A Class of Self-Routing Strictly Nonblocking Photonic Switching Networks

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***Abstract*— Nonblocking interconnection networks are always favored to be used as switching networks whenever possible. Crosstalk-free requirement in photonic networks adds a new dimension of constraints for nonblockingness. Routing algorithms play a fundamental role in nonblocking networks, and any algorithm that requires more than linear time would be considered too slow for real-time applications. One remedy is to use multiple processors to route connections in parallel and the other is to construct cost effective self-routing nonblocking networks. In this paper, we propose a new class of self-routing strictly nonblocking networks by studying the connection capacity of Banyan-type networks. Compared with existing strictly nonblocking self-routing networks, the presented new networks have lower hardware cost, shorter connection diameter, and much smaller number of required wavelengths. Consequently, they are more feasible for implementation with reduced optical signal attenuation and crosstalk.**

***Index Terms*— Self-routing, crossbar, Banyan network, crosstalk, optical switching, nonblocking network.**

I. Introduction

The deployment of optical fibers as a transmission medium aroused the problem of speed mismatching between transmission and switching. To build a large IP router with capacity of 1 Tb/s and beyond, either electronic or optical switching can be used. Optical communications with photonic switching are promising to provide high bandwidth and low error probability.

A switching network usually comprises a number of electronic or photonic switching elements (SEs) grouped into several stages interconnected by a set of wires or optical links. Each SE has two inputs and two outputs, and two states, namely, *bar* and *cross* (see Fig. 1).

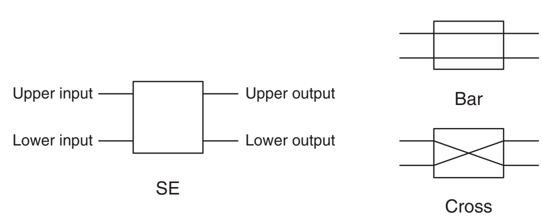

Fig. 1. An SE and its two states.

An electronic SE can be implemented by a 2×2 crossbar[1], and a photonic SE can be implemented by a 2×2 electro-optical SE such as a common lithium-niobate ($LiNbO_3$) SE (e.g. [4], [5], [15]). Each electro-optical SE is a directional coupler with two inputs and two outputs. Depending on the amount of voltage at the junction of two waveguides, optical signals carried on either of inputs can be coupled to either of outputs. An electronically controlled optical SE can have switching speed ranging from hundreds of picoseconds to tens of nanoseconds [13]. However, due to the nature of optical devices, photonic switching holds their own challenges. One problem is *path dependent loss*, the substantial signal loss on the longest connection path, which is directly proportional to *connection diameter*, the number of SEs on this path. Another problem is *crosstalk*, which is caused by undesired coupling between signals with the same wavelength carried in two waveguides so that two signal channels interfere with each other. Fig. 2 shows an example of crosstalk in an electro-optical SE. For the bar state, a small fraction of input signal injected at the upper input may be detected at the lower output (see Fig. 2). Crosstalk can also occur when an electro-optical SE is in the cross state. Consequently, the input signal will be distorted at the output due to the loss and crosstalk accumulated along a connection path.

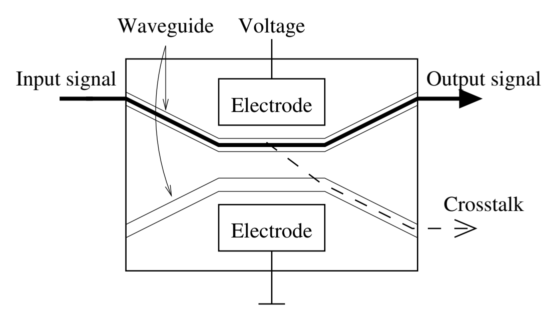

Fig. 2. Crosstalk in an electro-optical SE.

In a switching network, if multiple connections contend for a link at the same time, *link conflict* occurs. In addition to link conflict, the only type of blocking in electronic switching networks, the crosstalk problem in photonic switching networks introduces a new type of blocking, called *node conflict*, which happens when multiple connections with the same wavelength try to pass through the same SE at the same time.

If a connection path does not have any link (resp. node) conflict with other connection paths, it is called a *link conflict-free* (resp. *node conflict-free*) path. Clearly, node conflict-free path is also link conflict-free, but the converse is not true. The

[1]In this paper, an $M \times N$ network means that it has M inputs and N outputs.

process of establishing conflict-free connection paths to satisfy connection requests is called *switch routing*. A *switch routing algorithm* is needed to find these paths.

Nonblocking networks have been favored in switching systems because a conflict-free connection path is always available to connect any idle input to any idle output. One type of nonblocking networks, called *strictly nonblocking* networks, in which the connection can be established without disturbing existing connections, has the highest degree of connection capability. Routing algorithms play a more fundamental role in nonblocking networks since the nonblockingness depends on them. The high complexity of the routing algorithms may become a performance bottleneck for high-speed switching networks. Thus, switching networks, called *self-routing* networks, have been proposed. In a self-routing network, a connection can be established only by the addresses of its source and destination regardless of other connections. A self-routing network can be either blocking such as a Banyan-type network or nonblocking such as a crossbar.

To reduce path dependent loss, an optical switching network must have a small connection diameter. Crossbar network is not scalable for constructing large optical switches because of its relatively large diameter. Banyan-type networks with logarithmic diameters have been the focus of implementing optical switches. However, they are blocking networks. Although nonblocking networks can be built by horizontally concatenating extra stages to a Banyan-type network and vertically stacking multiple copies of the extended Banyan [7], [8], [10], [17], [18], routing K connections sequentially in these networks needs $\Omega(K \log N)$ time. When the number of connection requests is large, the routing time complexity is greater than $O(N)$. It turned out that simultaneously finding multiple connection paths in these networks is not a simple problem. Routing algorithms with sublinear time for this class of networks using parallel processing techniques were proposed in [9].

In this paper, we propose a self-routing strictly nonblocking network, $T(N,\alpha)$, to further reduce routing time. α is defined as *crosstalk factor*. That is, $\alpha = 0$ if the network has only link conflict-free constraint, and $\alpha = 1$ if the network has node conflict-free constraint. Networks $T(N,0)$ and $T(N,1)$ are suitable for electronic and optical implementation, respectively. Compared with existing strictly nonblocking self-routing networks, the presented new networks $T(N,\alpha)$ have lower hardware cost, shorter connection diameter, and much smaller number of required wavelengths.

The remainder of this paper is organized as follows. In Section II, we discuss existing self-routing networks. In Section III, we study the connection capacity of Banyan network, propose a new structure $T(N,\alpha)$ for self-routing strictly nonblocking networks, and compare it with existing self-routing networks. Finally, we conclude our paper in Section IV.

II. Existing self-routing networks

A. Crossbar

Basically, an $N \times M$ crossbar, as shown in Fig 3 (a), consists of an array of $N \times M$ individually operated switching points. For electronic switching, these points are called *crosspoints*. Each crosspoint has two logical states: *cross* and *bar* states, as shown in Fig 3 (b). For photonic switching, switching points can be implemented by electro-optical SEs, as shown in Fig 3 (c).

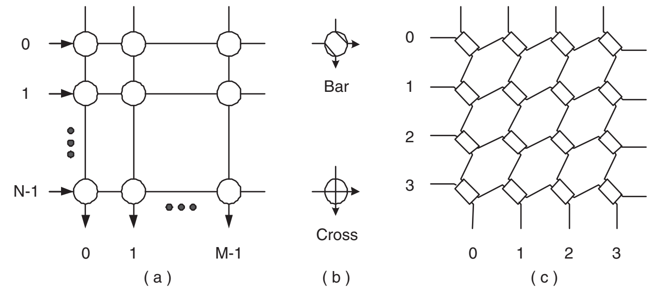

Fig. 3. (a) Crossbar. (b) States of crosspoint. (c) A 4×4 crossbar for photonic switching.

A connection between input i and output j in a crossbar is established by setting the (i,j)-th switching point to be bar state while letting other switching points along the connection remain the cross state. The bar state of a switching point can be triggered individually by the destination of each incoming connection.

The crossbar has three attractive properties: it is strictly nonblocking, simple in architecture, and self-routing. For an $N \times N$ crossbar, however, the hardware cost in terms of the number of crosspoints and SEs is N^2 and its connection diameter is $2N-1$ (because the longest connection path from 0 to $N-1$ needs to pass $2N-1$ switching points). To our knowledge, all known strictly nonblocking networks with hardware cost less than $O(N^2)$ are not entirely self-routing.

B. Banyan-type Network

A network belonging to the class of *Banyan-type* networks satisfies the following basic properties:

(i) It has N inputs, N outputs, $\log N$-stages and $N/2$ SEs in each stage[2].

(ii) There is a unique path between each input and each output.

(iii) Let u and v be two SEs in stage i, and let $S_j(u)$ and $S_j(v)$ be two sets of SEs to which u and v can reach in stage j, $0 < j = i+1 \leq \log N$. Then $S_j(u) \cap S_j(v) = \emptyset$ or $S_j(u) = S_j(v)$ for any u and v.

Several well-known networks, such as *Banyan*, *Omega*, *Shuffle*, and *Baseline*, belong to this class. It has been shown that these networks are topologically equivalent [1], [20]. In this paper, we use Baseline network as the representative of Banyan-type networks.

An $N \times N$ Baseline network, denoted by $BL(N)$, is constructed recursively. A $BL(2)$ is a 2×2 SE. A $BL(N)$ consists of a switching stage of $N/2$ SEs, and a shuffle connection, followed by a stack of two $BL(N/2)$'s. Thus a $BL(N)$ has $\log N$ stages labeled by $0, \cdots, \log N - 1$ from left to right, and each stage has $N/2$ SEs labeled by $0, \cdots, N/2-1$ from top to bottom. The upper and lower outputs of each SE in stage i are connected with two $BL(N/2^{i+1})$'s, named *upper subnetwork* and *lower subnetwork*, respectively. The N links interconnecting two adjacent stages i and $i+1$ are called *output links* of stage i and *input links* of stage $i+1$. The N

[2]In this paper, we let $n = \log N$ and all logarithms are in base 2.

input links in the first stage of $BL(N)$ are connected with the N inputs of $BL(N)$ and the N output links in the last stage of $BL(N)$ are connected with N outputs of $BL(N)$. To facilitate our discussions, the label of each stage, link and SE is represented by a binary number. Let $a_l a_{l-1} \cdots a_1 a_0$ be the binary representation of a. An example is shown in Fig. 4.

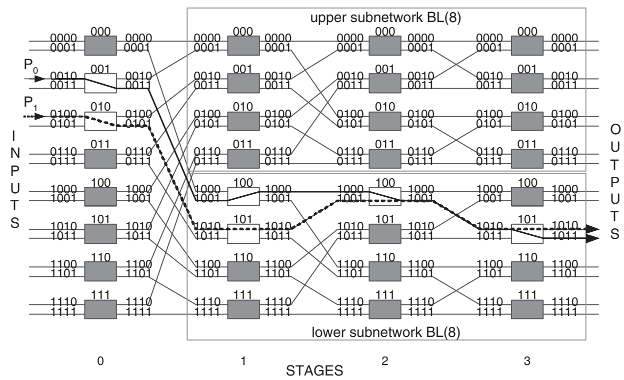

Fig. 4. Self-routing of Baseline network $BL(16)$.

Self-routing in $BL(N)$ is decided by the destination address, $d_{n-1}d_{n-2} \cdots d_0$, of each connection. If $d_{n-i-1} = 0$, the input of the SE on the connection path in stage i is connected to the SE's upper output, and to the lower output otherwise (i.e., $d_{n-i-1} = 1$). As shown in Fig. 4, the connection paths P_0 and P_1 are set up by self-routing in $BL(16)$. For example, for connection from 0010 to 1011, since its destination is 1011, the connection path P_0 passes the lower, upper, lower, and lower outputs of the SEs 1, 4, 4 and 5 in stages 0, 1, 2, and 3, respectively. P_0 and P_1 have the output link conflict in stage 2 and input link conflict in stage 3. If each SE is an electro-optic SE in $BL(16)$, then they also have node conflicts at SEs 4 and 5 in stages 2 and 3, respectively.

The Banyan-type network has the following advantages. Firstly, it has the hardware cost $O(N \log N)$ in terms of the number of crosspoints and SEs, which makes it much more feasible than crossbar for the construction of large switching networks. Secondly, self-routing is an attractive feature in that no complex routing mechanism is needed for establishing connections. Thirdly, due to its modular and recursive structure, large-scale networks can be easily built by adding one stage of SEs and a set of links with a shuffle connection without modifying its original structure. Finally, it has short connection diameter $\log N$, which makes it suitable for optical switching. However, it is a blocking network, and it has been shown that its performance degrades rapidly as the size of the network increases.

III. A New Class of Self-Routing Strictly Nonblocking Networks

Based on $BL(N)$, we propose a new class of self-routing strictly nonblocking switching networks with $\log N$ connection diameter and less SEs and wavelengths compared with crossbar.

A. Connection Capacity of $BL(N)$

Let I be a set of N inputs, $I_0, \cdots, I_{N-1}$, and O be a set of N outputs, $O_0, \cdots, O_{N-1}$, of $BL(N)$. Let $g = 2^i$, $0 \le i \le n$. Then the k-th *modulo-g input group* comprises inputs $I_{(k-1)g}, I_{(k-1)g+1}, \cdots, I_{kg-1}$, and the k-th *modulo-g output group* comprises outputs $O_{(k-1)g}, O_{(k-1)g+1}, \cdots, O_{kg-1}$, where $1 \le k \le N/g$.

We say that two connections *share* a modulo-g input (resp. output) group if their sources (resp. destinations) are in the same modulo-g input (resp. output) group. Clearly, if two connections do not share any modulo-g_1 input (resp. output) group, then they do not share any modulo-g_2 input (resp. output) group with $g_2 \le g_1$. Let us study the connection capability of $BL(N)$ first.

Lemma 1: For any connection set C of $BL(N)$, if no two connections in C share any modulo-g input group, then the connection paths for C are node conflict-free in the first $\log g$ stages; if no two connections in C share any modulo-g output group, then the connection paths for C are node conflict-free in the last $\log g$ stages, $2 \le g \le 2^n$.

It is easy to verify that Lemma 1 is true according to the topology of $BL(N)$. For brevity, we omit the proof of this lemma. For example, in Fig. 4, two connections along paths P_0 and P_1 do not share any modulo-4 input group, and thus, there is no node conflict in the first two stages. But they share the first modulo-8 input group and the sixth modulo-2 output group, and thus, there are node conflicts in stages 2 and 3. By Lemma 1, the following claim can be derived.

Lemma 2: Given a connection set C of $BL(N)$, if any two connections in C do not share any modulo-$2^{\lfloor \frac{n+\alpha}{2} \rfloor}$ input group and also do not share any modulo-$2^{\lfloor \frac{n+\alpha}{2} \rfloor}$ output group, then
(i) for $\alpha = 0$, there is no link conflict in $BL(N)$;
(ii) for $\alpha = 1$, there is no node conflict in $BL(N)$.

Proof: We prove the lemma by considering the following two cases.

1) n is even:
We have $2^{\lfloor \frac{n+\alpha}{2} \rfloor} = 2^{\frac{n}{2}}$. Since there are no two connections sharing any modulo-$2^{\frac{n}{2}}$ input and output groups, by Lemma 1, there is no node conflict in the first $\frac{n}{2}$ and last $\frac{n}{2}$ stages. Since $\frac{n}{2} + \frac{n}{2} = n$, there is no node conflict in all n stages of $BL(N)$. Since no node conflict in stage i implies no link conflict in stage i. Thus, there is neither link conflict nor node conflict in $BL(N)$.

2) n is odd:
2.1) For $\alpha = 0$, we have $2^{\lfloor \frac{n+\alpha}{2} \rfloor} = 2^{\frac{n-1}{2}}$. Since there are no two connections sharing any modulo-$2^{\frac{n-1}{2}}$ input and output groups, by Lemma 1, there is no node conflict in the first $\frac{n-1}{2}$ stages, stage 0 to stage $\frac{n-3}{2}$, and last $\frac{n-1}{2}$ stages, stage $\frac{n+1}{2}$ to stage $n-1$. Thus, there is no node conflict in all stages except the central stage, stage $\frac{n-1}{2}$, of $BL(N)$. Since the output links of stage $\frac{n-3}{2}$ is the input links of stage $\frac{n-1}{2}$ and the input links of stage $\frac{n+1}{2}$ is the output links of stage $\frac{n-1}{2}$, there is no link conflict in all stages of $BL(N)$.
2.2) For $\alpha = 1$, we have $2^{\lfloor \frac{n+\alpha}{2} \rfloor} = 2^{\frac{n+1}{2}}$. By Lemma 1, there is no node conflict in the first $\frac{n+1}{2}$ and last $\frac{n+1}{2}$ stages Since $\frac{n+1}{2} + \frac{n+1}{2} > n$, there is no node conflict in $BL(N)$. □

By Lemma 2, if we only allow one connection to pass through each modulo-$2^{\lfloor \frac{n}{2} \rfloor}$ input and output groups at any time, then we can route connections in $BL(N)$ without link conflict; if we only allow one connection to pass through each modulo-$2^{\lfloor \frac{n+1}{2} \rfloor}$ input and output groups at any time, then we can route connections in $BL(N)$ without node conflict. The new class of self-routing strictly nonblocking networks will be built based on this idea.

B. Constructing $T(N,\alpha)$

In this subsection, we assume that $M = 2^m = \frac{N^2}{2^{1-\alpha}}$ and $g = \frac{N}{2^{1-\alpha}} = 2^{n-1+\alpha}$.

Lemma 3: Given a connection set C of $BL(M)$, if neither do two connections share any modulo-g input group nor do they share any modulo-g output group in a given connection set C, then C can be set up without conflict in $BL(M)$.

Proof: By $M = 2^m = \frac{N^2}{2^{1-\alpha}} = (2^n)^2 2^{-1+\alpha} = 2^{2n-1+\alpha}$, we have $m = 2n-1+\alpha$. According to Lemma 2, if any two connections in C do not share any modulo-$2^{\lfloor \frac{m+\alpha}{2} \rfloor} = 2^{\lfloor \frac{2n-1+2\alpha}{2} \rfloor} = 2^{n-1+\alpha}$ input and output groups at any time, then we can route the connections of C in $BL(M)$ with link conflict-free constraint (i.e. $\alpha = 0$) or with node conflict-free constraint (i.e. $\alpha = 1$). □

We select the first input in each modulo-g input group of $BL(M)$ as a *useful* input of $BL(M)$, and the first output in each modulo-g output group of $BL(M)$ as a *useful* output of $BL(M)$. Clearly, $M/g = N$. Thus, restricted to these useful inputs and outputs, $BL(M)$ can be used as an $N \times N$ self-routing switching network with link or node conflict-free constraint, depending on the value of α by Lemma 3. In the following we show how to construct an $N \times N$ self-routing strictly nonblocking network, denoted by $T(N,\alpha)$, from $BL(M)$.

We first give some definitions. A link (resp. SE) is called a *redundant link (resp. SE)* if its removal will not affect the switching functionality of $BL(M)$ for establishing connections from N useful inputs to N useful outputs; otherwise it is called an *essential link (resp. SE)*. $T(N,\alpha)$ is constructed from $BL(M)$ by performing the following two steps to remove all redundant links and SEs.

Step 1. Because $BL(M)$ has $m = 2n-1+\alpha = n + \log g$ stages, the subnetworks of $BL(M)$ induced by the SEs from stage n to the last stage form a set of 2^n $BL(g)$'s. Since each of these $BL(g)$'s is connected with exactly one useful output of $BL(M)$, at most one of any given set of connections from useful inputs to useful outputs is routed though each $BL(g)$. We replace each of these $BL(g)$'s by a $g \times 1$ combiner, and set the output of this combiner as an output of $T(N,\alpha)$.

Step 2. To complete the construction of $T(N,\alpha)$, we need to remove additional redundant SEs and links in the first n stages of $BL(M)$. It can be done by starting from stage 0 to stage $n-1$ as follows. Initially, N useful inputs are considered to be connected with N essential links in stage 0. In stage i, $0 \le i \le n-1$, do the following operations. Firstly, we identify all essential SEs and links: if an SE has one of input connecting with an essential link, it is marked as an essential SE and its two output links are marked as essential links. Secondly, we remove all redundant SEs and links: if a link is not an essential link, it is removed; if both input links of an SE have been removed, this SE and its two output links are considered redundant and removed.

Fig. 5 (a)(i) and (b)(i) show $BL(32)$ and $BL(64)$, respectively, where essential links and SEs are highlighted with dark color and redundant links and SEs are colored gray. Fig. 5 (a)(ii) and (b)(ii) show $T(8,0)$ and $T(8,1)$ constructed from $BL(32)$ and $BL(64)$, respectively.

In $BL(M)$, we know that two outputs of each SE in one stage are connected with two SEs of next stage, one in the upper subnetwork and the other in the lower subnetwork. Thus, the number of essential SEs in stage i ($0 \le i \le n-1$) equals to $\min\{2^i N, M/2\} = \min\{2^{n+i}, 2^{2n-2+\alpha}\}$. Let $s(N,\alpha)$ denote the number of SEs in $T(N,\alpha)$. It is easy to verify that there are 2^{n+i} essential 1×2 SEs in stage i, ($0 \le i \le n-2$), $2^{2n-2+\alpha}$ essential $(2-\alpha) \times 2$ SEs in stage $n-1$, and zero essential SE in the remaining stages of $BL(M)$. Therefore, by a simple calculation, the total number of SEs in $T(N,\alpha)$ is

$$s(N,\alpha) = \sum_{i=0}^{n-2} 2^{n+i} + 2^{2n-2+\alpha} = \frac{3+\alpha}{4} N^2 - N$$

$$= \begin{cases} \frac{3N^2}{4} - N, & \text{if } \alpha = 0 \\ N^2 - N, & \text{if } \alpha = 1 \end{cases}$$

In $T(N,\alpha)$, input (resp. output) i is corresponding to input (resp. output) i' of $BL(M)$, where the binary representation of i' is the binary representation of i concatenating with $\log g$ 0s at the end. It means that the first $\log M - \log g = n$ bits for i and i' are the same. Therefore, the routing process in $T(N,\alpha)$ is the same as that in $BL(N)$, which is self-routing.

We summarize the above discussions by the following claim.

Theorem 1: $T(N,\alpha)$ is an $N \times N$ self-routing strictly nonblocking network of $\log N$ stages. For $\alpha = 0$, it consists of $\frac{3N^2}{4} - N$ SEs, among which $\frac{N^2}{2} - N$ SEs are of size 1×2

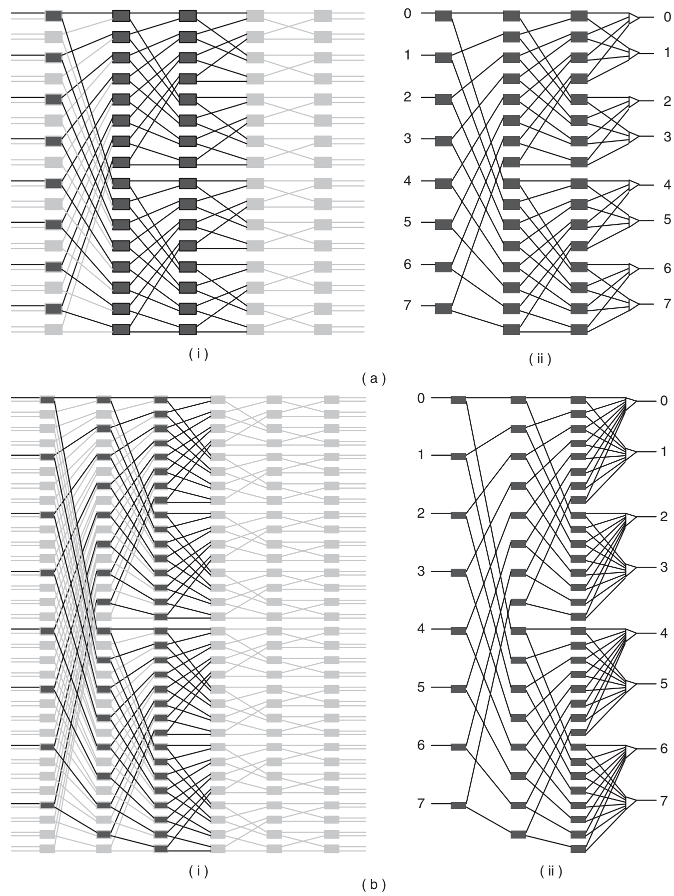

Fig. 5. (a) Construction of $T(8,0)$ from $BL(32)$. (b) Construction of $T(8,1)$ from $BL(64)$.

and $\frac{N^2}{4}$ SEs are of size 2×2; for $\alpha = 1$, it consists of $N^2 - N$ SEs, all of size 1×2.

An optical switching network is considered *crosstalk-free* if the connections passing through the same SE have different wavelengths ([3], [12], [14], [19]) provided any two connections neither share an input nor share an output of this network. For practical reasons, the number of wavelengths used must be small. Clearly, if two connection paths are allowed to pass through an SE, then at least two wavelengths are required. In general, two wavelengths are not sufficient for an optical switching network. For example, for an $N \times N$ crossbar, in order to establish an identity permutation, which means input i is mapped to output i, then N wavelengths are necessary for crosstalk-free routing. In this aspect, $T(N, \alpha)$ is superior, as indicated in the following claim.

Corollary 1: $T(N, 1)$ is crosstalk-free with one wavelength and $T(N, 0)$ is crosstalk-free with two wavelengths.

Proof: Since all SEs in $T(N, 1)$ are of size 1×2, there is only one connection can be passed through an SE at one time. Thus, one wavelength is sufficient for crosstalk-free routing in $T(N, 1)$. All SEs in $T(N, 0)$ are of size 1×2 except the ones in the last stage. Thus, a total of two wavelengths are sufficient to ensure that the connections passing trough the same SEs use different wavelengths. □

C. Comparison

Compared with self-routing Banyan-type networks, $T(N, \alpha)$ is strictly nonblocking, which is promising for high performance switching.

Smaller connection diameter is very important for optical implementation. The attenuation of light passing through optical switching networks has several components such as fiber-to-switch and switch-to-fiber coupling loss, propagation loss in the medium, loss at waveguide bends, loss at the couplers, etc. In a large switching network, a substantial part of this attenuation is directly proportional to the number of couplers that the optical path passes through. Thus, the connection diameter is used to characterize the signal loss [11].

Compared with an $N \times N$ crossbar for photonic switching, $T(N, 1)$ requires slightly fewer number of SEs and only one wavelength; $T(N, 0)$ requires much fewer number of SEs with two wavelengths available. The difference between $N \times N$ crossbar and $T(N, \alpha)$ for photonic switching is much more noticeable as shown in Table I.

Networks	Number of SEs	Diameter	Number of wavelengths
Crossbar	N^2	$2N - 1$	N
$T(N, 0)$	$\frac{3N^2}{4} - N$	$\log N$	2
$T(N, 1)$	$N^2 - N$	$\log N$	1

TABLE I

COMPARISON OF SELF-ROUTING STRICTLY NONBLOCKING PHOTONIC SWITCHING NETWORKS

IV. CONCLUSION

For the design of a switching network, in addition to its hardware cost in terms of the cost of SEs and interconnection links and wavelengths, we must take the routing complexity into consideration. One major contribution of this paper is the design of a strictly nonblocking self-routing network $T(N, \alpha)$ with connection diameter of $\log N$ and routing time of $O(\log N)$. Compared with crossbar, the presented new self-routing nonblocking networks have lower hardware cost, shorter connection diameter, and much smaller number of required wavelengths. The results of this paper have valuable architectural implications for design and implementation of future large-scale electronic and optical switching networks.

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