A parallel optical processor for control of optical crossbar switches

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Introduction

N x N optical crossbar switches provide photonic switching networks with non-blocking programmable interconnections that have a channel bandwidth compatible with optical fibers. These switches have been realized in two basic forms: integrated-optic and free-space optical crossbars [1-2]. Processing of information to set-up switch crosspoints has traditionally been relegated to electronic processors. It is expected that optical interconnection networks will be required to dynamically route broad-band signals at rates in excess of 1 GHz, therefore electronic processing of routing algorithms may present a bottleneck [3]. Optical processing of these algorithms can be used to alleviate this bottleneck by increased throughput due to high channel bandwidth [4] and the parallelism of free space optical systems.

Information may be routed through a switching network by a process known as self-routing, whereby destination information is encoded and transmitted with a data packet. Decoding of this destination information may be performed in a distributed fashion by processors associated with each switching node, permitting the routing of the data in real-time along a pre-established route. As shown in figure 1, data and destination information are split at a photonic switching node to both the optical switch crosspoint and optical processor. Destination information is decoded by the processor to produce a control signal at the crosspoint, thereby routing the data to the appropriate output. An optical delay is needed to match the optical processor delay. Recent experimental work has demonstrated that simple analog fiber-optic processors can decode routing information in order to control a single switching node [3-6]. This routing processor belongs to the class of pipelined optical processors [4]. Pipelined optical processing extends the processing bandwidth towards the channel bandwidth of optical fibers and the processing delay to the fiber-optic propagation delay.

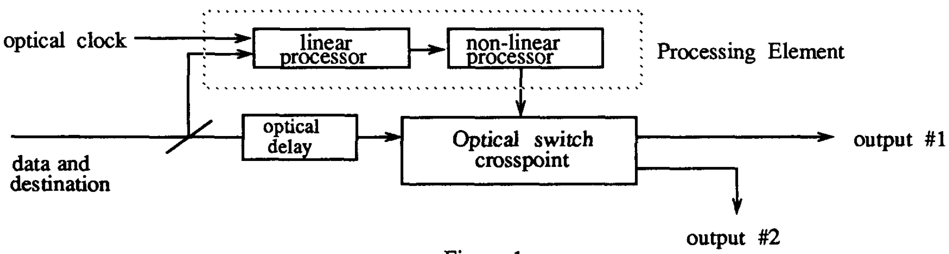

Figure 1

The algorithm used for routing control in this paper is based on a pulse position coding technique demonstrated in [6], whereby a data bit is encoded as a pulse positioned in a synchronous time frame. This position determines the eventual destination of the data bit. Data is encoded and routed as follows: An optical clock with pulse width corresponding to a destination time slot and a repetition rate equal to the user data rate, is modulated by electronic data to create a duty cycle modified data stream. This modified data is synchronously delayed using fiber-optic delay lines to a time slot representing the destination address. Routing information is decoded synchronously at the switching node by incoherently summing encoded data with an appropriately delayed optical clock (linear processor, fig. 1). Thresholding is employed to detect coincidence between the delayed clock pulse and the encoded data (nonlinear processor, fig. 1). The resultant logic signal controls the routing decision (to output #1 or output #2).

Control Architecture and Formalism

Extension of this routing technique to control of an N x N optical crossbar requires that a decision be made as to which of N output crosspoints to activate for each input. Crossbar switches require activation of one of N^2 crosspoints per input/output connection. Control of each crosspoint needs to be performed independently. We present a technique which allows the processing of routing information and activation of N^2 switches to occur in parallel using an optical pipelined processing element (PE) for control of each crosspoint. Functionally, the parallel processor described performs a mapping of encoded input frames from a time-space to a space-space representation (similar to a serial-to-parallel conversion).

Mathematically, N x N crossbar switches permute inputs to outputs by performing a vector-matrix multiplication. Here, this matrix operation is controlled by an architecture which processes routing information in a three-dimensional format. The control architecture consists of an array of the PE's described in the previous section and will be referred to as a parallel optical pipelined (POP) processor. The inputs to the POP are derived from the N inputs to an N x N crossbar and the set of delayed optical clock pulses produced by a centralized laser as shown in figure 2. Data is encoded by modulating the optical clock using integrated-optic modulators located at the transmitters T_N.

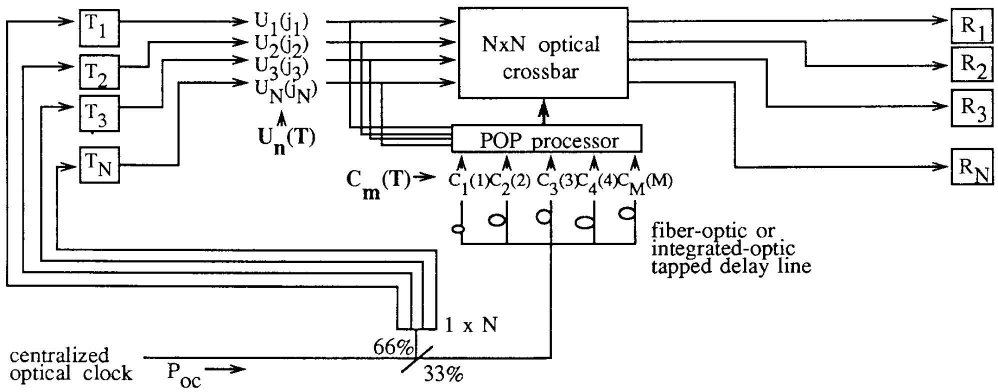

Figure 2

Destination encoded data and delayed optical clock signals are represented to a first approximation by unit height pulse functions $U_n(j_n)$ and $C_m(m)$ occuring within a time frame T (see figure 3), where the parameters n, j, and m are defined (for clarity we represent the switch as size N x M) as:

n = crossbar input channel number , $1 < n < N$
j = pulse position in input frame , $1 < j < M$
m = POP input clock number and pulse position in clock frame , $1 < m < M$

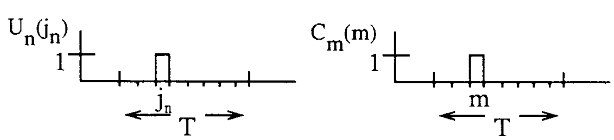

Figure 3

We define a synchronous **pulse coincidence function** $A_{nm}(j_n,m)$ (equation 1), which represents the logical connection of a path from input n to output m :

$$A_{nm}(j_n,m) = U_n(j_n) + C_m(m) = \begin{cases} 1\ , & j_n \neq m \\ 2\ , & j_n = m \end{cases} \qquad (1)$$

$A_{nm}(j_n,m)$ represents the peak value obtained from the addition of frames $U_n(j_n)$ and $C_m(m)$. The **control function** $S_{nm}(j_n,m)$ is derived from $A_{nm}(j_n,m)$ by operation with a threshold function. This threshold function, with parameter **t**, may be represented by a modified **Sgn** function with levels 0 and 1 (representative of the amplitude of optical signals) instead of the conventional ± 1.

$$S_{nm}(j_n,m) = \mathbf{Sgn}\{ A_{nm}(j_n,m) - \mathbf{t} \} = \begin{cases} 0, & j_n \neq m, \\ 1, & j_n = m, \end{cases} \quad \text{for } 1 < t < 2 \tag{2}$$

$$= \delta_{j_n,m} \quad \text{(the Delta function)} \qquad \text{for the same } \mathbf{t}$$

The sets of data and clock inputs are represented by vectors $\mathbf{U_n(T)}$ and $\mathbf{C_m(T)}$ as shown in figure 2. These vectors are converted to matrices by multiplication with unity vectors $\mathbf{I_m}$ and $\mathbf{I_n}$. The resultant matrix $\mathbf{U_{nm}(T)}$ is column replicative and $\mathbf{C_{nm}(T)}$ is row replicative (shown schematically in figure 4).

$$\mathbf{U_{nm}(T)} = \mathbf{U_n(T)} \cdot \mathbf{I_m} \tag{3}$$

$$\mathbf{C_{nm}(T)} = \mathbf{I_n} \cdot \mathbf{C_m(T)} \tag{4}$$

The crossbar switch crosspoints are controlled directly by the output of the POP. This output, termed the **control matrix** $\mathbf{S_{nm}(j_n,m)}$, is derived from equations 1 - 4 and given by equation 5.

$$\mathbf{S_{nm}(j_n,m)} = \mathbf{Sgn}\{ \mathbf{A_{nm}(j_n,m)} - \mathbf{t_{nm}} \}, \quad \text{for} \begin{cases} 1 < \mathbf{t_{nm}} < 2 \\ 1 < n < N \\ 1 < m < M \end{cases}$$

$$= \begin{bmatrix} \delta_{j_1,1} & \delta_{j_1,2} & \delta_{j_1,3} & \cdots & \delta_{j_2,M} \\ \delta_{j_1,1} & \delta_{j_1,2} & \delta_{j_1,3} & \cdots & \delta_{j_2,M} \\ \vdots & & & & \vdots \\ \delta_{j_N,1} & \delta_{j_N,2} & \delta_{j_N,3} & \cdots & \delta_{j_N,M} \end{bmatrix} \tag{5}$$

Implementation

Free-space optical systems are a natural domain for three-dimensional processing architectures. The POP processor is designed using passive optical components as shown in figure 4. Fiber-optic input vectors $\mathbf{U_n(T)}$ and $\mathbf{C_m(T)}$ are replicated as described by (3) and (4) using binary phase gratings [7]. Matrices $\mathbf{U_{nm}(T)}$ and $\mathbf{C_{nm}(T)}$ are added by a beam combiner to produce two pulse coincidence matrices $\mathbf{A_{nm}(j_n,m)}$. Thresholding is performed using arrays of optical logic or bistable elements. The resultant control matrix $\mathbf{S_{nm}(j_n,m)}$ is used to directly activate crosspoints in a bulk optical crossbar switch by illumination onto an optically controlled spatial light modulator (SLM). The crosspoints are latched in an open state for the duration of a bit or packet using optical bias signals. For control of $LiNbO_3$ crossbars, an opto-electronic interface is required. Thresholding and opto-electronic conversion may be performed in the same stage using an array of photoconductive AND gates as described by Desuvire *et. al.* [8]. The pair of output matrices are used to generate the two different switching voltages necessary for reverse stepped delta-beta couplers [1].

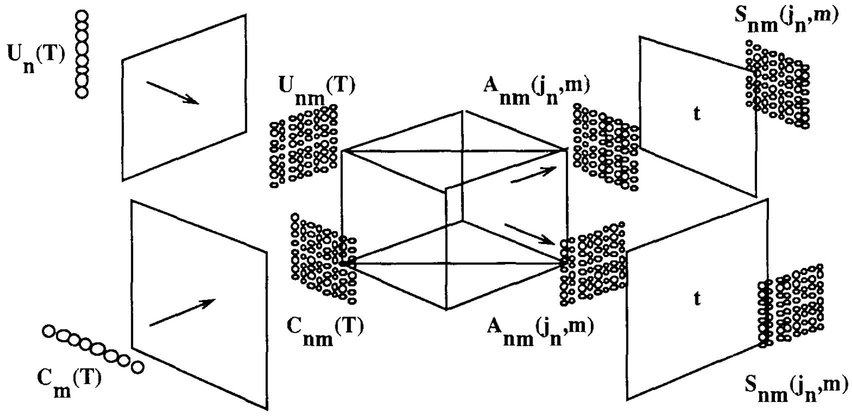

Figure 4

Efficiency

The switching power level at each threshold element in **t** is given by:

$$P_s(t) = \frac{P_{oc}}{4N^2} \qquad (6)$$

A 100 x 100 crossbar network supporting users at a 100 Mbit/s transmission rate, requires 100 ps pulses for encoding destination. A centralized laser with output power P_{oc} = 150 W will deliver a 3.75 mW switching level to each element in **t**, corresponding to a required switching energy of .375 pJ. The peak power of the control signals may be increased using an array of optical amplifiers prior to thresholding.

Summary

The important problem of controlling optical crossbar switches has been analyzed. A control formalism and it's implementation based on parallel processing have been described. The bandwidth of the processor is commensurate with the extreme bit rates offered by optical fibers. The described control method lends itself to an entirely optical implementation utilizing nonlinear optical devices, though described here with reference to electronic control signals.

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