Design of Optical Rearrangeable Nonblocking MINs Under Various Crosstalk Constraints

Xiaohong Jiang and Susumu Horiguchi
Graduate School of Information Science,
TOHOKU University, Aobayama 09, Aramaki SENDAI 980-8579, Japan.
Phone/Fax: +81-22-217-7066
Email: {jiang, susumu}@ecei.tohoku.ac.jp

Hong Shen
Graduate School of Information Science, JAIST,Japan.

Abstract⁻ Optical interconnection networks suffer from the intrinsic crosstalk problem that should be overcome to make them work properly. Vertical stacking of optical banyan networks is a novel scheme for constructing nonblocking optical multistage interconnection networks (MINs). Rearrangeable nonblocking optical MINs are feasible since they have lower complexity than their strictly nonblocking counterparts. In this paper, we determine the sufficient condition for these MINs to be rearrangeable nonblocking under various crosstalk constraints. We show how the crosstalk constraint affects the design of rearrangeable nonblocking MINs and demonstrate that these networks can tolerate a stricter crosstalk constraint without increasing their hardware complexity significantly. The results in the paper will be useful in designing optical MINs with reasonable hardware cost and crosstalk level.
Keywords: Banyan networks, optical crosstalk, optical MINs, rearrangeable nonblocking.

1. Introduction

It is expected that users of present and future telecommunication services like Internet, web browsing, and tele-education will increase dramatically. This has already now significantly increased the demand for high bandwidth and high capacity communication systems. Optical networks are considered as a promising candidate to meet the demand. Optical multistage interconnection networks (MINs) are a class of important optical interconnection networks, and the basic 2×2 switching element (SE) in optical MINs is usually a directional-coupler (DC) that is created by manufacturing two waveguides close to each other [1]. DC-based optical MINs can switch signals at very high speed and with multiple wavelengths. Crosstalk in DCs is a major shortcoming of DC-based optical networks. It occurs between two signals carried in the two waveguides of a DC [1, 2]. When two optical signals pass through a DC, a portion of the optical power in one waveguide will be coupled into the another unintended waveguide and this undesirable coupling is called first-order crosstalk. It will then propagate stage by stage, introducing high-order crosstalks at a reduced magnitude. Due to the stringent bit-error rate requirement of optical transmission facilities, elimination of crosstalk has become an important issue for making optical interconnection networks work properly.

Banyan networks [3] and their topological equivalence (e.g., *baseline*, *omega*) [4, 5] are a class of important MINs and they are generally referred as *banyan networks* [6]. A typical $N\times N$ banyan network consists of $\log_2 N$ stages, each containing $N/2$ 2×2 switches and the link connections between adjacent stages are implemented by recursively applying the butterfly interconnection pattern, as shown in Fig. 1.

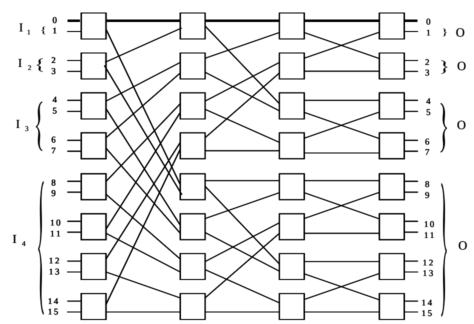

Fig. 1. 16×16 banyan network (even number of stages).

A banyan network has a simple switch setting ability (self-routing) and also a small and same number of SEs along a path between an input-output pair. These characteristics have made banyan networks attractive for constructing DC-based optical MINs because loss and attenuation of an optical signal are proportional to the number of couplers that the optical signal passes through. In banyan networks, there is a unique path between an input-output pair and hence when two connections intend to use the same link, one of them will be blocked. This is called link-blocking. There is, however, another type of blocking in optical banyan networks. If adding the connection causes some paths including the new one to violate the specified crosstalk constraint, the connection cannot be added even if the path is available. We refer to this second type of

⁻ This work is support in part by Grant-in-Aid for Scientific Research (B) under Grant No.14380138 and 16700056, Japan Science Promotion Society.

blocking as crosstalk-blocking. It is the additional crosstalk-blocking that makes the analysis of optical banyan networks different from that of the electronic ones.

Vertical stacking of multiple copies of a optical banyan network is a novel scheme for constructing nonblocking optical MINs with neither increasing the number of stages nor sacrificing the loss uniformity property of banyan networks [7]. Fig. 2 illustrates the vertical stacking scheme.

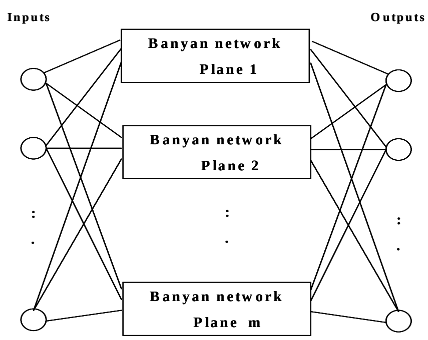

Fig. 2. Creating nonblocking network based on the vertical stacking scheme.

Rearrangeable nonblocking is an interesting choice for optical MINs. This kind of networks can route any idle input to any unused output, but one or more existing connections may have to be rerouted to establish the path. The cost and signal degradation of a rearrangeable optical network are always lower than its strictly nonblocking and wide-sense nonblocking counterparts, making rearrangeable nonblocking optical networks attractive [8, 9]. We shall focus on rearrangeable nonblocking optical MINs in this paper. The sufficient condition for a rearrangeable nonblocking optical MIN has been determined for two extreme cases of the crosstalk constraint, that is for optical MINs without any crosstalk constraint (i.e., equivalent to the analysis of electronic MINs) [7] and for optical MINs with zero first-order crosstalk [9]. Our interests of this paper is to find the sufficient condition for these MINs to be rearrangeable nonblocking under general crosstalk constraints.

2. Definitions

All paths of a banyan network have the same property in terms of blocking. To study the blocking property, we can arbitrarily select an input and an output in a banyan network and set up a connection between them. Through out this paper, we will select the path between the first input and the first output and try to set up a connection between them. We call the path between the input-output pair the tagged path. The links and the SEs along the path are called the tagged links and the tagged SEs, respectively. The stages of SEs are numbered from left (stage 1) to right (stage $\log_2 N$). The stages of links are also numbered from left (stage 0 of the input link) to right (stage $\log_2 N$ of the output link). For a tagged path, an input intersecting set I_i associated with stage i ($\forall\ 1 \le i \le \log_2 N$) is defined as the set of all inputs that intersects a tagged SE at stage i. Likewise, an output intersecting set O_i associated with stage i is the set of all outputs that intersects a tagged SE at stage $\log_2 N - i + 1$.

Since the first-order crosstalk in DCs is much bigger than the high order crosstalk, we consider only the first-order DC crosstalk in this paper, and we use the word "crosstalk" as an abbreviation for "first-order crosstalk". Note that the crosstalk occurs if two optical signals pass through a DC simultaneously, we refer to such DC as crosstalk DC (CDC). A good estimation of the level of crosstalk is given by counting the number of CDCs along a path. For an optical MIN built on the vertical stacking of banyan network, we use the notation *RB* (*c*) to refer to an $N \times N$ MIN that has the maximum of *c* CDCs along the path of each connection. The parameter *c* indicates the level of crosstalk in the network. The main work of this paper is to determine the number of planes required for a rearrangeable nonblocking *RB* (*c*) network for different values of *c*.

3. Conditions for Nonblocking Networks

In this section, we will determine the sufficient condition for *RB* (*c*) networks to be rearrangeable nonblocking under various crosstalk constraints.

3.1 *RB* ($\log_2 N$) networks

The nonblocking condition for a *RB* ($\log_2 N$) network (i.e., without any crosstalk constraint) has been determined in [7]. Here, we study the condition from another viewpoint. The method will be used to analyze the nonblocking conditions of *RB* (*c*) networks.

Theorem 1: A *RB* ($\log_2 N$) network is rearrangeable nonblocking if its number of planes *p* satisfies the following sufficient condition:

$$p \ge \begin{cases} \sqrt{N}, & \text{if } \log_2 N \text{ is even} \\ \frac{1}{2}\sqrt{2N}, & \text{if } \log_2 N \text{ is odd.} \end{cases}$$

Proof: For the following discussion, we introduce the following notations: when $\log_2 N$ is even, we define

$$U_I(N) = \bigcup_{i=1}^{(1/2)\log_2 N} I_i,\ U_I(N-1) = \bigcup_{i=1}^{(1/2)\log_2 N - 1} I_i,\ I(N) = I_{(1/2)\log_2 N}$$

Similarly, we use the notations $U_O(N)$, $U_O(N\text{-}1)$ and $O(N)$ for the corresponding output sets; when $\log_2 N$ is odd, we define

$$U_I(N-1) = \bigcup_{i=1}^{(1/2)(\log_2 N - 1)} I_i,\ I(N-1) = I_{(1/2)(\log_2 N - 1)},\ I(N+1) = I_{(1/2)(\log_2 N + 1)}$$

Similarly, we use the notations $U_O(N\text{-}1)$, $O(N\text{-}1)$ and $O(N\text{+}1)$ for the corresponding output sets.

Under the no crosstalk constraint, only link blocking can occur. So we need only to consider the tagged links in the following discussion.

We first examine the case when $\log_2 N$ is even (Fig. 1). The maximum number connections that can block the tagged path (between the first input and the first output) is determined by the number of inputs from the set $U_I(N)$ and the number of outputs from the set $U_O(N)$. The worst-case scenario of conflict with the tagged path is when each input and each output in the sets above generate a connection to block the tagged path. Since we are seeking for the condition for the rearrangeable nonblocking *RB* ($\log_2 N$) network, we need to find the minimum value of p for the network to be nonblocking. Under the worst-case scenario, connections from $I(N)$ must go to $O(N)$ to block the tagged path, each of these connections share the tagged link in the middle stage $(1/2)\log_2 N$ and must be in a separate plane.

To block the tagged path, a connection from $U_I(N\text{-}1)$ will be either destined for an output in set $U_O(N\text{-}1)$ or not. If a connection from $U_I(N\text{-}1)$ is destined for an output in set $U_O(N\text{-}1)$, then the connection will share the tagged link in the middle stage $(1/2)\log_2 N$ and must be in a separate plane other than the planes devoted to the connections from $I(N)$ to $O(N)$. If the connection is not destined for an output in set $U_O(N\text{-}1)$, then there is at least one connection destined for the set $U_O(N\text{-}1)$ which is not originated from the set $U_I(N\text{-}1)$. Thus, the two connections will share one of the planes devoted to the connections from $I(N)$ to $O(N)$. Thus, the worst-case scenario for blocked planes is when all the inputs from set $U_I(N)$ are destined to outputs in set $U_O(N)$. Therefore, only half of the total elements in these sets will be used in counting the number of blocked planes that equals $2^0+2^1+2^2+\cdots+2^{(\log_2 N)/2-1}=\sqrt{N}-1$. The tagged connection must be established in an extra plane, which brings the minimum value of p to $\sqrt{N}$ to guarantee the network to be nonblocking.

When $\log_2 N$ is odd (Fig. 3), the discussion is similar. Under no crosstalk constraint, the maximum number of connections that can block the tagged path is determined by the number of inputs from set $U_I(N\text{-}1)$ and the number of outputs from set $U_O(N\text{-}1)$. The worst-case scenario of conflict with the tagged path is when each input and each output in the above sets generates a connection to block the tagged path. To block the tagged path, the connections from $U_I(N\text{-}1)$ will be either destined for outputs in set $U_O(N\text{-}1)$ or not. Since $\sum_{i=1}^{(1/2)(\log_2 N-1)}|I_i| = \sum_{i=1}^{(1/2)(\log_2 N-1)}|O_i| = (1/2)\sqrt{2N}-1$, we suppose that there are m ($0 \le m \le (1/2)\sqrt{2N}-1$) connections from $U_I(N\text{-}1)$ which are addressed to the outputs in set $U_O(N\text{-}1)$, the m connections will share tagged links in stages $(1/2)(\log_2 N\text{-}1)$ and $(1/2)(\log_2 N+1)$ and must be in separate planes.

Note that a connection coming from set $U_I(N\text{-}1)$ but not going to set $U_O(N\text{-}1)$ can share a plane with a connection going to set $U_O(N\text{-}1)$ but not coming from set $U_I(N\text{-}1)$. Thus, the other $(1/2)\sqrt{2N}-1-m$ connections from set $U_I(N\text{-}1)$ and the $(1/2)\sqrt{2N}-1-m$ connections destined for set $U_O(N\text{-}1)$ can block at most $(1/2)\sqrt{2N}-1-m$ additional planes other than these m planes devoted to the m connections from $U_I(N\text{-}1)$ to $U_O(N\text{-}1)$. One example of such scenarios is when all these $(1/2)\sqrt{2N}-1-m$ connections from the set $U_I(N\text{-}1)$ are destined for set $O(N+1)$ (all these $(1/2)\sqrt{2N}-1-m$ connections going to set $U_O(N\text{-}1)$ are originated from set $I(N+1)$), so these $\sqrt{N}-1-m$ connections will share the tagged link in stage $(1/2)(\log_2 N\text{-}1)$ ($(1/2)(\log_2 N+1)$) and must be in separate planes other than the m planes devoted to the m connections from $U_I(N\text{-}1)$ to $U_O(N\text{-}1)$. Thus, the number of blocked planes equals $((1/2)\sqrt{2N}-1-m)+m=(1/2)\sqrt{2N}-1$ regardless the value of m. An extra plane is needed to carry the tagged connection, which brings the total number of planes to $(1/2)\sqrt{2N}$.

QED.

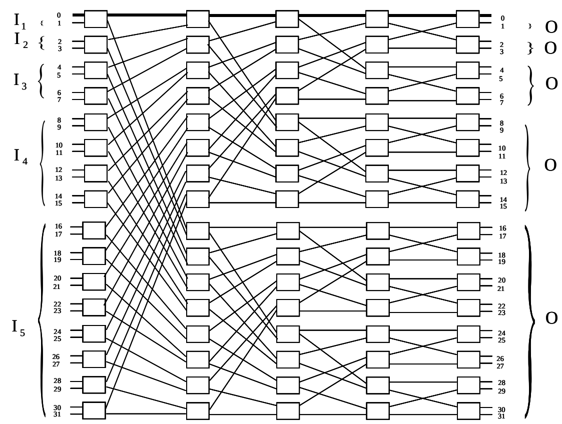

Fig. 3. 32×32 banyan network (odd number of stages).

3.2 *RB* (0) networks

A *RB* (0) is a ideal network because it has zero crosstalk. However, it usually requires a higher hardware complexity. The following theorem finds the condition for rearrangeable nonblocking *RB* (0) network.

Theorem 2: A *RB* (0) network is rearrangeable nonblocking if its number of plans satisfies:

$$p \ge \begin{cases} \sqrt{N}, & \text{if } \log_2 N \text{ is even} \\ \sqrt{2N}, & \text{if } \log_2 N \text{ is odd.} \end{cases}$$

Proof: Under the constraint of zero crosstalk, only one light signal is allowed to pass through an SE at a time. Whenever one tagged SE is used by a connection, the path is blocked. Thus, the theorem can be proved in a similar way as that of Theorem 1 except that the tagged SEs instead of tagged links should be used in the discussion, as shown in [9].

3.3 *RB* (*c*) networks

For general *RB* (c) networks that allow c ($\forall\ 0< c < \log_2 N$) CDCs along the path of a connection, the nonblocking condition will be a function of c. Note that under a specific crosstalk constraint c, both link-blocking and crosstalk-blocking can occur and the results in Theorem 1 and Theorem 2 will be the lower bound and the upper bound of the nonblocking condition of a *RB* (c) network, respectively. The following theorem finds the sufficient condition for a *RB* (c) network to be rearrangeable nonblocking.

Theorem 3: A *RB* (c) network, where $\log_2 N$ is even, is rearrangeable nonblocking if the following is true:

$p \geq \sqrt{N}, \quad 0 \leq c \leq \log_2 N.$

If $\log_2 N$ is odd, the condition will be:

$$p \geq \begin{cases} \frac{1}{2}\sqrt{2N} + \left\lfloor \frac{1}{c+2}\sqrt{2N} \right\rfloor, & if \ \ 0 < c \leq \frac{1}{2}(\log_2 N - 1) \\ \frac{1}{2}\sqrt{2N} + \left\lfloor \frac{1}{2(c+2)}\sqrt{2N} \right\rfloor, & if \ \ \frac{1}{2}(\log_2 N - 1) < c < \log_2 N. \end{cases}$$

Proof: Under a specific crosstalk constraint c, both link-blocking and crosstalk-blocking can occur and the nonblocking condition of a *RB* (c) network will be bounded by the results in Theorem 1 and Theorem 2. So the nonblocking condition for a *RB* (c) network can be obtained easily from these two theorems when $\log_2 N$ is even. In the following discussion, we shall focus on the case when $\log_2 N$ is odd.

Note that for a *RB* (c) network where $\log_2 N$ is odd (Fig. 3), the results in Theorem 1 and Theorem 2 indicate that the connections from set $U_I(N\text{-}1)$ and connections destined for set $U_O(N\text{-}1)$ can block at most $\sum_{i=1}^{(1/2)(\log_2 N-1)} |I_i| = \sum_{i=1}^{(1/2)(\log_2 N-1)} |O_i| = (1/2)\sqrt{2N} - 1$ planes regardless of the type of blocking. So, for any value of c, we need $(1/2)\sqrt{2N}$ planes to guarantee a *RB* (c) network to be rearrangeable nonblocking if we consider only the connections from set $U_I(N\text{-}1)$ and the connections destined for set $U_O(N\text{-}1)$. Under a crosstalk constraint, however, we have to consider the connections from set $I(N+1)$ to set $O(N+1)$, since they may suffer from crosstalk-blocking caused by adding the new connection of tagged path. Based on a similar treatment established in [8], we are going to find the additional number of planes that can be blocked by the connections between set $I(N+1)$ and set $O(N+1)$.

We start with the case when $1 \leq c \leq (1/2)(\log_2 N\text{-}1)$. Assume that adding the new connection will cause another connection from set $I(N+1)$ to set $O(N+1)$ violating the crosstalk constraint. To make this happens, the following two conditions must be met: 1) two elements in sets $I(N+1)$ and $O(N+1)$ have been used to establish the existing connection, and 2) c elements in sets $I(N+1)$ and $O(N+1)$ has created c CDCs along that path. Therefore, we need in total $c+2$ elements in sets $I(N+1)$ and $O(N+1)$ to cause a crosstalk violation. There are $2 \cdot 2^{(\log_2 N+1)/2-1} = \sqrt{2N}$ elements in set $I(N+1)$ and set $O(N+1)$. Thus, we need at most $\left\lfloor \sqrt{2N}/(c+2) \right\rfloor$ additional planes other than the $(1/2)\sqrt{2N}$ planes (where only the connections from set $U_I(N\text{-}1)$ and the connections destined for set $U_O(N\text{-}1)$ are considered) to guarantee the *RB* (c) network to be rearrangeable nonblocking.

We should note that although the connections from set $U_I(N\text{-}1)$ and the connections destined for set $U_O(N\text{-}1)$ can block at most $(1/2)\sqrt{2N} - 1$ planes regardless of the type of blocking, the sources and destinations of these connections may be in set $I(N+1)$ and set $O(N+1)$. Also, the connections from set $I(N+1)$ to set $O(N+1)$ may be able to share these $(1/2)\sqrt{2N} - 1$ planes devoted to the connections from set $U_I(N\text{-}1)$ and the connections destined for set $U_O(N\text{-}1)$. If considering all these factors in the discussion above, we may get a tighter bound for the case $1 \leq c \leq (1/2)(\log_2 N\text{-}1)$. The problem is that too many details are to be considered. For the case $(1/2)(\log_2 N\text{-}1) < c < \log_2 N$, however, we can tighten the bound by including sets $I(N\text{-}1)$ and $O(N\text{-}1)$ alone in the discussion (we should note that ignoring sets I_i and O_i $\forall\ 1 \leq i \leq (1/2)(\log_2 N\text{-}3)$ also indicates that the bound developed below is not the tightest either).

We are now considering the case $(1/2)(\log_2 N\text{-}1) < c < \log_2 N$. Recall that in the analysis for the connections from set $U_I(N\text{-}1)$ and the connections destined for set $U_O(N\text{-}1)$ that can block $(1/2)\sqrt{2N} - 1$ planes, we have assumed that each connection from the two sets will block the tagged path. This can be either link-blocking or crosstalk-blocking. If it is link-blocking, the connections from set $I(N\text{-}1)$ must be destined for set $O(N+1)$, this takes out $2^{(\log_2 N-1)/2-1} = (1/4)\sqrt{2N}$ elements from set $O(N+1)$. A similar discussion can be applied to set $O(N\text{-}1)$. As a result, the number of elements in sets $I(N+1)$ and $O(N+1)$ that can be used for additional crosstalk-blocking is reduced to $\sqrt{2N} - 2 \cdot (1/4) \cdot \sqrt{2N} = (1/2) \cdot \sqrt{2N}$. If the blocking is crosstalk-blocking, then a connection from set $I(N\text{-}1)$ must already have c CDCs along its path and at least one of them is from set $I(N+1)$. Similar discussions apply to set $O(N+1)$. Under this case, the number of elements of sets $I(N+1)$ and $O(N+1)$ that can be used for additional crosstalk-blocking is also reduced to $(1/2)\sqrt{2N}$. So we can conclude that when $(1/2)(\log_2 N\text{-}1) < c < \log_2 N$, then number of additional planes will be $\left\lfloor \sqrt{2N}/2(c+2) \right\rfloor$.

QED.

4. Comparisons

To illustrate the effects of the crosstalk constraint on the number of planes in a *RB* (c) network, we show in Table I the number of planes (p) required for rearrangeable nonblocking *RB* (c) networks with different sizes of the network (N) and different crosstalk constraints (c).

Table I Number of plans (p) for rearrangeable nonblocking *RB* (c) networks.

	c										
	0	1	2	3	4	5	6	7	8	9	10
N=4	2	2	2								
N=8	4	3	2	2							
N=16	4	4	4	4	4						
N=32	8	6	6	4	4	4					
N=64	8	8	8	8	8	8	8				
N=128	16	13	12	11	9	9	9	8			
N=256	16	16	16	16	16	16	16	16	16		
N=512	32	26	24	22	21	18	18	17	17	16	
N=1024	32	32	32	32	32	32	32	32	32	32	32

The results in Table I indicate that for a *RB* (c) network that has an even number of stages, we can impose the strictest restriction on the crosstalk level without the need to increase the hardware cost. For a *RB* (c) network that has an odd number of stages, we can also have a stricter crosstalk constraint without increasing the hardware significantly.

When $N = 1024$, the number of planes required by a $RB(0)$ network is 32 which is same as that of a $RB(10)$ network that does not has any crosstalk constraint; for a 32×32 network with a crosstalk constraint $c = 5$, the number of planes p is 4. This number of planes will increase only to 6 if we impose a much stricter crosstalk constraint of $c = 1$ to the network.

5. Conclusions

Vertical stacking of optical banyan network is a novel scheme for constructing optical multistage interconnection networks (MINs). In this paper, we have studied the rearrangeable nonblocking conditions for this class of optical MINs under different crosstalk constraints. An interesting conclusion drawn from our paper is to design a rearrangeable nonblocking MIN that has an even number of stages, we can impose the strictest crosstalk constraint without adding any extra hardware. For a rearrangeable nonblocking MIN that has an odd number of stages, our results indicate that we can impose a much stricter crosstalk constraint without increasing the hardware significantly. The results in this paper provide us with an efficient tool for designing optical MINs.

References

[1] H.S. Hinton: An introduction to Photonic Switching Fabrics, Plenum, New York, 1993.

[2] V.R. Chinni et al.: Crosstalk in a lossy directional coupler switch, IEEE/OSA J. Lightwave Technol., vol. 13, no. 7 (July 1995), pp. 1530-1535.

[3] G.R. Goke et al.: Banyan networks for partitioning multiprocessor systems, Proc.1st Annu. Symp. Comp. Arch, 1973, pp. 21-28.

[4] C.P. Kruskal et al.: The performance of multistage interconnection networks for multiprocessors, IEEE Trans. Commun., vol. COM-32, no. 12 (Dec. 1983), pp. 1091-1098.

[5] J.H. Patel: Performance of processor-memory interconnections for multiprocessors, IEEE Trans. Comput., vol. C-30, no. 10 (Oct. 1981), pp. 771-780.

[6] F. Thomson Leighton: Introduction to Parallel Algorithms and Architectures: Arrays, Trees, Hypercubes, Morgan Kaufmann, 1992.

[7] C.-T. Lea: Muti-$\log_2 N$ networks and their applications in high speed electronic and photonic switching systems, IEEE Trans. Commun., vol. 38, no. 10 (Oct. 1990), pp. 1740-1749.

[8] M.M. Vaez et al.: Strictly nonblocking directional-coupler-based switching networks under crosstalk constraint, IEEE Trans. Commun., vol. 48, no. 2 (Feb. 2000), pp. 316-323.

[9] G. Maier et al.: Design of photonic rearrangeable networks with zero first-order switching-element-crosstalk, IEEE Trans. Commun., vol. 49, no. 7 (July 2001), pp. 1268-1279.

Xiaohong Jiang (M'03) received his B.S., M.S. and Ph.D degrees in 1989, 1992, and 1999 respectively, all from Xidian University, Xi'an, China. He is currently an associate professor in the Department of Computer Science, Graduate School of Information Science, TOHOKU University, Japan. Before joining TOHOKU University, Dr.Jiang was an assistant professor in the Graduate School of Information Science, Japan Advanced Institute of Science and Technology (JAIST), from Oct.2001 to Jan.2005. Dr. Jiang was a JSPS (Japan Society for the Promotion of Science) postdoctoral research fellow at JAIST from Oct.1999-Oct. 2001. He was a research associate in the Department of Electronics and Electrical Engineering, the University of Edinburgh from Mar.1999-Oct.1999. Dr. Jiang's research interests include optical switching networks, WDM networks, interconnection networks, IC yield modeling, timing analysis of digital circuits, clock distribution and fault-tolerant technologies for VLSI/WSI. He has published over 50 referred technical papers in these areas.

Susumu Horiguchi (M'81-SM'95) received the B.Eng the M.Eng and PhD degrees from Tohoku University in 1976, 1978 and 1981 respectively. He is currently a full professor in the Graduate School of Information Science, Tohoku University. He was a visiting scientist at the IBM Thomas J. Watson Research Center from 1986 to 1987. He was also a professor in the Graduate School of Information Science, JAIST (Japan Advanced Institute of Science and Technology). He has been involved in organizing international workshops, symposia and conferences sponsored by the IEEE, IEICE, IASTED and IPS. He has published over 150 papers technical papers on optical networks, interconnection networks, parallel algorithms, high performance computer architectures and VLSI/WSI architectures. Prof. Horiguchi is members of IEICE, IPS and IASTED.