PERFORMANCE OF OPTICAL MULTISTAGE INTERCONNECTION NETWORKS

Thesis submitted in partial fulfillment of the requirements for the award of degree of

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in
Computer Science & Engineering

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Certificate

I hereby certify that the work which is being presented in the thesis entitled, **"Performance of Optical Multistage Interconnection Networks"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in Computer Science and Engineering submitted in Computer Science and Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Rinkle Aggarwal and refers other researcher's works which are duly listed in the reference section.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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Abstract

Optical communication is the fast communication. It provides reliable services than the wired communication. Due to the Advancement in the communication, it has made optical communication a reliable networking choice to meet the increasing demands for high bandwidth for the high-performance applications. So optical networks gives high performance in terms of bandwidth. Although optical MINs hold great promise and have advantages over their electronic networks, they also hold their own challenges. In this the reason of why the optical communication is better for communication applications is given Also it includes the Comparison of different interconnection Networking techniques and the problems of the optical networking. More research has been done on Electronic Multistage Interconnection Networks, (EMINs) but these days optical communication is a good networking choice to meet the increasing demands of high-performance computing communication applications for high bandwidth applications. The electronic Multistage Interconnection Networks (EMINs) and the Optical Multistage Interconnection Networks (OMINs) have many similarities, but there are some fundamental differences between them such as the optical-loss during switching and the crosstalk problem in the optical switches. To reduce the negative effect of crosstalk, various approaches which apply the concept of dilation in either the space or time domain have been proposed. With the space domain approach, extra SEs are used to ensure that at most one input and one output of every SE will be used at any given time. For an Optical network without crosstalk, it is needed to divide the messages into several groups, and then deliver the messages using one time slot (pass) for each group, which is called the time division multiplexing. This thesis discusses the permutation passability behavior of various optical MINs. The bandwidth of optical MINs with or without crosstalk has also been explained. The results thus obtained shows that the performance of the networks improve by allowing limited crosstalk.

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1. Interconnection Networks

Interconnection Networks play a major role in the performance of modern parallel computers. Many aspects of Interconnection Networks, such as implementation complexity, routing algorithms, performance evaluation, and fault tolerance, have been the subject of research over the years [41]. There are many factors that may affect the choice of appropriate interconnection network for the underlying parallel computing environment. An interconnection network is a complex connection of switches and links permitting processors in a multiprocessor system to communicate among themselves or with memory modules [8]. It is the path, the data must travel in order to access memory in a shared memory computer or to communicate with another processor in a distributed memory environment.

1.1 A classification of Interconnection Networks

1.1.1 Switching methodology: There are two major switching methodologies:

a) Packet switching

In packet switching, a message is broken into small packets transmitted through the network in a “store-and-forward” mode. Thus, a packet experiences a random delay at each switching point, depending on the traffic in the network along its path to the destination.

b) Circuit switching

Circuit switching actually establishes a physical path between a source and a destination. A time delay is needed when the path is being established. Once the path is completed, it is held for the entire data transmission. In general, circuit switching is much more suitable for long messages, and packet switching is more efficient for short messages.

1.1.2 Control strategy

Control strategy mainly concerns the way control signals direct the dataflow generated in a network. In a centralized control scheme, all the control signals come from a single source [10]. Obviously, the central controller creates a system bottleneck and directly affects the performance and reliability of the entire system.

The design of this central controller must be very complex to retain good system performance. These drawbacks can be avoided through the use of distributed control strategies in which a small controller is associated with each component of the system.

1.1.3 Operational modes

Operational modes can either be synchronous or asynchronous or a combination of the two. Synchronous mode is useful for either a data manipulating function or for a data instruction broadcast. Synchronous control techniques are characterized by a global clock, which broadcasts clock signals to all devices in a system so that the entire system operates in lock-step fashion. Asynchronous communication is needed for multi processing in which connection requests are issued dynamically. Asynchronous techniques do not utilize a single global clock.

1.1.4 Network topology

A network can be represented by a graph in which nodes indicate switches and edges represent communication links. Interconnection networks are made up of switching elements and topology is the pattern in which the individual switches are interconnected to other elements such as processors, memories. Direct topologies connect each switch directly to a node, while in indirect topologies at least some of the switches connect to other switches [1]. The topologies can be categorized into two groups, static and dynamic as shown in Figure 1.

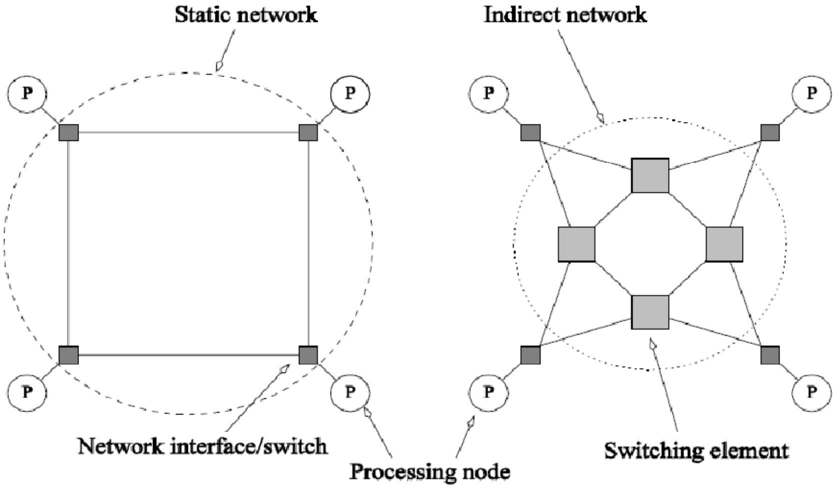


Figure 1: Static and Dynamic Networks

1.1.4.1 Static Network

In static topology, links between two processors are with passive and dedicated buses cannot be reconfigured for direct connection with other processors. Static networks that are generally used in message-passing architectures [9]. The following network topologies are commonly used.

a) Ring Network

The type of network topology in which each of the nodes of the network is connected to two other nodes in the network and with the first and last nodes being connected to each other, forming a ring as shown in Figure 2(a). All data that is transmitted between nodes in the network travels from one node to the next node in a circular manner and the data generally flows in a single direction only.

b) Star Network

A star topology connects all nodes to a central point of concentration as shown in Figure 2(b). This point is usually a hub or switch. Nodes communicate across the network by passing data through the hub. The main disadvantage of this kind of topology is that if central hub stops working then there will be no transmission at any node.

c) Fully connected Network

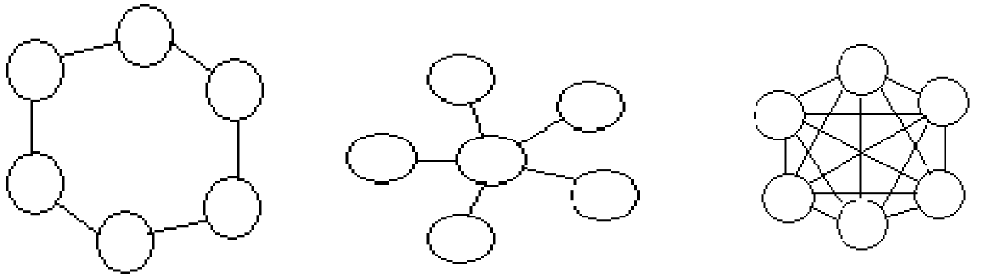
The type of network topology in which each node is connected to every other nodes of the network with a point-to-point link as shown in Figure 2(c). This makes it possible for data to be simultaneously transmitted from any single node to all of the other nodes.

d) Tree Network

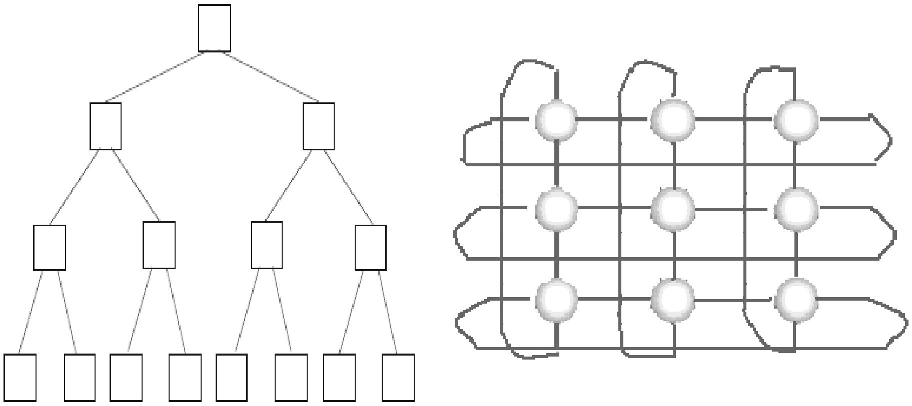
The type of network topology in which a central 'root' node (the top level of the hierarchy) is connected to one or more other nodes that are one level lower in the hierarchy (i.e., the second level) with a point-to-point link between each of the second level nodes and the top level central 'root' node, while each of the second level nodes that are connected to the top level central 'root' node will also have one or more other nodes that are one level lower in the hierarchy (i.e., the third level) connected to it as shown in Figure 2(d).

e) Mesh Network

A mesh simply connects one processor to four others, as shown in Figure 2(e). Consider a chessboard with a processor in each square. A connection would be made from each square to four its neighbors.



(a): Ring (b): Star (c): Fully Connected



2(d): Tree 2(e): Mesh

Figure 2: Static Networks

1.1.4.2 Dynamic Networks

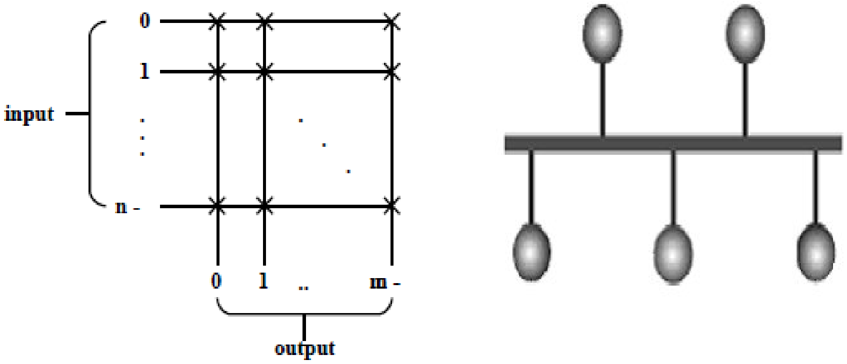
Links in dynamic topology can be reconfigured by setting network's active switching elements. Dynamic interconnection networks implement one of the following main alternatives:

a) Crossbar Network

The crossbar makes a connection from a given vertical bus to the appropriate horizontal bus and allows traffic to flow along this path. In crossbar network, the other horizontal or vertical buses can be supporting a flow of traffic at the same time as shown in Figure 3(a).

b) Bus Network

In a bus network, processors share a single communication channel, called bus shown in Figure 3(b). A bus is highly non scalable architecture, because only one processor can communicate on the bus at a time. A bus network design offers minimum bandwidth. It is highly inefficient and unreliable because of a single bus, the failure of which will make it unusable.



(a): Crossbar **(b): Bus**

Figure 3: Dynamic Networks

1.2 Multi-stage Interconnection Networks

Multistage interconnection networks (MINs) consist of more than one stages 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. The parameter N is called the size of the network. There are several different multistage interconnection networks proposed and studied in the literature. Figure 4 illustrates a structure of multistage interconnection network, which are representatives of a general class of networks. Figure 4 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.

Multistage interconnection networks are:

- Attempt to reduce cost.
- Attempt to decrease the path length.

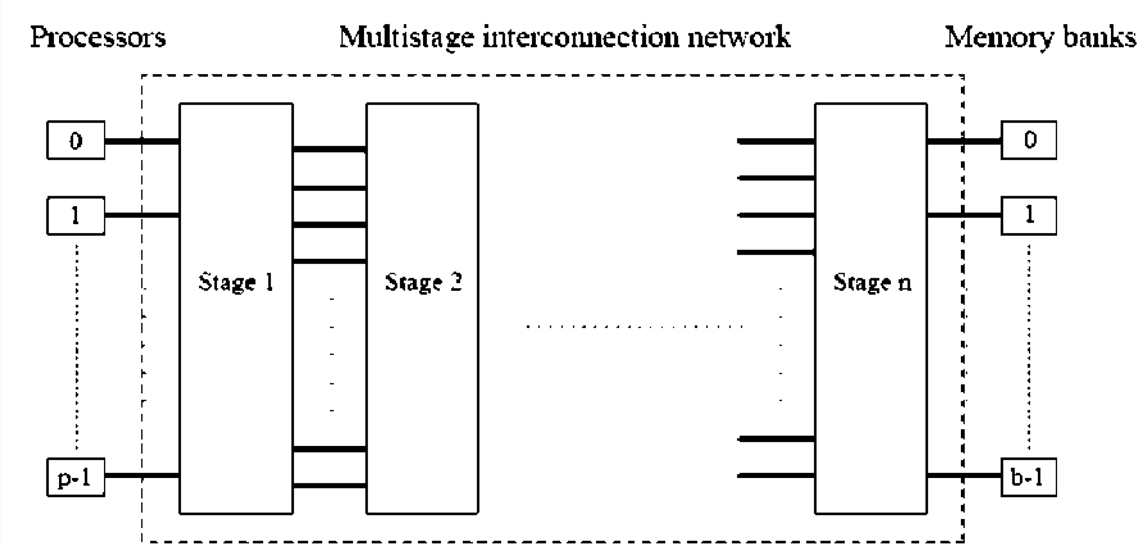


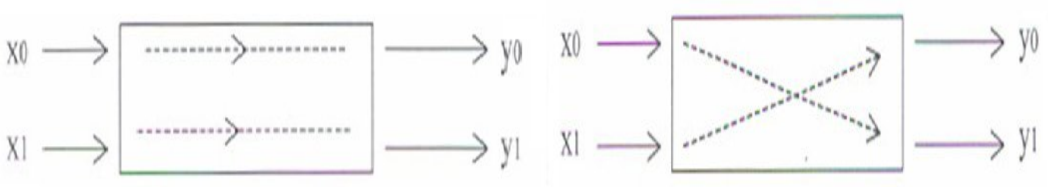
Figure 4: A Multistage Network

Table 1: Comparison of Bus, Crossbar and Multi-stage Interconnection Networks:

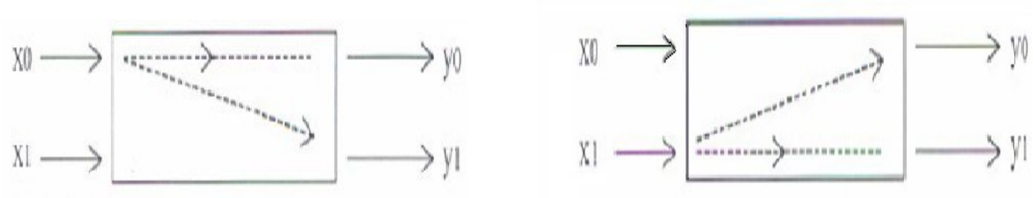
Property	Bus	Crossbar	Multistage
Speed	Low	High	High
Cost	Low	High	Moderate
Reliability	Low	High	High
Configurability	High	Low	Moderate
Complexity	Low	High	Moderate

1.2.1 Switching Elements

The switching element is the basic element of a multistage interconnection network. It may be viewed as a very small network. These switches are the devices having multiple inputs and multiple output. A switch box have any one of the following four states i.e. straight, exchange, upper broadcast and lower broadcast shown in Figure.5.



(a): Straight **(b): Exchange**



(c):Upper broadcast **(d):Lower broadcast**

Figure 5: Switching elements

1.2.2 Classification of Multistage Interconnection Networks

Multistage interconnection networks can be classified according to different categories. The main classification categories are:

- According to number of paths
- According to switch
- According to control
- According to availability of path

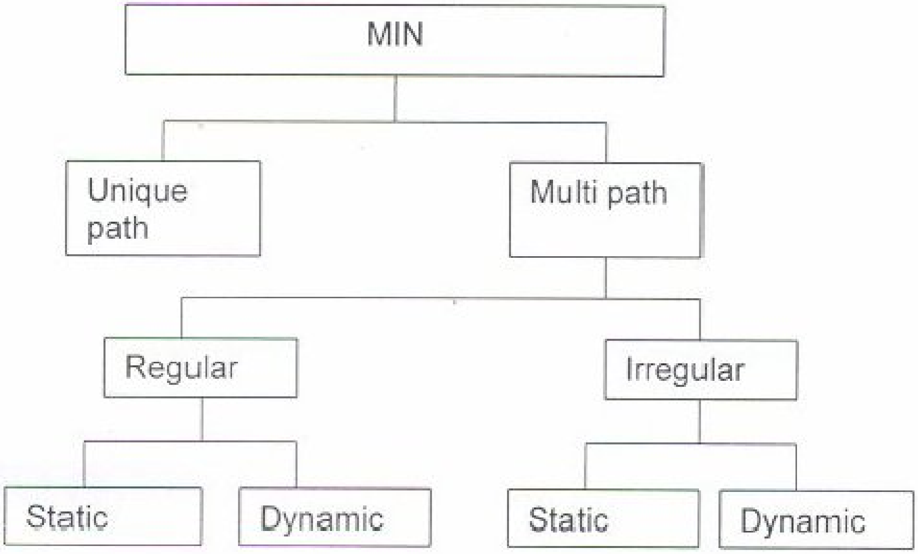


Figure 6: Classification of Multistage Network

1.2.2.1 Classification according to No of Paths

a) Unique path networks*:* These networks provide unique path between every source and destination. The failure of any switching element along the path disconnects some source destination pairs. These are not reliable for a large multiprocessor system, as they cannot tolerate even a single fault. These networks provide poor performance as a source destination connection may be blocked by a previously established connection [25].

b) Multi path networks*:* These provide more than one path between source and destination. In case, there is a failure of one switching element in the path, the request is routed through some alternative path. Multi path multistage interconnection networks can be static or dynamic. For static networks, backtracking is used if fault is encountered,. In dynamic networks, if a fault is encountered in a particular stage, a switching element in preceding stage will re-route data through an alternative available path [25].

1.2.2.2 Classification according to Switches

a) Regular networks*:* Regular multistage interconnection networks have an equal number of switching elements per stage. As a result they may impose equal time delay to all h requests passing through them [36].

b) Irregular networks*:* Irregular multistage interconnection networks have unequal number of switching elements at each stage and thus they are inherently multi path in nature. For a given source destination pair, multiple paths are available [36].

1.2.2.3 Classification according to Control

a) Flip controlled networks*:* Flip controlled multistage interconnection networks have a common control signal for switching in various switching elements at a given stage [7]. These networks are less complicated due to lesser number of control signals but have lesser bandwidth.

b) Distributed control networks: Distributed control multistage interconnection networks have a separate control signal for every switching element. These have higher bandwidth due to selection of source destination pair at a given time and are quite complex [7].

1.2.2.4. Classification according to Availability of Path

a) Blocking networks*:* Blocking is the conflict that arises between two paths established between two source and destination pairs. When sources generate connection requests to an identical destination, it is possible that some paths need to pass simultaneously through an identical output of the SE. A path can never share the output with another path at any point in time, and hence blocking arises in the SE. Omega network is a type of blocking network [37].

b) Non blocking networks*:* A network is called non blocking if it is possible to route from any source to any destination, in presence of other established source-destination routes, provided no two sources have same destination. In other words, networks that can handle all possible connections without blocking is called non-blocking network [37].

1.3 Optical Multistage Interconnection Networks

Optical communication is necessary for achieving reliable, quick and flexible communication. Advances in optical technologies have made optical communication a reliable networking choice to meet the 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. Advances in electro-optic technologies have made optical communication a good networking choice for the increasing demands of high channel bandwidth and low communication latency of high-performance computing/communication applications. Fiber optic communications offer a combination of high bandwidth, low error probability, and gigabit transmission capacity. Multistage Interconnection Networks (MINs) are very popular in switching and communication applications and have been used in telecommunication and parallel computing systems. But these days with growing demand for bandwidth, optical technology is used to Implement interconnection networks and switches. In electronic MINs electricity is used, where as in Optical MINs (OMIN) light is used to transmit the messages[21]. The electronic MINs and the optical MINs have many similarities, but there are some fundamental differences between them such as the optical-loss during switching and the crosstalk problem in the optical switches.

Optical interconnections have the potential of becoming an appealing alternative to electrical interconnections. For long and medium range distances (e.g., local area networks and telecommunication), optical technology (fibers) is the technology of choice, offering better performance and lower costs than electrical wires[21]. There is a trend for optics to replace electronics for shorter distances and larger connectivity applications.Optical interconnections are insensitive to radio wave interference effects, are free from transmission line capacitive loading, do not have geometrical planar constraints, and can be reconfigurable (circuit-switched).

Table 2: Difference between Electronic and Optical Networks

CHARACTERISTICS	**ELECTRONIC MULTISTAGE NETWORKS**	**OPTICAL MULTISTAGE NETWORKS**
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

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. 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[27]. 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 occurs 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 neonate directional couplers, can have switching speeds from hundreds of picoseconds to tens of nanoseconds.

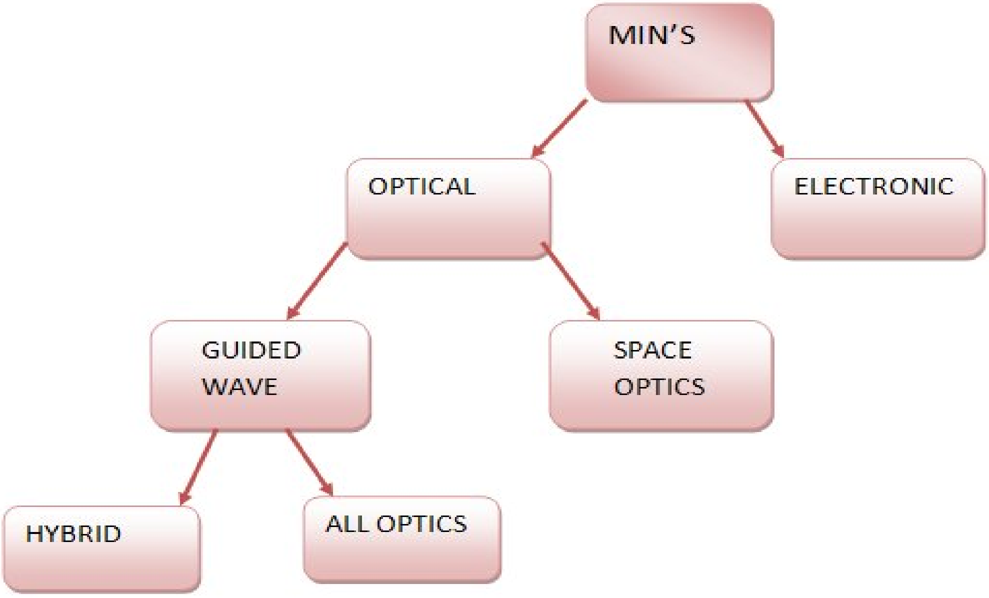


Figure 7: Types of Multistage Networks

1.3.1 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. For this reason, circuit switching is usually preferred in optical MINs. So we assume that circuit switching is used.

1.3.2 Various Optical MINs:

Crossbar network is a squared (or rectangular), wide-sense no blocking network without Crosstalk. It has first order Crosstalk and requires N^2 switches.

The Partitioned Optical Passive Star (POPS) network is a SIMD interconnection network that uses multiple optical passive star couplers. OPS coupler is an all-optical passive device which is capable of receiving an optical signal from one of its d sources and broad cast it to all of its d destinations. Being a passive all-optical technology, it benefits from a number of characteristics such as no opto-electronic conversion, high noise immunity, and low latency.

Omega networks implemented by free-space digital optics have been widely used in optical computing and photonic switching systems because of its flexibility, simplicity, and identity of link functions.

Double crossbar network consists of two crossbar-like structures placed on top of each other.It is a strictly no blocking network without first order switch crosstalk. But it has crossover and uses $2N^2$ switches.

Banyan network has the best results on the number of switch elements $((N\log_2 N)/2)$ and the path length $(\log_2 N)$. But it is a blocking network with first order switch crosstalk.

Cantor network is one of the symmetrical, strictly non-blocking networks. Unlike the unique-path and rearrangeable networks, strictly non-blocking networks have the ability to provide paths among the inputs and the outputs without disturbing the ongoing communications.

Benes network can be considered as a Banyan network concatenated with a reverse Banyan network and the middle stage overlapped. It is a rearrangeable nonblocking network with first order switch crosstalk and complicated control algorithm.

Dilated Benes network vertically stacks Benes network and adds one extra at the end of it DBN solves the first order switch crosstalk problem by following the restriction that at most one input at every switch element can be active at a time. It is a rearrangeable nonblocking network built using recursive construction.

Extended baseline network is constructed by adding a cross-connect stage after the recursive baseline network. This cross-connect stage provides one more path.

1.3.3 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.

1.3.3.1 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. 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.

1.3.3.2 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 [21]. 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, first-order crosstalk can be eliminated by ensuring that a switch is not used by two input signals simultaneously. 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.

1.3.4. Ways to solve Crosstalk Problem

1.3.4.1 Space Domain Approach

One way to solve the crosstalk problem is a space domain approach, where a MIN is duplicated and combined to avoid crosstalk. The number of switches required for the same connectivity in a network 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.[27] With the space domain approach, extra switching elements (SEs) are used to ensure that at most one input and one output of every SE will be used at any given time.

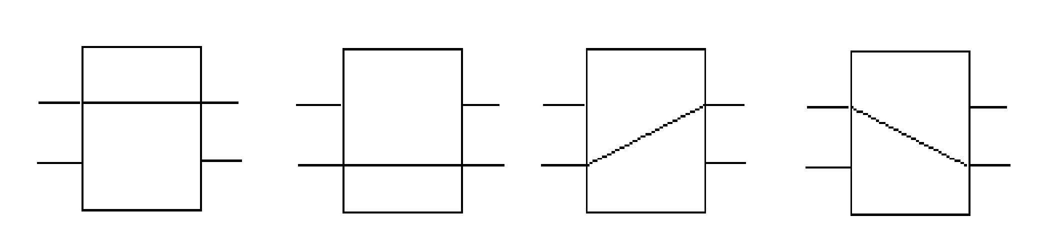


Figure 8: Ways to Avoid Crosstalk in the Network using Space Domain Approach

1.3.4.2 Time Domain Approach:

Another way to solve the problem of crosstalk is the time domain approach. 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 [21].

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.

Second, there is a mismatch between the routing control and the fast signal transmission speed. To avoid crosstalk, we use the TDM approach, which is to partition the set of messages into several groups such that the messages in each group can be sent simultaneously through the network without any crosstalk. If we don't allow crosstalk in the network that is if the crosstalk in the network is zero the performance of the optical networks will be less. But if we allow limited crosstalk in the network that is if we allow crosstalk in the earlier stages the performance of the networks improves. The performance of the optical networks will be very less than the non optical networks if the crosstalk is zero. But the performance starts increasing if we allow limited crosstalk in the earlier stages of the networks. The bandwidth of a non-optical network is much more than optical networks.

Window Method is a technique used to find which messages should not be in the same group because they introduce crosstalk in the network. WM can be described as follows: For network size N*N, there are N source and N destination address. Each source and its corresponding destination address is combined to produce a combination matrix. From this matrix, the optical window size is M-1 where M= log and N is the size of the network[28]. This window is used in the combination matrix from left to right except first and last column. If two messages have the same bit pattern, they will cause conflict in the network. Hence, they must be routed in different passes.

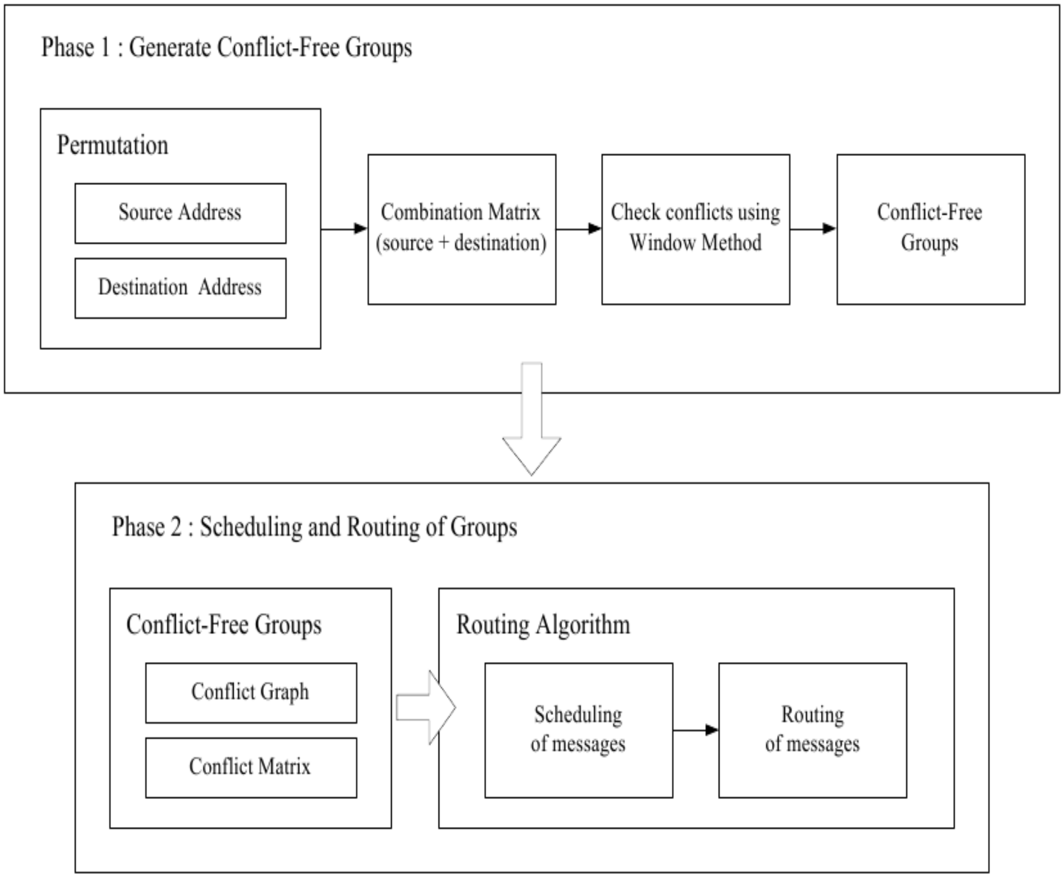
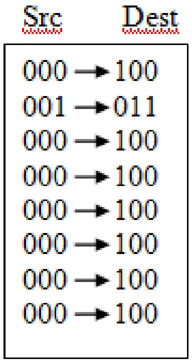


Figure 9: Time Dilation Approach[28]

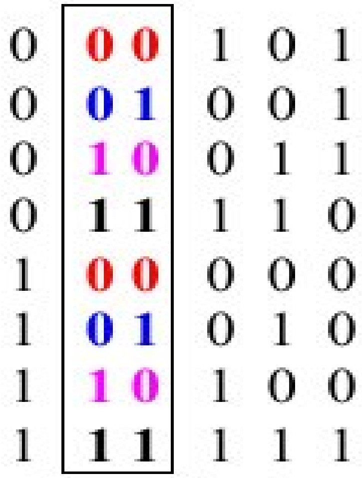
To see how the window method works, refer to the following example. The network size is 8*8 and permutation is shown



Src Dest

000 → 100
001 → 011
000 → 100
000 → 100
000 → 100
000 → 100
000 → 100
000 → 100

Using the window method the window size is M-1=2 (M= log 8 =3) and the number of windows is M=3 (, ,).



0 0 0 1 0 1
0 0 1 0 0 1
0 1 0 0 1 1
0 1 1 1 1 0
1 0 0 0 0 0
1 0 1 0 1 0
1 1 0 1 0 0
1 1 1 1 1 1

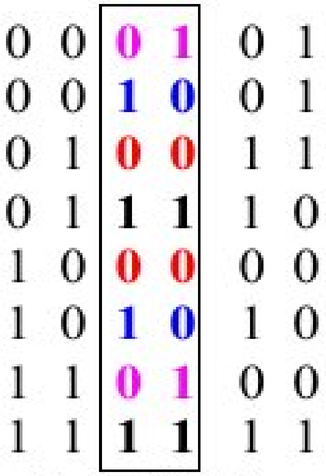
Step 1(w_0)

msg 000 and 100 has conflict

msg 001 and 101 has conflict

msg 010 and 110 has conflict

msg 011 and 111 has conflict



0 0 0 1 0 1
0 0 1 0 0 1
0 1 0 0 1 1
0 1 1 1 1 0
1 0 0 0 0 0
1 0 1 0 1 0
1 1 0 1 0 0
1 1 1 1 1 1

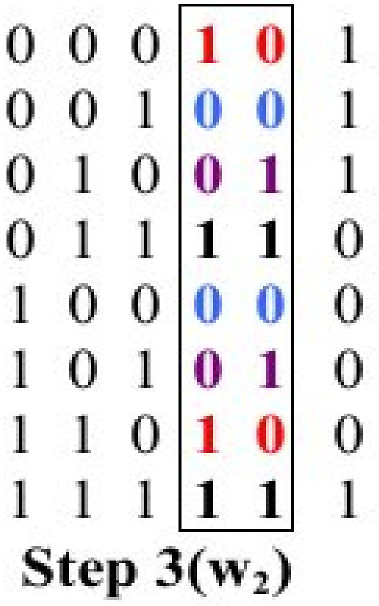
Step 2(w_1)

msg 000 and 110 has conflict

msg 001 and 101 has conflict

msg 010 and 100 has conflict

msg 011 and 111 has conflict



0	0	0	1	0	1
0	0	1	0	0	1
0	1	0	0	1	1
0	1	1	1	1	0
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 3(w_2)

msg 000 and 110 has conflict

msg 001 and 100 has conflict

msg 010 and 101 has conflict

msg 011 and 111 has conflict

Figure 10: Optical Window Method

From the research it is studied that Optical communication is better than the electronic communication in terms of bandwidth and latency. There are various similarities between the two networks but optical multistage interconnection networks have their own challenges. These problems can be removed by using the various techniques. For all these various literatures which are studied from them are as follows:-

1) **"A New Scheme to Realize Crosstalk-free Permutations in Optical MINs with Vertical Stacking"**

In this paper a new concept vertical stacking, a new approach for constructing nonblocking multistage interconnection networks (MINs) is explained. It discusses the crosstalk-free permutation in rearrangeable, self-routing Banyan-type optical MINs built on vertical stacking and propose a new scheme for realizing permutations in this class of optical MINs crosstalk-free.

2) **"Permutation Capability of Optical Multistage Interconnection Networks"**

In this paper, a new concept, semi-permutation, to analyze the permutation capability of optical MINs under the constraint of avoiding crosstalk. For the blocking banyan network, it shows that not all semi-per-mutations are realizable in one pass, and gave the number of realizable semi-permutations. It shows that optical networks are better than electronic networks in terms of bandwidth.

3) **"Analyzing the performance of optical multistage interconnection networks with limited crosstalk"**

In this paper the interest is on the study of the performance of unbuffered optical multistage interconnection network using the banyan network. The uniform reference model approach is assumed for the purpose of analysis. In this paper, the analytical modeling approach is applied to an $N \times N$ Banyan Network with limited crosstalk. The analysis is performed by calculating the bandwidth and throughput of the network operating under a load l and allowing random traffic and using a greedy routing strategy. A number of equations are derived using the theory of probability.

4) **"A module design of rearrangeable nonblocking double omega optical network using binary optics elements"**

In this paper there is a study about multistage interconnection networks (Banyan networks) that are frequently proposed as connections in multiprocessor systems, in ATM switches, or in Gigabit Ethernet switches. It contains the idea about how analytical models are useful for evaluating the performance of the networks. Analytical models are much faster for this purpose than simulation. But on the other hand, It is derived that the development of an analytical model is very time-consuming. In this paper, the author presented a method for the automatic and fast generation of an analytical network model. The generated analysis handles networks of arbitrary size, arbitrary switching element sizes, arbitrary buffer lengths in each network stage, an arbitrary (but uniform) traffic pattern, and an arbitrarily chosen network load. The arbitrary traffic patterns include multicast traffic, which has not been considered by former models.

5) **"Fast Method To Find Conflicts In Optical Multistage Interconnection Networks"**

Window Method is used to find out which messages have conflict and should not be in the same group. In this paper, fast window method based on bitwise operations (BWM) is represented. This algorithm is applied on Omega network.

6) **"Permutation Capability of Optical Cantor Network"**

In this paper, Crosstalk problem can be removed in the optical network by using the space dilation. Then, we show that any permutation is realizable under the constraint of avoiding cross-talk. Based on space domain approach, a routing scheme for realizing an all-to-all permutation by one pass in an optical Cantor network is also presented.

7) **"Progress in Optical Networking"**

This article summarizes the present state of optical networking, how we got to this point, and what needs to be done to complete the job.

8) **"Wire vs Wireless communication"**

This article summarizes the differences between the two approaches.and gives the brief idea about the differences between the two approaches

9)**"Permutation Capability and Connectivity of Enhanced Multistage Interconnection Network(E-MIN)"**

In this paper new permutation capability technique called semi permutation is considered. Bandwidth and probability of acceptance of E-MIN is evaluated and compared with Crossbar and Delta networks.

.

10)**"Optical Multistage Interconnection Networks :New Challenges and Approaches"**

In this paper information about Optical interconnections for communication networks and multiprocessor systems is given. It contains a study of optical switching networks is a directional coupler with two inputs and two outputs or switching elements. Depending on the control voltage applied to it, an input optical signal is coupled to either of the two outputs, setting the SE to either the straight or cross state. A class of topologies that can be used to construct optical networks is multistage interconnection networks, which interconnect their inputs and outputs via several stages of SEs (Switching elements), are also mentioned in this paper. In this I have studied various ways to deal with the unique problem of avoiding crosstalk in the SEs (Switching elements).

11) **"Optimal all to all personalizes exchange in a class of Optical Multistage Networks"**

In this paper, Issue of realizing all-to-all personalized exchange in o ptical multistage networks is given. Advances in electro-optic technologies have made optical communication a promising networking choice to meet the increasing demands for high channel bandwidth and low communication latency of high-performance computing/communication applications. Although optical multistage networks hold great promise and have demonstrated advantages over their electronic counterpart, they also hold their own challenges. Due to the unique properties of optics, crosstalk in optical switches should be avoided to make them work properly. In this paper, optimal scheme for realizing all-to-all personalized exchange in a class of unique-path, self routing optical multistage networks crosstalk-free is defined.

.12) **"High-Speed Crosstalk-Free Routing for Optical Multistage Interconnection Networks"**

In this paper MINs and OMINs are studied . This paper shows that how Multistage interconnection networks (MINs) can be used to construct electro optic switches. To implement crosstalk free switching in such a switch, two I/O connecting paths cannot share a common switching element (SE). Thus, a permutation must be decomposed into partial permutations, each being routed through the switch without crosstalk. This reexamines the permutation capacity of MINs, present a simpler proof for semi permutation decomposability, and propose a parallel decomposition algorithm of logarithmic time.

Advances in electro-optic technologies have made optical communication a good networking choice for the increasing demands of high channel bandwidth and low communication latency of high-performance computing/communication applications. Fiber optic communications offer a combination of high bandwidth, low error probability, and gigabit transmission capacity. Multistage Interconnection Networks (MINs) are very popular in switching and communication applications and have been used in telecommunication and parallel computing systems.But these days with growing demand for bandwidth, optical technology is used to implement interconnection networks and switches. In electronic MINs electricity is used, where as in Optical MINs (OMIN) light is used to transmit the messages. The electronic MINs and the optical MINs have many similarities, but there are some fundamental differences between them such as the optical-loss during switching and the crosstalk problem in the optical switches.

Multistage interconnection networks (MINs) have been an attractive interconnecting structure for high performance parallel computing systems. 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. To transfer messages from a source address to a destination address on an optical network without crosstalk, we need to divide the messages into several groups, and then deliver the messages using one time slot (pass) for each group, which is called the time division multiplexing (TDM) In each group, the paths of the messages going through the network should be crosstalk free.

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. Permutation passability of various optical networks is checked. Different probabilities equations are derived under a given load for the different networks which allow limited crosstalk in the network. Then various networks are considered again in which no crosstalk is allowed, again for this type of network different probabilities for the switches are assumed. After that, the bandwidth for both of these networks is calculated, and it has been observed that the bandwidth of networks with limited crosstalk is more than the network which do not allow any crosstalk.

4.1 Permutation Passability

A one to one correspondence between a source and a Destination is called Permutation. Permutation passability means how many input requests occurring simultaneously at the input are able to pass through a given network and how many of them will successfully mature i.e. will reach their destination [21]. The request always pass from the most suitable path available (generally, the minimum length path), if such path is busy or faulty then the request is pass through an alternate path. If no alternate path is available then the request has to be simply dropped or said to be having clash. So some of the requests will pass through the most favorable path, others have to be routed through an available alternative path. If no alternative paths are available then some requests cannot be served at all. 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. If we allow the limited crosstalk in the optical networks the permutation passibility of the optical networks will be increased[21].

4.2 Semi permutations

A semi-permutation is a partial permutation in which we say that there is only one active link passing through each input switch and output switch. Thus it eliminates the problem of crosstalk that occurs in the first and last stage of the network. But there's also a need to eliminate crosstalk in the middle stages of the network for optical communication. [3,21].

Example 1 for n = 8

$$\begin{pmatrix} 0 & 3 & 4 & 6 \\ 1 & 5 & 3 & 7 \end{pmatrix}$$

is a semi-permutation, because we have

$$\left\{\left\lfloor\frac{0}{2}\right\rfloor,\left\lfloor\frac{3}{2}\right\rfloor,\left\lfloor\frac{4}{2}\right\rfloor,\left\lfloor\frac{6}{2}\right\rfloor\right\} = \{0,1,2,3\} \text{ , and}$$

$$\left\{\left\lfloor\frac{1}{2}\right\rfloor,\left\lfloor\frac{5}{2}\right\rfloor,\left\lfloor\frac{3}{2}\right\rfloor,\left\lfloor\frac{7}{2}\right\rfloor\right\} = \{0,2,1,3\} = \{0,1,2,3\}$$

Example 2 for n = 8

$$\begin{pmatrix} 0 & 1 & 4 & 6 \\ 1 & 4 & 3 & 7 \end{pmatrix}$$

is not semi-permutation, because we have

$$\left\{\left\lfloor\frac{0}{2}\right\rfloor,\left\lfloor\frac{1}{2}\right\rfloor,\left\lfloor\frac{4}{2}\right\rfloor,\left\lfloor\frac{6}{2}\right\rfloor\right\} = \{0,0,2,3\} \text{ , and}$$

$$\left\{\left\lfloor\frac{1}{2}\right\rfloor,\left\lfloor\frac{4}{2}\right\rfloor,\left\lfloor\frac{3}{2}\right\rfloor,\left\lfloor\frac{7}{2}\right\rfloor\right\} = \{0,2,1,3\} = \{0,2,2,3\}$$

Thus, we can say that in the optical networks if we don’t allow crosstalk, not even in the single stage, this permutation is not possible. Thus the performance of the network will be very poor. But if we allow limited crosstalk that is crosstalk in the earlier stages or the network the performance of the network improves. it means that we allow those switches in the network which allow multiple signals to be passed. There will be limited crosstalk but it improves the permutation passibility and hence the performance.

4.3 Banyan Network

Banyan networks were first introduced by Goke and Lipovski using a graph model. In a simplifying approach, any multistage network for which there is a unique path from each network input to each network output is called a banyan network. The banyan network is an N X N network composed of k X k (k >= 2) switches, where N $=K^n$ The network has n stages of switches and the switches in the consecutive stages are linked by interconnection patterns [21]. All switches in the network are buffered switches in the sense that a buffer (FIFO queue) is placed on each input link of the switch. Each buffer can hold upto B packets and B is referred to as buffer length. Any permutation can be decomposed to two semi-permutations. In general, the decomposition is not unique. Many admissible permutations to a unique-path multistage network have decomposition to two admissible semi-permutations to the network. For example, the admissible permutation

$$\begin{bmatrix} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ 2 & 6 & 0 & 5 & 7 & 3 & 1 & 4 \end{bmatrix}$$

to an 8X8 banyan network (with link-disjoint paths) can be decomposed to two admissible semi permutations to the network (with node-disjoint paths)..

$$\begin{bmatrix} 0 & 3 & 4 & 6 \\ 2 & 5 & 7 & 1 \end{bmatrix} \qquad \begin{bmatrix} 1 & 2 & 5 & 7 \\ 6 & 0 & 3 & 4 \end{bmatrix}$$

However, there are some admissible permutations which cannot be decomposed to two admissible semi-permutations (with node-disjoint paths). On the other hand, there are some permutations which are not admissible to a unique-path multistage network but can be decomposed to two admissible semi-permutations (with node-disjoint paths) to the network. For example the permutation

$$\begin{bmatrix} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ 2 & 0 & 6 & 5 & 7 & 3 & 1 & 4 \end{bmatrix}$$

cannot be realized in the 8X8 banyan network, but it can be decomposed into two semi-permutation.

$$\begin{bmatrix} 0 & 3 & 4 & 6 \\ 2 & 5 & 7 & 1 \end{bmatrix} \qquad \begin{bmatrix} 1 & 2 & 5 & 7 \\ 0 & 6 & 3 & 4 \end{bmatrix}$$

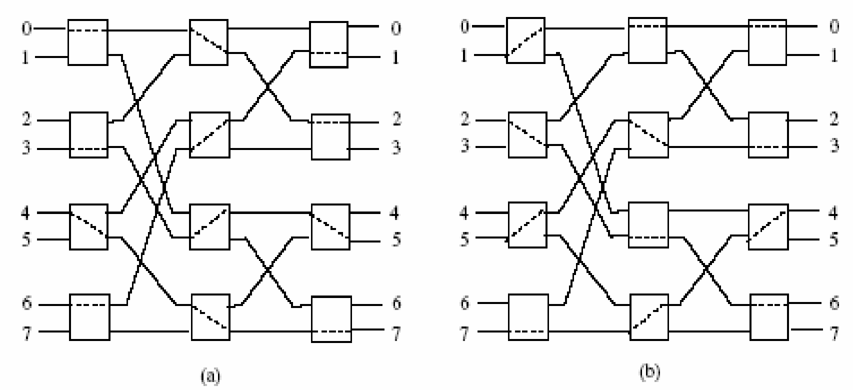


Figure 11: Example of permutation to a banyan network being decomposed [21]

4.3.1 Semi Permutations of Banyan Network

If we consider an NxN multistage interconnection network with n inputs and n outputs where n=2^m. A permutation for a network is a pairing of its inputs and outputs such that each input appears in exactly one pair and each output appears also in exactly one pair**.** In other words, a permutation is a full one-to-one mapping between the network inputs and outputs. For an NxN network, suppose input x_i is mapped to output yi, where xi = i and yi E [0, 1, ..., n-1] for i = 0, 1, ..., n-1

Input: x_o x_1 ……x_{n-1}

Output: y_0 y_1……y_{n-1}

Permutation is having one property, that any permutation can be decomposed into semi-permutations.For Example Figure 12 shows the pairing of inputs with their desired outputs for the following pairs:-

Inputs	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Outputs	**7**	**0**	**5**	**2**	**3**	**6**	**1**	**4**

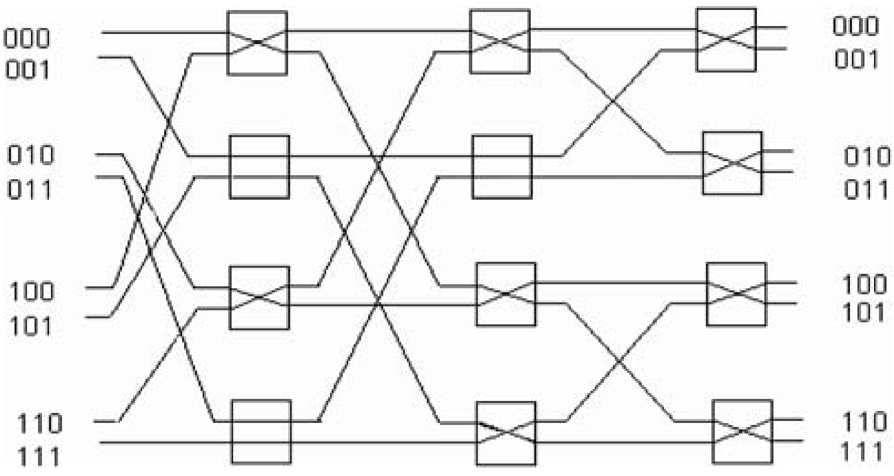


Figure 12: 8x8 Banyan Network

As for the Optical MIN's, only one input is allowed to pass through the switch at one time, therefore permutations are used to solve this path routing problem for the optical MIN's. For this the permutation are calculated at each stage of the network, resulting in various levels of permutations. These levels are then further decomposed into further permutations called as semi permutations.

4.3.1.1 Algorithm used for Decomposition[21]

Step 1: Construct a bipartite graph G for the given permutation.

Step 2: For each connected component of G, start from a vertex of this component in V1 , traverse through an unvisited edge to the neighbor vertex in V2 , back and forth until returning to the starting vertex. (During the traversing, a visited edge is marked ``forward" if the traverse direction on this edge is from V1 to V2 and is marked ``backward" if the direction is opposite.)

Step 3: Take all one-pair mappings corresponding to the edges marked with ``forward," to form one semi-permutation; let the remaining one-pair map- pings, corresponding to the edges marked with ``backward," form another semi-permutation.

End

For Example bipartite graph and edge traverses are shown in given figure 13, where

$$e_0 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, e_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, e_2 = \begin{pmatrix} 2 \\ 7 \end{pmatrix}, e_3 = \begin{pmatrix} 3 \\ 5 \end{pmatrix},$$

$$e_4 = \begin{pmatrix} 4 \\ 3 \end{pmatrix}, e_5 = \begin{pmatrix} 5 \\ 4 \end{pmatrix}, e_6 = \begin{pmatrix} 6 \\ 6 \end{pmatrix}, e_7 = \begin{pmatrix} 7 \\ 2 \end{pmatrix}.$$

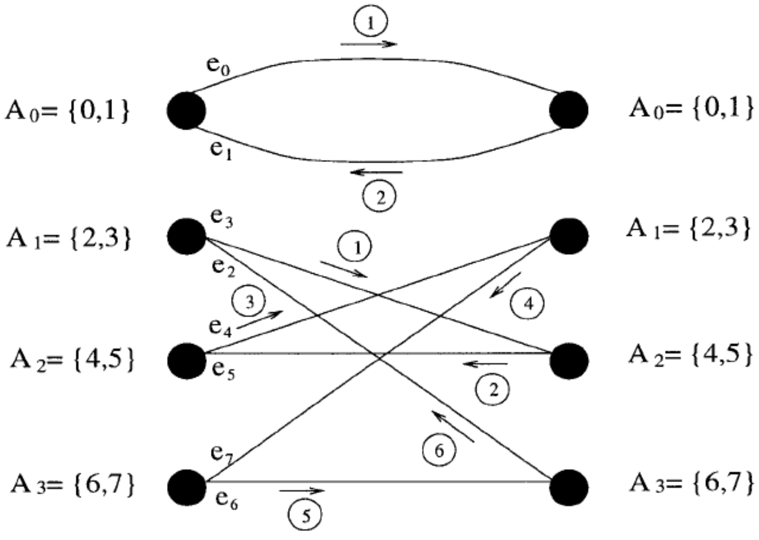


Figure 13: Bipartite graph[21]

Then the ``forward'' pairs e0 , e3 , e4 , and e6 form

$$\begin{bmatrix} 0 & 3 & 4 & 6 \\ 1 & 5 & 3 & 6 \end{bmatrix}$$

And the ``backward'' pairs e1 , e2 , e5 , and e7 form

$$\begin{bmatrix} 1 & 2 & 5 & 7 \\ 0 & 7 & 4 & 2 \end{bmatrix}$$

This completes the decomposition.

4.3.2 Calculation of Passes in Banyan Network

To avoid Crosstalk only one input is allowed to pass through one switch For Example In Banyan network if all the 8 inputs get active only 4 inputs would be allowed to pass through the network towards its output to avoid the problem of cross talk.

Inputs	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Outputs	**7**	**0**	**5**	**2**	**3**	**6**	**1**	**4**

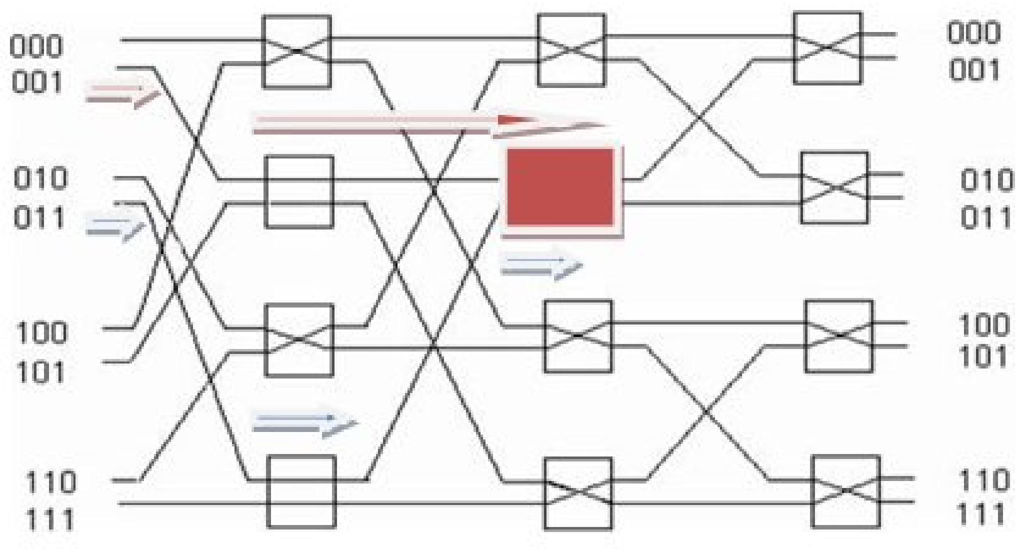
It is decomposed into two permutations in the first Pass

Inputs	**0**	**1**	**2**	**3**
Outputs	**7**	**0**	**5**	**2**

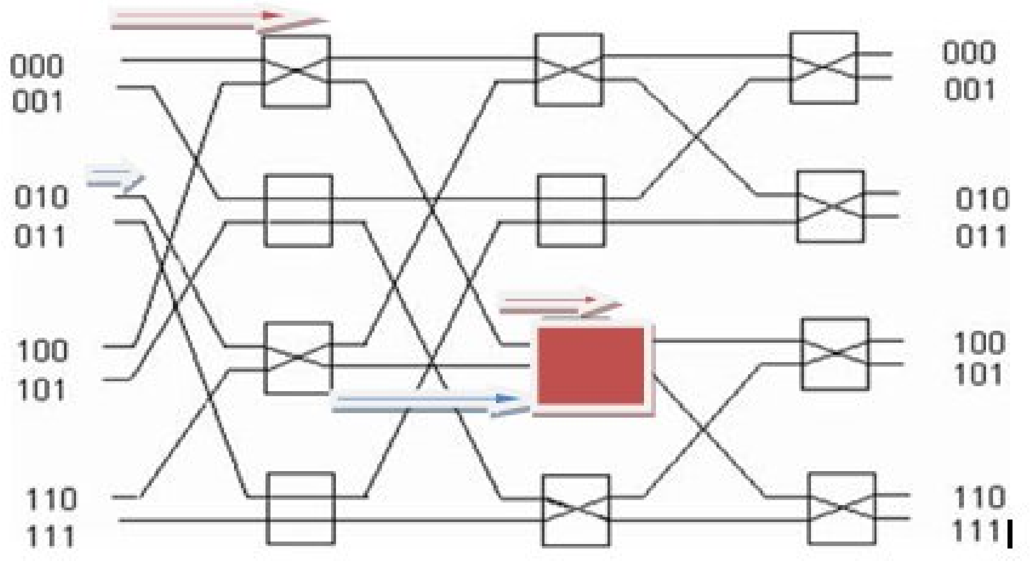
Inputs	**4**	**5**	**6**	**7**
Outputs	**3**	**6**	**1**	**4**

These two passes would solve the crosstalk problem at the first and last stage, the Intermediate stage would still be having the problem of crosstalk. Thus the permutations again has to break to avoid the crosstalk problem.This can be done with the decomposition again. It can be possible with the bipartite graph. Crosstalk is the dangerous problem for the banyan Network. This should be removed.

Inputs	**0**	**1**	**2**	**3**
Outputs	**7**	**0**	**5**	**2**



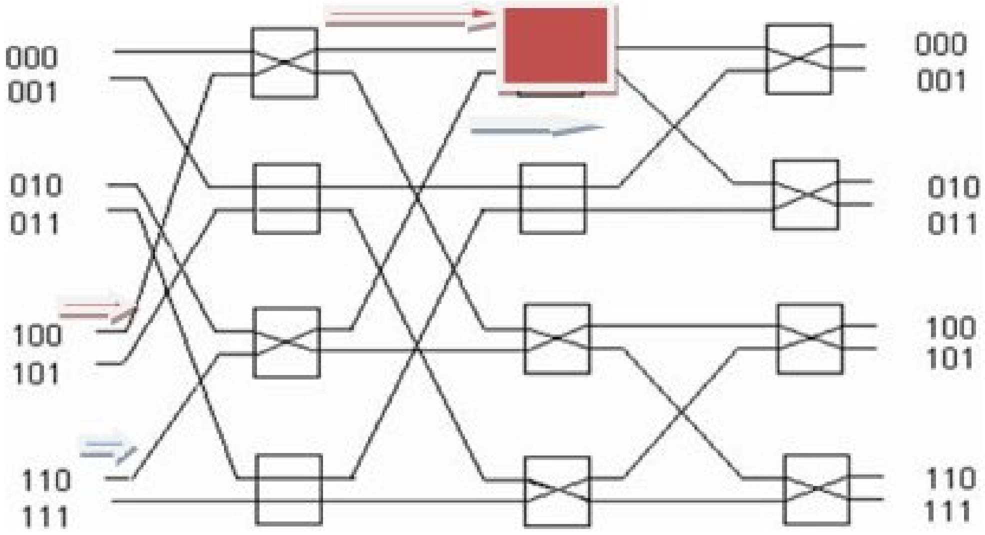
(a): Crosstalk at the Middle stage in Pass1



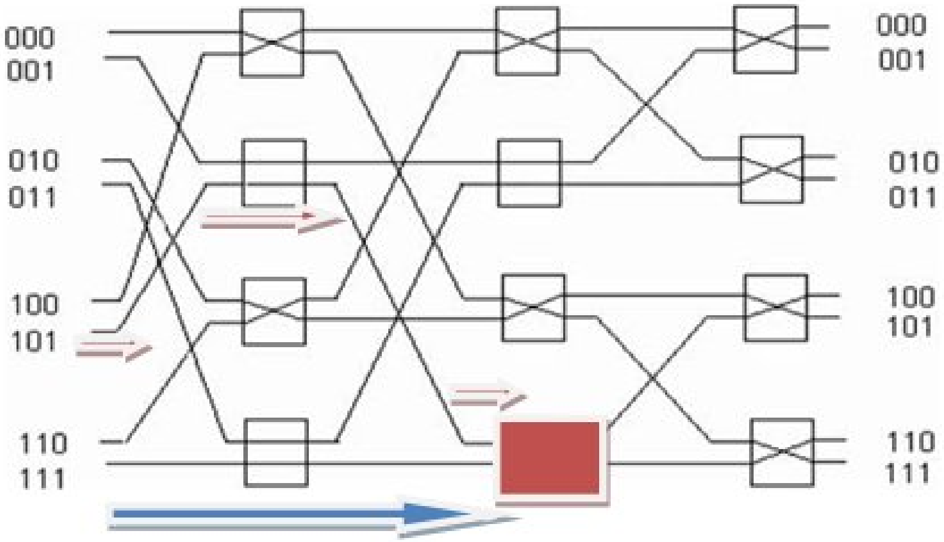
(b): Crosstalk at the Middle stage in Pass1

Inputs 4 5 6 7

Outputs 3 6 1 4



(c): Crosstalk at the Middle stage in Pass2



(d): Crosstalk at the Middle stage in Pass2

Figure 14 : Crosstalk in Banyan Network

To avoid this problem (crosstalk at the intermediate stage), we divide the permutations into semi permutations.

Therefore Semi permutation of pass 1 in the given example:-

Input	**0**	**1**	**2**	**3**
Outputs	**7**	**0**	**5**	**2**

Inputs	**0**	**1**
Outputs	**7**	**0**

1st semi permutation

Inputs	**2**	**3**
Outputs	**5**	**2**

2nd semi permutation

Semi permutation of pass 2

Inputs	**4**	**5**	**6**	**7**
Outputs	**3**	**6**	**1**	**4**

Inputs	**4**	**5**
Outputs	**3**	**6**

1st semi permutation

Inputs	**6**	**7**
Outputs	**1**	**4**

2nd semi permutation

4.4 Omega Network

The Omega Network is one of several connection networks that are used in parallel machines. In the applet below, a small but typical network illustrates the common attributes of such a network, which includes:

- $2^k = N$ inputs and a like number of outputs. Between these are $\log_2 N$ stages each having N/2 exchange elements at each stage.
- The inputs are connected to the first stage using a perfect shuffle connection system, and this is repeated prior to each group of exchange elements. But from the last group to the destination elements the connections are direct.
- An Omega network is typically a semi blocking network. When an exchange element is in use, the next message or data packet that needs this element must wait.

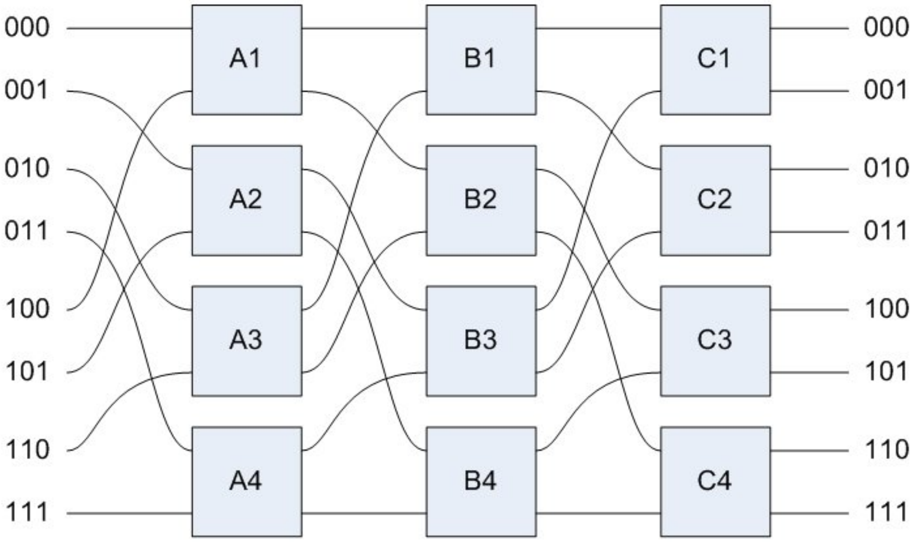


Figure 15: 8x8 Omega Network showing various paths

4.4.1 Routing in Omega Network

Routing is represented as the bitwise shuffle-exchange. The resulting address after a shuffle corresponds to the switch input at each stage, and the resulting address after an exchange corresponds to the switch output at each stage. A complete routing requires shuffle-exchanges until the packet reaches its destination. The address labels in Figure 16 show an example of this operation.

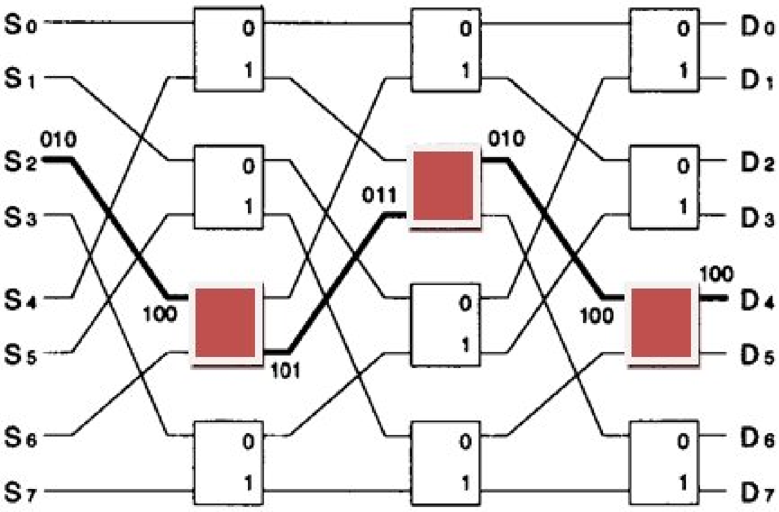


Figure 16: Routing shown in Omega Network

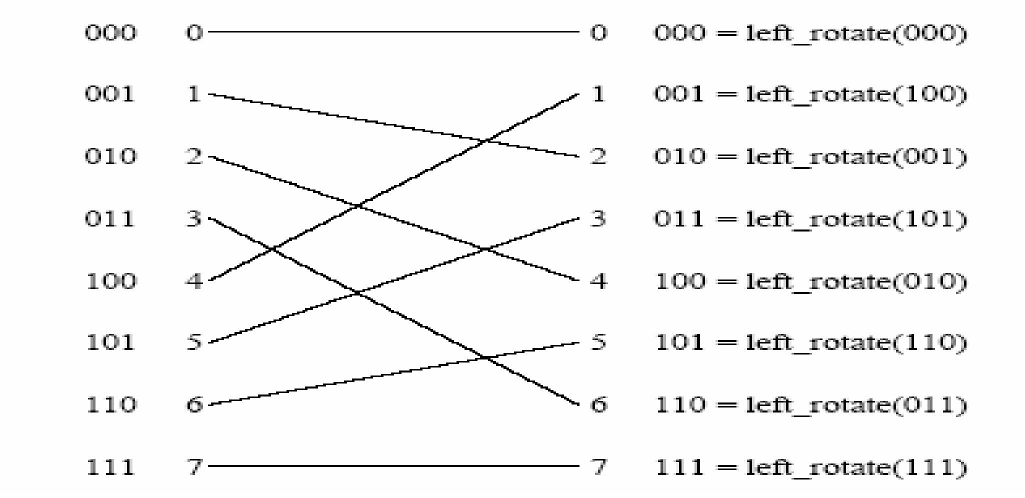


Figure.17: Shuffle connection between stages

4.4.2 Permutation in Optical Omega Network

An NxN non-Optical Omega network can support multiple connections between N inputs and N outputs. It has been observed that the permutation capability of Optical Omega network using time division is same as extra stage non optical omega network

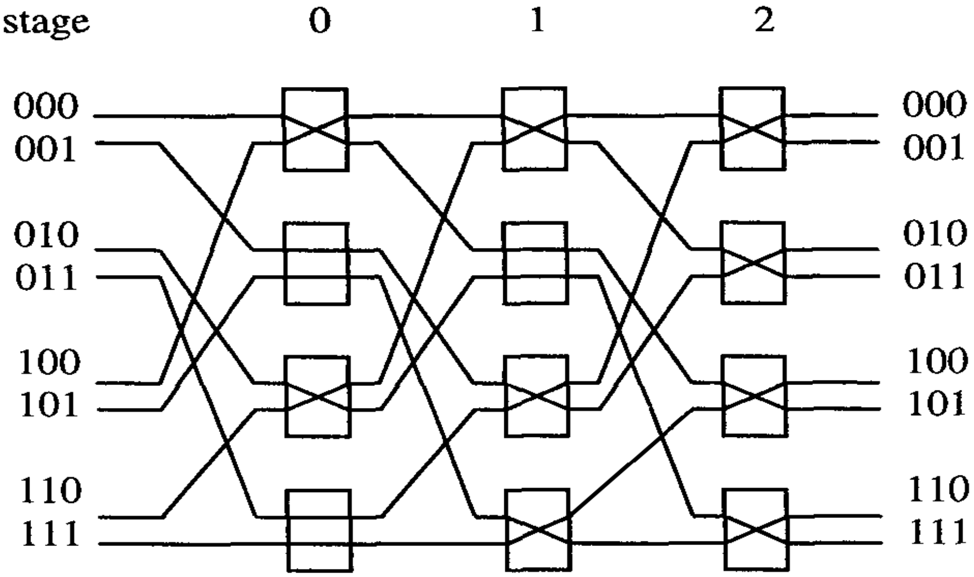


Figure 18: An example of 8x8 Omega network

4.4.2.1 Omega Network using Space Domain approach

A dilated NxN network uses a 2Nx2N regular MIN with only half of the input and output ports being used. Fig. 19 shows a dilated 4x4 Omega network in which only of the two inputs (or output) ports of each switch at the first and last stages is allowed to use. In a dilated network, a connection between an input and output is established by choosing an appropriate path in the network so that no switch in the network will have both input ports active at the same time. Obviously, an NxN dilated Omega has the same hardware cost as that of a 2Nx2N regular Omega. It is shown that an NxN dilated Omega network used as an optical switch has the same permutation capability as an NxN Omega network used as a non-optical switch, but the cost is more than doubled.

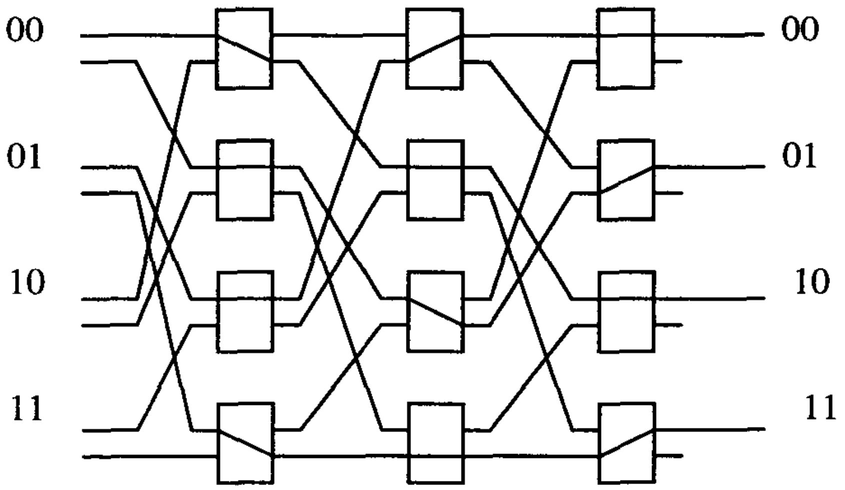


Figure 19: An example of 4x4 dilated Omega Network

4.4.2.2 Omega Network using Time Domain approach

It uses window method for breaking the permutation into the groups so that no conflict or crosstalk occurs.

Source: 0 1 2 3 4 5 6 7
Destination: 4 1 2 3 0 5 6 7

Group A = {(000, 100), (001, 001), (010, 010), (111, 111)};
Group B –{(011, 011), (100, 000), (101, 101), (110, 110)}.

Thus these two permutations can be break into two parts so that no conflict occurs. these two permutations are conflict free. Fig. 20 shows an example of one-extra-stage Omega network.

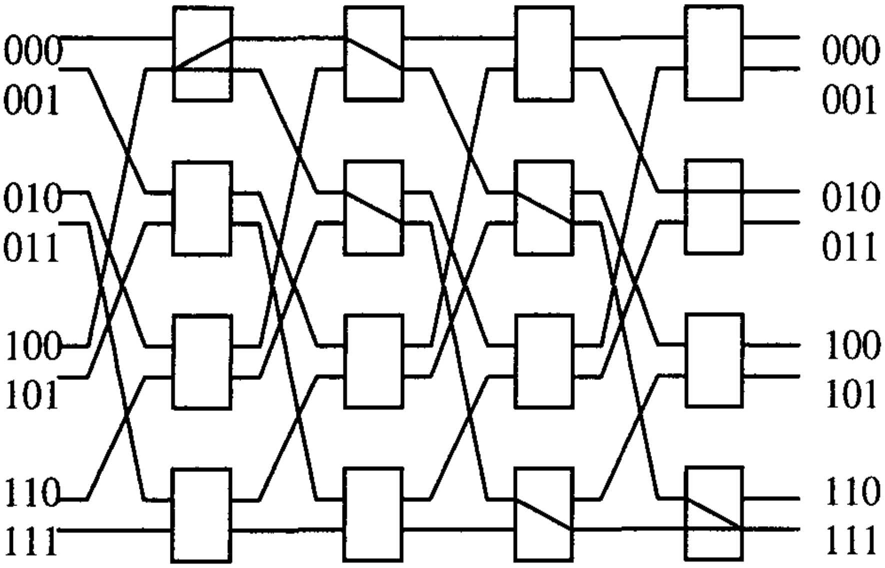


Figure 20: Extra-stage Omega network provides two disjoint paths between 100 and 111.

4.5 Cantor Network

Cantor network [15] is one of the symmetrical, strictly non-blocking networks. Unlike the unique-path and rearrangeable networks, strictly non-blocking networks have the ability to provide paths among the inputs and the outputs without disturbing the ongoing communications. For N inputs, Cantor network can be constructed using $4N \log_2 N$ cross-points and $2\log_2 N+1$ depth (stages), as shown in Fig.21

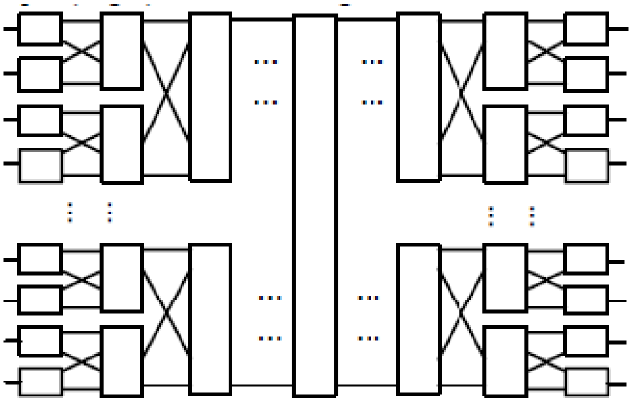


Figure 21: Cantor Network

Every stage has N/2 $\log_2 N$ $2*2$ SEs. The interconnection function between the stages is q shuffle exchange [16, 34]:

$$S_{q,r}(i) = (qi + i/r) \bmod qr$$

In the above equation: between the stage 1 and stage 2:

$$(q, r) = (2, \log_2 N)$$

Between the stage $2\log_2 N$ and stage $2\log_2 N + 1$:

$$(q, r) = (\log_2 N, 2)$$

Between the stage n and stage n+1

Where $2 <= n <= \log_2 N$:

$$(q, r) = (2, 2^{n-1} \log 2N)$$

Between the stage n and stage n+1

Where $\log_2 N + 1 <= n <= 2\log_2 N - 1$:

$$(q,r) = (2^{n-1} \log_2 N, 2).$$

That is, the first half part and last half part are symmetrical to the middle stage[22]. At first, the SEs are divided into $N / 2$ groups in which $2 \log N$ SEs are interconnected by q shuffle exchange. Then, the number of groups reduces by one half and the number of SEs in each group doubles until all the SEs are shuffle exchanged as one group (the middle stage).

4.5.1 Permutation in Cantor Network

The space domain approach is one of the more successful methods in optical communication network. Low port-count switch elements are fairly easy to construct, but larger MINs present challenges for realization, especially when strictly non-blocking is required. The Cantor network allows the high connectivity level, even for a large network. For a $N \times N$ Cantor network, the number of cross-points is less than that of a Clos network, if $N = 2k$ $(N \geq 29)$; k is an integer [34].

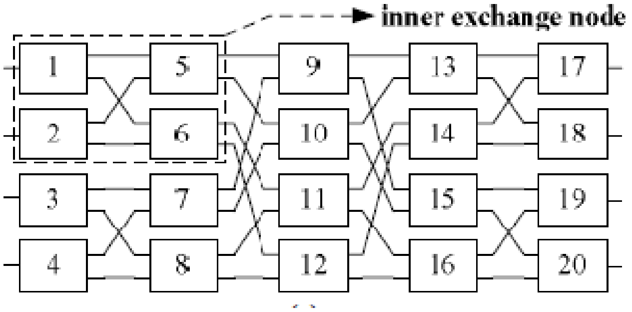


Figure 22: Routing in Cantor Network[34]

The set of SEs $S1 = \{1,2,5,6\}$ can be considered as a whole because the nodes in it are innerly exchanged, so do the sets $S2 = \{3,4,7,8\}$,$S3 = \{13,14,17,18\}$ and $S4 = \{15,16,19,20\}$. Then, a 4 ×4 Cantor network can be simplified to a graph as Figure. 23. This graph is composed of two complete bipartite graphs, where the nodes of the middle stage are classified into two clusters. To avoid cross-talk, we must go according to the following conditions:

Condition 1: We must make sure that one inner exchange node does not have two edges linked to both nodes in one cluster.

Condition 2: Two inner exchange nodes must not have two edges linked to one node in the middle stage at the same time.

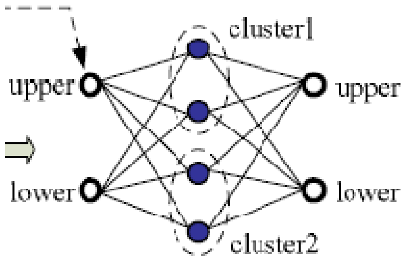


Figure 23: Graph Conversion

We can see that one of the properties of Cantor network is scattering. In the first stage of Cantor network, one input signal can choose one of $\log_2 N$ SEs in the next stage through a $1\times\log_2 N$ SE [34]. Another property of Cantor network is the recursive construction pattern from the middle stage to both sides. There is more than one path between one input-output pair because of this symmetrical and recursive property and this property is most obvious when the port addresses of source and destination are equal. For example, in a 4 ×4 Cantor network, the number of paths from input 0 to output 0 is 4.

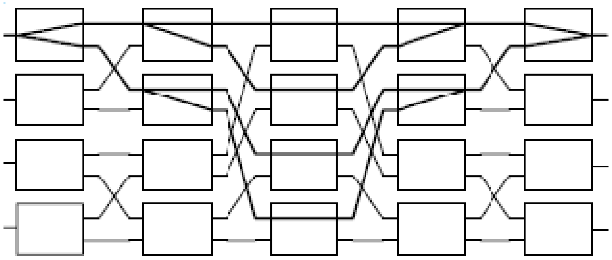


Figure 24: Path Availaibility[34]

For a $N \times N$ Cantor network, the number of the paths between an input-output pair with same ports is,

$P = 2^{\log_2^{n-1}}\log_2 N = N\log_2 N/2$

It has been observed that from the source node to the destination node, there are many redundant paths that we can easily choose an appropriate path to avoid cross-talk.

Chapter 5 Bandwidth

5.1 Cube Interconnection Network

In a cube, vertical lines connect vertices whose addresses differ in most significant bit Position, Vertices at both ends of diagonal lines differ in middle bit position [5]. Horizontal lines differ in least significant bit positions. The unit cube concept can be extended to an n-dimensional unit space, called n-cube, with n bits per vertex.

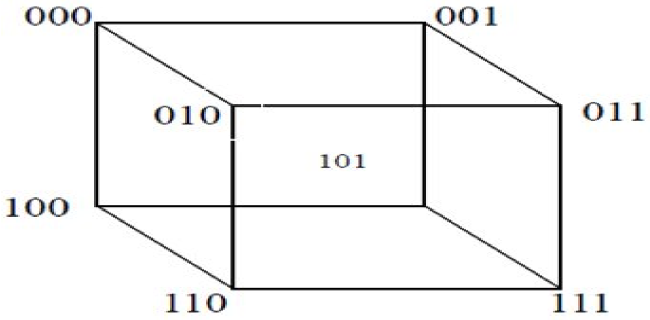


Figure 25: Cube Network

In this we analyze bandwidth of E-MIN and compared it with Crossbar and Delta network by taking Bandwidth as the parameters for judging the performance using their bandwidth equations.

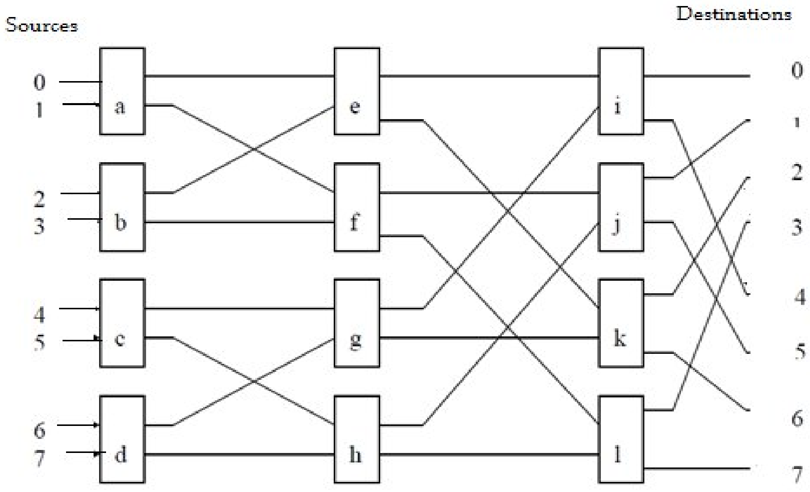


Figure 26: 8x8 Cube Network

The expected bandwidth BW_C is given by the expressions

$BW_c = m - m(1-r/m)^p$

where r is the probability that processor generate the request during a cycle.

5.2 Enhanced Multistage Network

E-MIN network comes under the category of Banyan type, which is a fault tolerant. Extra staging and chaining [26, 31] are two good approaches for ensuring fault tolerance in MINs. Extra staging, adds an extra stage to a given MIN, so that multiple paths can be provided between a source and destination pair. But all MINs are not extra stagable [31, 44]. In Chaining, SEs within a given stage are interconnected. Therefore, chaining introduces additional complexity in the design of the SE. The chained networks need an adaptive routing strategy which is difficult to implement [10]. Extrastage Multistage interconnection networks [44] are implemented using simple 2x2 SEs. The networks obtained using this technique are maximally robust and are less expensive than the corresponding chained network. We call this technique enhancement. A MIN obtained using this technique is referred to as an Enhanced MIN (E-MIN).This motivates us to convert every link stage of the MIN, except the last and first one by two link stages each having only 4- Edge Loops, interconnected by a switching stage [10]. These E-MINs are more robust.

Consider the MIN shown in Figure 27

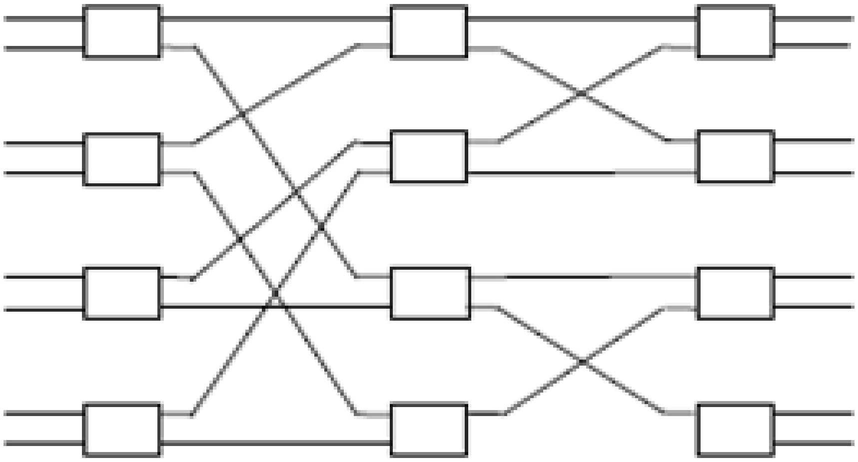


Figure 27: 8x 8 Multistage Interconnection Networks

The Enhanced Multistage interconnection network (E-MIN) is more generic than extra staged networks. The fault free routing strategy of the E-MIN is similar to the destination tag based routing strategy [14, 17]. E-MIN is less expensive than chained network. Regarding fault tolerance E-MIN performs more reliability than other networks. E-MIN is shown in Figure 28 which is obtained from MIN.

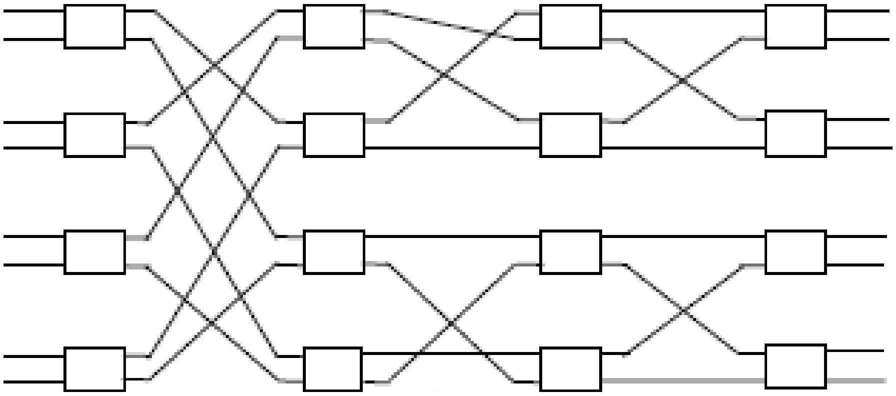


Figure28: 8x8 Enhanced Multistage Interconnection Network [29]

Bandwidth, BW_E an N x N E-MIN is given by

$$\mathbf{BW_E=2^{n+1}r_{2n-2}}$$

Where $n= \log_2 N$ and $r_i = r_{i-1} - r^2_{i-1}/4$ for $2<= i <=2n-2$ and $r_0 =r$ is the rate of request by each processor.

5.3 Delta Interconnection Network

Delta networks are a class of multistage interconnection networks that can be used to interconnect a large number of modules in a modular computing system. In a packet communication environment, the modules in a system communicate asynchronously using fixed size packets. In this environment, delta networks exhibit a large parallelism in packet transfer leading to good performance. They also allow for local control in packet routing, extensibility, clean interfaces, speed independence, and simple proofs of correctness. They can be augmented to improve reliability, and pruned to have different numbers of input and output links. Feedback paths can be added to provide a range of performance. Special extreme cases of (N x N) delta networks are the full crossbar switch, which has O(N('2)) gates and O(N) ideal bandwidth, and the single bus, which has O(N) gates and 0(1) bandwidth. Delta networks constructed from fixed size basic switches have O(N log N) gates and O(N) ideal bandwidth. The performance of delta networks with fixed size basic switches is comparable to that of the full crossbar switch in realistic environments as well. The class of delta networks includes several other networks that have been proposed in the literature. Thus, this study applies to these networks as well. Unbuffered delta networks have no internal buffers within the network. A simple model for network operation can be used to obtain a network characteristic that can then be used to obtain good estimates of performance for other models and environments. Using priority schemes in arbitrating between conflicting packets (that require passage through the same link at the same time) leads to a deterioration in performance as compared to arbitration with equiprobable selection from conflicting packets. Inserting a buffer between the stages of a delta network leads to a considerable improvement in performance, making its performance better than that of the (same size) unbuffered crossbar switch. However, as the number of buffers between stages is increased, the network bandwidth saturates quickly to a constant, while the delay that a packet encounters in the network increases almost linearly with buffer size. Thus, the buffer size for most practical applications should be limited to one or two. The performance obtained is also sensitive to precisely how the switches in the network operate. The switch operation policy needs to be chosen depending on the values of certain network parameters in an implementation. There are many ways of pruning delta networks. Optimal pruned delta networks, with buffers between stages, have a no intuitive topology. Introducing feedback paths leads to a range of performance and cost. However, packets can deadlock in such networks. It is possible to detect and recover from deadlocks. For good performance to be obtained, it is necessary to prevent the frequent occurrence of deadlocks. This can be achieved by controlling the flow of packets into the networks. Delta network uses a x b SEs. So, E-MIN is a special case of delta network for SE size a=2 and b=2. Hence, the bandwidth of E-MIN can be determined in the similar way as was done for delta network[26]. The following equations determine the bandwidth, BWD and a^n x b^n delta network.

$$\mathbf{BW_d = b^n r_n}$$

Where $r_i = 1-(1-r_{i-1}/b)^a$ and $r_0 = r$ is the rate of Request generated by each processor.

The variation of bandwidth with respect to the size of network has been shown. The bandwidth versus number of processors is plotted taking semi logarithmic scale on y axis for bandwidth which is more appropriate.

5.4 Banyan Network

Bandwidth represents the capacity of the connection. The greater the capacity, the more likely that greater performance will be. Bandwidth is calculated in terms of bits per second (bps). The term comes from the field of electrical engineering, where bandwidth represents the total distance or range between the highest and lowest signals on the communication channel (band).It is the difference between highest frequency and the lowest frequency.The bandwidth of stage banyan network ($N = 2^n$ is the network size) is given by :-

BW = P (n) ×Size of Network[45]

The value of *P (n)* can be obtained from the probabilistic Equations In this the effect of limited Crosstalk is studied on the Permutation of Optical MINS. Optical multistage interconnection networks (OMINS), which interconnect their inputs and outputs via several stages of switching elements using optical guided waves or free space, is studied. Although optical MINS hold great promises and have demonstrated advantages over their electronic counterparts, they also introduce new challenges and problems of avoiding cross-talks in the switching elements [45].

In this the effect of limited Crosstalk is studied on the Permutation of Optical MINS. Optical multistage interconnection networks (OMINS), which interconnect their inputs and outputs via several stages of switching elements using optical guided waves or free space, is studied. Although optical MINS hold great promises and have demonstrated advantages over their electronic counterparts, they also introduce new challenges and problems of avoiding cross-talks in the switching elements. 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 and When the two paths sharing a switch could experience some undesired coupling from one path to another within a switch. 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, first-order crosstalk can be eliminated by ensuring that a switch is not used by two input signals simultaneously. 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. Initially it is checked that bandwidth of Optical Networks with crosstalk is greater than without crosstalk networks for Banyan and Baseline network. The bandwidth is calculated in terms of probability of whether the switch is active or not using the probability equations. the bandwidth without crosstalk and with crosstalk is calculated. Hence there are switches where 0, 1 or 2 messages can be allowed at the same time. In other words a switch can be 2-active, 1-active or 0-active. Both 0-active and 1- active switches do not allow any crosstalk where as the 2-active switch produces optical conflicts and hence could potentially contribute to crosstalk. First, performance of all the given networks allowing limited crosstalk is analyzed on Banyan, Baseline and Omega network. For instance, one of the best ways for analyzing the performance is to calculate the bandwidth (BW) of various optical networks operating under a load L. Load is defined as the probability, that an input is active. Thus, the expected number of active inputs at load L for an N ×N banyan network is NL. Some of the equations are derived for such networks to find the Bandwidth, built with 2 × 2 unbuffered switches.

Let P (j) be the probability that a request exists at an input link of a switch in stage j , and Let P(j +1) be the probability that an output link of this switch is used for routing a request. The analysis involves the iterative computation of P (j +1) in terms of P(j), starting with P(1). Therefore, in this Optical Banyan Network is considered and it shows that the bandwidth of Optical MINS with some crosstalk is better than the network without crosstalk. Various probabilities equations are used and finally the bandwidth for the networks is calculated.

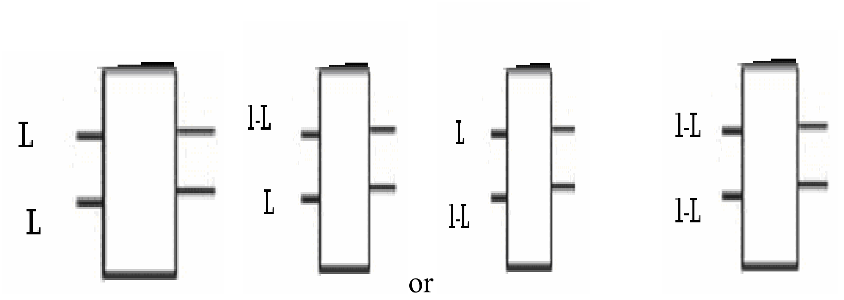
5.4.1 For the Network which allow limited Crosstalk.

In this three types of switches are considered: 2-active, 1-active or 0- active switches, for each stage j ($1 \leq j \leq n$), therefore:

P2(j) = probability that a given switch is 2-active.

P1(j) = probability that a given switch is 1-active.

P0(j) = probability that a given switch is 0-active.



2- active **1-active** **0-active**

Figure 29: Various Probabilities for the switches with limited Crosstalk

Given the definition of load at stage 1, for the switches shown in Fig. below:-

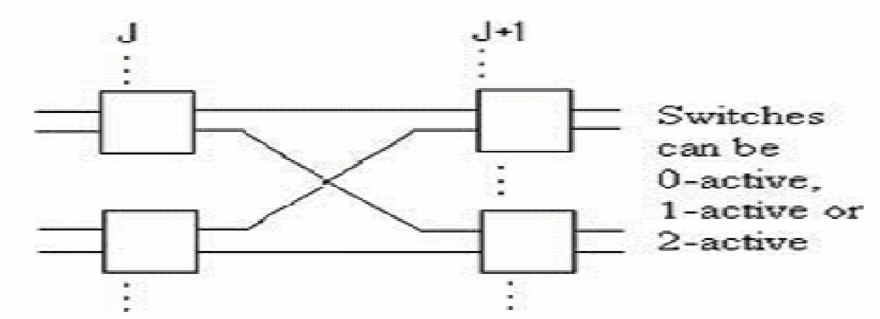


Figure 30: Interconnection of switch pairs [45]

5.4.1.1 Equations for Stage 1[45]

1.For 2-active switch: If in a Multistage network both inputs are active for a switch and are operating under load L then according to the theory of probability, both inputs are selected and $P_2(j)$ is given by:

$$\mathbf{P2\ (j) = L x L = L^{2}}$$

2. For 1-active switch: If in a Multistage network only one input is active and the other is not active, then one input is operating at load L and the other input is operating at load (1 − L). In that case Probability is given as

$$\mathbf{P_1\ (j) = L\ (1-L) + (1-L)\ L = 2L\ (1-L)}$$

3.For 0-active switch: If in a Multistage Network If both inputs are not active for a switch, then they are operating at load (1 − L), and according to the theory of probability, both inputs are not selected and $P_0(j)$ is given by:

$$P_0(j)=(1-L)*(1-L)=(1-L)^2$$

5.4.1.2 Equations for Stage 2[45]

From one stage j to the next stage $j+1$ $(1 \leq j \leq n)$ in the Multistage network network, let us consider the two pair of switches in the two stages that are connected. The equations for the next stage of a network always depend on its previous stage except for the first stage, which in turn depends on their previous stages.

1. **For 2-active switch:** According to the theory of probability, $P_2(j+1)$ is given by:

$$P_2(j+1)= p_2(j)*p_2(j)+p_1(j)/2*p_2(j) + p_2(j)*p_1(j)/2+p_1(j)/2*p_1(j)/2$$

$$P_2(j+1) = p_2(j)^2+p_1(j)p_2(j)+p_1(j)^2/4$$

2. For a switch to be 1-active: According o the theory of probability, $P_1(j+1)$ is given by:

$$P_1(j+1)= p_0(j) * p_1(j)/2 + p_1(j)/2 * p_0(j) + p_0(j) * p_2(j) + p_2(j) * p_0(j) + p_1(j)/2 * p_2(j) + p_2(j) * p_1(j)/2 + p_1(j)/2 * p_1(j)/2$$

$$P_1(j+1) = p_0(j) * p_1(j) + 2p_0(j) * p_2(j) + p_1(j) * p_2(j) + p_1(j)^2/4$$

3. For a switch to be 0-active: According o the theory of probability, $P_0(j+1)$ is given by:

$$P_0(j+1) = p_0(j)*p_0(j) + p_0(j)/2*p_0(j) + p_0(j)*p_1(j)/2 + p_1(j)/2*p_1(j)/2$$

$$P_0(j+1) = p_0(j)^2 + p_0(j)p_1(j) + p_1(j)^2/4$$

5.4.1.3 Equations for last Stage[45]

1. For the 0- active switch: The probability equation would be:

$$P_0(n) = p_0(n-1)^2 + p_0(n-1) * p_1(n-1) + p_1(n-1)^2/4$$

2. For the 1-active switch: The probability equation would be:

$$P_1(n) = p_0(n-1) * p_1(n-1) + 2p_0(n-1) * p_2(n-1)$$
$$+ p_1(n-1) * p_2(n-1) + p_1(n-1)^2/4$$

3. For the 2- active switch : The probability equation would be:

$$P_2(n) = p_2(n-1)^2+p_1(n-1)p_2(n-1)+p_1(n-1)^2/4$$

5.4.2 For the Network which do not allow Crosstalk[45]

5.4.2.1 Equations for Stage1

1. For 1-active switch:

$$P_1(j)=L(1-L)+(1-L)L=2L(1-L)$$

2. .For 0-active switch

$$P_0(j)=(1-L)*(1-L)=(1-L)^2$$

5.4.2.2 Equations for Stage2[45]

1 For 1-active switch:

$$P_1(j+1) = p_0(j) * p_1(j) + p_1(j)^2/4$$

2. For 0-active switch:

$$P_0(j+1) = p_0(j)^2 + p_0(j)p_1(j) + p_1(j)^2/4$$

5.4.2.3 Equations for last Stage[45]

1. For the 0- active switch: the probability equation would be:

$$P_0(n-1) = p_0(n-1)^2 + p_0(n-1)p_1(n-1) + p_1(n-1)^2/4$$

2. For the 1-active switch the probability equation would be:

$$P_1(n) = p_0(n-1) * p_1(n-1) + p_1(n-1)^2/4$$

6.1 Bandwidth calculation of Cube Network

Table 3: Cube Network Bandwidth

SIZE	4	8	16	32	64	128	256	512	1024
BANDWIDTH	2.7	5.3	10.3	20.5	40.6	81.1	162.1	323.9	647.5

6.2 Bandwidth calculation of Enhanced Multistage Interconnection Network

Table 4: E-MIN Network Bandwidth

SIZE	4	8	16	32	64	128	256	512	1024
BANDWIDTH	5.11	7.2	11.6	19.3	33.08	58.16	103.84	187.7	342.5

6.3 Bandwidth calculation of Delta Network

Table 5: Delta Network Bandwidth

SIZE	4	8	16	32	64	128	256	512	1024
BANDWIDTH	2.4	4.12	7.2	12.77	23.1	41.88	76.86	142.3	264.72

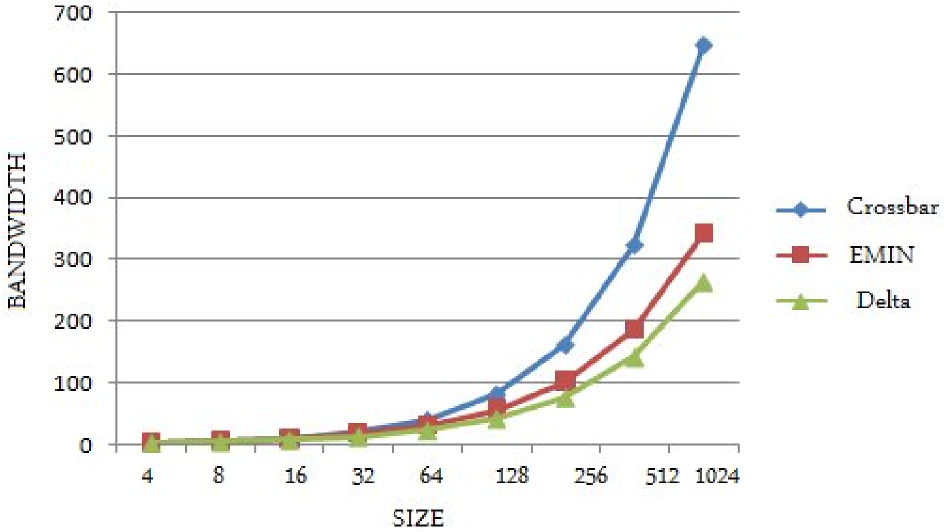
6.3 Bandwidth calculation of Banyan Network

Table 6: Banyan Network Bandwidth(0.9)

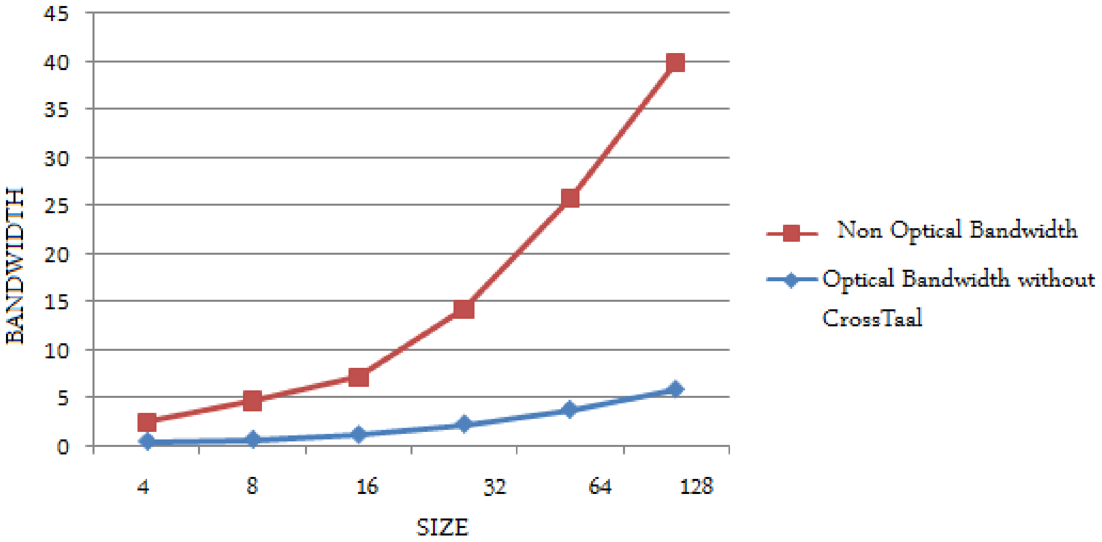
SIZE	4	8	16	32	64	128	256
BANDWIDTH	1.9	3.81	6.2	12.1	22	33	41.3

Table 7: Banyan Network Bandwidth(0.8)

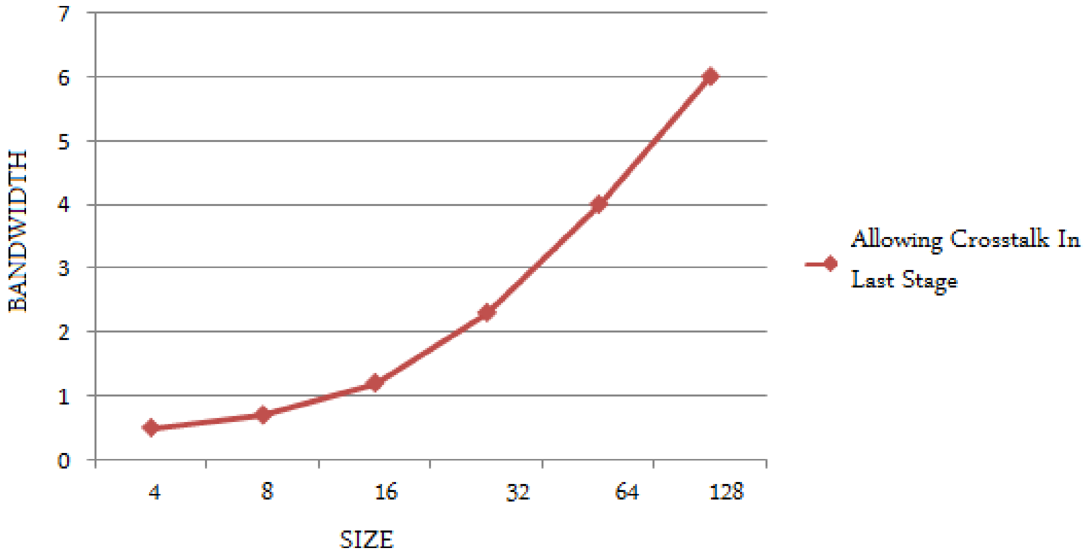
SIZE	4	8	16	32	64	128	256
BANDWIDTH	1.91	3.84	7.1	14.3	29	50	75.3



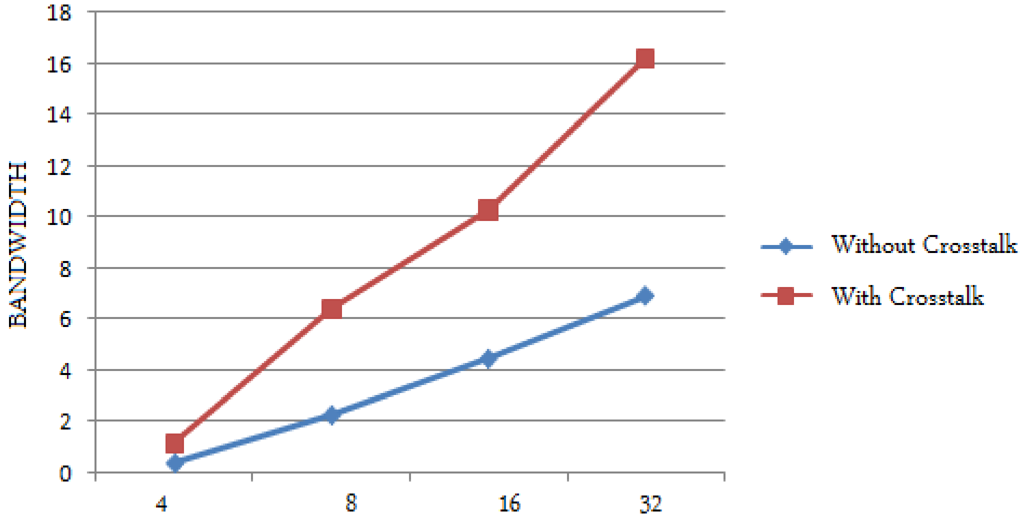
Graph 1: Bandwidth comparison of three networks



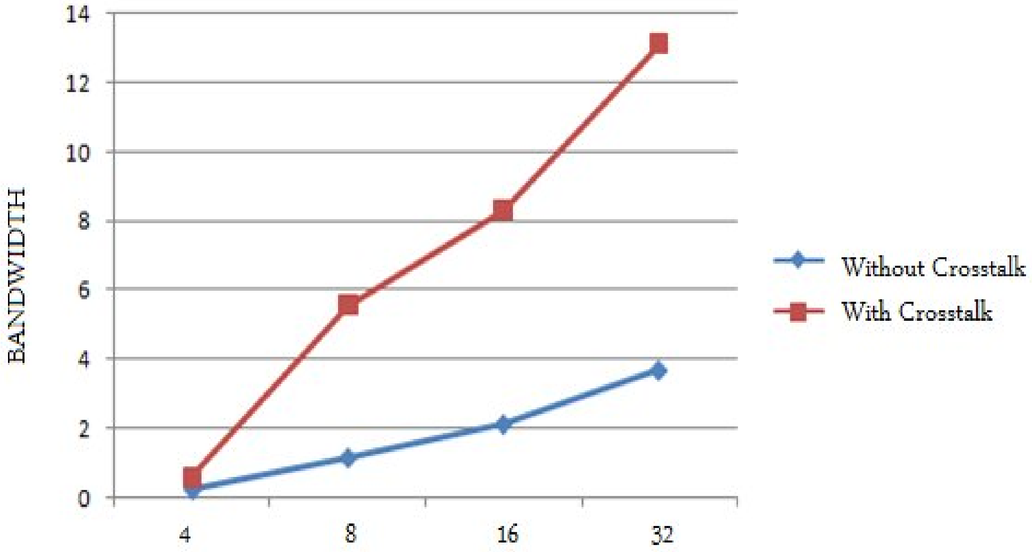
Graph 2: Bandwidth comparison of Non optical and Optical Networks without crosstalk



Graph 3: Bandwidth by allowing Crosstalk in the last stage



Graph 4: Bandwidth comparison of Banyan Network at load 0.9



Graph 5: Bandwidth comparison of Banyan Networks at load 0.8

Conclusion

In this thesis Optical and Electronic MINs have been analyzed and compared. It has been observed that Optical MINs is a better choice for high bandwidth and low latency. The crosstalk problem of OMINs can be avoided by space and time domain approaches.

Various methods for getting the semi permutations after decomposing permutations have been explained with examples.

Bandwidths of OMINs have been analyzed with, without and with limited crosstalk. It has been observed that OMINs provide higher bandwidth with limited crosstalk than without crosstalk.

Future Scope

1. The Network approach can be used to design routing algorithm for multipath OMINs.

2. Bandwidth can be calculated under Traffic and Bursty conditions.

3. Performance can be calculated for OMINs that do not have self-routing capabilities.

4. Permutations Capability of more networks with or without faults can be checked.

References

[1]Adams George B, Agrawal Dharma P, Siegel Howard Jay, "A Survey and Comparison of Fault-Tolerant Interconnection Networks", IEEE Transactions on Computers, pp.14-27, June 1987.

[2]A.Subramanyam, E.V.Prasad, C.Nadamuni Reddy, "Performance of Processor Memory interconnection Networks", proceedings of 2nd Natnl, "NCMCM – 2003", pp 389 - 394, June 2003.

[3]A. Himeno, and M. Kobayashi, "4 _ 4 optical-gate matrix switch", J. Light wave Technology, vol. 3, pp. 230-235, April 1985.

[4]Bhuyan, L.N. Agrawal, D.P, "Design and performance of generalized interconnection networks", IEEE Transactions on Computers, vol. 32, pp. 1081-1090, 1983.

[5]Benjamin A. Small, Keren Bergman, "Optimization of Multiple-Stage Optical Interconnection Networks", IEEE Photonics Technology Letters, vol. 18, no. 1, January 2006

[6]Brenner M, Tutsch D, Hommel G, "Measuring transient performance of a multistage interconnection network using ethernet networking equipment", Proceedings of the International Conference on Communications in Computing 2002 (CIC'02), pp. 211–216, Las Vegas, USA, 2002

[7]Bhuyan Laxmi N, Yang Qing, Aggarwal P Dharma, "Performance of Multiprocessor Interconnection Networks", Proceeding of IEEE, pp. 25-37, February 1989.

[8]Blaket James T, Trivedi Kishor S, "Reliabilities of Two Fault-Tolerant Interconnection Networks", Proceeding of IEEE, pp. 300-305, 1988.

[9]Chuan-Lin Wu, Tse-Yun Feng, "The Reverse-Exchange Interconnection Network", IEEE Transactions on Computers, vol. c-29, no. 9, pp. 801-811, September 1980.

[10]Chi Hsin-Chou, Wu Wen-Jen, "Routing Tree Construction for Interconnection Networks with Irregular Topologies", Proceeding of the Eleventh Euromicro Conference on Parallel, Distributed and Network-Based Processing (Euro-PDP), 2003.

[11]C. Qiao, “A two-level process for diagnosing crosstalk in photonic dilated Benes network”, Journal of Parallel and Distributed Computing, vol. 41, no. 1, pp. 53-66, 1997.

[12]C.Wu, T. Feng, “On a class of multistage interconnection networks”, IEEE Transactions on. Computers, vol. c-29, pp. 694–702, August 1980.

[13]D. K. Hunter, I. Andonovic, “Guided wave optical switch architectures”, International Journal of Optoelectronics, vol. 9, no. 6, pp. 477-487, 1994.

[14]D.Nassimi, S.Sahni, “A self routing benes network and parallel permutation algorithms”, IEEE Transactions on computers, vol. c-30 (5), pp. 332-340, 1981.

[15]D. Cantor, “On nonblocking switching networks”, vol. 1, 1971.

[16]D. K. Pradhan, K. L. Kodandapani, “A uniform representation of single and multistage interconnection networks used in SIMD machines,” IEEE Transactions on Computers. vol. 29, pp. 777–791, Sept. 1980.

[17]E.V.Prasad, A.K.Sarjee “Performance Evaluation of Multiprocessor System Modelled as t-out-of-Systems”, International of Journal of High Speed Computing, vol. 5, no.1, pp 91-87, 1993.

[18]Goke, L.R, Lipovski, “Banyan networks for partitioning multiprocessing systems”, International: Proceedings of the First International Symposium on Computer Architecture, pp. 21-28, 1973.

[19]H. Hinton, “A non-blocking optical interconnection network using directional couplers”, Proc. IEEE, Global Telecommunications Conference, pp. 885-889, November 1984.

[20]Hao Tian, Yi Pan, Ajay K Katangur, Jiling Zhong, “A novel modularized Optical Multistage Interconnection architecture with multicast capability”, Department of Computer Science Georgia State University, Atlanta, GA 30303.

[21]Jianchao Wang, YiPan,“ Permutation Capability of Optical Multistage Interconnection Networks”, International and Symposium on Parallel and Distributed Processing, Parallel processing Symposium, April 1998.

[22]K.M. Sivalingam, S. Subramaniam, “Optical WDM Networks, Principles and Practice”, Kluwer Academic Publishers, 2000.

[23]K.V Arya, R.K. Ghosh “Designing a New Class of Fault Tolerant Multistage Interconnection Networks”, Journal of Interconnection Networks, vol. 6, No 4, pp. 361-382, 2005.

[24]K. Padmanabhan, A.N. Netravali, " Dilated networks for photonic switching", IEEE Transactions on.Communications, vol. 35,no. 12, pp. 1357-1365, December 1987.

[25]Mittal R, Cherian D, Mohan P.J, " Routing and Performance of the double tree (DOT) network", Proceeding of International Conference on Computer Digital Technology, vol. 142, no. 2, pp. 93-97, March 2005.

[26]M.Xu, S.Shen, " A new fault-tolerant generalized cube with an extra stage", Proc.Intl. Comp.Sc.Conf.(ICSC'92), pp. 99-105, December 1992.

[27]"Optical Multistage Interconnection Networks: New Challenges and Approaches", IEEE Communications Magazine , February 1999.

[28]Othman M, Abedi F, "Fast Method to find conflicts in Optical Multistage Interconnection Networks", International Journal of The Computer, The Internet and Management ,vol. 16, pp. 18-25, April 2008.

[29]Prasad A.R, Reddy E.V, "Permutation Capability and Connectivity of Enhanced Multistage Interconnection", ADCOM 2006, International Conference on Advanced Computing and Communications, pp. 8-11, December 2006

[30]Qiao, C.Zhou, "Scheduling switching element disjoint connections in a stage controlled photonic banyans", IEEE Transactions on.Communications, vol.47, pp. 139-148, 1999.

[31]Qiao, C, Melhem, R, Chiarulli, D, Levitan S, "A time domain approach for avoiding crosstalk in optical blocking multistage interconnection networks", J. Light. Technology, pp. 1854-1862, 1994.

[32]R.A. Thompson, "The dilated slipped banyan switching network architecture for use in an all-optical local-area network", J. Lightwave Technology, vol. 9, no. 12, pp. 1780-1787, December 1991.

[33]Regis Bates, J. "Optical Switching and Networking", Handbook.McGraw-Hill, New York, 2001.

[34]Ren Kaixin, G.U Naijie, "Permutation Capability of Optical Cantor Network", Eighth International Conference on Parallel and Distributed Computing, Applications and Technologies, 2007.

[35]Shen, X., Yang, F., Pan, Y.: "Equivalent permutation capabilities between time division optical omega networks and non-optical extra-stage omega networks." IEEE/ACM Transactions on Networks **9**(4), pp. 518–524, 2001.

[36]Sengupta J, Bansal P.K, “Performance of Regular and Irregular Dynamic MINs”, Proceeding of International Conference IEEE Tencon, pp. 427-430,1999.

[37]Sengupta J, Bansal P.K, Gupta Ajay, “ Permutation and Reliability measures of Regular and Irregular MINs”, International Conference IEEE, pp. I-531-I-536, 2000.

[38]Tse-yun Feng, Seung-Woo Seo, “New Routing Algorithm for a Class of Rearrangeable Networks”, IEEE Transactions on computer, vol. 43, No. 11, November 1999.

[39]Vaez M.M, Lea C.T, “Strictly nonblocking directional-couplerbased switching networks under crosstalk constraint”, IEEE Transactions on. Communications, vol. 48, pp. 316-323 , 2000.

[40]Varma A, Raghavendra C.S, “Interconnection Networks for Multiprocessors and Multicomputers”, Theory and Practice, IEEE Computer Society Press, Los Alamitos ,1994.

[41]Wu Xingfu, Sun Xian-He,“Performance Modeling for Interconnection Networks”, Proceeding of International Conference IEEE, pp. 380-385, 2000

[42]Xiaohong Jiang, Hong Shen,“A New Scheme to Realize Crosstalk-free Permutations in Optical MINs with Vertical Stacking”, Proceedings of the International Symposium on Parallel Architectures,pp. 341,2002

[43]Yuanyuan Yang, Jianchao Wang “Permutation Capability of Optical Multistage Interconnection Networks”, Journal of Parallel and Distributed Computing, vol. 60, pp. 72-91 , 2000.

[44]Y.Yeh, T.Feng, “On a class of rearrangeable networks”, IEEE Transactions on computers, vol. 141 (11), pp 1361-1379, 1992.

[45]Yi Pan, Ajay K Katangur, Somasheker, “Analyzing the performance of optical multistage interconnection networks with limited crosstalk”,Kluwer Academic Publishers, vol. 10, 2007.

[46]Yuanyuan Yang,Jianchao Wang,“Optimal All-to-All Personalized Exchange in a Class of Optical Multistage Networks”, IEEE Transactions on Parallel and Distributed Systems,vol 12 ,pp. 567 - 582, june 2001.

[47]Zheng S.Q, Lu E, “High-speed crosstalk-free routing for optical multistage interconnection networks”, Computer Communications and Networks, ICCCN 2003, Proceedings on the 12th International Conference on Networks, pp. 249-254, October 2003.

Papers Published

1. Sandeep Kaur, Rinkle Aggarwal, " Optical Multistage Interconnection Networks: An analysis", National Conference on Emerging Trends in Software and Networking Technologies, Amity University, U.P, pp. 20-23, April 17-18, 2009.
2. Sandeep Kaur, Rinkle Aggarwal, "Permutation of Optical Multistage Interconnection Networks: A survey" ,International Conference on Innovative Technologies (ICIT-09): Research and Development in Science, Technology and Management, Paper id p-500,June 18-19, 2009.(Accepted for Publication)