

## Short Paper

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# Multicasts on WDM All-Optical Butterfly Networks<sup>\*</sup>

XINCHEN LIU AND QIAN-PING GU<sup>+</sup>

*Department of Computer Science and Engineering  
The University of Aizu*

*Fukushima, 965-8580 Japan*

<sup>+</sup>*School of Computing Science*

*Simon Fraser University*

*Burnaby B.C. Canada V5A 1S6*

*E-mail: qgu@cs.sfu.ca*

On the wavelength-division multiplexing (WDM) optical networks, when the number of wavelengths for realizing a set  $R$  of routing requests is beyond the number of wavelengths supported by an optical link, multiple rounds of routing for  $R$  are required.  $R = \{(u, v)\}$  is a set of multicasts if each source  $u$  sends a message to at least one destination  $v$  and each destination  $v$  receives a message from exactly one source  $u$ . In this paper, we propose routing algorithms for a set of multicasts on  $n$ -dimensional WDM all-optical butterfly networks. For a network with wavelength converters, we give algorithms which realize any set of multicasts by  $2^{\lceil (n-1)/(k+1) \rceil}$  wavelengths in  $k$  rounds of routing. For  $k = 1$ , the upper bound is tight to the lower bound.

**Keywords:** multicast, WDM all-optical networks, multi-hop routing, multistage inter-connection networks, off-line routing algorithms

## 1. INTRODUCTION

All optical-networks use optical switches to enable the data stream to be transmitted in optical form from the source to the destination. This approach eliminates the well-known bottleneck of electro-optic conversions at electronic switches and improves greatly the performance of the optical network. Due to their huge bandwidth, all-optical networks provide very high-bandwidth network facilities for bandwidth intensive applications, such as web browsing, Java applications, video conferencing, and so on. A huge amount of research work has been done on all-optical networks [2, 4-6, 12, 13, 16, 17, 20, 22]. WDM (wavelength-division multiplexing) is currently the favorite multiplexing technology for realizing high capacity optical networks by partitioning the huge bandwidth of optical fibers into multiple non-overlapping wavelengths, where each wavelength supports a communication channel. Given a set  $R = \{(u, v)\}$  of source-destination

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pairs, to realize  $R$  in one-hop (or all-optical) routing, one needs to set up a routing path to connect  $u$  and  $v$  for every pair  $(u, v) \in R$  and needs to assign wavelengths to the paths so that any different data streams will not be transmitted by the same wavelength on the same link. We refer the reader to [20, 22] for more details of WDM optical networks.

Since the number of wavelengths available in an optical link is limited, it is critical to minimize the number of wavelengths required for a routing request set  $R$ . This issue has attracted much attention [5-10, 12, 13, 16, 25]. Let  $W$  be the number of wavelengths supported by an optical link, and  $l_R$  be the number of wavelengths for realizing  $R$  in all optical routing. If  $l_R \leq W$ , then  $R$  can be realized in *one round* of all-optical routing. For  $R$  with  $l_R > W$ , *multiple rounds* of all-optical routing are needed. An efficient approach is multi-hop routing [14, 15]: In  $k$ -hop routing, a data stream from a source is transmitted through  $k - 1$  intermediate destinations before reaching its final destination. At each intermediate destination, the data stream is converted from light into electronic form and retransmitted in optical form. A  $k$ -hop routing approach requires  $k$  rounds of routing. It is important to minimize the number of routing rounds for realizing  $R$  with  $l_R > W$ .

A fundamental communication problem in computer/communication networks is multicast: A source transmits a data stream to multiple destinations. Routing request set  $R = \{(u, v)\}$  is a set of multicasts if each source  $u$  sends a data stream to at least one destination  $v$  and each destination  $v$  receives a data stream from exactly one source  $u$ . Multicasts are required by many applications, such as video conference, video on demand, barrier synchronization and write update in parallel/distributed processing, and so on.

In this paper, we study the problem of minimizing the number of wavelengths and the number of routing rounds for realizing a set of multicasts on WDM all-optical butterfly network. The butterfly network and its variants are important multistage interconnection networks (MINs), which are attractive virtual topologies for optical networks [22]. They have been in for parallel computing systems such as IBM SP1/SP2 [23] and NEC Cenju-3 [11], and used in the internal structures of optical couplers (e.g., star couplers) [20] as well.

Much work has been done on multicasts in the parallel processing and electronic network communities (see [3], for example). Recently, multicasts have received much attention from the optical network community as well [9, 19, 21, 26] due to the fact that many bandwidth-intensive applications require multicasts, and because optical networks can support multicasts more efficiently by using the inherent light splitting capability of optical switches than they can by copying data in electronics. Although this paper seems to be the first to address multicasts on WDM all-optical MINs, some studies have considered related problems. The number of routing rounds for realizing a set of multicasts by edge-disjoint paths on electronic MINs were studied in [18, 24]. The above works imply that any set of multicasts can be realized by means of two wavelengths in six rounds of routing on optical MINs. A special case of multicasts is permutations. The following result for permutations also holds for multicasts: There are permutations on  $n$ -dimensional MINs (having  $N = 2^n$  inputs/outputs) that need at least  $2^{\lceil (n-1)/2 \rceil}$  wavelengths [1]. Although many works have studied upper bounds and algorithms for permutations on MINs (see [1, 5, 6], for example), their results may not hold for multicasts because the set of permutations is a proper subset of the set of multicasts; there are  $N!$  permutation patterns and  $N^N$  multicasts patterns on  $n$ -dimensional MINs.

In this paper, we present algorithms for multicasts on the all-optical butterfly network based on the multi-hop approach. In what follows, let  $BW_n$  denote the  $n$ -dimensional all-optical butterfly network with wavelength converters. Our results are: Deterministic algorithms which realize any set of multicasts by at most  $2^{\lceil (n-1)/(k+1) \rceil}$  wavelengths in  $k$  rounds of routing on  $BW_n$ .

The worst case lower bound on the number of wavelengths for realizing a set of multicasts in one round of routing on the  $n$ -dimensional butterfly network is  $2^{\lceil (n-1)/2 \rceil}$ . The upper bound  $2^{\lceil (n-1)/2 \rceil}$  for one round of routing on  $BW_n$  is tight to the lower bound. Currently, the number  $W$  of wavelengths supported by an optical link is as large as  $2^7$  [22]. For the network  $BW_n$  with  $W = 2^7$ , any set of multicasts can be realized in one round of routing for  $n \leq 15$  ( $N \leq 2^{15}$ ) and in two rounds of routing for  $n \leq 22$  ( $N \leq 2^{22}$ ).

The rest of this paper is organized as follows. In the next section, we give preliminaries. The algorithms for multicasts on  $BW_n$  is given in section 3. The final section concludes this paper.

### 2. PRELIMINARIES

The  $n$ -dimensional butterfly network has  $n$  stages and  $N = 2^n$  inputs and outputs. The inputs/outputs are labeled by means of  $n$  bit binary numbers of  $\{0, 1\}^n$ . Each stage of the butterfly has  $N/2$   $2 \times 2$  switches (nodes). We number the stages  $0, 1, \dots, n - 1$  from left to right. We label the nodes at stage  $i$  ( $0 \leq i \leq n - 1$ ) as  $\langle w, i \rangle$ , where  $w$  is an  $(n - 1)$ -bit binary number of  $\{0, 1\}^{n-1}$  that denotes the row of the node. For  $w = w_1 \dots w_{i-1} w_i w_{i+1} \dots w_{n-1} \in \{0, 1\}^{n-1}$ ,  $w^{(i)} = w_1 \dots w_{i-1} \bar{w}_i w_{i+1} \dots w_{n-1}$  denotes the binary number that differs from  $w$  in precisely the  $i$ th bit. Two nodes  $\langle w, i \rangle$  and  $\langle w', i' \rangle$  are connected by an edge if and only if  $i' = i + 1$  and  $w = w'$  or  $w^{(i+1)} = w'$ . The 3-dimensional butterfly network is shown in (a) of Fig. 1. We call edge  $(\langle w, i \rangle, \langle w, i + 1 \rangle)$  a *straight edge* and edge  $(\langle w, i \rangle, \langle w^{(i+1)}, i + 1 \rangle)$  a *cross edge*.

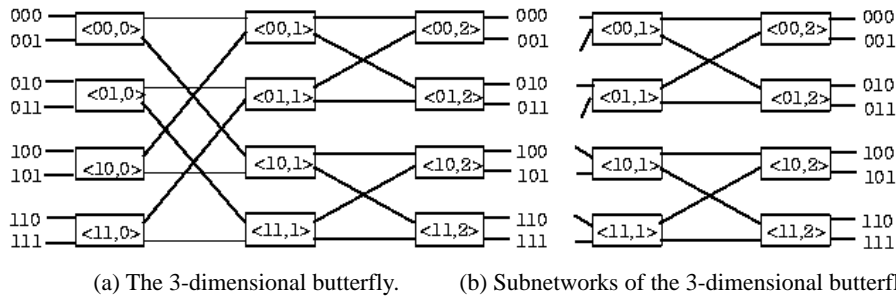


Fig. 1. The 3-dimensional butterfly network and subnetworks.

Notice that for message routing, the butterfly network is viewed as a directed graph; i.e., messages can be routed only in the direction from the input to the output. A path in a graph is a sequence of edges of the form  $(s_1, s_2)(s_2, s_3) \dots (s_{k-1}, s_k)$ , where  $s_i$  ( $1 \leq i \leq k$ ) are the nodes of the graph and  $s_i \neq s_j$  for  $i \neq j$ . We sometimes denote the path from  $s_1$  to  $s_k$  as  $s_1 \rightarrow s_k$ . Two paths are *edge-disjoint* if they have no common edge.

Given an arbitrary pair  $(u, v)$  consisting of input  $u$  with binary label  $x_1 \dots x_n$  and output  $v$  with binary label  $y_1 \dots y_n$  in the butterfly, there is a unique path  $e_1 \dots e_{n-1}$  from  $u$  to  $v$ , where  $e_i$  is an edge  $(\langle w, i-1 \rangle, \langle w', i \rangle)$  with  $w = y_1 \dots y_{i-1} x_i \dots x_{n-1}$  and  $w' = y_1 \dots y_i x_{i+1} \dots x_{n-1}$ . Given two pairs  $(u, v)$  and  $(u', v')$  of inputs and outputs, the paths  $u \rightarrow v = e_1 \dots e_{n-1}$  and  $u' \rightarrow v' = e'_1 \dots e'_{n-1}$  have a common edge if there is an  $i$  ( $1 \leq i \leq n-1$ ) such that  $e_i = e'_i$ .

The following property of the butterfly is important in this paper: For the integer  $0 \leq k \leq n-1$ , the subgraph of the  $n$ -dimensional butterfly induced by the nodes at stages from  $k$  to  $n-1$  is a collection of  $2^k$  disjoint  $(n-k)$ -dimensional butterflies. The 2-dimensional butterflies induced by the nodes of stages from 1 to 2 are shown in (b) of Fig. 1.

We assume that each  $2 \times 2$  optical switch in  $BW_n$  directs the signal of every wavelength from each of its input links to one or two of its output links. There is a wavelength converter in the switch which may convert the wavelength of the input into a different wavelength of the output. For  $BW_n$ , the switching and splitting of signals, and wavelength conversion in the butterfly are done optically. Electro-optic conversion and storage for data streams are available at the end systems connected to the input/output terminal of  $BW_n$ . A routing request set on  $BW_n$  is a set of input-output pairs of  $BW_n$ .

### 3. ROUTING ON $BW_n$

#### 3.1 One Round of Routing

The path for connecting each input and output pair of  $BW_n$  is unique, and there is a wavelength converter in each switch. Therefore, the key to realizing a routing request on  $BW_n$  is to find the number of data streams on each link. For a routing request  $R$  on  $BW_n$  and each edge  $e$  of  $BW_n$ , we define  $a_R(e)$  as the number of data streams for realizing  $R$  that pass through edge  $e$ . For  $BW_n$ , the number of wavelengths for realizing  $R$  is  $\max\{a_R(e) | e \in E(BW_n)\}$ . For the set  $R$  of multicasts, the number of data streams on an edge is the number of paths of distinct inputs that pass through the edge.

**Lemma 1** For any set  $R$  of multicasts on  $BW_n$ ,  $\max\{a_R(e) | e \in E(BW_n)\} \leq 2^{\lceil (n-1)/2 \rceil}$ .

**Proof:** For any edge  $e$  in  $BW_n$  between stage  $k-1$  and stage  $k$  ( $1 \leq k \leq n-1$ ),  $e$  is connected to  $2^k$  inputs and  $2^{n-k}$  outputs of  $B_n$ . Since each output receives at most one data stream,  $a_R(e) \leq \min\{2^k, 2^{n-k}\}$ . The value  $\min\{2^k, 2^{n-k}\}$  reaches the maximum when  $k = \lceil (n-1)/2 \rceil$ .  $\square$

**Theorem 2** Both the upper and lower bounds on the number of wavelengths for realizing any set of multicasts on  $BW_n$  in one round of routing is  $2^{\lceil (n-1)/2 \rceil}$ .

**Proof:** By Lemma 1, any set of multicasts can be realized by means of  $2^{\lceil (n-1)/2 \rceil}$  wavelengths in one round of routing. To show the lower bound of the theorem, we construct a set  $R$  of multicasts that needs at least  $2^{\lceil (n-1)/2 \rceil}$  wavelengths in one round of routing.

Let

$$R = \{(u, v_u) | u = x_1 \dots x_n, v_u = y_1 \dots y_n = x_n \dots x_1\}$$

be the bit-reversal permutation on  $\{0,1\}^n$ . Then  $R$  is also a set of multicasts. For each pair  $(u, u_i)$  in  $R$ , the unique path  $u \rightarrow v_u$  has the edge

$$(\langle y_1 \dots y_{i-1} x_i \dots x_n, i-1 \rangle, \langle y_1 \dots y_i x_{i+1} \dots x_n, i \rangle) = (\langle x_n \dots x_{n-i+2} x_i \dots x_n, i-1 \rangle, \langle x_n \dots x_{n-i+1} x_{i+1} \dots x_n, i \rangle).$$

For  $i = \lceil (n-1)/2 \rceil$ , there are  $2^{\lceil (n-1)/2 \rceil}$  paths that share the same edge:

$$(\langle x_n \dots x_{n-i+2} x_i \dots x_n, i-1 \rangle, \langle x_n \dots x_{n-i+1} x_{i+1} \dots x_n, i \rangle).$$

Thus,  $R$  needs at least  $2^{\lceil (n-1)/2 \rceil}$  wavelengths in one round of routing on  $BW_n$ .  $\square$

Since the path for each input and output pair of  $BW_n$  is unique, the algorithm for realizing a set of multicasts on  $BW_n$  in one round of routing is straightforward. The algorithm is shown in Fig. 2. There are at most  $N$  paths for  $R$ , and each path has  $O(\log N)$  edges. By checking the edges in each path, we can find the number of data streams on the edge. Therefore, Algorithm One\_Round takes  $O(N \log N)$  time. The memory space for the algorithm is also  $O(N \log N)$ .

**Algorithm One\_Round**

**Input:** A set  $R$  of multicasts on  $BW_n$ .

**Output:** A wavelength assignment to edges of  $BW_n$ .

**begin**

Check the number of data streams on each edge  
based on the routing paths for  $R$  and assign to each  
data stream on each edge a distinct wavelength.

**end.**

Fig. 2. The algorithm for multicasts in one round of routing on  $BW_n$ .

**3.2 Multi-round Routing**

We will first show how a set of multicasts can be realized in two rounds of routing and then extend idea to more rounds of routing. We will follow the multi-hop approach. For each input-output pair in  $R$ , we find an intermediate destination for the pair. We route the message from the input to the intermediate destination in the first round of routing and then from the intermediate destination to the output in the second round of routing. Notice that once the intermediate destination is fixed, the routing paths in the two rounds are uniquely defined. Therefore, the key task in the two rounds of routing is selecting the intermediate destinations.

The basic idea for selecting intermediate destinations is that after the first round of routing, the original set  $R$  of multicasts is reduced to  $l = 2^k$  subsets  $R_1, \dots, R_l$  of multicasts on  $l$   $(n-k)$ -dimensional subnetworks  $BW_{n-k}^1, \dots, BW_{n-k}^l$  of  $BW_n$ , one set  $R_i$  per subnetwork  $BW_{n-k}^i$ . In the second round, each subset  $R_i$  of multicasts is realized on the subnetwork  $BW_{n-k}^i$ . The details of this idea is as follows:

- The first round.

Let  $BW_{n-k}^i$  be one of the subnetworks of  $BW_n$  that consists of the nodes from stage  $k$  to stage  $n-1$ . For any  $(u, v) \in R$  and  $v$  is an output of  $BW_{n-k}^i$ , we connect the source  $u$  of a multicast to an input  $x_u$  of  $BW_{n-k}^i$  (an input of a node at stage  $k$  of  $BW_n$ ). Notice that input  $x_u$  is unique even though  $u$  has multiple destinations  $v$ 's in  $BW_{n-k}^i$ . The path  $u \rightarrow x_u$

is unique and consists of edges from the node at stage 0 to the node at stage  $k$ . After this, we extend the path  $u \rightarrow x_u$  to a path  $u \rightarrow x_u \rightarrow y_u$ , where  $y_u$  is an output of  $BW_{n-k}^i$  and the intermediate destination for  $(u, v)$  (see (a) of Fig. 3). Notice that  $u \rightarrow x_u$  can be extended to any output  $y$  of  $BW_{n-k}^i$ , but that each  $y$  can be connected to at most one source  $u$ . That is, the choice of  $y_u$  is not unique. On the other hand, each input  $x$  of  $BW_{n-k}^i$  may be connected to multiple sources,  $u$ 's. In this case, we need to scatter the multiple sources connected to the same  $x$  to different output  $y$ 's so that each  $y$  is connected to exactly one source. We use the following principle for the scatter: Let  $e$  and  $e'$  be the two input edges of a node  $\langle w, j \rangle$  in  $BW_{n-k}^i$ , and let  $a(e)$  and  $a(e')$  be the numbers of sources that are connected to  $\langle w, j \rangle$  via edge  $e$  and  $e'$ , respectively. We scatter  $(a(e) + a(e'))/2$  sources to each of the two output edges of  $\langle w, j \rangle$  (see Fig. 4). Once the output  $y_u$  is fixed, the path  $x_u \rightarrow y_u$  is uniquely defined.  $R_i = \{(y_u, v) | (u, v) \in R \text{ and } v \text{ is an output of } BW_{n-k}^i\}$  is a set of multicasts on  $BW_{n-k}^i$ .

$R' = \{(u, y_u) | (u, v) \in R\}$  is a new set of multicasts on  $BW_n$  and can be realized by Algorithm One\_Round.

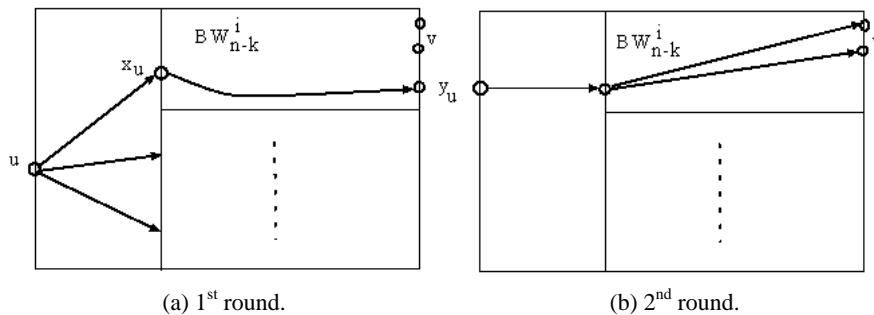


Fig. 3. Two rounds routing for multicasts.

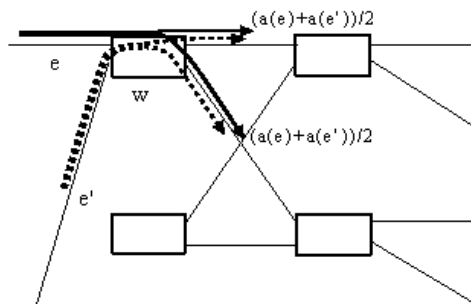


Fig. 4. Scatter the sources of multicasts.

• The second round.

Connect each  $y_u$  to  $BW_{n-k}^i$  by means of straight edges and then realize  $R_i$  on  $BW_{n-k}^i$  by means of Algorithm One\_Round (see (b) of Fig. 3).

An algorithm based on the above idea is shown in Fig. 5.

**Algorithm Two\_Rounds**

**Input:** A set  $R$  of multicasts on  $BW_n$ .

**Output:** The paths and wavelength assignment to the links of the paths for  $R$  in two rounds of routing on  $BW_n$ .

**begin**

/\*The first round\*/

For each subnetwork  $BW_{n-k}^i$ , each  $(u, v) \in R$ , and  $v$  an output of  $BW_{n-k}^i$ , connect  $u$  to the input

$x_u$  of  $BW_{n-k}^i$  by the unique path  $u \rightarrow x_u$ .

For each node  $\langle w, j \rangle$  ( $k \leq j \leq n-2$ ) in  $BW_n$ ,

extend the  $a(e) + a(e')$  paths  $u \rightarrow \langle w, j \rangle$  to

$(a(e) + a(e'))/2$  paths  $u \rightarrow \langle w, j+1 \rangle$  and

$(a(e) + a(e'))/2$  paths  $u \rightarrow \langle w^{(j+1)}, j+1 \rangle$ .

For each path  $u \rightarrow \langle w, n-1 \rangle$ ,

take one output of  $\langle w, n-1 \rangle$  as  $y_u$  s.t.

$y_u$  is connected to one source.

Realize  $R' = \{(u, y_u) \mid (u, v) \in R\}$  on  $BW_n$

by Algorithm One\_Round.

/\*The second round\*/

For each  $R_i = \{(y_u, v)\}$ , connect  $y_u$ 's

to the input of  $BW_{n-k}^i$  by straight edges and

realize  $R_i$  on  $BW_{n-k}^i$  by Algorithm One\_Round.

**end.**

Fig. 5. The algorithm for multicasts in two rounds of routing on  $BW_n$ .

**Theorem 3** Algorithm Two\_Round realizes any set  $R$  of multicasts by  $2^{\lceil (n-1)/3 \rceil}$  wavelengths in two rounds of routing on  $BW_n$ .

**Proof:** We will first show the correctness of the algorithm. For each source  $u$  of a multicast in  $R$ , obviously,  $u$  is connected to an output  $y_u$  of  $BW_{n-k}^i$  if  $u$  has a destination in  $BW_{n-k}^i$ . Since  $BW_{n-k}^i$  has  $2^{n-k}$  outputs, the inputs of  $BW_{n-k}^i$  receive at most  $2^{n-k}$  sources. In the scatter step, each subnetwork  $BW_{(n-j)}^i$  ( $k \leq j \leq n-1$ ) receives at most  $2^{n-j}$  sources. From this, each output of  $BW_{n-k}^i$  is connected to at most one source. Thus,  $R_i$  obtained in the first round of Algorithm Two\_Round is a set of multicasts on  $BW_{n-k}^i$ , and the algorithm realizes  $R$  in two rounds of routing.

Next, we will estimate the number of wavelengths used by the algorithm. Let  $P = u \rightarrow y_u$  be any path constructed in the first round of routing. The number of data streams in any edge of  $P$  between stage  $i-1$  and stage  $i$  ( $1 \leq i \leq k$ ) is at most  $2^k$ . Since  $a(e) \leq 2^k$  and  $a(e') \leq 2^k$ , the number of data streams on each edge from stage  $i-1$  to stage  $i$  ( $k+1 \leq i \leq n$ ) is at most  $2^k$ . Therefore,  $2^k$  wavelengths are enough for the first round.

From Theorem 2, each  $R_i$  can be realized by at most  $2^{\lceil (n-k-1)/2 \rceil}$  wavelengths. Taking  $k = (n-1)/6$ , we have the theorem.  $\square$

The second round of Algorithm Two\_Round takes  $O(N \log N)$  time and  $O(N \log N)$  memory space. In the first round of the algorithm, in addition to assigning wavelengths

to the data streams in each link, there is a step for determining an intermediate destination  $y_u$  in each subnetwork for every input  $u$  with  $(u, v) \in R$ , where  $v$  is an output of the subnetwork. This step can be done in  $O(N \log N)$  time using  $O(N \log N)$  memory space. Thus, the time complexity and space complexity of Algorithm Two\_Round are  $O(N \log N)$ .

The idea behind two rounds of routing can be extended to more rounds of routing. We will show how  $R$  can be realized in three rounds of routing. Further extensions would be similar. To realize  $R$  in three rounds, we reduce  $R$  to  $l = 2^{k_1}$  subsets  $R_1, \dots, R_l$  of multicasts on  $l(n - k_1)$ -dimensional subnetworks  $BW_{n-k_1}$ 's of  $BW_n$ , one subset  $R_i$  per subnetwork  $BW_{n-k_1}$ . In the second round of routing, we reduce each subset  $R_i$  into  $m = 2^{k_2}$  subsets  $S_1, \dots, S_m$  of multicasts on  $m(n - r)$ -dimensional ( $r = k_1 + k_2$ ) subnetworks  $BW_{n-r}$ 's of  $BW_{n-k_1}$ , one subset  $S_j$  per subnetwork  $BW_{n-r}$ . In the third round of routing, each subset  $S_j$  of multicasts is realized on the subnetwork  $BW_{n-r}$ . Taking  $k_1 = k_2 = \lceil (n - 1)/4 \rceil$ , it can be shown that  $R$  can be realized by means of  $2^{\lceil (n-1)/4 \rceil}$  wavelengths in three rounds of routing. In general, we have the following result.

**Theorem 4** For  $1 \leq k$ , any set  $R$  of multicasts can be realized by means of  $2^{\lceil (n-1)/(k+1) \rceil}$  wavelengths in  $k$  rounds of routing on  $BW_n$ .

#### 4. CONCLUDING REMARKS

We have proposed algorithms for multicasts on WDM all-optical butterfly networks with wavelength converters. Our algorithms realize any set of multicasts on the  $n$ -dimensional butterfly by means of  $2^{\lceil (n-1)/(k+1) \rceil}$  wavelengths in  $k$  rounds of routing. For  $k = 1$ , the upper bound on the number of wavelengths is tight to the lower bound. It is interesting to develop algorithms with better upper bound on the number of wavelengths for  $k \geq 2$ . Other open problems may include finding efficient algorithms for the butterfly network without wavelength converters.

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**Xinchen Liu** received his M.S. degree in computer science and engineering from The University of Aizu, Japan, in 2002. His research interests include wide-area networks and optical networks.

**Qian-Ping Gu** received his B.S., M.S., and Ph.D. degrees in computer science from Shandong University, China, Ibaraki University, Japan, and Tohoku University, Japan, in 1982, 1985, and 1988, respectively. He is currently a faculty member at School of Computing Science, Simon Fraser University, Canada. He was with the Department of Computer Software, The University of Aizu, Japan, from 1993 to 2001. He was a visiting researcher at the Department of Electrical and Computer Engineering, the University of Calgary, Canada, from 1991 to 1993, and a visiting professor at School of Computer Science, Birmingham University, U.K., in 2001. His research interests include network communications and algorithms, parallel/distributed processing, analysis of algorithms and computation, machine learning, and computational biology. He has published over 30 papers in archival journals in these areas. He is a member of ACM, IEEE, IEEE Computer Society, and IEICE of Japan.