A Space Dilated Lightwave Network–A New Approach

F. M. Suliman, A. B. Mohammad, and K. Seman

Faculty of Electrical Engineering
Universiti Teknologi Malaysia
81310 Skudai, JB, Malaysia
Email: fakher@ieee.org

***Abstract*--In this paper, the space dilation concept for reducing crosstalk in Ti:LiNbO$_3$ directional coupler-based photonic switches operating at a single wavelength is applied using a new approach. A novel switch architecture is proposed for unicast nonblocking photonic switching networks to fully exploit the advantages of this method. Some properties of the switch architecture are derived and analyzed. The *performance of the switch is also discussed and compared* with other well-known network architectures.**

***Keywords*-- optical communication, optical switches, optical couplers, optical crosstalk, optical losses**

I. INTRODUCTION

Photonic switching architectures based on 2 x 2 optical switching elements (SEs) are attractive since they can be constructed from directional couplers. The directional coupler switch is a device with two inputs and two outputs, both of which are optical signals [1]. The state of the device is controlled electrically by applying different levels of voltage on the electrodes.

Although other materials can be used as a substrate, lithium niobate is the most mature technology for directional coupler optical switch fabrication. A feature of these switches is they can route optical information regardless of its bit rate or coding format. Several directional coupler-based architectures had been proposed in the literature [2,4,5,9,10,11].

Performance of optical architectures may be characterized by the following parameters:

1. Optical path loss (worst case)
2. Crosstalk (worst case)
3. Total number of couplers required.
4. Blocking properties

Attenuation of light passing through the optical architecture is directly proportional to the number of couplers that the optical signal passes through. Therefore, for the purposes of this paper, the number of couplers in an inlet-outlet path will be used to characterize the optical path loss.

There are two ways in which optical paths can interact with each other in a planar switching network causing optical crosstalk. The channels (wave-guides) carrying the signals could cross each other in order to imbed a particular topology. This is called channel crossover. Alternatively, two paths sharing a switching element will experience some undesired coupling from one path to the other. This is called the switch crosstalk. The channel crossover however can be made negligible if the intersection angle is greater than 3°[4]. Thus, we will assume that switch crossovers are the major source of crosstalk in directional-coupler-based optical switching networks. The number of switching elements is a measure of the networks' implementation cost. Regarding the blocking properties, a network is either nonblocking in the strict sense, nonblocking in the wide-sense, rearrangeable, or blocking [3].

The principal contribution of this paper is a novel architecture for nonblocking multistage space photonic switches implemented using Ti:LiNbO$_3$ directional couplers. The networks utilize a new approach of space dilation that guarantees connections between inputs and outputs with minimum switch crossovers and hence reduced crosstalk. Some properties including the number of SEs required, number of crossovers, system attenuation, and signal-to-noise ratio (SNR) are derived.

Section II of this paper provides an overview of the basic element of our new architecture. In section III, the development of the new NxN nonblocking switching network architecture is explained. The network properties are derived in section IV and the performance of the developed switch compared with other well-known designs is discussed in section V. Section VI concludes the discussion.

II. THE BASIC ELEMENTS

The spatial dilation concept for reducing crosstalk in switches operating at a single wavelength is well known [6]. It has been shown that adding more switches and switching signals via paths where only one signal is active can reduce the crosstalk. Fig. 1 illustrates the dilation principle. A 2 x 2 basic element switch is shown together with its dilated version. If ε denotes the crosstalk intensity for the 2 x 2 switch element, it is straightforward to show that the dilated version exhibits crosstalk of O (ε^2).

The basic elements of our design are based on this concept. They are modified versions of Fig. 1 (b) as shown in Fig. 2.

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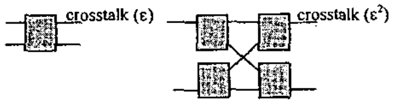
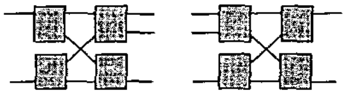


(a) (b)

Fig. 1 (a) A 2 x 2 switch and (b) its space-dilated version



(a) (b)

Fig. 2 A space-dilated element: (a) 2 x 3, and (b) 3 x 2

We will consider the 2 x 3 element as an input element and the 3 x 2 element as an output element. Without applying any control on them both elements suffer crosstalk at only one stage (i.e. the second stage of the input element and the first stage of the output element). The input element can however, be controlled – as in dilated Benes networks – to be free of first order crosstalk. For unicast connections, only two signals will arrive at the inputs of the output element and therefore both elements are nonblocking in the strict sense.

III. THE SWITCH ARCHITECTURE

The elements of Fig. 2 are symbolized in Fig. 3. The proposed architecture is constructed by adapting the idea of the Clos network. The input elements will be used on the input (left) side while the output elements will be used on the output (right) side of the network. In our case -of course- we have more stages because we are using the input elements and the output elements in correspondence to the elements of the first and the last stages of the Clos network (and subnetworks) respectively.

The general NxN switch network where $N=2^n$, n is an integer and $n \geq 2$ is illustrated in Fig. 4. The analysis of the network can be made in the following manner. For this network and all its' subnetworks, all input switches are 2x3 elements and all output switches are 3x2 elements. Connection between a given input switch and a given output switch is made via three subnetworks each consisting of N/2xN/2 similar architecture. The analysis is recursively applied on the subnetworks themselves.

To illustrate an example a 4x4 network employing the 2x3 and 3x2 elements is presented in Fig. 5 .The network consists of two 2x3 input elements, three 2x2 subnetwork switches, and two 3x2 output elements. The 2x3 and 3x2 switches are shown inside dashed boxes. Actually, the 4 x 4 switch represents the smallest network that can exploit the advantages of this space dilation approach and the basic 2x2 SE represents the smallest possible subnetwork.

(a) (b)

Fig. 3. The symbols for (a) the 2 x 3 and (b) the 3 x 2 element

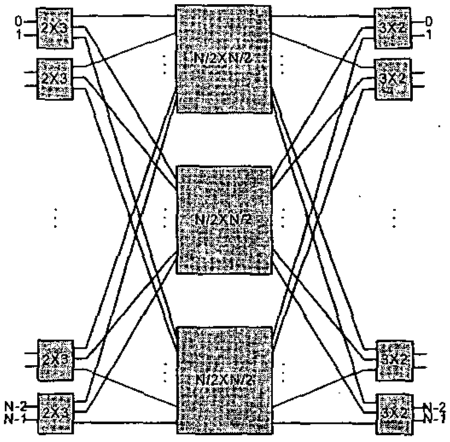


Fig. 4. The proposed N x N network

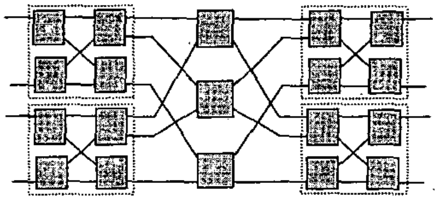


Fig. 5. A 4 x 4 space dilated network

IV. SOME PROPERTIES OF THE PROPOSED NETWORK

A. Nonblocking Characteristics

The proposed network is shown to be nonblocking in the strict-sense by the following properties:

Lemma 1 *The 2x3 and 3x2 elements are strict-sense nonblocking.*

Any future connection can always be made without disturbance or additional rearrangement of the existing paths.

Lemma 2 *The architecture guarantees that the network is free of internal blocking.*

This is true because the network follows the same idea of the 3-stage Clos architecture and therefore a free path always exists to connect a new call.

B. Total Number of Switching Elements

To calculate the total number of SEs for the proposed network let SE_T and SE_S represent the SEs of the complete network and of the subnetwork, respectively. Since any NxN network has N basic elements each consisting of 4 switches and three subnetworks, we can write:

$$SE_T = 4N + 3.SE_S \tag{1}$$

If the subnetworks are analyzed in the same way and SE_S is recursively substituted a general formula can be obtained. So generally;

$$SE_T = 3^{n-1} + 2^n \sum_{x=1}^{n-1} 2^{n-x}.3^x \tag{2}$$

C. System Attenuation

The system attenuation of an optical network is determined primarily by the insertion loss of the architecture. For simplicity, we ignore the effect of the crossover factor, which is less significant to the system attenuation. The insertion loss is dependent upon the number of SEs that a connection must travel. A switch in $LiNbO_3$ has an insertion loss L, in dB, associated with it. An additional attenuation occurs due to waveguide-to-fiber coupling and is represented by W, in *dB*. Typically, L=1dB and W=1-2 dB.

It can be shown that each connection on the proposed network has to travel across a number of $(4n-3)$ SEs. Thus, the maximum insertion loss for the network is given by:

$$IL = (4n-3)L + 2.W \tag{3}$$

D. Signal to-Noise Ratio

Each SE that signal passes through introduces a small amount of crosstalk from other channel into the desired signal channel. The signal-to-noise ratio (SNR) for an optical switch can be estimated by determining the number of SEs that the signal passes through and how much power will be leaked into the signal channel at each point.

For the proposed network, because of the dilation approach applied and the architecture adopted, crosstalk is only encountered at all even stages plus the middle stage. In the 4x4 network of Fig. 5, for instance, crosstalk occurs at stage two and four plus the middle stage, stage three. the total number of SEs that can cause crosstalk in the worst case is therefore $2\log_2 N - 1$. The SNR can be calculated using an approach similar to that in [9].

Let $P_{out(i)}$ represent the total power in dB of a signal that arrives at a given outlet i. Thus,

$$P_{out(i)} = P_{in(i)} - IL \tag{4}$$

Where $P_{in(i)}$ is the power in dB entered into inlet i and IL is the system insertion loss. The noise that enters the outlet is the sum of the noise power that enters in the form of crosstalk. In the worst case, the noise that enters the outlet i from inlet j, $P_{N(i,j)}$, can be calculated as,

$$P_{N(i,j)} = P_{in(i)} - X - IL \tag{5}$$

Where X is the extinction ratio of the switch element. The total noise in the outlet i is the sum of the noise power caused by $2\log_2 N - 1$ channels. Therefore, we have

$$P_{N(total)}[Watts] = (2n-1).P_{N(i,j)}[Watts] \tag{6}$$

Converting into decibels gives

$$P_{N(total)}[dB] = 10\log_{10}(2n-1) + P_{N(i,j)}[dB] \tag{7}$$

The worst case SNR is

$$SNR = P_{out(i)} - P_{N(total)} \tag{8}$$

By equations (4), (5), and (7), we have

$$SNR = X - 10\log_{10}(2n-1) \tag{9}$$

E. Maximum Number of Crossovers Between an Inlet-Outlet Pair

The number of crossovers in a single substrate optical switch has an important influence on the performance [8]. Crossovers may cause crosstalk, signal loss, and design complexity. The maximum number of crossovers that a path for an inlet-outlet pair must travel is related to the worst case system attenuation and the SNR. Let C(N) represent the maximum number of crossovers between an inlet-outlet pair in an NxN network and C(N/2) represent the maximum number of crossovers inside the subnetwork. Observing Fig. 7, the maximum number of crossovers that can be traveled by a signal along the worst-case inlet-outlet path is:

$$C(N) = 2(N-1) + C(N/2) \tag{10}$$

By recursively calculating for the crossovers inside the subnetworks,

$$\begin{aligned} C(N) &= 2(N-1) + 2(N/2-2) + 2(N/4-2) \\ &+ \ldots + 2(N/N/4-2) + 2(n-1) \end{aligned} \tag{11}$$

With N=2^n, we have

$$C(N) = 2(n-1) + 2\sum_{k=0}^{n-2}(2^{n-k} - 2) \quad (12)$$

V. PERFORMANCE ANALYSIS AND COMPARISON

Several photonic switching architectures are compared with the proposed network. They are the crossbar, the N-stage planar, the Benes, the 3-stage Clos, and the NWN networks. Most of these networks have been analyzed and compared in the literature [4,9,10,11]. We compare them further with our network. A summary on the characteristics of these networks is given in Table 1.

A. Blocking Characteristics

The proposed network shows same nonblocking performance as the Clos network which is better than the performance of the other networks. The crossbar switch used to be reported as strictly nonblocking because it is easy to enforce. We list it as nonblocking in wide sense by definition.

B. Number of SEs Required

The number of SEs required in each type of network is plotted in Fig. 6. The 3-stage Clos network is made up by n x m subnetworks at the first stage, r x r subnetworks at the middle stage, and m x n subnetworks at the last stage. It can be shown that $N=r.n$. It is also well known that a 3-stage Clos network is nonblocking if $m=2n-1$. We assume crossbar switches are used in each stage of Clos network. The Benes, the N-stage planar, and the NWN networks require fewer SEs than the others. The proposed network, however, requires fewer couplers than the Crossbar and the Clos networks.

C. Insertion Loss

The system insertion loss in dB for each network is plotted in Fig. 7, where L=1dB and W=2dB. As in [10] the maximum attenuation allowed for the system without amplification or regeneration is assumed to be 30 dB.

The Benes, the EBN, and the NWN networks have the lower insertion. However, the Benes network is rearrangeably nonblocking while the extended baseline has more crossovers. Since the NWN network results in a far lower IL from the assumed constrain of 30dB, it is possible to apply the design idea for larger size networks (≈128).

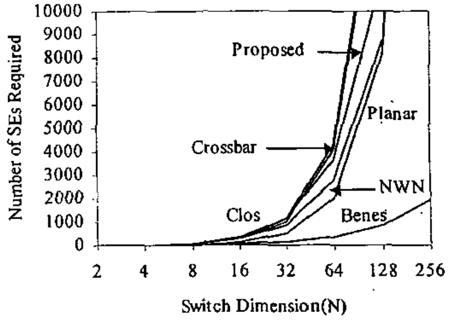


Fig. 6 The number of SEs required for various network topologies

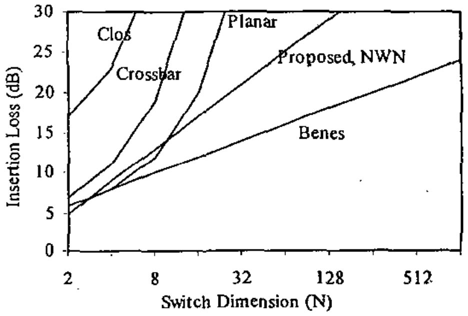


Fig. 7 The system insertion loss for various network topologies

TABLE 1
CHARACTERISTICS OF VARIOUS TYPES OF NETWORKS

Network	Nonblocking	Number of SEs	IL(dB)	SNR(dB)	Crossovers
Crossbar	Wide-sense	N^2	$(2N-1).L+2.W$	$X-10\log_{10}(N-1)$	0
Planar	Rearrangeably	$N.(N-1)/2$	$N.L+2.W$	$X-10\log_{10}N$	0
Benes	Rearrangeably	$(N/2).(2n-1)$	$2n.L+2.W$	$X-10\log_{10}(2n-1)$	$2(N-n-1)$
Clos	Strict-sense	$2.n.m.r+m.r^2$	$(2.n+2.m+2.r-3).L+6.W$	$X-10\log_{10}(n+m+r)$	$2.(m-1).(r-1)$
NWN	Wide-sense	$3^{n-1}+\sum_{x=1}^{n-1}2^{n+1}.(3/2)^x$	$(4n-3).L+2.W$	$X-10\log_{10}(2n-1)$	$4\sum_{k=1}^{n-1}(2^{n-k}-1)$
Proposed	Strict-sense	$3^{n-1}+2^n\sum_{x=0}^{n-2}2^{n-x}.3^x$	$(4n-3).L+2.W$	$X-10\log_{10}(2n-1)$	$2(n-1)+2\sum_{k=0}^{n-2}(2^{n-k}-2)$

D. Signal -to- Noise Ratio

The SNR in dB for each network is plotted in Fig. 8. The extinction loss is assumed to be 20 dB. To achieve a bit error rate of lower than 10^{-9}, the required SNR should be greater than 11dB (rough approximation). The proposed network has the same SNR performance as NWN and Benes, which is the best among the given designs. When the SNR is assumed to be 11 dB, the achievable switch dimension of the proposed network can be as large as 32

E. Maximum Number of Crossovers Between an Inlet Outlet Pair

The maximum number of crossovers between an inlet-outlet pair in the worst case for each design is plotted in Fig. 9. The crossbar and planar networks have zero crossovers (not shown in the graph). The Benes, Clos, and NWN networks have fewer crossovers than the proposed network. However, crossbar and Clos require more SEs while planar and Benes are rearrangeably nonblocking.

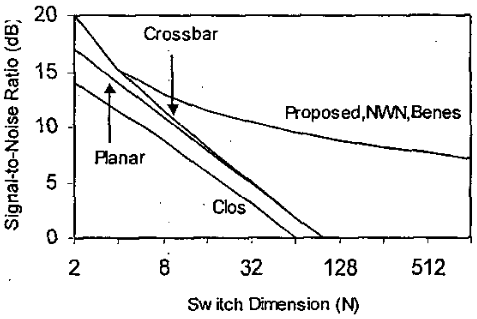


Fig. 8 The signal-to-noise ratio for various network topologies

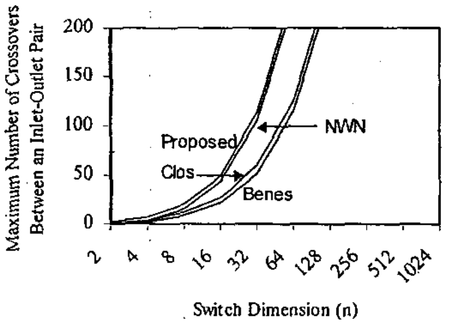


Fig. 9 The maximum number of crossovers between an inlet outlet pair for various network topologies

VI. CONCLUSION

A new approach for applying space dilation concept on lightwave networks has been presented. Based on this approach a new architecture for photonic switching networks has been proposed. The architecture is shown to be strict-sense nonblocking. Some characteristics of the proposed network are analyzed and compared with other well-known topologies.

Compared with Clos network, the proposed network requires fewer number of SEs, suffers less insertion loss, has better SNR, and can be constructed completely using 2x2 directional couplers.

Although the authors did not present all the properties of the dilated Benes network in [6] we can safely claim that the proposed network is superior to the dilated Benes in the total number of SEs required and the nonblocking performance.

ACKNOWLEDGMENT

We are indebted to the Ministry of Science, Technology and Environment (MOSTE), Malaysia for supporting this work under Vote No. 72317. F. M. Suliman extends his thanks to the Sudan government and the Sudan University of Science and Technology.

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