CHAPTER 2

Review of Multistage Interconnection Networks

This chapter provides an overview of various Multistage Interconnection Networks. It also carries the review of existing literature on the subject that has been undertaken to find the gaps in the research.

2.1 Introduction

Much of the literature available on the subject proposes many different networks between the extremes of single bus and the cross bar to solve the problem of providing fast, reliable and efficient communication at a reasonable cost in large parallel processing systems. Such interconnection networks can be constructed from single or multiple stages of switches. In a single stage network, data may have to be passed through the switches several times before reaching the final destination. In multistage network, one pass of multistage stages of switches is usually sufficient. The way input units are connected with the output units, determine the functional characteristics of the network, i.e., the allowable interconnections.

2.2 Construction and Performance of MINs

2.2.1 Cube Interconnection Networks

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. 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.
The implementation of a single stage cube network is given in Figure 2.1 for 8 nodes. The interconnection of the switching elements, corresponding to three routing functions is shown separately in Figure 2.2.

**Figure 2.1: A Three-dimensional Binary Cube**

![Diagram of a three-dimensional binary cube with nodes labeled 0 to 7.]

**Figure 2.2: The Recirculating Cube Network for N = 8**

The same set of cube routing functions, $c_0$, $c_1$, $c_2$ can also be implemented by using a three stage cube network. Two functions switch boxes, i.e., straight and exchange are used in constructing multistage cube network. The stages are numbered as 0 at input end and increased to n-1 at output. The stage i implements $c_i$ routing function.
for \( i = 0, 1, 2 \ldots (n-1) \). So, switch box at stage \( i \) connects an input line to output line that differs from it only at \( i \)th bit position as shown in Figure 2.3. The generalized cube network is a multistage cube-type network topology that was introduced as a standard for comparing network topologies (Siegel and McMillen, 1981). The Generalized Cube Network of size 8x8 is exhibited in Figure 2.4.

Figure 2.3 : A Multistage Cube Network for \( N = 8 \)

Figure 2.4 : Generalized Cube Network with \( N = 8 \)
2.2.1.1 Extra Stage Cube (ESC)

The Extra Stage Cube, a fault-tolerant multistage interconnection network, was proposed by Adams and Siegel (1982) for use in large-scale parallel and distributed supercomputer systems. It has all the interconnecting capabilities of the multistage cube-type networks that have been proposed for many super systems. The ESC network is derived from the Generalized Cube with one additional stage along with a number of multiplexers and demultiplexers. The ESC is capable of operating in both SIMD and MIMD environments. The extra stage provides an additional path from each source to each destination. The ESC is a single fault-tolerant (Adams, et al., 1984). An ESC of size 8x8 is shown in Figure 2.5.

![Extra Stage Cube Network of 8x8](image)

**Figure 2.5 : Extra Stage Cube Network of 8x8**

2.2.2 Shuffle Exchange Network

Shuffle exchange network is based on two routing functions, shuffle and exchange. A perfect shuffle of N = 8 is presented in Figure 2.6 (a). Perfect shuffle cuts the deck into two halves from the center and then intermixes them evenly. Inverse
perfect shuffle does the opposite to restore the original ordering as shown in Figure 2.6 (b). These shuffle exchange functions can be implemented as either recirculating network or a multistage network. Figure 2.7 produces a single stage recirculating shuffle exchange network.

(a) Perfect Shuffle (b) Inverse Perfect Shuffle

Figure 2.6 : (a) Perfect Shuffle (b) Inverse Perfect Shuffle

Figure 2.7 : Shuffle Exchange Recirculating Network for N = 8

A multistage SEN has $N = 2^n$ inputs, termed sources (S), and $2^n$ outputs, termed destinations (D). It has $n$ stages and each stage has $N/2$ switching elements. There is a unique path between each source-destination pair. Figure 2.8 exhibits a SEN of size 8 x 8. The SEN is a self-routing network (Blake and Trivedi, 1988b). That is, a message
from any source to a given destination is routed through the network according to the binary representation of the destination's address. For example, if source $S = 000$ wants to send a message to destination $D = 101$, the first bit of the destination address is used by $SE_{0,1}$ for routing. So output link 1 of $SE_{0,1}$ is used for routing. At $SE_{1,2}$ the second bit of $D$ is used and output link 0 of $SE_{1,2}$ is used. Finally, at $SE_{2,3}$ the third bit of $D$ is used and output link 1 of $SE_{2,3}$ is selected as shown in Figure 2.9.

\[\text{Figure 2.8 : Shuffle Exchange Network (SEN) of Size 8x8}\]

\[\text{Figure 2.9 : Routing in SEN for Communication Between } S = 000 \text{ and } D = 101\]
2.2.3 SEN with an Extra Stage (SEN+)

A SEN+ is an NxN SEN with an additional stage (Blake and Trivedi, 1988a). The SEN+ system has N inputs and N outputs, with two paths between each source–destination pair. It has \( n = (\log_2 N) + 1 \) stages and each stage has \( N/2 \) SEs. In general, the switch complexity for the \( N \times N \) SEN+ is \( N/2 ((\log_2 N)+1) \). Thus, the additional cost of SEN+ is \( N/2 \) switches or a fractional increase of \( 1/\log_2 N \), which is small for a large \( N \). Figure 2.10 demonstrates a SEN+ of size 8x8.

![Figure 2.10 : SEN with an Extra Stage (SEN+) of Size 8x8](image)

The addition of an extra stage to the SEN allows two paths for communication between each source and destination (Gunawan, 2008b). A comparison of reliability using the mean-time-to-failure by Blake and Trivedi (1988a) showed that SEN+ is superior to SEN. Gunawan (2008b) compared three types of shuffle exchange network (SEN) systems: SEN, SEN with an additional stage (SEN+), and SEN with two
additional stages (SEN+2). As measures of network performance, the terminal, broadcast, and network reliability of these three networks were evaluated. It was observed from the numerical results that the terminal reliability of SEN+ is the highest among the three networks. Although the number of broadcast paths in SEN+2 is greater than that of SEN+, the broadcast reliability of SEN+2 is the lowest among these three networks. From this evaluation, it was concluded that SEN+ is the most reliable network in terms of broadcast reliability. Similar conclusions were drawn for the network reliability of the three systems. That is, SEN+ has the highest, while SEN+2 has the lowest reliability.

2.2.4 Augmented Shuffle Exchange Network (ASEN-2)

Augmented Shuffle Exchange Network (ASEN-2) is a regular network, having equal number of switches in each stage. ASEN-2 network is constructed from Shuffle Exchange network by adding 2×1 multiplexers at the initial stage and 1×2 demultiplexers at the last stage (Kumar and Reddy, 1987). It provides multiple paths between any source and destination pair. The ASEN-2 shown in Figure 2.11 has a loop size of two in every stage except the last one. Therefore, this network is called ASEN-2. Switches that differ in the second most significant bit of their binary labels form the loops in ASEN-2. In general, an ASEN in which the number of switches in a loop in $i^{th}$ stage is equal to $\text{Min} (2^{n-2-i}, K)$ is called ASEN-K. Blake and Trivedi (1988a) showed that on the basis of reliability, ASEN-2 is superior to SEN and SEN+. 
2.2.5 Omega Network

The shuffle exchange has been implemented with multistage Omega network. Figure 2.12 presents an Omega network for $N=8$. An $N \times N$ Omega network consists of $\log_2 N$ identical stages and between two stages there is a perfect shuffle interconnection (Bhuyan, 1987). This network maintains a uniform connection pattern between stages. Every input terminal has a unique path to every output terminal, and exhibits the property of self-routing, i.e., routing is performed in a distributed manner using destination address as the routing tag.
Sengupta and Bansal (2001) introduced a new fault-tolerant multistage interconnection network named as Phi Network (PHN). PHN is an altered Omega network retaining lesser number of switching elements (SEs) in the intermediary stages, consisting of N/2 SEs of size 2x2 in the input and output stage, whereas the intermediate stages consist of N/4 SEs of size 3x3. A Phi Network of size N x N, having N sources and N destinations in \( n = \log_2 N \) stage network, comprises of two groups, denoted as \( G_i \). The input stage 1 has N/2 2x2 SEs, and intermediary (\( n-2 \)) stages have varying number of 3x3 SEs, interconnected through express links. Each of the N sources is connected to both the groups through N 2x1 multiplexers before the input stage and N 1x2 demultiplexers to the N destinations after the output stage. Stages are numbered as 1, 2, \ldots, (\log_2 N), while switches in a group are numbered from top to bottom.
bottom chronologically as 0, 1, ... (N/4^i-1) for the ith stage. The express links have a marked dominance on the fault-tolerance of PHN. Thus irregular PHN provides different routes of differing path lengths providing much lower latency as compared to the Omega Network. Figure 2.13 shows a PHN for N=8.

![Figure 2.13: Phi Network (PHN) of Size 8x8](image)

2.2.7 Double Tree (DOT) Network

A DOT network is an irregular type of MIN. It consists of a right and a left half. Each half of the network resembles a binary tree. The left and right trees are mirror images of each other. A DOT network of size 2^n x 2^n has 2^n input and 2^n output terminals and 2n-1 number of stages (Mittal et al., 1995). Further, it has 2^{n+1}-3 switching elements (Bansal et al., 1991b). Each of the stages i and 2n-i have exactly 2^{n-i} switching elements of size 2x2 for i = 1,2,3,...,n. A DOT network of size 8x8 is shown in Figure 2.14. Kumar (2007) proposed a new mathematical model for performance evaluation of the buffered Fault Tolerant Double tree packet switching network under uniform traffic.
condition. An algorithm to implement this model is also presented and results obtained are compared with the results of simulation. It has been shown that as the size of network increases, throughput decreases and delay increases.

![Double Tree (DOT) Network of Size 8x8](image)

**Figure 2.14**: Double Tree (DOT) Network of Size 8x8

### 2.2.8 Modified Double Tree Network (MDOT)

MDOT is an example of non-fault-tolerant irregular network, having different number of switches at each stage. Figure 2.15 exhibits a modified double tree network for N = 8. Total number of stages in this type of network are 2n-1, where n = log2N and the number of switching elements are 2^n+1-3 (Aggarwal and Bansal, 2002). The number of switching elements at the last and first stage is equal. Similarly, number of switching elements in the next stages is equal.
2.2.9 Fault-tolerant Double Tree (FDOT) Network

An FDOT-k network of size NXN introduced by Bansal et al. (1991b) is designed by dividing N inputs and N outputs into k disjoint partitions of N/k sources and N/k destinations, where k >=2 and N >k, are the powers of 2. There are k independent subnetworks, and an extra one, such that a connection path between each source-destination pair can be established via any one of the subnetworks. All the (k+1) subnetworks are of identical type. The extra subnetwork helps to enhance fault-tolerant capability and to keep a desired level of performance even in the presence of faults. Each source and destination is linked to all the (k+1) subnetworks via kx1 multiplexers and 1xk demultiplexers. An FDOT-k consists of (2n-1) number of stages and (k+1) (2n+1-3) number of switching elements, where n = log₂(N/k). FDOT network of size 8x8 is shown in Figure 2.16. FDOT provides full access capability in the presence of multiple faults. Bansal et al. (1991b) found that
FDOT supports on-line repairability and is cost-effective than other fault-tolerant multistage interconnection networks, namely, INDRA, ESC and 3-Rep.

Figure 2.16: Fault-tolerant Double Tree (FDOT) Network of Size 8x8

2.2.10 Extra Group Network (EGN)

Wei and Lee (1988) introduced a new class of fault-tolerant multistage interconnection networks named as Extra Group Networks (EGNs). An EGN is designed by dividing N sources and N destinations into several disjoint partitions. There are several independent subnetworks (groups), one for each partition and the extra one, such that a connection path of each source-destination pair can be established via any one of the groups. The extra group helps to enhance fault-tolerant capability and to keep a desirable level of performance even in the presence of faults. Thus, an EGN of size N has one mlx multiplexer stage (input stage), \( \log_2(N/m) \) stages (intermediate stages) of 2x2 crossbar switches, and one 1xm demultiplexer stage (output stage) as shown in
Figure 2.17. There are $N/2+N/2m$ switches in each of the intermediate stages, $N+N/m$ multiplexers in the input stage, and $N+N/m$ demultiplexers in the output stage. Each unique $m$-path network of size $N/m$ plus its associated multiplexers and demultiplexers will be called a group. These groups including the extra one will be denoted by $G^0, G^1, \ldots, G^m$. The EGN is more reliable and cost-effective than existing networks SEN and INDRA.

Figure 2.17 : Extra Group Network (EGN) of Size 8x8

2.2.11 Augmented Baseline Network (ABN)

Bansal et al. (1991a) introduced a new class of fault-tolerant multistage interconnection networks named as Augmented Baseline Networks (ABNs). An ABN is
a baseline network with two less stages, additional intra-stage auxiliary links, multiplexers, demultiplexers, and slightly more complex switches. The ABN is more reliable and cost-effective than baseline. Figure 2.18 shows an Augmented Baseline Network (ABN) of size 16x16.

![Figure 2.18: Augmented Baseline Network (ABN) of Size 16x16](image)

Liu et al. (2002) proposed a new type of MIN called Advanced Baseline Network by using 4x4 switches instead of 2x2 switches. The Advanced Baseline Network has simple routing technique and better performance but increased cost.

### 2.2.12 Four-Tree (FT) Network

An NxN FT is constructed by using two identical groups each consisting of MDOT network of size N/2xN/2, which are arranged one above the other (Aggarwal
and Bansal, 2002). Both the stages $i$ and $2m-i$ in the group have $2^{n+i}$ switches (where, $i = 1, 2, 3, \ldots, m$, $m = \log_2 N/2$, and $N = 2^n$). The switches in a stage having the same number are chained together to form a loop, except the last stage. Each source and destination is connected with multiplexers and demultiplexers as shown in Figure 2.19.

![Figure 2.19: Four-Tree (FT) Network of Size 16x16](image)

### 2.2.13 Quad Tree (QT) Network

Bansal et al. (1992a) introduced a new fault-tolerant multistage interconnection network named as Quad Tree (QT). An $N \times N$ QT is constructed by using two identical groups each consisting of MDOT network of size $N/2 \times N/2$, which are arranged one above the other as depicted in Figure 2.20. All the SEs are $3 \times 3$ in size except the ones in the last stage which are $2 \times 2$. Each source and destination is connected to both the groups through multiplexers and demultiplexers. The delay of the network is directly proportional to the path length encountered on the way to the destination.
2.2.14 Zeta Network (ZTN)

The idea of QT Network is used in the designing of a 16 x 16 multipath ZTN (Nitin, 2006). ZTN has extra SEs in intermediate stages with additional express chaining links to provide better fault-tolerance to the network. A ZTN of size $2^n \times 2^n$, $n = \log_2 N$, and $m = \log_2 (N/2)$ for $2^n$ sources and $2^n$ destinations, is constructed with the help of two identical groups $G^N$ [where, $N = 0, 1$], each consisting of a DOT network of size $2n-1 \times 2n-1$, which are arranged one above the other. Figure 2.21 shows a ZTN of size 16x16. The two groups are formed based on the most significant bit (MSB) of the source-destination terminals. Each source and destination is connected to both groups with the help of MUX and DEMUX. Nitin and Subramanian (2006) found that the reliability and cost-effectiveness analysis of the hybrid ZTNs with ABNs and QTNs shows a remarkable improvement in reliability.
2.2.15 Gamma Interconnection Network (GIN)

A GIN of size $N = 2n$ has $n + 1$ stages being labeled from 0 to $n$ and each stage involves $N$ switches (Parker and Raghavendra, 1984). Basically, switches of sizes 1x3 and 3x1 are coupled with the first and last stage respectively. Moreover, each switch located at intermediate stages is a 3x3 crossbar. And each switch number $j$ at stage $i$ has three output links connecting to switches at stage $(i + 1)$ according to the plus-minus-$2^i$ function. In other words, the $j$th switch at stage $i$ has three output links to switches $[(j - 2^i) \mod N], j,$ and $[(j + 2^i) \mod N]$ at each consecutive stage. Figure 2.22 illustrates a GIN network with size 8x8.
Furthermore, to improve the fault-tolerant capability of GIN, several schemes have been introduced, such as extra stage gamma network (Yoon and Hegazy, 1988), CGIN (Chuang, 1996), composite banyan (Seo and Feng, 1995), PCGIN, FCGIN (Chen et al., 2000) and B-network (Lee and Yoon, 1990). Among them, extra stage gamma, CGIN, composite banyan network, FCGIN and PCGIN can provide at least 2-disjoint paths. On the other hand, FCGIN and B-network use dynamic rerouting to tolerate faults, but B-network cannot guarantee one-fault tolerant whereas FCGIN is one-fault tolerant. Chen et al., (2003) proposed a new 3-disjoint path network namely, 3-disjoint GIN (3DGIN). This 3DGIN can tolerate two links or switch faults, and its hardware cost is almost equal to GIN.

2.3 Literature Review of Multistage Interconnection Networks

Many researchers have worked on Multistage Interconnection Networks. Some of the most promising works have been presented in Table 2.1.
<table>
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<tr>
<th>S. No.</th>
<th>Citation</th>
<th>Main Contribution</th>
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<tbody>
<tr>
<td>1.</td>
<td>Adams and Siegel, 1984</td>
<td>In this paper, a survey of existing networks, namely, Extra Stage Cube, Delta Network, Modified Baseline Network, Data Manipulator and Gamma Network was made. Network characteristics such as degree of fault-tolerance, routing and permutation capability have been discussed.</td>
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<tr>
<td>2.</td>
<td>Adams and Siegel, 1982</td>
<td>This paper presented the Extra stage cube (ESC) Multistage Interconnection network, derived from the Generalized Cube by the addition of one extra stage of interchange boxes and a bypass capability for two stages. It is shown that the ESC provides fault-tolerance for any single failure.</td>
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<td>3.</td>
<td>Bansal et al., 1994</td>
<td>This paper introduced a class of fault-tolerant MINs named as Augmented Baseline Networks (ABNs). Performance and reliability analysis has shown that ABNs are more reliable and cost-effective than baseline.</td>
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<tr>
<td>4.</td>
<td>Bansal et al., 1991a</td>
<td>This paper introduced a new fault-tolerant Multistage Interconnection Network named as Augmented Baseline Network (ABN). Performance of ABN is analyzed and compared with Omega and Crossbar networks.</td>
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<tr>
<td>5.</td>
<td>Bansal et al., 1991b</td>
<td>This paper presented a new fault-tolerant MIN named as Fault-tolerant Double Tree (FDOT) network. Performance of FDOT is analyzed and compared with ESC, INDRA and 3-Rep networks. It has been shown that FDOT is more reliable.</td>
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</table>
This paper introduced a new fault-tolerant MIN named as Quad Tree (QT). It has been shown that QT is single switch fault-tolerant and is more cost-effective than ESC, INDRA and ASEN-2 networks.

This paper described the basics of parallel systems, classification of interconnection networks and basic terminologies for performance evaluation of interconnection networks.

8. Bhuyan, 1987  
This article was a first attempt to survey fault-tolerant networks. It compared the properties of different networks and provided the reader with the state of the art in this area.

9. Blake and Trivedi, 1988a  
In this paper, authors compared the reliabilities of two fault-tolerant multistage interconnection networks; one relies on an extra stage for increased reliability, the other uses intra-stage links. A comparison of the mean-time-to-failure and cost of SEN+ and ASEN networks was presented, and it was shown that on the basis of reliability, ASEN is superior to SEN and SEN+.

10. Blake and Trivedi, 1988b  
In this paper, a transient reliability analysis of the SEN and SEN+ networks has been performed. Exact closed-form expressions for the reliability of 8x8 and 16x16 SEN and SEN+ networks were derived. A comparison of the mean-
<table>
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<th>No.</th>
<th>Author(s) and Year</th>
<th>Description</th>
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<tbody>
<tr>
<td>11.</td>
<td>Chen and Chung, 2005</td>
<td>This paper presented a fault-tolerant network called CSMIN with two disjoint paths between any source-destination pair to guarantee one fault-tolerance. CSMIN has the ability to switch packets between these two routing paths at each stage and keeps low rerouting hops (one rerouting hop on average), the collision ratio of CSMIN is lower than GIN, B-network and CGIN. CSMIN has advantages over other related disjoint paths networks (GIN, CGIN, B-network) in both re-routability and fault-tolerance capability.</td>
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<td>12.</td>
<td>Chen and Fu, 2004</td>
<td>This paper presented a minimal links traversed dynamic rerouting network called MinGIN. MinGIN provided the dynamic rerouting method to guarantee one fault-tolerance. Moreover, MinGIN needs 0 rerouting hops to find an alternative path. Because of the property of 0 rerouting hops, MinGIN presented better fault-tolerance and throughput than other fault-tolerant networks, viz. GIN, CGIN and B-networks.</td>
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<tr>
<td>13.</td>
<td>Cheng and Ibe, 1992</td>
<td>This paper considered the reliability of extra-stage interconnection networks. Three types of reliability, namely, terminal, network and broadcast are analyzed.</td>
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<td>14.</td>
<td>Das et al., 1998</td>
<td>This paper presented an $O(Nn)$ algorithm that checks whether a given permutation $P$ is admissible in an $m$ stage SEN, $1 \leq m \leq n$, and determines in $O(Nn \log n)$ time the minimum time-to-failure of these networks showed that on the basis of reliability, the SEN+ is superior to the SEN.</td>
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<td><strong>15.</strong></td>
<td>Das and Das, 1997</td>
<td>In this paper the restriction on the size of MIN has been removed and a new NxN generalized shuffle-exchange (GSE) with ( \log N ) stages has been introduced. It has been shown that the GSE is a full access MIN, which can interconnect any number of processors at minimum cost. Routing in GSE is simple.</td>
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<td><strong>16.</strong></td>
<td>Gupta and Bansal, 2008</td>
<td>This paper provides fundamentals of interconnection networks. A survey of static (Baseline Network, Shuffle Exchange Network, Delta Network, Generalized Shuffle Exchange Network, Data Manipulator Network, Indirect Binary n-Cube Network and Butterfly Network) and dynamic multistage interconnection networks (Alpha Network, Phi Network, Augmented Shuffle Exchange Network, Augmented Baseline Network and Quad-Tree Network) has been carried out.</td>
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<td><strong>17.</strong></td>
<td>Gunawan, 2008a</td>
<td>The reliability bounds methodology presented in this paper provides reasonable and simple estimates for reliability of a complex large-scale gamma network. The reliability block diagrams of a gamma network are designed and utilized to obtain a lower and upper bounds. An 8x8 gamma network demonstrates the application and accuracy of the proposed methodology.</td>
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<td><strong>18.</strong></td>
<td>Gunawan, 2008b</td>
<td>In this paper, three types of shuffle-exchange network (SEN) systems are compared: SEN, SEN with an additional stage</td>
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<tr>
<td>(SEN+), and SEN with two additional stages (SEN+2). As measures of network performance, the terminal, broadcast, and network reliability of these three networks are evaluated.</td>
<td>19. Kumar and Reddy, 1987</td>
<td>This paper described the structure, topology, redundancy graph and reliability of SEN, ASEN, ASEN-2 and ASEN-MAX MINs.</td>
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<tr>
<td>To provide fault tolerance and improve system reliability and performance, a class of fault-tolerant multistage interconnection networks, called augmented shuffle-exchange networks (ASEN) has been proposed. ASEN are gracefully degradable; although an individual component failure reduces ASEN performance, it does not cause a total network failure. The paper analyzed how these component failures affect ASEN performance.</td>
<td>20. Kumar and Reibman, 1989</td>
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<td>On the basis of the idea of Delta and Baseline networks, a new type of MIN, Advanced Baseline is proposed in this paper. The new network is designed using 4 x 4 switches. This paper expounds its topological properties, routing technique and compares the performance of the Advanced Baseline with that of the existing Crossbar, Delta and Baseline networks. It has been shown that the performance/cost ratio of the Advanced Baseline network is obviously superior to that of Crossbar, Delta and Baseline networks.</td>
<td>21. Liu et al., 2002</td>
<td></td>
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<tr>
<td>On the basis of the idea of Delta and Omega networks, a new</td>
<td>22. Mahajan and Vig, 2008</td>
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</table>
type of MIN, Advanced Omega is proposed in this paper. The new network is designed using 4 x 4 switches. This paper expounds its topological properties, routing technique and compares the performance of the Advanced Omega with that of the existing Omega Network.

| 23. | Nitin and Subramani-an, 2006 | The reliability and cost-effectiveness analysis of the hybrid Zeta, ABN and QT MINs has been made and compared in this paper. |
| 24. | Nitin, 2006 | This paper presented a new irregular MIN, viz. ZTN, which is constructed from two identical DOT networks. The reliability bound analysis of ZTN has been made and compared with the existing ASEN-2 network. |
| 25. | Nitin et al., 2009 | This paper provides a more comprehensive and accurate algorithm that always generates correct routing-tags for two disjoint paths for every source-destination pair in the existing CSMIN. The CSMIN has been modified to design new Fully Chained CSMIN in order to reduce the cost. |
| 26. | Sengupta and Bansal, 1999 | In this paper, Fault-tolerant behavior of an irregular network, Quad Tree has been analyzed and compared with a regular network, Augmented Baseline Network, under fault-free conditions and in the presence of faults. |
| 27. | Sengupta and Bansal, 1998 | Efficient and simple routing algorithms have been developed for two Irregular MINs, viz. MFDOT and QT. Static routing provides full access for MFDOT, whereas minimal multiple
paths to reach the destination are provided through dynamic routing in QT network.

<table>
<thead>
<tr>
<th>28.</th>
<th>Sengupta and Bansal, 2001</th>
<th>This paper introduced a new fault-tolerant MIN Phi. Further, the fault-tolerance and performance abilities of the proposed Phi Network are compared with its predecessor, Omega Network.</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.</td>
<td>Sengupta et al., 2000</td>
<td>This paper studies the performance of a well-known regular network, ASEN; irregular network FT; and the proposed new irregular network, Smart Four Tree (SFT). It has been found that the reliability of SFT network is better among these three networks, at the expense of increased cost.</td>
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</table>

### 2.4 Gaps in Existing Research Literature

- Most of the research has been carried out on regular networks. There is a lack of research effort on Irregular MINs.
- Comparative analysis of regular vs irregular MINs is either missing or non-comprehensive.
- For performance analysis, the exact design consideration has not been accounted for. For example, all computations assume the switch size of 2x2.

### 2.5 Chapter Summary

In this chapter, different unique path and multipath Multistage Interconnection Networks, possessing regular or irregular topology, have been examined. Diverse techniques to provide fault-tolerance in MINs have also been investigated. These
investigations provide help in the design of new fault-tolerant, high speed switching networks.

In the next chapter, the Design and Routing of three new fault-tolerant irregular MINs, viz. IASEN, IFT and IABN have been proposed and compared with the existing ones.