is required, and could for example be accomplished by distributing the clock between nodes on a separate wavelength or using a self-timed approach.

Optical packets are transmitted in a bit-parallel format as described in [1]. Each packet consists of two header bits and four payload bits. A packet identification number is contained in the payload in order to track packets through the switch (i.e payload one contains the number one, payload two the number two, etc). One header bit denotes the desired switch output-port and the other bit contains the packet priority. The packet duration is approximately equal to the data bit duration, which without the guard band is 50 ns. Each packet is coded on six discrete optical wavelengths. The payload is generated using DFB lasers temperature tuned to 1304.2, 1306.5, 1308.8, and 1310.1 nm. The header, consisting of two control bits, is generated using two single mode Fabry-Perot lasers temperature tuned to 826 and 828.4 nm. The switch was completely operable with the four data bits shown, however, due to problems with one of the receivers at the data demultiplexer, our results display only three of the data bits.

The experiment was carried out as follows: a predetermined set of packets were sequentially inserted at input-port 0 at a rate equal to the fiber feedback path. Therefore, packets from the previous cycle with new header information arrive via the feedback path at approximately the same time as new packets entering the switch. Using this setup, packets can be programmed to traverse the switch an arbitrary number of times. Appropriate packet sequences were chosen to generate output port contention. Headers were demultiplexed from the payload at each input and the header bits further demultiplexed and processed by the RCP. The RCP uses a combinatoric circuit to perform deflection routing. A bus arbitration circuit is used to accommodate the case of equal priority. The RCP controls the 2×2 switch state (cross or bar state) and generates two new header bits for the packet exiting port 1. Whichever packet exits output port 1 has its current control bits binary complemented. This facilitates verification of the RCP operation. Packet payloads are detected at output-port 0 using a grating demultiplexer, whose output is focused into three 625 μm core multimode fibers spaced 180μm apart using silicon V-grooves. These fibers are coupled to optical

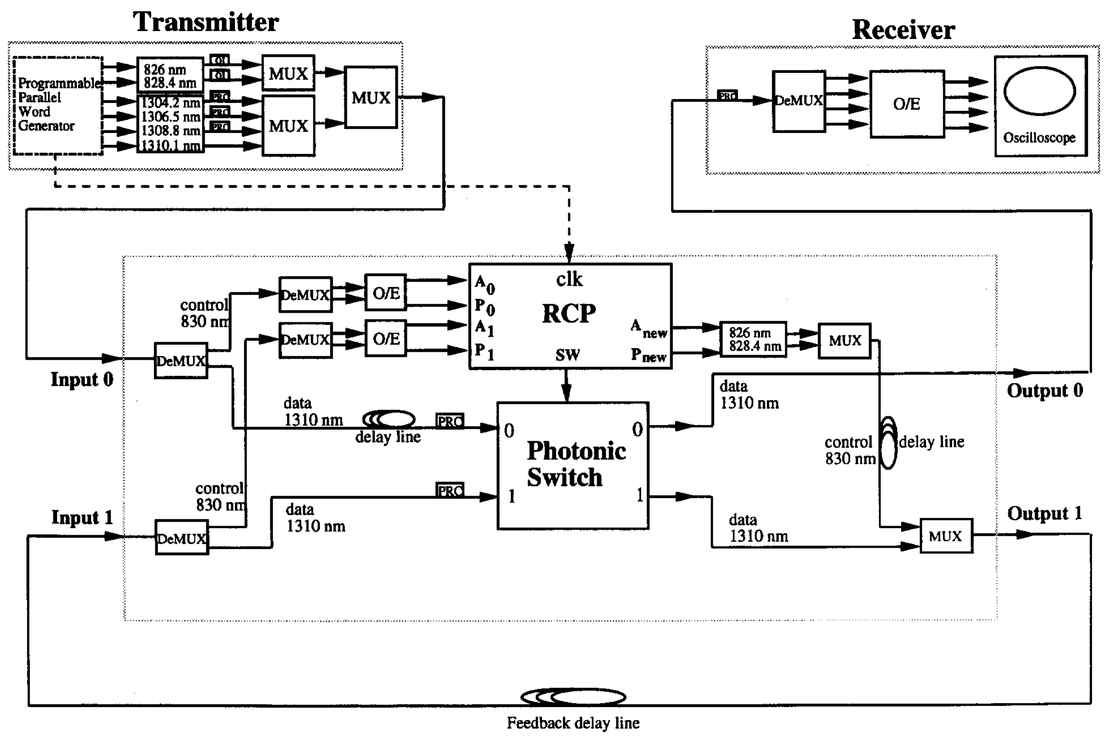

Fig. 3. Experimental setup used to demonstrate all-optical multihop photonic packet switching.

receivers that are connected to an oscilloscipe for viewing the payloads. Demultiplexing was achieved with less than −30 dB interchannel crosstalk between bits.

IV. Results

Two separate experiments were performed to verify correct switch operation and measure the maximum number of hops without optical amplification. In the first experiment, correct switch operation is verified. Each payload contained three data bits identifying packets 1 through 7. The following packet sequence was transmitted cyclically using the convention [data bit 0, data bit 1, data bit 2, address bit, priority bit]: [1, 0, 0, 0, 1]; [0, 1, 0, 0, 1]; [1, 1, 0, 1, 1]; [0, 0, 1, 1, 1]; [1, 0, 1, 1, 1]; [0, 1, 1, 0, 1]; [1, 1, 1, 1, 1]. With the switch set in a static cross state, the lower three traces in Fig. 4a show packets passing through the switch in order at out port 0 with a single switch delay. The second through fourth traces illustrate real-time routing with header reinsertion and contention resolution. The packets arrive at output-port 0 in the order 1, 2, 7, 3, 5, 4, 6. The reordering of packets demonstrates multihop packet routing since packets traversing the switch multiple times will arrive later than packets traversing the switch less times or not at all.

Three hop routing is demonstrated in Fig. 4b, where each payload contains two data bits. The following packets were sent cyclically as defined above: [1, 0, 0, 1] [0, 1, 1, 1] [1, 1, 1, 1]. This sequence causes the packets to correctly appear at output-port 0 in the order 1, 3, 2. Packet 1 is switched straight through, while packet 2 traverses the switch twice, and packet 3 traverses the switch three times verifying three switch hops without optical amplification. Switch loss is illustrated by the relative power level change between packets that switch straight through, packets that traverse the switch twice, and packets that traverse the switch three and four times. The combined losses from input-port 0 to input-port 1 through the feedback loop were measured at −13 dB.

The routing decision time, including demultiplexing, detection, and RCP delays was approximately 100 ns. Although we injected packets at a rate determined by the feedback path length, the maximum packet rate is currently determined by the bit duration of 50 ns. Assuming a guard band of 5 ns per packet, the throughput per input port is 18.2 Mega-packets-per-second (MP/s) corresponding to an aggregate switch throughput of 109 Mbps for three bit packets and 145.6 Mbps for four bit packets. Implementation of the RCP in ECL logic would allow 5 ns bits plus 5 ns guardband yielding a potential switch throughput of 200 MPps or 800 Mbps for a four-bit packet. Addition of more lasers will increase this throughput proportionally. The accumulated laser intensity noise from the four payload lasers can be seen in the DC coupled receiver trace D_2 and the AC coupled receiver trace D_1 in Fig. 4.

V. Summary

In this paper we have described the first reported demonstration of all-optical multihop routing in a photonic packet

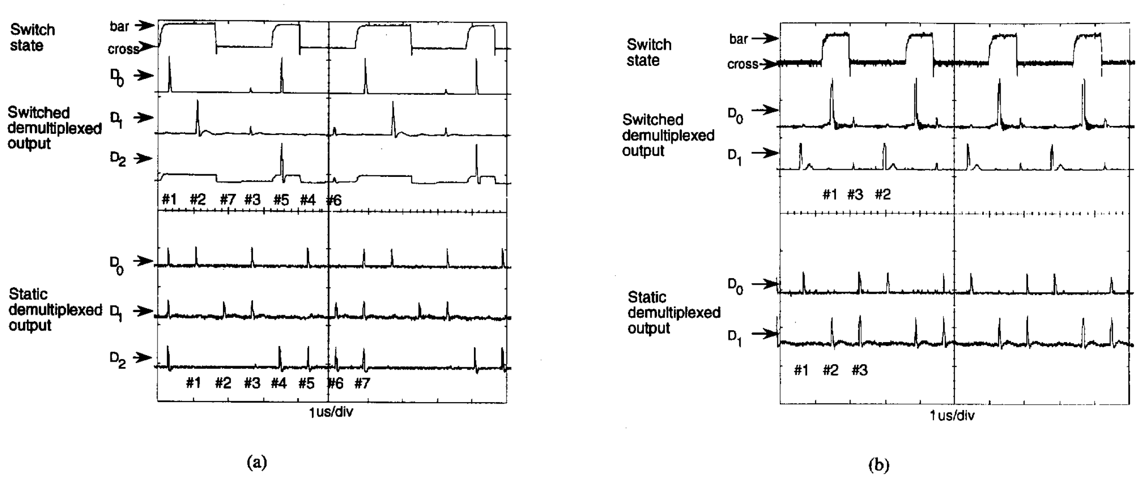

Fig. 4. Demultiplexed switch outputs.

switch. Optical packets are routed with contention resolution and header regeneration/reinsertion performed at each switch pass. The switch also routes multiple optical wavelengths simultaneously as demonstrated by the switching of bit-parallel payloads. The electronics were only required to run at the packet rate due to WDM transmission of bit-parallel packets. Synchronization of the new control bits with the thoroughgoing data bits was accomplished with fiber delay lines. The throughput per input-port was 18.2 Mega-packets-per-second (MP/s) corresponding to an aggregate switch throughput of 109 Mb/s for three bit packets and 145.6 Mb/s for four bit packets. This throughput can be increased by implementing the RCP in faster gate technologies and/or by adding more parallel bits to each packet. Packets were shown to traverse the switch up to three times and circulate up to two times around the fiber feedback loop before excess losses limited detection. The excess losses per round trip switch pass were measured at -13 dB. In a more mature system, optical amplifiers and optimized WDM components will be used to compensate for losses due to switching, coupling, and attenuation.

While the basic purpose of this demonstration was to show multihop operation and header regeneration, the use of out-of-band signaling to transmit control and bit-parallel transmission of the payload raise important issues that are outside the scope of this letter. Chromatic dispersion leads to bit skew and misalignment of the control and header. As with any WDM based system, the power in any individual wavelength is limited by nonlinear crosstalk in the optical fiber. Compensation of switch losses with optical amplification will lead to buildup of amplified spontaneous emission and an increase in nonlinear interaction distance. The combined effects in multihop all-optical networks is a complex function of multiple parameters and can be modeled for a given architecture [2].

Acknowledgment

This work would not have been possible without the generous donation of the DFB lasers by Bell Northern Research, Ottawa Canada. Corning Inc. donated the fiber and Hewlett Packard was kind enough to loan us their Optical Spectrum Analyzer while our unit was on order. This work was supported by the NSF and the Air Force Office of Scientific Research.

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