EXPERIMENTAL IMPLEMENTATIONS OF MULTIWAVELENGTH PHOTONIC PACKET SWITCHES

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Abstract

Photonic packet switches offer the high speed, data rate and format transparency, and flexibility required by future computer communications and cell-based telecommunications networks. We review experimental progress in Multiwavelength photonic packet switches with an emphasis on all-optical guided wave systems. The term all-optical implies that the data portion of a packet remains in optical format from the source to the destination. While the data remains all-optical, both optical and optoelectronic techniques have been used to process packet routing functions based on extremely simple routing protocols. An overview of the design issues for all-optical photonic packet switching is given and contrasted to electronic packet switch implementations. Low level functions that have been experimentally implemented include routing, contention resolution, synchronization, and header regeneration. System level demonstrations, including centralized photonic switching and distributed all-optical multihop networks, will be reviewed.

Introduction

In future fiber-optic packet switched communications networks, the high transmission link data rates as well as the large number of packets transmitted per second will place severe demands on the aggregate network bandwidth. For packet-based applications (e.g. computer communications, ATM-based telecommunications), packets or cells are individually routed and the switch reconfiguration speed is of prime importance. Although electronic technology can achieve high switching speeds, it is not well matched to the transmission bandwidths of fiber-optic links. Photonic switches provide both the high switching speeds and a transmission bandwidth compatible with the fiber link bandwidth. Perhaps more important, photonic packet switches open the possibility for new network architectures that are transparent to the packet data rate and format, extending the success of point-to-point links to the switched network level.

In this paper we review progress towards the realization of photonic packet switches that have the functionality required to build complete switching networks. A complete review of this subject is given in [1]. Design and implementation issues are very different from their electronic counterparts and new approaches in switch architecture and protocol design are required. Current progress towards experimental implementation of "all-optical" photonic packet switches is examined. The term all-optical implies that the data portion of a packet is maintained in optical format from the source to the destination. However, the control portion of the packet may or may not be optoelectronically regenerated at each switch depending on the control technique used. optical and optoelectronic approaches to routing control are discussed.

Data-Rate and Format Transparency

Photonic switch research over the past ten years has focused on how to best utilize the wide available bandwidth to increase performance or fill requirements difficult to perform with electronic switching. One example is the capability of photonic switches in conjunction with optical fibers to maintain data in all-optical format from the source to final destination. This characteristic allows the simultaneous transport of multiple data rates *(data-rate transparency)* and multiple formats *(format transparency)*. Photonic packet switches are characterized as elastic-buffered or passive-buffered. Here, the term passive-buffered implies that only passive delay lines are used, typically fiber loops.

Functionality and Design Principles

The basic functionality required for a packet switch can be summarized by the five low-level functions:

- Routing
- Flow Control and Contention resolution
- Synchronization
- Header regeneration/reinsertion
- Cascadability

Additionally, the following set of principles are important in designing an all-optical photonic switch:

- preservation of the optical bandwidth and end-to-end optical transparency throughout the routing process,
- minimization of the number of optical buffers or memories,
- use of extremely simple routing protocols,
- reduction of optical loss and crosstalk,

• reduction of the number of photonic switch elements,
• use of synchronization techniques amenable to switching without elastic buffers,
• meeting telephony synchronization standards.

Optical Packet Coding Techniques

A packet can be functionally described using a layered model. At the physical network level there are effectively two layers, the payload and the header. The payload contains information processed only by the sources and destinations; the header contains information processed only by the switches. Information that might be included in the payload include data, packet number, and source address. Examples of information in the header include destination address, priority, packet empty-full bit, and packet length.

Several optical packet coding techniques have been experimentally demonstrated, and are summarized in Fig. 1. Each technique exploits the data rate and format transparency of photonic switches, and are classified according to the way the information is transported in the fiber. Three basic categories are bit-serial, out-of-band-signaling, and bit-parallel. Bit-serial coding demonstrations have been performed at the bit level, where each bit carries routing information, and at the packet level, where a string of bits are transported in the payload portion of a packet preceding a routing header. Bit-level coding has been demonstrated using optical code division multiplexing (OCDM) [2] where a series of pulses, called chips, represent an orthogonal destination address for that bit. Each bit is correlated with a fiber-optic tapped-delay-line transversal filter to determine if the bit should be switched to the local destination or passed through to the next switch. OCDM coded bits have been generated at chip rates up to 12.5 Gchips/sec with a bit width T_b of 10 ns [3].

Optical pulse interval and mixed rate time domain techniques have been employed to generate packets with multiple information fields in a bit-serial format. Optical pulse interval coding is structured so that the header can be processed optically, allowing the routing control processor to operate at the same bandwidth as the photonic switch and optical fiber [4]. The packet is of duration T_p, and consists of a header followed by a data payload. The header is comprised of a framing pulse of duration t followed by several identification fields. The framing pulse is used to extract routing information in a self-timed manner. Field #1 contains the packet destination address and field #2 contains the packet length. Packets with 10 ns long header and 80 ps per slot have been experimentally generated [5]. Mixed rate time domain coding is structured for electronic processing of the header and photonic routing of the payload. The header information is transmitted at a slower rate than the payload so that electronics can easily perform high-level routing functions, yet the high-bandwidth information is routed through the photonic switch. Experimental generation of mixed rate bit-serial packets has been reported at 100 Mbps for the header and 700 Mbps for the payload [6].

Out-of-band signaling involves transmission of a signaling or control channel on a frequency-band separate from the data channel. In photonic packet switching, two types of out-of-band signaling techniques have been experimentally demonstrated. In both approaches, the payload and header are transmitted in parallel, on separate channels, within the same fiber link. We refer to this technique as out-of-band/in-fiber signaling. The first approach is to use subcarrier multiplexing (SCM) to encode the payload and header as radio frequency (RF) sidebands on the optical carrier, each at a distinct sideband frequency. The sideband separation is dictated by the payload and header data rates. Packets have been transmitted on an optical carrier at 1.3 mm, with a baseband payload rate of 2.5 Gbps and a 40-Mbps header coded on a 3 GHz subcarrier [7]. The second approach is to code the payload and header at two separate optical wavelengths l_p and l_h. In [8], a packet switching demonstration transported the payload at 1.3 mm at a rate of 933 Mbps and the header at 1.55 mm at a rate of 155 Mbps.

Optical packets can also be transmitted bit-parallel with each bit in the packet at a separate frequency in a single-mode fiber [9-11]. At transmission, the bit-parallel packet occupies a time frame slightly larger than a single bit-duration. Fiber dispersion will spread the bits leading to *bit-skew*. Six-bit packets have been experimentally transmitted with a channel spacing of 2 nm [12]. The packet consists of a four-bit payload at 1.3 um and a two-bit header at 830 nm. The individual bit-rate per wavelength was 50 Mbps, yielding a bit-parallel payload rate of 200 Mbps. The generation of bit-parallel packets can also be accomplished using a mixture of multi-wavelength and subcarrier multiplexing [13].

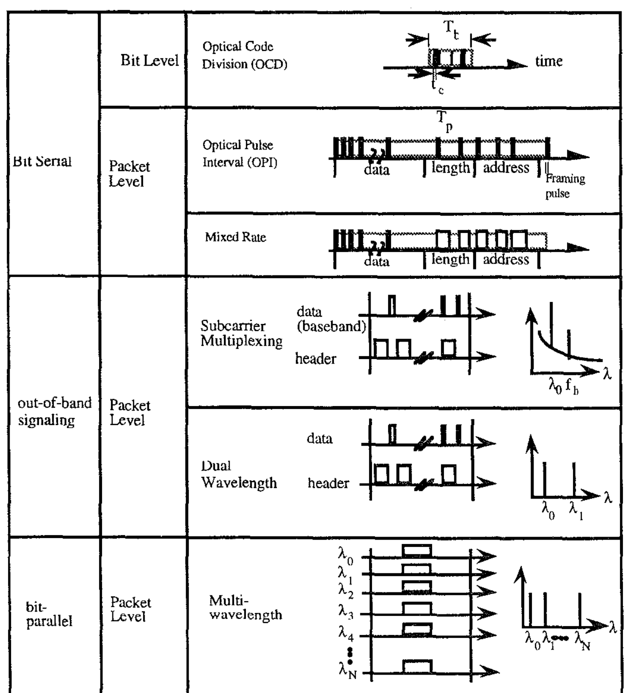

Figure 1

Experimental Self-Routing 1xN Switches

A general diagram of an experimental photonic packet switch is shown in Figure 2. At the switch inputs, packet headers are directed to the RCP through the input interface. Three different methods have been used: tapping of optical power using a fiber coupler [2,4- 7], separation of wavelength multiplexed headers from the payload [8,11], and detection of gain modulation in a semiconductor laser amplifier [14]. Power tapping removes a portion of the complete optical packet with loss that can be compensated for with an optical amplifier; wavelength multiplexing removes only the header allowing the payload to pass through the switch with only a small decrease in optical power due to excess losses; detection of gain modulation in a laser amplifier allows monitoring of the header while simultaneously amplifying the complete packet.

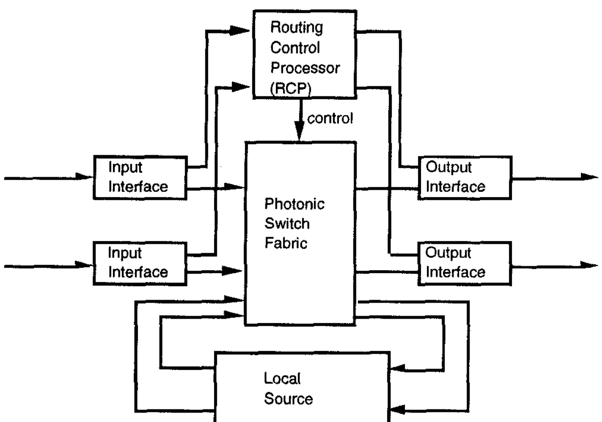

Figure 2

In 1987, the first reported photonic packet switch experiment involved bit-level destination address coding using optical code-division multiplexing at 100 Mchip/s with 32-chip packet headers in a $LiNbO_3$ electrooptic Mach-Zehnder integrated-optic modulator [2]. In a subsequent demonstration, this experiment was scaled up to a $LiNbO_3$ 8x8 crossbar photonic switch with a 12.5 Gchips/s with 125-bit packet headers and a switch reconfiguration rate of 1.33 GHz [3]. Numerous experiments using optical correlation followed, and a comprehensive review is given in [15]. These experiments addressed more complex issues for low-level routing functions in optically controlled switches such as: Optical time-division routing [16-19] to improve coding bandwidth; Optical self-clocked pulse-interval routing to allow timing acquisition on a packet-by-packet basis [20]; Optoelectronic correlation technique using a photoconductive "AND" gate [21,22] to increase the speed and throughput of the header recognition process.

Beginning in 1991, a series of electronically controlled packet switch experiments were reported. A self-routing experiment that demonstrated header extraction by monitoring a semiconductor laser amplifier bias current [14].

A self-routing photonic packet switch that transported header and payload in parallel using SCM [5]. This technique simplifies clock and signal recovery over the bit-serial mixed rate technique. An important issue is the integrity with which the header information can be transmitted and decoded. Errors in decoding a packet header lead to unintentional misrouting of a packet. Out-of-band-signaling using the dual-wavelength technique was first demonstrated by [9] for a bit-parallel deflection routed switch, and later demonstrated in [8] in a dual-wavelength demonstration for ATM cell switching.

Self-routing through cascaded 1x2 switches

An important step in experimental photonic packet switching was to demonstrate that multiple 1x2 self-routed switches could be cascaded. Distributed control of a 1x4 $LiNbO_3$ tree switch using pulse interval coding [21]. A subsequent demonstration of electronic self-routing in two cascaded 1x2 semiconductor amplifier gate array switches using mixed-rate, bit-serial packets was reported in [23]. This experiment demonstrated cascaded operation of amplified photonic switch elements. BER measurements were made with a received signal power of -24 dBm and the combined RCP and switching risetime were on the order of 8 ns.

Contention Resolution in Photonic Switches

The next important development in photonic packet switching was to extend the previous self-routing work in 1xN switches to NxN switches. This required demonstration of contention resolution on optical payloads. For the most part, contention resolution methods have previously been classified according to the manner in which they resolve packet collisions: Buffering, blocking, dropping, or deflecting. Experimental demonstrations of contention resolution have focused on deflection routing and buffering with a small number of buffers as these techniques are well matched to currently available photonic techniques. $LiNbO_3$ directional couplers [24] and semiconductor laser optical amplifier gate arrays [25].

Store-and-forward techniques, where packets are stored in static memories, are well-suited for electronic switches in which flow-control algorithms and buffers can be implemented inexpensively with electronic logic. If storage buffers are expensive, as is presently the case with optical technology, then deflection or "hot-potato" routing [26] can be used, provided the number of input links to a crosspoint is the same as the number of output links [27]. The deflection routing protocol is ideally suited to nodes in which storage is difficult [10].

Routing decisions are based on destination addresses and packet priorities. For example, when packets simultaneously entering both inputs of a 2x2 switch are destined for the same output port, the packet with higher priority is directed to the desired output-port and the other packet deflected to the remaining output-port. Deflection routing techniques require that the network topology be multipath or recirculatory (e.g., shuffle exchange networks, Manhattan Street networks), so that deflected packets can be routed to the destination over an alternate path. The priority of deflected packets is increased to reduce end-to-end latency and to avoid deflecting a packet indefinitely [28].

The first experimental demonstration of deflection routing in a photonic packet switch was reported in [11]. This was also the first demonstration of a full 2x2 switch where packets were injected into both input ports, producing real contention conditions for the same output port. Contention conditions were created and resolved in a 2x2 $LiNbO_3$ switch. Independent packets were injected into both ports by optical power splitting of a serially generated packet stream, delaying one arm by a single packet delay, thereby aligning sequential packets in parallel at the switch inputs. This switch routed bit-parallel multi-wavelength packets employing out-of-band-signaling to transport the payload and header at separate wavebands (1300 nm and 830 nm). The header field consists of two bits that correspond to four final destination addresses and one priority bit. The routing table maps the four addresses into one of the two output-ports. In order to fully support deflection routing by updating the priority of deflected packets, this switch reinserts new headers.

The performance of deflection routing in terms of packet latency variance can be improved by reducing the probability of deflection through the use of a small number of buffers [29.30]. The use of feedforward buffers (e.g., time slot interchangers) in photonic switches, is desirable from the perspective that they are simple to control, preserve the fiber bandwidth, and do not suffer the buildup of optical amplifier noise as is the case with amplified recirculatory buffers. A recently demonstrated experimental 2x2 photonic packet switch operating at 1.25 Gbps with drop/add capabilities [31].

Header Regeneration

Header regeneration is the process of computing, generating, and reinserting a header with the associated payload at the appropriate switch output port. There are several circumstances where this functionality is required: (i) in all-optical photonic switches where the header is completely removed from the payload for processing (e.g., multiwavelength out-of-band-signaling) or (ii) where routing strategies require a modification of the packet header (e.g., priority updating in deflection routed switches, cell routing in ATM switches). Generally, it is important that a header regeneration technique be employed that can operate for cascaded switches, and independent of the number of switches a packet traverses. Reinsertion of a new optical header with a throughgoing packet can be acheived by impressing header information on a continuous wave (CW) period of light embedded within an optical packet [32]. The same semiconductor amplifier laser gate that is used to route the packet is also used to modulate the CW packet section.

A more general approach has been demonstrated that allows regeneration of new headers with each switch pass [12]. The overall switch is similar to the deflection routing 2x2 switch described in [11]. This information is merged with the outgoing payloads using wavelength division multiplexers at the output interfaces. The parallelism of out-of-band-signaling greatly simplifies reassembly of the packets as timing is less critical than with a bit-serial approach. Fiber delay lines are required at the output stages to match alignment of headers with the payload.

All-Optical Multihop Routing

All-optical multihop routing is the complete routing of packets through multiple general-purpose photonic switch stages without optoelectronic conversion of the payload except at the endpoints. At each stage, the full functionality of routing, contention resolution, header regeneration, and synchronization is required since switch nodes have multiple inputs and outputs. The first demonstration of all-optical multihop packet routing that performed routing, contention resolution and header regeneration for each packet at each stage was reported in [10]. This switch routed packets three all-optical payload hops without optical amplification.

The switch 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. 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 -13dB.

Summary

The main challenges in using photonic switches for packet-switched networks relates to providing high-speed, high-throughput control functions such as routing, contention resolution, synchronization, cascadability, header reinsertion, and multihop operation, as well as minimizing the use of elastic buffers, which are currently not practical with optical technology. Progress has been made in several areas with respect to photonic packet switching. These include the development of:

- A deeper understanding of the beneficial tradeoffs involved in combining optical and electronic technologies in packet switched networks,
- The development of "lightweight" optical protocols suitable for packet switched network architectures with all-optical interiors,
- Demonstration of basic switch functions for multihop photonic packet switching.

A review of experimental demonstrations of these photonic packet-switch control functions has been provided. Routing controllers based on optical and optoelectronic processing techniques were reviewed. Simplified routing strategies, such as one-bit per Banyan stage, are the most easily implemented with all-optical processing, whereas more complex functions can be handled by optoelectronically detecting and regenerating the headers at each switch stage. Experimental demonstrations of multihop photonic packet switching and packet synchronization were discussed and are important steps towards demonstrating the functionality required to construct large scale all-optical packet switched networks. Photonic packet switching is at the stage where optoelectronic and photonic integration will make this a potentially viable commercial technology as well as reduce the cost and improve reliability of these systems. For the immediate future, integration is essential to scale network demonstrators to the level where higher level network functions can be developed and interaction between multiple switches in a realistic network environment can be studied.

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