

Behavior Analysis of Multilayer Multistage Interconnection Network With Extra Stages

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

Master of Engineering

in

Computer Science and Engineering

Submitted By

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, "*Behavior Analysis of Multilayer Multistage Interconnection Networks with Extra Stages*", 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 *Dr. (Mrs.) Rinkle Rani* and refers other researcher's work which are duly listed in the reference section.


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

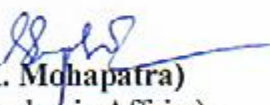

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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.


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The works like this are never completed single handed. There are many persons working behind the screen but are equally important. I take this opportunity to express our deep sense of gratitude towards all those.

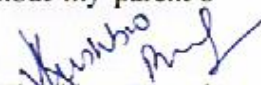
First of all, humble bow before the almighty God for his blessing and for driving me with faith, hope and courage in the thinnest of the times.

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ABSTRACT

Multilayer Multistage Interconnection Networks (MLMINs) has been an active area of research for quite longtime. Multistage interconnection networks (MINs) are a class of high-speed computer networks usually composed of processing elements (PEs) on one end of the network and memory elements (MEs) on the other end, connected together by switching elements (SEs).

Multistage Interconnection Networks plays a vital role in the parallel computing system. In these systems, the MINs are an important part that enables the processors to communicate with themselves and with memory modules. Multistage Interconnection Networks consists of more than one stage of small interconnection element called switching element and links interconnecting them, sufficient work has been done on Multistage Interconnection network but less work done on Multilayer MINs.

A Multilayer Multistage Interconnection Network (MLMIN) can be defined as a network used to interconnect a group of N inputs to a group of M outputs using several stages of small size Switching Elements (SEs) followed (or preceded) by link states. Its main characteristics are its topology, routing algorithm, switching strategy and flow control mechanism. A Multilayer Multistage Interconnection Network, a very efficient network for multicasting.

This Research analyses the effect of extra stages on the behavior of regular MLMINs. The multilayer are compared with regular and replicated MINs on the basis of Crosspoint cost and Buffer cost.

In Regular MINs, all packets can use the same routing tag to reach a certain network output independently of the input at which they enter the networks. In Replicated MINs, network enlarges regular multistage interconnection networks by replicating those L times that are arranged in L layers. In Multilayer Multistage Interconnection Networks Multicasting and broadcasting are two important functionalities for communication.

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1.1 Parallel Systems

A Parallel system means a set of different processors of computers interconnected together to improve the performance. Use of more than one processing units at a time to enhance the overall output is called multiprocessing or multicomputing[1].The performance of a computer depends directly on the time required to performance a basic operation and the number of these basis operation that can be performed concurrently. High performance computing system can be designed using parallel processing.

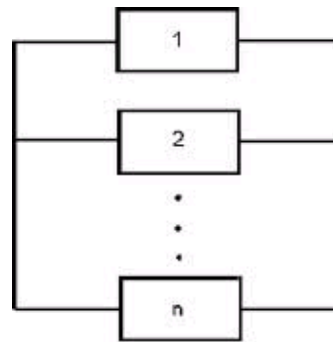


Figure 1: Parallel System

A large task can either be performed serially, one step following another, or can be decomposed into smaller tasks to be performed simultaneously, i.e. in parallel. Parallelism is achieved by:

- Breaking up the task into smaller tasks
- Assigning the smaller tasks to multiple processing elements
- Processing elements solve the problem by coordinating with each other.

The principle target in designing any parallel system is to reduce the communication overheads between both, the processors, as well as the memory. Following are the desirable characteristics for the communication between processors and the memory units:

- High speed
- High reliability
- On-line reparability
- Good performance even under faults
- Low cost
- Full access capability

However, Multiple Processor system have a number of potential disadvantages, probably the most important being the very real problem of using the processing power in an efficient manner. This involves a number of factors such as, the ability to decompose a problem into an optimum number of modules, their size, and to define them in such a way that communication between processors may be carried out with the absolute minimum wait time and minimum delay time across the communication network. This communication network is a link between different processor as well as memory modules. The primary reasons for using parallel systems:

- Save time
- Solve larger problems
- Provide concurrency (do multiple things at the same time)

1.1.1 Classification of parallel system

Generally, parallel systems are of two categories, multicomputer and multiprocessors.

Multicomputer [2]

A Multicomputer comprises a number of computers, or nodes, linked by an interconnection network. Each computer executes its own program. This program may access local memory or may send and receive message over the networks i.e. message passing. Messages are used to communicate with other computer or equivalently to read and write remote memories. In the idealized network, the cost of message passing between two nodes is independent of both, node location and other network traffic, but does depend on message length.

Therefore, multicomputer means different computers, not sharing memory, connected by some communication link with ring, star, linear, bus and tree topologies, used generally for those applications which require less inter-processor interactions because the interaction processors or computers. Store and forward techniques are used to pass on the message from a source to a destination. Thus, there is a lot of communication overhead involved.

Multiprocessor

In a computer system it is common to connect multiple components, such as processors and memory. Except for the memory with the embedded processors, processors do not have memory and memory does not include a processor in it. Multiprocessors are a common architecture today, so there is also the need to connect more than one processor with more than one memory modules in an efficient manner. A multiprocessor system is a single computer that contains multiple processors of approximately comparable capabilities.

All processors may share access to memory modules, I/O channels and peripheral devices. Most important, the entire system must be controlled by a single integrated operating system providing interaction between processors and their programs at various levels. Besides the shared memories and I/O devices, each processor has its own local memory and private devices. Interprocessor communications can be done through the shared memories. Multiprocessor system can asynchronously, autonomously execute different instruction on different data.

1.2 Interconnection Networks

Interconnection Networks are a complex connection of switches and links permitting processors in a multiprocessor system to communicate among themselves or with memory modules [1, 2]. 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.

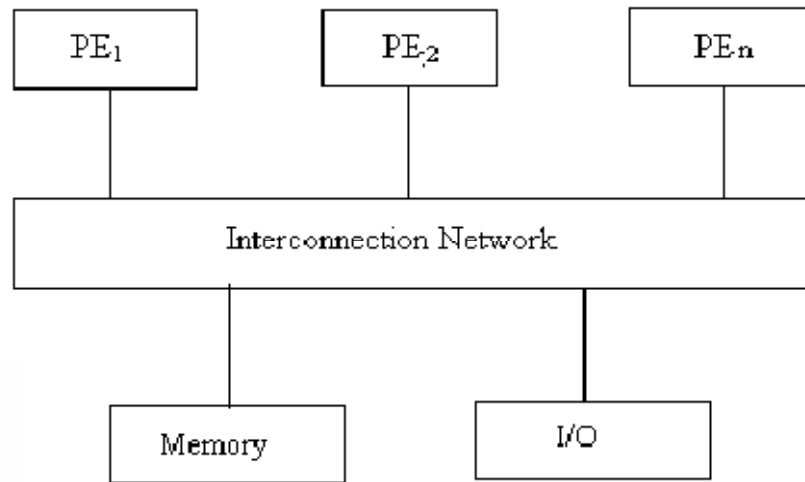


Figure 2:An Interconnection Network

Interconnection network make a major factor to differentiate modern multiprocessor architecture. They can be categorized according to a number of criteria such as topology, routing strategy and switching techniques.

1.2.1 Switching Elements

The Switching element may be viewed as a very small network. These switches are the devices having multiple inputs/outputs [2, 5]. The number of inputs/outputs and the input-to output connections supported within a switch can assume either the straight or the exchange states.

A four-function switch box can be in any one of the following four states i.e. straight, exchange, upper and lower broadcast as shown in Figure 3.

The principle characteristics of a multiprocessor system are the ability of each processor to share a set of main memory, possibly and I/O devices. This sharing capability is provided through a set of two interconnection networks.

- Between the processor and memory modules.
- Between the processor and the I/O subsystem.

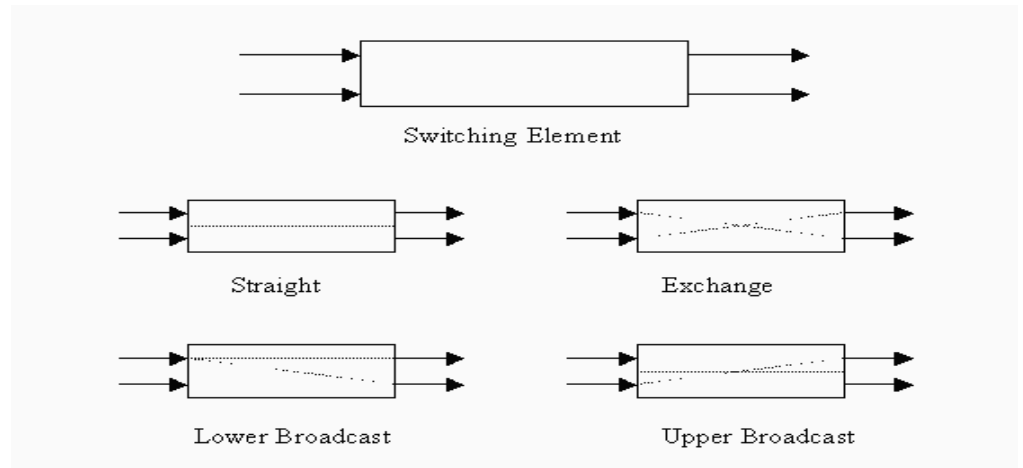


Figure 3: Switching elements

The performance criteria for Interconnection Networks are:

- Fast communication
- Low cost
- Reliability during failures
- Efficiency

However, there is no network that provides the best performance criteria. But there are several different configuration which give optimum performance criteria.

1.2.2 Design Dimensions

The key design dimensions for Interconnection Networks are

- Operational mode
- Switching methodology
- Network topology

The space of Interconnection Networks can be represented by Cartesian product of this entire dimension i.e. operational mode, switching methodology and network topology. The choice of a particular interconnection network depends upon an application demands, technology support and cost effectiveness.

1.2.2.1. Operational Modes

Operational modes can either be synchronous or asynchronous or a combination of the two.

- i. Synchronous modes: It is useful for either a data manipulating functions 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.
- ii. Asynchronous communication: It is needed for multiprocessing in which connection request are issued dynamically. Asynchronous techniques do not utilize a single global clock.

1.2.2.2 Switching Methodology

Switching is the process of connecting two (or more) points together within network or communication devices. These connections can be physically connected (mechanical switch) or connected logically (through software). The first telephone systems performed the switching of calls by human operators. The operators interconnected telephone lines by manually connecting cables at switchboards. Switching systems have evolved from manual switchboard systems (wires and plugs) to logical (digital) switches.

Two major switching methodologies are:

- i. Circuit Switching
- ii. Packet Switching

In Circuit switching an end to end physical path is actually established between a source and the destination. This path is actually established between a source and the destination. This path exists as long as the data transmission is not complete. Circuit switching is suitable for bulk transmission of data.

In Packet switching data is divided into packet that is routed through the interconnection network without establishing a physical end to end connection path. These packets are transmitted from source to destination in store

andforward manner, which introduces delay at each of the switching point. This delay depends on the traffic in the network along its path to the destination. Packet switching is more efficient for many short messages.

Combining the capabilities of both circuit switching and packet switching, the third type of switching mythology can be called integrated switching.

1.2.2.3 Network Topology[2]

A Network can be represented by a graph in which nodes indicate switching and edges represent communication links. Interconnection networks are made up of switching elements. Topology is the pattern in which the individual switched are interconnected to other elements such as processors, memories and other switching elements.

Topology can be understood as the shape or structure of a network. This shape does not necessarily correspond to the actual physical design of the devices on the computer network. The computers on a home network can be arranged in a circle but it does not necessarily mean that it represents a ring topology.

Direct topologies switch directly connect to node, while in indirect topologies at least some of the switches connect to other switches. The topologies can be categorized into two groups, static and dynamic.

- i. **Static Topology:**It links between two processors are with passive and dedicated buses cannot be reconfigured for direct connection with other processors. Statics networks that are generally used in message-passing architectures, the following network topologies are commonly used:-

- Ring network
- Completely connected network
- Star connected network
- Linear array or ring of processors
- Mesh network
- Hypercube network

- **Linear Array(1-D Mesh)**

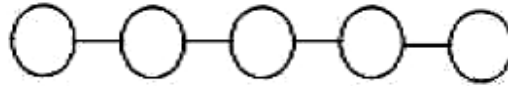


Figure 4: Linear Array

In this topology, all nodes are connected through single bus. Each node has two connections.

- **Star**

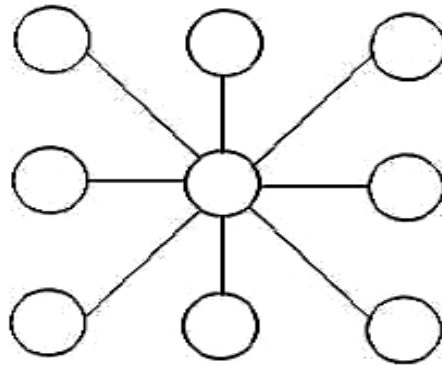


Figure 5: Star

In this topology, there is one central node to which all other nodes are connected.

- **Binary Tree**

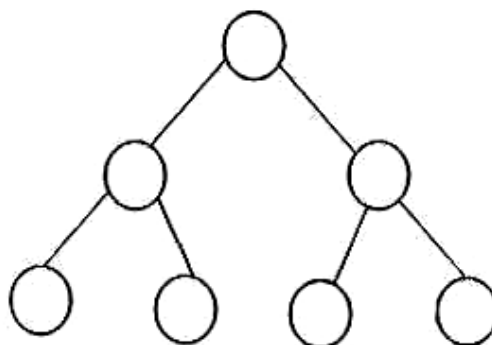


Figure 6: Binary Tree

Each node is connected to almost two nodes.

- **2-DMesh**

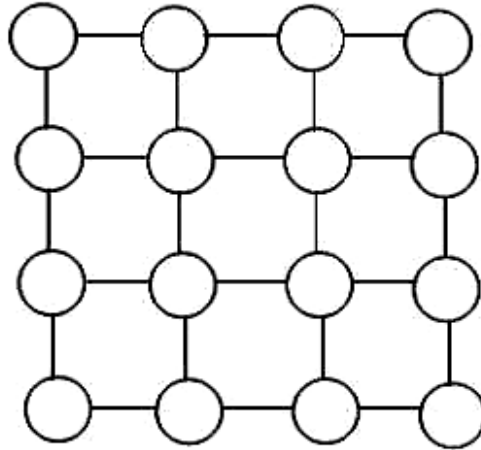


Figure 7: 2-D Mesh

The simplest and easiest way to connect the nodes of a parallel computer is to use mesh. Each node can be connected to 2, 3 or 4 nodes. The cost incurred is $2(N \times N)$. Anormal sized mesh can be extended to any size.

- **Three-D Cube**

In this topology, a node can be connected to 3, 4, 5 or 6 other nodes to communicate.

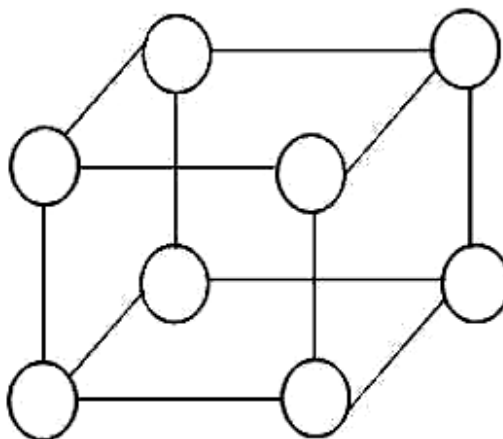


Figure 8: Three-D Cube

- **Fully connected or all-to-all**

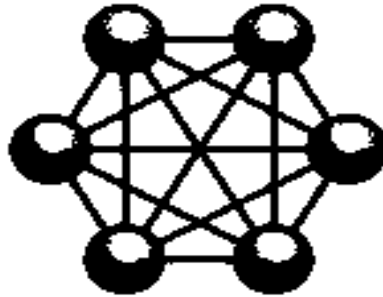


Figure 9: Fully connected

This is the most powerful interconnection network (topology). Each node is directly connected to all other nodes. Each node has $N-1$ connections ($N-1$ nearest neighbors) giving a total of $N(N-1)/2$ connections for the network implemented for small values of N .

- ii. **Dynamic topology:** It can be reconfigured by setting network's active switching elements. Dynamics interconnection network implement one of the following main alternatives:
 - Bus based network
 - Crossbar networks
 - Multistage Interconnection Networks

1.3 Multistage Interconnection Networks

Multistage Interconnection Networks (MINs) consist of more than one stage of small interconnection elements, called switching elements and links interconnecting them [5]. Multistage interconnection networks (MINs) are a class of high-speed computer networks usually composed of processing elements (PEs) on one end of the network and memory elements (MEs) on the other end, connected together by switching elements (SEs). The switching elements themselves are usually connected to each other in stages.

Such networks include omega networks, delta networks and many other types. MINs are typically used in high-performance or parallel computing as a low-latency interconnection, though they could be implemented on top of a packet switching network. Though the network is typically used for routing purposes.

Multistage networks are described by three characteristic features switching elements, network topology and control structure. The crossbar interconnection network is scalable in term of performance but unscalable in term of cost. Conversely, the shared bus network is scalable in term of cost but unscalable in term of performance. An intermediate class of network called Multistage Interconnection Networks lies between two extremes. A Multistage Interconnection Networks is actually a compromise between crossbar and shared bus networks, as shown in Table 1, describing the properties of various types of Multiprocessor Interconnections Networks.

Table 1: Properties of Multiprocessor Interconnections 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

Multistage Interconnection Networks:

- Attempt to reduce cost.
- Attempt to decrease diameter.

In a Multistage Interconnection Networks, as in a crossbar, switching elements are distinct from processors. However, fewer than $O(P^2)$ switches are used to connect P processors. Instead messages pass through a series of switch stages.

Figure 10 illustrates general MINs, which are representatives of a general class of networks. The network can be constructed from switches and links, in which case it is folded so that the processors on the left and right are the same. Alternatively, it can be constructed from bi-directional switches and links.

In unidirectional MINs, all messages must traverse the same number of wires, and so the cost of sending a message is independent of processor location. In effect, all processors are equidistant.

In bi-directional MINs, the number of wires traversed depends to some extent on processor location, although to a lesser extent than a mesh or hypercube.

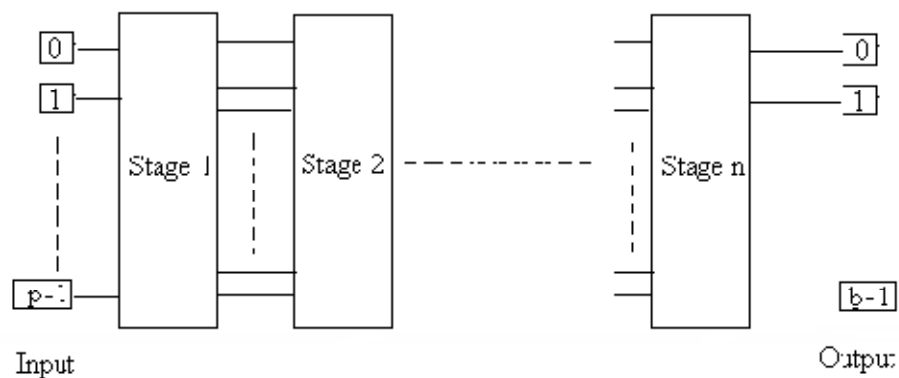


Figure 10: Multistage Interconnection Networks [4]

1.3.1 Important Concept in MINs[4]

There are many important concepts which are related with the MINs. Some of them are discussed below:

1.3.1.1 Type of connection in MINs

There are four types of connections, which are commonly used in Multistage Interconnection Networks. These are:

- One to one connection: One to one connection passes information from a source to destination. The exact route taken by the information is determined by path itself.

- **Multipath connection:** Multipath means many one to one connections are active simultaneously.
- **Permutation connection:** A set of one to one connection such that no two connections have the same source or destination. Such connection is meaningful only in cases of equal number of sources and destinations.
- **Broadcast connection:** Information flows from source to various destinations either some or all. Thus a number of destinations simultaneously receive the information.

1.3.1.2 Routing in MINs

No decision regarding the routing in networks is perfect one. To acquire nearly complete knowledge for routing would require so much overhead that traffic throughout would be simultaneously reduced. For example, if there is minimal traffic, the network path with minimum number of links will normally be the best. If a node or switching elements fails, then the path with minimum number of links that by passes the failures will be the best. As traffic builds up, however this simple routing strategy can give poor result at times because the shortest path may happen to be congested. So the networks as a whole should employ a routing strategy that would bypass areas of congestion.

There are several objectives of routing strategy:

- Minimize the transmit
- Minimize the cost
- Maximize the network throughput capability

To minimize the transmit times under condition of changing load, many control signal or overhead would be sent so that network throughput would be reduced. On the other hand, Maximizing the throughput could be done at the expense of packet transmit times.

1.4 Classification of Multistage Interconnection Networks

Multistage Interconnection Networks can be classified according to different categories. Major classification categories are as follows.

1.4.1 According to number of paths

- i. **Unique path networks:** These networks provide unique path for every source and destination. The failure of any switching element along the path disconnects source-destination pairs, thus adversely affecting the capabilities of existing network.
- ii. **Multi path networks:** 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. Multipath Multistage Interconnection Networks can be either static or dynamic. For static networks, if a fault is encountered, then data has to backtrack, the source or some fixed point to select an alternative path in the network. The implementation of backtracking is expensive in terms of the hardware. 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.

1.4.2 According to number of switches

- i. **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 requests passing through them.
- ii. **Irregular networks:** Irregular Multistage Interconnection Networks have unequal number of switching elements as per stage and thus

they are inherently multi path in nature. For a given source destination pair, there are different path lengths available.

1.4.3 According to controls

- i. Flip controlled networks: Flip controlled Multistage Interconnection Networks have a common control signal for switching in various switching elements at a given stage. These networks are less complicated due to lesser number of control signals but have lesser bandwidth.
- ii. 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.

1.4.4 According to availability of paths

- i. Blocking networks: In Blocking network, simultaneous connections of more than one terminal may result a confliction in the use of network communication links. For example Omega network.
- ii. Non-blocking networks: A network is called none 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, a network that can handle all possible connections without blocking is called non-blocking network.

1.5 Types of routing in MINs

There are basically three types of routing that are commonly used in Multistage Interconnection Networks.

- i. Non-adaptive routing: In this method a source learns a path when a path it is attempting to establish reaches the faulty network component. A notice of fault is sent to the source, which tries next

alternative path. This method has poor performance though it requires less hardware.

- ii. Adaptive routing: It can be of following two types:
 - a. Notification on demand: With notification on demand, a source maintains a table of faults it encountered in attempting to establish paths and uses this information to guide the future routing.
 - b. Broadcast routing: With broadcast notification of fault, all sources are notified of the fault components are diagnosed.
- iii. Dynamic routing: A dynamic routing can be accomplished in Multistage Interconnection Networks constructed of switches, which are capable of performing the necessary tag revision.

2.1 Multilayer Interconnection Networks

Interconnection networks play a major role in the performance of modern parallel computers. These networks can provide the communication in a parallel processing system consisting of a large number of processors that are working together to perform a single overall task. Multistage Interconnection Networks (MINs) are designed to provide fast and efficient communication at a reasonable cost. In general, MINs consist of layers of switching elements (SEs) with a specific topological pattern. These networks provide interconnection between the set of processors (inputs) and the set of memory modules (outputs).

They fall within the category of indirect networks as they rely on intermediate elements to provide the interconnection between the input and output elements. It has been extensively used in both circuit switching and packet switching networks with the introduction of buffered switches.

The number of stages, interconnection topology, and the type of SEs used in the network configuration differentiate each MINs. Examples of the widely used MINs include: Shuffle-Exchange network (SEN) [8–10], Gamma network [11], Extra-Stage Gamma network [12], Delta network, Tandem–Banyan network [7] and Multilayer MINs[13]. Due to the size of its SEs and uncomplicated configuration of SENas shown in Figure 11, it is one of the most commonly used MINs.

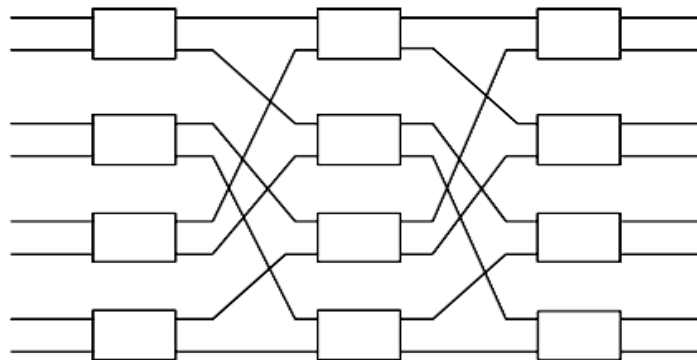


Figure 11: 8×8 Shuffle-Exchange network (SEN), [1]

2.2 Architecture of SEN Networks[6]

The SEN is a unique-path MINs that has N input switches, N output switches and n stages, where $n = \log_2 N$. Each stage consists of $N/2$ interchange boxes, where each box being controlled individually through routing tags. An eight-input/eight-output SEN with three stages, 12 SEs and 32 links is shown in Figure 11. It is noted that there is only a single path between a particular input S_i , $i=1, 2, 3, 4$, and a particular output D_i in the 8×8 SEN.

From the reliability point of view, this system can be represented as a parallel system path, consisting of $(\log_2 N) - 1$ SEs each. Where, each path is connecting the input and output SE in series.

SEN+1 are a two-path derived from the SEN by adding an extra-stage. Figure 12 shows an eight-input/eight output SEN+1 with four stages consisting of 16 SEs and 40 links. Since the SEN+1 are two-path MINs, there are two connection paths between a particular input and output.

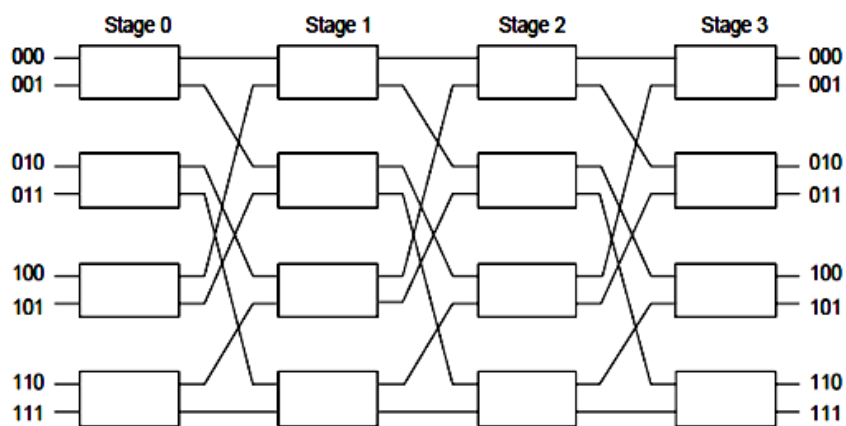


Figure 12: 8×8 Shuffle-Exchange network with additional stages (SEN+1), [1]

An 8×8 SEN+2 consists of eight inputs and eight outputs, four SEs per stage, five stages, and 48 links as demonstrated in Figure 13.

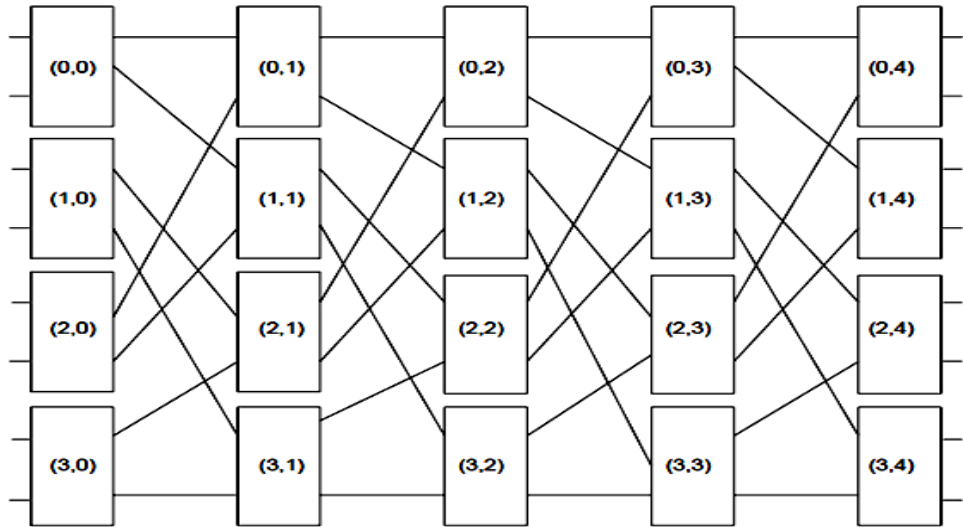


Figure 13: 8×8 Shuffle-Exchange network with additional stages (SEN+2),[1]

2.3 Regular MINs

Multistage Interconnection Networks with the SEN property are networks with unique path from an input to an output exist. Such MINs of size $N \times N$ consist of $c \times c$ switching elements with $n = \log_c N$ stages in Figure 14. That means it is a SEN network where all packets can use the same routing tag to reach a certain network output independently of the input at which they enter the networks.

To achieve synchronously operating switches, the network is internally clocked. In each stage k ($0 \leq k \leq n-1$), there is a FIFO buffer of size $m_{max}(k)$ in front of each switch input. The packets are routed by store and forward routing or cut-through switching from a stage to its succeeding one by Backpressure mechanism. Multicasting[14] is performed by copying the packets within the $c \times c$ switches. In ATM context, this scheme is called cell replication while routing (CRWR) [19]. Figure 15 shows such a scenario for an 8×8 MINs consisting of 2×2 SEs.

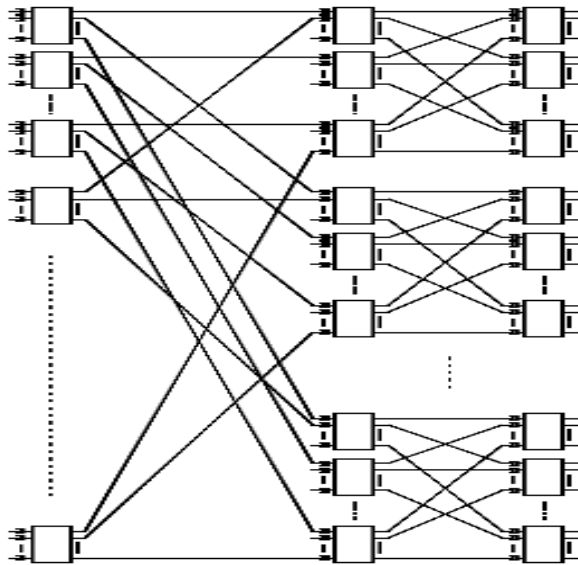


Figure 14: 3- stage SEN Network consisting $c \times c$ SEs

A packet is received by Input 3 and destined to Output 5 and Output 7. The packet enters the network and is not copied until it reaches the middle stage. Then, two copies of the packet proceed their way through the remaining stages. Packet replication before routing in the above example would copy the packet and send it twice into the network.

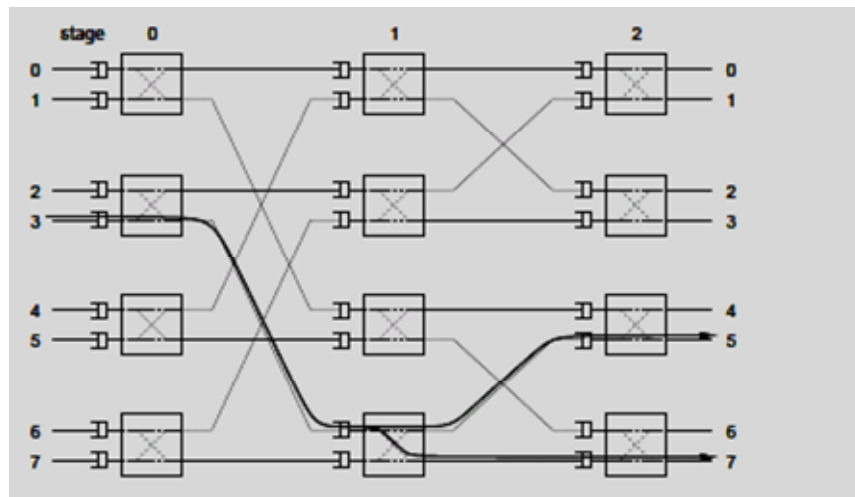


Figure 15: Multicasting while Routing

Therefore, packet replication while routing reduces the amount of packets in the first stages. Comparing the packet density in the stages in case of replication while routing shows that the greater the stage number, the higher is the amount of packets.

In other words, there are much more packets in the last stages due to replication than in the first stages. The only exception is if the traffic pattern results in such a destination distribution that packet replication has to take place at the first stage. Then, the amount of packets is equal in all stages. But such a distribution is very unlikely, in general.

To set up Multistage Interconnection Networks which is appropriate for multicasting, the previously mentioned different traffic densities of the stages must be considered.

2.4 Replicated MINs

Replicated MINs enlarge regular Multistage Interconnection Networks by replicating them L times [12]. The resulting MINs are arranged in L layers. Corresponding input ports are connected as well as corresponding output ports. Figure 16 shows the architecture of an 8×8 replicated MINs consisting of two layers in a three-dimensional view. A lateral view of the same network is given in Figure 17. Such a concept was introduced by Kruskal and Snir [17].

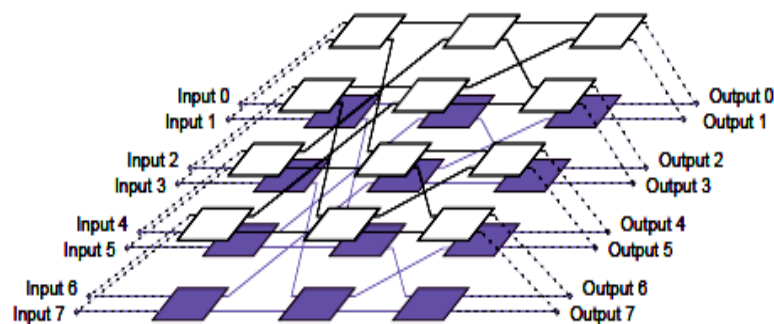


Figure 16: Replicated Multistage Interconnection Networks(L=2,3D view)

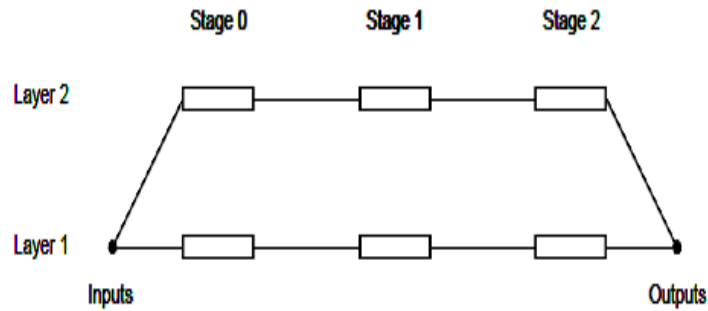


Figure 17: Replicated Multistage Interconnection Networks ($L=2$, Lateral view), [2]

Packets are received by the inputs of the network and distributed to the layers. Layers may be chosen by random, by roundrobin, dependent on layer loads, or any other scheduling algorithm. The distribution is performed by a $1:L$ demultiplexer. At each network output, an $L:1$ multiplexer collects the packets from the corresponding layer outputs and forwards them to the network output.

Two different output schemes are distinguished: single acceptance (SA) and multiple acceptances (MA). Single acceptance means that just one packet is accepted by the network output per clock cycle. If there are packets in more than one corresponding layer output, one of them is chosen. All others are blocked at the last stage of their layer.

The multiplexer decides according to its scheduling algorithm which packet to choose. Multiple acceptance means that more than one packet may be accepted by the network output per clock cycle. Either all packets are accepted or just an upper limit R . If an upper limit is given, R packets are chosen to be forwarded to the network output and all others are blocked at the last stage of their layer. As a result, single acceptance is a special case of multiple acceptances with $R = 1$.

In contrast to regular Multistage Interconnection Networks, replicated MINs may cause out of order packet sequences. Sending packets belonging to the same connection to the same layer avoids destruction of packet order.

2.5 Multilayer MINs

Multilayer Multistage Interconnection Networks (MLMINs) consider the multicast traffic characteristics [16]. As mentioned above, the amount of packets increases from stage to stage due to packet replication. Thus, more switching power is needed in the last stages compared to the first stages of networks. To supply the network with the required switching power, the network structure replicates the number of layers in each stage. The factor with which the number of layers is increased is called growth factor $G_F (G_F \in \mathbb{N} \setminus \{0\})$. Figure 18 shows an 8×8 MLMIN (3 stages) with growth factor $G_F = 2$ in lateral view. That means the number of layers is doubled each

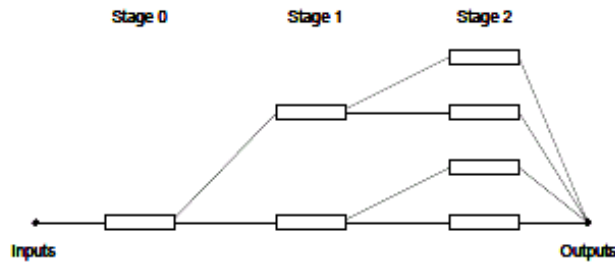


Figure18: Multilayer Multistage Interconnection Network ($G_F=2$)

stage and each switching element has twice as much outputs as inputs. Consider for instance that 2×2 SEs is used. Such architecture ensures that even in case of two broadcast packets at the inputs all packets can be sent to the outputs. On the other hand, unnecessary layer replications in the first stages are avoided. Choosing $G_F = c$ ensures that no internal blocking occurs in an SE, even if all SE inputs broadcast their packets to all SE outputs.

Nevertheless, blocking may still occur at the network output depending on R . A drawback this architecture arises from the exponentially growing number of layers for each further stage. The more network inputs are established, the more stages and the more layers result.

To limit the number of layers and therefore the amount of hardware, two options are considered: starting the replication in a more rear stage and/or

stopping further layer replication if a given number of layers are reached. The first option is demonstrated in Figure 19 in lateral view. The example presents an 8×8 MLMINs in which replication starts not before Stage 2 (last stage) with $G_F=2$. A 3D view is given in Figure 20.

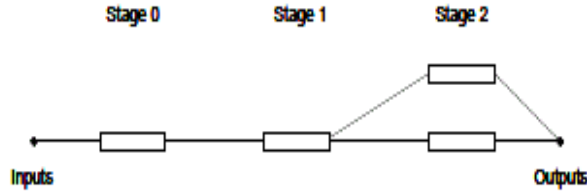


Figure 19: MLMINs in which replication start at stage 2

(Lateral View)

The stage number in which replication starts is defined by $G_S(G_S \in \mathbf{N})$. Figures 19 and 20 introduce a MLMINs with $G_S = 2$. Of course, moving the start of layer replications some stages to the rear not just reduces the number of layers. It also reduces the network performance due to less SEs and therefore less paths through the network.

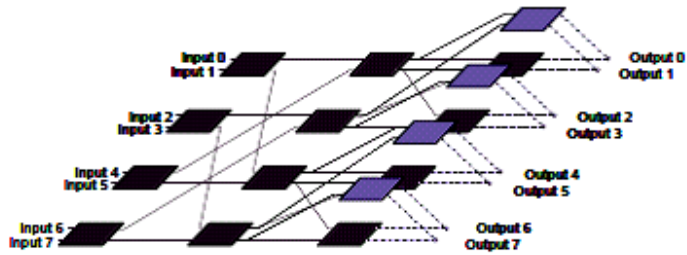


Figure20: MLMINs in which replication start at stage 2(3D view)

Stopping further layer replication if a given number G_L of layers is reached also reduces the network complexity ($G_L \in \mathbf{N} \setminus \{0\}$). It prevents exponential growth in case of large networks. Figure 21 shows such a MLMINs with limited

number of layers in lateral view. 3D view is presented in Figure 22. The number of layers of this 8×8 MLMINs

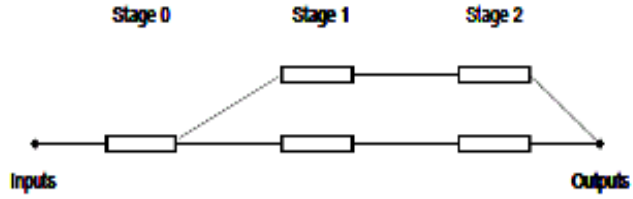


Figure 21: MLMINs with limited number of layer (Lateral View)

is limited to an upper number of $G_L= 2$. Layers are replicated with a growth factor of $G_F= 2$. As in the previous option, the reduced amount of SEs decreases network performance as well.

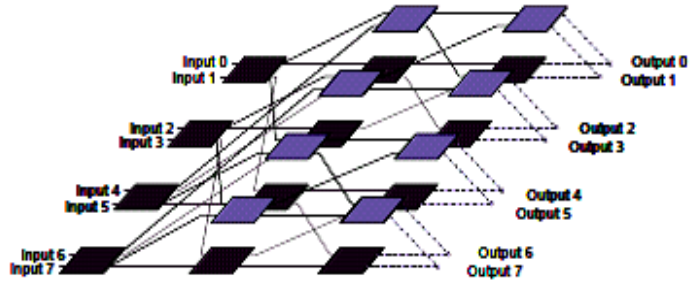


Figure22: MLMINs with limited number of layer (3D View)

Both presented options can be combined to reduce network complexity further. Such a network is determined by parameters G_S (start of replication), G_F (growth factor), and G_L (layer limit). For instance, Figure 22 shows a MLMINs with $G_S= 1$, $G_F= 2$, and $G_L= 2$. Regular MINs and replicated MINs can be considered as special cases of MLMINs. Regular MINs are equivalent to MLMINs with $G_F=1$. In this case, G_S and G_L do not affect. Replicated MINs are equivalent to MLMINs with $G_S= 0$, $G_F= L$ and $G_L= L$.

Chapter 3 Problem Statement

The problem undertaken for dissertation is “**Behavior Analysis of Multilayer Multistage Interconnection Network with Extra Stages**”. The Multilayering is performed on the SEN Networks. How SEN, SEN+1 and SEN+2 show better results with Multilayering as compare to the Regular and Replicated MINs. Multilayering is the major consideration in the design of these MINs.

It mainly considers the multicast traffic characteristic. In this amount of packet increases from stage to stage due to packet replication. The main idea is to replicate the number of layer at each stage so that packet sends to the destination without any interruptions. Layers are doubled at each stage. In regular MINs no such work is done. In replicated MINs the whole network is replicated.

The objective of the Research include:-

- To Study Multistage Interconnection Network and its Layered Architecture.
- Design of Multilayered variant of SEN having one and two extra stages.
- Analyze performance of proposed multilayer MINs in term of Crosspoint Cost and Buffer Cost.
- Performance comparison of existing and purposed Multilayer MINs.

The Methodology used for Research include:-

- Taking SEN as the base network design SEN+1 and SEN+2, using the same destination routing method.

- Compute Crosspoint and Buffer Cost for new SEN+1 and SEN+2 networks for the Regular, Replicated and Multilayered Architecture.
- Draw Charts in Excel and Compare performance of SEN, SEN+1 and SEN+2.

Chapter 4 Design and Implementation

4.1 Working of SEN, SEN+1 and SEN+2 in Regular, Replicated Multilayered architecture.

In Regular MINs, when a packet enters in the network, it reaches to the middle stage and then copied. Then these packets proceed through the remaining stages. Therefore, packet replication while routing reduces the amount of packet in the first stages. If there is any destination disturbance packet replication has to take place at the first stages.

Replicated MINs enlarges its whole networks by replicating them L times and are arranged in L layers, corresponding input port are connected as well as corresponding output port. Layers are chosen by random, by round robin or any scheduling algorithm. But replicated MINs can cause out of order packet sequences. Sending packets belonging to the same connection to the same layer avoid destruction of packet order.

Multilayer MINs consider the multicast traffic characteristics. In Multilayer MINs there are three factors G_F , G_L and G_S factor. G_F is growth factor where layers get increased. But the drawback with this is that there is exponentially growing number of layers for each stage. For removing this drawback two factors are considered G_L and G_S . G_L is that factor which stops further layer replication if it reaches the given layer number and then stop further layer replication and reduce network complexity. G_S is the factor where replication starting in a more rear stage and reduces the number of layers.

4.1.1 Crosspoint Cost of SEN Network for Regular, Replicated and ML MINs

Crosspoint Cost [16]: -The number of Crosspoint within a switching element and by the number of switching element within the network.

SEs of regular MINs consists of c^2 Crosspoints if $c \times c$ SEs is used. That means the Crosspoint Cost P_{MIN} of an $N \times N$ MINs, which consists of $n = \log_c N$ stages with N/c SEs in each stage, results in

$$P_{MIN} = n$$

$$P_{MIN} = n \cdot \frac{N}{c} \cdot c^2$$

$$= n \cdot c^{n+1} (1)$$

4.1.1.1 Crosspoint Cost for Regular MINs in SEN

Regular MINs are equivalent to MLMINs with $G_F=1$. In this case G_S and G_L do not effect. The structure of SEs allows increasing number of stages in the succeeding stage is slightly changed to regular SEs.

$$P_{MLMIN\text{inlimit}}$$

$$= \frac{N}{c} \cdot ((G_S - 1) \cdot C^2 \cdot G_F \cdot \sum_{i=0}^{n-1-G_S} G_F^i + G_F^{n-G_S} \cdot c^2) + N \cdot G_F^{n-G_S} (2)$$

$$= c^n \cdot (c \cdot (G_S - 1 + G_F \frac{G_F^{n-G_S}}{G_F-1} + G_F^{n-G_S}) + G_F^{n-G_S}) (3)$$

In SEN for Regular MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

When network is 1248 that means its G_S is 1 the network starts replicating from the first stage. $G_F=2$ it means that the growth factor is 2. The Crosspoint values are shown in Table 2 of Chapter 5.

4.1.1.2 Crosspoint Cost for Replicated MINs in SEN

Replicated MINs are equivalent to MLMINs with $G_S=0, G_F=L$ and $G_L=L$. Replicating MINs are established by L layers of MINs, there is a demultiplexer at each input, and a multiplexer at each output. Each demultiplexer is composed of L Crosspoint to distribute the incoming packets among the layers. A multiplexer is composed of L Crosspoint to collect the packet from the L layers. Thus the Crosspoint Cost P_{RepMIN} of a replicated MIN are given by

$$P_{RepMIN} = L \cdot n \cdot c^{n+1} + L \cdot c^n + L \cdot c^n$$

$$= L \cdot c^n \cdot (n \cdot c + 2) \quad (4)$$

In SEN for Replicated MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

If network is 8888 that means the whole network is replicated by value $L=8$. If network is 4444 that means the whole network is replicated by value $L=4$. The Crosspoint values are shown in Table 2 of Chapter 5.

4.1.1.3 Crosspoint Cost for Multilayer MINs in SEN

Multilayer MINs has three factors G_S, G_F and G_L . Thus the Crosspoint Cost $P_{MLMINlimit}$ of Multilayer MIN are given by

$$= C^n \cdot (c \cdot (G_S - 1 + G_F \frac{G_L - 1}{G_F - 1} + (n + 1 - G_S - \log_{G_F} G_L) \cdot G_L) + G_L) \quad (5)$$

In SEN for Multilayer MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

If network is 1888 then its $G_S=1$, means the growth starts at early stage. $G_F=8$, factor with which layers are replicated. $G_L=8$, where layer stop further replication. In 1188 network in this the layers start from the stage 2 that is $G_S=2$ but the G_F and G_L should be same. In this when layer does not start at early its Crosspoint Cost is less than if it starts from starting stage. The Crosspoint Cost values are shown in Table 2 of Chapter 5.

4.1.2 Buffer Cost of SEN Network for Regular, Replicated and MLMINs

Buffer Cost[16]:- The Buffer Cost of a network is determined by the number of buffer and the size m_{max} of each buffer. There is H constant which

represents the hardware cost relation between Crosspoint Cost and the Buffer Cost for one packet.

4.1.2.1 Buffer Cost for Regular MINs in SEN

Each layer stage consist of N buffer (due to N SE at each stage and layer) leading to Buffer Cost of a MIN with no layer limit of

$$\begin{aligned}
 &= H \cdot m_{max} \cdot N (G_S - 1 + \sum_{i=0}^{n-G_S} G_F^i) \\
 &= H \cdot m_{max} \cdot N (G_S - 1 + \frac{G_F^{n+1-G_S} - 1}{G_F - 1}) \quad (6)
 \end{aligned}$$

In SEN for Regular MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

When network is 1248 that means its G_S is 1 the network starts replicating from the first stage. $G_F=2$ it means that the growth factor is 2. The Buffer Cost values are shown in Table 5 of Chapter 5.

4.1.2.2 Buffer Cost for Replicated MINs in SEN

Replicated MINs consist of L layers of MINs. Each $N \times N$ MINs is established by n stages of SEs. All N SE inputs of a stage are connected to a buffer. Therefore, the Buffer Cost of a replicated MIN is given by

$$B_{RepMIN} = H \cdot m_{max} \cdot L \cdot N \cdot n \quad (7)$$

In SEN for Replicated MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

If network is 8888 that means the whole network is replicated by value $L=8$. If network is 4444 that means the whole network is replicated by value $L=4$. The Buffer Cost values are shown in Table 5 of Chapter 5.

4.1.2.3 Buffer Cost for Multilayer MINs in SEN

The Buffer Cost of MLMINs with a layer limit result in

$$\begin{aligned}
 & \mathbf{B}_{MLMIN\text{limit}} \\
 &= H \cdot m_{\max} \cdot N(G_s - 1 + \sum_{i=0}^{x-G_s} G_F^i + (n - x) \cdot G_L) \\
 &= H \cdot m_{\max} \cdot N(G_s - 1 + \frac{G_L G_F^{-1}}{G_F - 1}) + (n - G_s - \log_{G_F} G_L) \cdot G_L \quad (8)
 \end{aligned}$$

In SEN for Multilayer MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

If network is 1888 then its $G_s=1$ that means the growing start at early stage. $G_F=8$, the factor with which layers are replicated. $G_L=8$, where layer stop further replication. In 1188 network in this the layers start from the stage 2 that is $G_s=2$ but the G_F and G_L should be same. In this when layer does not start at early its Buffer Cost is less than if it starts from starting stage. The Buffer Cost values are shown in Table 5 of Chapter 5.

4.1.3 Crosspoint Cost of SEN+1 Network for Regular, Replicated and MLMINs

SEs of regular MINs consists of c^2 Cross points if $c \times c$ SEs is used. That means the Crosspoint Cost P_{MIN} of an $N \times N$ MINs, which consists of $n = \log_c N$ stages with N/c SEs in each stage, results in

$$\begin{aligned}
 P_{MIN} &= n \cdot \frac{N}{c} \cdot c^2 \\
 &= n \cdot c^{n+1} \quad (1)
 \end{aligned}$$

4.1.3.1 Crosspoint Cost for Regular MINs in SEN+1

Regular MINs are equivalent to MLMINs with $G_F=1$. In this case G_s and G_L do not effect. The structure of SEs, allows increasing number of stages in the succeeding stage is slightly changed to regular SEs.

$P_{MLMINolimit}$

$$= \frac{N}{c} \cdot ((G_S - 1) \cdot C^2 \cdot G_F \cdot \sum_{i=0}^{n-1-G_S} G_F^i + G_F^{n-G_S} \cdot C^2) + N \cdot G_F^{n-G_S} \quad (2)$$

$$= c^n \cdot (c \cdot (G_S - 1 + G_F \frac{G_F^{n-G_S}}{G_F-1} + G_F^{n-G_S}) + G_F^{n-G_S}) \quad (3)$$

In SEN+1 for Regular MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

when network is 12488 that means its G_S is 1 the network starts replicating from the first stage. $G_F=2$ it means that the growth factor is 2. The Crosspoint Cost values are shown in Table 3 of Chapter 5.

4.1.3.2 Crosspoint Cost for Replicated MINs in SEN+1

Replicated MINs are equivalent to MLMINs with $G_S=0, G_F=L$ and $G_L=L$. Replicating MINs are established by L layers of MINs, there is a demultiplexer at each input, and a multiplexer at each output. Each demultiplexer is composed of L crosspoints to distribute the incoming packets among the layers. A multiplexer is composed of L crosspoint to collect the packet from the L layers. Thus the Crosspoint Cost P_{RepMIN} of a replicated MINs are given by

$$P_{RepMIN} = L \cdot n \cdot c^{n+1} + L \cdot c^n + L \cdot c^n$$

$$= L \cdot c^n \cdot (n \cdot c + 2) \quad (4)$$

In SEN+1 for Replicated MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

If network is 88888 that means the whole network is replicated by value $L=8$. If network is 44444 that means the whole network is replicated by value $L=4$. The Crosspoint Cost of replicated MINs of SEN+1 is equal to the

Crosspoint Cost of the Regular MINs because in both cases the whole network replicates. The Crosspoint Cost values are shown in Table 3 of Chapter 5.

4.1.3.3 Crosspoint Cost for Multilayer MINs in SEN+1

Multilayer MINs has three factors G_S, G_F and G_L . Thus the Crosspoint Cost P_{MLMIN} of Multilayer MIN are given by

$$= C^n \cdot (c \cdot (G_S - 1 + G_F \frac{G_L - 1}{G_F - 1} + (n + 1 - G_S - \log_{G_F} G_L) \cdot G_L) + G_L) \quad (5)$$

In SEN+1 for Regular MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

If network is 11888 then its $G_S=2$, the growing start at second stage. $G_F=8$ that means the factor with which layers are replicated. $G_L=8$, where layer stop further replication. In 11188 networks in this the layers start from the stage 3 that is $G_S=3$ but the G_F and G_L should be same. In this when layer does not start at early its Crosspoint Cost is less than if it starts from starting stage. In Multilayer MINs the Crosspoint Cost of the SEN+1 is less than the SEN network. The Crosspoint Cost values are shown in Table 3 of Chapter 5.

4.1.4 Buffer Cost of SEN+1 Network for Regular, Replicated and MLMINs

4.1.4.1 Buffer Cost for Regular MINs in SEN+1

$$= H \cdot m_{max} \cdot N(G_S - 1 + \sum_{i=0}^{n-G_S} G_F^i)$$

$$= H \cdot m_{max} \cdot N(G_S - 1 + \frac{G_F^{n+1-G_S} - 1}{G_F - 1}) \quad (6)$$

When network is 12488 that means its G_S is 1 the network starts replicating from the first stage. $G_F=2$ it means that the growth factor is 2. The Buffer Cost values are shown in Table 6 of Chapter 5.

4.1.4.2 BufferCost for Replicated MINs in SEN+1

Replicated MINs consist of L layers of MINs. Each $N \times N$ MINs is established by n stages of SEs. All N SE inputs of a stage are connected to a buffer. Therefore, the Buffer Cost of a replicated is given by

$$B_{RepMIN} = H \cdot m_{max} \cdot L \cdot N \cdot n \quad (7)$$

In SEN+1 for Regular MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

If network is 8888 that means the whole network is replicated by value $L=8$. If network is 4444 that means the whole network is replicated by value $L=4$. The Buffer Cost of replicated MINs of SEN+1 is equal to the Buffer Cost of the Regular MINs because in both cases the whole network replicates. The Buffer Cost values are shown in Table 6 of Chapter 5.

4.1.4.3 BufferCost for Multilayer MINs in SEN+1

The Buffer Cost of MLMIN with a layer limit result in

$$\begin{aligned} & \mathbf{B}_{MLMINlimit} \\ &= H \cdot m_{max} \cdot N(G_S - 1 + \sum_{i=0}^{x-G_S} G_F^i + (n - x) \cdot G_L) \\ &= H \cdot m_{max} \cdot N(G_S - 1 + \frac{G_L \cdot G_F^{-1}}{G_F - 1}) + (n - G_S - \log_{G_F} G_L) \cdot G_L \quad (8) \end{aligned}$$

If network is 11888 then its $G_S=2$, means the growth start at second stage. $G_F=8$, means the factor with which layers are replicated. $G_L=8$, means layer stop further replication. In 11188 networks in this the layers start from the stage 3 that is $G_S=3$ but the G_F and G_L should be same. When layer start replication at

early stages its Buffer Cost is less than if it starts from the starting stage. In MultilayerMINs the Buffer Cost of the SEN+1 is less than the SEN network. The Buffer Cost values are shown in Table 6 of Chapter 5.

4.1.5 Crosspoint Cost of SEN+2 Networks for Regular, Replicated and MLMINs

SEs of regular MINs consists of c^2 Crosspoints if $c \times c$ SEs is used. That means the Crosspoint Cost P_{MIN} of an $N \times N$ MIN, which consists of $n = \log_c N$ stages with N/c SEs in each stage, results in

$$P_{MIN} = n \cdot \frac{N}{c} \cdot c^2$$

$$= n \cdot c^{n+1} \quad (1)$$

4.1.5.1 Crosspoint Cost for Regular MINs in SEN+2

Regular MINs are equivalent to MLMIN with $G_F=1$. In this case G_S and G_L do not effect. The structure of SEs that allows increasing number of stages in the succeeding stage is slightly changed to regular SEs.

$$P_{MLMIN \text{ in limit}}$$

$$= \frac{N}{c} \cdot ((G_S - 1) \cdot C^2 \cdot G_F \cdot \sum_{i=0}^{n-1-G_S} G_F^i + G_F^{n-G_S} \cdot c^2) + N \cdot G_F^{n-G_S} \quad (2)$$

$$= c^n \cdot (c \cdot (G_S - 1 + G_F \frac{G_F^{n-G_S}}{G_F-1} + G_F^{n-G_S}) + G_F^{n-G_S}) \quad (3)$$

In SEN+2 for Regular MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

when network is 112488 that means its G_S is 1 the network starts replicating from the first stage. $G_F=2$ it means that the growth factor is 2. Thus the Crosspoint Cost of regular MINs of SEN+2 is same as compare to SEN+1 and SEN. The Crosspoint values are shown in Table 4 of Chapter 5.

4.1.5.2 Crosspoint Cost for Replicated MINs in SEN+2

Replicated MINs are equivalent to MLMINs with $G_S=0, G_F=L$ and $G_L=L$. Replicating MINs are established by L layers of MINs, there is a demultiplexer at each input, and a multiplexer at each output. Each demultiplexer is composed of L crosspoints to distribute the incoming packets among the layers. A multiplexer is composed of L crosspoint to collect the packet from the L layers. Thus the Crosspoint Cost P_{RepMIN} of a replicated MINs are given by

$$P_{RepMIN} = L \cdot n \cdot c^{n+1} + L \cdot c^n + L \cdot c^n$$

$$= L \cdot c^n \cdot (n \cdot c + 2) \quad (4)$$

In SEN+2 for Regular MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

If network is 888888 that means the whole network is replicated by value $L=8$. If network is 444444 that means the whole network is replicated by value $L=4$. The Crosspoint Cost of replicated MINs of SEN+2 is equal to the Crosspoint Cost of the SEN+1 and SEN because in both cases the whole network replicates. The Crosspoint values are shown in Table 4 of Chapter 5.

4.1.5.3 Crosspoint Cost for Multilayer MINs in SEN+2

Multilayer MINs has three factors G_S, G_F and G_L . Thus the Crosspoint Cost $P_{MLMINlimit}$ of Multilayer MINs are given by

$$= C^n \cdot \left(c \cdot \left(G_S - 1 + G_F \frac{G_L - 1}{G_F - 1} + (n + 1 - G_S - \log_{G_F} G_L) \cdot G_L \right) + G_L \right) \quad (5)$$

In SEN+2 for Regular MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

If network is 111888 then its $G_S=3$ that means the growing start at third stage. $G_F=8$ that means the factor with which layers are replicated. $G_L=8$ it means where layer stop further replication. In 111888 networks in this the layers start from the stage 4 that is $G_S=4$ but the G_F and G_L should be same. In this when layer doesnot start at early its Crosspoint Cost is less than if it starts from starting stage. In MultilayerMINs the Crosspoint Cost of the SEN+2 is less than the SEN+1 and SEN network. The Crosspoint values are shown in Table 4 of Chapter 5.

4.1.6 Buffer Cost of SEN+2 Networks for Regular, Replicated and MLMINs

4.1.6.1 Buffer Cost for Regular MINs in SEN+2

The no of buffers of an MLMINs with no layer limit is determined by G_S-1 stages where no growing occurs and by the remaining $n+1-G_S$ stages where layer grow with factor G_F . Each layer stage consist of N buffer (due to N SE at each stage and layer) Leading to Buffer Cost of a MINs with no layer limit of

$$\begin{aligned}
 &= H \cdot m_{max} \cdot N (G_S - 1 + \sum_{i=0}^{n-G_S} G_F^i) \\
 &= H \cdot m_{max} \cdot N (G_S - 1 + \frac{G_F^{n+1-G_S} - 1}{G_F - 1}) \quad (6)
 \end{aligned}$$

When network is 112488 that means its G_S is 1 the network starts replicating from the first stage. $G_F=2$ it means that the growth factor is 2. Thus the Buffer Cost of regular MINs of SEN+2 are same as compare to SEN+1 and SEN. The Buffer Cost values are shown in Table 7 of Chapter 5.

4.1.6.2 Buffer Cost for Replicated MINs in SEN+2

Replicated MINs consist of L layers of MINs. Each $N \times N$ MINs is established by n stages of SEs. All N SE inputs of a stage are connected to a buffer. Therefore, the Buffer Cost of replicated MINs is given by

$$B_{RepMIN} = H \cdot m_{max} \cdot L \cdot N \cdot n \quad (7)$$

In SEN+2 for Regular MINs two cases are consider:

- 8 layers at the end.
- 4 layers at the end.

If network is 888888 that means the whole network is replicated by value L=8. If network is 444444 that means the whole network is replicated by value L=4. The Buffer Cost of replicated MINs of SEN+2 is equal to the Buffer Cost of the SEN+1 and SEN because in both cases the whole network replicates. The BufferCost table values are shown in Table 7 of Chapter 5.

4.1.6.3 Buffer Cost for Multilayer MINs in SEN+2

The Buffer Cost of MLMINs with a layer limit result in

$$\begin{aligned}
 & \mathbf{B}_{MLMlimit} \\
 &= H \cdot m_{max} \cdot N(G_s - 1 + \sum_{i=0}^{x-G_s} G_F^i + (n - x) \cdot G_L) \\
 &= H \cdot m_{max} \cdot N(G_s - 1 + \frac{G_L \cdot G_F^{-1}}{G_F - 1}) + (n - G_s - \log_{G_F} G_L) \cdot G_L \quad (8)
 \end{aligned}$$

If network is 111888 then its $G_s=2$ that means the growing start at third stage. $G_F=8$ that means the factor with which layers are replicated. $G_L=8$ it means where layer stop further replication. In 111888 networks in this the layers start from the stage 4 that is $G_s=4$ but the G_F and G_L should be same. In this when layer does not start at early its Buffer Cost is less than if it starts from starting stage. In MultilayerMINs the Buffer Cost of the SEN+2 is less than SEN+1 and SEN network. The Buffer Cost table values are shown in Table 7 of Chapter 5.

5.1 Performance

This section compares the performance of various MINs namely SEN, SEN+1 and SEN+2. Following performance measure has been considered

- Normalized throughput S_i at the input of the network
- Normalized throughput S_o at the output of the network
- $d(k)$ is the mean delay time of the packet in each stage
- d_{tot} is the mean queue length of the buffer in each stage can be considered

Assumptions:

- 16×16 network consist of 2×2 SEs
- Buffer size $m_{max}=1$ at each stage
- Multiple acceptance means that more than one packet may be accepted
- In this case $R=4$ is considered.

5.1.1 Crosspoint Cost of SEN

Table 2: Performance of SEN with 8 layers in last stage

Network	Parameters			Costs
	G_s	G_F	G_L	Crosspoint
1248	1	2	-	832
1888	1	8	8	1152
1188	2	8	8	928
8888	Rep MIN L=8			1280

Table 2 three types of networks Regular, Replicated and Multilayered of SEN have been shown with computed Crosspoint cost.

- First network is Regular Network i.e.1248 in which two values are there G_s and G_F there is no need of G_L . In this layer replicates from stage 1 with the growing factor of 2.
- 1888 and 1188 are the Multilayer Networks. In 1888 replication start from the Stage 1 with the growing factor of 2 till layer limit reaches to 8. There is another network i.e. 1188 in which the replication start later.
- 8888 is the replicated layer there is no need of G_s, G_L and G_F . There is only one factor i.e. L factor which is replicated factor.

Table 2 shows that the Crosspoint Cost of 1188 network is less as compare to another network because the replication starts at later stages. The Crosspoint Cost of replicated MINs is maximum because in this the whole network is replicated.

5.1.2 Crosspoint Cost of SEN+1

Table 3: Performance of SEN+1 with 8 layers in last stage

Network	Parameters			Costs
	G_s	G_F	G_L	Crosspoint
12488	1	2	-	832
11888	2	8	8	928
11188	3	8	8	704
88888	Rep MIN L=8			1280

- First network is Regular Network i.e.12488 in which two values are there G_s and G_F there is no need of G_L . In this layer replicates from stage 1 with the growing factor of 2.
- 11888 and 11188 are the Multilayer Networks. In 11888 replication start from the Stage 2 with the growing factor of 8 till layer limit reaches to 8. There is another network i.e. 11188 in which the replication start later i.e. from the 3 stage and replicated till the layer limit reaches to 8.

- 88888 is the replicated layer there is no need of G_s, G_L and G_F . There is only one factor i.e. L factor which is replicated factor. It is replicated with $L=8$.

Table 3 shows that the Crosspoint Cost of 11188 networks is less as compare to another network because the replication starts at later stages. The Crosspoint Cost of replicated MINs is maximum because in this the whole network is replicated.

5.1.3 Crosspoint Cost of SEN+2

Table 4: Performance of SEN+2 with 8 layers in last stage

Network	Parameters			Costs
	G_s	G_F	G_L	Crosspoint
112488	1	2	-	832
111888	3	8	8	704
111188	4	8	8	480
888888	Rep MIN $L=8$			1280

- First network is Regular Network i.e. 124888 in which two values are there G_s and G_F there is no need of G_L . In this layer replicates from stage 1 with the growing factor of 2.
- 111888 and 111188 are the Multilayer Networks. In 111888 replication start from the Stage 3 with the growing factor of 8 till layer limit reaches to 8. There is another network i.e. 111188 in which the replication start later i.e. from the 4 stage and replicated till layer limit reaches to 8.
- 888888 is the replicated layer there is no need of G_s, G_L and G_F . There is only one factor i.e. L factor which is replicated factor. It is replicated with $L=8$.

Table 4 shows that the Crosspoint Cost of 11188 networks is less as compare to another network because the replication starts at later stages. The Crosspoint Cost of replicated MINs is maximum because in this the whole network is replicated.

5.1.4 Comparison of SEN, SEN+1 and SEN+2 on the Basis of Crosspoint Cost

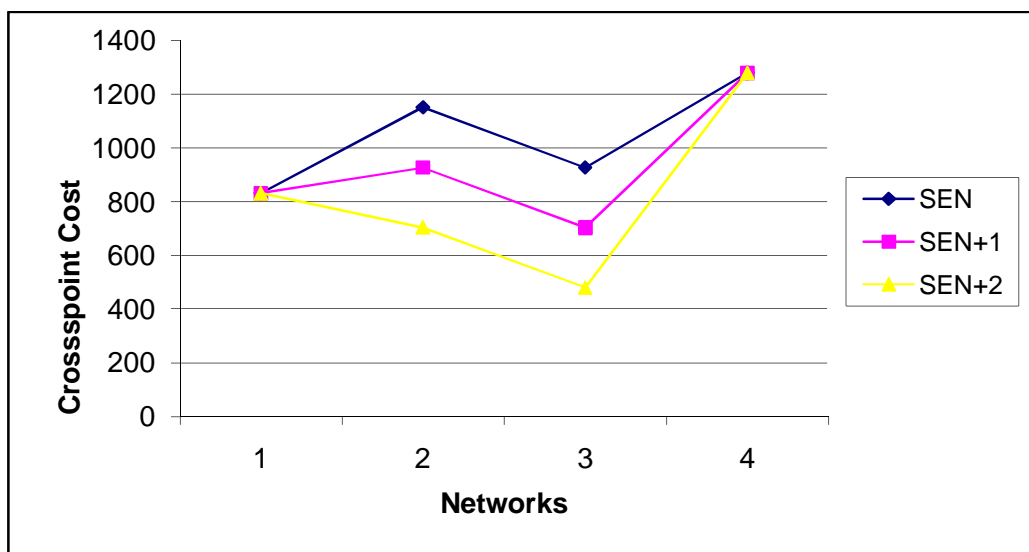


Figure 19: Crosspoint Cost comparison with 8 layers in Last Stage

From Figure 19 it is clear that the Crosspoint Cost of the SEN+2 is less as compare to the SEN+1 and SEN because as the network size grows, the layering of stages should be done at the later stages that are not possible in the SEN and SEN+1. Whereas the SEN+1 show the better result as compare to the SEN because it has more no of stages than the SEN so replication at the latter stages are possible. Multilayering also show better performance in SEN+2 as compare to the SEN+1 and SEN. Whereas Replicated MINs show least performance in term of Crosspoint cost.

5.1.5 Buffer Cost of SEN

- First network is Regular Network i.e.1248 in which two values are there G_s and G_F there is no need of G_L . In this layer replicates from stage 1 with the growing factor of 2.
- 1888 and 1188 are the Multilayer Networks. In 1888 replication start from the Stage 1 with the growing factor of 2 till layer limit reaches to 8. There is another network i.e. 1188 in which the replication start later.
- 8888 is the replicated layer there is no need of G_s, G_L and G_F . There is only one factor i.e. L factor which is replicated factor.

Table 5: Performance of SEN with 8 layers in last stage

Network	Parameters			Costs
	G_s	G_F	G_L	Buffer
1248	1	2	-	240.H
1888	1	8	8	400.H
1188	2	8	8	288.H
8888	Rep MIN L=8			512.H

Table 5 shows that the Buffer Cost of 1188 network is less as compare to another network because the replication starts at later stages. The Buffer Cost of replicated MINs is maximum because in this the whole network is replicated.

5.1.6 Buffer Cost of SEN+1

- First network is Regular Network i.e.12488 in which two values are there G_s and G_F there is no need of G_L . In this layer replicates from stage 1 with the growing factor of 2.

Table 6:Performance of SEN+1 with 8 layers in last stage

Network	Parameters			Costs
	G_s	G_F	G_L	Buffer
12488	1	2	-	240.H
11888	2	8	8	360.H
11188	3	8	8	220.H
88888	Rep MIN L=8			512.H

- 11888 and 11188 are the Multilayer Networks. In 11888 replication starts from the Stage 2 with the growing factor of 8 till the layer limit reaches 8. There is another network i.e. 11188 in which the replication starts later i.e. from the 3 stage and is replicated till the layer limit reaches 8.
- 88888 is the replicated layer; there is no need for G_s, G_L and G_F . There is only one factor i.e. L factor which is the replicated factor. It is replicated with $L=8$.

Table 6 shows that the Buffer Cost of 11188 networks is less as compared to another network because the replication starts at later stages. The Buffer Cost of replicated MINs is maximum because in this the whole network is replicated.

5.1.7 Buffer Cost of SEN+2

Table 7:Performance of SEN+2 with 8 layers in last stage

Network	Parameters			Costs
	G_s	G_F	G_L	Buffer
112488	1	2	-	240.H
111888	3	8	8	264.H
111188	4	8	8	96.H
888888	Rep MIN L=8			512.H

- First network is Regular Network i.e.124888 in which two values are there G_s and G_F there is no need of G_L . In this layer replicates from stage 1 with the growing factor of 2.
- 111888 and 111188 are the Multilayer Networks. In 111888 replication start from the Stage 3 with the growing factor of 8 till layer limit reaches to 8. There is another network i.e. 111188 in which the replication start later i.e. from the 4 stage and replicated till layer limit reaches to 8.
- 888888 is the replicated layer there is no need of G_s, G_L and G_F . There is only one factor i.e. L factor which is replicated factor. It is replicated with $L=8$.

Table 7 shows that the Crosspoint Cost of 11188 networks is less as compare to another network because the replication starts at later stages. The Buffer Cost of replicated MINs is maximum because in this the whole network is replicated.

5.1.8 Comparison of SEN, SEN+1 and SEN+2 on the basis of Buffer Cost

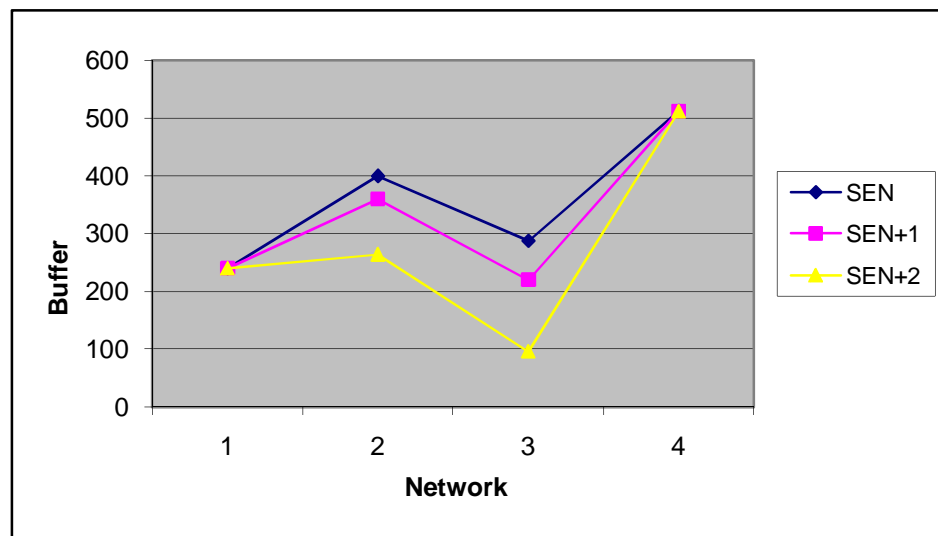


Figure 21: Buffer Cost comparison with 8 layers in Last Stage

From Figure 21 it is clear that the Buffer Cost of the SEN+2 is less as compare to the SEN+1 and SEN because the data stored in buffer should be less due to the network size because the layering shouldbe done at the later stages and that are not possible in the SEN and SEN+1.

Whereas the SEN+1 show the better result as compare to the SEN because it has one more stage than the SEN so replication at the later stages are possible. Multilayering also show better performance in SEN+2 as compare to the SEN+1 and SEN. Whereas Replicated MINs show least performance in term of Buffer cost.

5.2 Performance of SEN, SEN+1 and SEN+2 having 4 layers at end

5.2.1 Crosspoint Cost of SEN

Table 8:Performance of SEN with 4 layers in last stage

Network	Parameters			Costs
	G_s	G_F	G_L	Crosspoint.
1244	1	2	-	832
1244	1	2	4	640
1124	2	2	4	544
4444	Rep MIN L=4			640
5555	Rep MIN L=5			800
6666	Rep MIN L=6			960

- First network is Regular Network i.e.1244 in which two values are there G_s and G_F there is no need of G_L . In this layer replicates from stage 1 with the growing factor of 2.

- 1244 and 1124 are the Multilayer Networks. In 1244 replication start from the Stage 1 with the growing factor of 2 till layer limit reaches 4. There is another network i.e. 1124 in which the replication start later.
- 4444 is the replicated layer there is no need of G_s, G_L and G_F . There is only one factor i.e. L factor which is replicated factor.

Table 8 shows that the Crosspoint Cost of 1124 network is less as compare to another network because the replication starts at later stages. The Crosspoint Cost of replicated MINs is maximum because in this the whole network is replicated.

5.2.2 Crosspoint Cost of SEN+1

Table 9: Performance of SEN+1 with 4 layers in last stage

Network	Parameters			Costs
	G_s	G_F	G_L	Crosspoint.
11244	1	2	-	832
12244	2	2	4	544
11124	3	2	-	488
44444	Rep MIN L=4			640
55555	Rep MIN L=5			800
66666	Rep MIN L=6			960

- First network is Regular Network i.e. 11244 in which two values are there G_s and G_F there is no need of G_L . In this layer replicates from stage 1 with the growing factor of 2.
- 12244 and 11124 are the Multilayer Networks. In 12244 replication start from the Stage 2 with the growing factor of 4 till layer limit reaches 4. There is another network i.e. 11124 in which the replication start later i.e. from the 3 stage and replicated till layer limit reaches to 4.

- 44444 is the replicated layer there is no need of G_s, G_L and G_F . There is only one factor i.e. L factor which is replicated factor. It is replicated with $L=4$.

Table 9 shows that the Crosspoint Cost of 11124 networks is less as compare to another network because the replication starts at later stages. The Crosspoint Cost of replicated MINs is maximum because in this the whole network is replicated.

5.2.3 Crosspoint Cost of SEN+2

- First network is Regular Network i.e.111244 in which two values are there G_s and G_F there is no need of G_L . In this layer replicates from stage 1 with the growing factor of 2.
- 112244 and 111124 are the Multilayer Networks. In 112244 replication start from the Stage 3 with the growing factor of 4 till layer limit reaches 4. There is another network i.e. 111124 in which the replication start later i.e. from the 4 stage and replicated till the layer limit reaches to 4
- 444444 is the replicated layer there is no need of G_s, G_L and G_F . There is only one factor i.e. L factor which is replicated factor. It is replicated with $L=4$.

Table 10 shows that the Crosspoint Cost of 111124 networks is less as compare to another network because the replication starts at later stages. The Crosspoint Cost of replicated MINs is maximum because in this the whole network is replicated.

Table 10: Performance of SEN+2 with 4 layers in last stage

Network	Parameters			Costs
	G_s	G_F	G_L	Crosspoint
111248	1	2	-	832
112244	3	2	4	488
111124	4	2	4	352
444444	Rep MIN L=4			640
555555	Rep MIN L=5			800
666666	Rep MIN L=6			960

5.2.4 Comparison of SEN, SEN+1 and SEN+2 on the Basis of Buffer Cost with 4 layers at the end

This is the network with 4 layers at the end. According to this graph shown above the Crosspoint Cost of the SEN+2 is less as compare to the SEN+1 and SEN because as the network size grows the layering of stages should be done at the later stages that are not possible in the SEN and SEN+1. Whereas the SEN+1 show the better result as compare to the SEN because it has one more stage than the SEN so replication at the latter stages are possible. Multilayering also show better performance in SEN+2 as compare to the SEN+1 and SEN. Whereas Replicated MINs show least performance in term of Crosspoint cost.

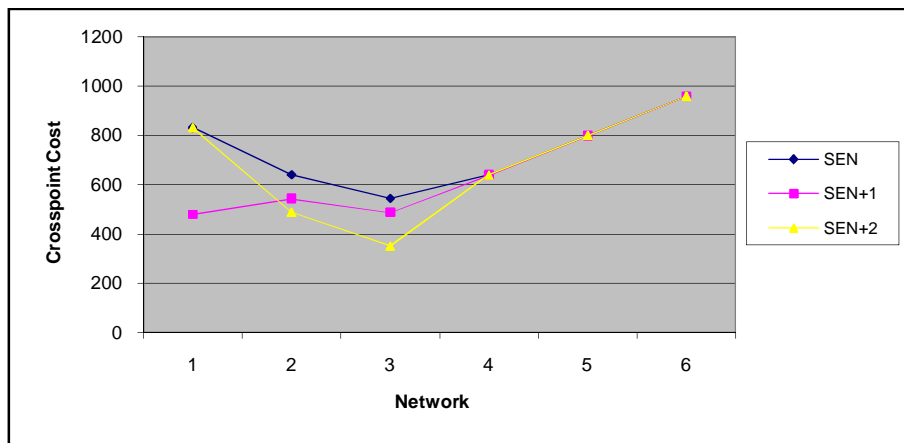


Figure 21: 4 Crosspoint Cost comparison with 4 layers in Last Stage

5.2.5 Buffer Cost of SEN

- First network is Regular Network i.e.1244 in which two values are there G_s and G_F there is no need of G_L . In this layer replicates from stage 1 with the growing factor of 2.

- 1244 and 1124 are the Multilayer Networks. In 1244 replication start from the Stage 1 with the growing factor of 2 till layer limit reaches 4. There is another network i.e. 1124 in which the replication start later.

Table 11: Performance of SEN with 4 layers in last stage

Network	Parameters			Costs
	G_s	G_F	G_L	Buffer
1248	1	2	-	240.H
1244	1	2	4	240.H
1124	2	2	4	192.H
4444	Rep MIN L=4			256.H
5555	Rep MIN L=5			320.H
6666	Rep MIN L=6			384.H

- 4444 is the replicated layer there is no need of G_s, G_L and G_F . There is only one factor i.e. L factor which is replicated factor.

Table 11 shows that the Buffer Cost of 1188 network is less as compare to another network because the replication starts at later stages. The Buffer Cost of replicated MINs is maximum because in this the whole network is replicated.

5.2.6 Buffer Cost of SEN+1

- First network is Regular Network i.e. 111244 in which two values are there G_s and G_F there is no need of G_L . In this layer replicates from stage 1 with the growing factor of 2.

Table 12: Performance of SEN+1 with 4 layers in last stage

Network	Parameters			Costs
	G_s	G_F	G_L	Buffer
11248	1	2	-	240.H
12244	2	2	4	240.H
11124	3	2	4	180.H
44444	Rep MIN L=4			256.H
55555	Rep MIN L=5			320.H
66666	Rep MIN L=6			384.H

- 112244 and 111124 are the Multilayer Networks. In 112244 replication start from the Stage 3 with the growing factor of 4 till layer limit reaches 4. There is another network i.e. 111124 in which the replications start later i.e. from the 4 stage and replicated till layer limit reaches to 4.
- 444444 is the replicated layer there is no need of G_s, G_L and G_F . There is only one factor i.e. L factor which is replicated factor. It is replicated with $L=4$.

Table 12 shows that the Crosspoint Cost of 111124 networks is less as compare to another network because the replication starts at later stages. The Buffer Cost of replicated MINs is maximum because in this the whole network is replicated.

5.2.7 Buffer Cost of SEN+2

- First network is Regular Network i.e. 111244 in which two values are there G_s and G_F there is no need of G_L . In this layer replicates from stage 1 with the growing factor of 2.
- 112244 and 111124 are the Multilayer Networks. In 112244 replication start from the Stage 3 with the growing factor of 4 till layer limit reaches 4. There is another network i.e. 111124 in which the replication start later i.e. from the 4 stage and replicated till layer limit reaches to 4.

Table 13: Performance of SEN+2with 4 layers in last stage

Network	Parameters			Costs
	G_s	G_F	G_L	Buffer
111248	1	2	-	240.H
112244	3	2	4	180.H
111124	4	2	4	144.H
444444	Rep MIN L=4			256.H
555555	Rep MIN L=5			320.H
666666	Rep MIN L=6			384.H

- 444444 is the replicated layer there is no need of G_s, G_L and G_F . There is only one factor i.e. L factor which is replicated factor. It is replicated with L=4.

Table 13 shows that the Buffer Cost of 111124 networks is less as compare to another network because the replication starts at later stages. The Buffer Cost of replicated MINs is maximum because in this the whole network is replicated.

5.2.8 Comparison of SEN, SEN+1and SEN+2 on the Basis of Buffer Cost with 4 layers at the end

From Figure 22 it is clear that the Buffer Cost of the SEN+2 is less as compare to the SEN+1 and SEN because the data stored in buffer should be less due to the network size because the layering should be done at the later stages and that are not possible in the SEN and SEN+1.

Whereas the SEN+1 show the better result as compare to the SEN because it has one more stage than the SEN so replication at the latter stages are possible.

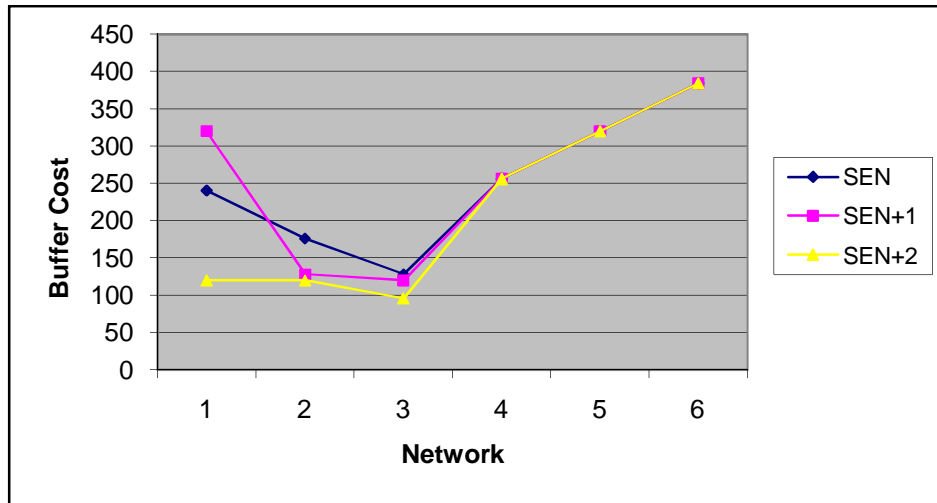


Figure 22: Buffer Cost comparison with 4 layers in Last Stage

MultilayerMINs also show better performance in SEN+2 as compare to the SEN+1 and SEN. Whereas Replicated MINs show least performance in term of Buffer cost.

6.1 Conclusion

The present dissertation work was aimed to explore the field of Multilayer MINs, which is a most important parameter to analyse the performance in term of Crosspoint Cost and Buffer Cost of SEN networks. The work was carried out using different SEN network and Regular, Replicated and Multilayered architecture of on SEN, SEN+1 and SEN+2.

The conclusion drawn from the present study includes:

1. Multilayer MINs of SEN+2 show better performance in Crosspoint Cost and Buffer Cost than SEN+1 and SEN, which has more number of stages than the SEN and SEN+1.
2. Multilayer MINs Crosspoint Cost and the Buffer Cost decreases by increasing the stages. Whereas Replicated MINs show poor performance in SEN networks.
3. Comparing various MLMINs architectures, it is observed that the most powerful architecture consist of a layer growth factor equal to the switching element size. A structure in which growth at stage1 should be preferred.

6.2 Summary of Thesis

The work done in this thesis is summarized as:

- i. Study the Multistage Interconnection Network and its architecture.
- ii. Design SEN+1 and SEN+2 by adding extra stages in existing SEN networks.
- iii. Analyse the behavior of the Regular, Replicated and Multilayered MINs.
- iv. Compute the Crosspoint Cost and Buffer Cost of SEN networks on the basis of Regular, Replicated and Multilayered MINs.

- v. Compare the performance of various SEN Networks.
- vi. Compare How Multilayer MINs is better than Regular and Replicated.

6.2 Future Work

No work is perfect done for the first time. There is always a scope for the improvement. The field of Multilayer MINs can be further explored in the light of the following suggestions:-

- An investigation of the influence of buffer size on the optimal number of network layers must be performed.
- Dealing with various kinds of network traffic will also help to characterize MLMINs in more detail.

References

- [1] A.Varma and C.S.Raghavendra, “Interconnection Networks for Multiprocessors and Multicomputer, Theory and Practice”, *IEEE Computer Press*, 1994.
- [2] J.Sengupta, “Interconnection networks for parallel processing”, Nutech Books, Deep and Deep publications, New Delhi, (ISBN-81-7629-736-4), pp. 7-8, 15-19, 42-45, 69-70, 2005.
- [3] C.P. Kruskaland M. Shir, “Performance of Multistage Interconnection Networks for Multiprocessors”, *IEEE transactions on computers*, vol. C-32, 1983 December.
- [4] N. Laxmi Bhuyan, Q. Yang and P. Dharma Aggarwal, “Performance of Multiprocessor Interconnection Networks”, In *Proceeding of Intelligent systems and technologies for the new millennium*, pp. 25-37, 1989.
- [5] A.Subramanian and Nitin, “On a performance of Multi-stage Interconnection Network”, In *Proceedings of the 10th WSEAS International Conference on Computers*, pp.73-79, December 2004.
- [6] I. Gunawan, “Reliability analysis of shuffle-exchange network systems”, *Reliability Engineering and system safety*, pp. 271–276, 13 October 2006.
- [7] J.H. Patel, “Performance of processor–memory Interconnections for Multiprocessors”, *IEEE Transaction on Computers*, vol. C–30, no.10, pp.771–780, October 1981.
- [8] J.T.Blake and K.S. Trivedi, “Multistage Interconnection Network reliability”, *IEEE Transaction on Computer*, vol.38, no.11, pp.1600–1604, 1989.
- [9] B.L.Menezes and U.Bakhru, “New bounds on the reliability of augmented Shuffle-exchange networks”, *IEEE Transaction on Computers*, vol. 44, no.1, pp.123–129, 1995.
- [10] J.L.Trahan, D.X.Wang and S.Rai, “Multimode failures in reliability evaluation of extra-stage shuffle-exchange MINs”, *IEEE Transactions on Reliability*, vol.44, no.1, pp.73–86, 1995.

- [11] K.Y.Lee and W.Hegazy, "The Extra Stage Gamma Network", *IEEE Transaction on Computers*, vol.37,no.11,pp.1445–1449,1988.
- [12] C. P. Kruskal and M. Snir, "The performance of Multistage Interconnection Networks for Multiprocessors", *IEEE Transactions on Computers*, vol. C– 32, no. 12, pp.1091–1098, 1983.
- [13] D. Tutsch and M. Brenner, "Multicast probabilities of Multistage Interconnection Networks", *In Proceedings of the 12th European Simulation Symposium 2000 (ESS'00)*; Hamburg, pp. 554–558,2000.
- [14] D. Tutsch, M.Hendler and G. Hommel, "Multicast performance of Multistage Interconnection Networks with shared buffering", *In Proceedings of the IEEE International Conference on Networking(ICN 2001)*, pp. 478–487, July 2001.
- [15] C. Wu and T.Y. Feng, "On a class of Multistage Interconnection Networks", *IEEE transactions on Computers*, pp. 1145–1155, 1980.
- [16]D. Tutsch and G.Hommel, "Multilayer Multistage Interconnection Networks", Available at:http://scholar.google.co.in/scholar?cluster=13421100522468729844&hl=en&as_sdt=2000.
- [17] C.P. Kruskal and M. Snir, "The performance of Multistage Interconnection networks for Multiprocessors", *IEEE Transactions on Computers*, vol. C–32, no.12, pp.1091–1098, 1983.
- [18] T. Soumiya, K. Nakamichi, S. Kakuma, T. Hatano and A. Hakata, "The large capacity ATM backbone switch", *Computer Networks*, vol.31, no.6, pp.603–615, 1999.
- [19] R.Y. Awdeh and H.T. Mouftah, "Survey of ATM switch architectures", *Computer Networks and ISDN Systems*, vol. 27, pp.1567–1613, 1995.
- [20] D.M. Dias and J. Robert Jump, "Analysis and simulation of buffered delta networks", *IEEE Transactionson Computers*, vol.C–30, no.4, pp.273–282, April 1981.
- [21] V.E. Benes, "Optimal rearrange able multistage connecting Networks", *Bell System Technology Journal*, vol.43, pp. 1641–1656, March 1964.

- [22] K. Hwang and F.A. Bridge, "Computer architecture and parallel processing", McGraw Hill book company, New York, 1985.
- [23] V.P. Kumar and S.M. Reddy, "Augmented Shuffle Exchange Multistage Interconnection Network", *Proceeding of International Computer*, vol. 20, pp. 30-40, 1987.
- [24] P.K. Bansal, K. Singh and R.C. Joshi, "On Fault tolerant Multistage Interconnection Network", *Conference on Computer and Electrical Engineering*, vol. 20, no.4, pp. 335-345, 1994.
- [25] S. Sibal and J. Zhang, "On a class of banyan networks and tandem banyan switching fabrics", *IEEE Transactions on Communications*, vol.43, no.7, pp.2231–2240, July 1995.
- [26] H. Xu, Y. Gui and L.M. Ni, "Optimal software multicast in wormhole-routed multistage Networks", *IEEE Transactions on Parallel and Distributed Systems*, vol. 8, no.6, pp.597–606, June 1997.
- [27] A.K. Katangur, Y. Pan, and M. D. Fraser, "Message Routing and Scheduling in Optical Multistage Networks Using Simulated Annealing", *Proceedings of the International Parallel and Distributed Processing Symposium (IPDPS2002)*, pp. 201-208, 2002.
- [28] F.A. Tobagi, T. Kwok and F.M. Chiussi, "Architecture, performance and implementation of the tandem-banyan fast packet switch", *IEEE Journal on Selected Areas of Communication*, vol.9, no.8, pp.1173–1193, October 1991.
- [29] R. Aggarwal and H. Aggarwal, "Performance Analysis of Regular and Irregular Multistage Interconnection Networks", *International Journal of Information and Computing Science*, vol. 11, no. 2, Dec 2008.
- [30] R. Aggarwal and L. Kaur, "Design Scheme and Performance evaluation of a new Fault-tolerant Multistage Interconnection Network", *International Journal of Computer Science and Network Security*, vol. 9, no.9, pp.270-276, September 2009.

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- 1) Khushboo Bansal and Rinkle Aggarwal, "Behaviour Analysis of Multilayer Multistage Interconnection Networks with Extra Stages", "International Journal of Applied Engineering Research", vol 7,no.3, pp.947-958,June 2011.