Multistage Interconnection Networks: A Transition from Electronic to Optical

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***Abstract*—Optical communication are necessary for achieving reliable, fast and flexible communication. Advances in electro-optic technologies have made optical communication a reliable networking choice to meet the increasing demands for high bandwidth and low communication latency of high-performance computing/communication applications. So optical networks gives high performance as well as low latency. Although optical MINs hold great promise and have advantages over their electronic networks, they also hold their own challenges. This paper compares electronic and Optical MINs. The design issues and solution approaches available for optical MINs are also explained and analyzed.**

***Index Terms*— Multistage Interconnection Networks (MIN), Optical networks, Crosstalk, Window methods.**

I. INTRODUCTION

To meet the increasing demands of high performance computing applications for high channel bandwidth and low communication latency, traditional metal-based communication technology used in parallel computing systems is becoming a potential bottleneck. Now, the need arise either for some significant progress in the traditional interconnects or for some new interconnect technology be introduced in parallel computing systems. Electro-optic technologies have made optical communication a promising network choice to meet the increasing demands with its advancement in the technology. Fiber optic communications offer a combination of high bandwidth, low error probability and gigabit transmission capacity.

Multistage interconnection networks have been extensively accepted as an interconnecting scheme for parallel computing systems. As optical technology advances, there is considerable interest in using optical technology to implement interconnection network and switches. A multistage interconnection network is composed of several stages of switch elements by which any input port can be connected to any output port in the network. Optical MIN represents a very important class of interconnecting schemes used for constructing Optical interconnections for communication networks and multiprocessor systems. This network consists of N inputs, N outputs and n stages ($n=\log_2 N$). Each stage has N/2 switching elements each SE has two inputs and two outputs connected in a certain pattern. The most widely used MINs are the electronic MINs. In electronic MINs, electricity is used, since in optical MINs, light is used to transmit the messages. Although electronic MINs and optical MINs have many similarities but there are some fundamental differences between them. Available optical MINs were built mainly on banyan or its equivalent (e.g. *baseline*, *omega*) networks because they are fast in switch setting (self-routing) and also have a small number of switches between an input-output pair. Banyan networks have a unique path between an input-output pair, and this makes them blocking networks. Non-blocking networks can be constructed by either appending some extra stages to the back of a regular banyan network. Crosstalk in optical networks is one of the major shortcomings in optical switching networks, and avoiding crosstalk is an important for making optical communication properly. To avoid a crosstalk, many approaches have been used such as time domain and space domain approaches. Because the messages should be partitioned into several groups to send to the network, some methods are used to find conflicts between the messages.

II. MULTISTAGE INTERCONNECTION NETWORKS

Multistage interconnection networks (MINs) consist of more than one stage of small interconnection elements called switching elements and links interconnecting them. Multistage interconnection networks (MINs) are used in multiprocessing systems to provide cost-effective, high-bandwidth communication between processors and/or memory modules. A MIN normally connects N inputs to N outputs and is referred as an N × N MIN [9,10]. The parameter N is called the size of the network. There are several different multistage interconnection networks

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proposed and studied in the literature. Figure 1 illustrates a structure of multistage interconnection network, which are representatives of a general class of networks. This figure shows the connection between p inputs and b outputs, and connection between these is via number of stages. Multistage interconnection network is actually a compromise between crossbar and shared bus networks of various types of multiprocessor interconnections networks [1]. Multistage interconnection networks attempt to reduce cost and decrease the path length

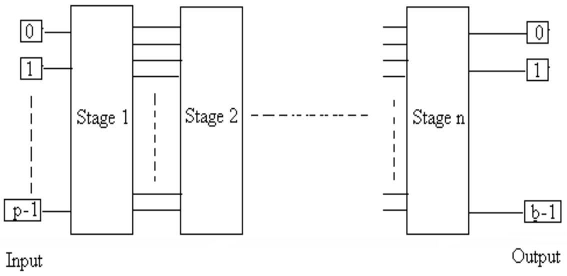

Figure 1: A MultistageNetwork

TABLE I
PROPERTIES OF DIFFERENT INTERCONNECTION TECHNIQUES

Property	***Bus***	***Crossbar***	***Multistage***
Speed	Low	High	High
Cost	Low	High	Moderate
Reliability	Low	High	High
Configurability	High	Low	Moderate
Complexity	Low	High	Moderate

III. OPTICAL MULTISTAGE INTERCONNECTION NETWORKS

An optical MIN can be implemented with either free-space optics or guided wave technology. It uses the Time Division Multiplexing. To exploit the huge optical bandwidth of fiber, the Wavelength Division Multiplexing (WDM) technique can also be used. With WDM, the optical spectrum is divided into many different logical channels, and each channel corresponds to a unique wavelength. Optical switching, involves the switching of optical signals, rather than electronic signals as in conventional electronic systems. Two types of guided wave optical switching systems can be used [5]. The first is a hybrid approach in which optical signals are switched, but the switches are electronically controlled. With this approach, the use of electronic control signals means that the routing will be carried out electronically. As such, the speed of the electronic switch control signals can be much less than the bit rate of the optical signals being switched. So, with this approach there is a big speed mismatch occur due to the high speed of optical signals. The second approach is all-optical switching. This has removed the problem that occurred with the hybrid approach but, such systems will not become practical in the future and hence only hybrid optical MINs are considered. In hybrid optical MINs, the electronically controlled optical switches, such as lithium niobate directional couplers, can have switching speeds from hundreds of picoseconds to tens of nanoseconds.

A. Switching in optical networks

In optical networks, circuit switching is used. Packet switching is not possible with Optical Multistage Interconnection Networks. If packet switching is used, the address information in each packet must be decoded in order to determine the switch state. In a hybrid MIN, it means it require conversions from optical signals to electronic ones, which could be very costly [4]. For this reason, circuit switching is usually preferred in optical MINs.

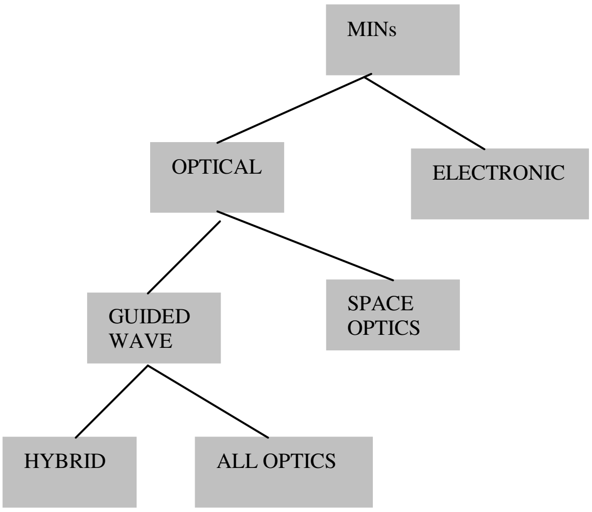

Figure 2: Types of Multistage Networks

B. Comparison of Electronic and Optical Networks

There are lots of benefits of optical networks over the electronic ones. The main benefit of the optical networks over the electronic network is the high speed of the Optical signals. In the optical networks light is transmitted which has a very good speed but in the electronic Multistage interconnection networks electricity is used which has very slow speed. The second advantage is the Bandwidth. Now a day’s applications in communication require high bandwidth, the optical networks gives combination of very high bandwidth and low latency. Therefore, they have been used in the parallel processing applications. Optical MINs are also used in wide area networks, which require less error probability and very high bandwidth. Fiber optic transmission distance is significantly greater than the electronic ones, signal need not to be regenerated in optical networks. Optical fiber has very less weight in comparison to electronic MINs. Thus Optical networks give the combination of high bandwidth and low latency.

TABLE II
COMARISON OF ELECTRONIC AND OPTICAL NETWORKS

Characteristics	***Electronic Multistage Netwotks***	***Optical Multistage Networks***
Speed	Less	High
Energy Transmitted	Electricity	Light
Bandwidth	Used for less bandwidth applications	Used for high bandwidth applications
Latency	High	Less
Error Probability	High	Less
Weight	More	Less
Cost	Less	More
Switching	Packet Switching	Circuit Switching
Path	Provide Multi path from source to destination.	Provide single path from source to destination
Complexity	More Complex	Less Complex
Structure considered	2-dimensional	3-dimensional

IV. PROBLEMS IN OPTICAL NETWORKS

Due to the difference in speeds of the electronic and optical switching elements and the nature of optical signals, optical MINs also hold their own challenges.

A. Path Dependent Loss

Path dependent loss means that optical signals become weak after passing through an optical path. In a large MIN, a big part of the path-dependent loss is directly proportional to the number of couplers that the optical path passes through [16]. Hence, it depends on the architecture used and its network size. Hence, if the optical signal has to pass through more no of stages or switches the path dependent loss will be more.

B. Optical Crosstalk

Optical crosstalk occurs when two signal channels interact with each other. There are two ways in which optical paths can interact in a switching network. The channels carrying the signals could cross each other. Alternatively; two paths sharing a switch could experience some undesired coupling from one path to another within a switch. For example, assume that the two inputs are y and z, respectively, the two outputs will have ly+lxz and lz+lxy, respectively, where l is path loss and x is signal crosstalk in a switch. Using the best device x=35 dB and l=0.25 dB. For more practically available devices, it is more likely that x=20 dB and l=1 dB [5]. Hence, when a signal passes many switches, the input signal will be distorted at the output due to the loss and crosstalk introduced on the path.

Crosstalk problem is more dangerous than the path-dependent loss problem with current optical technology. Thus, switch crosstalk is the most significant factor that reduces the signal-to-noise ratio and limits the size of a network. Luckily, ensuring that a switch is not used by two input signals simultaneously can eliminate first-order crosstalk. Once the major source of crosstalk disappears, crosstalk in an optical MIN will have a very small effect on the signal-to-noise ratio and thus a large optical MIN can be built and effectively used in parallel computing systems.

V. APPROACHES TO SOLVE CROSSTALK

A. Space Domain Approach

One way to solve crosstalk problem is a space domain approach, where a MIN is duplicated and combined to avoid crosstalk [8]. The number of switches required for the same connectivity in networks with space domain approach is slightly larger than twice that for the regular network. This approach uses more than double the original network hardware to achieve the same. Thus for the same permutation the hardware or we can say the no of switches will be double. Thus cost will be more with the networks using space domain approach. In all the four cases only one input and only one output is active at a given time so that no cross talk occurs. With the space domain approach, extra switching elements (SEs) and links are used to ensure that at most one input and one output of every SE will be used at any given time.

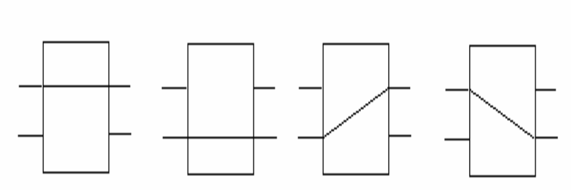

Figure 3. Crosstalk avoidance using space domain approach

B. Time Domain Approach

Another way to solve the problem of crosstalk is the time domain approach [3]. With the time domain approach, the same objective is achieved by treating crosstalk as a conflict; that is, two connections will be established at different times if they use the same SE. Whereas we want to distribute the messages to be sent to the network into several groups, a method is used to find out which messages should not be in the same group because they will cause crosstalk in the network. A set of connections is partitioned into several subsets such that the connections in each subset can be established simultaneously in a network. There is no crosstalk in these subsections. This approach makes importance in optical MINs for various reasons. First, most of the multiprocessors use electronic processors and optical MINs. There is a big mismatch between the slow processing speed in processors and the high communication speed in networks carrying optical signals [15]. Second, there is a mismatch between the routing control and the fast signal transmission speed. To avoid crosstalk, the TDM approach is used, where the set of messages are partitioned into several groups such that the messages in each group can be sent simultaneously through the network without any crosstalk.

VI. METHODS FOR MESSAGE PARTITIONING IN TDM APPROACH

A. *Window method*

Window method is the method that is used to find the messages that are not in the same group because it causes crosstalk in the network. If we consider the network of size N x N, there are N source and N destination address. Combining source and its destination address forms combination matrix. From this, optical window size is M -1 where $M = \log_2 N$ and N is size of network. In window method, the number of windows is equal to the number of stages [11].

After finding conflicts using window method, conflict graph is generated shown in figure. The number of nodes is the size of the network. The nodes that are having conflict are connected through edge. Degree of each message is the number of conflicts to the other message. Conflict graph is shown in figure 4.

The conflict matrix is a square matrix with N x N entry, it consists of the output of the window method, as shown in figure 5. The definition of Conflict Matrix is the matrix M_{ij} with size N x N. N is the size of the network.

B. *Improved window method*

In this method the first window is eliminated for this we make the conflict matrix initialized to 0, here Number of windows is M-1. It takes less time to find conflicts than the windows method. Therefore, it is called improved windows method [11,12].

```
0 0 0 1 0 1     message 000 and 100 have conflict
0 0 1 0 0 1     message 001 and 101 have conflict
0 1 0 0 1 1     message 010 and 110 have conflict
0 1 1 1 1 0     message 011 and 111 have conflict
1 0 0 0 0 0
1 0 1 0 1 0
1 1 0 1 0 0
1 1 1 1 1 1
Step 1(w0)

0 0 0 1 0 1       message 000 and 110 have conflict
0 0 1 0 0 1       message 001 and 101 have conflict
0 1 0 0 1 1       message 010 and 100 have conflict
0 1 1 1 1 0       message 011 and 111 have conflict
1 0 0 0 0 0
1 0 1 0 1 0
1 1 0 1 0 0
1 1 1 1 1 1
Step 2(w1)

0 0 0 1 0 1       message 000 and 110 have conflict
0 0 1 0 0 1       message 001 and 100 have conflict
0 1 0 0 1 1       message 010 and 101 have conflict
0 1 1 1 1 0       message 011 and 111 have conflict
1 0 0 0 0 0
1 0 1 0 1 0
1 1 0 1 0 0
1 1 1 1 1 1
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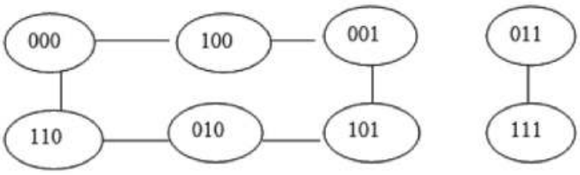
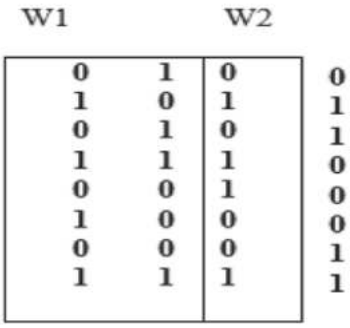


Figure 4. Conflict graph

msg	000	1	0	1	0	1	0	1
0	0	0	0	0	1	0	1	0
1	0	0	0	0	1	1	0	0
0	0	0	0	0	1	1	1	0
1	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0

Figure 5. Conflict matrix



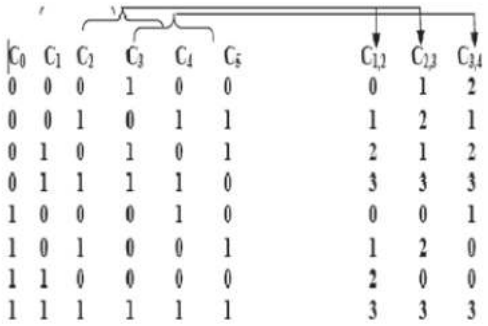
W1		W2	
0	1	0	0
1	0	1	1
0	1	0	1
1	1	1	0
0	0	1	0
1	0	0	0
0	0	0	1
1	1	1	1

Figure 6. Improved window method

C. *Bitwise combination matrix*

For Bitwise combination matrix, all binary bits of single rows is each windows are converted to decimal, no. of window is reduced to *n*. By this method, time is reduced approximately by ten times. It is very effective method even when the network is very large.

For example the bitwise combination matrix for 8 8 network size is demonstrated in Fig. 5. The number of columns in WM is 6 (*Ci*, *i* = 2*n*) and for bitwise WM is 2 *(Ci, i = n)* [11,12].

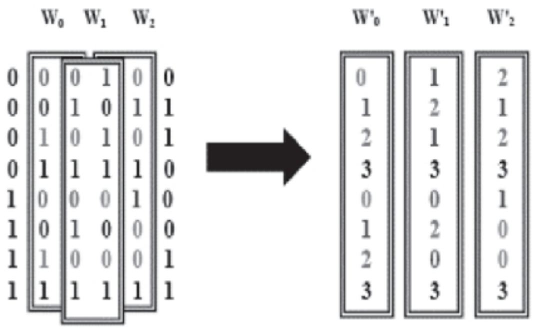


C_0	C_1	C_2	C_3	C_4	C_5	$C_{1,2}$	$C_{2,3}$	$C_{3,4}$
0	0	0	1	0	0	0	1	2
0	0	1	0	1	1	1	2	1
0	1	0	1	0	1	2	1	2
0	1	1	1	1	0	3	3	3
1	0	0	0	1	0	0	0	1
1	0	1	0	0	1	1	2	0
1	1	0	0	0	0	2	0	0
1	1	1	1	1	1	3	3	3

Combination Matrix Bitwise Combination Matrix

D. *Bitwise window method*

In this method, source and destination address is in decimal format. Number of windows is $\log_2 N$. Thus, from combination matrix, the optical window size is only one for a different network size and the number of window is $\log_2 N$. In other words, there are only one decimal number in each row and each window for comparison and finding a conflict [11,12].



W_0		W_1		W_2		W'_0	W'_1	W'_2
0	0	0	1	0	0	0	1	2
0	0	1	0	1	1	1	2	1
0	1	0	1	0	1	2	1	2
0	1	1	1	1	0	3	3	3
1	0	0	0	1	0	0	0	1
1	0	1	0	0	0	1	2	0
1	1	0	0	0	1	2	0	0
1	1	1	1	1	1	3	3	3

Figure 7. Bitwise window method

VII. CONCLUSION

In this paper properties of electronic and optical MINs have been explained and compared. It is concluded that for today's applications such as in wide area networks (WANs) optical networks is the promising choice to meet the high demand of Speed and Bandwidth. The paper also describes the problems and solutions of optical MINs. Various methods available in literature, which are used for crosstalk avoidance in TDM approach, are described in detail. It has been observed that the improved window method takes lesser time to find conflicts as compared to window method. The bitwise window method reduces the execution time ten times than the other algorithms even when the network size is large.

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