Chapter 1. Introduction

Communication technology has significant impact on modern civilization. Incorporation of powerful computers in the communication networks has originated the concept of so called *Information Age*. Service disruption is no longer being tolerated by industries due to increased necessity of communications with bankers, purchasing managers, stock brokers retailers, and so forth. That is why a survivable communication network is now an obvious concept.

Service disruption causes both tangible and intangible losses for users as well as for service providers. To ensure service continuity, service providers have increased their efforts to alleviate such disruption [1]. Therefore, network planners, designers, and researchers are now giving considerable effort to design a survivable network to ensure service continuity. The purpose of this thesis is to tackle the problem of network protection by reviewing the works that have been done, investigating some network topologies and analyzing them. Although ensuring service continuity at affordable cost is a current challenging task, the question of cost is not explicitly considered. This is because the network considered is one specified by the sponsor of this work. Basically two different highly survivable network topologies are studied (the one specified and a slight variant) to investigate different issues of survivability and they are compared with topologies on which studies have been done previously. Finally another interesting regular network topology is introduced which has more regularity than the two topologies (termed topology 1 & 2) which are primarily discussed in this thesis.

1.1 Cause of Network Failure

Network failures can be attributed to hardware or software problems or to natural catastrophes [1]. Among network failures, the cable cut has become a common system failure, according a Bellcore report [2]. Most fiber cable cuts are caused by natural disasters or fiber-optic cables that are inadvertently dug up [2]. A well-known software failure occurred in January 1990 when AT&T's 4ESS switches blocked 65 million long-distance calls for about nine hours [1]. Catastrophic failures due to fire or other natural disasters do not occur very often. However, when they do occur, the impact on user communities is significant.

In this thesis emphasis is given to the usual link cuts or hub (or node) failures. A node failure may occur due to hardware or software problems or catastrophic events.

1.2 Service Survivability Planning

Service survivability planning of a communication network can be classified into four phases [1]. As shown in Figure 1.1 the phases are:

1. Prevention
2. Prompt detection
3. Network self-healing through robust design
4. Restoration

The first phase emphasizes preventing network failures. In this phase, efforts are directed to minimize problems created by people and the environment (e.g. fire). Suggested guidelines for this phase include plans for limited building access, environmental control, fire safety, armored cables, etc.

The second phase focuses on quick detection of network component failures. In distributed routing strategy (either static or dynamic), nodes have routing maps, which lets them know the connected neighboring nodes and to determine the shortest path from source to destination. When a node tries to take that desired shortest route and fails to send traffic through that path, it understands that a component(s) on that route has failed. Then it tries to reroute the traffic in an alternative route according to the rerouting strategy adopted. This detection process should be quick to reduce the latency.

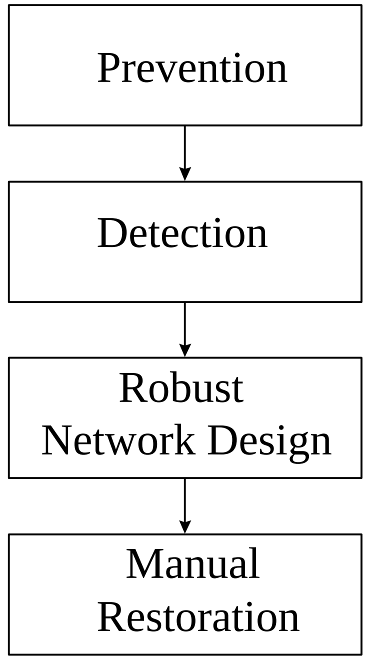

Figure 1.1: Service survivability planning [1].

Phase three focuses on the network self-healing capability during network failure. In the self-healing concept, network protection is built into the network from the beginning, rather than added later. This phase emphasizes building a survivable network that can provide a self-healing capability whenever failures occur and includes survivability strategies, survivable network architecture, and survivable network design. Diversity is the prime factor to give a survivable network architecture. A topology having lots of alternate paths from source to destination is said to have high diversity. Regular network topologies can be adopted to minimize the variance in utilization factors. Considerable effort is devoted in this thesis to determine the survivable topology.

The last phase focuses on planning and practicing restoration in case the network cannot fix the problem itself. Equipment availability, backup procedures, skilled personnel, management responsibility are the factors in this phase. This phase is totally out of the scope of this thesis.

1.3 Terms and Definitions

The survivability of a network is defined as its ability to satisfy certain communication requirements between all pairs of nodes under failure condition [3]. The failure conditions occur when a link or a node failure(s) or a combination of link and node failure takes place. Node survivability is a measure of the ability of the network to satisfy a set of specified communication requirements in the presence of a node failure. Complete node survivability may be defined as the ability of a network to satisfy a set of specified communication requirements between all node pairs excluding node pairs involving the failed node, under all possible single-node failures. A necessary condition for complete node survivability is that no node may lie on all the possible routes between any two nodes in the network [3].

Similarly link survivability is a measure of the ability of the network to satisfy a set of specified communication requirements in the presence of a link failure. Complete link survivability may be defined as the ability of a network to satisfy a set of specified communication requirements between all node pairs under all possible single-link failures. These definitions can be extended for the cases of multiple failure.

Traffic type in a network is another important issue as will be seen in this thesis. Determining the traffic distribution in a network is a very complex process and in most practical cases a standard traffic model is chosen to simulate the network load. But in some cases the standard traffic model may be far from the actual scenario. Statistical methods are used in those cases to determine the nature of the traffic in the network. Needless to say, the traffic distribution is a function of the topology, the relative positions and number of the source and destination nodes and the presence of high, medium or low traffic carrying source-destination node pairs.

Due to the unknown nature of the original traffic type in the network it is easier in most cases to assume the traffic in the network to be uniform. When there exists a single unit of traffic between all possible source-destination node pairs, the network is said to be loaded with uniform traffic. The uniform traffic assumption is useful in providing a general idea about the properties of the network. Throughout the thesis it is assumed that the traffic is uniform. In general the amount of traffic between a source-sink pair is the amount of information carried between them. The measure of traffic is dependent on the switching strategy followed by the system. If a packet switched network is considered then the minimum packet size may be defined as one unit of traffic. If a circuit switched network is considered an arbitrary small amount of time can be considered as the amount of traffic. But for either of the cases we will assume that a direct or virtual connection has been established between the source sink pair prior to initiation of the information transfer. So while routing the information through the pre-established path some specific links and nodes will be utilized. When a unit amount of traffic is routed through a link or a node, it is said that, that particular link or node has been utilized once.

Thus utilization of a node or a link (under uniform loading in our case) is defined as the number of times the node or link in question has been used. The link and node utilization factors are very important in designing a network because we want the network to utilize its nodes and links as uniformly as possible. Four important utilization properties are used throughout this thesis. The first three are the maximum, minimum and average utilization. The fourth property is the standard deviation of utilization. It is desirable that the maximum and minimum utilization factors are close to the average utilization factor, and consequently there is a very small standard deviation.

In both fault-free and faulty cases it is desired to route the traffic through the minimum distance between a source-sink pair. This is because we want smaller delay and also because it is desired to minimize the average traffic per link. Since the network type we are discussing is a LAN, it is assumed that essentially a zero transmission time is required to route information through the links. We also assume that all latencies arise from the intermediate nodes present on the routing path. So we want to choose the routing path in such a way that the minimum number of nodes are encountered. It is interesting to note that the number of intermediate links is also same as the number of nodes. So a route length between a source-sink pair is defined thereby by the number of nodes (or links) a route faces on its way.

Path length is also an important criterion in choosing a network topology. Maximum and average path lengths are investigated for the topologies. For a better network we need both the maximum and average route length to be small. The average route length is a very important property as it is a measure of the overall latency of the network. It is also proportional to the average link and node utilization.

1.4 Overview

In Chapter 2, we define in detail the topologies that we considered. Properties such as average route length and distribution of minimum route length paths for both topologies are explored.

In Chapter 3 we define link and node utilization factors (LUF and NUF). LUF and NUF for both topologies are found and tabulated in the fault-free case.

Chapter 4 gives introductory ideas about network failures and their consequences. Different routing strategies that are adopted under failure condition are discussed. The concept of *Static Disjoint Routing* is introduced. A comparison is made between *Static Disjoint Routing* and *Dynamic Shortest Distance Routing*.

Chapter 5 provides the LUF and NUF under link failure conditions.

In Chapter 6 we compare topology 1 and 2. We also compare these topologies with other standard topologies, such as the full-ring, star and square grid. Star-Ring topology is introduced in this chapter, and also compared with topologies 1 and 2.

In Chapter 7 we give a condensed comparison between the topologies 1 and 2. We also give some idea about the future work that might be done.

Chapter 2. Network Definition

2.1 Literature Survey

Considerable work has been done before in the area of survivability of a communication network. So before discussing the work done by us, we wish to give a very brief description of the work that has been done in this area. H. K. Leung did a comprehensive study [4] to compare the different standard communication network topologies, such as star, mesh, toroidal grid, full ring, and minimum distance ring. He showed how these topologies behave in cost, circuit mileage and capacity when the number of nodes is increased. He also devised a minimum distance routing technique for toroidal grid networks. A comprehensive total cost model was also developed.

A. P. Kulkarni extended the work done by Leung by studying the modified toroidal grid topology [3]. He introduced *link-traffic summation* as a metric of total link capacity requirement of a network. He also extended the work of Leung by considering both uniform and bivalued traffic distribution. In bivalued traffic distribution he considered that nodes might have either low or high workload. He did considerable simulation and analysis to compare the aforesaid topologies.

2.2 Network Definitions

The project titled "Modeling and Simulation of a Shipboard Communication Network", done by Virginia Polytechnic Institute and State University (Virginia Tech) for Newport News Shipbuilding (NNS) gave us the scope to explore the survivability of two special communication network topologies. The communication network will be used in an aircraft carrier, which will be built for the US Navy by NNS. In this project NNS supplied a specific 16-node network topology (topology1), and requested us to investigate its survivability. We introduced another alternative topology (topology 2) and also explored its survivability. We compared both the topologies from different points of view. The network topologies are drawn in Figure 2.1 and Figure 2.3 respectively.

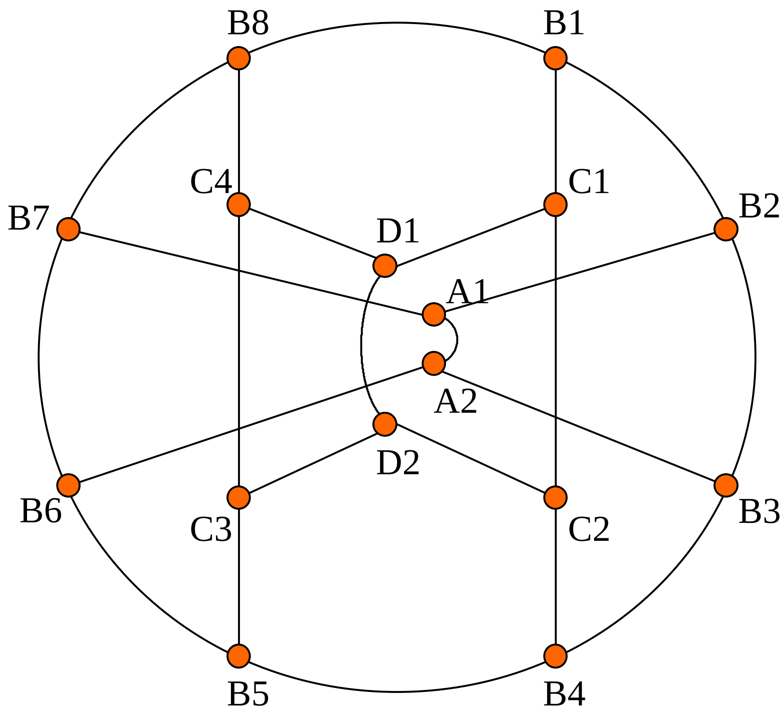

Figure 2.1: Network Topology 1.

Topology 1 is a 16 hub (equivalently node) network with 24 links connecting the nodes. Each link connecting two nodes is comprised of two simplex links. So in one sense it is a 48 simplex link topology. But in this thesis we say that the topologies have 24 links. It is always understood that each link is comprised of two simplex links. The two simplex links are used to route traffic in the opposite directions. In figure 2.2 the two simplex links are shown which exist between nodes B4 and C2.

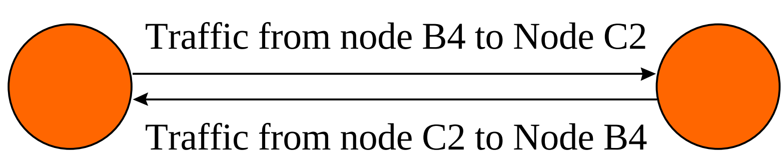

Figure 2.2: Every consecutive node pair has two simplex links connected between them.

We see from Figure 2.1 that there are 8 peripheral nodes and 8 interior nodes. The peripheral nodes are named as B nodes (B1 through B8). According to the relative position the interior nodes are classified into 3 groups, namely A, C and D nodes. We have four C nodes (C1 through C4), two A nodes (A1 and A2) and two D nodes (D1 and D2).

The network has a connectivity of three, which means there are 3 links connecting each node. A network having the same number of links connected to each node is said to be a regular network. The distance between two nodes is defined as the number of links that is traversed while starting from one node and terminating at the other. So the distance between B2 and B3 is 1 when B2-B3 path is traversed, and is 3 when B2-A1-A2-B3 is traversed. We notice that the maximum of the shortest distances in this topology is 5. This is seen when we take D2, A1 or D1, A2 as source-destination pairs. The shortest route between D2 and A1 is D2-C3-B5-B6-A2-A1, a distance of 5 units. We always will try to route information in the shortest possible path in order to reduce the latency.

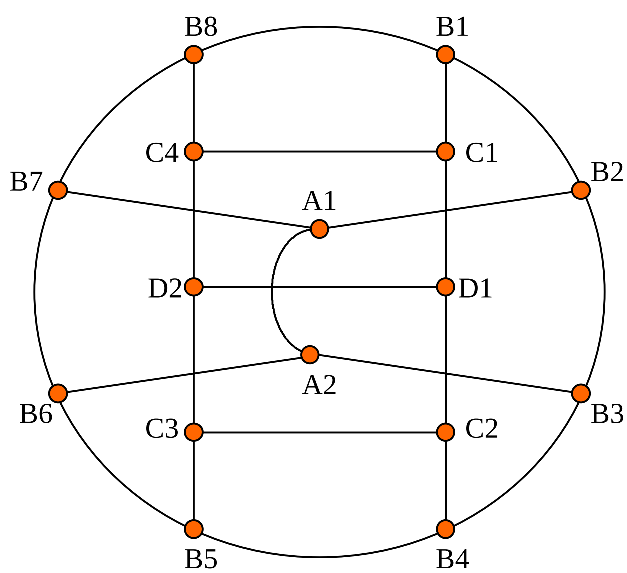

Figure 2.3: Network Topology 2.

In Figure 2.3 the network topology 2 is shown. This is also regular network of connectivity 3 with 16 nodes and 24 links. Like topology 1, this topology has also eight peripheral nodes and eight interior nodes. Names of the nodes are quite similar to that of topology 1. Unlike topology 1 the maximum shortest distance is 4 in this topology. Actually there are 22 node pairs in this topology which are 4-unit distance apart.

2.3 Distribution of the Minimum Distance Node Pairs

In both the topologies there are 16 nodes. So the possible number of source-destination pairs is ${}^{16}P_2 = 240$. In this section we try to find the shortest distance between every possible source-destination pair. This shortest distance will usually be used to route the traffic between that specific source-destination pair in the fault-free case.

Now as we see that both the topologies have 24 links, it is obvious that there are 24 possible source-destination pairs in both the topologies, which are unit distance apart. In the same way we might find the shortest distance between all possible node pairs. It is found that for topology 1 there are 40, 38, 16 and 2 node pairs which are respectively 2,3,4 and 5 unit distance apart. In topology 2 we find that there are 36, 38 and 22 node pairs which are respectively 2, 3 and 4-unit distance apart. Table 1 and 2 shows all possible node-pairs arranged according to the shortest distance for both the topologies.

Table 2.1: All Possible Node Pairs are Tabulated Against the Shortest Distance (Route Length) Between Them for Topology 1.

Shortest Distance Between Node Pairs	Node Pairs
1	(B1,B2), (B1,B8), (B1,C1), (B2,B3), (B2,A1), (B3,B4), (B3,A2), (B4,C2) (B4,B5), (B5,B6), (B5,C3), (B6,B7), (B6,A2), (B7,B8), (B7,A1), (B8,C4) (C1,C2), (C1,D1), (C2,D2), (C2,C4), (C3,D2), (C4,D1), (D1,D2), (A1,A2)
2	(B1,B3), (B1,B7), (B1,C4), (B1,A1), (B1,C2), (B1,D1), (B8,B6), (B8,A1) (B8,C3), (B8,D1), (B8,C1), (B8,B2), (B2,C1), (B2,A2), (B2,B7), (B2,B4) (B3,A1), (B3,C2), (B3,B5), (B3,B6), (B4,A2), (B4,C1), (B4,D2), (B4,B6) (B4,C3), (B5,B7), (B5,A2), (B5,C4), (B5,D2), (B5,C2), (B6,A1), (B6,C3) (B7,C4), (B7,A2), (C1,D2), (C1,C4), (C2,D1), (C2,C3), (C3,D1), (C4,D2)
3	(B1,B6), (B1,B4), (B1,C3), (B1,A2), (B1,D2), (B2,C2), (B2,D1), (B2,C4) (B2,B5), (B2,B6), (B3,B8), (B3,B7), (B3,C1), (B3,D2), (B3,C3), (B4,B7) (B4,A1), (B4,D1), (B4,C4), (B5,B8), (B5,D1), (B5,A1), (B5,C1), (B6,C2) (B6,C4), (B6,D2), (B7,C1), (B7,C3), (B7,D1), (B8,A2), (B8,D2), (B8,C2) (C1,C3), (C1,A1), (C2,C4), (C2,A2), (C3,A2), (C4,A1)
4	(B1,B5), (B2,D2), (B2,C3), (B3,C4), (B3,D1), (B4,B8), (B6,C1), (B6,D1) (B7,C2), (B7,D2), (C1,A2), (C2,A1), (C3,A1), (C4,A2), (D1,A1), (D2,A2)
5	(D1,A2), (D2,A1)

Table 2.2: All Possible Node Pairs are Tabulated Against the Shortest Distance (Route Length) Between Them for Topology 2.

Shortest Distance Between Node Pairs	Node Pairs
1	(B1,B2), (B1,B8), (B1,C1), (B2,B3), (B2,A1), (B3,B4), (B3,A2), (B4,C2) (B4,B5), (B5,B6), (B5,C3), (B6,B7), (B6,A2), (B7,B8), (B7,A1), (B8,C4) (C1,C4), (C1,D1), (C2,D1), (C2,C3), (C3,D2), (C4,D2), (D1,D2), (A1,A2)
2	(B1,B3), (B1,B7), (B1,C4), (B1,A1), (B1,d1), (B2,B8), (B2,C1), (B2,A2) (B2,B4), (B2,B7), (B3,A1), (B3,C2), (B3,B5), (B3,B6), (B4,B6), (B4,C3) (B4,A2), (B4,D1), (B5,B7), (B5,A2), (B5,C2), (B5,D2), (B6,C3) (B6,B8) (B6,A1) (B7,A2), (B7,C4), (B8,C1), (B8,A1), (B8,D2), (C1,C2) (C1,D2) (C2,D2), (C3,D1) (C3,C4), (C4,D1)
3	(B1,B4), (B1,A2), (B1,B6), (B1,D2), (B1,C2), (B2,C4), (B2,D1), (B2,B6) (B2,B5), (B2,C2), (B3,B8), (B3,B7), (B3,C1), (B3,D1), (B3,C3), (B4,B7) (B4,A1), (B4,D2), (B4,C1), (B5,B8), (B5,D1), (B5,A1), (B5,C4), (B6,C2) (B6,C4), (B6,D2), (B7,C1), (B7,C3), (B7,D2), (B8,A2), (B8,D1), (B8,C3) (C1,C3), (C1,A1), (C2,C4), (C2,A2), (C3,A2), (C4,A1)
4	(B1,B5), (B1,C3), (B2,D2), (B2,C3), (B3,C4), (B3,D2), (B4,B8), (B4,C4) (B5,C1), (B6,C1), (B6,D1), (B7,C2), (B7,D1), (B8,C2), (C1,A2), (C2,A1) (C3,A1), (C4,A2), (A1,D1), (A1,D2), (A2,D1), (A2,D2)

The following table (Table 2.3) shows the distribution of the node pairs as a function of shortest distance between them.

Table 2.3: Distribution of Number Node Pairs as a Function of Shortest Distance Between Them.

Shortest Distance Between Node Pairs	Number of Node Pairs (Topology 1)	Number of Node Pairs (Topology 2)
1	24	24
2	40	36
3	38	38
4	16	22
5	2	0

The following figure (Figure 2.4) is a graphical representation of the distribution of the node pairs as a function of the shortest distance between them as depicted in Table 2.4.

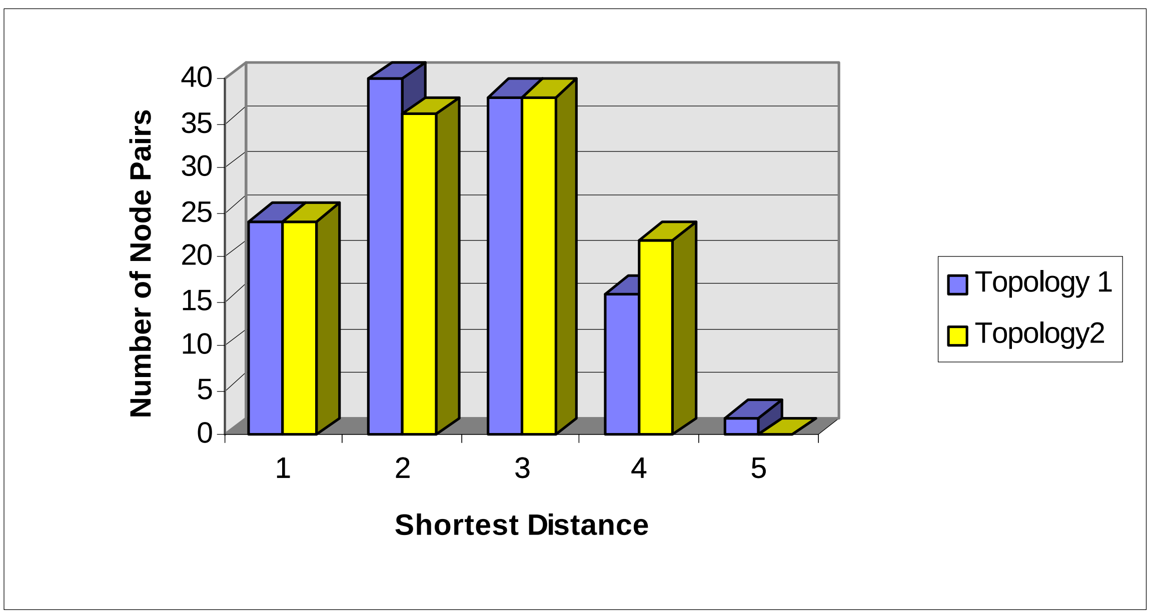

Figure 2.4: Distribution of node pairs as a function of shortest distance between them.

2.4 Average Route Length

Average route length (or average distance) of a network is an important property, which indicates the average latency over all information routing. Average route length of a network can be found by the following formula:

$$\overline{D} = \frac{\sum d_x n_x}{\sum n_x}$$

where,

$\overline{D}$ = Average route - length

d_x = Distance of x - th entry

n_x = Number of node pairs in x - th entry

Therefore,

the average route length of topology 1 is

$$\overline{D_1} = \frac{1\times 24 + 2\times 40 + 3\times 38 + 4\times 16 + 5\times 2}{24 + 40 + 38 + 16 + 2} = \frac{292}{120} = 2.43333$$

Similarly the average route length of topology 2 is

$$\overline{\mathrm{D}_2} = \frac{1\times 24 + 2\times 36 + 3\times 38 + 4\times 22}{24 + 36 + 38 + 22} = \frac{298}{120} = 2.48333$$

From the average route length calculation we see that topology 1 is showing a marginally better (2.055%) performance than topology 2.

2.5 Summary

In this chapter we start with introducing some previous works that have been done in the area of network survivability. The definition of the two topologies is given next. The concept of *shortest distance routing* is given. It is intuitive that we take the shortest distance between the source-destination node pair, because it is expected to give the minimum latency. However, routing under network failure is a topic of great importance. Routing under failure conditions is considered in detail in Chapter 4. We tabulate all the shortest-distance node pairs for both topologies. Average route length is defined next and calculated next for both topologies. Average route length will be considered throughout the thesis as a figure of merit of a communication network. It is seen that topology 1 has a lower average route length although it has a large maximum shortest route length (5) than its counterpart (4).

Chapter 3. Link and Node Utilization

Utilization is a very important property to be evaluated when selecting a network topology. Two types of utilization are discussed in this thesis, namely *Link Utilization* and *Node Utilization*. Utilization is a numeric measure, which says how often a link, or a node is utilized. We need to distribute the traffic within the links of the network in such a way so that no links become over-utilized. The best loading rule says to distribute the traffic amongst the links so that all the links have almost the same amount of utilization factor.

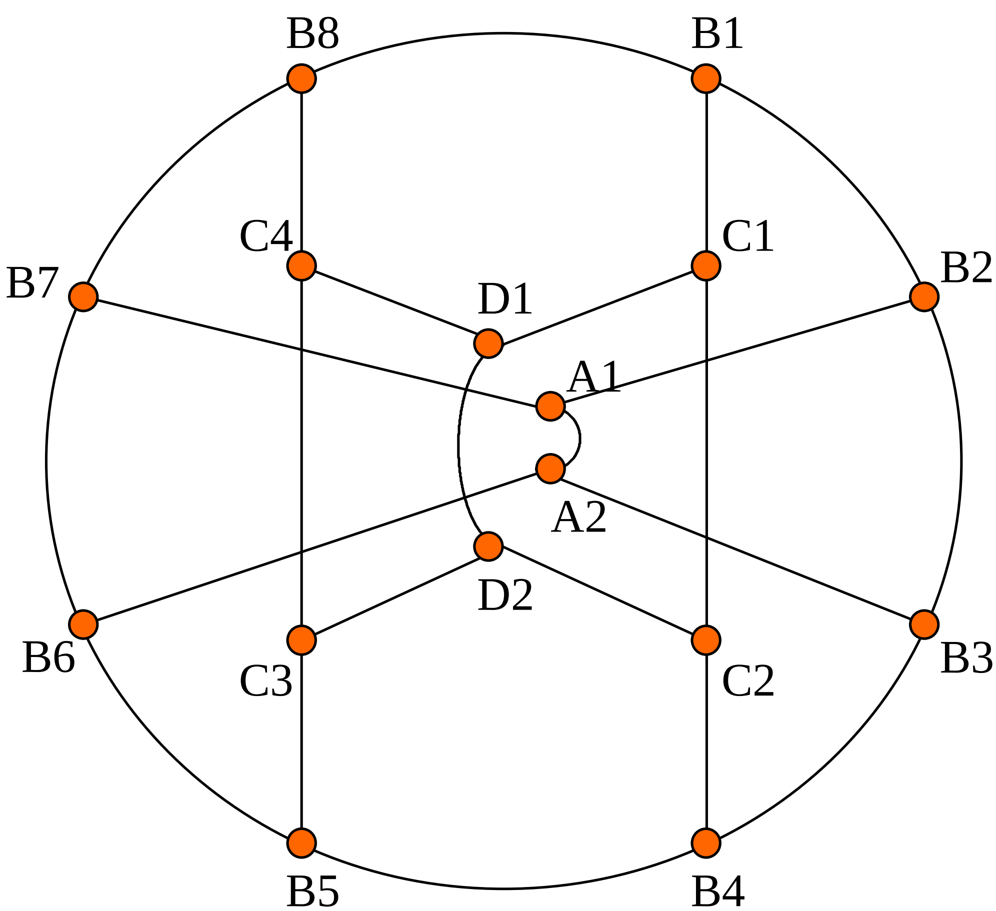

Figure 3.1: Topology 1 redrawn for explaining utilization factors.

3.1 Link Utilization

Link utilization factor is a numeric measure of the traffic carried by that specific link under a specific traffic distribution type. For example, consider topology 1 (Figure 3.1) and use B1 as a source and C3 as a sink (destination), with the route chosen as B1-C1-C2-D2-C3. Then it can be said that links (B1-C1), (C1-C2), (C2-D2) and (D2-C3) have been utilized once. Now consider another source-destination pair is (B2, C2) with the route chosen as B2-B1-C1-C2. If we calculate the utilization then we see that, while carrying these two said traffics, links (B1-C1) and (C1-C2) have been utilized twice while links (B1-B2), (C2-D2) and (D2-C3) have been utilized once.

As mentioned in Chapter 1 a uniform loading is assumed throughout this thesis, and we shall assume that one unit of traffic exists between every source-destination pair. As there are 120 node pairs in both the topologies, there are a total of 240 source-destination pairs. This is because both nodes in a pair can be a sending or a receiving node. Assuming a uniform loading and adopting a shortest distance strategy we can calculate the link utilization factors (LUFs) of all the links. Table 3.1 and 3.2 shows the LUFs for topology 1 and 2 respectively. It is important to notice that the LUFs are same for both the simplex links between node pairs in fault-free case. The only difference is that the simplex links carry traffic in the opposite directions, as stated before. Figures 3.2 and 3.3 are pictorial representations of Tables 3.1 and 3.2.

Table 3.1: Link Utilization Factors for Topology 1.

Link Number	Links	Utilization
1	(B1-B2), (B3-B4), (B5-B6) or, (B7-B8)	17
2	(B1-C1), (B8-C4), (B4-C2) or, (B5-C3)	15
3	(B4-B5) or, (B1-B8)	14
4	(B2-B3) or, (B6-B7)	12
5	(C1-C2) or, (C3-C4)	10
6	(D1-D2)	10
7	(A1-A2)	10
8	(C1-D1), (C2-D2), (C3-D2) or, (C4-D1)	9
9	(A1-B2), (A1-B7), (A2-B3) or, (A2-B6)	9

Table 3.2: Link Utilization Factors for Topology 2.

Link Number	Links	Utilization
1	(B1-B2), (B3-B4), (B5-B6) or, (B7-B8)	17
2	(B1-C1), (B8-C4), (B4-C2) or, (B5-C3)	15
3	(B2-B3) or, (B6-B7)	13
4	(C1-D1), (C2-D2), (C3-D2) or, (C4-D1)	13
5	(A1-A2)	11
6	(B1-B8) or, (B4-B5)	9
7	(A1-B2), (A1-B7), (A2-B3) or, (A2-B6)	9
8	(C1-C4) or, (C2-C3)	9
9	(D1-D2)	9

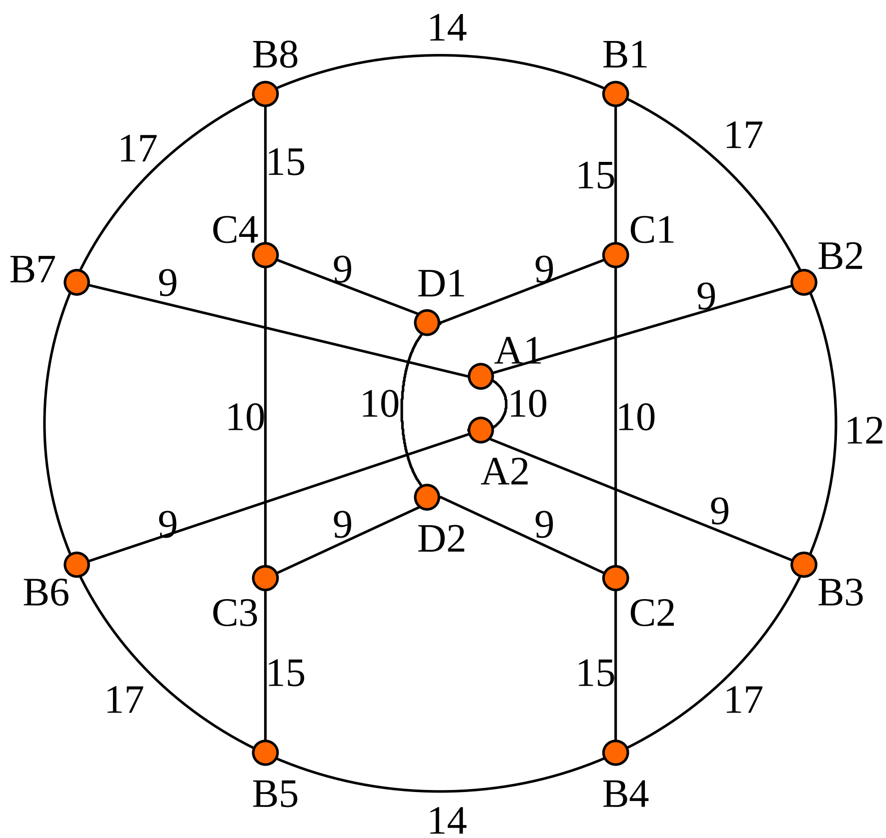

Figure 3.2: LUF for topology 1. LUFs are given on the corresponding links.

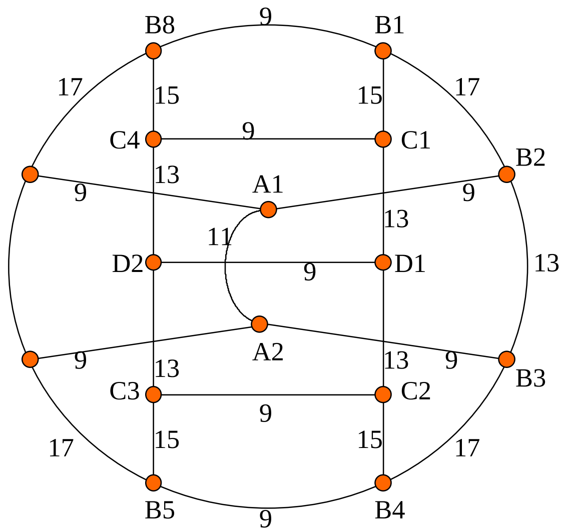

Figure 3.3: LUF for topology 2. LUFs are given on the corresponding links.

From the tables (or equivalently graphs) we see that the maximum and minimum LUFs for both the topologies are 17 and 9 respectively. So neither topology has an advantage over the other from the maximum or minimum LUF point of view. But we find that average LUF for topology 1 is 12.167 while the average LUF of topology 2 is 12.417. Also, topology 1 has a standard deviation (S.D.) of link utilization of 3.104 while topology 2 has a S.D. of 3.027. So from the point of average link utilization topology 1 has a better (lower) value than its counterpart but it has a higher variance of link utilization. It is important to note that a lower average LUF indicates a smaller overall latency of the network, while a lower S.D. of LUF indicates that the links are being used more uniformly, and there is less variation in the latency.

We have shown in the previous chapter that topology 1 has a lower average route length than topology 2 which indicates that topology 1 has smaller overall latency. This same fact is proven here again using the LUF. In fact it can be shown that the average link utilization factor is a scaled version of average distance of the network. So the following relation should be true,

$$\frac{\text{Average LUF of topology 1}}{\text{Average distance of topology 1}} = \frac{\text{Average LUF of topology 2}}{\text{Average distance of topology 2}} \qquad (1)$$

We actually notice that, $\frac{\text{Average LUF of topology 1}}{\text{Average distance of topology 1}} = \frac{12.167}{2.4333} = 5$

and also $\frac{\text{Average LUF of topology 2}}{\text{Average distance of topology 2}} = \frac{12.417}{2.4833} = 5$

Actually the ratio of average LUF to average distance is also equal to the ratio of total number of routes to total number of node pairs. This fact is proved below.

Let, d_i = length of route i

Average route length $\langle D \rangle = \sum_{i=1}^{240} d_i / 240$ where 240 = number of simplex routes

Let L_k = utilization factor of simplex link k

Average link utilization factor $\langle LUF \rangle = \sum_{k=1}^{48} L_k / 48$ where 48 = number of simplex links

But $\sum_{i=1}^{240} d_i = \sum_{k=1}^{48} L_k$ = total number of simplex links that are utilized

Therefore, $\frac{\langle LUF \rangle}{\langle D \rangle} = \frac{240}{48} = 5$

It will be shown in the next section that the relationship of equation 1 can be extended for average node utilization factors also.

3.2 Node Utilization

Node utilization is the similar measure when we consider a node. For the example of traffic from B1 to C3 and B2 to C2 considered in the previous section we notice that nodes B1, C1 and C2 have been utilized twice while nodes B2, D2 and C3 are utilized only once.

It can be shown that for both topologies, the NUF is simply the sum of the LUFs of the 3 connected links to that node which are either entering or going out of that node. To prove it Figure 3.4 is drawn, which shows node C1 and the connected six simplex links to it.

It is clearly evident from Figure 3.4 that the incoming links with LUFs X_1, X_2, or X_3 brings a total traffic of $(X_1+X_2+X_3)$ units, which ultimately goes out of the node through the outgoing links. So the NUF of node C1 is $(X_1+X_2+X_3)$ = Sum of the LUFs of the connected incoming or outgoing links.

Tables 3.3 and 3.4 show the NUFs of topology 1 and 2 respectively. Figure 3.5 shows the corresponding graphical representations.

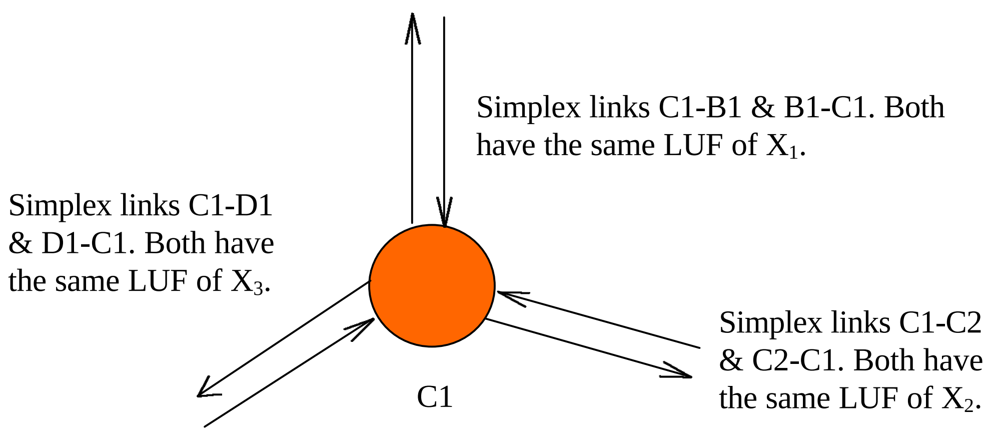

Figure 3.4: NUF calculation from LUFs of the connected links.

Table 3.3: Node Utilization Factors (NUFs) of Topology 1.

Node Number	Nodes	Utilization Factor
1	B1, B4, B5 or, B8	46
2	B2, B3, B6 or, B7	38
3	C1, C2, C3 or C4	34
4	D1 or, D2	28
5	A1 or A2	28

Table 3.4: Node Utilization Factors (NUFs) of Topology 2.

Node Number	Nodes	Utilization Factor
1	B1, B4, B5 or, B8	41
2	B2, B3, B6 or, B7	39
3	C1, C2, C3 or C4	37
4	D1 or, D2	35
5	A1 or A2	29

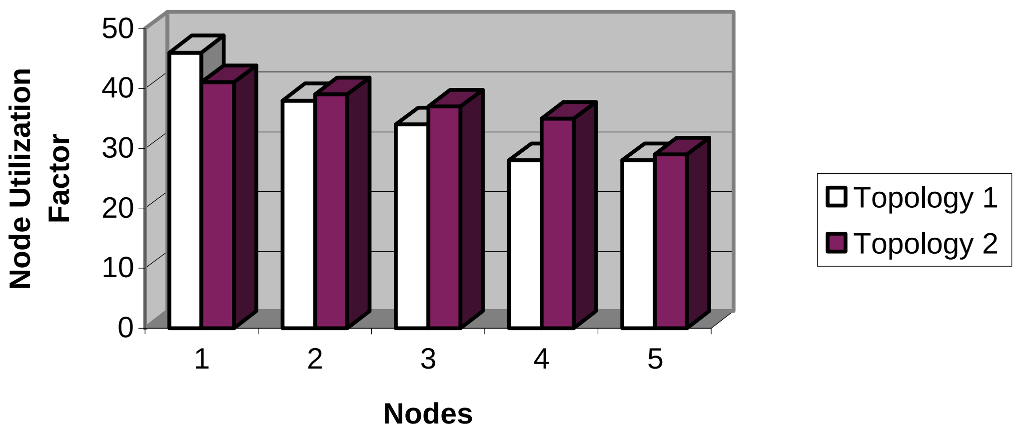

Figure 3.5: Node utilization factors of both topologies.

From the tables (or equivalently from the graphs) it is seen that the topologies have nearly the same minimum NUFs (28 for topology 1 while 29 for topology 2) but topology 1 has a substantially higher maximum NUF of 46 than that of topology 2, which is 41. The average NUF of topology 1 is 36.5 while that of topology 2 is 37.25. So topology 1 is better in the sense of average node utilization. But the S.D. of NUF of topology 1 is 6.54 while that of topology 2 is 3.67. So topology 2 utilizes the nodes much more uniformly than topology 1. This is a very important property for selecting a network topology as will be shown later. Although topology 1 has a better average NUF than topology 2, it can be shown that this improvement is nothing but the same properly of average distance or average link utilization factor (LUF) as explored before. The average NUF is related to average LUF by the following formula

Average NUF = 3$\times$ Average LUF

[For topology 1; Average NUF = 36.5 = 3 $\times$12.167 (Average LUF). While for topology 2; Average NUF = 37.25 = 3$\times$12.417 (Average LUF)]

It is an obvious outcome, because, each node is connected to three nodes, so expected value of NUF should be equal to three times the expected value of LUF. So an improvement in NUF is not an exclusively different property, rather it is the same property but having a different aspect. Again as average NUF is a scaled version of average LUF, Equation 1 can also be extended for NUF.

3.3 Summary

Link and node utilization factors (LUF and NUF) are introduced in this chapter. LUF and NUF for both topologies are tabulated and graphically represented. It is shown that LUF and NUF are actually a scaled version of *average route length.* The ratio of LUF to average route length is found to be 5. The ratio of NUF to LUF is 3.

It is seen that topology 1 has lower LUF and NUF but S.D. of utilization factors are greater for topology 1. A lower S.D. of utilization factors indicates that the corresponding links and nodes are being utilized more uniformly. It is important to note that, S.D. of NUF of topology 2 is significantly lower than topology 1, which will be used as a significant advantage of topology 2 over topology in Chapter 6.

Chapter 4. Failure Situations

4.1 Overview

A failure in the network is caused when a link or a node or combination of link(s) and node(s) failures takes place. For convenience failure situations are divided into three groups. They are:

1. Single-link failure
2. Single-node failure
3. Multiple failure

Multiple failures occur when two or more failures occur simultaneously. In this thesis, single-link and node failures are investigated thoroughly. In addition, some general thoughts and results on multiple failures are given. Specific emphasis is given to double-link failure.

Several detrimental effects are observed when a network failure occurs. The figures of merits of the network topologies that have been discussed in the previous chapters (i.e. average route length, average LUF or NUF, or S.D. of NUF or LUF) tend to worsen in presence of failure(s). Suppose the link C1-C2 of topology 1 is lost. Then all the traffic that was carried by this link needs to be carried by other links. For example, lets consider the case where source-node is C1 and destination-node is C2. As C1-C2 link has failed, this traffic needs to be re-routed through either C1-D1-D2-C2 or, C1-B1-B2-B3-B4-C2 path (see Figure 4.1). Obviously both routes increase the route length. If the second route is chosen, link-length increases more, because route length of first and second routes are 3 and 5 respectively. Utilization factors also increase in presence of failure. For this specific example, we note that, LUF is increased by 2 or 4, if we choose the first or second route. NUF is also increased by the same amount.

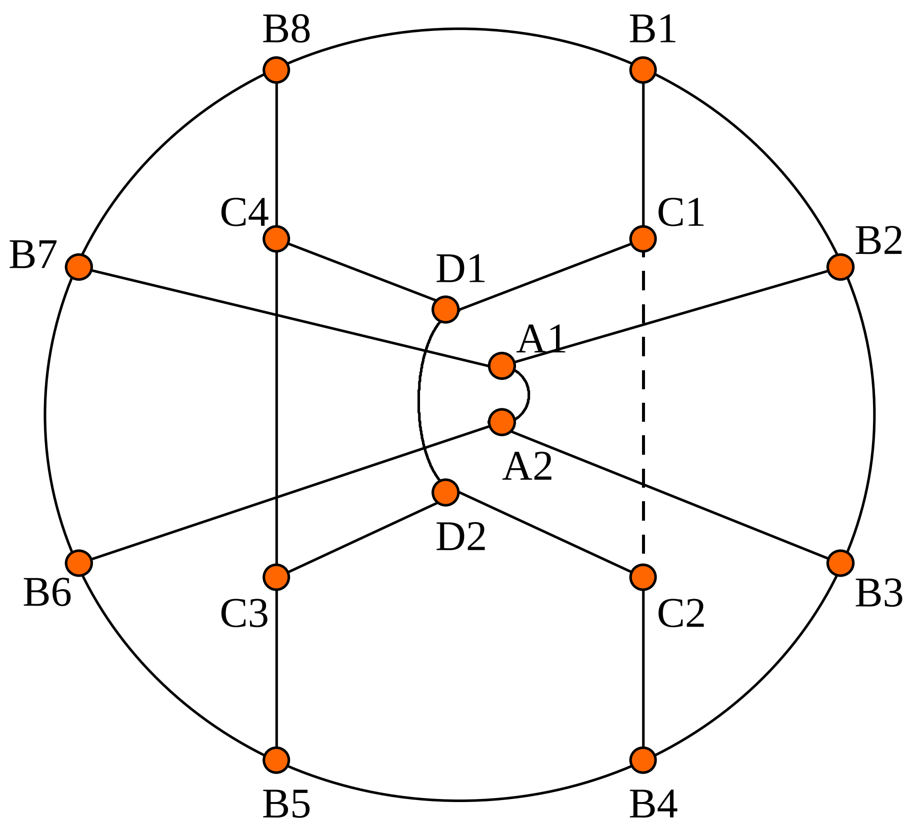

Figure 4.1: Link failure (C1-C2) illustrated. As C1-C2 fails traffic originally carried by link C1-C2, should be carried by alternative paths, e.g. C1-D1-D2-C2 or C1-B1-B2-B3-B4-C2.

It is clear that a lost node can never act as a source or a sink. A lost node also forces all three connected links to that node to fail. But in case of a single-link failure no traffic is disrupted. So node failures are more damaging than link failures. Some important decisions have also been taken using this fact, which will be discussed later.

In case of multiple failure, partitioning of the network might take place. A network is said to be partitioned when a group of failed links or nodes divides the network. When a network is partitioned, connectivity between the nodes of a particular subgroup remains, but no communication is possible between the subgroups. We see for both topologies that there is no situation where a single or a double failure (either link or node) can cause network partitioning. The smallest number of failures that might cause a network partitioning is 3. We stated before that both the topologies are regular networks with connectivity 3. It can be easily shown from elementary graph theory that the smallest number of failures that might cause partitioning in a regular network is its connectivity. Detailed partitioning aspects are discussed in sections 4.6 and 4.7.

Another important aspect to be considered is the optimal routing strategy when a fault has occurred. As discussed before, in the fault-free case we have taken the shortest distance route between all source-destination pairs to minimize the network latency and to increase the overall throughput. Details of the routing schemes will be discussed in section 4.2.

The deleterious effects of network failures can be summarized as follows.

1. Increases the minimum route length
2. Increases the network latency
3. Increases the utilization factors (LUF and NUF)
4. Increases the congestion in the network
5. Decreases the overall throughput
6. Causes partitioning in the network
7. Disrupts some specific traffic in the network (in case of a node failure)

4.2 Routing

The goal of routing in a communication network is to direct traffic from source to destination in accordance with the traffic's service requirements and the network's service restrictions [5]. This seemingly simple characterization hides the fact that routing is often realized as a complex system of distinct, yet independent operations, shaped by potentially conflicting objectives and constraints. Objectives include maximizing network performance (e.g., delay and throughput) while minimizing the cost (e.g. equipment and facilities) of the network itself. Constraints are imposed by underlying network switching technology, the dynamics of the switching network and user traffic, and network services rendered and user services requested.

As a multiobjective, multiconstraint optimization problem, routing is a rich area for research. The evolution of networking technologies constantly reveals new opportunities for routing research and development [5]. Referring to the 7-layer OSI model of a communication network, it can be said that routing is done at the network layer (Figure 4.2). Usually the data-link layer handles point-to-point or multi-access communication. The transport layer handles source to destination transactions and the network layer is responsible for the routing.

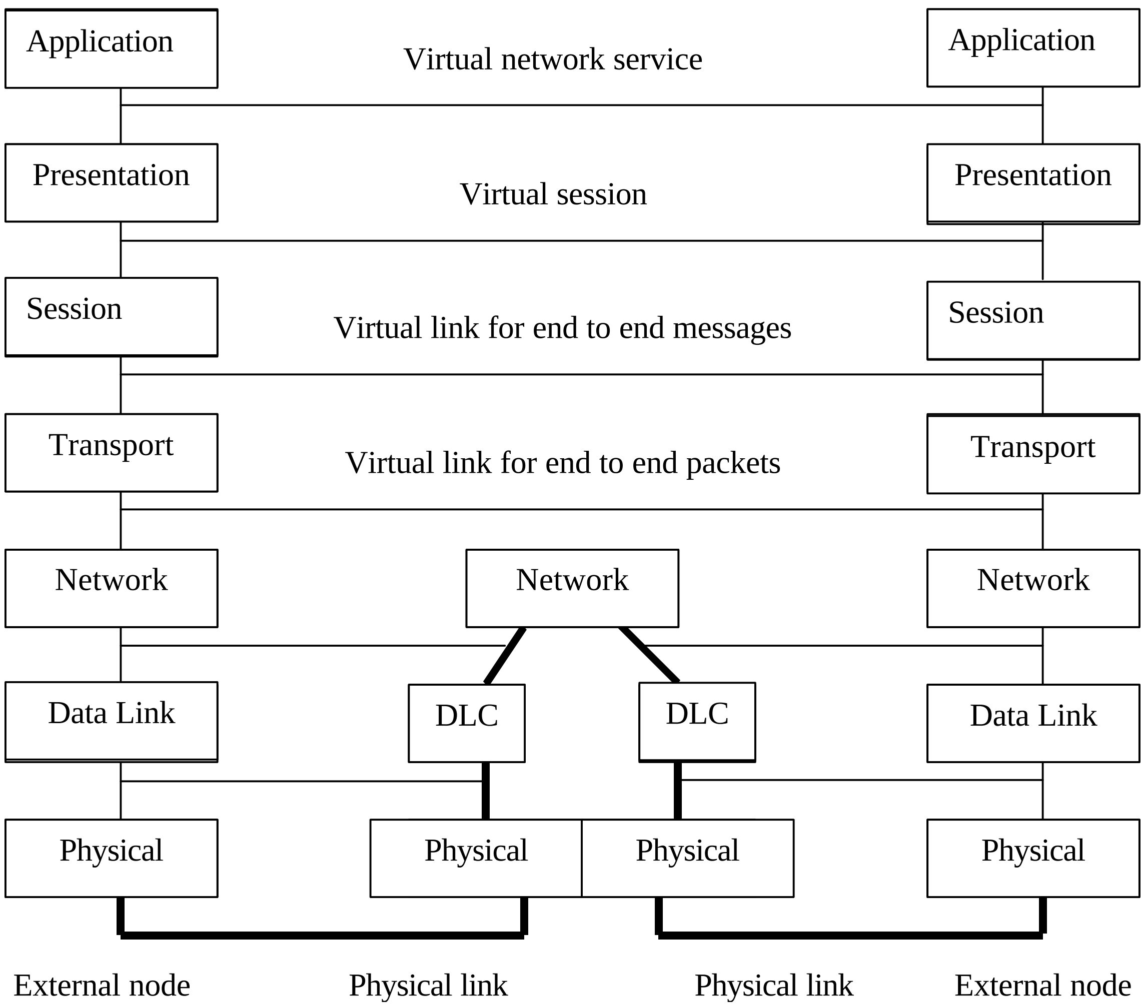

Figure 4.2: Routing is done at Network Layer [13].

In this thesis, considerable effort was devoted to devising an optimal re-routing strategy under failure conditions. Needless to say that an optimal re-routing strategy should ensure most of the following properties.

1. Low average route length
2. Low variance in route length
3. Low average in link utilization factor (LUF)
4. Low variance in LUF
5. Low node utilization factor (NUF)
6. Low variance in NUF

Properties 2,4 and 6 indicate that the maximum and minimum of the concerned properties should be close to their average value.

4.3 Classification of Routing

There are several ways for categorizing routing. According to the location where the routing decision is taken, routing can be divided in two groups, namely centralized and distributed routing [5].

With a centralized implementation, a single entity performs the given routing functions. Centralized procedures are easy to manage because the functionality resides at a single entity, simplifying the management functions, such as modifying or isolating faults within the implementation. Moreover, if specialized resources are required to perform the routing function, these resources can be concentrated in one place, thus reducing costs.

There are, however, disadvantages of centralized implementations. When the central entity performing the routing function fails or is otherwise separated from the network, that routing functionality is unavailable for the duration of the separation.

With a distributed implementation, multiple peer entities independently provide portions of the functionality and cooperate to provide the complete functionality by exchanging results. Although distributed routing complicates management of the routing of the routing system, it has many advantages. Replicating functionality at multiple entities increases the fault endurance of the routing system. It also reduces response delay by spreading the load among multiple entities and by enabling functionality to be placed close to the portion of the network that requires it. Distributed functionality over multiple entities also reduces the amount of routing system resources required at any single entity and also enables the routing system to grow incrementally with the size of the network.

In both the topologies the entities of functionality are the nodes. Throughout the thesis we have used the distributed implementation of routing.

Routing strategy can be static or dynamic in nature. Static routing involves virtually no real-time activities other than traffic forwarding and thus requires almost no computational resources within the network itself. Quasi-static routing systems are static routing systems that also modify traffic routing in response to exceptional events (e.g. link or node failures) or at relatively long time intervals. Manual updating of network traffic routing is often sufficient in static and quasi-static routing systems, as routing changes are infrequent.

On the contrary, dynamic routing systems autonomously update traffic routing by adapting in real time to perceived changes in the user and network state. These state changes include not only link and node outages but also fluctuations in user traffic and availability of network resources. Dynamic routing systems rely on active participation by entities within the network to measure user traffic and network performance and to compute routes on demand, accounting for current user traffic and network state. Thus dynamic routing requires memory and computational resources resident within the network for real-time information gathering and control decisions [5].

The appropriate degree of dynamism for a given routing system depends on several factors, including the processing, memory, and transmission resources available to support the routing functions; the type and frequency of changes in the network and user traffic state; the expected performance degradation resulting from a mismatch between selected routes and actual state; and the limitations or response delay imposed in assembling, propagating, and acting upon state information [5].

Routing in a highly dynamic network environment presents interesting challenges. A dynamic routing system that is able to keep up with rapid state changes may not always be practical because of the quantity of network resources required. Complicated cost and performance tradeoffs are necessary when designing a routing system for a specific networking environment. In this thesis we have investigated both static and dynamic routing strategies. We devised a specific static routing strategy, called *Static Disjoint Routing Strategy*, which is very close in performance to that of the dynamic routing strategy for the uniform traffic model. A detailed comparison between *Disjoint Static Routing Strategy* and *Dynamic Routing Strategy* is discussed in section 4.5.

4.4 Static Disjoint Routing Strategy

Routes existing between a specific source-destination pair are said to be disjoint (or mutually exclusive) when none of the routes has a common link or node among them, other than the source and destination nodes. For example, in topology 1, the routes, B8-B7-B6-B5, B8-C4-C3-B5 and B8-B1-B2-B3-B4-B5, are disjoint (or mutually exclusive) for the source-destination pairs (B8, B5). The advantage of disjoint routing is that, if a route fails, we can easily switch to the next route with all confidence, because we know in advance that all the routes that are used in the routing table are mutually exclusive. So if we can construct a routing table which will have all the possible source-destination pairs and the disjoint routes between them, we can use that routing table to deal with the link and node failures in a static fashion. But the question is whether all the source-destination pairs have sufficient disjoint routes.

As described before, both the topologies are regular networks with connectivity 3. In other words, every node has three outgoing and three terminating links. From basic graph theory it follows that there might be a maximum of 3 disjoint routes between every source-destination pair. It is very interesting to note that, in both the topologies, all 240 source-destination pairs have exactly 3 disjoint paths between them.

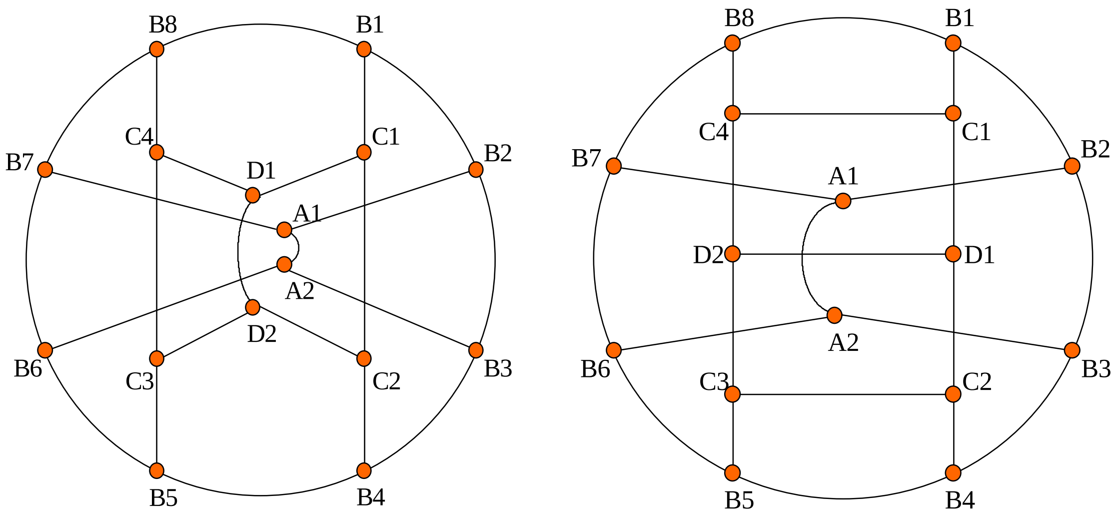

Figure 4.3: Both the topologies have exactly 3 disjoint routes between all possible source-destination pairs.

So we can easily construct routing tables for both the topologies where we will list all the source-destination pairs and the 3 disjoint routes between them. The corresponding routing tables are constructed and provided in Appendix A and B. Naturally the first route (which will be used in the fault-free case) is the shortest route. The other two entries (routes) of the table are arranged in ascending order of the route length.

Some interesting things should be mentioned about the routing table. For instance, consider the source-destination pair (C4, D1) for topology 2. From the routing table it is seen that the chosen disjoint routes are C4-D2-D1, C4-C1-D1 and C4-B8-B1-B2-B3-B4-C2-D1 respectively. Note that first two routes are equal in length. Now if we always use C4-D2-D1 in the fault-free case we would utilize (C4-D2) and (D2-D1) links frequently.

As we want to utilize the links uniformly we can use two approaches. Firstly, for the instances where we have two equal-length routes, we can choose either of the routes at random, with probability of choosing either of them to be 0.5. Secondly, we can use the route C4-D2-D1 always in the fault-free case when C4 is the source and D1 is the destination and the route D1-C1-C4 always when source-destination pair is reversed (i.e. D1 is source and C4 is the destination). The second option appears more practical because it works in a straightforward fashion and ignores the account keeping processes for the probability. The second approach also gives us the easy rule of always taking the counter-clockwise route when there is a stalemate between two routes. Our routing table has been constructed using the second approach. Also it is important to note that the routing table has only 120 entries. The reverse routes can be found just by reversing the route and also altering the first two routes, if they are equal in length.

Route length might be equal for the second and third entries. For example consider the source-destination pair (B4, B5) of topology 1. The corresponding disjoint routes are B4-B5, B4-C2-D2-C3-B5 and B4-B3-A2-B6-B5. The last two entries are of equal length of 4. If the link B4-B5 fails then we always can take the first route for the said source-destination pair, and take the second route always when source-destination pair is reversed.

4.5 Comparison Between Static Disjoint Routing and Dynamic Shortest Distance Routing

We mentioned before that *Static Disjoint Routing* algorithm significantly reduces the computational complexity and associated delays for the shortest route computation. But it doesn't always provide the shortest possible path. On the other hand, Dynamic Shortest Route search algorithm always gives the shortest route available at any instance. But it requires distributed highly sophisticated computational resources for its operation. So there exists a tradeoff between them. Consider the same example of topology 2 given in the previous section where the source destination pair is (C4, D1). The available three routes from the disjoint routing table are C4-D2-D1, C4-C1-D1 and C4-B8-B1-B2-B3-B4-C2-D1 respectively. Say both the links C4-D2 and C4-C1 fail. So if we use a static disjoint routing table we would take the third available option; i.e., C4-B8-B1-B2-B3-B4-C2-D1. But the dynamic shortest route search algorithm will give the shortest route available; i.e., C4-B8-B1-C1-D1, which is 3-units smaller than its counterpart. So it is clear that dynamic shortest route search algorithm always gives the shortest route while the static disjoint routing algorithm does not.

Also the static disjoint routing algorithm fails when more than 2 failures occur simultaneously. The dynamic shortest route search algorithm, on the other hand, remains operational until the whole network crashes. But we can assume that for these specific 16-node, 24-link LANs, the probability of more than two simultaneous failures is very very low. So static disjoint routing algorithm might be used if it is proven to be comparable in performance to the dynamic shortest route search algorithm.

Table 4.1 shows the effect on average route length when a single-node failure occurs for topology 1. In section 3.1 it is proved that link and node utilization factors are directly proportional to the average route length. So the results of Table 4.1 can be considered as a scaled version of LUF and NUF. Note that:

- Disjoint routing strategy always gives a higher average route length. But the increment is very small. The highest increment is seen when we lose either of the nodes B1, B4, B5 or B8; which is only 1.106 %.
- In the first three entries of the table it is seen that the average route length is greater than that of fault-free case (2.433). But in the last two entries it is less (2.428 in place of 2.433). It is a general expectation that average route length should increase in a faulty case. It is always true in case of a link failure. But in case of node failure, we lose all traffic originating from and terminating to that node. So losing a node might result in a lower average route length if some of the lost traffic has larger route lengths.

- The overall average route length (or expected route length) is 2.5118 for disjoint routing and 2.4952 for dynamic minimum distance routing. The difference is only 0.872%, which is quite small. So we see that static disjoint routing is very close in performance to the dynamic shortest routing.

Table 4.1: Average Route Length of Topology 1 Under Single-Node Failure.

Lost Node	Disjoint Minimum Distance	Simple Minimum Distance	% increase
B1,B4,B5,B8	2.6095	2.5809	1.106
B2,B3,B6,B7	2.505	2.4952	0.393
C1,C2,C3,C4	2.5047	2.4952	0.381
A1,A2	2.428	2.4095	0.77
D1,D2	2.428	2.4095	0.77
Overall	2.5118	2.4952	0.872
Overall % increase from faultless case	3.226 %	2.544 %	

Table 4.2 shows the similar results for topology 2. Note that:

- Unlike topology 1, each entry has larger average route length than the fault-free case (2.4833).
- If we lose a B node the average route length increases the most. This indicates that B nodes are usually heavily loaded in fault-free case.
- The overall route length for disjoint algorithm is 2.577 while for dynamic minimum route search algorithm it is 2.558. They are 3.78% and 3% more than the fault-free case (2.4833). The route length increases by only 0.6185% when we choose disjoint routing algorithm.
- Under single-node failure topology 1 performs better. The percentage increment in route length is higher in topology 2 (3.78% and 3.0%) than topology 1 (3.226% and 2.544%).

Table 4.2: Average Route Length of Topology 2 Under Single-Node Failure.

Lost Node	Disjoint Minimum Distance	Simple Minimum Distance	% increase
B1,B4,B5,B8	2.619	2.609	0.383
B2,B3,B6,B7	2.619	2.609	0.383
C1,C2,C3,C4	2.552	2.524	0.555
A1,A2	2.514	2.476	1.538
D1,D2	2.524	2.505	0.772
Overall	2.577	2.558	0.6185
Overall % increase from faultless case	3.78 %	3.0 %	

Similar results can be explored for single-link failures. We have indicated before that all traffic associated with a node is lost when that node fails. But in case of single (also with all double) link failures no traffic is lost. So it is obvious that average route length increases for any single (or double) link failure. In some cases of triple link failures we notice partitioning of the network. If we lose all the links connected to a node, then the node forcibly goes out of operation, even though the node is not damaged. So in that case, multiple link failures may cause some of the traffic to terminate abnormally.

We have also mentioned before that each link can be considered as two simplex links, carrying traffic in opposite directions. So in the case of a single-link failure we might lose a simplex link in one direction or we might lose the whole link. The latter scenario is expected to give larger average route length than the former. The results of all possible link failures of topology 1 are given in Table 4.3. Note that:

- Losing simplex links in both directions rather than in one direction, results in higher average route length.

- Dynamic shortest routing gives marginally better performance than disjoint routing. The increment in route length is only 0.391% when a simplex link is lost and is 0.724% when both the simplex links are lost.
- The increase of average route length approximately doubles when we lose both the simplex links compared to losing just a single simplex link.
- The overall average route length becomes 2.47 and 2.48 respectively for dynamic shortest routing and static disjoint routing when we lose a single simplex link. These values are 1.508% and 2.48% larger than the fault-free value (2.433).
- The overall average route length becomes 2.507 and 2.525 respectively for dynamic shortest routing and static disjoint routing when we lose both single simplex link. These values are 3.03% and 3.77% larger than the fault-free value (2.433).

Table 4.3: Average Route Length of Topology 1 Under Single-Link Failure.

Loosing link	Link lost in one (either) direction			Link lost in both directions		
	Dynamic Shortest Routing Algorithm	Static Disjoint Routing Algorithm	% increase	Dynamic Shortest Routing Algorithm	Static Disjoint Routing Algorithm	% increase
(B1-B2),(B3-B4), (B5-B6),(B7-B8)	2.483	2.492	0.362	2.533	2.55	0.671
(B1-B8),(B4-B5)	2.487	2.504	0.684	2.542	2.575	1.298
(B2-B3),(B6-B7)	2.47	2.47	0.0	2.508	2.508	0.0
(A1-B2),(A1-B7), (A2-B6),(A2-B3)	2.454	2.463	0.367	2.475	2.492	0.687
(B1-C1),(B4-C2), (B5-C3),(B8-C4)	2.495	2.508	0.521	2.558	2.583	0.977
(C1-C2),(C3-C4)	2.466	2.47	0.162	2.5	2.508	0.32
(C1-D1),(C4-D1), (C2-D2),(C3-D2)	2.454	2.463	0.367	2.475	2.492	0.687
(D1-D2)	2.441	2.454	0.533	2.45	2.475	1.02
(A1-A2)	2.441	2.458	0.696	2.45	2.483	1.347
Overall	2.47	2.48	0.391	2.507	2.525	0.724
% increase from fault-free case	1.508	1.92		3.03	3.77	

- All the B-links (i.e. links from B-nodes) are usually heavily utilized during fault-free case. This is because we see a higher average route length when we lose a B-link.
- All the entries have higher average route length than the fault-free case (2.433).

Results in Table 4.4 are for all possible single-link failures for topology 2. Note that:

- All the qualitative properties are almost same as topology 1. For example:
  1. All B-links are heavily utilized.
  2. All faulty cases increase the average route length.
  3. Increase in average route length approximately doubles when we lose simplex links in both direction rather than losing a single simplex link.
  4. Dynamic routing is marginally better than disjoint routing.

Table 4.4: Average Route Length of Topology 2 Under Single-Link Failure.

Losing link	Link lost in one (either) direction			Link lost in both directions		
	Dynamic Shortest Routing Algorithm	Static Disjoint Routing Algorithm	% increase	Dynamic Shortest Routing Algorithm	Static Disjoint Routing Algorithm	% increase
(B1-B8),(B4-B5)	2.508	2.508	0.0	2.533	2.533	0.0
(B1-B2),(B7-B8),(B3-B4),(B5-B6)	2.576	2.576	0.0	2.67	2.67	0.0
(B2-B3),(B6-B7)	2.546	2.546	0.0	2.608	2.608	0.0
(C1-D1),(C2-D1),(C3-D2),(C4-D2)	2.526	2.533	0.277	2.566	2.583	0.662
(C2-C3),(C1-C4)	2.491	2.508	0.682	2.5	2.533	1.32
(A1-B2),(A1-B7),(A2-B6),(A2-B3)	2.508	2.516	0.32	2.533	2.55	0.671
(D1-D2)	2.491	2.508	0.682	2.5	2.533	1.32
(A1-A2)	2.491	2.526	1.36	2.5	2.566	2.64
(B1-C1),(B8-C4),(B4-C2),(B5-C3)	2.53	2.55	0.79	2.575	2.617	1.63
Overall	2.526	2.536	0.373	2.57	2.588	0.688
% increase from fault-free case	1.719	2.119		3.488	4.216	

- All of the corresponding figures are slightly worse (higher) in topology 2 than topology 1. We only see that the percentage increase in route length is less in topology 2 when we take disjoint routing rather than dynamic routing. So topology 1 is giving slightly improved performance over its counterpart.

4.6 Partitioning of the Network

We mentioned before that a network partitioning might take place in a regular network if the number of failures exceeds its connectivity. Network partitioning will be explored in detail in this section. Consider the following scenario of topology 1 (Figure 4.4a) where all the connected links to node C2 fail. Even though node C2 didn't fail, it forcibly goes to outage, as all connected links are no longer operational. This is the simplest case where a network partitioning takes place. If node C2 had failed, instead of all 3 connected links that would not be a network-partitioning example. This is because in network partitioning at least one operational node is required which would be isolated from the remainder of the network.

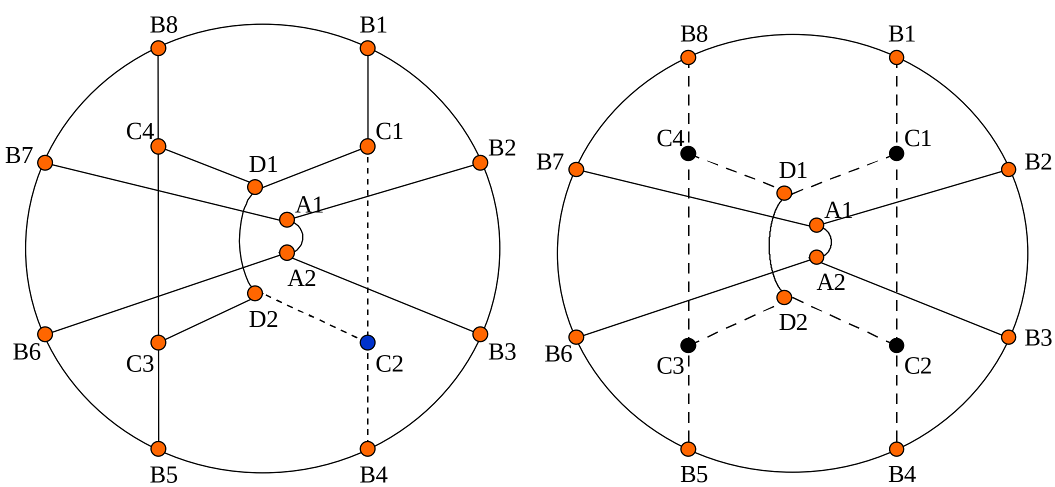

Figure 4.4: (a) Simplest scenario of network partitioning. Node C2 goes into forced outage when all the connected links to that node fails. (b) Simultaneous failure of all C-nodes isolates D-nodes from rest of the network.

Another example of network partitioning is shown in Figure 4.4b where D-nodes are detached from rest of the network because all C-nodes have failed.

4.7 Network Partitioning Due to Multiple Node Failure

The simplest case of network partitioning due to multiple node failure takes place when all three nodes, which are connected to a single-node, fail. Only 16 such instances can be found out of 560 combinations (C_3^{16}). There is no other example where three simultaneous node failures can sever the network. This holds for both the topologies.

We notice almost similar partitioning instances for both the topologies when quadruple simultaneous node failure takes place. Throughout the next section, quadruple node failure situations are described. Note from section 2.2, nodes can be divided into two classes. They are

1. External nodes (All B-nodes), and
2. Internal nodes (All A, C and D nodes).

For both the topologies there exists only one instance out of 70 possible combinations (C_4^8) where the network is divided due to internal node failure (failure of all C-nodes). For both the topologies D-nodes are partitioned. Figure 4.4b shows this instance for topology 1.

There exist only four instances out of 70 possible combinations (C_4^8) where network is partitioned due to external node failure (same for both the topologies). The instances are;

- Failure of B1, B4, B6 and B7 nodes. Partitioned nodes are B2, B3, A1, and A2.
- Failure of B5, B8, B2 and B3 nodes. Partitioned nodes are B6, B7, A1, and A2.
- Failure of B6, B7, B2 and B3 nodes. Partitioned nodes are A1, A2.

- Failure of B1, B4, B5 and B8 nodes. Partitioned nodes are C1, C2, C3, C4, D1, and D2.

There are a number of instances where combination of external and internal node failures can cause network partitioning.

4.8 Summary

In this section we discuss the link and node failures which might be either single or multiple in nature. Importance of an optimal re-routing strategy under failure is discussed. The concept of *static disjoint routing algorithm* is introduced. Comparison between disjoint routing and dynamic routing is explored. It is shown that disjoint routing eases the re-routing of traffic for these specific 16-node LANs, as it is expected that probability of more than two simultaneous failures is very low. Disjoint routing also gives performance close to the dynamic routing. Finally, some discussion on network partitioning is made. It is shown that both the topologies have many diverse paths to maintain connectivity in presence of multiple failures. So both the topologies have highly survivable backbone.

Chapter 5. Utilization Factors Under Failure

5.1 Overview

Link and node utilization factors have been defined before in Chapter 3. Utilization is a very important property of a communication network. One of the goals of designing a good communication network is to keep all of its link and node utilization factors close to their average values. In other words, routing in a network should not be chosen in such a way that no links or nodes become heavily over or under utilized. In this chapter we investigate effect of utilization factors when a network failure occur. As described before, a node failure also eliminates the traffic to and from that failed node. A link failure does not eliminate network traffic unless it causes a network partitioning. So a node failure might result in reduced utilization factor. In section 4.5 it is shown that the average route length is reduced for topology 1 when there are node failures. A reduced average route length also indicates a reduced utilization factor. It is because route length and utilization factors are proportional. But on the contrary, in case of link failures without network partitioning, all the existing traffic remains, and some of the links (and eventually nodes) are found to be heavily utilized. That is why, we concentrated our discussion only on link failures. Single-link failure is exhaustively investigated for both the topologies. Some specific double-link failure situations are also investigated.

Traffic carried by the links before failure must be redistributed to other links after the failure occurs. Dynamic shortest routing or static disjoint routing can do the traffic redistribution as described before. Both algorithms tend to give minimum latency (since they are designed to take the shortest route) but fail to give optimal utilization. If we try to optimize the utilization factors, network latency increases and eventually throughput is decreased. So, there exists a tradeoff between these two objectives. In regular communication networks, some other objectives like cost, error rate, congestion control, etc., are also tried to be fulfilled. Obtaining such multiple purposes requires devising an optimal routing algorithm. There are several algorithms for optimizing the routing.

Distance Vector Routing [6,7], Link State Routing [8,9,10] and Deflection Routing [11,12] are some of the examples. In this thesis multivariable optimization is not considered. We consider primarily static disjoint routing and investigate the utilization factors under this *static disjoint routing.*

5.2 Single-link Failure

All possible single-link failure situations are explored for both the topologies. Full link-failure (i.e. both simplex connections are lost) is assumed throughout. Two specific link failure cases (two highest utilized links) are studied for both the topologies. First link utilization is discussed. Node utilization is discussed later.

5.2.1 Link Utilization Factors (LUFs)

From section 3.1 we notice that in fault-free case, for both the topologies B1-B2, B3-B4, B5-B6 and B7-B8 links have highest link utilization factor (17). Again for both the topologies B1-C1, B4-C2 B5-C3 and B8-C4 links have second highest link utilization factor (15). Naturally, we can assume the worst case scenario when we lose these links. The following two tables (Tables 5.1 & 5.2) show the changes of LUF for topology 1 and topology 2 when link B1-B2 is lost.

Note the following points:

- The fractional part in the utilization factor comes from the fact that, there are some routes in the disjoint routing table which have equal route length in second and third route. So we use the counter-clockwise routing technique as described in section 4.4 which causes the LUF to be a fraction.
- The maximum LUF for topology 1 under this failure condition is 24. The average LUF is 14.1458 and S.D. of LUF is 5.

Table 5.1: Change in LUF When Link B1-B2 is Lost for Topology 1.

Links	LUF before Failure	Change in LUF after failure	Total LUF after failure
B1-B2	17	0	0
B1-B8	14	3.5	17.5
B1-C1	15	1	16
B2-B3	12	2.5	14.5
B2-A1	9	3	12
B3-B4	17	7	24
B3-A2	9	2.5	11.5
B4-B5	14	0.5	14.5
B4-C2	15	7	22
B5-B6	17	2	19
B5-C3	15	1	16
B6-B7	12	3.5	15.5
B6-A2	9	3.5	12.5
B7-B8	17	7	24
B7-A1	9	3.5	12.5
B8-C4	15	2	17
C1-C2	10	3.5	13.5
C1-D1	9	0.5	9.5
C2-D2	9	3	12
C3-C4	10	0.5	10.5
C3-D2	9	0.5	9.5
C4-D1	9	2.5	11.5
A1-A2	10	2.5	12.5
D1-D2	10	2	12

Table 5.2: Change in LUF When Link B1-B2 is Lost for Topology 2.

Links	LUF before Failure	Change in LUF after failure	Total LUF after failure
B1-B2	17	0	0
B1-B8	9	4	13
B1-C1	15	1.5	16.5
B2-B3	13	2	15
B2-A1	9	4	13
B3-B4	17	5	22
B3-A2	9	3	12
B4-B5	9	0.5	9.5
B4-C2	15	6	21
B5-B6	17	1	18
B5-C3	15	0	15
B6-B7	13	2.5	15.5
B6-A2	9	1.5	10.5
B7-B8	17	11	28
B7-A1	9	7.5	16.5
B8-C4	15	4.5	19.5
C1-C4	9	2	11
C1-D1	13	3.5	16.5
C2-D1	13	5.5	18.5
C2-C3	9	0.5	9.5
C3-D2	13	0.5	13.5
C4-D2	13	1.5	14.5
A1-A2	11	2.5	13.5
D1-D2	9	1	10

- As B1-B2 link is lost no traffic is carried by that link. So in this failure case LUF is decreased by 17 (traffic carried by link B1-B2 before failure) but the total is increased by 64 (sum of third column).

- The maximum LUF for topology 2 is 28 (link B7-B8). The average LUF is 14.66 and S.D. of LUF is 5.28
- Failure of link B1-B2 causes LUF to decrease by 17 (traffic carried by link B1-B2 before failure) but the total increases by 71 (sum of third column).
- Topology 1 has a lower maximum LUF, average LUF and S.D. of LUF. Increase in LUF is also lower (64 in comparison to 71). So topology 1 performs better under B1-B2 (busiest) link failure.

The following figures (Figure 5.1 and 5.2) show the same result in graphical format.

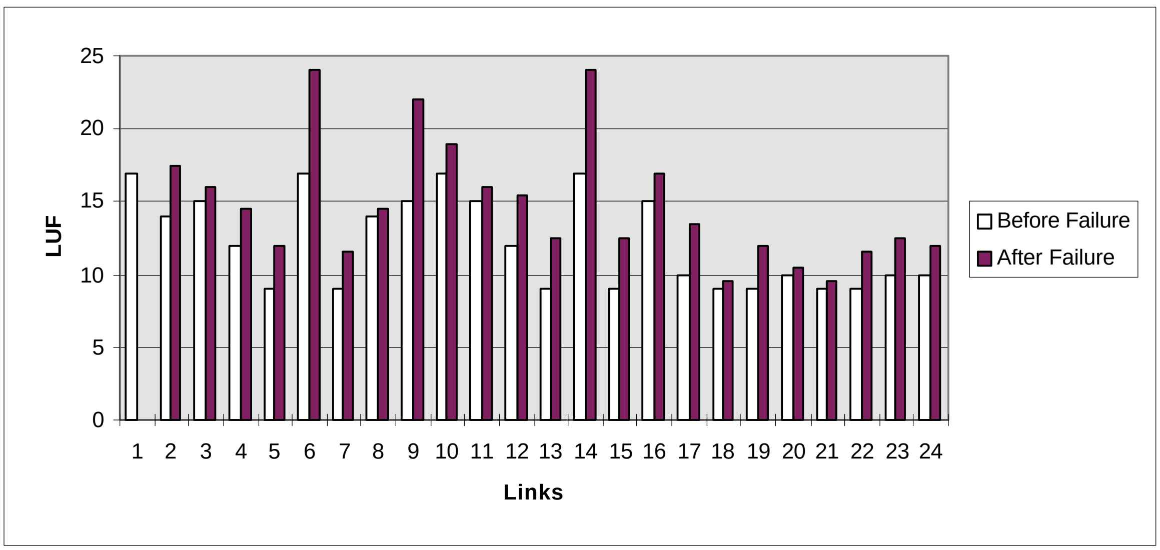

Figure 5.1: Graphical representation of LUF of topology 1 when busiest link B1-B2 fails.

We have defined the links as numbers for both the topologies. The definitions of the links are given in Appendix C. We notice that LUF of links 14 (B7-B8) and 6 (B3-B4) increases about 41% relative to the fault-free case.

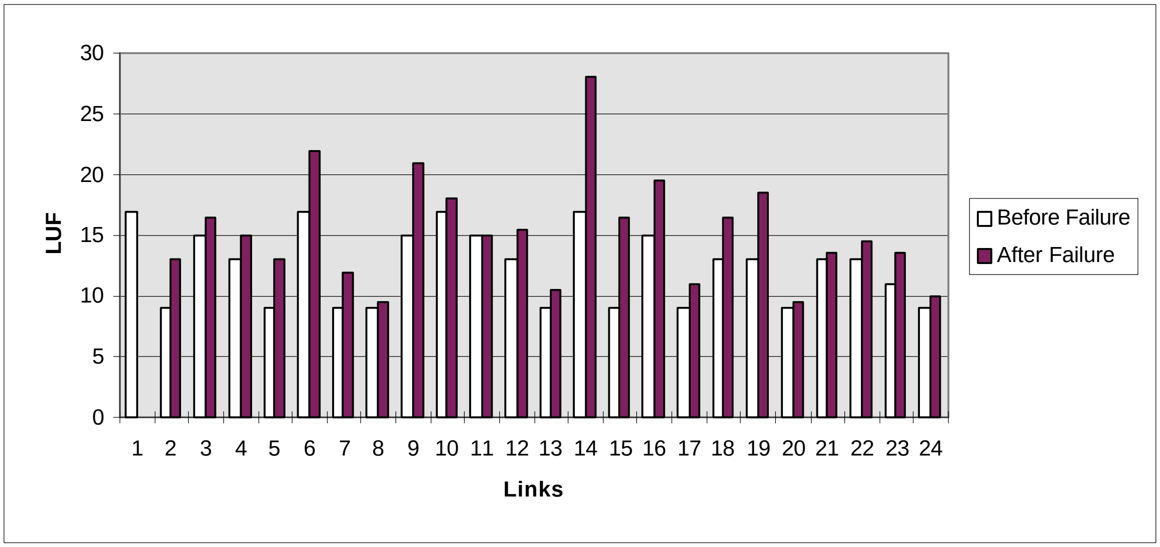

Figure 5.2: Graphical representation of LUF of topology 2 when busiest link B1-B2 fails.

Link 14 (B7-B8) has a 64 % increase in LUF, which is higher than topology 1.

5.2.2 Node Utilization Factors (NUFs)

As described in section 3.2 NUFs can be calculated directly from LUF tables (Tables 5.1 and 5.2) by just summing up the corresponding LUFs connected to that node. The NUFs for both the topologies are shown in the following tables (Table 5.3 and 5.4). Failed link is the same (i.e. link B1-B2) as before.

Note that:

- The maximum and minimum NUFs are 60.5 and 33. Average and S.D. of NUF are 44.56 and 8.37. Remember that the average and S.D. of NUF in no failure case were 36.5 and 6.54.

Table 5.3: Change in NUFs of Topology 1 When Link B1-B2 Fails.

Nodes	NUF before failure	Change in NUF after failure	Total NUF after failure
B1	46	4.5	50.5
B2	38	5.5	43.5
B3	38	12	50
B4	46	14.5	60.5
B5	46	3.5	49.5
B6	38	9	47
B7	38	14	52
B8	46	12.5	58.5
C1	34	5	39
C2	34	13.5	47.5
C3	34	2	36
C4	34	5	39
A1	28	9	37
A2	28	8.5	36.5
D1	28	5	33
D2	28	5.5	33.5

Table 5.4: Change in NUFs of Topology 2 When Link B1-B2 Fails.

Nodes	NUF before failure	Change in NUF after failure	Total NUF after failure
B1	41	5.5	46.5
B2	39	6	45
B3	39	10	49
B4	41	11.5	52.5
B5	41	1.5	42.5
B6	39	5	44
B7	39	21	60
B8	41	19.5	60.5
C1	37	7	44
C2	37	12	49
C3	37	1	38
C4	37	8	45
A1	29	14	43
A2	29	7	36
D1	35	10	45
D2	35	3	38

Note that:

- The maximum and minimum NUFs are 60.5 and 36. Average and S.D. of NUF are 46.125 and 6.73. Remember that the average and S.D. of NUF in no failure case were 37.25 and 3.66.
- Topology 2 has the same maximum NUF as topology 1. It has higher average NUF but a lower S.D. of NUF. Topology 2 is acting poorer in failure because the maximum NUF becomes equal to its counterpart (60.5) while it had much lower NUF in fault-free case (41 compared to 46). So the marginal increment of NUF is poorer in topology 2.

Corresponding graphical representations are given in Figure 5.3 and 5.4.Note that the nodes are also defined by numbers as was the links. The node definitions are given in Appendix D. Note that the maximum NUF of 60.5 is observed at node 4 (B4). It is 31% higher than the fault-free value (46).

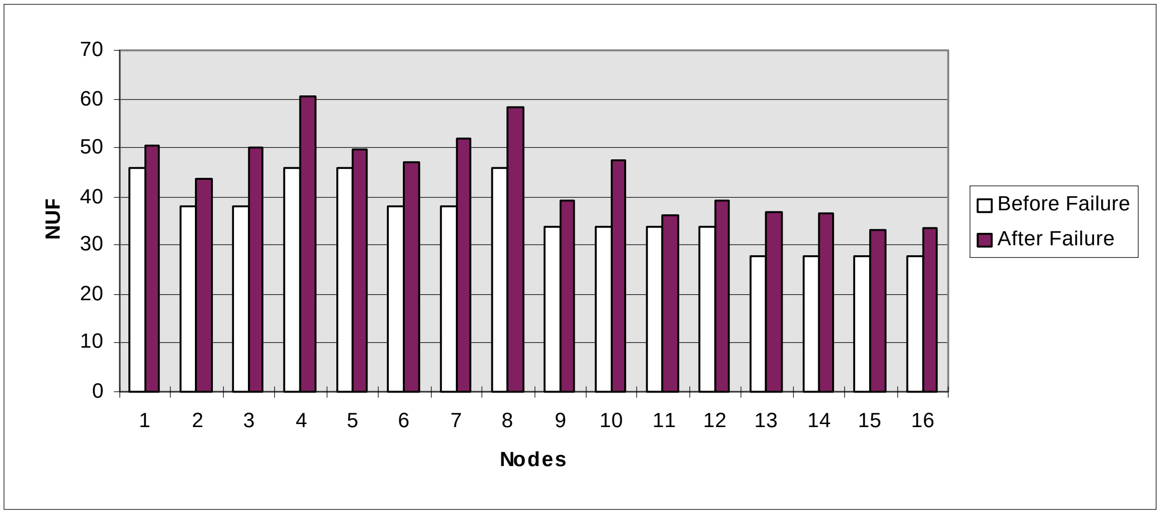

Figure 5.3: Graphical representation of NUF of topology 1 when busiest link B1-B2 fails

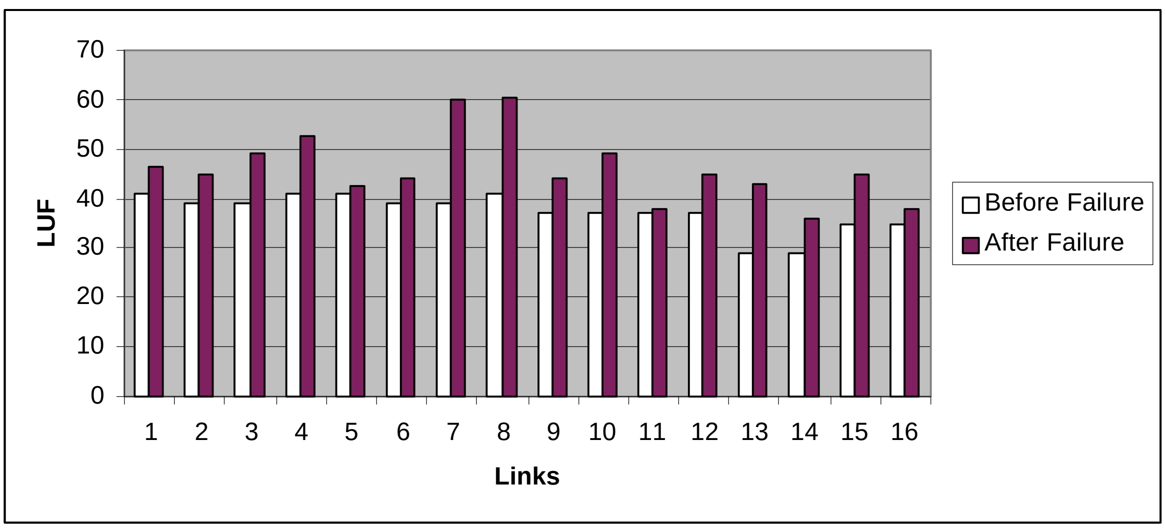

Figure 5.4: Graphical representation of NUF of topology 2 when busiest link B1-B2 fails.

Note that the maximum NUF of 60.5 is observed at node 8 (B8). It is 55% higher than the fault-free value (39). Also note that marginal increment in NUF (55% in place of 31%) is also much higher in topology 2.

Appendix E through H has all results (graphical representation) of utilization factors for both the topologies. More detailed discussion will be made about utilization factors in the next chapter where we will show comprehensive comparison between the topologies. Results are given in the following sub-sections.

5.3 Double-Link Failure

Double-link failures are more damaging for a communication network than single-link failures. Exhaustive double-link failure scenarios are not explored because there are 276 such different instances per topology. Rather we investigated what happens when we lose the highest loaded links. As described before, for both the topologies, B1-B2, B3-B4, B5-B6 and B7-B8 are most highly loaded links (LUF 17). We investigated what happens to LUF and NUF, when both B1-B2 and B3-B4 links fail simultaneously for both the topologies.

5.3.1 LUF Under Double-Link Failure:

Figure 5.5 shows the LUF of different links when both B1-B2 and B3-B4 links fail for topology 1. Note that:

- The maximum LUF is 34 for link 10 (B5-B6). Average and S.D. of LUF are 16.91 and 7.72. Remember that the average and S.D. of LUF in no failure case were 12.166 and 3.1.
- Link 10 (B7-B8) carries 17 unit of traffic in no-failure case. It carries 17 more units of load in this case. So utilization of link 10 is 100% greater than the fault-free case.

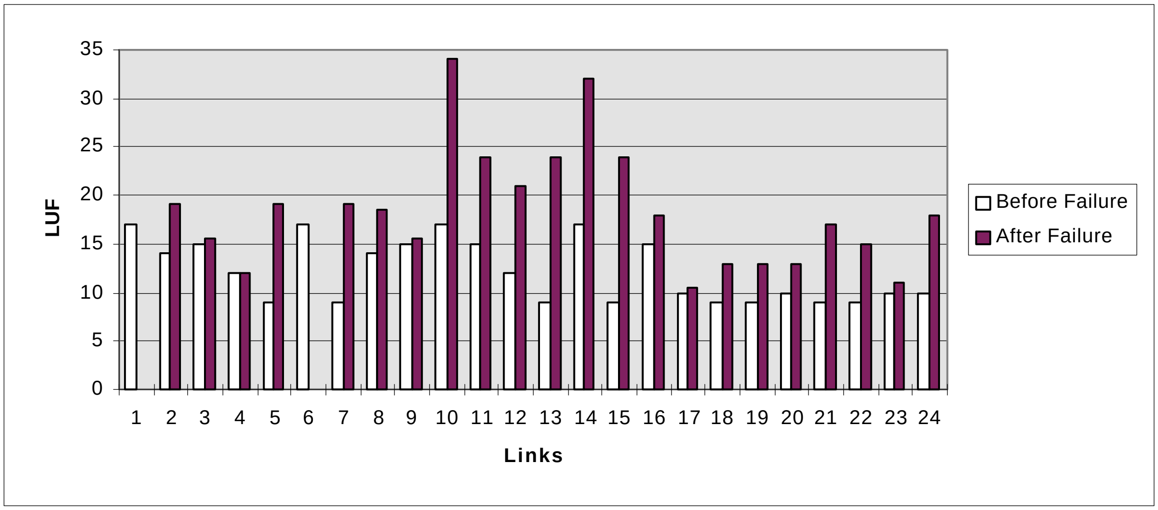

Figure 5.5: Utilization factors of different links when both B1-B2 and B3-B4 links fail simultaneously for topology 1.

Figure 5.6 shows similar results for topology 2.

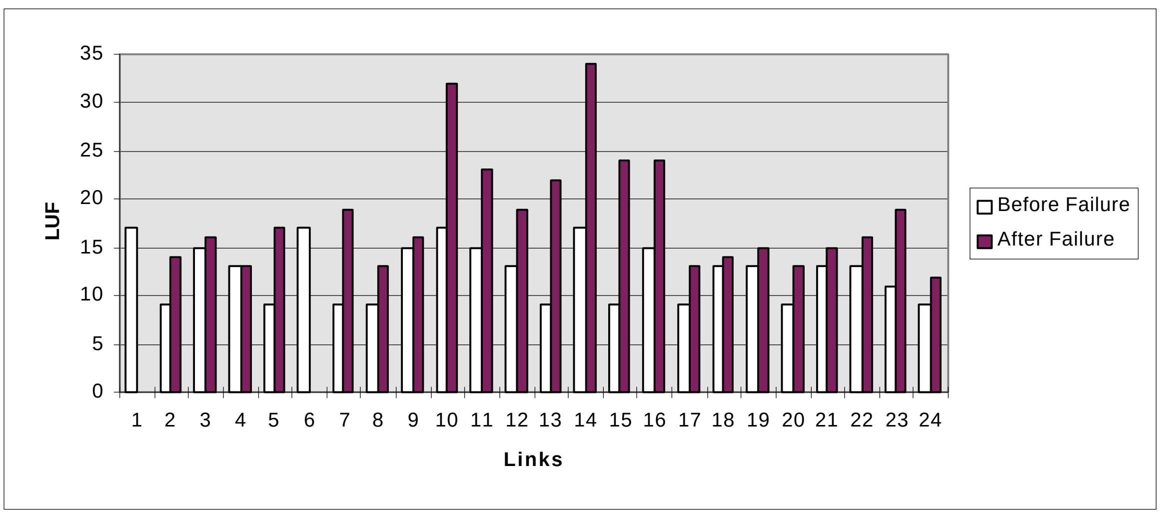

Figure 5.6: Utilization factors of different links when both B1-B2 and B3-B4 links fail simultaneously for topology 2.

- The maximum LUF is 34 for link 14 (B7-B8). Average and S.D. of LUF are 16.79 and 7.58. Remember that the average and S.D. of LUF in no failure case were 12.41 and 3.02.

- Link 14 (B7-B8) carries 17 units of traffic in no-failure case. It carries 17 more units of load in this case. So utilization of link 14 is 100% greater than the fault-free case. In double-link failure topology 2 is performing slightly better than topology 1. Both average LUF and S.D. of LUF are lower than topology 1.

5.3.2 NUF Under Double-Link Failure:

The following figures (Figure 5.7 and 5.8) show corresponding results for NUF. From Figure 5.7 note that for topology 1:

- Node 6 has highest NUF of 79 (39 in fault-free case). Utilization of this node is 108% greater than the fault-free case.
- Average NUF is 55.625 (36.5 in fault-free case). S.D. of NUF is 13.82 (6.54 in fault-free case).

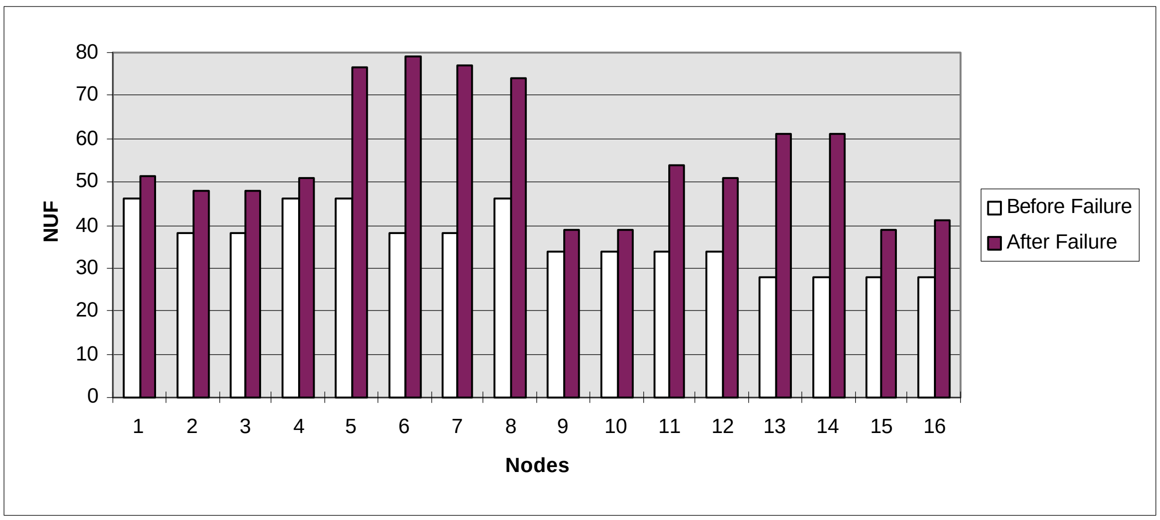

Figure 5.7: NUF of topology 1 when both B1-B2 and B3-B4 links fail simultaneously.

Figure 5.8 gives similar result for topology 2. Note that:

- Maximum NUF is 77 (node 7). Utilization of this node is 97.5% greater than the fault-free case.

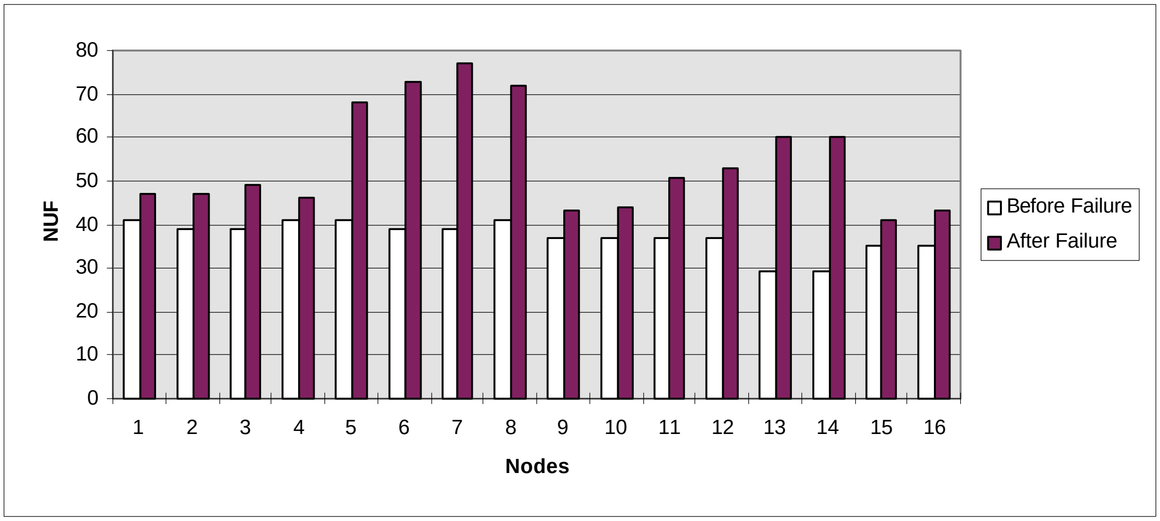

Figure 5.8: NUF of topology 2 when both B1-B2 and B3-B4 links fail simultaneously.

- Average NUF is 54.625 (37.25 in fault-free case) and S.D. of NUF is 11.68 (3.67 in fault-free case).
- In all respects topology 2 is performing better than topology 1 in this category.

5.4 Summary

Utilization factors under different failure conditions are studied in detail in this chapter. When a failure occurs traffic re-routing increases the utilization of other links and nodes. Only link failure cases are studied, because it gives the worst possible results. In general it is seen that average LUF and NUF are lower in topology 1 and S.D. of LUF and NUF are lower in topology 2. A structured comparison between topologies 1 and 2 will be done in the next chapter.

Chapter 6. Comparison Between Topologies

So far we have investigated different properties of both the topologies under normal and failure situations. In this chapter we will integrate all previous results to compare the topologies. Also in the second portion of this chapter, three different standard topologies (ring, star and square grid) are introduced. One special topology called the *star-ring* topology is also introduced, which will be shown to have some very desirable survivable capabilities. All these topologies are compared from different angles in this chapter.

6.1 Comparison Between Topology 1 and 2 in Fault-free Case

The following table (Table 6.1) shows the properties of both the topologies under normal (fault-free) condition.

Table 6.1: Summarized Properties of Both Topologies in Fault-free Condition.

Properties	Topology 1	Topology 2
Maximum route length	5	4
Average route length	2.43	2.48
Maximum link utilization factor (LUF)	17	17
Minimum LUF	9	9
Average LUF	12.17	12.42
S.D. of LUF	3.1	3.03
Maximum node utilization factor (NUF)	46	41
Minimum NUF	28	29
Average NUF	36.5	37.25
S.D. of NUF	6.54	3.67

From the table it is seen that maximum and minimum LUF for both the topologies are the same. So these two properties do not give any information about which one is the better topology. Note that topology 1 has higher maximum route length while it has lower average route length. Topology 1 also has lower average LUF and NUF. In section 3.1 it is proved that average LUF and average NUF are just scaled versions of average route length. So it is obvious that topology 1 should have lower average LUF and NUF, because it has lower average route length. So we might combine these three properties into one and say that topology 1 has only one advantage (either of average route length, average LUF or average NUF) over topology 2. On the other hand topology 2 has several distinct advantages over topology one. It has lower maximum route length, lower S.D. of LUF and NUF. It also has lower maximum NUF (41) than its counterpart (46). The minimum NUF in topology 2 is 29, which is higher than topology 1 (28). This is also an advantage, because both maximum and minimum utilization factors should be closer to their average value. So to summarize it can be said that topology 1 has lower average route length (or, average LUF or, average NUF) which indicates lower latency in the network; but it has several disadvantages in utilizing the links and nodes. So in fault-free case topology 2 performs better than topology 1.

6.2 Comparison Between Topology 1 and 2 in Faulty Cases

Single-link and node failure situations are investigated thoroughly. As there exists many combinations of double failures, some typical cases are studied. A fair idea can be obtained from these results. The following table (Table 6.2) shows the maximum route length to be traversed under different failure situations.

Table 6.2: Maximum Route Length Under Fault-free and Faulty (Single and Double) Conditions.

Failure Situation	Topology 1	Topology 2
No failure	5	4
Single-link failure	6	5
Single-node failure	6	5
Double-link failure	7	7
Double-node failure	7	7

Topology 2 is in clear advantageous position, because it is better than topology 1 in the first three rows of the table; i.e. topology 2 has lower maximum route length in no failure and single failure instances.

Table 6.3 shows the average route lengths in different failure situations.

Table 6.3: Average Route Length Under Fault-free and Faulty (Single and Double) Conditions.

Failure Situation	Topology 1	Topology 2
No failure	2.433	2.483
Single-link failure	2.525	2.588
Single-node failure	2.512	2.577
Double-link failure	3.383[1]	3.358[1]
Double-node failure	3.01[2]	2.89[2]

[1] Data taken for simultaneous link failure of links B1-B2 and B3-B4. This is not an overall average value. Rather it can be thought of worst average results for both the topologies

[2] Data taken for simultaneous node failure of B1 and B4. This is not an overall average value

A lower value of average route length is desired, because it means that the expected overall latency will be low. In this category, topology 1 shows better performance in fault-free and single failure cases. Topology 2 shows slightly better results in double failure situations. This result can also be extended for average LUF and average NUF. Those values will be just scaled versions of Table 6.3

Table 6.4 shows the maximum link utilization factor under fault-free and faulty situations. Note that no node failure instances are tabulated. We noted before that node failure has a smaller effect on route length because traffic injected and terminated from that node is disrupted.

Table 6.4: Maximum Link Utilization Factors (LUFs) Under Fault-free and Faulty (Single and Double-link Failure) Conditions.

Failure Situation	Topology 1	Topology2
No failure	17	17
Single-link failure	24	28
Double-link failure	34	34

The two topologies are essentially similar in no failure and double-link failure situations. Topology 1 performs better under single-link failure.

Table 6.5 shows S.D. of link utilization factor under no failure and failure situations. Node failure scenarios are not included again for the same reason.

Table 6.5: S.D. of Link Utilization Factor Under Fault-free and Faulty (Single and Double-link Failure) Conditions.

Failure Situation	Topology 1	Topology2
No failure	3.1	3.03
Single-link failure	4.62	4.82
Double-link failure	8.12	7.9

In this category topology 2 performs better in fault-free and double-link failure conditions. Topology 1 performs better in single-link failure situation.

Table 6.6 shows the maximum node utilization factor of both topologies under fault-free and faulty situations.

Table 6.6: Maximum Node Utilization Factor Under Fault-free and Faulty (Single and Double-link Failure) Conditions.

Failure Situation	Topology 1	Topology2
No failure	46	41
Single-link failure	60.5	60.5
Double-link failure	79	77

Topology 2 is again performing marginally better than its counterpart in faulty situation, but it performs considerably better in fault-free condition.

Table 6.7 shows S.D. of node utilization factor for both topologies under fault-free and faulty situations.

Table 6.7: S.D. of Node Utilization Factor Under Fault-free and Faulty (Single and Double-link Failure) Conditions.

Failure Situation	Topology 1	topology2
No failure	6.54	3.67
Single-link failure	7.33	5.43
Double-link failure	13.82	11.68

S.D. of NUF is far better for topology 2 in both fault-free and faulty cases.

In conclusion we may say that both the topologies are quite close in terms of properties that have been explored. Neither is superior to the other in all respects. In most of the cases it is seen that topology 1 has a lower average route length and utilization factors. However, topology 2 utilizes the links and nodes more uniformly. Now the choice of a topology is mostly dependent on the system requirement. If a more uniform utilization is required in the network, then topology 2 might be chosen. If a lower average utilization and route length is desired then topology 1 might be picked. But as indicated before, topology 1 is performing marginally better in the areas of average route length, NUF and LUF than its counterpart. But when we look at S.D. of utilization factors, which says about uniformity of utilization of the links and nodes, we see considerably better performance in topology 2. So we might recommend topology 2 as a better choice. Also as most of the time the network will be operating in fault-free situation, and as topology 2 is better in fault-free case, it would be a better choice. Also note that in all our calculations we considered a uniform loading on the network which is an oversimplification of the actual scenario. In tackling the actual traffic problem we might keep the highly loaded nodes closer to each other, so that the route length between them becomes less. Also from the uniform loading assumption we notice that nodes groups A and D are relatively under-utilized than node groups B and C. So in practical case we might try to form the routing table in such a way so that more of the traffic is carried through these underutilized A and D nodes in order to achieve uniformity in utilization.

6.3 Comparison Between the Topologies With Other Standard Topologies

Standard topologies that we consider for comparison are full ring, star and square grid. Figure 6.1 shows the standard topologies that we consider. For making a proper comparison we consider all the standard topologies to contain 16 nodes like our topologies. For all topologies two adjacent nodes have two simplex links connected between them, carrying traffic in opposite directions.

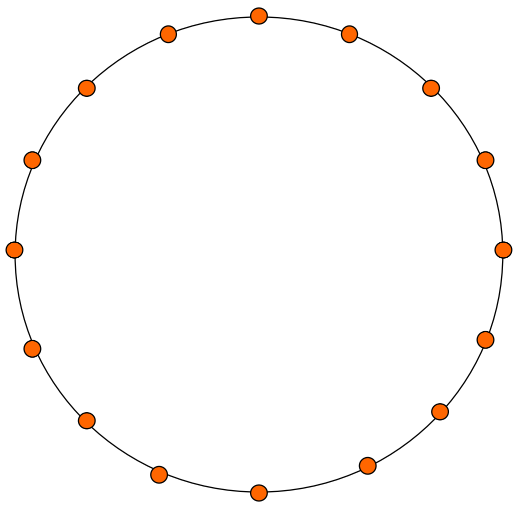

Figure 6.1(a): Full ring topology.

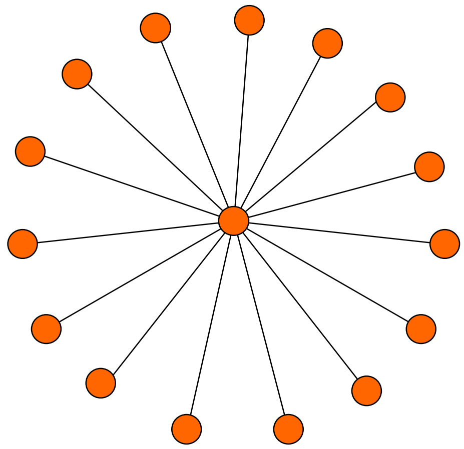

Figure 6.1 (b): Star topology.

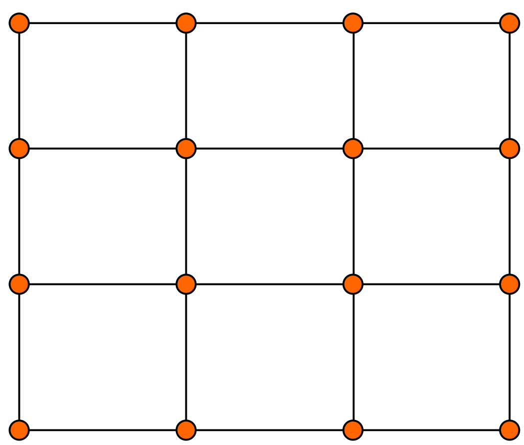

Figure 6.1 (c): Square grid topology.

Note that the ring topology is a regular network of connectivity 2, while the star and square grid topologies are not regular networks. In the star topology the central hub is connected to all peripheral nodes. If any two nodes want to communicate, they must do it via the central node. So it is seen that the central node in star topology is always heavily utilized. The central node takes part in every traffic routing. So if the central node fails the whole network goes into outage. That is why in star topologies a backup central hub is always kept for increasing the network survivability. The backup hub is also connected to every peripheral node but remains unoperational in normal mode. As soon as the central hub fails the backup central node starts acting as a central hub. It goes back to its original backup mode as soon as the central hub becomes operational. Note that the square grid topology is also a non-regular topology as the corner, side and interior nodes have different connectivity. There are 4 corner, 8 side, and 4 interior nodes in this square grid topology. The corner nodes have connectivity of 2, while the side and interior nodes have connectivity of 3 and 4 respectively.

In the following table (Table 6.8) some factors are tabulated for comparing these standard topologies with our topologies 1 and 2.

Table 6.8: Comparison of Topologies 1 & 2 With Other Standard Topologies.

Factors	Topology 1	Topology 2	Full Ring	Star	Square Grid
Number of links	24	24	16	15	24
Maximum route length (fault-free)	5	4	8	2	6
Average route length	2.43	2.48	4.26	1.87	2.7
Average route length under single-link failure	2.507	2.57	8	1.865	2.73
Average route length under single-node failure	2.495	2.558	7	**	2.6

From the table we see that ring has the minimum number of links. However it doesn't have any advantage over topologies 1 and 2 other than having fewer links. Fewer links will give a lower cost but eventually it increases the link utilization factors due to the lower number of links available. The ring topology has a maximum route length of 8. Such a high route length is observed when two diagonally opposite nodes try to communicate. The average route length is 4.26, which is substantially higher than both topologies 1 and 2. Average route lengths under failure situations are also higher for the full ring topology.

The square grid topology also has higher maximum route length (6) than both topologies 1 and 2. The maximum route length is observed when two corner nodes try to communicate. It also has a higher average route length in both fault-free and faulty situations. But we notice a decrease of average route length in a single-node failure situation from that of the fault-free case. This is a small advantage of square grid topology over topologies 1 and 2.

The star topology shows some interesting results, which need to be explained. The star topology has a maximum route length of only 2. We notice such route length when any 2 peripheral nodes communicate. It also has a substantially lower average route length than its counterparts in both fault-free and single-link failure cases. These advantages are obtained at the expense of higher link and node utilization factors and more vulnerability of the network under failure situations. Note that all communication is via the central node, which eventually indicates an abnormally high NUF of the central node. Also note that as the peripheral nodes have only one link which is connected to the central node, the corresponding LUF of all these links are approximately tripled relative to those of topologies 1 and 2. Note that topologies 1 and 2 have connectivity of 3, they can distribute the traffic to and from that node approximately equally among the connected three links. Both topologies 1 and 2 remain connected under all possible single and double failures (either link or node). But in star topology any link failure causes isolation (network partitioning) of that node from other nodes. This is a great disadvantage.

As described before, node failures in case of star topology may cause severe consequences. The failure of the central node causes the whole network to become unoperational. That is why in the Table 6.8 we use asterisks (**) in the node failure case. But we showed in section 4.7 that even with 4 or more simultaneous node failures the network (topologies 1 and 2) remain connected in most of the cases. By adding an additional central backup node the survivability of the star network can be increased. But in that case the number of links will increase to 31 which will cost more. So even though star topology is showing some advantages over topologies 1 and 2 it has some severe disadvantages which make this topology more vulnerable in survivability in case of network failures.

So we may conclude that both topologies 1 and 2 are better than all their counterparts in almost all respects.

6.4 The Star-Ring Topology

If we withdraw the central node from the star topology and connect the peripheral nodes with links like a full ring topology then we get a *star-ring* topology (see Figure 6.2). In other words, it is a full ring structure with all nodes having an additional connection with the node, which is diametrically opposite to it. This is a very interesting topology having some advantageous properties over topologies 1 and 2. Note that star-ring topology is also a regular network with connectivity 3. In fact star-ring topology is the most symmetric topology that one might get which has a connectivity of 3. It is the most symmetric structure because the rest of the network looks the same with respect to every node. We also notice some symmetry in topologies 1 and 2. Note that both the topologies are symmetric about either the A, D or C nodes. For example, topologies 1 and 2 look the same about either of the nodes C1, C2, C3 or C4 (Figure 6.3).

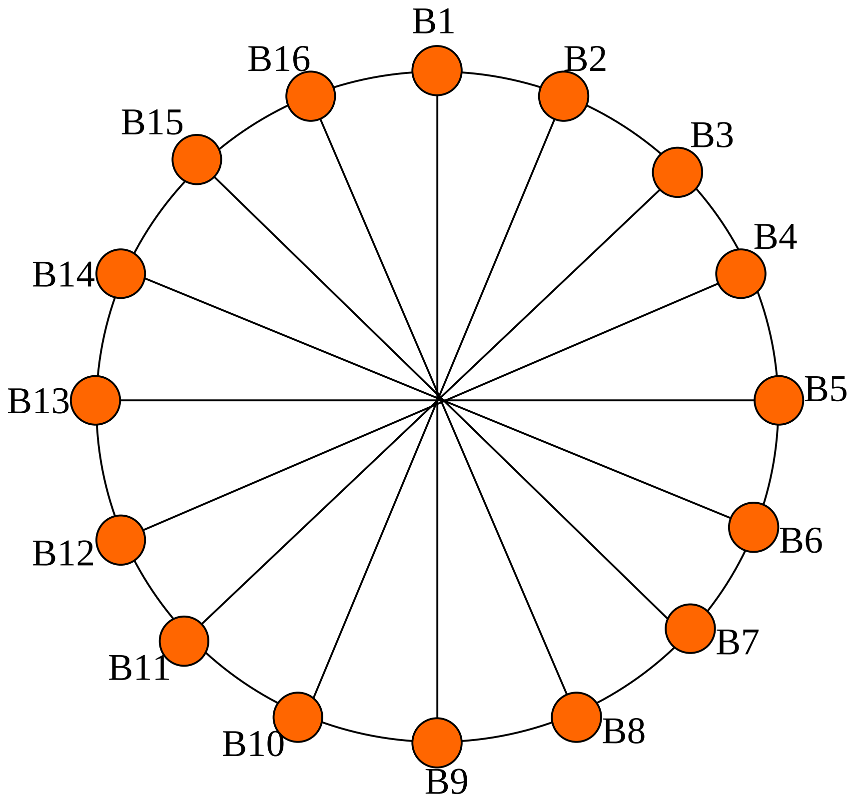

Figure 6.2: The Star-Ring topology.

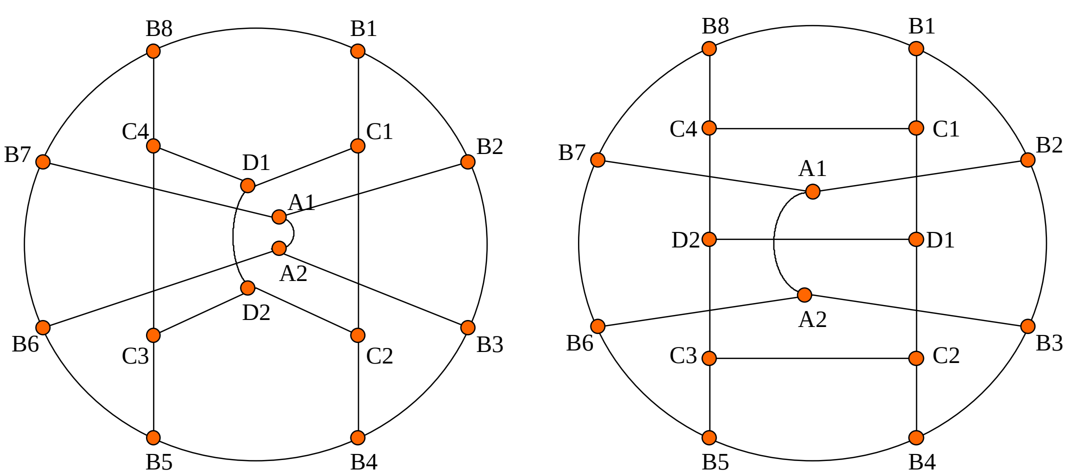

Figure 6.3: Topologies 1 and 2 have some symmetry, but not all of its nodes are symmetrical to each other.

This is why, we get similar results for these nodes (See Tables 3.3, 3.4, 4.1 and 4.2). Symmetry might also be extended to the links. We might say that links (B1-B2), (B3-B4), (B5-B6), and (B7-B8) are symmetric. That is why we also get same results for these links (see Tables 4.3 and 4.4). But the difference of symmetry between the topologies (1 and 2) and the star-ring topology is that, star-ring topology is fully symmetric, while topologies 1 and 2 are partially symmetric. There are a number of advantages of a symmetric (or regular) network. The routing strategy might be made relatively simpler in a regular network; i.e., the routes used by the symmetric source destination pair should be similar. A more regular network usually uses its nodes more uniformly; i.e., S.D. of NUF can be reduced if a regular network is used.

Note that for the star-ring topology there are
24 node pairs, which are 1-unit, distance apart,
32 node pairs, which are 2,3 or 4-unit, distance apart.

So the average distance:

$$\overline{D} = \frac{\sum d_x n_x}{\sum n_x} = \frac{1\times 24 + 2\times 32 + 3\times 32 + 4\times 32}{24+40+38+16+2} = \frac{312}{120} = 2.6$$

There are two types of links in this topology. The links in the circular ring are called *ring links* and the links connecting the diagonal nodes are called *diagonal links*. Due to symmetry each *ring-link* has the LUF of 16 while each *diagonal-link* has LUF of 7.

So, average LUF = $\dfrac{16\times 16 + 8\times 7}{24} = 13$

and S.D. of LUF = 4.24

NUF can be found just by adding the LUF of the corresponding node. Here all the nodes are connected to two ring-link and one diagonal-link. So every node has a utilization factor of, $(2\times 16 + 7) =$ 39. As all the nodes are symmetrical then the average NUF is same as the NUF of each node, i.e.; 39. So there is no variation in utilizing the nodes, which means that S.D. of NUF is 0.

6.4.1 Failure Situation

Consider that one of the ring-links (which is also the highest utilized link with LUF of 16) fails. In that case the average route length becomes 2.85. The following two figures (Figure 6.4 and 6.5) show the LUF and NUF of star-ring topology under single-link failure. The link and node definitions are given in Appendix I.

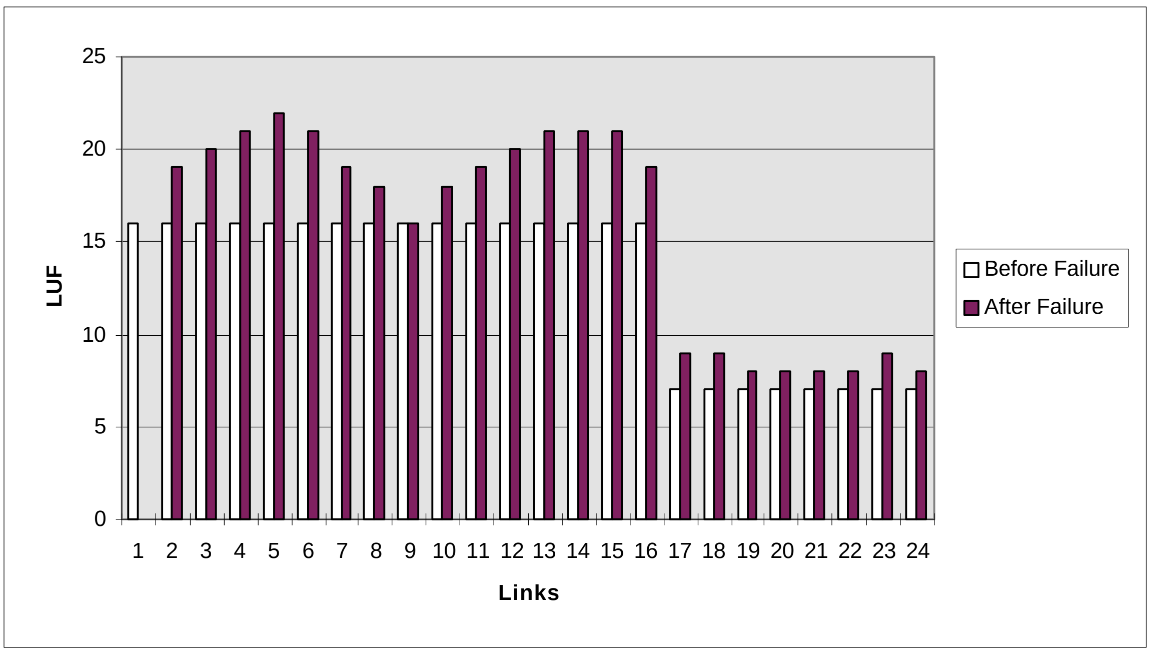

Figure 6.4: LUF of star-ring topology under link B1-B2 failed.

Note that the maximum LUF is 22 (link 5). The average LUF is 15.083 (13 in fault-free case) and S.D. of LUF is 6.257 (4.28 in fault-free case). Utilization of link 5 is 37.5% greater than the fault-free case.

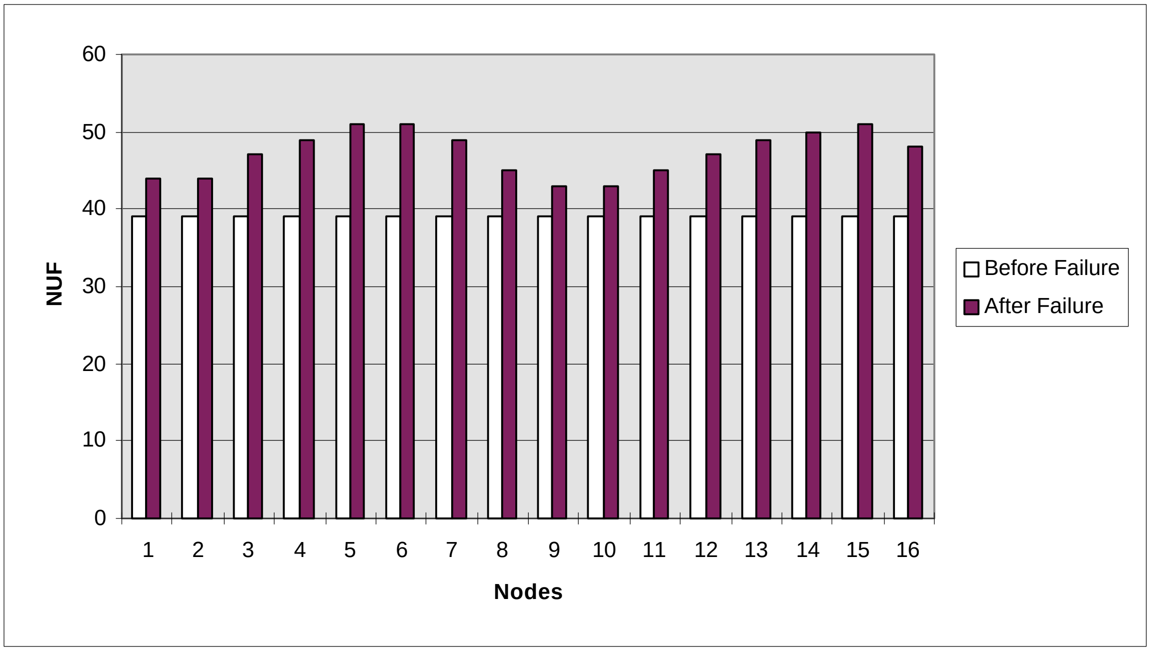

Figure 6.5: NUF of star-ring topology under link B1-B2 failed.

Note that, the maximum NUF is 51 (nodes 5, 6 and 15). The average NUF is 47.25 (39 in fault-free case) and S.D. of NUF is 2.817 (0 in fault-free case). Utilization of nodes 5, 6 and 15 are 30.77% greater than the fault-free case.

6.5 Comparison Among Topology 1, Topology 2 and the Star-Ring Topology

From Table 6.9 we get an overall comparative picture of topologies 1 and 2 and the star-ring topology. The average route length is 2.6, which is greater than both topologies 1 and 2. Star-ring topology is performing marginally poorer than topologies 1 and 2 when we consider LUFs. But due to high symmetry, star-ring topology is performing very well in utilizing the nodes.

Table 6.9: Comparison Among Topology 1, Topology 2 and the Star-Ring Topology

Properties	Topology 1	Topology 2	Star-Ring
Maximum route length	5	4	4
Average route length	2.43	2.48	2.6
Maximum link utilization factor (LUF)	17	17	16
Minimum LUF	9	9	7
Average LUF	12.17	12.42	13
S.D. of LUF	3.1	3.03	4.24
Maximum node utilization factor (NUF)	46	41	39
Minimum NUF	28	29	39
Average NUF	36.5	37.25	39
S.D. of NUF	6.54	3.67	0

The following tables (Table 6.10 through 6.15) show comparative performance of the three topologies under failure conditions.

Table 6.10: Maximum Route Length Under Fault-free and Faulty (Single and Double) Conditions.

Failure Situation	Topology 1	Topology 2	Star-Ring
No failure	5	4	4
Single-link failure	6	5	8
Single-node failure	6	5	8
Double-link failure	7	7	8
Double-node failure	7	7	8

Although the star-ring topology is somewhat better in fault-free case, it is poorer than both topologies 1 and 2 under failure conditions

Table 6.11 shows the average route length under fault-free and single failure situations. All worst possible results are tabulated. We note again that topologies 1 and 2 perform better than the star-ring topology.

Table 6.11: Average Route Length Under Fault-free and Faulty (Single Failure) Conditions.

Failure Situation	Topology 1	Topology 2	Star-Ring
No failure	2.433	2.483	2.6
Single-link failure	2.583	2.67	2.85
Single-node failure	2.61	2.62	2.75

Table 6.12 shows the maximum LUF under fault-free and single failure conditions. This is obviously an improved property of star-ring topology than its counterparts. The results are especially better under failure situations.

Table 6.12: Maximum LUF of Topologies 1 and 2 and the Star-Ring Topology Under Fault-free and Faulty (Single Failure) Conditions.

Failure Situation	Topology 1	Topology2	Star-Ring
No failure	17	17	16
Single-link failure	24	28	22
Double-link failure	34	34	28

Table 6.13 shows S.D. of link utilization factor under no failure and failure situations. Worst possible values are tabulated. It is seen that star-ring is performing poorer than

topologies 1 and 2. Value of S.D. for double-link failure is not calculated for star-ring topology. But it is assumed that it would be worse.

Table 6.13: S.D. of Link Utilization Factor Under Fault-free and Faulty (Single and Double-link Failure) Conditions.

Failure Situation	Topology 1	Topology2	Star-Ring
No failure	3.1	3.03	4.24
Single-link failure	5	5.71	6.26
Double-link failure	8.12	7.9	??

Table 6.14 shows the maximum node utilization factor of all the topologies under fault-free and faulty situations. In utilizing the nodes star-ring performs better than topologies 1 and 2 both in fault-free and faulty cases.

Table 6.14: Maximum Node Utilization Factor Under Fault-free and Faulty (Single and Double-link Failure) Conditions.

Failure Situation	Topology 1	Topology2	Star-Ring
No failure	46	41	39
Single-link failure	60.5	60.5	54
Double-link failure	79	77	69

Table 6.15 shows S.D. of node utilization factor for all topologies under fault-free and faulty situations. Star-ring topology is clearly performing better than its counterparts in this category. The substantially lower values of S.D. of NUF come from the regularity of the topology.

Table 6.15: S.D. of Node Utilization Factor Under Fault-free and Faulty (Single and Double-link Failure) Conditions.

Failure Situation	Topology 1	topology2	Star-Ring
No failure	6.54	3.67	0
Single-link failure	7.33	5.43	2.81
Double-link failure	13.82	11.68	??

So on the whole it can be said that although star-ring topology has slightly higher average route length (and also average LUF and NUF) than topologies 1 and 2, it utilizes all its links and nodes uniformly. So when uniformity of nodes is of prime concern this topology may be used.

Star-ring topology also suffers from some other disadvantages. This topology cannot be used for *static disjoint routing* because no source-destination pairs have 3 distinct disjoint paths between them.

6.6 Summary

This chapter concentrates on the comparison between different topologies. At first topologies 1 and 2 were compared. It is seen that both the topologies have some advantages and some disadvantages. Neither of them was proven to be better in all respects. In almost all of the cases topology 1 has lower average route length, LUF and NUF. But topology 2 has lower S.D. of LUF and NUF. Also in the fault-free case topology 2 has more advantages than its counterpart. Consequently topology 2 is recommended as a better topology.

Next these topologies were compared with full ring, star and square grid topologies. In all respects topologies 1 and 2 were proven to be superior.

Star-ring topology was introduced finally. It has more regularity than topologies 1 and 2. So it is found that uniformity in utilization is much better in star-ring topology than topologies 1 and 2. But it also has some disadvantage. It has higher average route length, LUF and NUF. It also cannot be used to adopt disjoint routing strategy.

Chapter 7. Conclusions

In the previous chapter we compared different properties of the two topologies. It was seen that neither topology is superior to the other in all respects. In this chapter we integrate the results of the previous chapter to provide an overall summary of the topologies.

Table 7: Overall Comparison Between the Topologies.

Properties	Topology 1	Topology 2
Fault-free		
Maximum Route Length		*
Average Route Length or, Average LUF or, Average NUF	*	
S.D. of LUF		*
Maximum Node Utilization		**
Minimum Node Utilization		*
S.D. Of NUF		**
Single-Link Failure		
Maximum Route Length		*
Average Route Length or, Average LUF or, Average NUF	*	
S.D. of LUF	*	
S.D. of NUF		*
Double-link Failure		
Average Route Length or, Average LUF or, Average NUF		*
S.D. of LUF		*
Maximum NUF		*
S.D. of NUF		*
Single-Node Failure		
Maximum Route Length		*
Average Route Length or, Average LUF or, Average NUF	*	
Double-node Failure		
Average Route Length or, Average LUF or Average NUF		*

Two different legends are used in the table instead of numeric values, which are provided in the previous chapter. An asterisk (*) is used to indicate a marginal superiority of a topology in that property. A double asterisk (**) indicates a clear superiority of the topology. Instances of *"stalemates"* between the topologies are not included in the table. The results are given in Table 7.

From the table it is clearly evident that in most of the cases topology 2 is better than topology 1. Topology 2 has eleven marginal advantages while topology 1 has only four. Also, Topology 2 also has two clear advantages while topology 1 has none. This is why on the whole we recommend that topology 2 is a better choice as a survivable topology.

One of the interesting extensions of the work done in this thesis might be evaluating performance of a larger network. A scaled network might be regular or non-regular. Referring to Figure 7.1 we notice a regular-scaled network (7.1 (a)) and a non-regular scaled network (Figure 7.1(b)). In the regular-scaled network the connectivity of 3 is maintained. Notice in Figure 7.1(b) the regularity of the network has not been maintained because of the insertion of node C5 that has a connectivity of 2 instead of 3. Also note that in Figure 7.1(a) that even though the regularity of the network is maintained, the symmetry of the network is severely harmed from its mother topology. It is expected that the performance of a scaled regular network would be better than the non-regular one. It is also expected that performance of a regular-symmetric network would be better than the regular-asymmetric network. In Figure 7.2 a regular symmetric network is shown. Note that this scaled version has maintained both regularity and symmetry. The scaled network of Figure 7.1 (a) is a regular-asymmetric network.

Application of graph theory might be an interesting future work. We have given the idea of disjoint routing in this thesis. We have also shown that both the topologies have exactly three disjoint paths between every source-destination node pairs. But we didn't investigate why these topologies have this interesting property. We can think of applying conjectures of graph theory on these topologies and investigate why these topologies are showing such property. We can also solve the problem of building a new network topology applying graph theory, which would have regularity, symmetry and disjoint paths to apply the easier disjoint routing method.

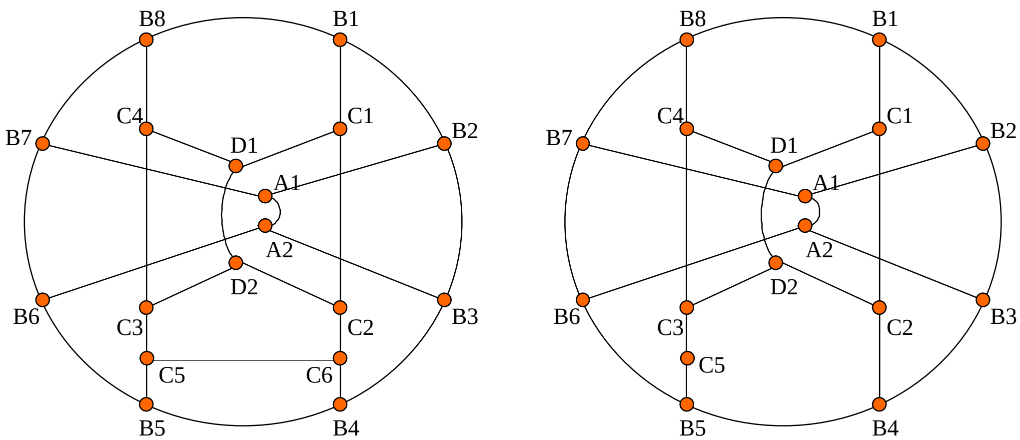

Figure 7.1: (a) A regular scaled version of topology 1. Note that by inserting nodes C5 and C6 and connecting them by a link the regularity of the network is maintained. (b) A non-regular scaled version of topology 1. Note that C5 has a connectivity of 2. So this scaled version is non-regular.

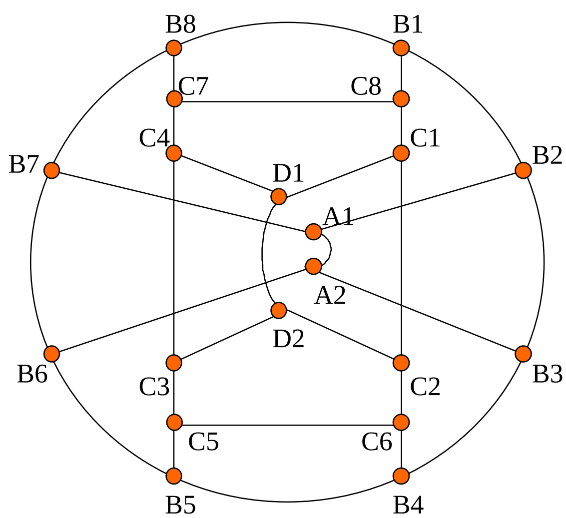

Figure 7.2: A regular symmetric scaled version of topology 1.

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Appendix A

ROUTING TABLE (Topology 1)

- The Routing Table is constructed with a minimum distance approximation.
- The usual or normal route is kept at the top.
- The other 2 routing paths also are shown which are fully mutually exclusive with each other.
- Table is formed according to route length.

Source	Destination	Route	Length
B1	B2	B1-B2 B1-B8-B7-A1-B2 B1-C1-C2-B4-B3-B2	1 4 5
B1	B8	B1-B8 B1-C1-D1-C4-B8 B1-B2-A1-B7-B8	1 4 4
B1	C1	B1-C1 B1-B8-C4-D1-C1 B1-B2-B3-B4-C2-C1	1 4 5
B2	B3	B2-B3 B2-A1-A2-B3 B2-B1-C1-C2-B4-B3	1 3 5
B2	A1	B2-A1 B2-B3-A2-A1 B2-B1-B8-B7-A1	1 3 4
B3	B4	B3-B4 B3-A2-B6-B5-B4 B3-B2-B1-C1-C2-B4	1 4 5
B3	A2	B3-A2 B3-B2-A1-A2 B3-B4-B5-B6-A2	1 3 4
B4	B5	B4-B5 B4-C2-D2-C3-B5 B4-B3-A2-B6-B5	1 4 4
B4	C2	B4-C2 B4-B5-C3-D2-C2 B4-B3-B2-B1-C1-C2	1 4 5
B5	B6	B5-B6 B5-B4-B3-A2-B6 B5-C3-C4-B8-B7-B6	1 4 5
B5	C3	B5-C3 B5-B4-C2-D2-C3 B5-B6-B7-B8-C4-C3	1 4 5
B6	B7	B6-B7 B6-A2-A1-B7 B6-B5-C3-C4-B8-B7	1 3 5
B6	A2	B6-A2 B6-B7-A1-A2 B6-B5-B4-B3-A2	1 3 4

B7	B8	B7-B8 B7-A1-B2-B1-B8 B7-B6-B5-C3-C4-B8	1 4 5
B7	A1	B7-A1 B7-B6-A2-A1 B7-B8-B1-B2-A1	1 3 4
B8	C4	B8-C4 B8-B1-C1-D1-C4 B8-B7-B6-B5C3-C4	1 4 5
C1	C2	C1-C2 C1-D1-D2-C2 C1-B1-B2-B3-B4-C2	1 3 5
C1	D1	C1-D1 C1-C2-D2-D1 C1-B1-B8-C4-D1	1 3 4
C2	D2	C2-D2 C2-C1-D1-D2 C2-B4-B5-C3-D2	1 3 4
C3	C4	C3-C4 C3-D2-D1-C4 C3-B5-B6-B7-B8-C4	1 3 5
C3	D2	C3-D2 C3-C4-D1-D2 C3-B5-B4C2-D2	1 3 4
C4	D1	C4-D1 C4-C3-D2-D1 C4-B8-B1-C1-D1	1 3 4
D1	D2	D1-D2 D1-C4-C3-D2 D1-C1-C2-D2	1 3 3
A1	A2	A1-A2 A1-B2-B3-A2 A1-B7-B6-A2	1 3 3
B1	B3	B1-B2-B3 B1-C1-C2-B4-B3 B1-B8-B7-A1-A2-B3	2 4 5
B1	B7	B1-B8-B7 B1-B2-A1-B7 B1-C1-C2-B4-B5-B6-B7	2 3 6
B1	C4	B1-B8-C4 B1-C1-D1-C4 B1-B2-B3-B4-B5-C3-C4	2 3 6
B1	A1	B1-B2-A1 B1-B8-B7-A1 B1-C1-C2-B4-B3-A2-A1	2 3 6
B1	C2	B1-C1-C2 B1-B2-B3-B4-C2 B1-B8-C4-D1-D2-C2	2 4 5
B1	D1	B1-C1-D1 B1-B8-C4-D1 B1-B2-B3-B4-C2-D2-D1	2 3 6

B8	B6	B8-B7-B6 B8-C4-C3-B5-B6 B8-B1-B2-B3-A2-B6	2 4 5
B8	A1	B8-B7-A1 B8-B1-B2-A1 B8-C4-C3-B5-B6-A2-A1	2 3 6
B8	C3	B8-C4-C3 B8-B7-B6-B5-C3 B8-B1-C1-D1-D2-C3	2 4 5
B8	D1	B8-C4-D1 B8-B1-C1-D1 B8-B7-B6-B5-C3-D2-D1	2 3 6
B8	C1	B8-B1-C1 B8-C4-D1-C1 B8-B7-B6-B5-B4-C2-C1	2 3 6
B8	B2	B8-B1-B2 B8-B7-A1-B2 B8-C4-C3-B5-B4-B3-B2	2 3 6
B2	C1	B2-B1-C1 B2-B3-B4-C2-C1 B2-A1-B7-B8-C4-D1-C1	2 4 6
B2	A2	B2-A1-A2 B2-B3-A2 B2-B1-B8-B7-B6-A2	2 2 5
B2	B7	B2-A1-B7 B2-B1-B8-B7 B2-B3-A2-B6-B7	2 3 4
B2	B4	B2-B3-B4 B2-B1-C1-C2-B4 B2-A1-A2-B6-B5-B4	2 4 5
B3	A1	B3-A2-A1 B3-B2-A1 B3-B4-B5-B6-B7-A1	2 2 5
B3	C2	B3-B4-C2 B3-B2-B1-C1-C2 B3-A2-B6-B5-C3-D2-C2	2 4 6
B3	B5	B3-B4-B5 B3A2-B6-B5 B3-B2-B1-B8-B7-B6-B5	2 3 6
B3	B6	B3-A2-B6 B3-B4-B5-B6 B3-B2-A1-B7-B6	2 3 4
B4	A2	B4-B3-A2 B4-B5-B6-A2 B4-C2-C1-B1-B2-A1-A2	2 3 6
B4	C1	B4-C2-C1 B4-B3-B2-B1-C1 B4-B5-C3-C4-D1-C1	2 4 5
B4	D2	B4-C2-D2 B4-B5-C3-D2 B4-B3-B2-B1-C1-D1-D2	2 3 6
B4	B6	B4-B5-B6	2

		B4-B3-A2-B6 B4-C2-C1-B1-B8-B7-B6	3 6
B4	C3	B4-B5-C3 B4-C2-D2-C3 B4-B3-B2-B1-B8-C4-C3	2 3 6
B5	B7	B5-B6-B7 B5-C3-C4-B8-B7 B5-B4-B3-A2-A1-B7	2 4 5
B5	A2	B5-B6-A2 B5-B4-B3-A2 B5-C3-C4-B8-B7-A1-A2	2 3 6
B5	C4	B5-C3-C4 B5-B6-B7-B8-C4 B5-B4-C2-D2-D1-C4	2 4 5
B5	D2	B5-C3-D2 B5-B4-C2-D2 B5-B6-B7-B8-C4-D1-D2	2 3 6
B5	C2	B5-B4-C2 B5-B4-C2-D2 B5-B6-B7-B8-C4-D1-D2	2 3 6
B6	A1	B6-A2-A1 B6-B7-A1 B6-B5-B4-B3-B2-A1	2 2 5
B6	C3	B6-B5-C3 B6-B7-B8-C4-C3 B6-A2-B3-B4-C2-D2-C3	2 4 6
B7	C4	B7-B8-C4 B7-B6-B5-C3-C4 B7-A1-B2-B1-C1-D1-C4	2 4 6
B7	A2	B7-A1-A2 B7-B6-A2 B7-B8-B1-B2-B3-A2	2 2 5
C1	D2	C1-D1-D2 C1-C2-D2 C1-B1-B8-C4-C3-D2	2 2 5
C1	C4	C1-D1-C4 C1-B1-B8-C4 C1-C2-D2-C3-C4	2 3 4
C2	D1	C2-D2-D1 C2-C1-D1 C2-B4-B5-C3-C4-D1	2 2 5
C2	C3	C2-D2-C3 C2-B4-B5-C3 C2-C1-D1-C4-C3	2 3 4
C3	D1	C3-D2-D1 C3-C4-D1 C3-B4-B5C2-C1-D1	2 2 5
C4	D2	C4-D1-D2 C4-C3-D2 C4-B8-B1-C1-C2-D2	2 2 5
B1	B6	B1-B8-B7-B6	3

		B1-B2-A1-A2-B6 B1-C1-C2-B4-B5-B6	4 5
B1	B4	B1-C1-C2-B4 B1-B2-B3-B4 B1-B8-C4-C3-B5-B4	3 3 5
B1	C3	B1-B8-C4-C3 B1-C1-D1-D2-C3 B1-B2-B3-B4-B5-C3	3 4 5
B1	A2	B1-B2-A1-A2 B1-B8-B7-B6-A2 B1-C1-C2-B4-B3-A2	3 4 5
B1	D2	B1-C1-D1-D2 B1-B8-C4-C3-D2 B1-B2-B3-B4-B5-C2-D2	3 4 5
B2	C2	B2-B3-B4-C2 B2-B1-C1-C2 B2-A1-A2-B6-B5C3-D2-C2	3 3 7
B2	D1	B2-B1-C1-D1 B2-A1-B7-B8-C4-D1 B2-B3-B4-C2-D2-D1	3 5 5
B2	C4	B2-B1-B8-C4 B2-A1-A2-B6-B5-C3-C4 B2-B3-B4-C2-D2-D1-C4	3 6 6
B2	B5	B2-B3-B4-B5 B2-A1-B7-B6-B5 B2-B1-B8-C4-C3-B5	3 4 5
B2	B6	B2-A1-B7-B6 B2-B3-A2-B6 B2-B1-C1-C2-B4-B5-B6	3 3 6
B3	B8	B3-B2-B1-B8 B3-A2-B6-B7-B8 B3-B4-B5-C3-C4-B8	3 4 5
B3	B7	B3-A2-B6-B7 B3-B2-A1-B7 B3-B4-C2-C1-B1-B8-B7	3 3 6
B3	C1	B3-B2-B1-C1 B3-B4-C2-C1 B3-A2-A1-B7-B8-C4-D1-C1	3 3 7
B3	D2	B3-B4-C2-D2 B3-A2-B6-B5-C3-D2 B3-B2-B1-C1-D1-D2	3 5 5
B3	C3	B3-B4-B5-C3 B3-A2-A1-B7-B8-C4-C3 B3-B2-B1-C1-D1-D2-C3	3 6 6
B4	B7	B4-B5-B6-B7 B4-B3-A2-A1-B7 B4-C2-C1-B1-B8-B7	3 4 5
B4	A1	B4-B3-A2-A1 B4-B5-B6-B7-A1 B4-C2-C1-B1-B8-B2-A1	3 4 5
B4	D1	B4-C2-D2-D1 B4-B5-C3-C4-D1	3 4

		B4-B3-B2-B1-C1-D1	5
B4	C4	B4-B5-C3-C4 B4-C2-C1-D1-C4 B4-B3-B2-B1-B8-C4	3 4 5
B5	B8	B5-C3-C4-B8 B5-B6-B7-B8 B5-B4-C2-C1-B1-B8	3 3 5
B5	D1	B5-C3-D2-D1 B5-B4-C2-C1-D1 B5-B6-B7-B8C4-D1	3 4 5
B5	A1	B5-B6-A2-A1 B5-B4-B3-B2-A1 B5-C3-C4-B8-B7-A1	3 4 5
B5	C1	B5-B4-C2-C1 B5-C3-D2-D1-C1 B5-B6-B7-B8-B1-C1	3 4 5
B6	C2	B6-B5-B4-C2 B6-A2-B3-B2-B1-C1-C2 B6-B7-B8-C4-D1-D2-C2	3 6 6
B6	C4	B6-B5-C3-C4 B6-B7-B8-C4 B6-A1-A2-B2-B1-C1-D1-C4	3 3 7
B6	D2	B6-B5-C3-D2 B6-B7-B8-C4-D1-D2 B6-A2-B3-B4-C2-D2	3 5 5
B7	C1	B7-B8-B1-C1 B7-A1-B2-B3-B4-C2-C1 B7-B6-B5-C3-D2-D1-C1	3 6 6
B7	C3	B7-B8-C4-C3 B7-B6-B5-C3 B7-A1-B2-B3-B4-C2-D2-C3	3 3 7
B7	D1	B7-B8-C4-D1 B7-A1-B2-B1-C1-D1 B7-B6-B5-C3-D2-D1	3 5 5
B8	A2	B8-B7-A1-A2 B8-B1-B2-B3-A2 B8-C4-C3-B5-B4-B6-A2	3 4 5
B8	D2	B8-C4-D1-D2 B8-B1-C1-C2-D2 B8-B7-B6-B5-C3-D2	3 4 5
B8	C2	B8-B1-C1-C2 B8-C4-C3-D2-C2 B8-B7-B6-B5-B4-C2	3 4 5
C1	C3	C1-C2-D2-C3 C1-D1-C4-C3 C1-B1-B2-B3-B4-B5-C3	3 3 6
C1	A1	C1-B1-B2-A1 C1-C2-B4-B3-A2-A1 C1-D1-C4-B8-B7-A1	3 5 5
C2	C4	C2-C1-D1-C4 C2-D2-C3-C4 C2-B4-B5-B6-B7-B8--C4	3 3 6

C2	A2	C2-B4-B3-A2 C2-C1-B1-B2-A1-A2 C2-D2-C3-B5-B6-A2	3 5 5
C3	A2	C3-B5-B6-A2 C3-C4-B8-B7-A1-A2 C3-D2-C2-B4-B3-A2	3 5 5
C4	A1	C4-B8-B7-A1 C4-C3-B5-B6-A2-A1 C4-D1-C1-B1-B2-A1	3 5 5
B1	B5	B1-B2-B3-B4-B5 B1-B8-B7-B6-B5 B1-C1-C2-D2-C3-B5	4 4 5
B2	D2	B2-B3-B4-C2-D2 B2-B1-C1-D1-D2 B2-A1-A2-B6-B5-C3-D2	4 4 6
B2	C3	B2-B3-B4-B5-C3 B2-A1-B7-B8-C4-C3 B2-B1-C1-D1-D2-C3	4 5 5
B3	C4	B3-B4-B5-C3-C4 B3-A2-B6-B7-B8-C4 B3-B2-B1-C1-D1-C4	4 5 5
B3	D1	B3-B4-C2-D2-D1 B3-B2-B1-C1-D1 B3-A2-A1-B7-B8-C4-D1	4 4 6
B4	B8	B4-B5-B6-B7-B8 B4-B3-B2-B1-B8 B4-C2-C1-D1-C4-B8	4 4 5
B6	C1	B6-B5-B4-C2-C1 B6-B7-B8-C4-D1-C1 B6-A2-A1-B2-B1-C1	4 5 5
B6	D1	B6-B5-C3-D2-D1 B6-B7-B8-C4-D1 B6-A2-B3-B2-B1-C1-D1	4 4 6
B7	C2	B7-B6-B5-B4-C2 B7-B8-C4-C3-D2-C2 B7-A1-B2-B1-C1-C2	4 5 5
B7	D2	B7-B6-B5-C3-D2 B7-B8-C4-D1-D2 B7-A1-A2-B3-B4-C2-D2	4 4 6
C1	A2	C1-B1-B2-A1-A2 C1-C2-B4-B3-A2 C1-D1-D2-C3-B5-B6-A2	4 4 6
C2	A1	C2-B4-B3-A2-A1 C2-C1-B1-B2-A1 C2-D2-C3-B5-B6-B7-A1	4 4 6
C3	A1	C3-B5-B6-A2-A1 C3-C4-B8-B7-A1 C3-D2-C2-B4-B3-B2-A1	4 4 6
C4	A2	C4-B8-B7-A1-A2 C4-C3-B5-B6-A2 C4-D1-C1-B1-B2-B3-A2	4 4 6

D1	A1	D1-C4-B8-B7-A1 D1-C1-B1-B2-A1 D1-D2-C3-B5-B6-A2-A1	4 4 6
D2	A2	D2-C3-B5-B6-A2 D2-C2-B4-B3-A2 D2-D1-C1-B1-B2-A1-A2	4 4 6
D1	A2	D1-C1-B1-B2-A1-A2 D1-C4-B8-B7-B6-A2 D1-D2-C2-B4-B3-A2	5 5 5
D2	A1	D2-C2-B4-B3-A2-A1 D2-C3-B5-B6-B7-A1 D2-D1-C1-B1-B2-A1	5 5 5

Appendix B

ROUTING TABLE (Topology 2)

- The Routing Table is constructed with a minimum distance approximation.
- The usual or normal route is kept at the top.
- The other 2 routing paths also are shown which are fully mutually exclusive with each other.
- Table is formed according to route length.

Source	Destination	Route	Length
B1	B2	B1-B2 B1-B8-B7-A1-B2 B1-C1-D1-C2-B4-B3-B2	1 4 6
B1	B8	B1-B8 B1-C1-C4-B8 B1-B2-A1-B7-B8	1 3 4
B1	C1	B1-C1 B1-B8-C4-C1 B1-B2-B3-B4-C2-D1-C1	1 3 6
B2	B3	B2-B3 B2-A1-A2-B3 B2-B1-C1-D1-C2-B4-B3	1 3 6
B2	A1	B2-A1 B2-B3-A2-A1 B2-B1-B8-B7-A1	1 3 4
B3	B4	B3-B4 B3-A2-B6-B5-B4 B3-B2-B1-C1-D1-C2-B4	1 4 6
B3	A2	B3-A2 B3-B2-A1-A2 B3-B4-B5-B6-A2	1 3 4
B4	B5	B4-B5 B4-C2-C3-B5 B4-B3-A2-B6-B5	1 3 4
B4	C2	B4-C2 B4-B5-C3-C2 B4-B3-B2-B1-C1-D1-C2	1 3 6
B5	B6	B5-B6 B5-B4-B3-A2-B6 B5-C3-D2-C4-B8-B7-B6	1 4 6
B5	C3	B5-C3 B5-B4-C2-C3 B5-B6-B7-B8-C4-D2-C3	1 3 6
B6	B7	B6-B7 B6-A2-A1-B7 B6-B5-C3-D2-C4-B8-B7	1 3 6
B6	A2	B6-A2 B6-B7-A1-A2 B6-B5-B4-B3-A2	1 3 4

B7	B8	B7-B8 B7-A1-B2-B1-B8 B7-B6-B5-C3-D2-C4-B8	1 4 6
B7	A1	B7-A1 B7-B6-A2-A1 B7-B8-B1-B2-A1	1 3 6
B8	C4	B8-C4 B8-B1-C1-C4 B8-B7-B6-B5-C3-D2-C4	1 3 6
C1	C4	C1-C4 C1-D1-D2-C4 C1-B1-B8-C4	1 3 3
C1	D1	C1-D1 C1-C4-D2-D1 C1-B1-B2-B3-B4-C2-D1	1 3 6
C2	D1	C2-D1 C2-C3-D2-D1 C2-B4-B3-B2-B1-C1-D2	1 3 6
C2	C3	C2-C3 C2-D1-D2-C3 C2-B4-B5-C3	1 3 3
C3	D2	C3-D2 C3-C2-D1-D2 C3-B5-B6-B7-B8-C4-D2	1 3 6
C4	D2	C4-D2 C4-C1-D1-D2 C4-B8-B7-B6-B5-C3-D2	1 3 6
A1	A2	A1-A2 A1-B2-B3-A2 A1-B7-B6-A2	1 3 3
D1	D2	D1-D2 D1-C1-C4-D2 D1-C2-C3-D2	1 3 3
B1	B3	B1-B2-B3 B1-B8-B7-A1-A2-B3 B1-C1-D1-C2-B4-B3	2 5 5
B1	B7	B1-B8-B7 B1-B2-A1-B7 B1-C1-D1-C2-B4-B5-B6-B7	2 3 7
B1	A1	B1-B2-A1 B1-B8-B7-A1 B1-C1-D1-C2-B4-B3-A2-A1	2 3 7
B1	C4	B1-B8-C4 B1-C1-C4 B1-B2-B3-B4-B5-C3-D2-C4	2 2 7
B1	D1	B1-C1-D1 B1-B8-C4-D2-D1 B1-B2-B3-B4-C2-D1	2 4 5
B2	B8	B2-B1-B8 B2-A1-B7-B8 B2-B3-B4-B5-C3-D2-C4-B8	2 3 7

B2	C1	B2-B1-C1 B2-A1-B7-B8-C4-C1 B2-B3-B4-C2-D1-C1	2 5 5
B2	A2	B2-A1-A2 B2-B3-A2 B2-B1-B8-B7-B6-A2	2 2 5
B2	B4	B2-B3-B4 B2-A1-A2-B6-B5-B4 B2-B1-C1-D1-C2-B4	2 5 5
B2	B7	B2-A1-B7 B2-B1-B8-B7 B2-B3-A2-B6-B7	2 3 4
B3	A1	B3-A2-A1 B3-B2-A1 B3-B4-B5-B6-B7-A1	2 2 5
B3	C2	B3-B4-C2 B3-A2-B6-B5-C3-C2 B3-B2-B1-C1-D1-C2	2 5 5
B3	B5	B3-B4-B5 B3-A2-B6-B5 B3-B2-B1-B8-C4-D2-C3-B5	2 3 7
B3	B6	B3-A2-B6 B3-B4-B5-B6 B3-B2-A1-B7-B6	2 3 4
B4	B6	B4-B5-B6 B4-B3-A2-B6 B4-C2-D1-C1-B1-B8-B7-B6	2 3 7
B4	C3	B4-B5-C3 B4-C2-C3 B4-B3-B2-B1-B8-C4-D2-C3	2 2 7
B4	A2	B4-B3-A2 B4-B5-B6-A2 B4-C2-D1-C1-B1-B2-A1-A2	2 3 7
B4	D1	B4-C2-D1 B4-B5-C3-D2-D1 B4-B3-B2-B1-C1-D1	2 4 5
B5	B7	B5-B6-B7 B5-B4-B3-A2-A1-B7 B5-C3-D2-C4-B8-B7	2 5 5
B5	A2	B5-B6-A2 B5-B4-B3-A2 B5-C3-D2-C4-B8-B7-A1-A2	2 3 7
B5	C2	B5-B4-C2 B5-C3-C2 B5-B6-B7-B8-B1-C1-D1-C2	2 2 7
B5	D2	B5-C3-D2 B5-B4-C2-D1-D2 B5-B6-B7-B8-C4-D2	2 4 5
B6	C3	B6-B5-C3 B6-A2-B3-B4-C2-C3 B6-B7-B8-C4-D2-C3	2 5 5
B6	B8	B6-B7-B8	2

		B6-A2-A1-B2-B1-B8 B6-B5-C3-D2-C4-B8	5 5
B6	A1	B6-A2-A1 B6-B7-A1 B6-B5-B4-B3-B2A1	2 2 5
B7	A2	B7-A1-A2 B7-B6-A2 B7-B8-B1-B2-B3-A2	2 2 5
B7	C4	B7-B8-C4 B7-A1-B2-B1-C1-C4 B7-B6-B5-C3-D2-C4	2 5 5
B8	C1	B8-B1-C1 B8-C4-C1 B8-B7-B6-B5-B4-C2-D1-C1	2 2 7
B8	A1	B8-B7-A1 B8-B1-B2-A1 B8-C4-D2-C3-B5-B6-A2-A1	2 3 7
B8	D2	B8-C4-D2 B8-B1-C1-D1-D2 B8-B7-B6-B5-C3-D2	2 4 5
C1	C2	C1-D1-C2 C1-C4-D2-C3-C2 C1-B1-B2-B3-B4-C2	2 4 5
C1	D2	C1-D1-D2 C1-C4-D2 C1-B1-B2-B3-B4-B5-C3-D2	2 2 7
C2	D2	C2-D1-D2 C2-C3-D2 C2-B4-B5-B6-B7-B8-C4-D2	2 2 7
C3	D1	C3-D2-D1 C3-C2-D1 C3-B5-B4-B3-B2-B1-C1-D1	2 2 7
C3	C4	C3-D2-C4 C3-C2-D1-C1-C4 C3-B5-B6-B7-B8-C4	2 4 5
C4	D1	C4-D2-D1 C4-C1-D1 C4-B8-B1-B2-B3-B4-C2-D1	2 2 7
B1	B4	B1-B2-B3-B4 B1-C1-D1-C2-B4 B1-B8-B7-B6-B5-B4	3 4 5
B1	A2	B1-B2-A1-A2 B1-B8-B7-B6-A2 B1-C1-D1-C2-B4-B3-A2	3 4 6
B1	B6	B1-B8-B7-B6 B1-B2-A1-A2-B6 B1-C1-D1-D2-C3-B5-B6	3 4 6
B1	D2	B1-B8-C4-D2 B1-C1-D1-D2 B1-B2-B3-B4-C2-C3-D2	3 3 6
B1	C2	B1-C1-D1-C2	3

		B1-B2-B3-B4-C2 B1-B8-C4-D2-C3-C2	4 5
B2	D1	B2-B1-C1-D1 B2-B3-B4-C2-D1 B2-A1-A2-B6-B5-C3-C2-D1	3 4 7
B2	C4	B2-B1-C1-C4 B2-A1-B7-B8-C4 B2-B3-B4-B5-C3-D2-C4	3 4 6
B2	B6	B2-A1-B7-B6 B2-B3-A2-B6 B2-B1-C1-D1-D2-C3-B5-B6	3 3 7
B2	B5	B2-B3-B4-B5 B2-A1-A2-B6-B5 B2-B1-C1-D1-D2-C3-B5	3 4 6
B2	C2	B2-B3-B4-C2 B2-B1-C1-D1-C2 B2-A1-A2-B6-B5-C3-C2	3 4 6
B3	B8	B3-B2-B1-B8 B3-A2-A1-B7-B8 B3-B4-C2-D1-D2-C4-B8	3 4 6
B3	C1	B3-B2-B1-C1 B3-B4-C2-D1-C1 B3-A2-A1-B7-B8-C4-C1	3 4 6
B3	B7	B3-A2-B6-B7 B3-B2-A1-B7 B3-B4-C2-D1-D2-C4-B8-B7	3 3 7
B3	D1	B3-B4-C2-D1 B3-B2-B1-C1-D1 B3-A2-A1-B7-B8-C4-D2-D1	3 4 7
B3	C3	B3-B4-C2-C3 B3-A2-B6-B5-C3 B3-B2-B1-C1-D1-D2-C3	3 4 6
B4	B7	B4-B5-B6-B7 B4-B3-A2-A1-B7 B4-C2-D1-D2-C4-B8-B7	3 4 6
B4	D2	B4-C2-D1-D2 B4-B5-C3-D2 B4-B3-B2-B1-C1-C4-D2	3 3 6
B4	A1	B4-B3-A2-A1 B4-B5-B6-B7-A1 B4-C2-D1-C1-B1-B2-A1	3 4 6
B4	C1	B4-C2-D1-C1 B4-B3-B2-B1-C1 B4-B5-B6-B7-B8-C4-C1	3 4 6
B5	B8	B5-B6-B7-B8 B5-C3-D2-C4-B8 B5-B4-B3-B2-B1-B8	3 4 5
B5	A1	B5-B6-A2-A1 B5-B4-B3-B2-A1 B5-C3-D2-C4-B8-B7-A1	3 4 6
B5	D1	B5-B4-C2-D1 B5-C3-D2-D1	3 3

		B5-B6-B7-B8-C4-C1-D1	6
B5	C4	B5-C3-D2-C4 B5-B6-B7-B8-C4 B5-B4-C2-D1-C1-C4	3 4 5
B6	C2	B6-B5-C3-C2 B6-A2-B3-B4-C2 B6-B7-B8-C4-D2-D1-C2	3 4 6
B6	D2	B6-B5-C3-D2 B6-B7-B8-C4-D2 B6-A2-A1-B2-B1-C1-C4-D2	3 4 7
B6	C4	B6-B7-B8-C4 B6-B5-C3-D2-C4 B6-A2-A1-B2-B1-C1-C4	3 4 6
B7	C3	B7-B6-B5-C3 B7-B8-C4-D2-C3 B7-A1-A2-B3-B4-C2-C3	3 4 6
B7	C1	B7-B8-C4-C1 B7-A1-B2-B1-C1 B7-B6-B5-B4-C3-D1-C1	3 4 6
B7	D2	B7-B8-C4-D2 B7-B6-B5-C3-D2 B7-A1-A2-B3-B4-C2-D1-D2	3 4 7
B8	D1	B8-B1-C1-D1 B8-C4-D2-D1 B8-B7-B6-B5-C3-C2-D1	3 3 6
B8	A2	B8-B7-A1-A2 B8-B1-B2-B3-A2 B8-C4-D2-C3-B5-B6-A2	3 4 6
B8	C3	B8-C4-D2-C3 B8-B7-B6-B5-C3 B8-B1-C1-D1-C2-C3	3 4 5
C1	A1	C1-B1-B2-A1 C1-C4-B8-B7-A1 C1-D1-C2-B4-B3-A2-A1	3 4 6
C1	C3	C1-C4-D2-C3 C1-D1-C2-C3 C1-B1-B2-B3-B4-B5-C3	3 3 6
C2	C4	C2-D1-C1-C4 C2-C3-D2-C4 C2-B4-B5-B6-B7-B8-C4	3 3 6
C2	A2	C2-B4-B3-A2 C2-C3-B5-B6-A2 C2-D1-C1-B1-B2-A1-A2	3 4 6
C3	A2	C3-B5-B6-A2 C3-C2-B4-B3-A2 C3-D2-C4-B8-B7-A1-A2	3 4 6
C4	A1	C4-B8-B7-A1 C4-C1-B1-B2-A1 C4-D2-C3-B5-B6-A2-A1	3 4 6
B1	B5	B1-B2-B3-B4-B5 B1-B8-B7-B6-B5	4 4

		B1-C1-D1-D2-C3-B5	5
B1	C3	B1-B8-C4-D2-C3 B1-C1-D1-C2-C3 B1-B2-B3-B4-B5-C3	4 4 5
B2	D2	B2-B1-C1-D1-D2 B2-A1-B7-B8-C4-D2 B2-B3-B4-C2-C3-D2	4 5 5
B2	C3	B2-B3-B4-C2-C3 B2-A1-A2-B6-B5-C3 B2-B1-C1-D1-D2-C3	4 5 5
B3	C4	B3-B2-B1-C1-C4 B3-A2-A1-B7-B8-C4 B3-B4-C2-D1-D2-C4	4 5 5
B3	D2	B3-B4-C2-D1-D2 B3-A2-B6-B5-C3-D2]B3-B2-B1-C1-C4-D2	4 5 5
B4	B8	B4-B3-B2-B1-B8 B4-B5-B6-B7-B8 B4-C2-D1-D2-C4-B8	4 4 5
B4	C4	B4-B5-C3-D2-C4 B4-C2-D1-C1-C4 B4-B3-B2-B1-B8-C4	4 4 5
B5	C1	B5-B4-C2-D1-C1 B5-C3-D2-C4-C1 B5-B6B7-B8-B1-C1	4 4 5
B6	C1	B6-B7-B8-C4-C1 B6-A2-A1-B2-B1-C1 B6-B5-C3-D2-D1-C1	4 5 5
B6	D1	B6-B5-C3-D2-D1 B6-A2-B3-B4-C2-D1 B6-B7-B8-C4-C1-D1	4 5 6
B7	C2	B7-B6-B5-C3-C2 B7-A1-A2-B3-B4-C2 B7-B8-C4-D2-D1-C2	4 5 5
B7	D1	B7-B8-C4-D2-D1 B7-B6-B5-C3-C2-D1 B7-A1-B2-B1-C1-D1	4 5 5
B8	C2	B8-B1-C1-D1-C2 B8-C4-D2-C3-C2 B8-B7-B6-B5-B4-C2	4 4 5
C1	A2	C1-B1-B2-A1-A2 C1-C4-B8-B7-B6-A2 C1-D1-C2-B4-B3-A2	4 5 5
C2	A1	C2-B4-B3-A2-A1 C2-C3-B5-B6-B7-A1 C2-D1-C1-B1-B2-A1	4 5 5
C3	A1	C3-B5-B6-A2-A1 C3-C2-B4-B3-B2-A1 C3-D2-C4-B8-B7-A1	4 5 5
C4	A2	C4-B8-B7-A1-A2 C4-C1-B1-B2-B3-A2 C4-D2-C3-B5-B6-A2	4 5 5

A1	D1	A1-B2-B1-C1-D1 A1-B7-B8-C4-D2-D1 A1-A2-B3-B4-C2-D1	4 5 5
A1	D2	A1-B7-B8-C4-D2 A1-B2-B1-C1-D1-D2 A1-A2-B6-B5-C3-D2	4 5 5
A2	D1	A2-B3-B4-C2-D1 A2-B6-B5-C3-D2-D1 A2-A1-B2-B1-C1-D1	4 5 5
A2	D2	A2-B6-B5-C3-D2 A2-B3-B4-C2-D1-D2 A2-A1-B7-B8-C4-D2	4 5 5

Appendix C

The link definitions of topology 1 are given in the following figure (Figure A3.1) and in Table A3.1.

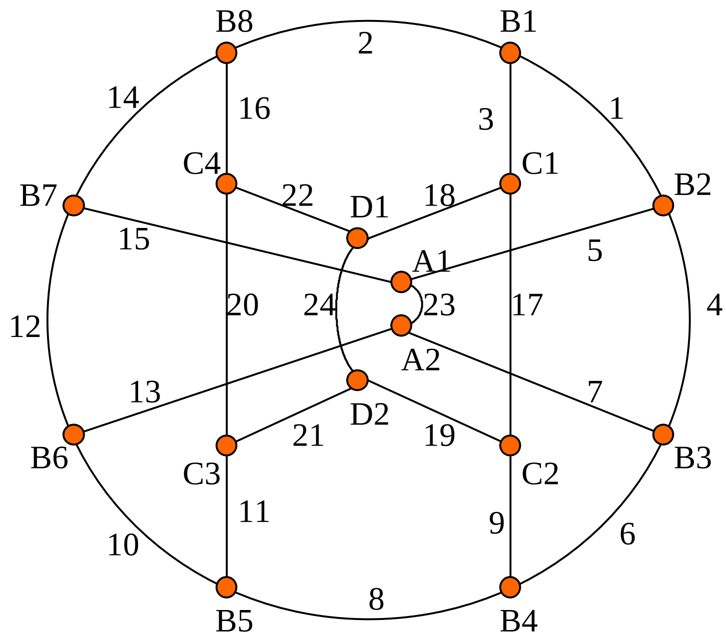

Figure A3.1: The links of topology 1 are defined by the numbers that appear on the links.

Links	Designated Number		Links	Designated Number
B1-B2	1		B6-A2	13
B1-B8	2		B7-B8	14
B1-C1	3		B7-A1	15
B2-B3	4		B8-C4	16
B2-A1	5		C1-C2	17
B3-B4	6		C1-D1	18
B3-A2	7		C2-D2	19
B4-B5	8		C3-C4	20
B4-C2	9		C3-D2	21
B5-B6	10		C4-D1	22
B5-C3	11		A1-A2	23
B6-B7	12		D1-D2	24

Table A3.1: Definition of the links of topology 1.

The link definitions of topology 2 are given in the following figure (Figure A3.2) and in Table A3.2.

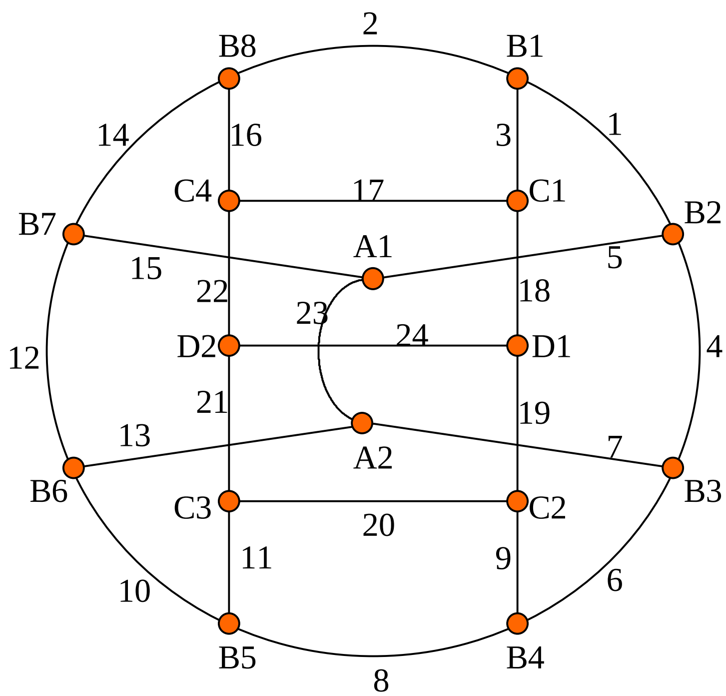

Figure A3.2: The links of topology 2 are defined by the numbers that appear on the links.

Links	Designated Number		Links	Designated Number
B1-B2	1		B6-A2	13
B1-B8	2		B7-B8	14
B1-C1	3		B7-A1	15
B2-B3	4		B8-C4	16
B2-A1	5		C1-C4	17
B3-B4	6		C1-D1	18
B3-A2	7		C2-D1	19
B4-B5	8		C2-C3	20
B4-C2	9		C3-D2	21
B5-B6	10		C4-D1	22
B5-C3	11		A1-A2	23
B6-B7	12		D1-D2	24

Table A3.2: Definition of the links of topology 2.

Appendix D

Node definitions of both the topologies are the same. Definitions are shown in Figure A4. Table A4 contains the corresponding definitions.

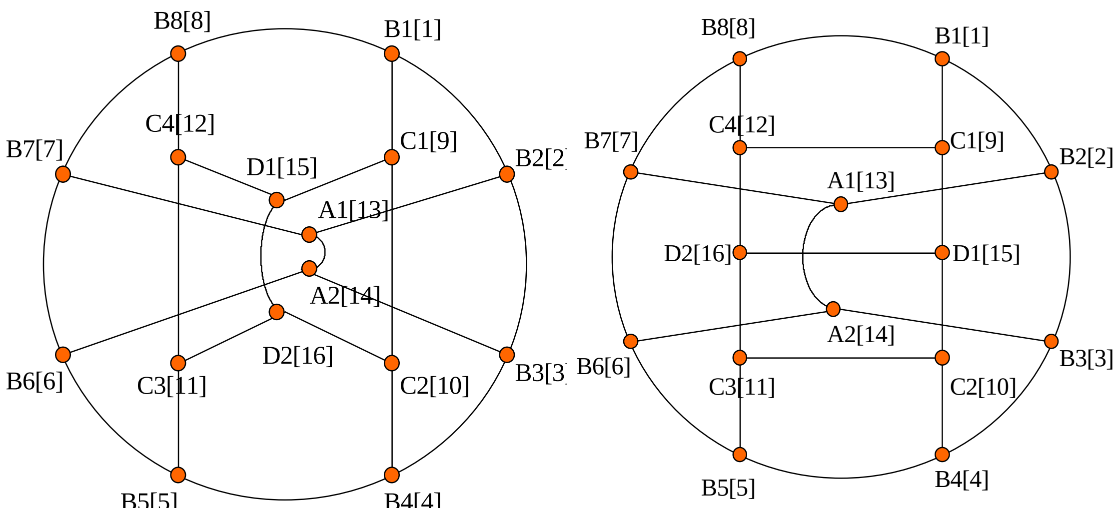

Figure A4: Corresponding node definitions are shown in square braces at every node. Note that definitions are same for both topologies.

Nodes	Designated Number		Nodes	Designated Number
B1	1		C1	9
B2	2		C2	10
B3	3		C3	11
B4	4		C4	12
B5	5		A1	13
B6	6		A2	14
B7	7		D1	15
B8	8		D2	16

Table A4: Tabulated format of node definitions.

Appendix E

Link Utilization Factors (LUFs) of all possible single-link failure scenarios (other than failure of B1-B2 link, which is shown in Figure 5.1) of topology 1 are contained in this section of appendix.

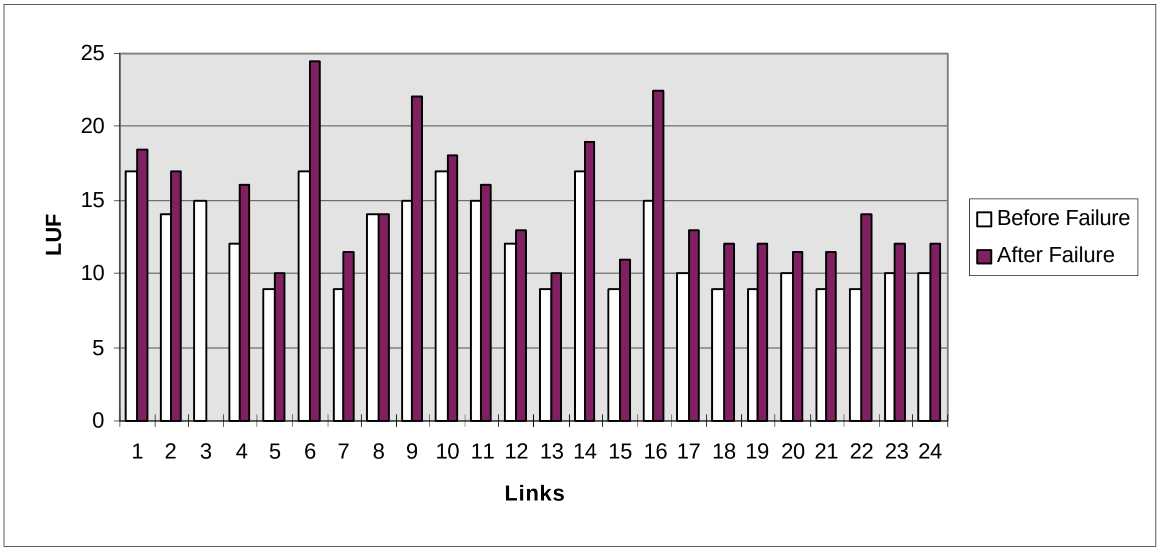

Figure A5.1: Failed Link is B1-C1. Max LUF 24.5 (Link 6), average LUF 14.21 (12.17 in fault-free case) and S.D. of LUF 4.99 (3.1 in fault-free case). Utilization of link 16 is 50% greater than the fault-free case.

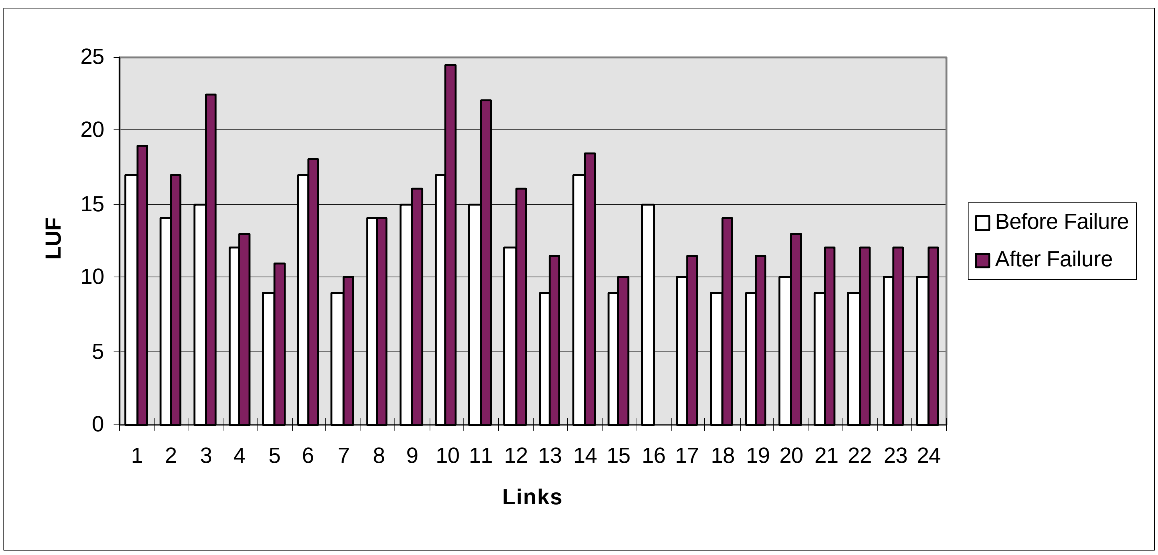

Figure A5.2: Failed Link is B8-C4. Max LUF 24.5 (Link 10), average LUF 14.21 (12.17 in fault-free case) and S.D. of LUF 4.99 (3.1 in fault-free case). Utilization of link 3 is 50% greater than the fault-free case.

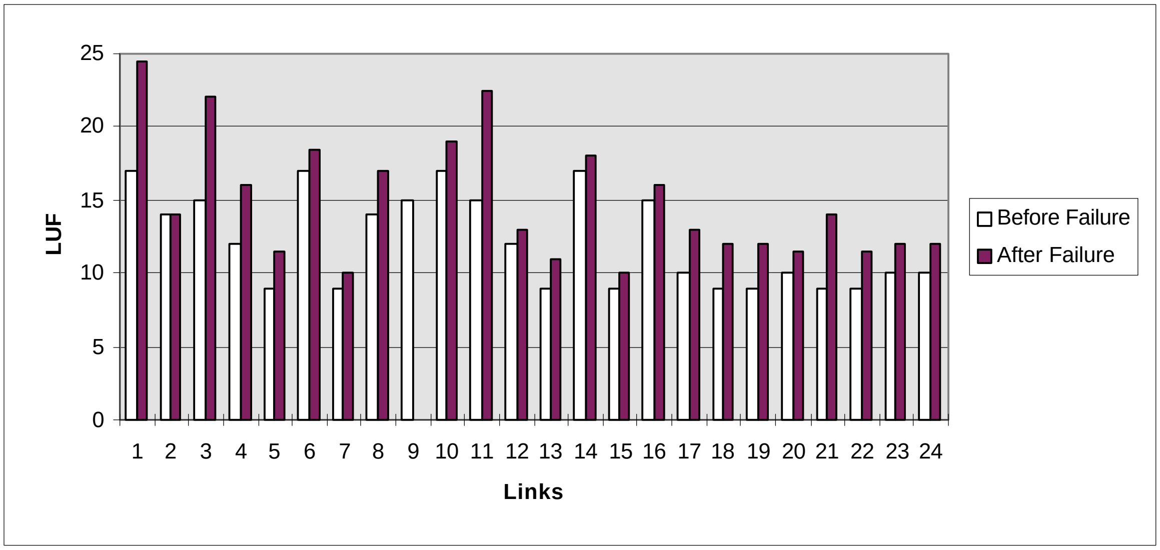

Figure A5.3: Failed Link is B4-C2. Max LUF 24.5 (Link 1), average LUF 14.21 (12.17 in fault-free case) and S.D. of LUF 4.99 (3.1 in fault-free case). Utilization of link11 is 50% greater than the fault-free case.

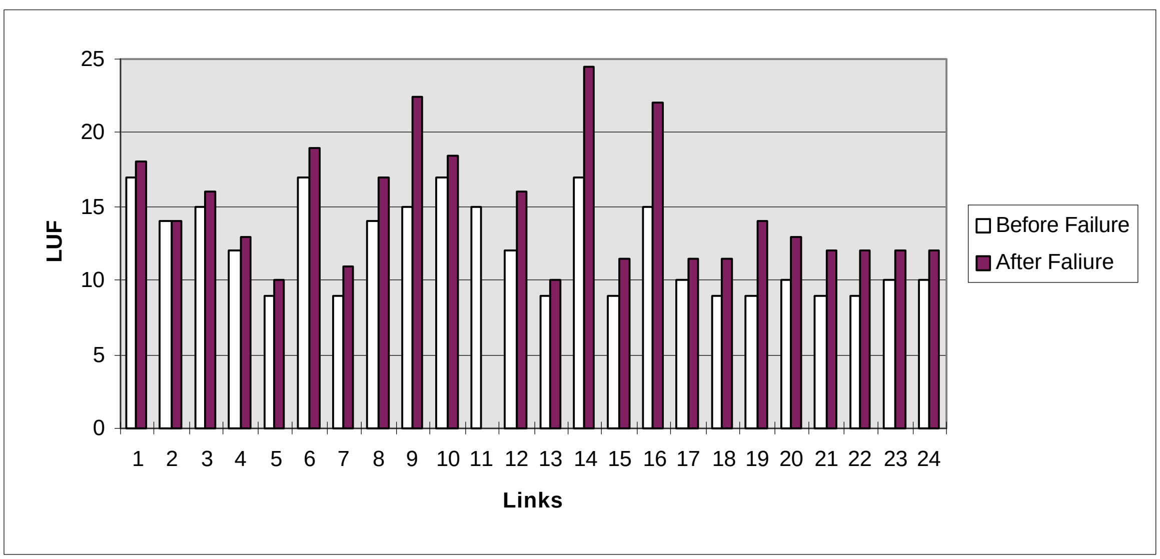

Figure A5.4: Failed Link is B5-C3. Max LUF 24.5 (Link 14), average LUF 14.21 (12.17 in fault-free case) and S.D. of LUF 4.99 (3.1 in fault-free case). Utilization of link 9 is 50% greater than the fault-free case.

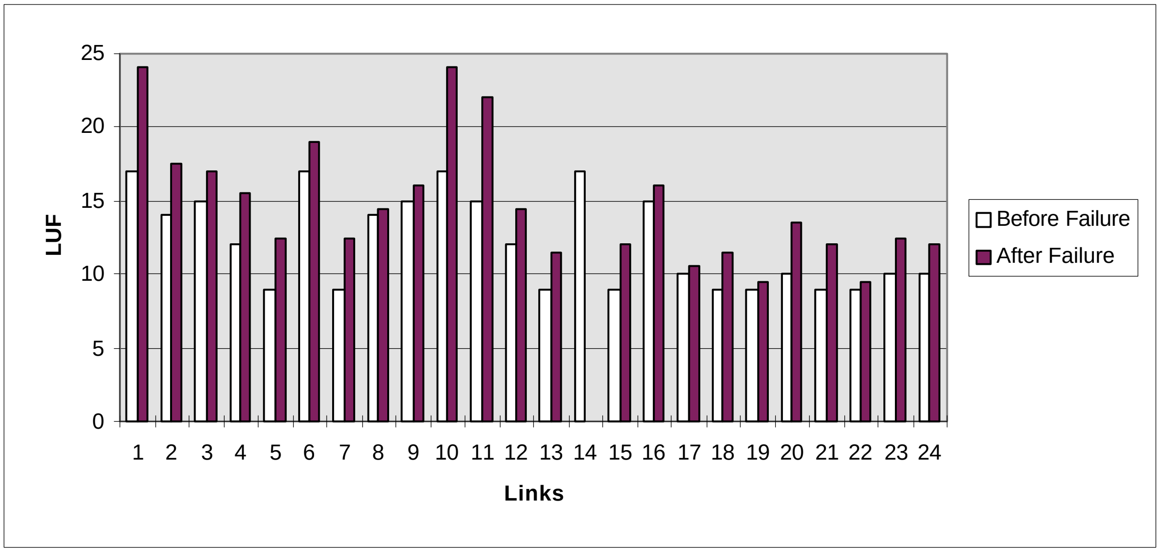

Figure A5.5: Failed Link is B7-B8. Max LUF 24 (Links 1 & 10), average LUF 14.14 (12.17 in fault-free case) and S.D. of LUF 5 (3.1 in fault-free case). Utilization of link11 is 46.67% greater than the fault-free case.

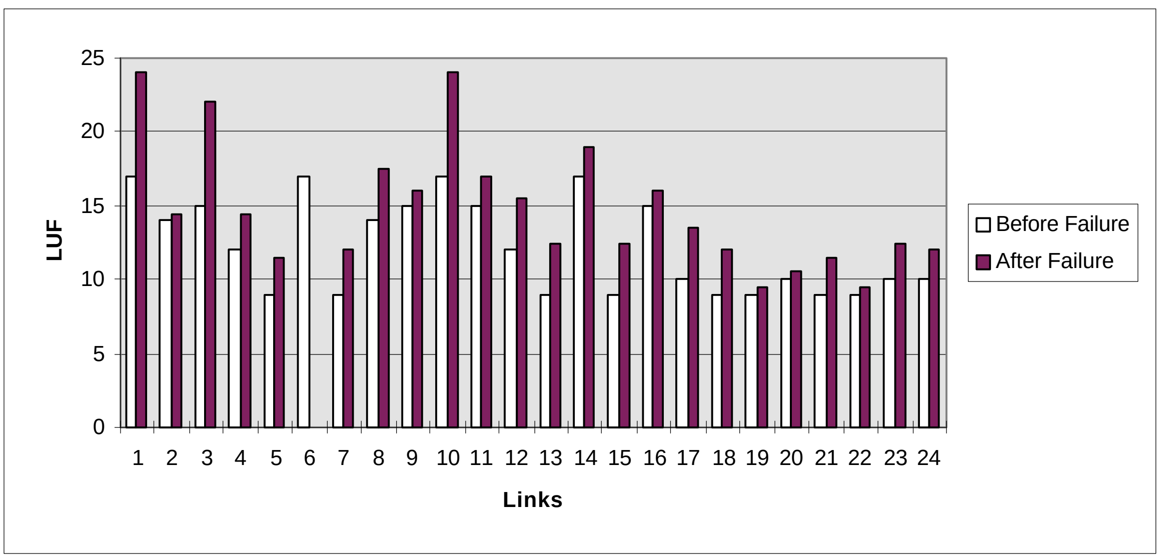

Figure A5.6: Failed Link is B3-B4. Max LUF 24 (Links 1 & 10), average LUF 14.14 (12.17 in fault-free case) and S.D. of LUF 5 (3.1 in fault-free case). Utilization of link 3 is 46.47% greater than the fault-free case.

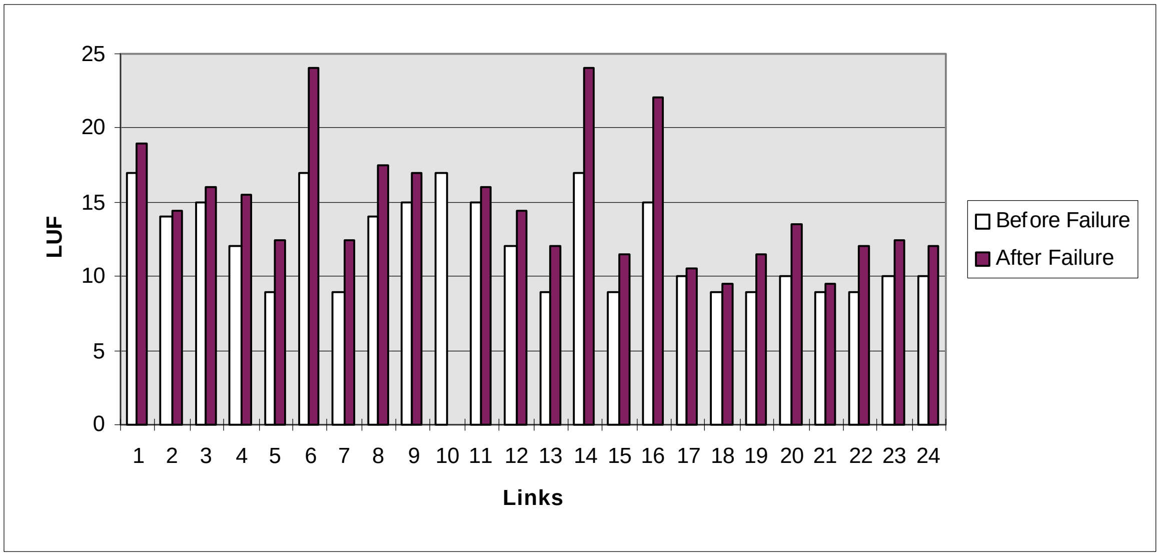

Figure A5.7: Failed Link is B5-B6. Max LUF 24 (Links 6 & 14), average LUF 14.14 (12.17 in fault-free case) and S.D. of LUF 5 (3.1 in fault-free case). Utilization of link 16 is 50% greater than the fault-free case.

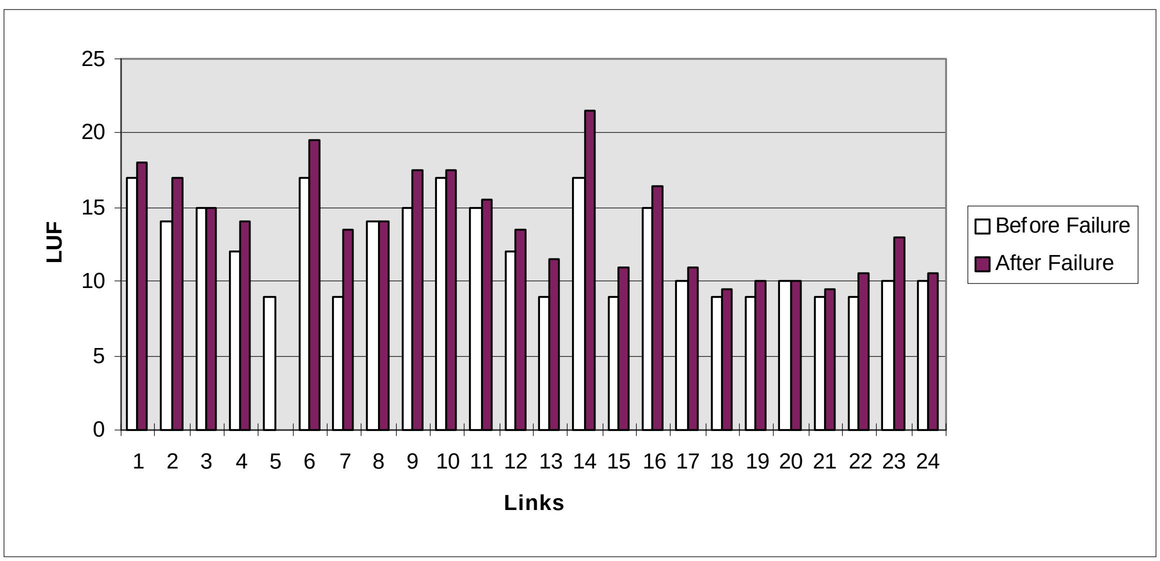

Figure A5.8: Failed Link is B2-A1. Max LUF 21.5 (Link 14), average LUF 13.31 (12.17 in fault-free case) and S.D. of LUF 4.34 (3.1 in fault-free case). Utilization of link 14 is 26.47% greater than the fault-free case.

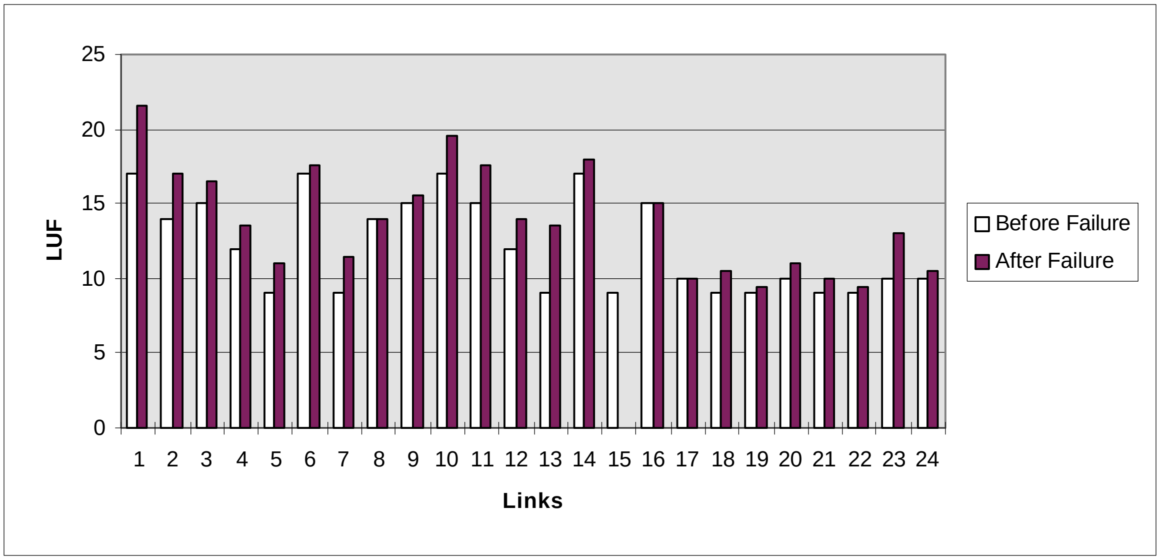

Figure A5.9: Failed Link is B7-A1. Max LUF 21.5 (Link 1), average LUF 13.31 (12.17 in fault-free case) and S.D. of LUF 4.34 (3.1 in fault-free case). Utilization of link 1 is 26.47% greater than the fault-free case.

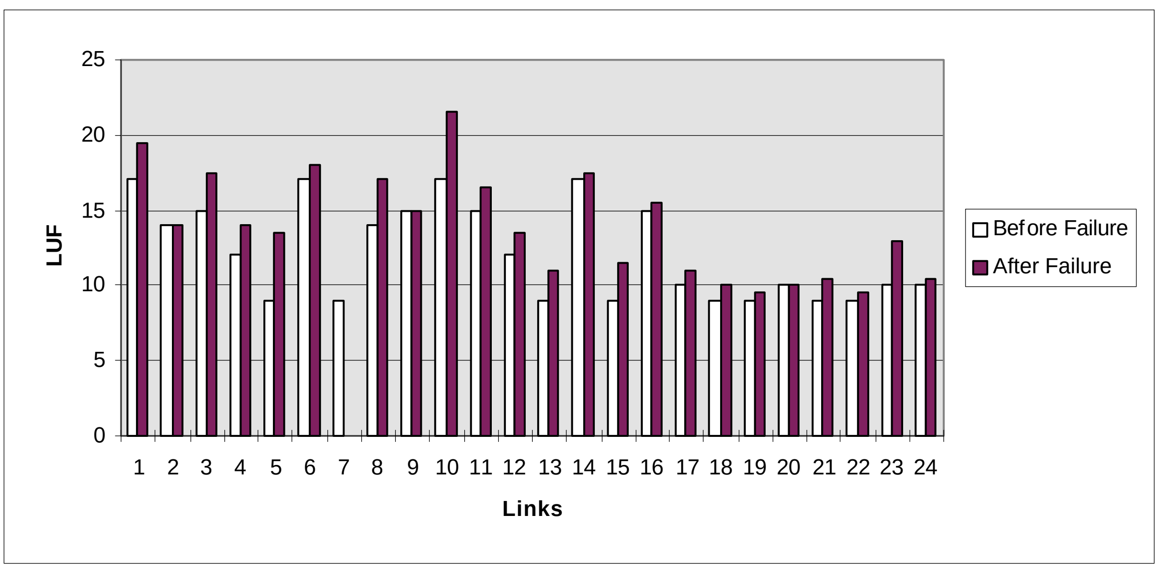

Figure A5.10: Failed Link is B3-A2. Max LUF 21.5 (Link 10), average LUF 13.31 (12.17 in fault-free case) and S.D. of LUF 4.34 (3.1 in fault-free case). Utilization of link 10 is 26.47% greater than the fault-free case.

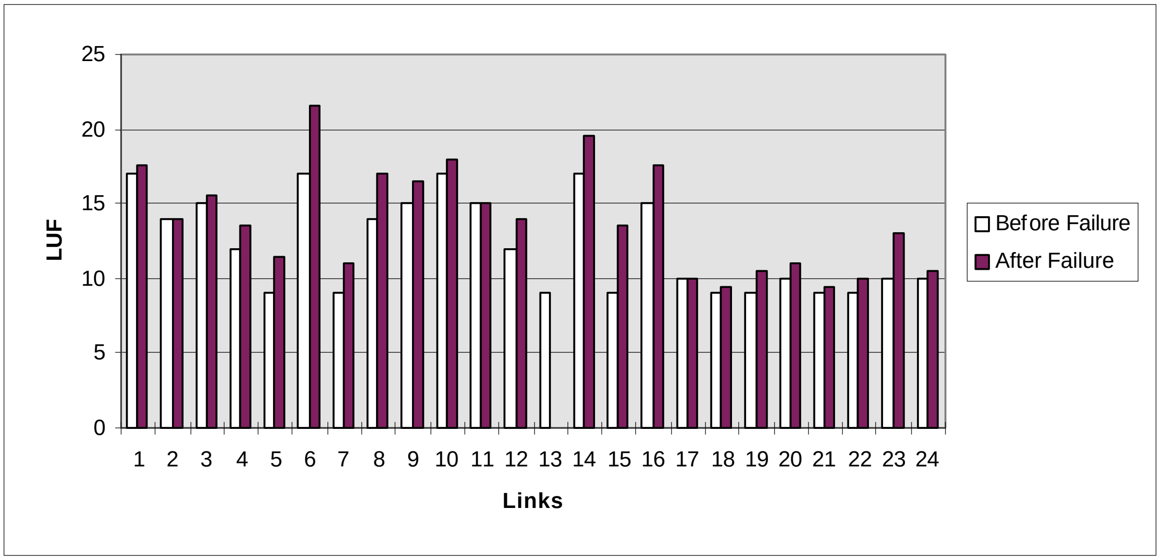

Figure A5.11: Failed Link is B6-A2. Max LUF 21.5 (Link 6), average LUF 13.31 (12.17 in fault-free case) and S.D. of LUF 4.34 (3.1 in fault-free case). Utilization of link 6 is 26.47% greater than the fault-free case.

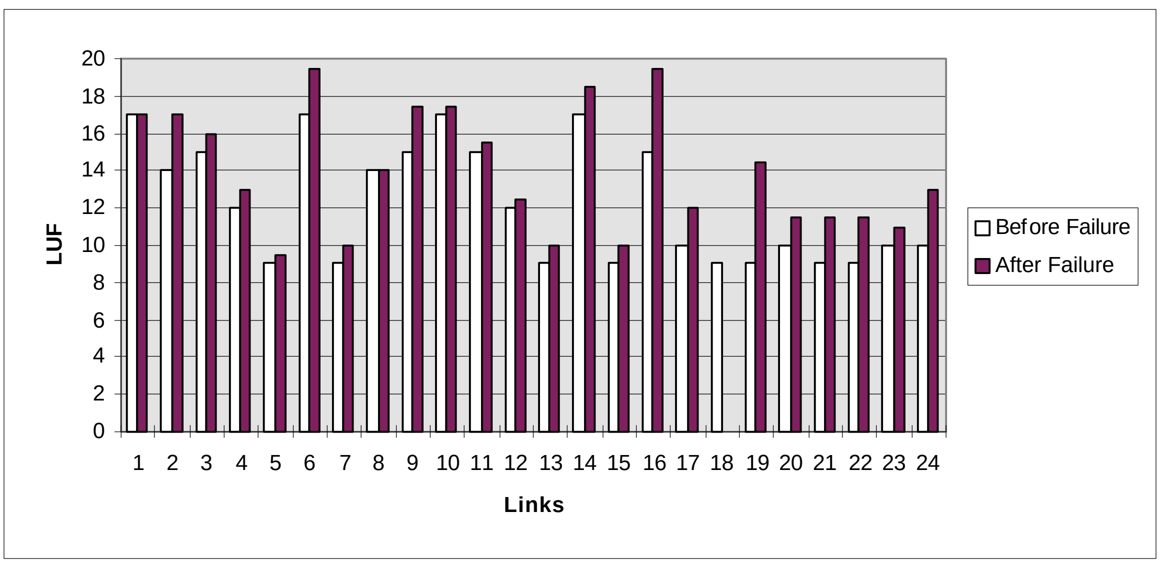

Figure A5.12: Failed Link is C1-D1. Max LUF 19.5 (Links 6 & 16), average LUF 13.41 (12.17 in fault-free case) and S.D. of LUF 4.19 (3.1 in fault-free case). Utilization of link 19 is 61.11% greater than the fault-free case.

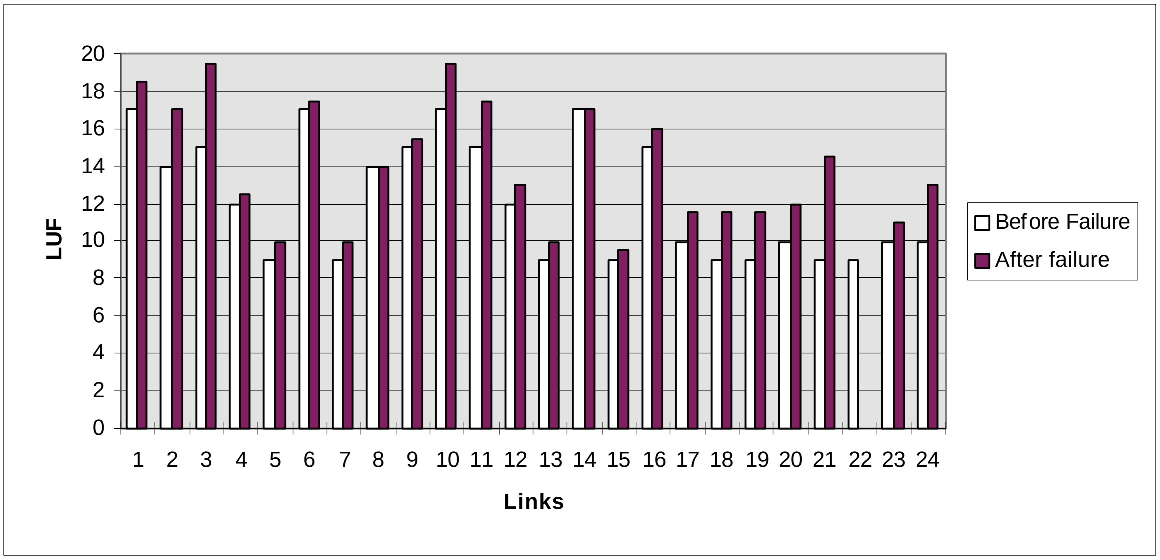

Figure A5.13: Failed Link is C4-D1. Max LUF 19.5 (Links 3 & 10), average LUF 13.41 (12.17 in fault-free case) and S.D. of LUF 4.19 (3.1 in fault-free case). Utilization of link 21 is 61.11% greater than the fault-free case.

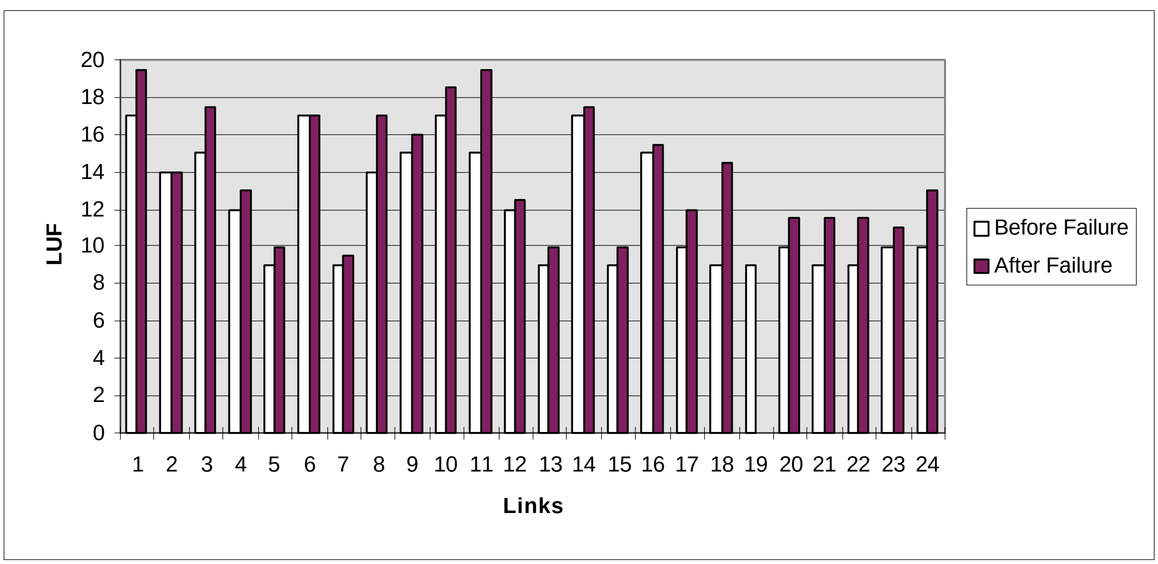

Figure A5.14: Failed Link is C2-D2. Max LUF 19.5 (Links 1 & 11), average LUF 13.41 (12.17 in fault-free case) and S.D. of LUF 4.19 (3.1 in fault-free case). Utilization of link 18 is 61.11% greater than the fault-free case.

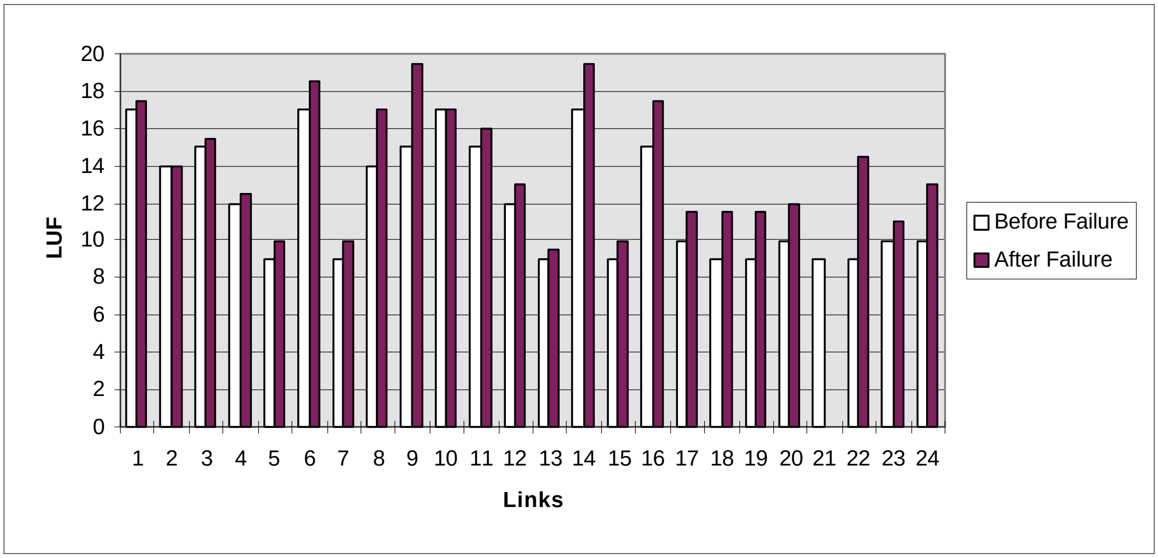

Figure A5.15: Failed Link is C3-D2. Max LUF 19.5 (Links 9 & 14), average LUF 13.41 (12.17 in fault-free case) and S.D. of LUF 4.19 (3.1 in fault-free case). Utilization of link 22 is 61.11% greater than the fault-free case.

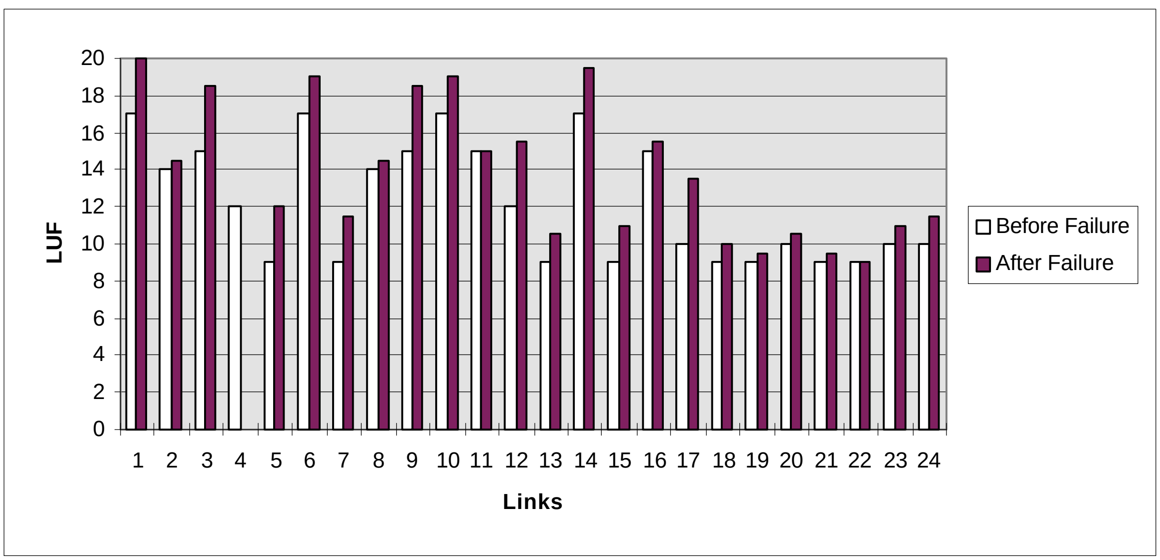

Figure A5.16: Failed Link is B2-B3. Max LUF 20 (Link 1), average LUF 13.29 (12.17 in fault-free case) and S.D. of LUF 4.51 (3.1 in fault-free case). Utilization of link 17 is 35% greater than the fault-free case.

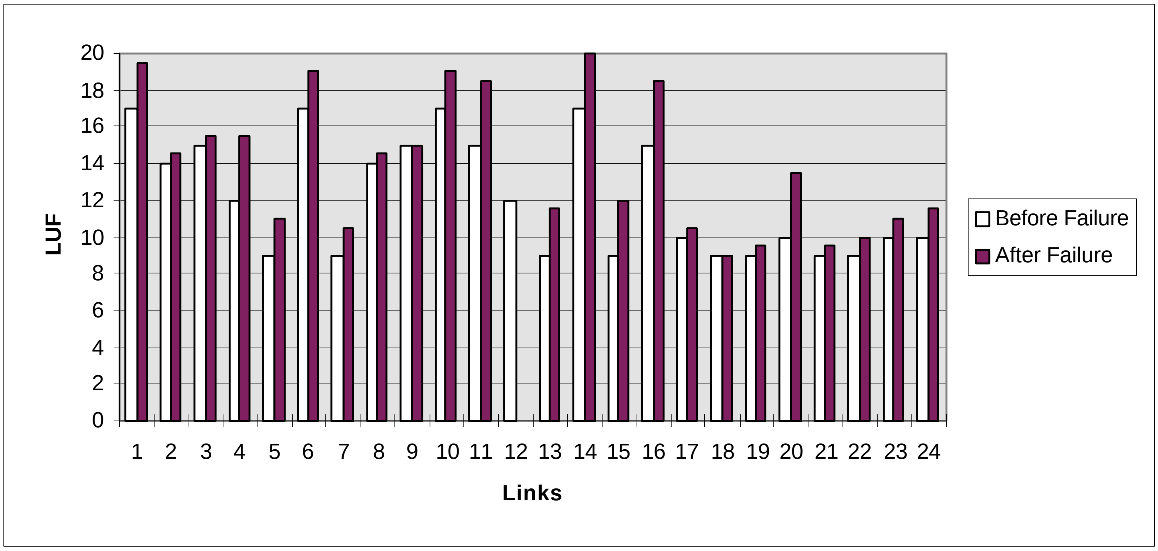

Figure A5.17: Failed Link is B6-B7. Max LUF 20 (Link 14), average LUF 13.29 (12.17 in fault-free case) and S.D. of LUF 4.51 (3.1 in fault-free case). Utilization of link 20 is 35% greater than the fault-free case.

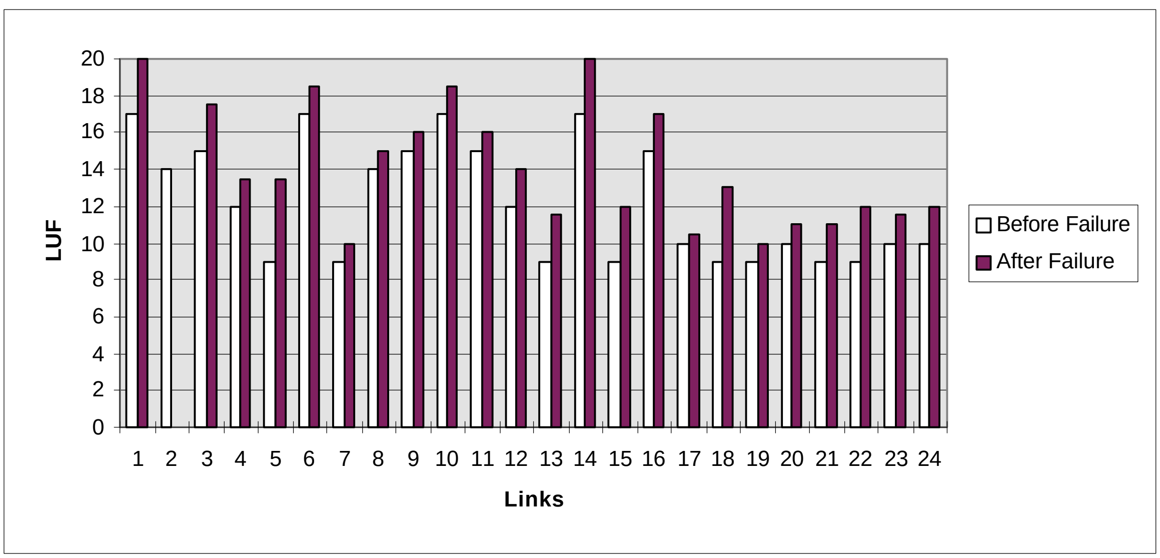

Figure A5.18: Failed Link is B1-B8. Max LUF 20 (Links 1 & 14), average LUF 13.5 (12.17 in fault-free case) and S.D. of LUF 4.19 (3.1 in fault-free case). Utilization of link 5 is 50% greater than the fault-free case.

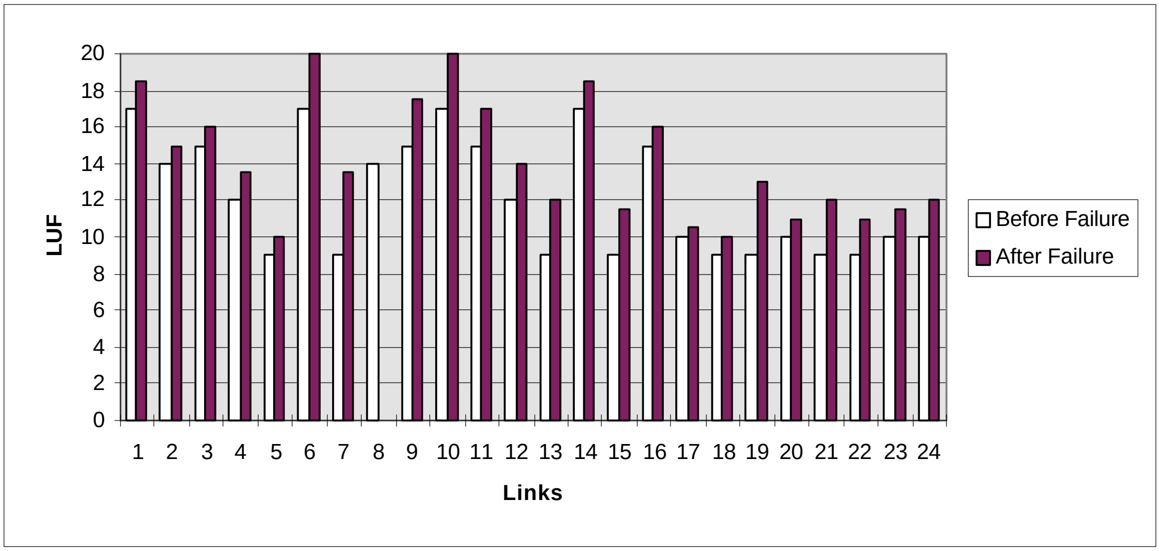

Figure A5.19: Failed Link is B4-B5. Max LUF 20 (Links 6 & 10), average LUF 13.5 (12.17 in fault-free case) and S.D. of LUF 4.19 (3.1 in fault-free case). Utilization of link 7 is 50% greater than the fault-free case.

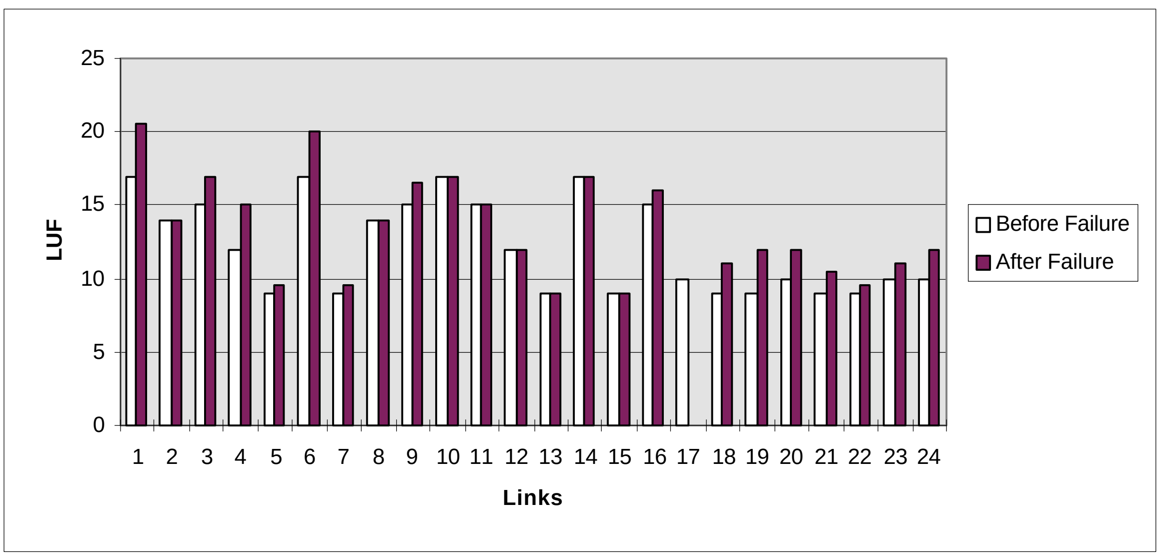

Figure A5.20: Failed Link is C1-C2. Max LUF 20.5 (Link1), average LUF 12.87 (12.17 in fault-free case) and S.D. of LUF 4.28 (3.1 in fault-free case). Utilization of link 1 is 20.6% greater than the fault-free case.

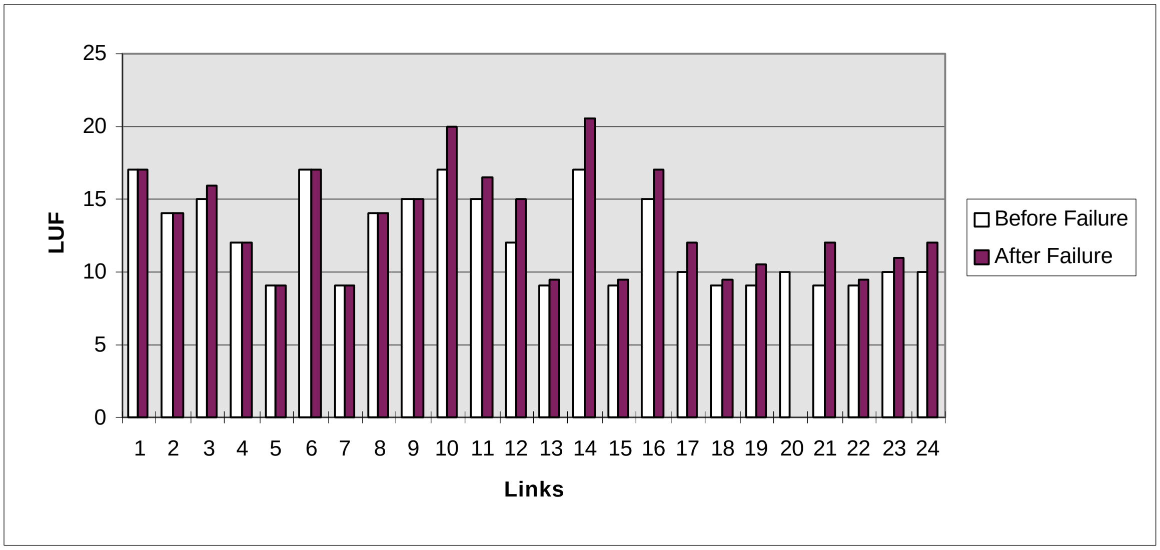

Figure A5.21: Failed Link is C3-C4. Max LUF 20.5 (Link14), average LUF 12.87 (12.17 in fault-free case) and S.D. of LUF 4.28 (3.1 in fault-free case). Utilization of link143 is 20.6% greater than the fault-free case.

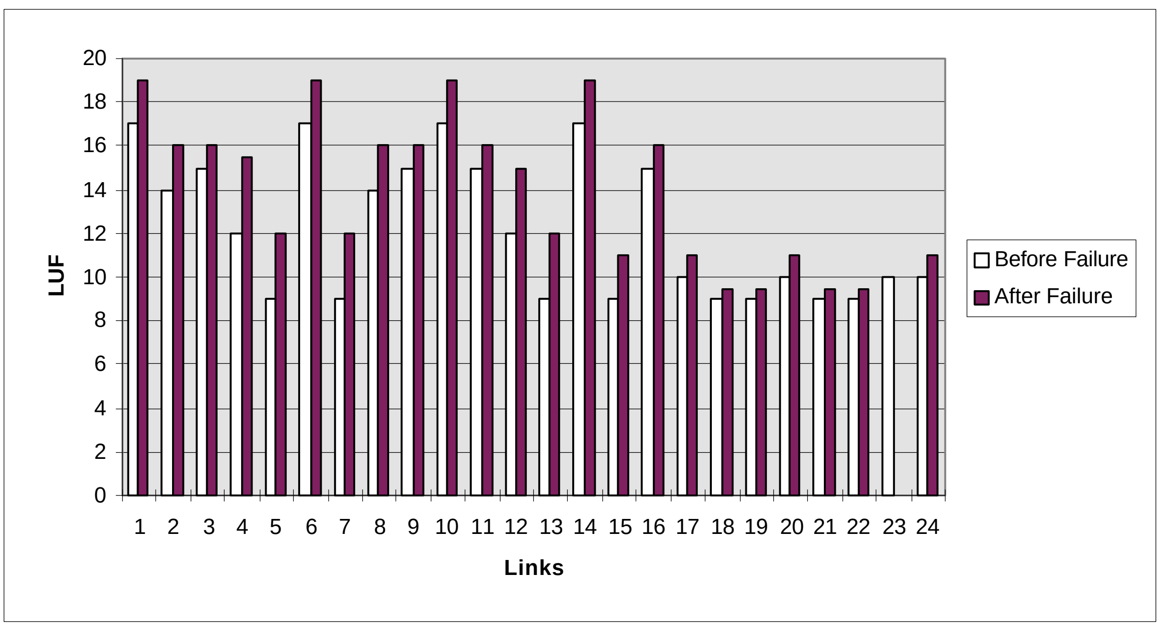

Figure A5.22: Failed Link is A1-A2. Max LUF 19 (Links1,6,10 &14), average LUF 13.35 (12.17 in fault-free case) and S.D. of LUF 4.29 (3.1 in fault-free case).Utilization of links 5,7 & 13 are 33.33% greater than the fault-free case.

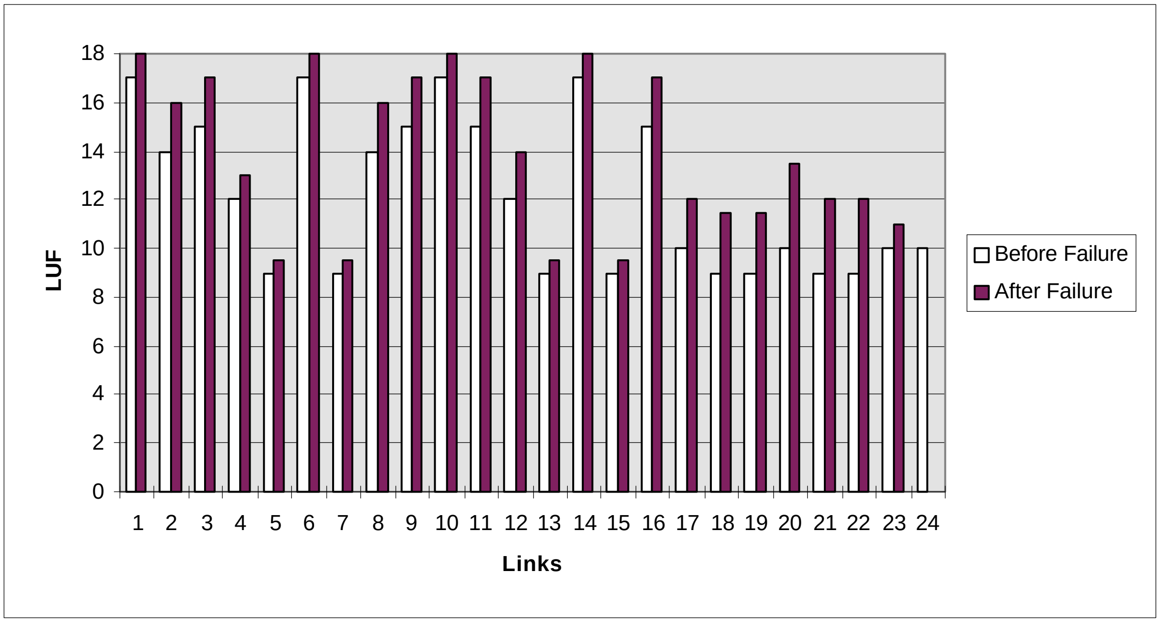

Figure A5.23: Failed Link is D1-D2. Max LUF 18 (Links1,6,10 &14), average LUF 13.35 (12.17 in fault-free case) and S.D. of LUF 4.13 (3.1 in fault-free case). Utilization of link 20 is 35% greater than the fault-free case.

Appendix F

Link Utilization Factors (LUFs) of all possible single-link failure scenarios (other than failure of B1-B2 link, which is shown in Figure 5.2) of topology 2 are contained in this section of appendix.

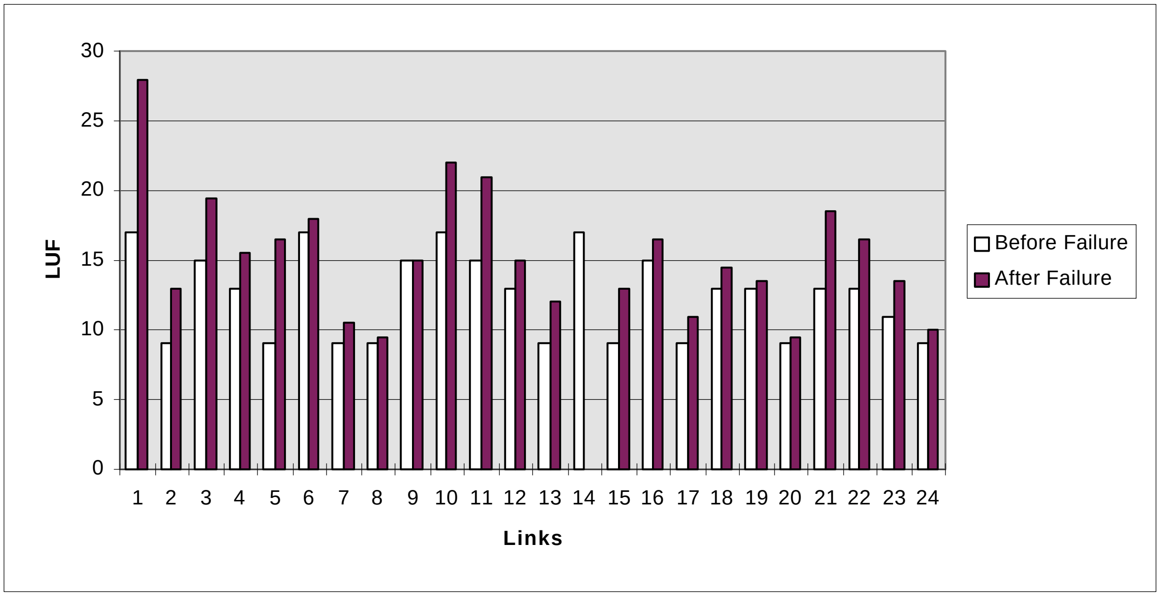

Figure A6.1: Failed Link is B7-B8. Max LUF 28 (Link 1), average LUF 14.67 (12.42 in fault-free case) and S.D. of LUF 5.27 (3.02 in fault-free case). Utilization of link 1 is 64.7% greater than the fault-free case.

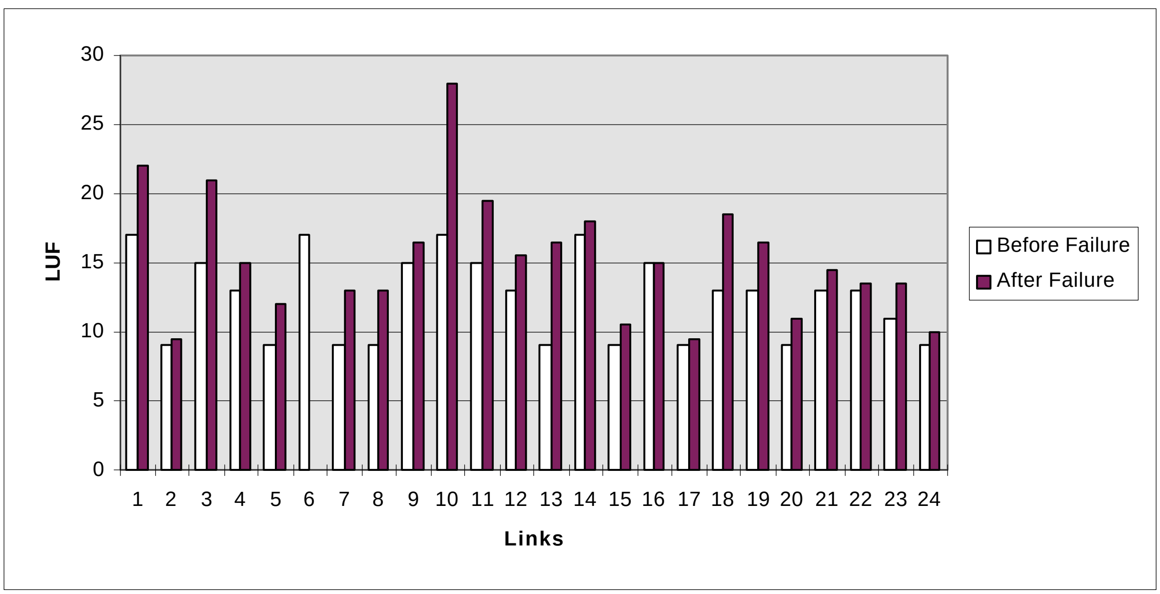

Figure A6.2: Failed Link is B3-B4. Max LUF 28 (Link 10), average LUF 14.67 (12.42 in fault-free case) and S.D. of LUF 5.27 (3.02 in fault-free case). Utilization of link 10 is 64.7% greater than the fault-free case.

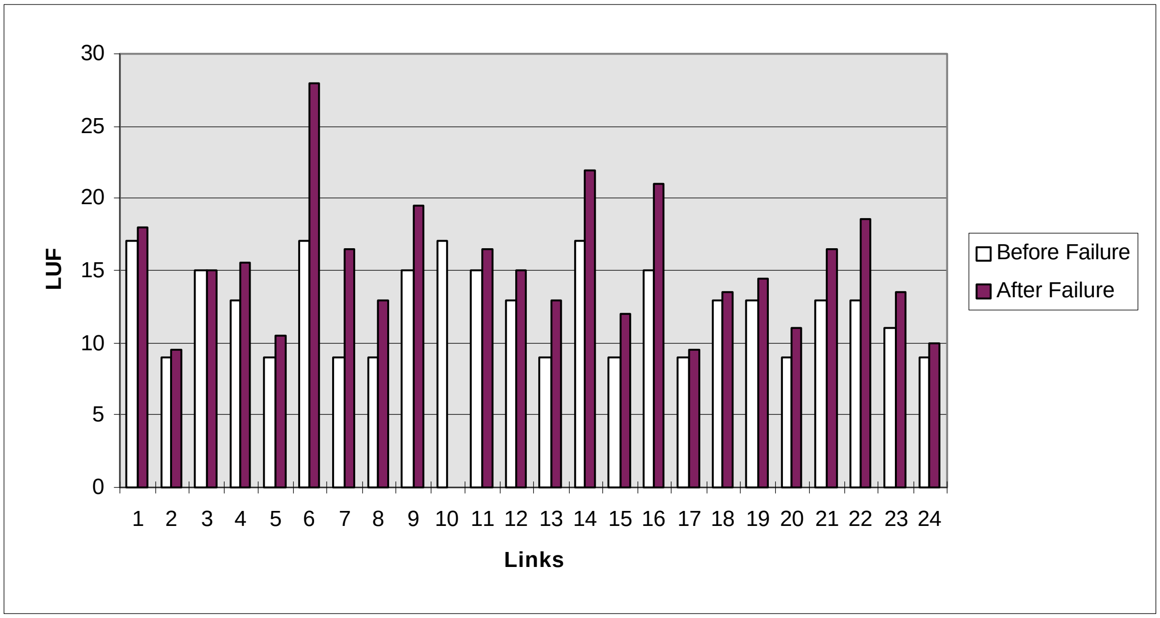

Figure A6.3: Failed Link is B5-B6. Max LUF 28 (Link 6), average LUF 14.67 (12.42 in fault-free case) and S.D. of LUF 5.27 (3.02 in fault-free case). Utilization of link 6 is 64.7% greater than the fault-free case.

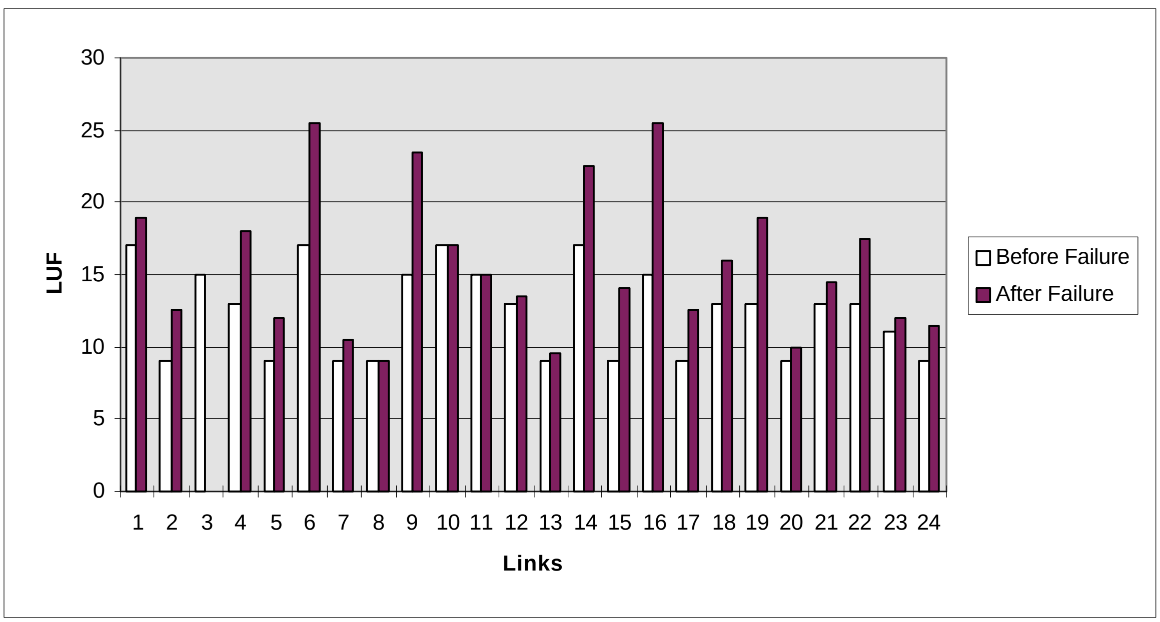

Figure A6.4: Failed Link is B1-C1. Max LUF 25.5 (Links 6 & 16), average LUF 15 (12.42 in fault-free case) and S.D. of LUF 5.71 (3.02 in fault-free case). Utilization of link 16 is 70% greater than the fault-free case.

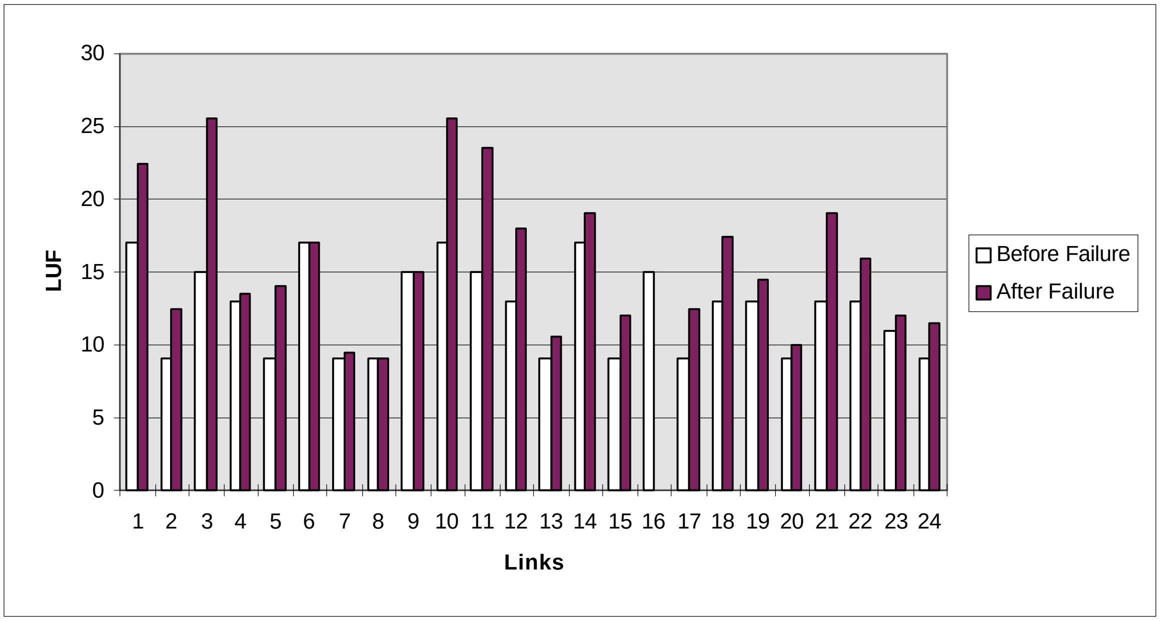

Figure A6.5: Failed Link is B8-C4. Max LUF 25.5 (Links 3 & 10), average LUF 15 (12.42 in fault-free case) and S.D. of LUF 5.71 (3.02 in fault-free case). Utilization of link 3 is 70% greater than the fault-free case.

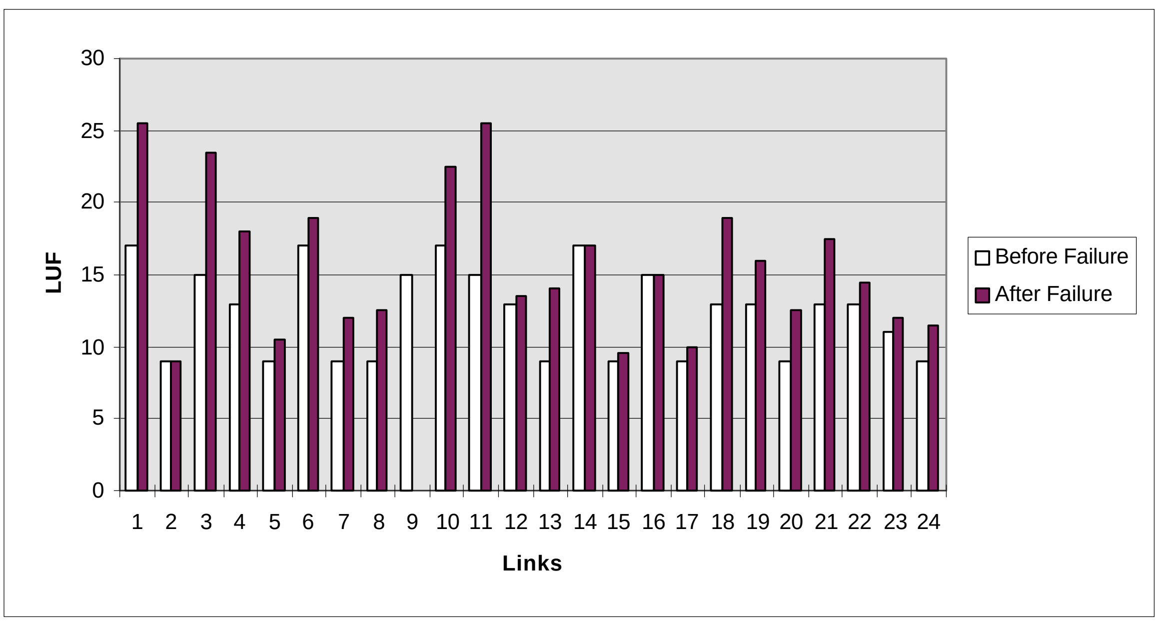

Figure A6.6: Failed Link is B4-C2. Max LUF 25.5 (Links 1 & 11), average LUF 15 (12.42 in fault-free case) and S.D. of LUF 5.71 (3.02 in fault-free case). Utilization of link 11 is 70% greater than the fault-free case.

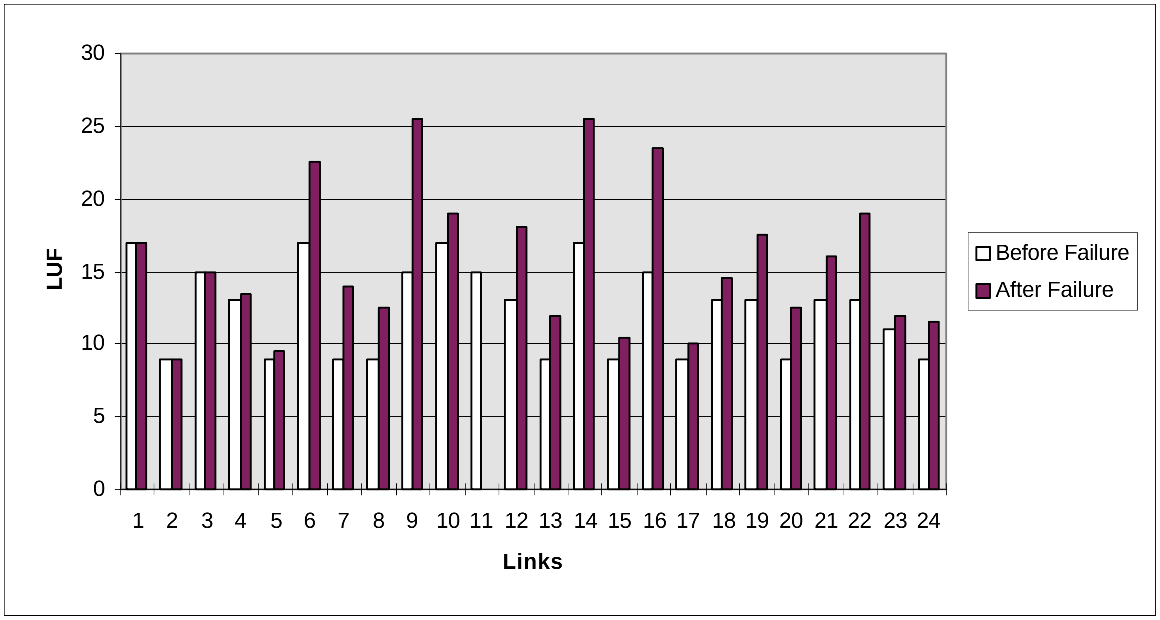

Figure A6.7: Failed Link is B5-C3. Max LUF 25.5 (Links 9 & 14), average LUF 15 (12.42 in fault-free case) and S.D. of LUF 5.71 (3.02 in fault-free case). Utilization of link 9 is 70% greater than the fault-free case.

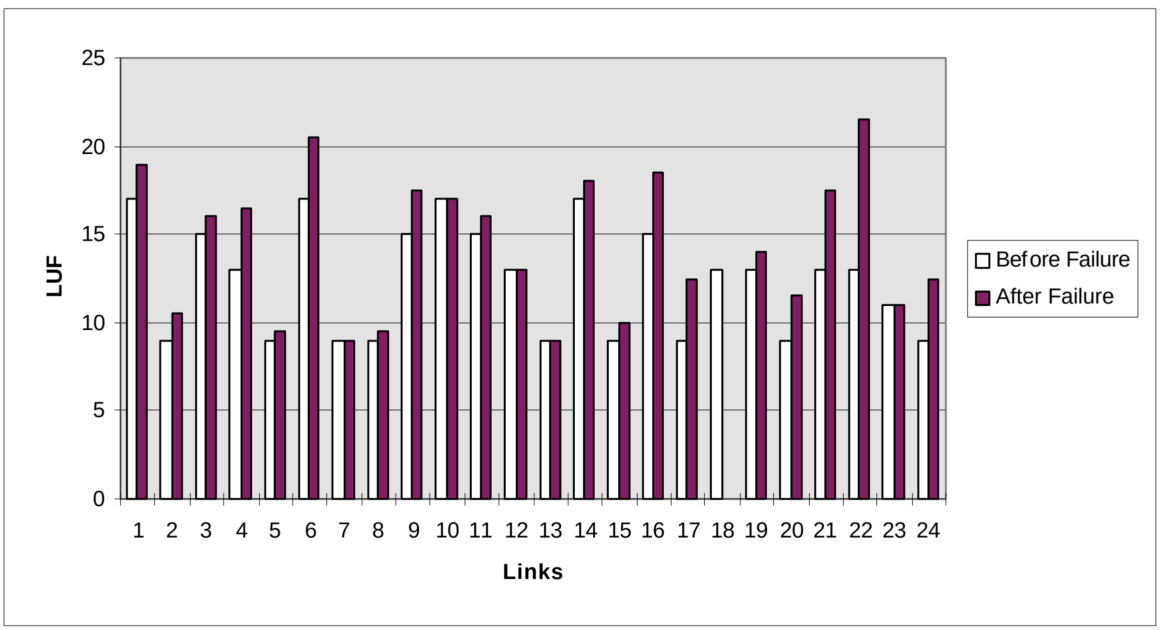

Figure A6.8: Failed Link is C1-D1. Max LUF 21.5 (Link 22), average LUF 13.75 (12.42 in fault-free case) and S.D. of LUF 4.75 (3.02 in fault-free case). Utilization of link 22 is 65.38% greater than the fault-free case.

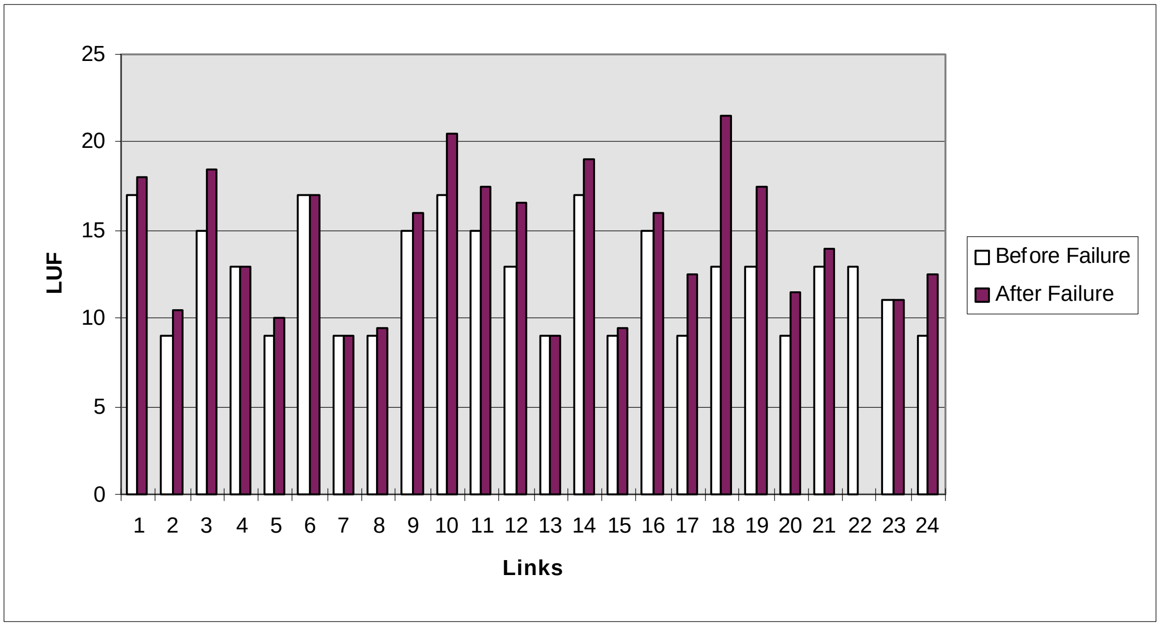

Figure A6.9: Failed Link is C4-D2. Max LUF 21.5 (Link 18), average LUF 13.75 (12.42 in fault-free case) and S.D. of LUF 4.75 (3.02 in fault-free case). Utilization of link 18 is 65.38% greater than the fault-free case.

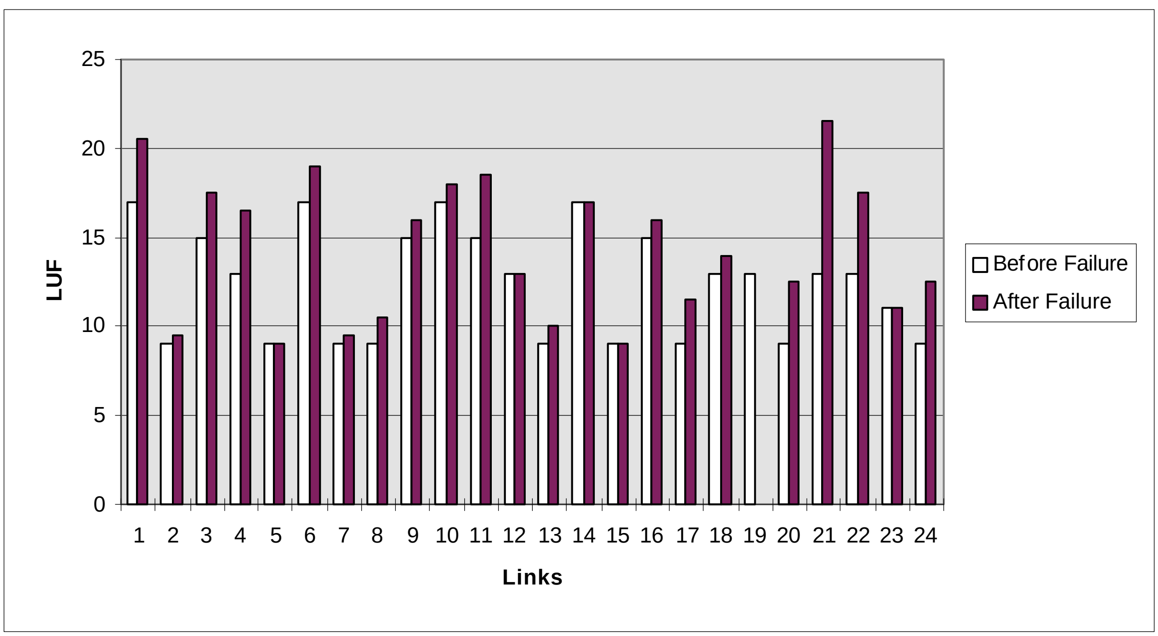

Figure A6.10: Failed Link is C2-D1. Max LUF 21.5 (Link 21), average LUF 13.75 (12.42 in fault-free case) and S.D. of LUF 4.75 (3.02 in fault-free case). Utilization of link 21 is 65.38% greater than the fault-free case.

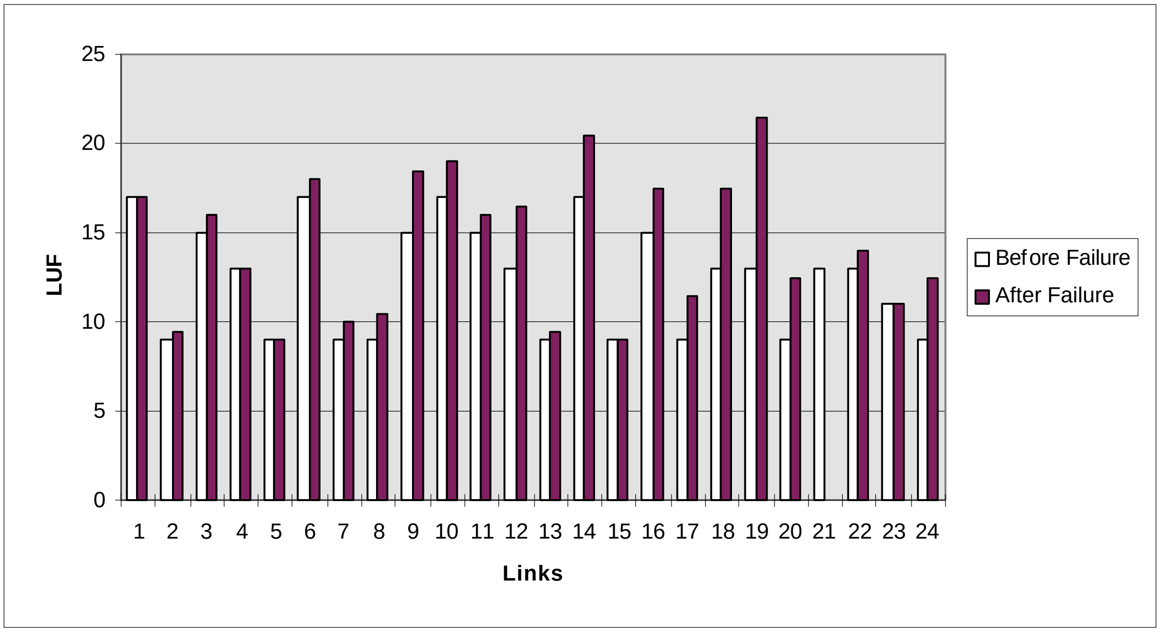

Figure A6.11: Failed Link is C3-D2. Max LUF 21.5 (Link 19), average LUF 13.75 (12.42 in fault-free case) and S.D. of LUF 4.75 (3.02 in fault-free case). Utilization of link 19 is 65.38% greater than the fault-free case.

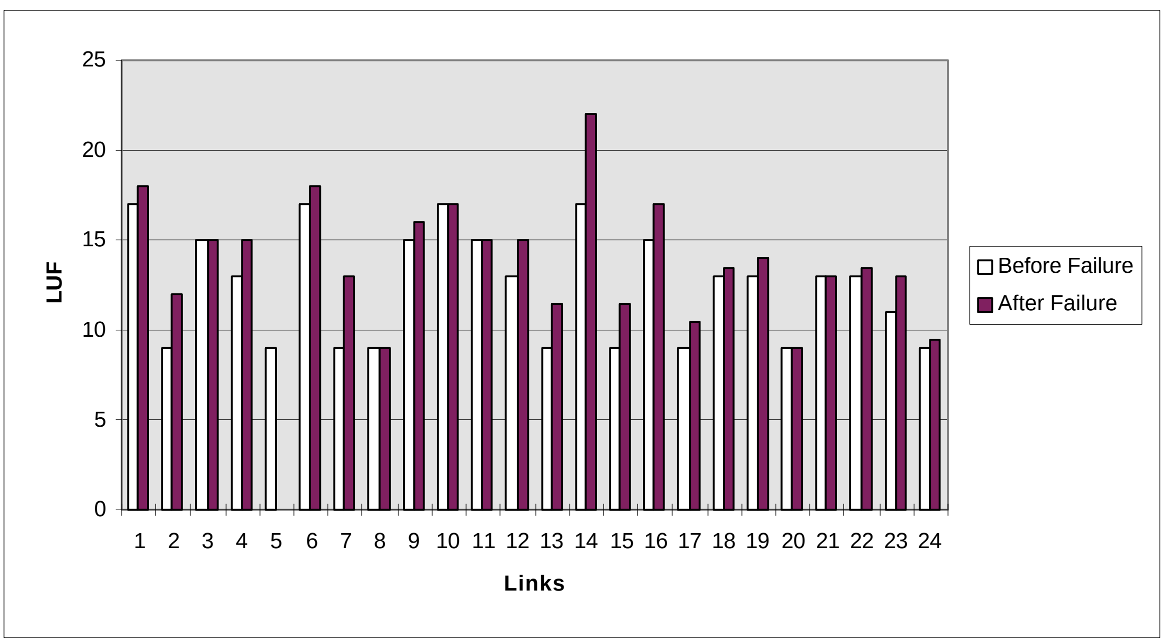

Figure A6.12: Failed Link is B2-A1. Max LUF 22 (Link 14), average LUF 13.37 (12.42 in fault-free case) and S.D. of LUF 4.14 (3.02 in fault-free case). Utilization of link 14 is 29.4% greater than the fault-free case.

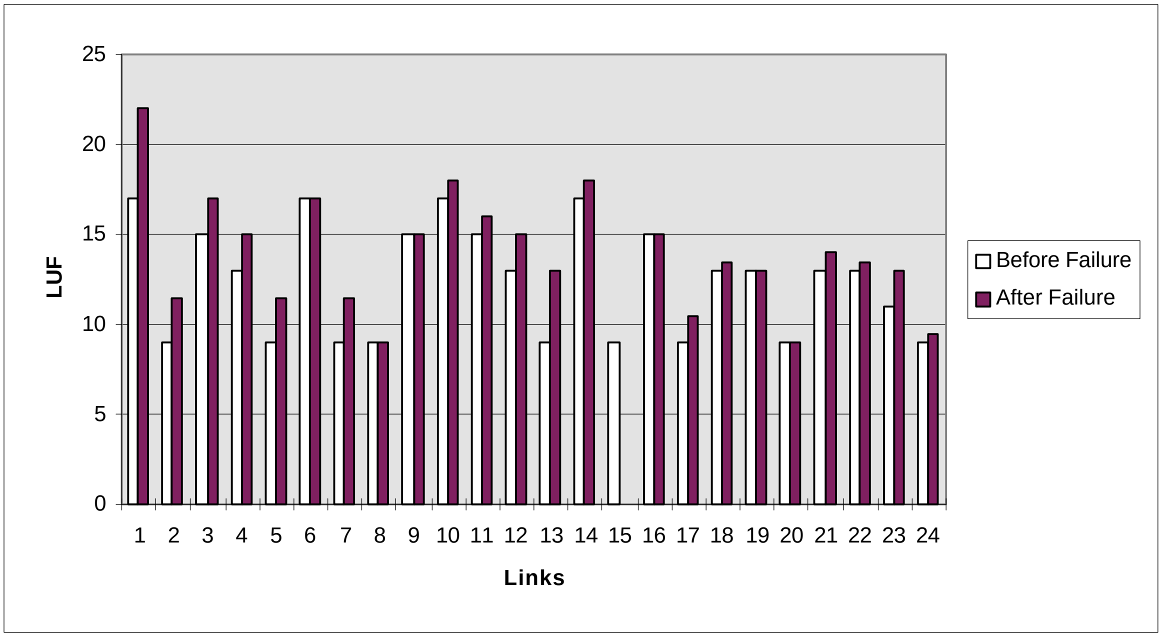

Figure A6.13: Failed Link is B7-A1. Max LUF 22 (Link 1), average LUF 13.37 (12.42 in fault-free case) and S.D. of LUF 4.14 (3.02 in fault-free case). Utilization of link 1 is 29.4% greater than the fault-free case.

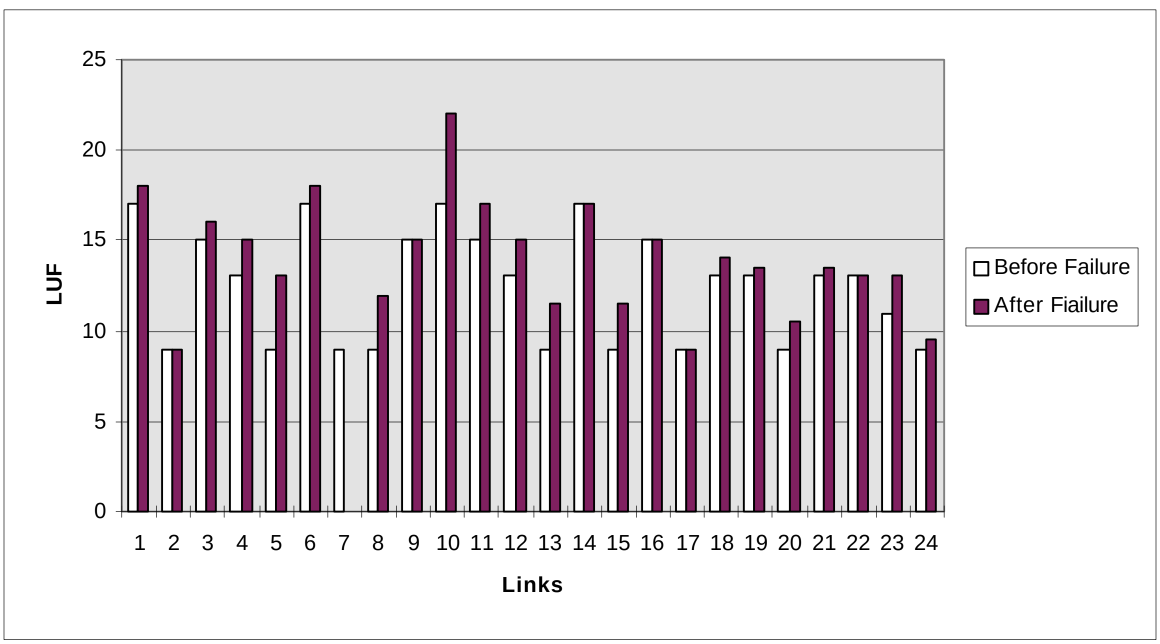

Figure A6.14: Failed Link is B3-A2. Max LUF 22 (Link 10), average LUF 13.37 (12.42 in fault-free case) and S.D. of LUF 4.14 (3.02 in fault-free case). Utilization of link 10 is 29.4% greater than the fault-free case.

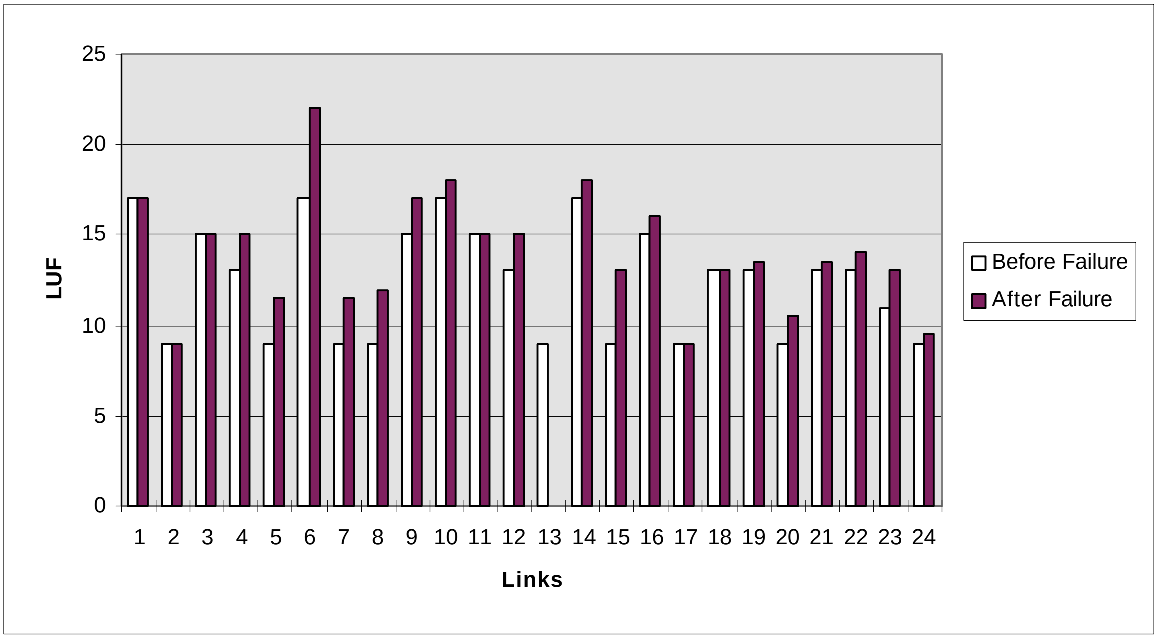

Figure A6.15: Failed Link is B6-A2. Max LUF 22 (Link 6), average LUF 13.37 (12.42 in fault-free case) and S.D. of LUF 4.14 (3.02 in fault-free case). Utilization of link 6 is 29.4% greater than the fault-free case.

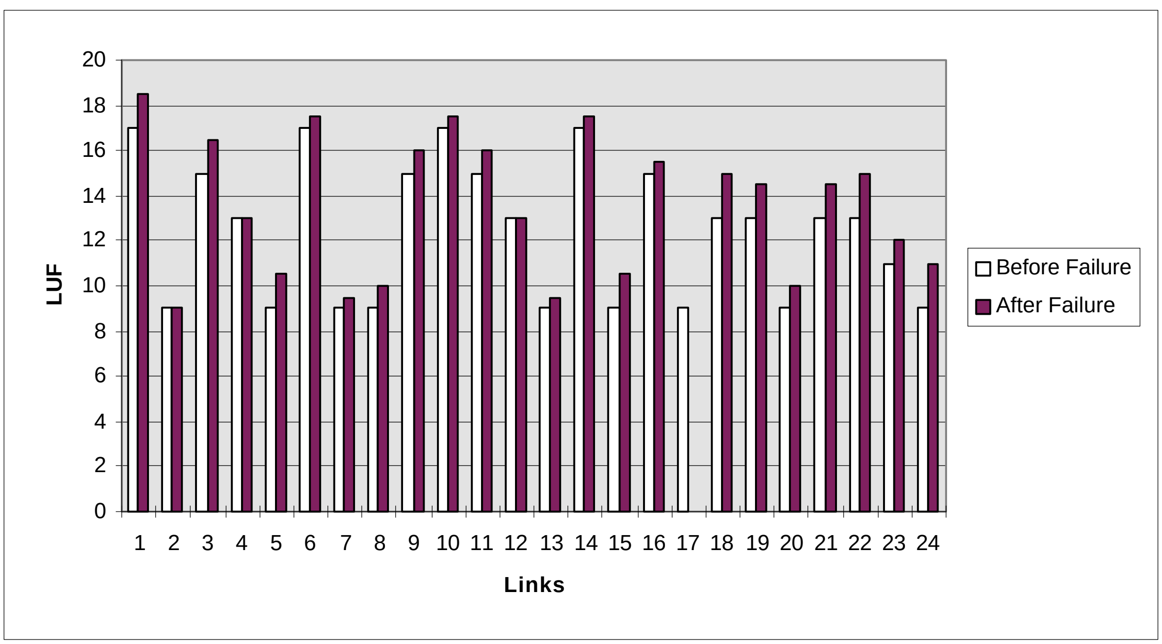

Figure A6.16: Failed Link is C1-C4. Max LUF 18.5 (Link 1), average LUF 13 (12.42 in fault-free case) and S.D. of LUF 4 (3.02 in fault-free case). Utilization of link 22 is 22.22% greater than the fault-free case.

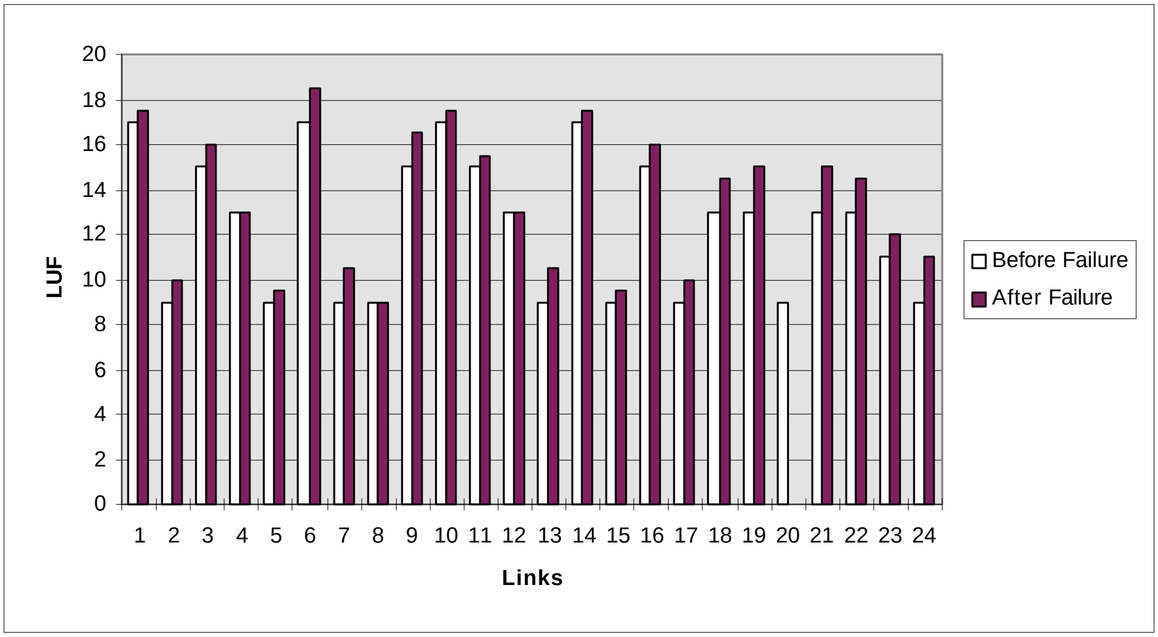

Figure A6.17: Failed Link is C2-C3. Max LUF 18.5 (Link 6), average LUF 13 (12.42 in fault-free case) and S.D. of LUF 4 (3.02 in fault-free case). Utilization of link 24 is 22.22% greater than the fault-free case.

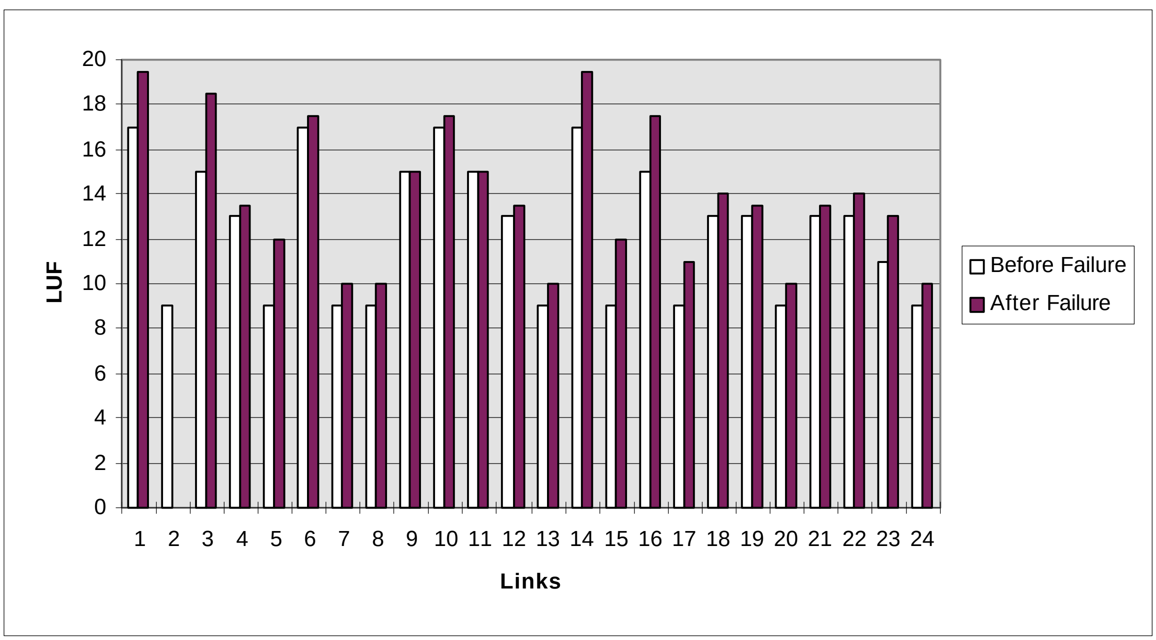

Figure A6.18: Failed Link is B1-B8. Max LUF 19.5 (Links 1 & 14), average LUF 13.33 (12.42 in fault-free case) and S.D. of LUF 4.1 (3.02 in fault-free case). Utilization of link 23 is 23.33% greater than the fault-free case.

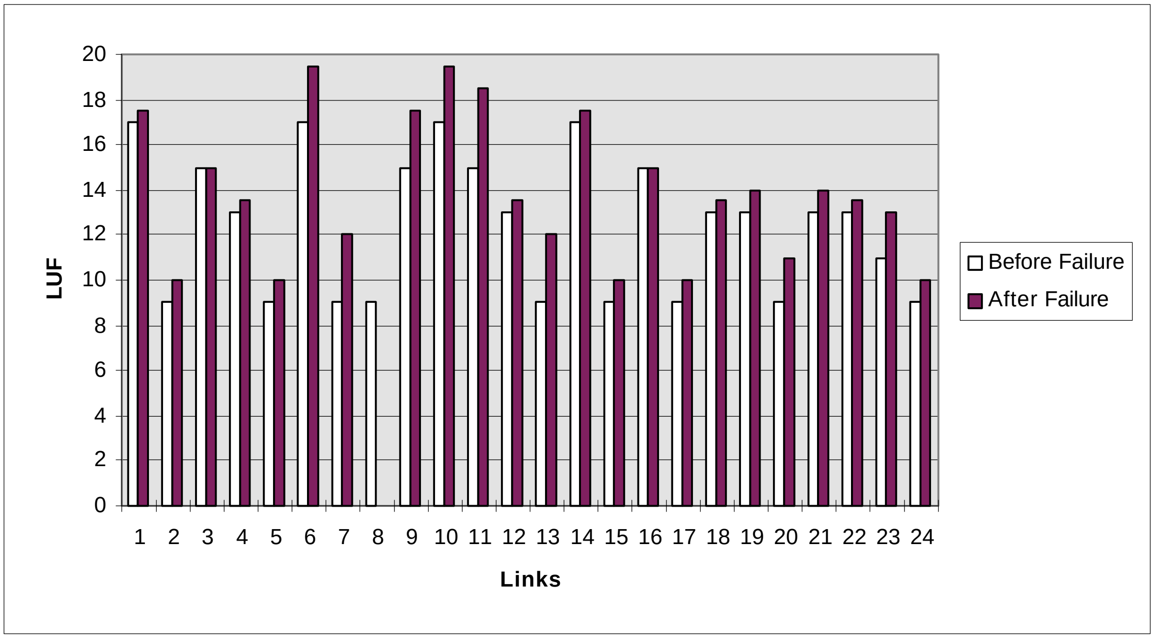

Figure A6.19: Failed Link is B4-B5. Max LUF 19.5 (Links 6 & 10), average LUF 13.33 (12.42 in fault-free case) and S.D. of LUF 4.1 (3.02 in fault-free case). Utilization of link 11 is 23.33% greater than the fault-free case.

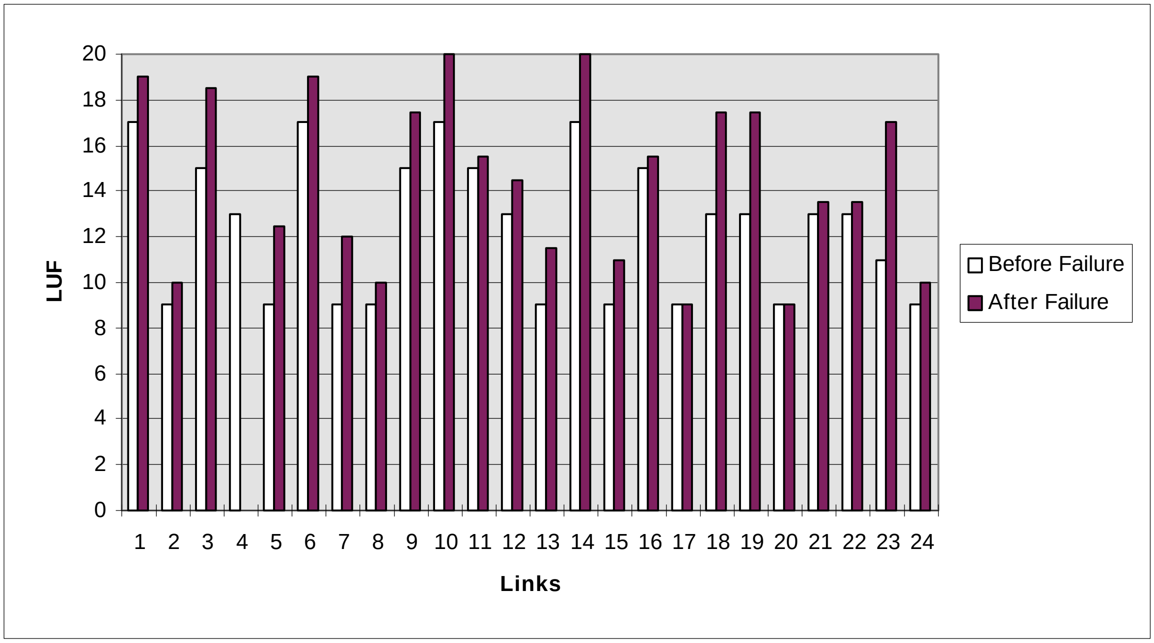

Figure A6.20: Failed Link is B2-B3. Max LUF 20 (Links 10 & 14), average LUF 13.33 (12.42 in fault-free case) and S.D. of LUF 4.1 (3.02 in fault-free case). Utilization of link 23 is 54.54% greater than the fault-free case.

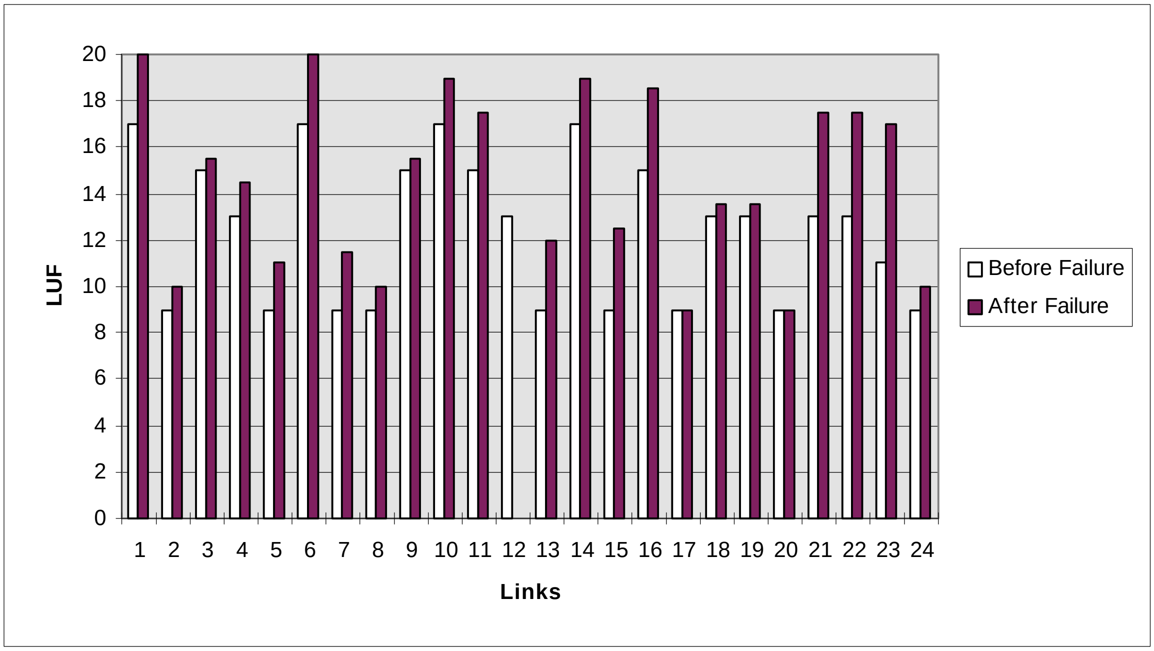

Figure A6.21: Failed Link is B6-B7. Max LUF 20 (Links 1 & 6), average LUF 13.33 (12.42 in fault-free case) and S.D. of LUF 4.1 (3.02 in fault-free case). Utilization of link 23 is 54.54% greater than the fault-free case.

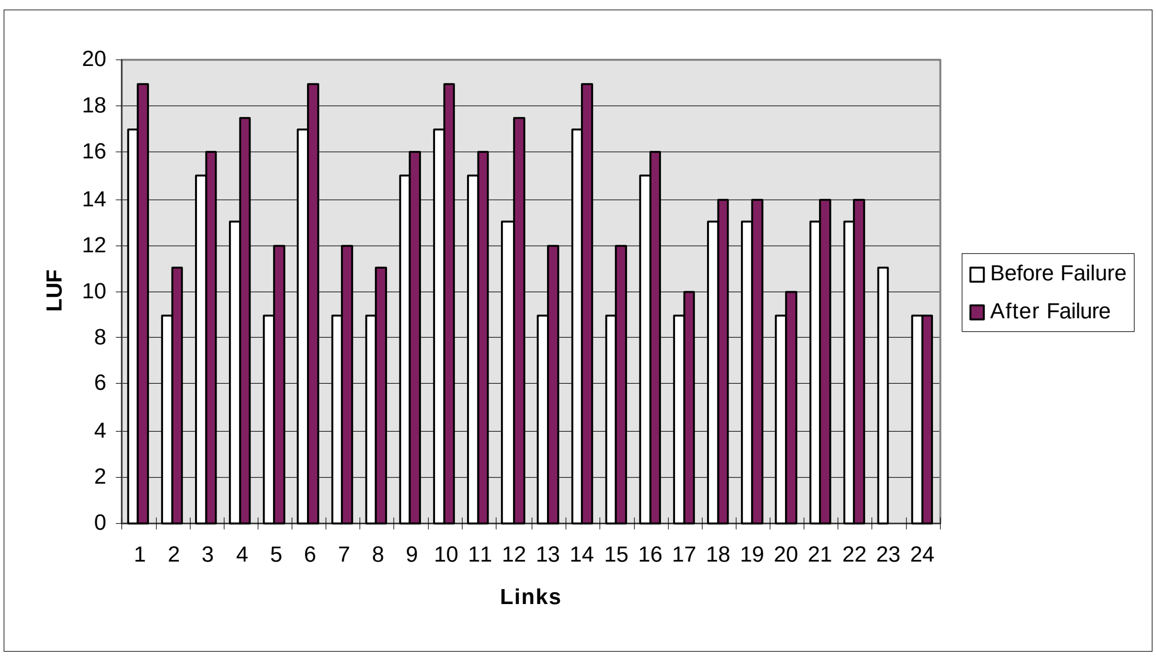

Figure A6.22: Failed Link is A1-A2. Max LUF 19 (Links 1,6,10 & 14), average LUF 13.75 (12.42 in fault-free case) and S.D. of LUF 4.21 (3.02 in fault-free case). Utilization of links 4 & 12 are 34.6% greater than the fault-free case.

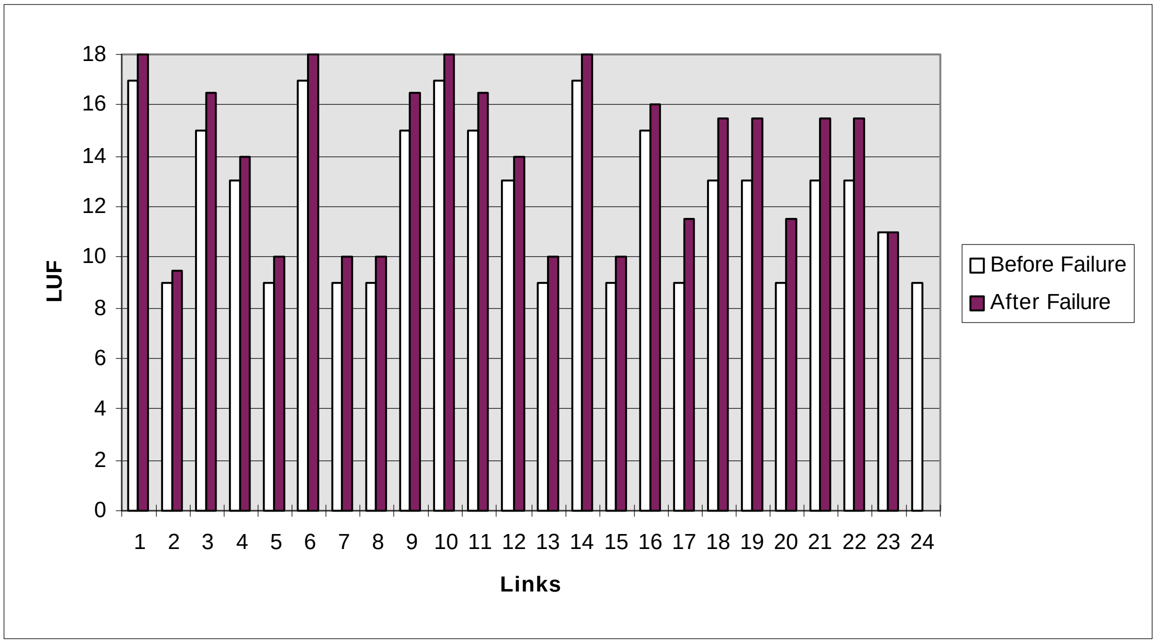

Figure A6.23: Failed Link is D1-D2. Max LUF 18 (Links 1,6,10 & 14), average LUF 13.37 (12.42 in fault-free case) and S.D. of LUF 4.1 (3.02 in fault-free case). Utilization of links 17 & 20 are 27.78% greater than the fault-free case.

Appendix G

Node Utilization Factors (NUFs) of all possible single-link failure scenarios (other than failure of B1-B2 link, which is shown in Figure 5.3) of topology 1 are contained in this section of appendix.

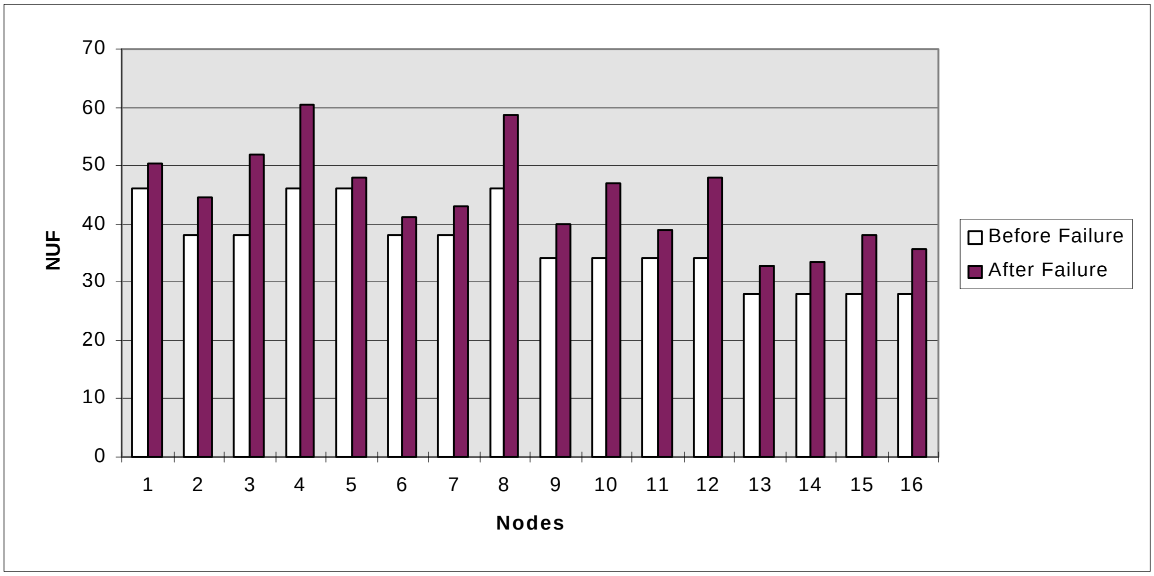

Figure A7.1: Failed Link is B1-C1. Max NUF 60.5 (Node 4), average NUF 44.5 (36.5 in fault-free case) and S.D. of NUF 7.97 (6.54 in fault-free case). Utilization of node 12 is 41.76% greater than the fault-free case.

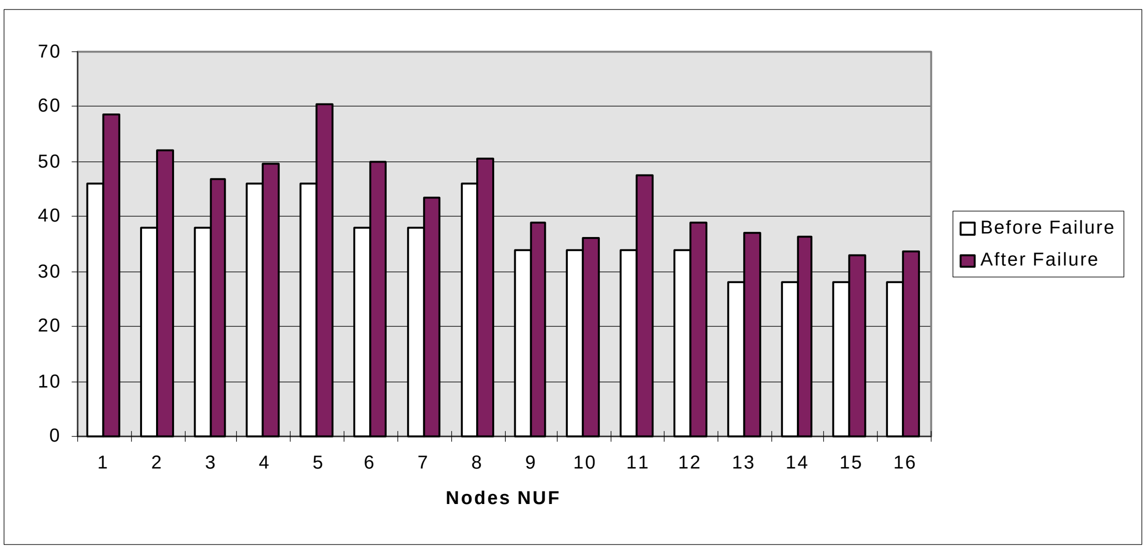

Figure A7.2: Failed Link is B7-B8. Max NUF 60.5 (Node 5), average NUF 44.56 (36.5 in fault-free case) and S.D. of NUF 8.37 (6.54 in fault-free case). Utilization of node 11 is 39.7% greater than the fault-free case.

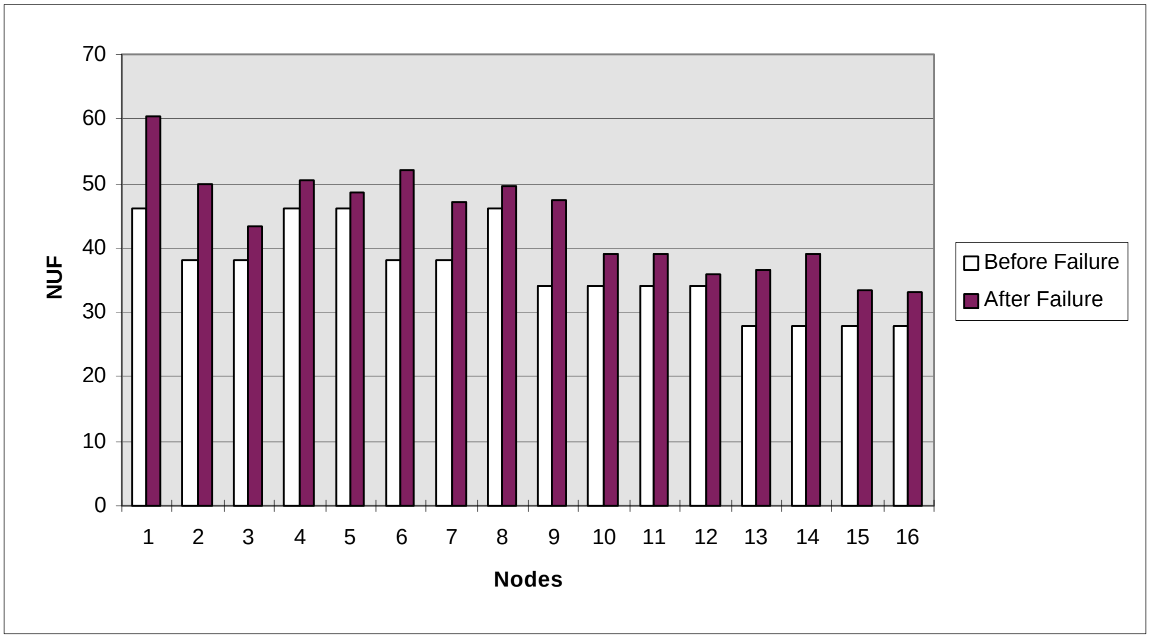

Figure A7.3: Failed Link is B3-B4. Max NUF 60.5 (Node 1), average NUF 44.06 (36.5 in fault-free case) and S.D. of NUF 7.55 (6.54 in fault-free case). Utilization of node 6 is 39.7% greater than the fault-free case.

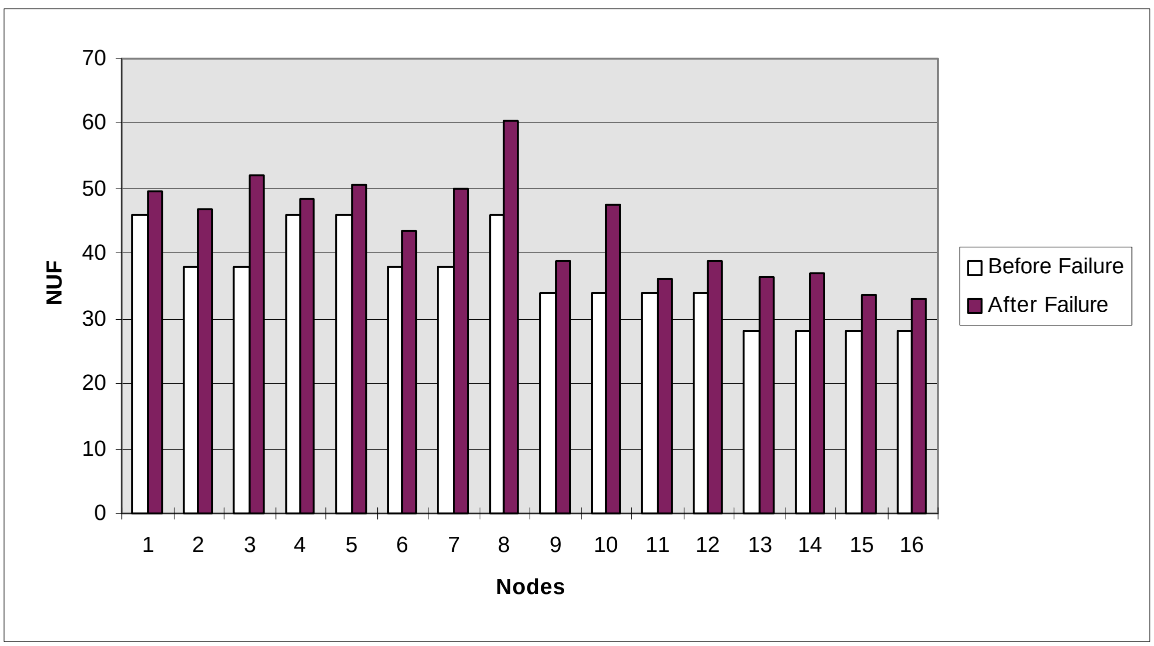

Figure A7.4: Failed Link is B5-B6. Max NUF 60.5 (Node 8), average NUF 43.94 (36.5 in fault-free case) and S.D. of NUF 7.65 (6.54 in fault-free case). Utilization of node 10 is 39.7% greater than the fault-free case.

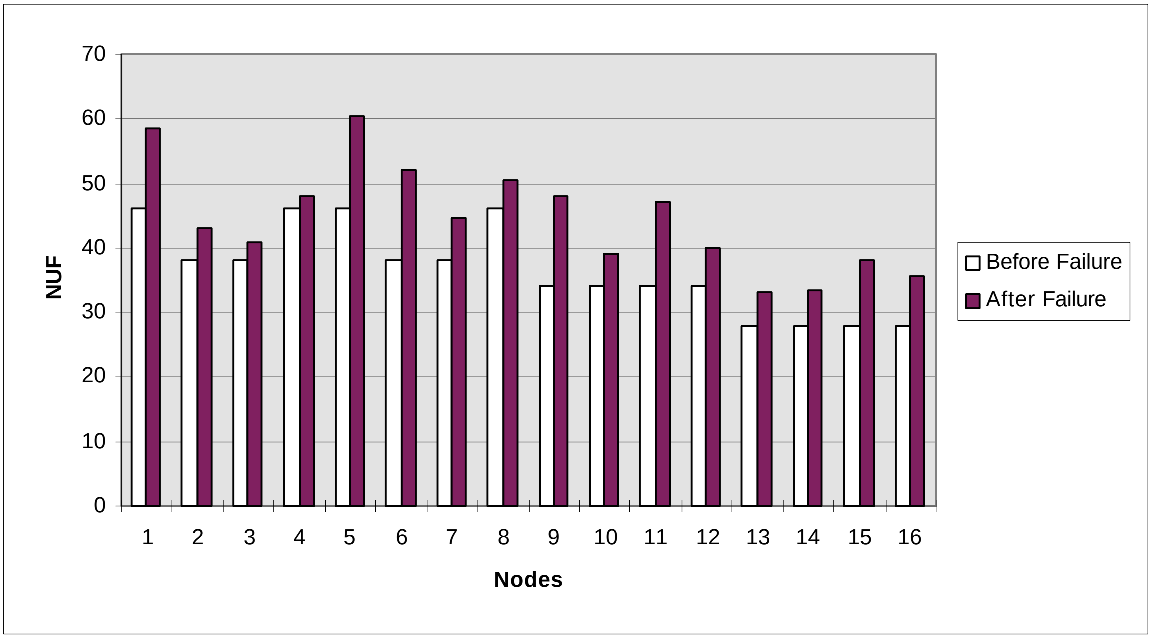

Figure A7.5: Failed Link is B8-C4. Max NUF 60.5 (Node 5), average NUF 44.5 (36.5 in fault-free case) and S.D. of NUF 7.97 (6.54 in fault-free case). Utilization of node 11 is 38.23% greater than the fault-free case.

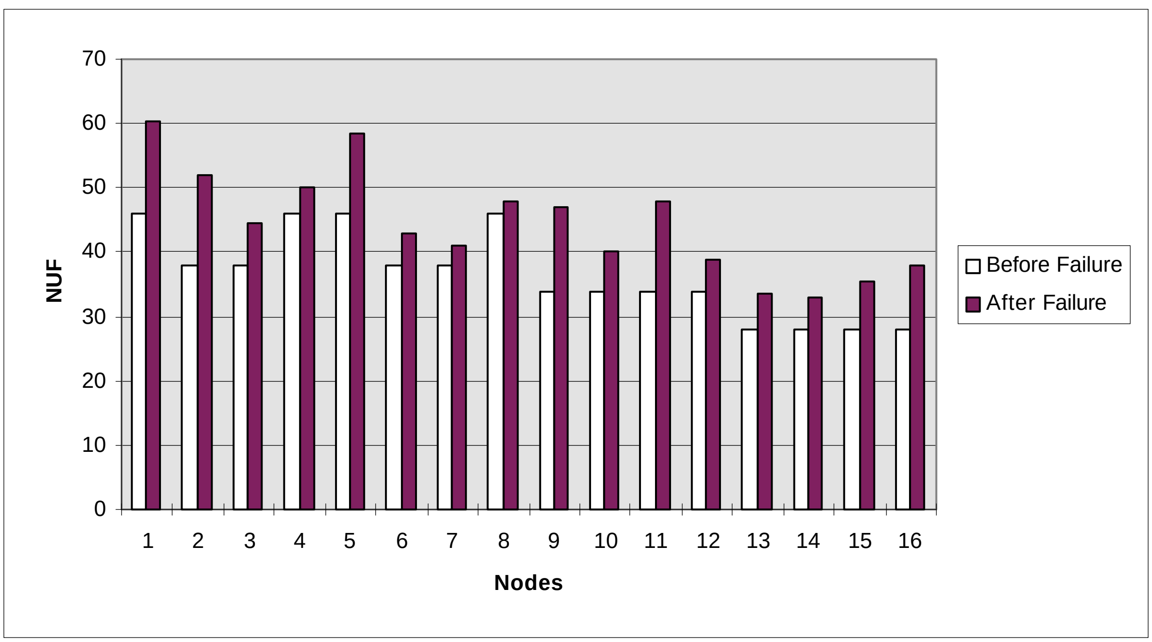

Figure A7.6: Failed Link is B4-C2. Max NUF 60.5 (Node 1), average NUF 44.47 (36.5 in fault-free case) and S.D. of NUF 7.95 (6.54 in fault-free case). Utilization of node 11 is 41.17% greater than the fault-free case.

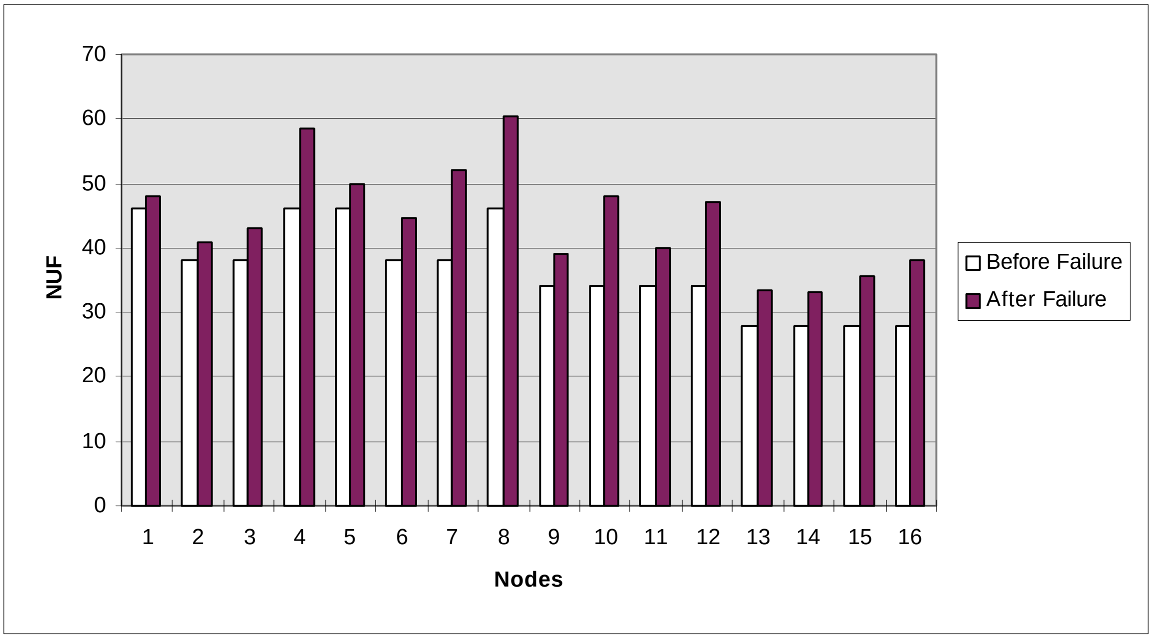

Figure A7.7: Failed Link is B5-C3. Max NUF 60.5 (Node 8), average NUF 44.47 (36.5 in fault-free case) and S.D. of NUF 7.95 (6.54 in fault-free case). Utilization of node 10 is 41.17% greater than the fault-free case.

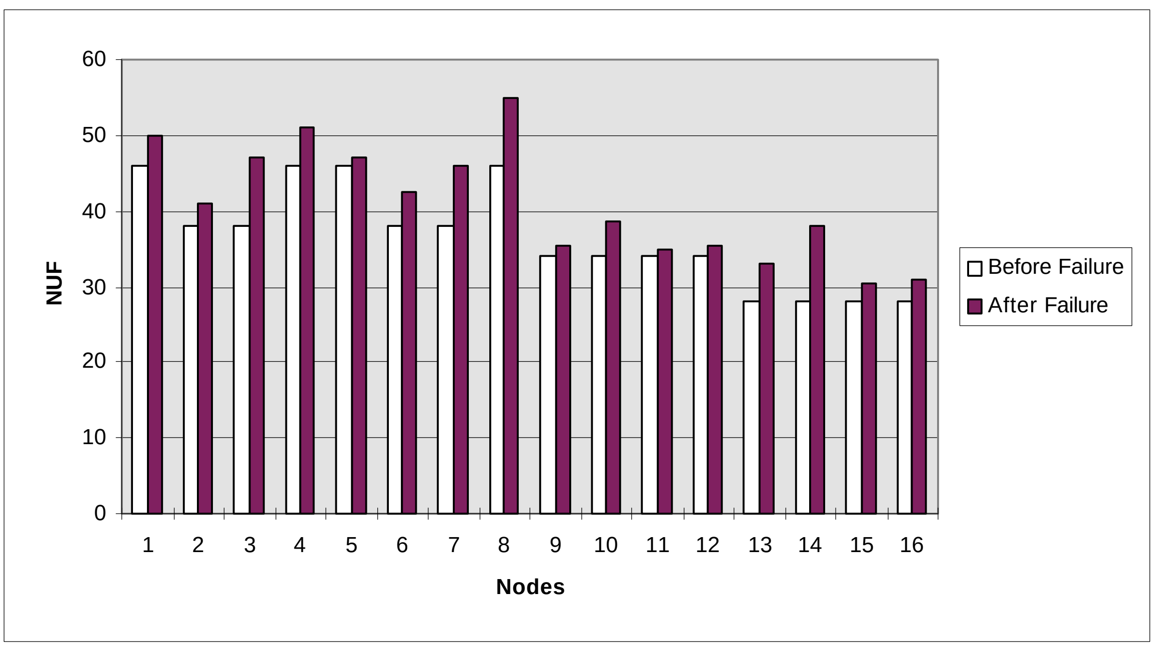

Figure A7.8: Failed Link is B2-A1. Max NUF 55 (Node 8), average NUF 41.03 (36.5 in fault-free case) and S.D. of NUF 7.34 (6.54 in fault-free case). Utilization of node 14 is 35.71% greater than the fault-free case.

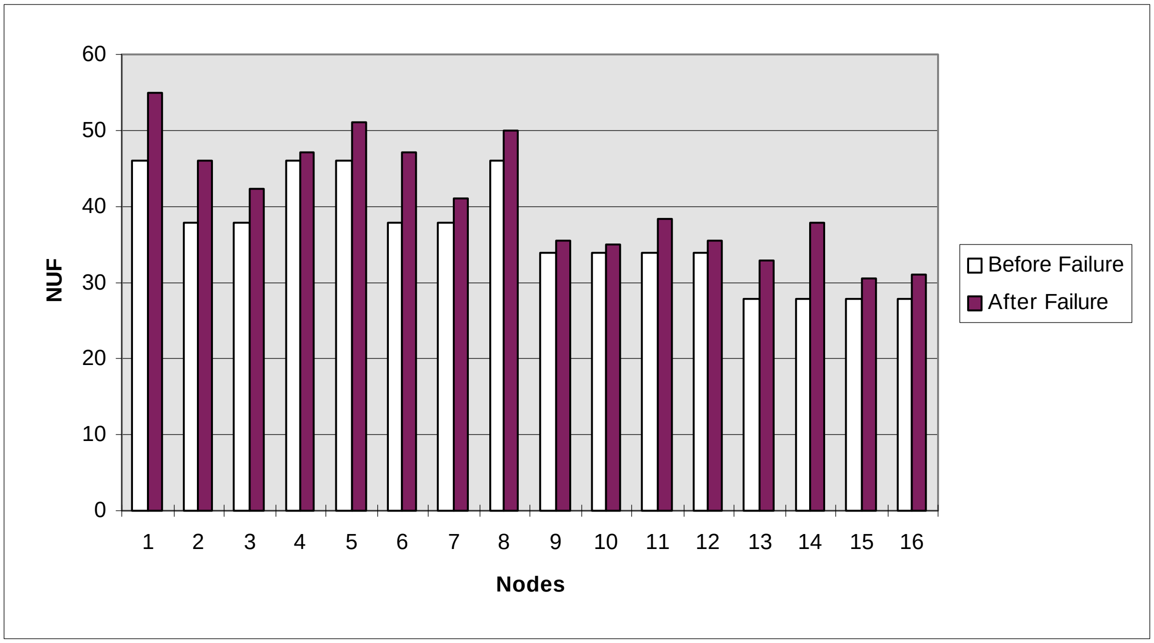

Figure A7.9: Failed Link is B7-A1. Max NUF 55 (Node 1), average NUF 41.03 (36.5 in fault-free case) and S.D. of NUF 7.34 (6.54 in fault-free case). Utilization of node 14 is 35.71% greater than the fault-free case

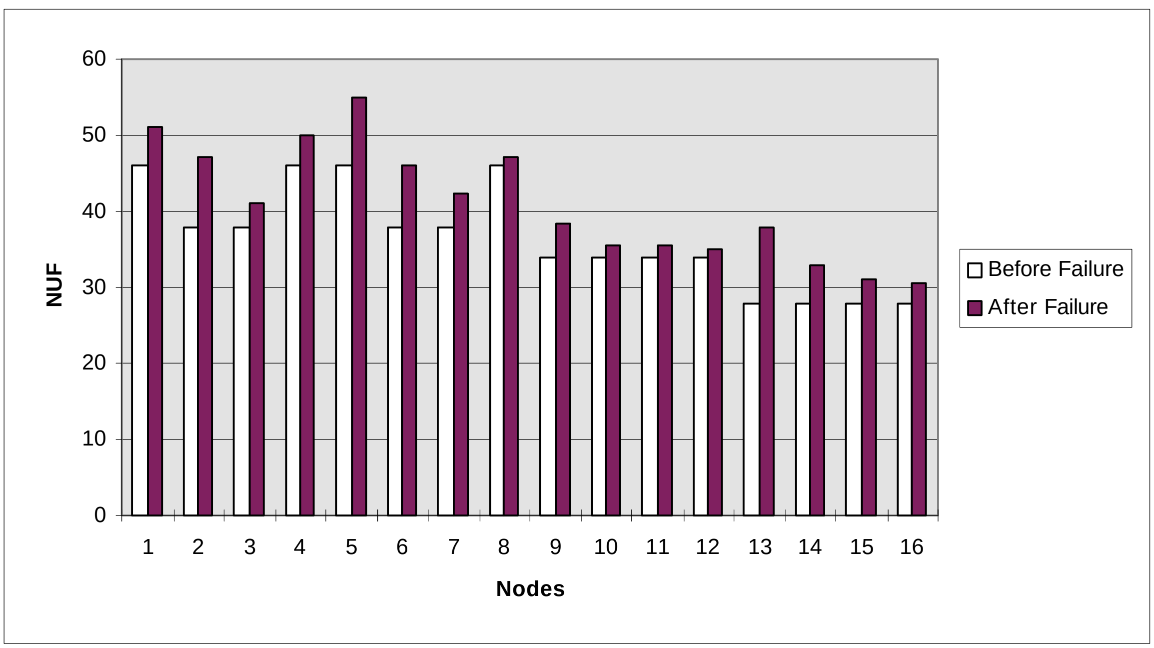

Figure A7.10: Failed Link is B3-A2. Max NUF 55 (Node 5), average NUF 41.03 (36.5 in fault-free case) and S.D. of NUF 7.34 (6.54 in fault-free case). Utilization of node 13 is 35.71% greater than the fault-free case

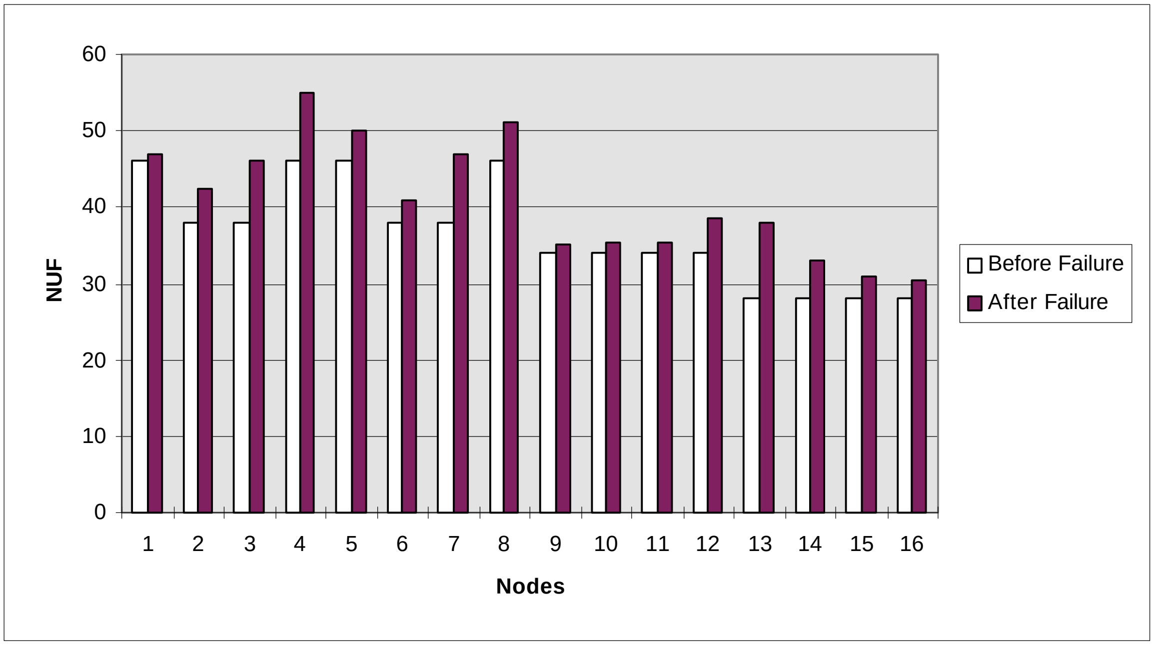

Figure A7.11: Failed Link is B6-A2. Max NUF 55 (Node 5), average NUF 41.03 (36.5 in fault-free case) and S.D. of NUF 7.34 (6.54 in fault-free case). Utilization of node 13 is 35.71% greater than the fault-free case

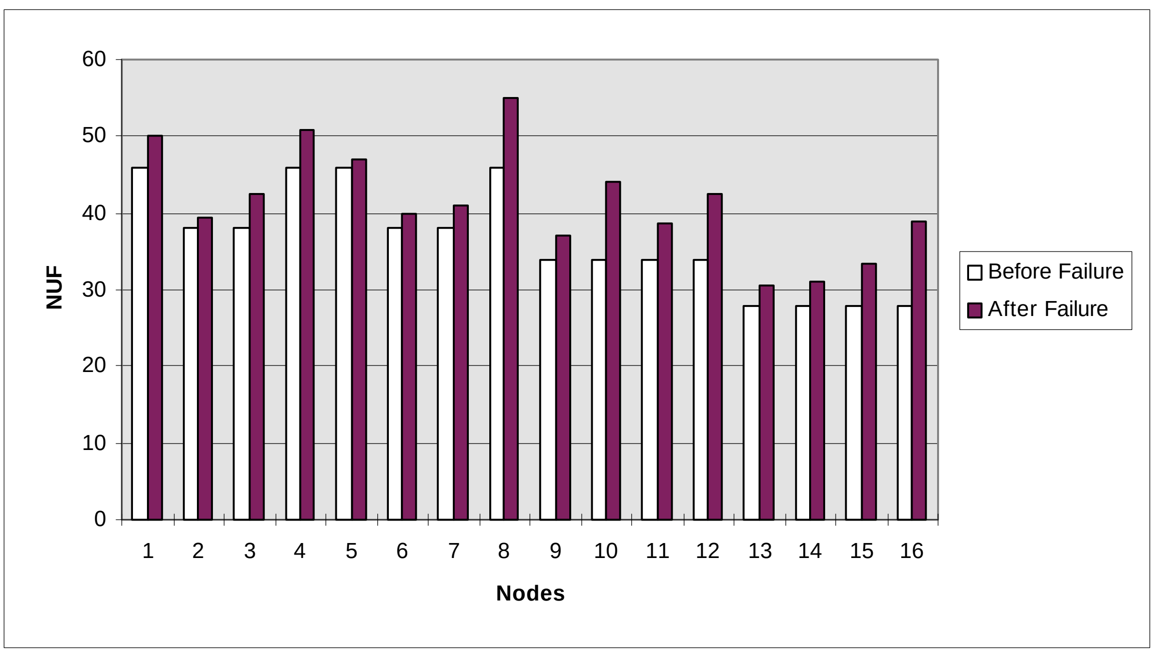

Figure A7.12: Failed Link is C1-D1. Max NUF 55 (Node 8), average NUF 41.37 (36.5 in fault-free case) and S.D. of NUF 6.71 (6.54 in fault-free case). Utilization of node 16 is 39.28% greater than the fault-free case.

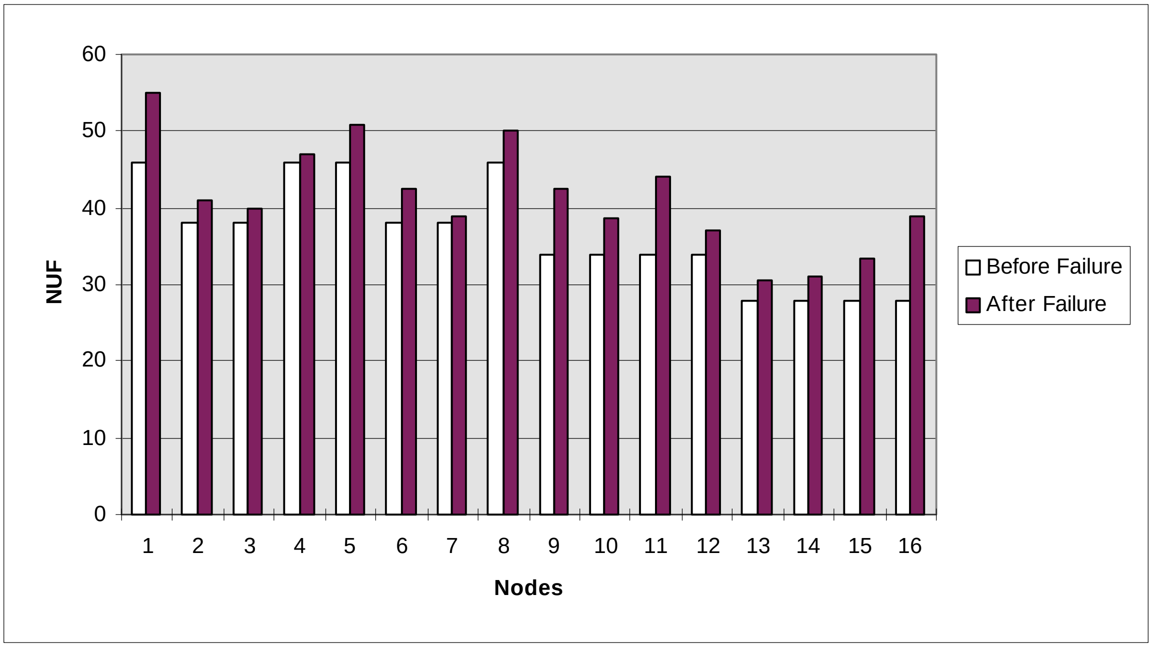

Figure A7.13: Failed Link is C4-D1. Max NUF 55 (Node 1), average NUF 41.34 (36.5 in fault-free case) and S.D. of NUF 6.72 (6.54 in fault-free case). Utilization of node 16 is 39.28% greater than the fault-free case.

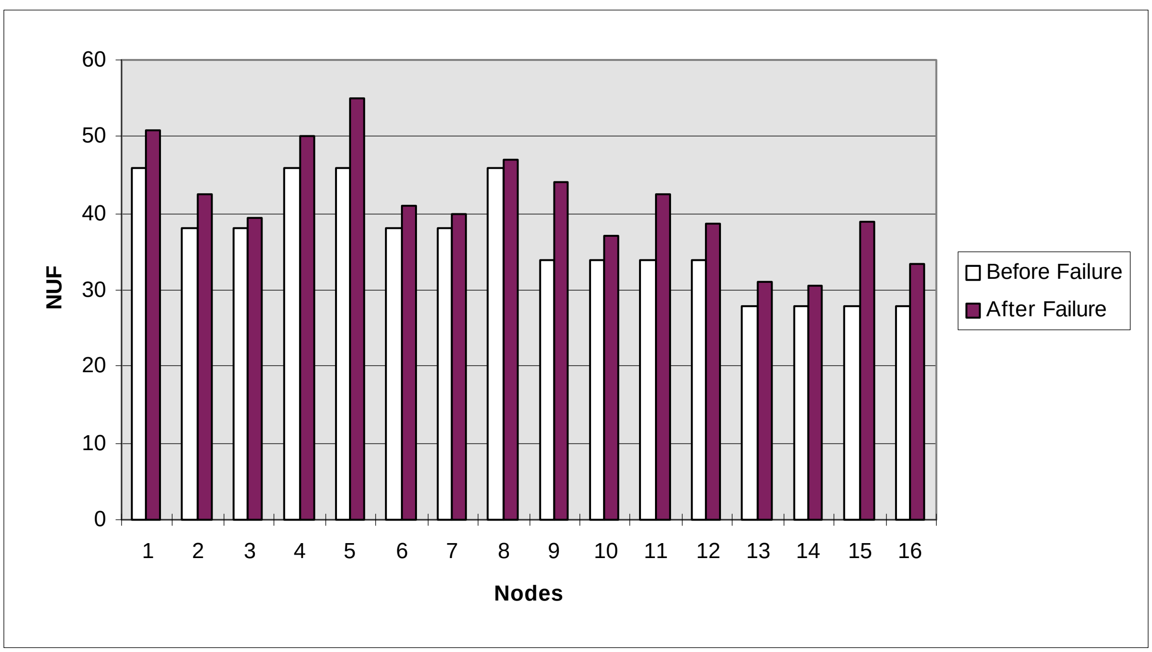

Figure A7.14: Failed Link is C2-D2. Max NUF 55 (Node 5), average NUF 41.37 (36.5 in fault-free case) and S.D. of NUF 6.71 (6.54 in fault-free case). Utilization of node 15 is 39.28% greater than the fault-free case.

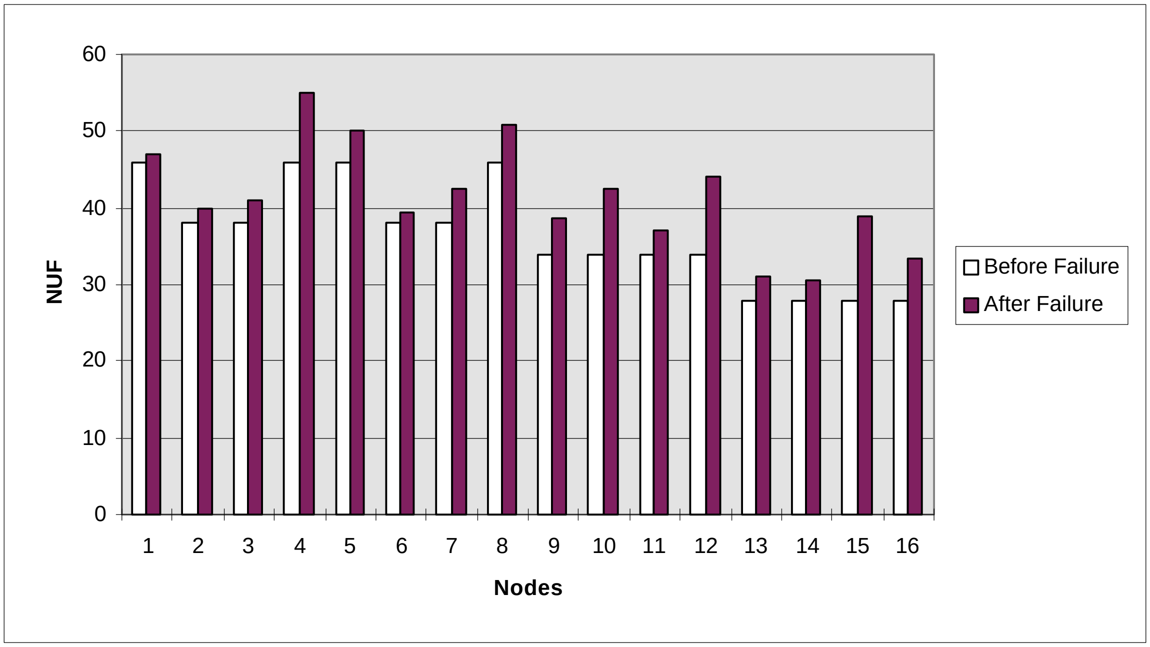

Figure A7.15: Failed Link is C3-D2. Max NUF 55 (Node 4), average NUF 41.37 (36.5 in fault-free case) and S.D. of NUF 6.71 (6.54 in fault-free case). Utilization of node 15 is 39.28% greater than the fault-free case.

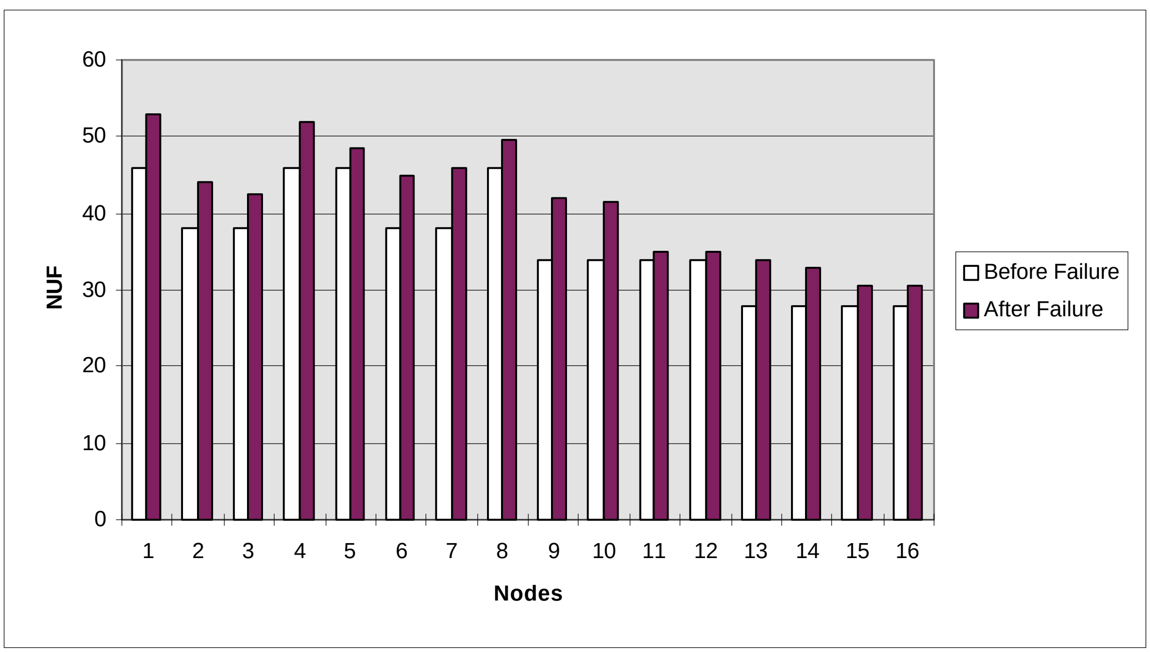

Figure A7.16: Failed Link is B2-B3. Max NUF 53 (Node 1), average NUF 41.37 (36.5 in fault-free case) and S.D. of NUF 7.29 (6.54 in fault-free case). Utilization of node 9 is 23.538% greater than the fault-free case.

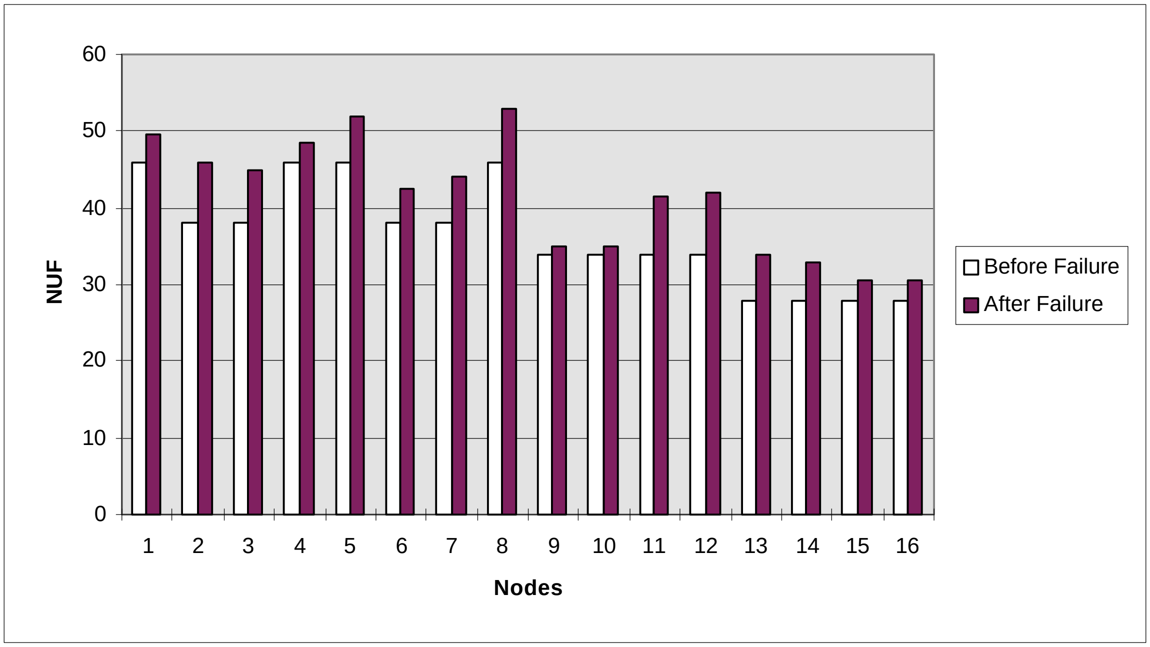

Figure A7.17: Failed Link is B6-B7. Max NUF 53 (Node 8), average NUF 41.37 (36.5 in fault-free case) and S.D. of NUF 7.29 (6.54 in fault-free case). Utilization of node 12 is 23.53% greater than the fault-free case.

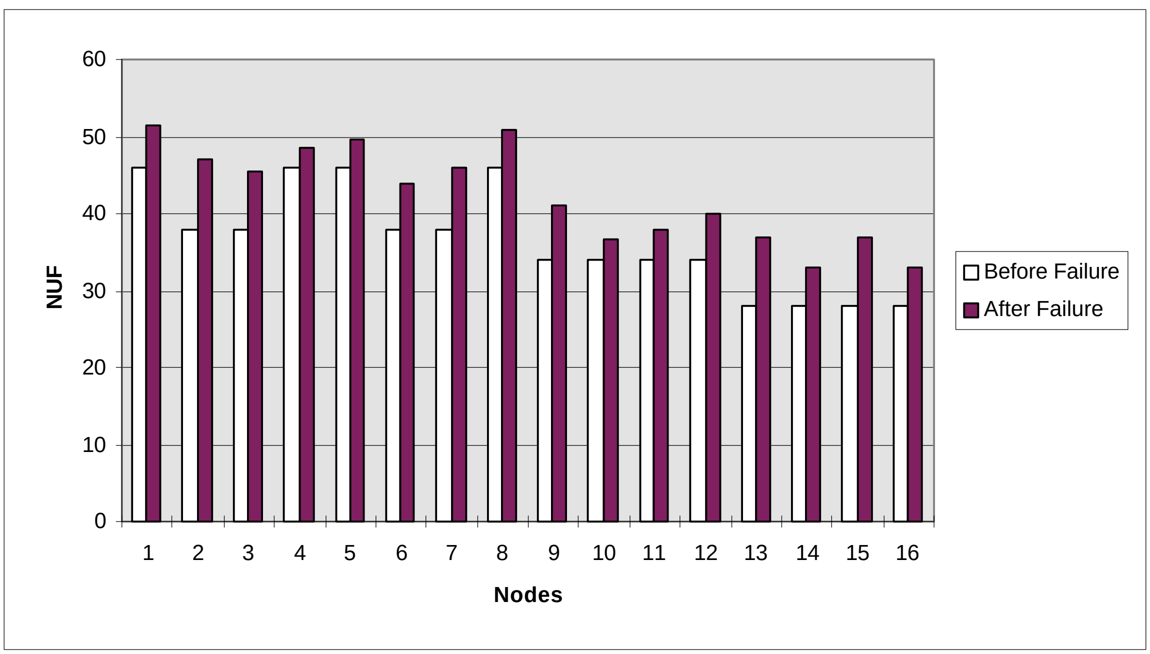

Figure A7.18: Failed Link is B1-B8. Max NUF 51.5 (Node 1), average NUF 42.41 (36.5 in fault-free case) and S.D. of NUF 6.06 (6.54 in fault-free case). Utilization of node 15 is 32.14% greater than the fault-free case.

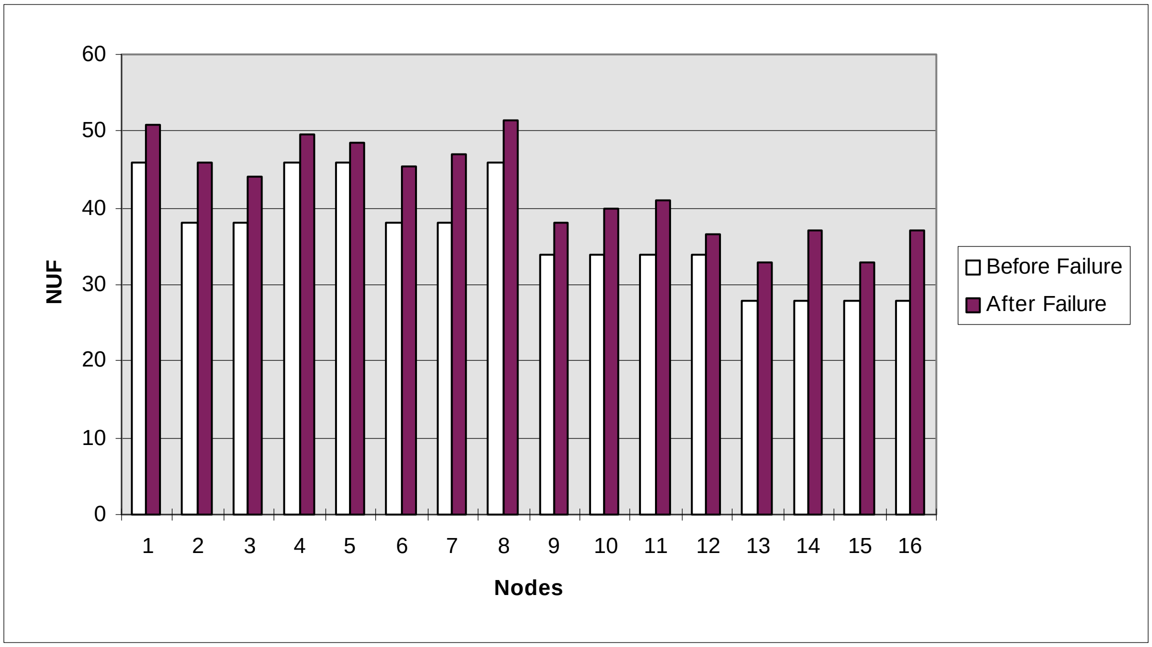

Figure A7.19: Failed Link is B4-B5. Max NUF 51.5 (Node 8), average NUF 42.41 (36.5 in fault-free case) and S.D. of NUF 6.06 (6.54 in fault-free case). Utilization of node 16 is 32.14% greater than the fault-free case.

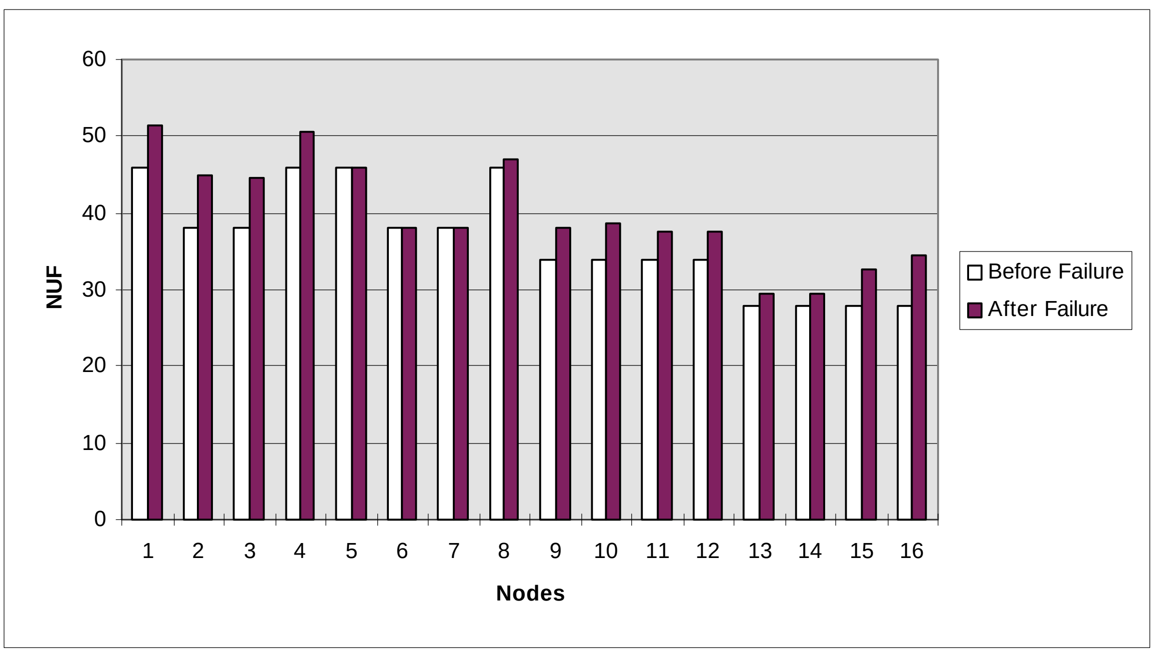

Figure A7.20: Failed Link is C1-C2. Max NUF 51.5 (Node 1), average NUF 39.88 (36.5 in fault-free case) and S.D. of NUF 6.64 (6.54 in fault-free case). Utilization of node 16 is 23.21% greater than the fault-free case.

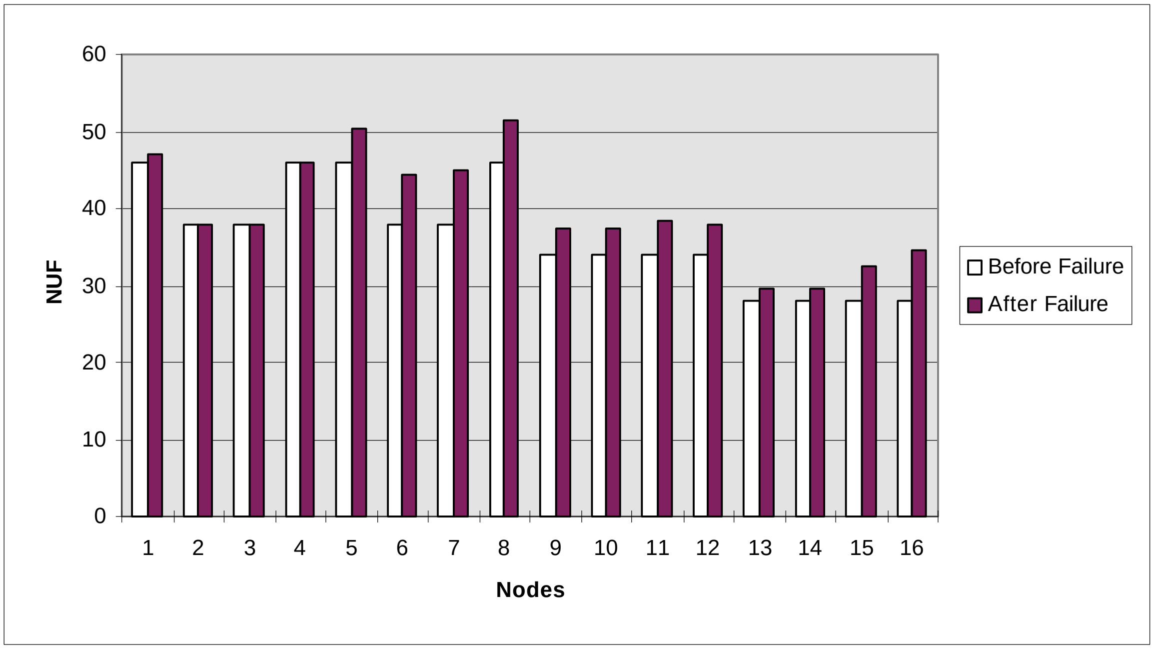

Figure A7.21: Failed Link is C3-C4. Max NUF 51.5 (Node 8), average NUF 39.88 (36.5 in fault-free case) and S.D. of NUF 6.64 (6.54 in fault-free case). Utilization of node 16 is 23.21% greater than the fault-free case.

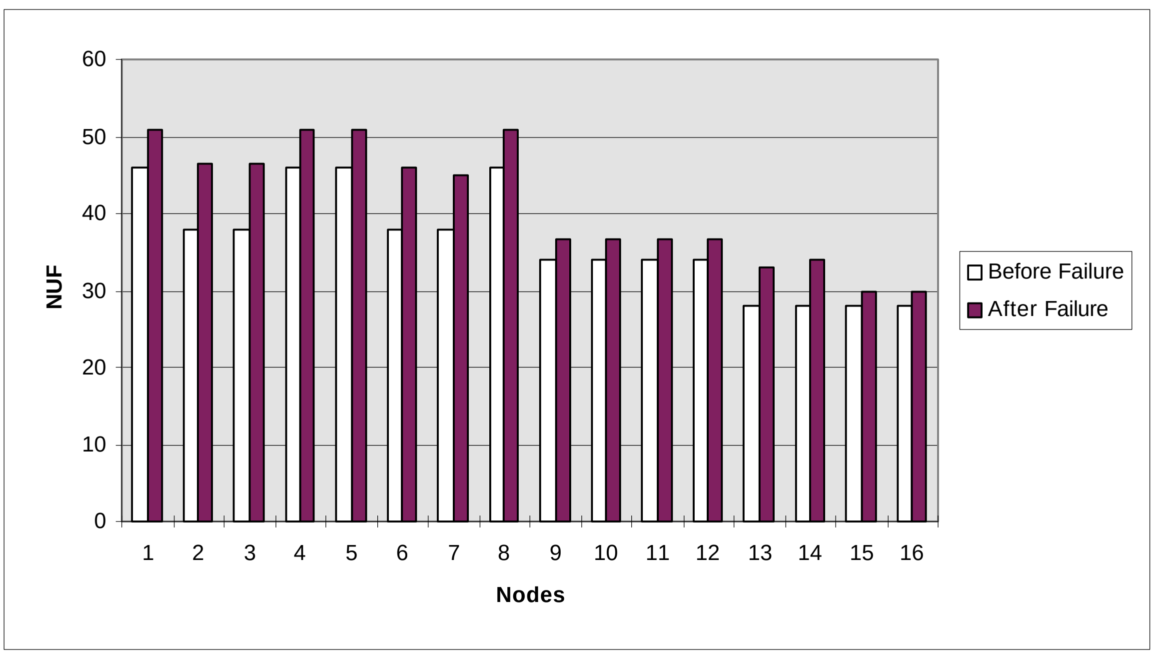

Figure A7.22: Failed Link is A1-A2. Max NUF 51.5 (Nodes 1,4,5 & 8), average NUF 41.31 (36.5 in fault-free case) and S.D. of NUF 6.65 (6.54 in fault-free case). Utilization of nodes 2 & 3 are 22.36% greater than the fault-free case.

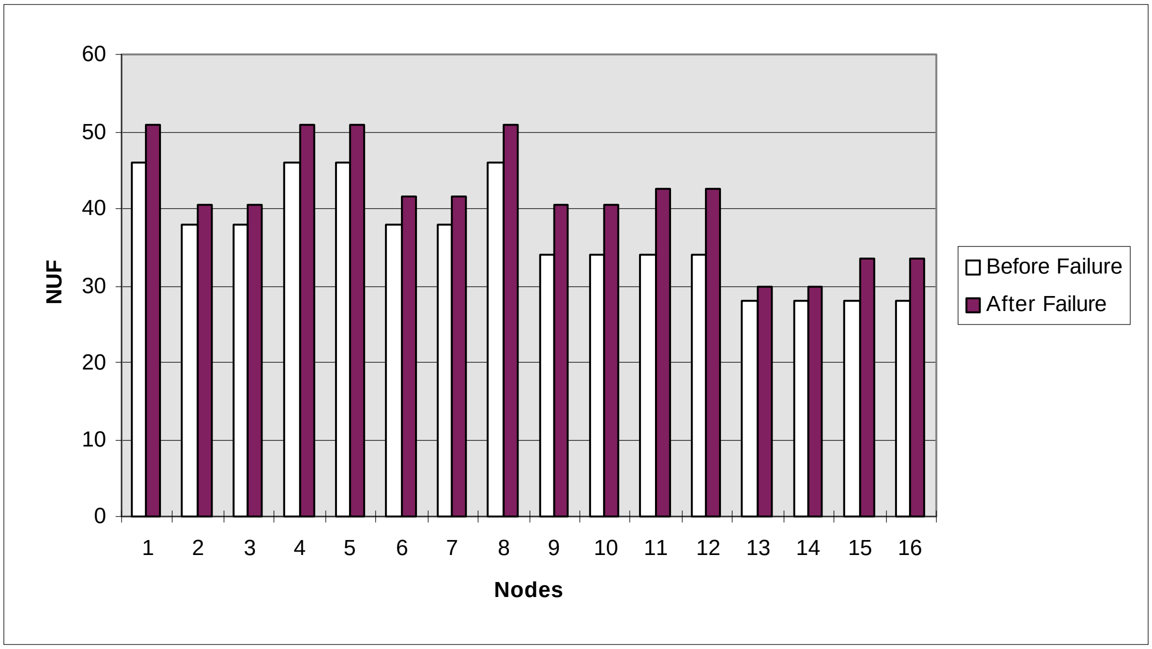

Figure A7.23: Failed Link is D1-D2. Max NUF 51.5 (Nodes 1,4,5 & 8), average NUF 41.31 (36.5 in fault-free case) and S.D. of NUF 6.88 (6.54 in fault-free case). Utilization of nodes 11 & 12 are 25% greater than the fault-free case.

Appendix H

Node Utilization Factors (NUFs) of all possible single-link failure scenarios (other than failure of B1-B2 link, which is shown in Figure 5.4) of topology 2 are contained in this section of appendix.

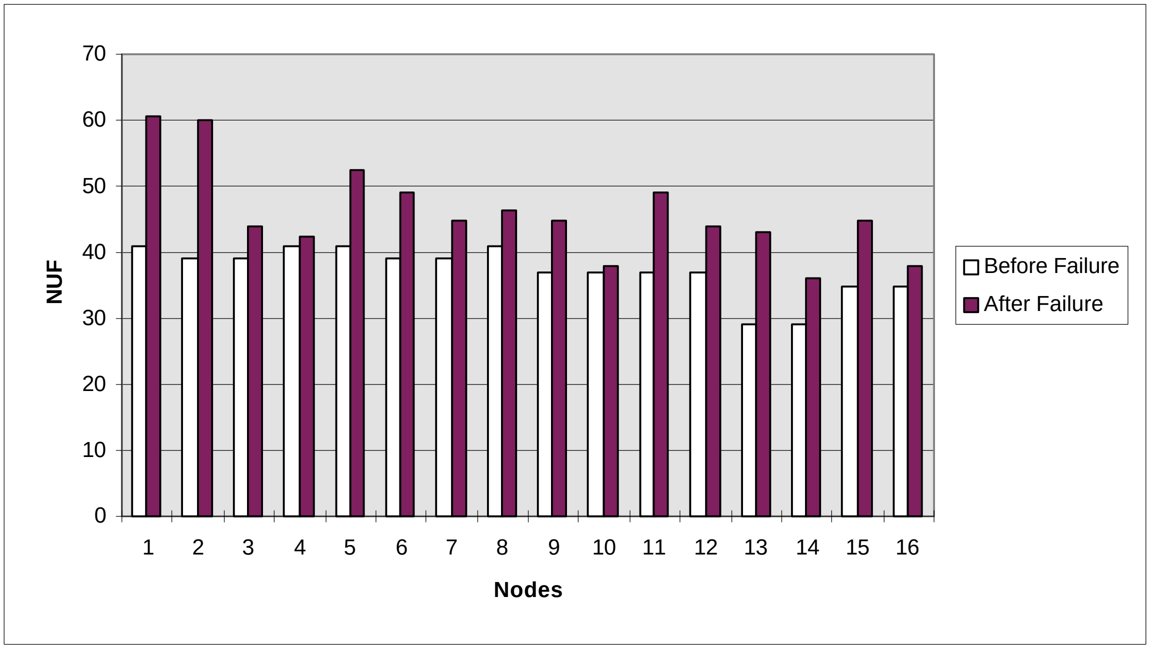

Figure A8.1: Failed Link is B7-B8. Max NUF 60.5 (Node 1), average NUF 46.125 (37.25 in fault-free case) and S.D. of NUF 6.74 (3.66 in fault-free case). Utilization of node 2 is 53.85% greater than the fault-free case.

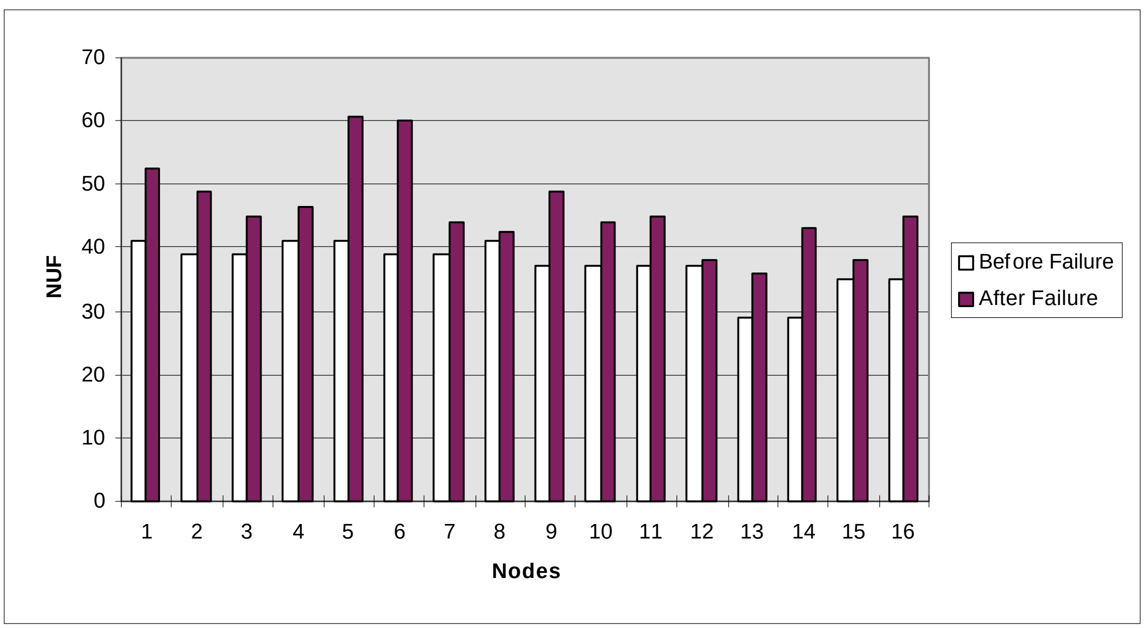

Figure A8.2: Failed Link is B3-B4. Max NUF 60.5 (Node 5), average NUF 46.125 (37.25 in fault-free case) and S.D. of NUF 6.74 (3.66 in fault-free case). Utilization of node 6 is 53.85% greater than the fault-free case.

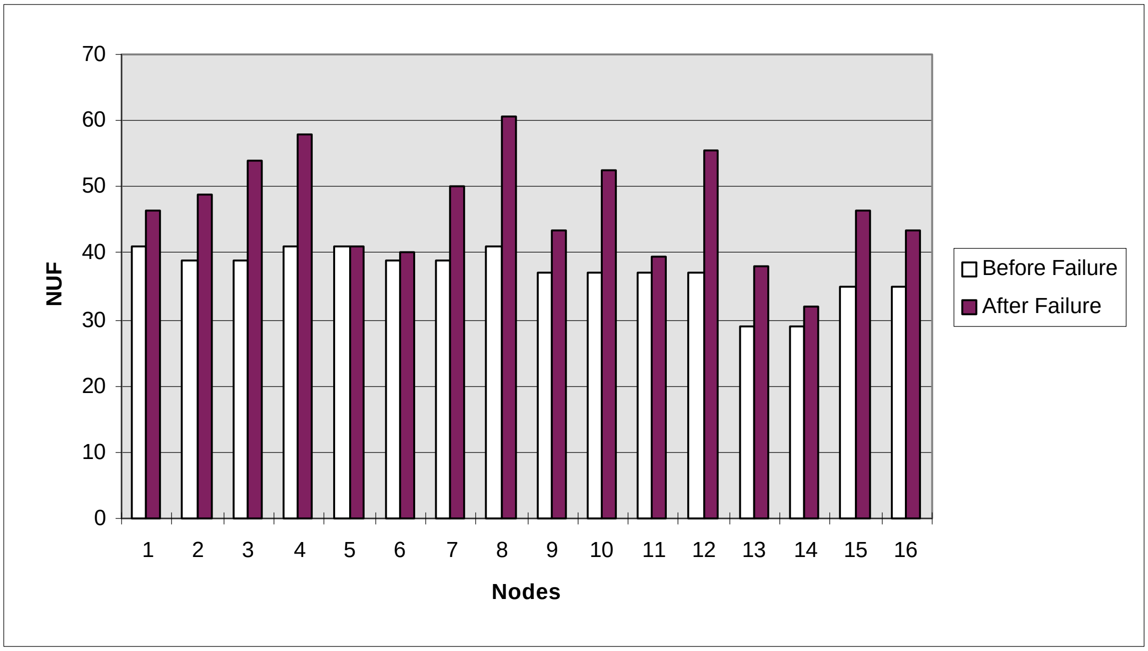

Figure A8.3: Failed Link is B1-C1. Max NUF 60.5 (Node 5), average NUF 46.875 (37.25 in fault-free case) and S.D. of NUF 7.66 (3.66 in fault-free case). Utilization of node 12 is 50% greater than the fault-free case.

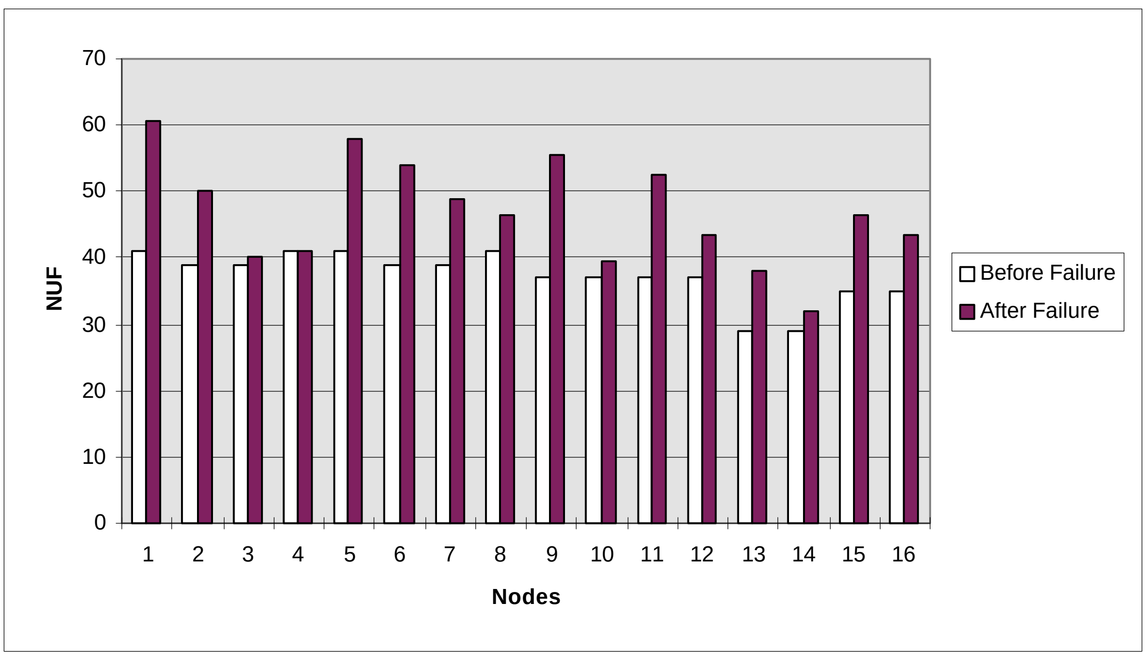

Figure A8.4: Failed Link is B8-C4. Max NUF 60.5 (Node 1), average NUF 46.875 (37.25 in fault-free case) and S.D. of NUF 7.66 (3.66 in fault-free case). Utilization of node 9 is 50% greater than the fault-free case.

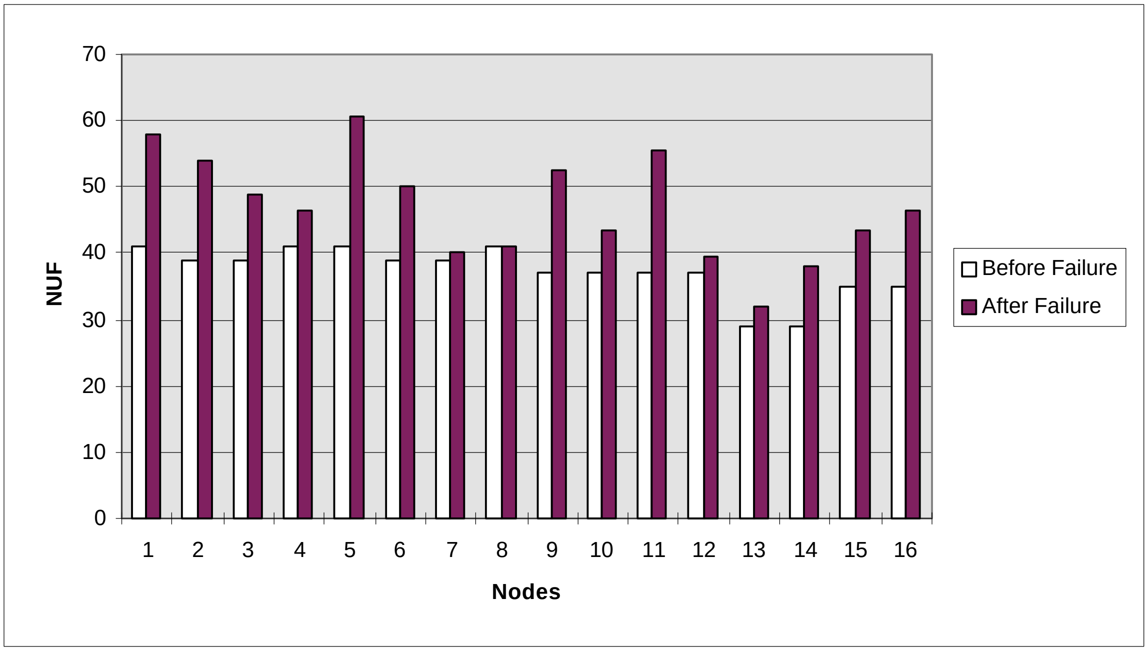

Figure A8.5: Failed Link is B4-C2. Max NUF 60.5 (Node 5), average NUF 46.875 (37.25 in fault-free case) and S.D. of NUF 7.66 (3.66 in fault-free case). Utilization of node 11 is 50% greater than the fault-free case.

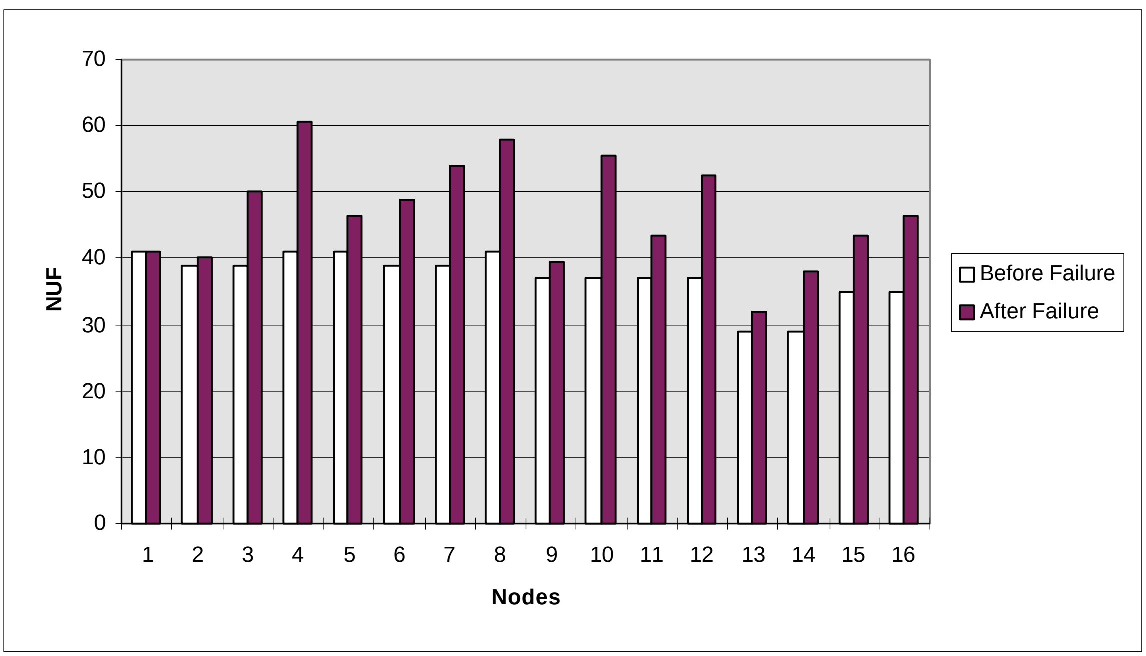

Figure A8.6: Failed Link is B4-C2. Max NUF 60.5 (Node 4), average NUF 46.875 (37.25 in fault-free case) and S.D. of NUF 7.66 (3.66 in fault-free case). Utilization of node 10 is 50% greater than the fault-free case.

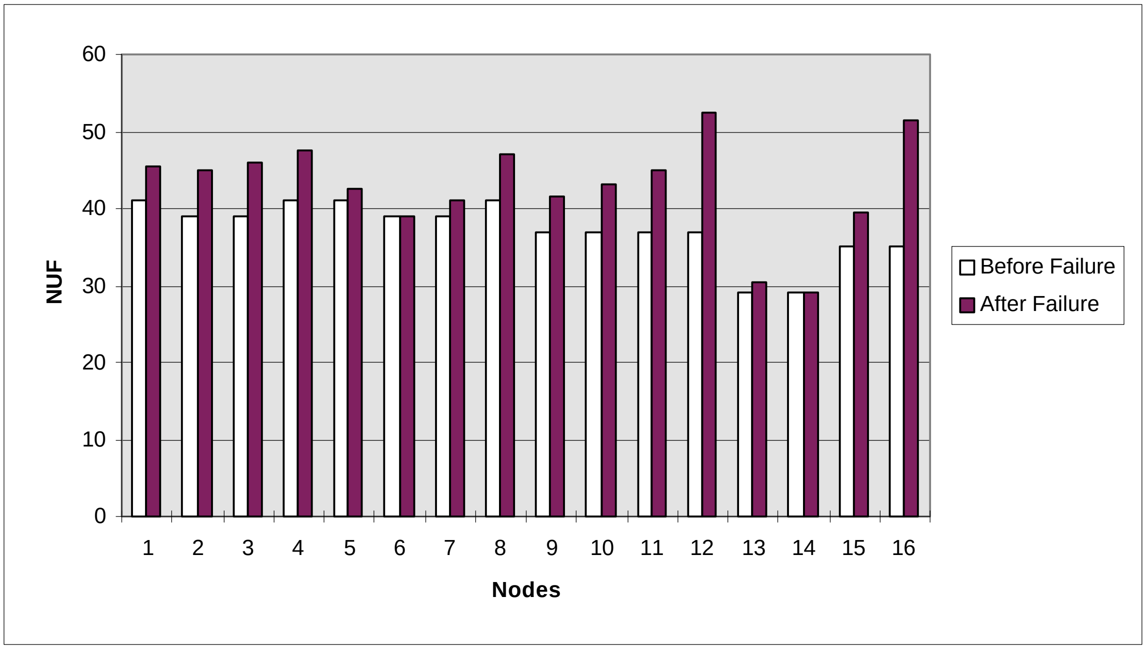

Figure A8.7: Failed Link is C1-D1. Max NUF 52.5 (Node 12), average NUF 42.875 (37.25 in fault-free case) and S.D. of NUF 6.17 (3.66 in fault-free case). Utilization of node 16 is 47.14% greater than the fault-free case.

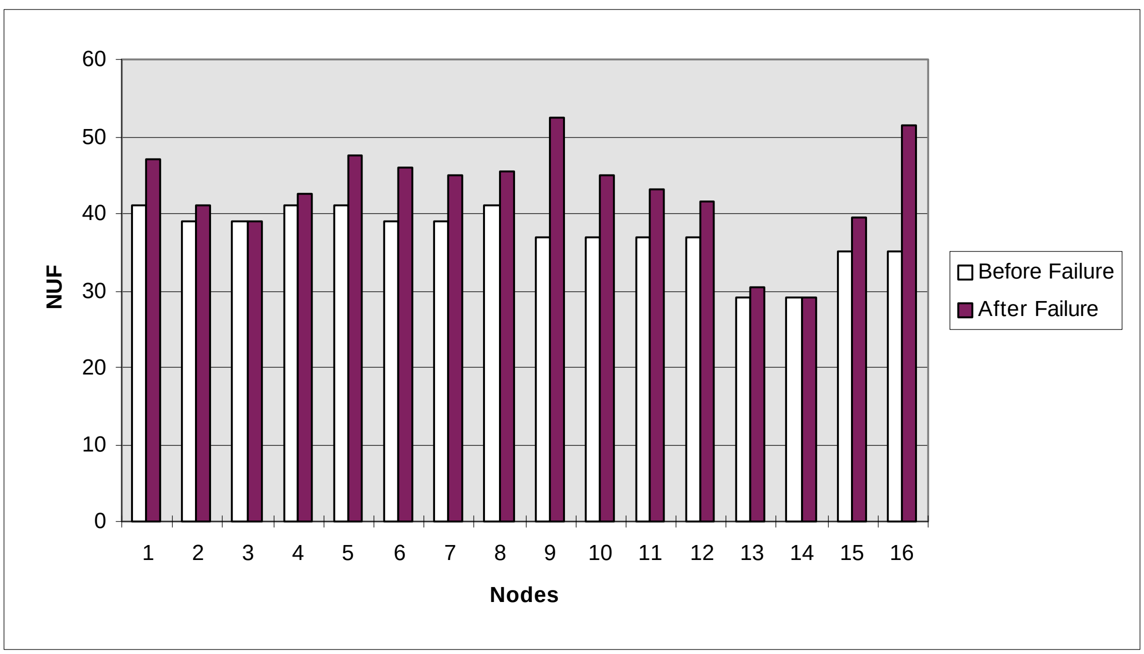

Figure A8.8: Failed Link is C4-D2. Max NUF 52.5 (Node 9), average NUF 42.875 (37.25 in fault-free case) and S.D. of NUF 6.17 (3.66 in fault-free case). Utilization of node 16 is 47.14% greater than the fault-free case.

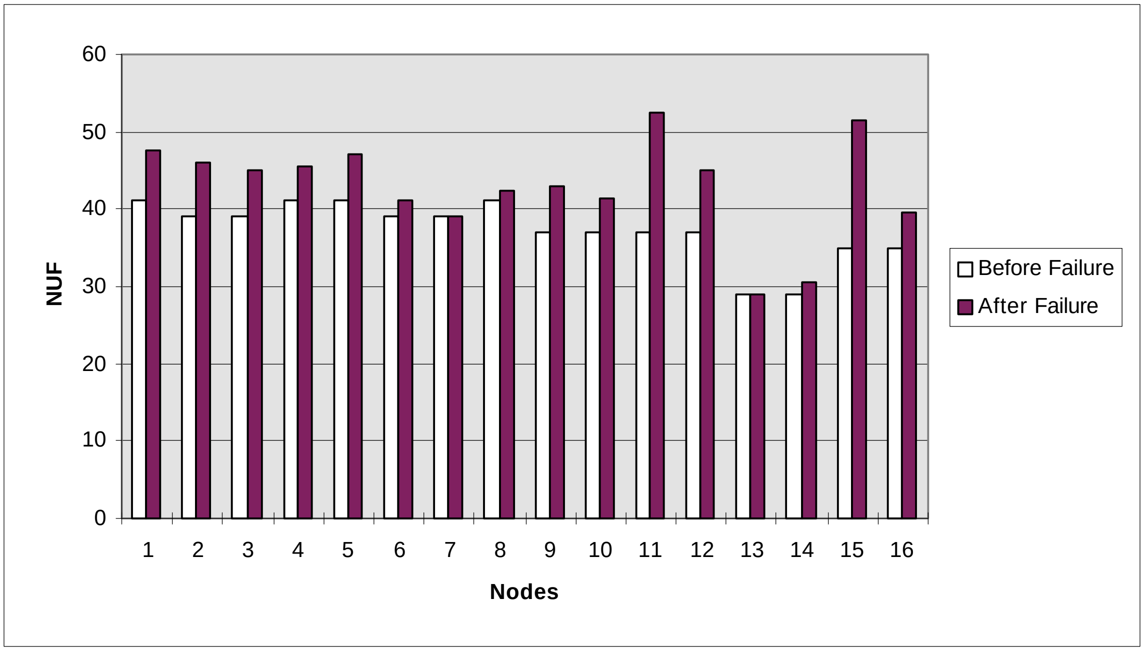

Figure A8.9: Failed Link is C2-D1. Max NUF 52.5 (Node 11), average NUF 42.875 (37.25 in fault-free case) and S.D. of NUF 6.17 (3.66 in fault-free case). Utilization of node 15 is 47.14% greater than the fault-free case.

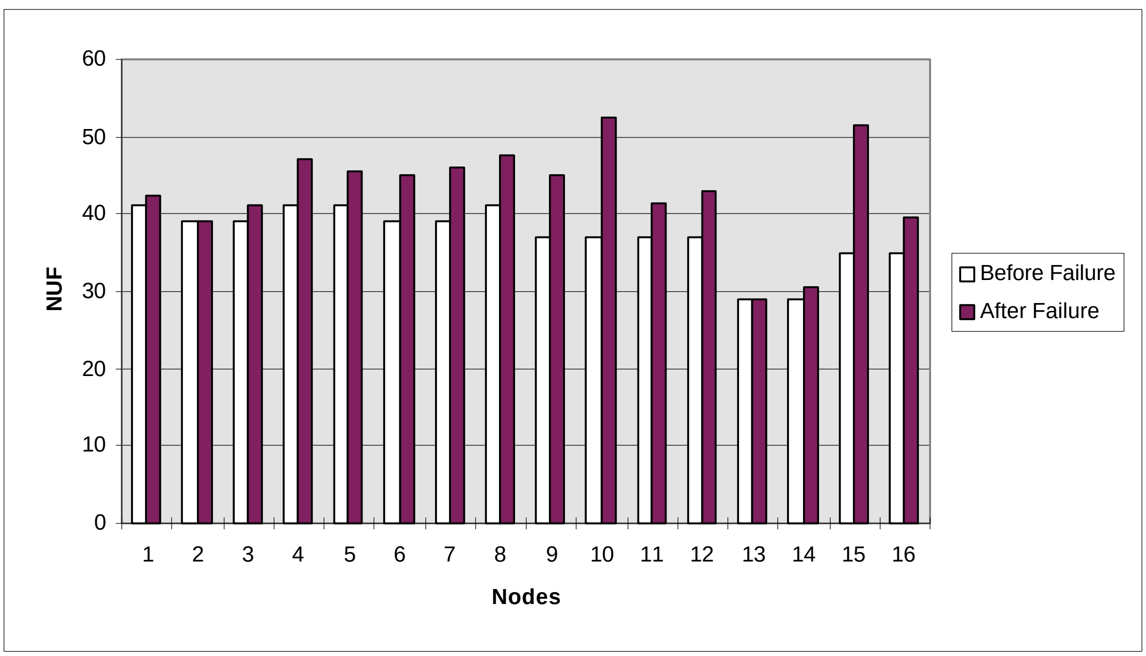

Figure A8.10: Failed Link is C3-D2. Max NUF 52.5 (Node 10), average NUF 42.875 (37.25 in fault-free case) and S.D. of NUF 6.17 (3.66 in fault-free case). Utilization of node 15 is 47.14% greater than the fault-free case.

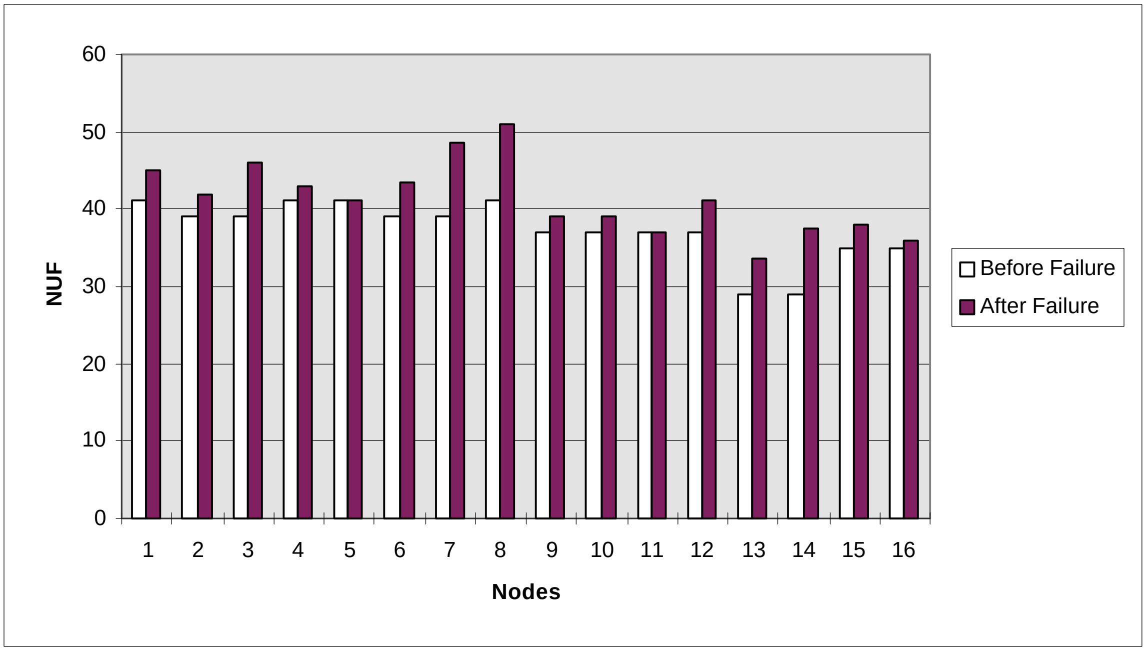

Figure A8.11: Failed Link is B2-A1. Max NUF 51 (Node 8), average NUF 41.31 (37.25 in fault-free case) and S.D. of NUF 4.56 (3.66 in fault-free case). Utilization of node 8 is 24.39% greater than the fault-free case.

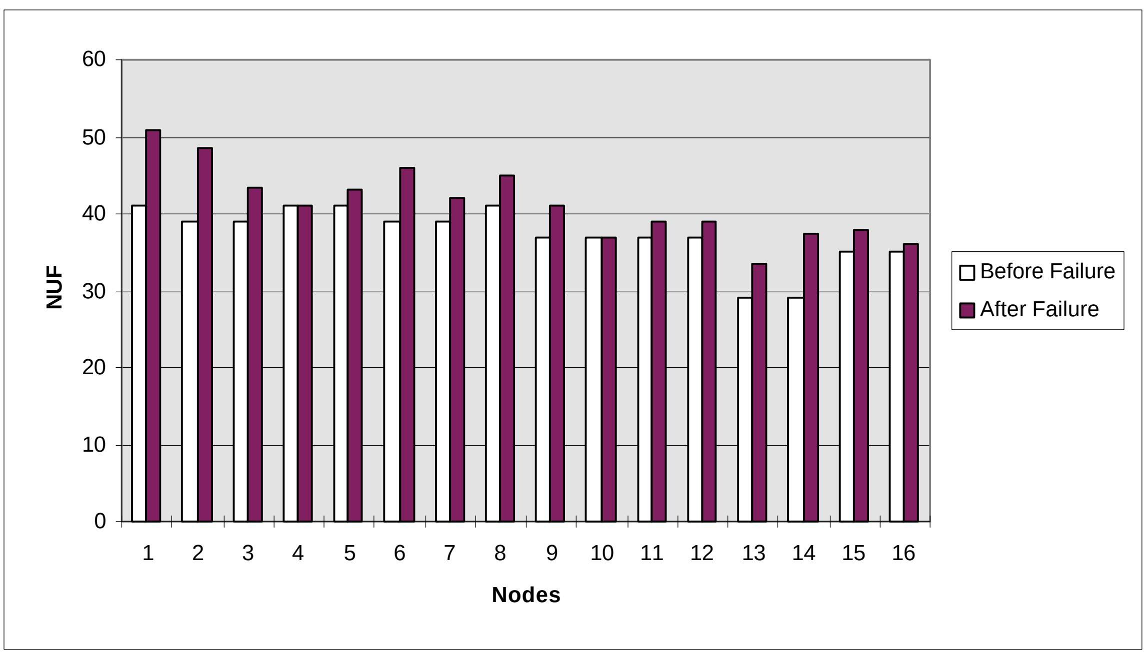

Figure A8.12: Failed Link is B7-A1. Max NUF 51 (Node 1), average NUF 41.31 (37.25 in fault-free case) and S.D. of NUF 4.56 (3.66 in fault-free case). Utilization of node 1 is 24.39% greater than the fault-free case.

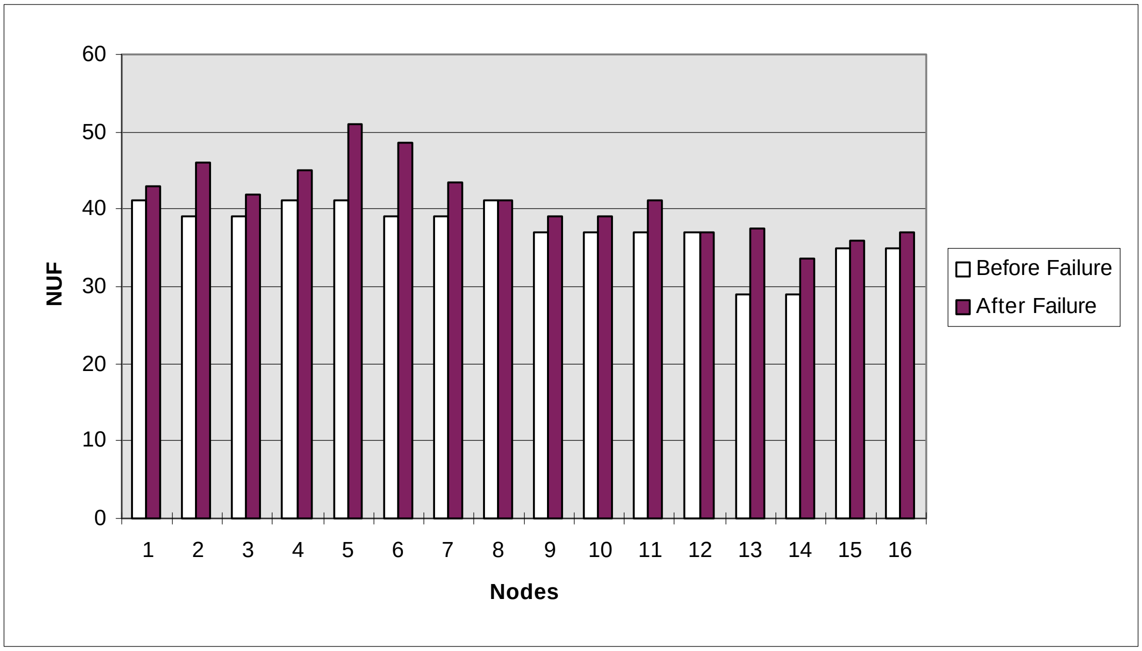

Figure A8.13: Failed Link is B3-A2. Max NUF 51 (Node 5), average NUF 41.25 (37.25 in fault-free case) and S.D. of NUF 4.61 (3.66 in fault-free case). Utilization of node 5 is 24.39% greater than the fault-free case.

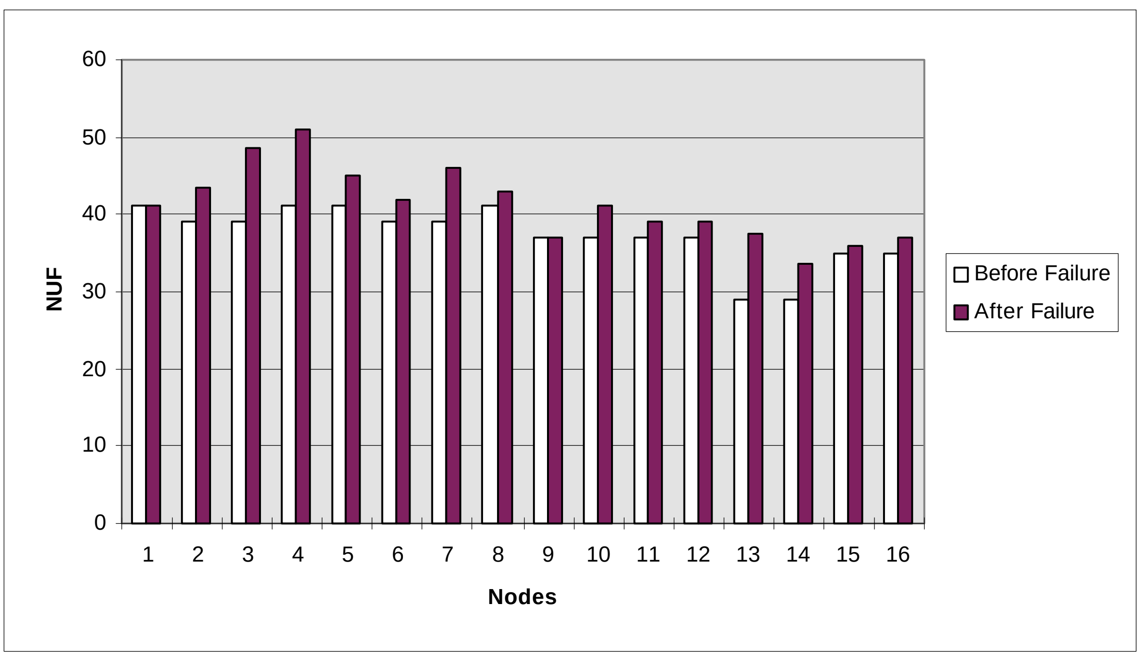

Figure A8.14: Failed Link is B6-A2. Max NUF 51 (Node 4), average NUF 41.25 (37.25 in fault-free case) and S.D. of NUF 4.61 (3.66 in fault-free case). Utilization of node 4 is 24.39% greater than the fault-free case.

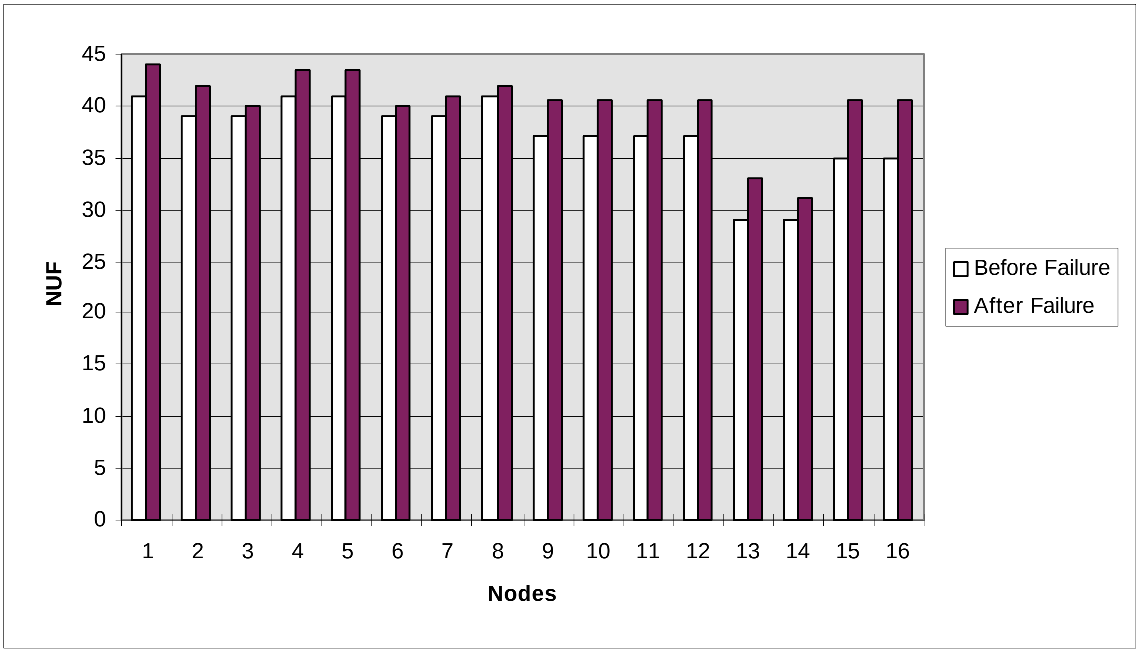

Figure A8.15: Failed Link is C1-C4. Max NUF 44 (Node 1), average NUF 40.18 (37.25 in fault-free case) and S.D. of NUF 3.36 (3.66 in fault-free case). Utilization of nodes 15 & 16 are 15.71% greater than the fault-free case.

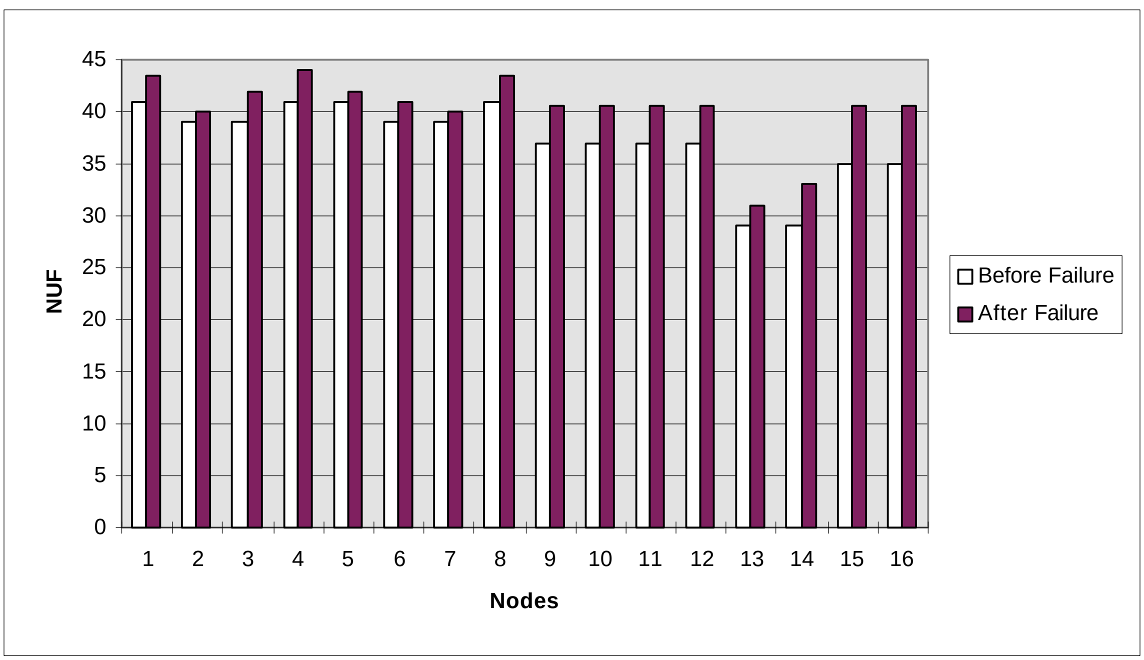

Figure A8.16: Failed Link is C2-C3. Max NUF 44 (Node 4), average NUF 40.18 (37.25 in fault-free case) and S.D. of NUF 3.36 (3.66 in fault-free case). Utilization of nodes 15 & 16 are 15.71% greater than the fault-free case.

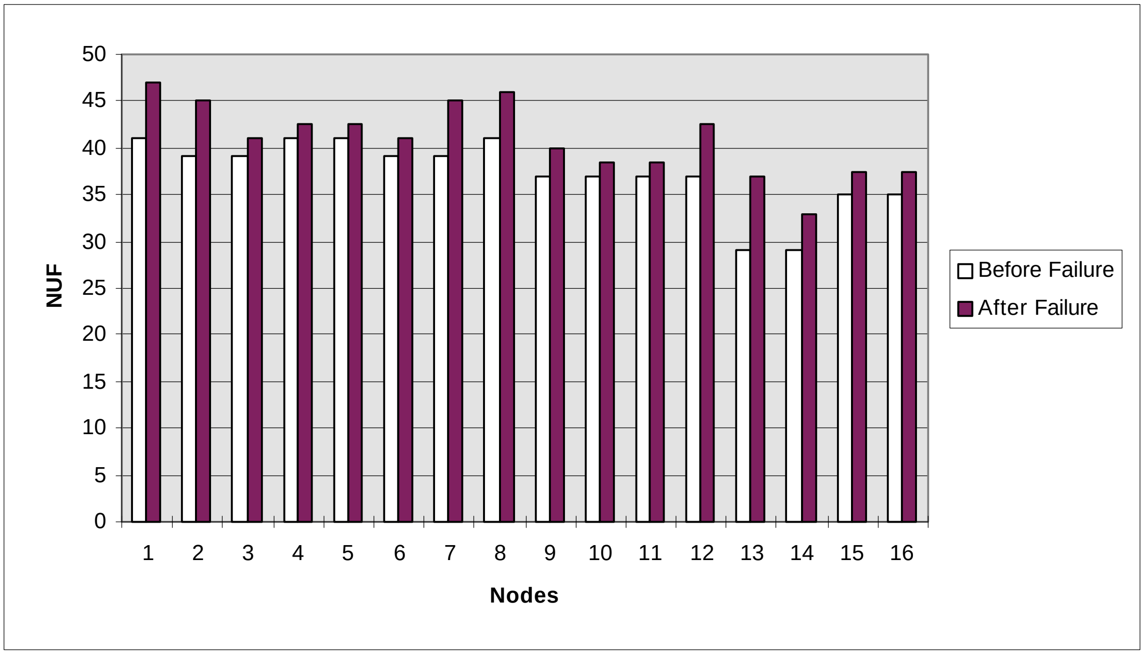

Figure A8.17: Failed Link is B1-B8. Max NUF 47 (Node 1), average NUF 40.91 (37.25 in fault-free case) and S.D. of NUF 3.69 (3.66 in fault-free case). Utilization of node 13 is 27.58% greater than the fault-free case.

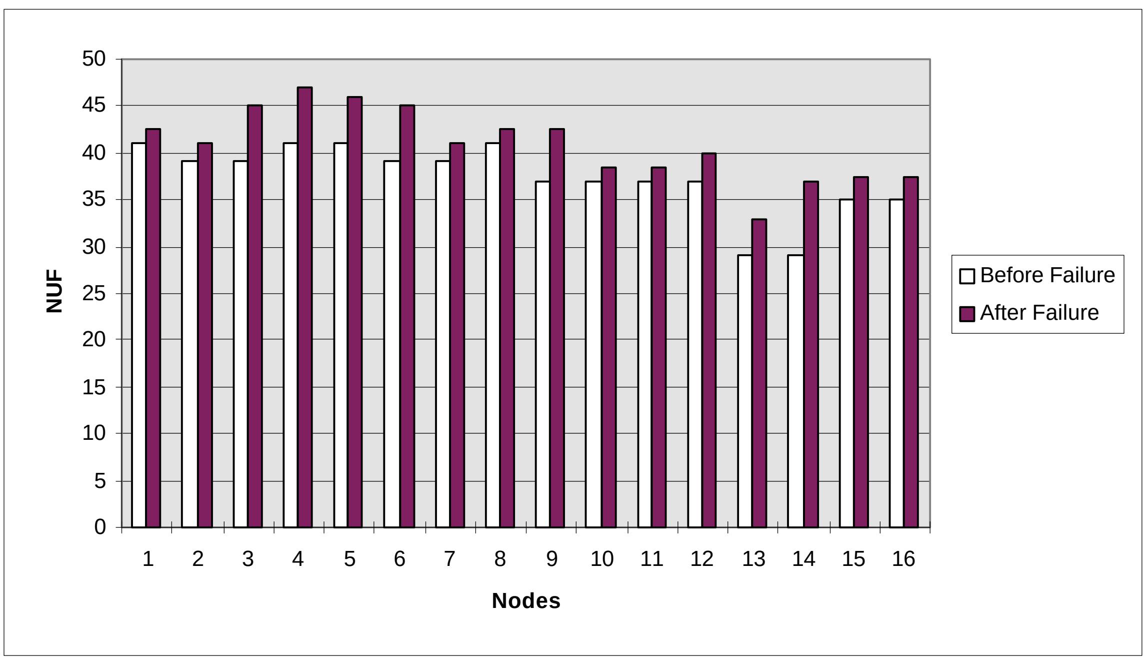

Figure A8.18: Failed Link is B4-B5. Max NUF 47 (Node 4), average NUF 40.91 (37.25 in fault-free case) and S.D. of NUF 3.69 (3.66 in fault-free case). Utilization of node 14 is 27.58% greater than the fault-free case.

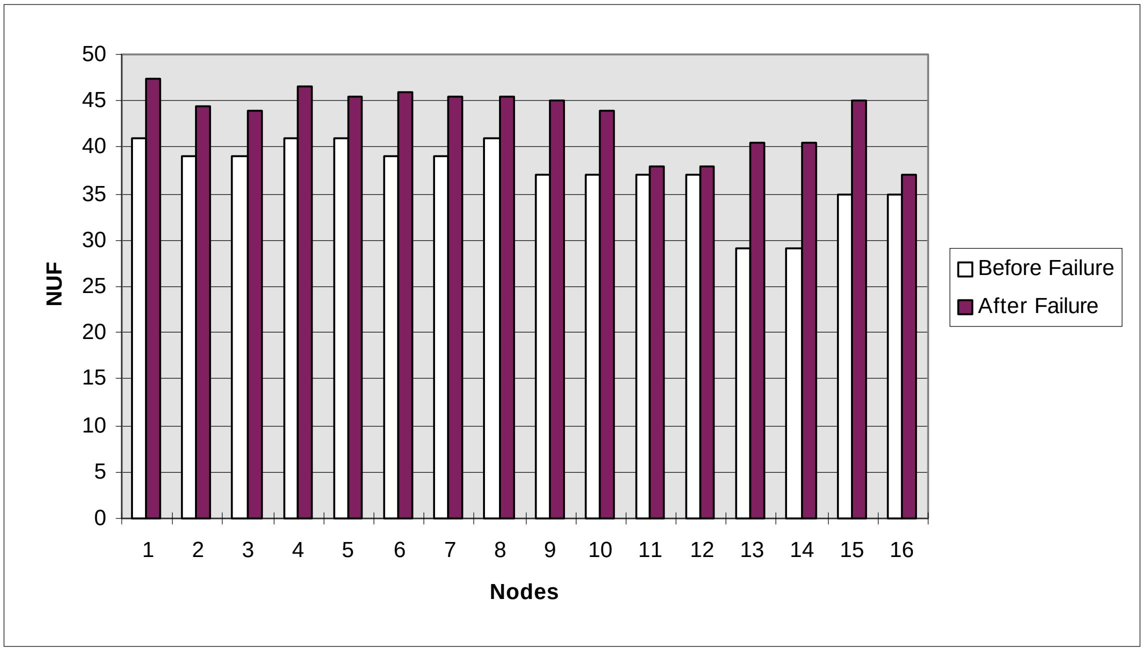

Figure A8.19: Failed Link is B2-B3. Max NUF 47.5 (Node 1), average NUF 43.31 (37.25 in fault-free case) and S.D. of NUF 3.25 (3.66 in fault-free case). Utilization of node 15 is 28.57% greater than the fault-free case.

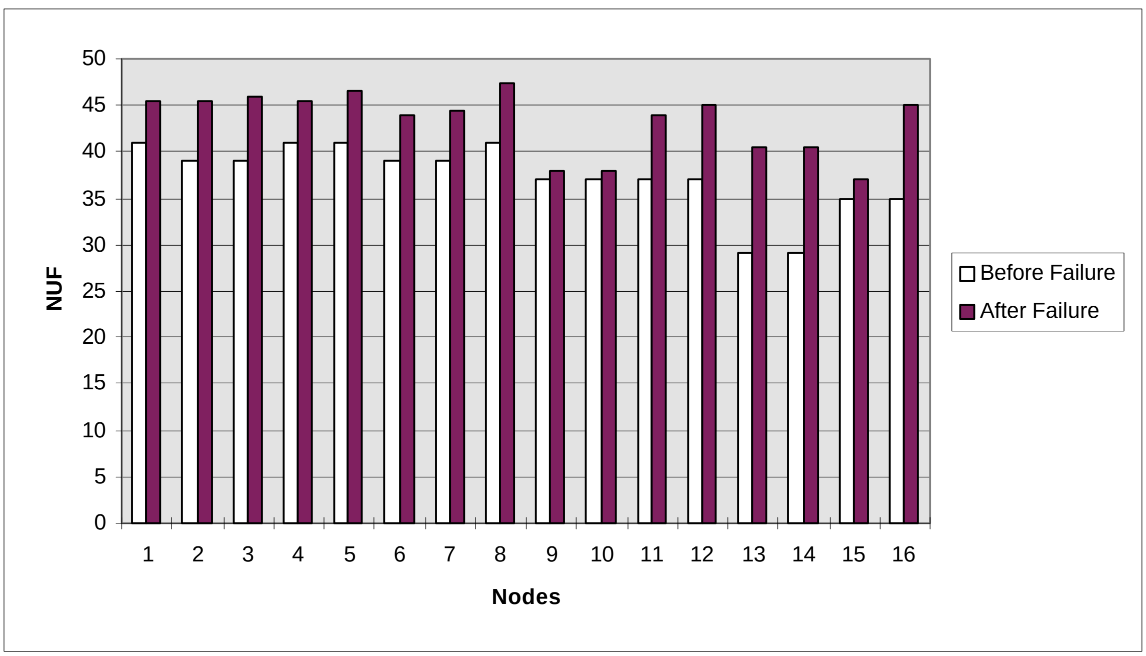

Figure A8.20: Failed Link is B6-B7. Max NUF 47.5 (Node 8), average NUF 43.31 (37.25 in fault-free case) and S.D. of NUF 3.25 (3.66 in fault-free case). Utilization of node 16 is 28.57% greater than the fault-free case.

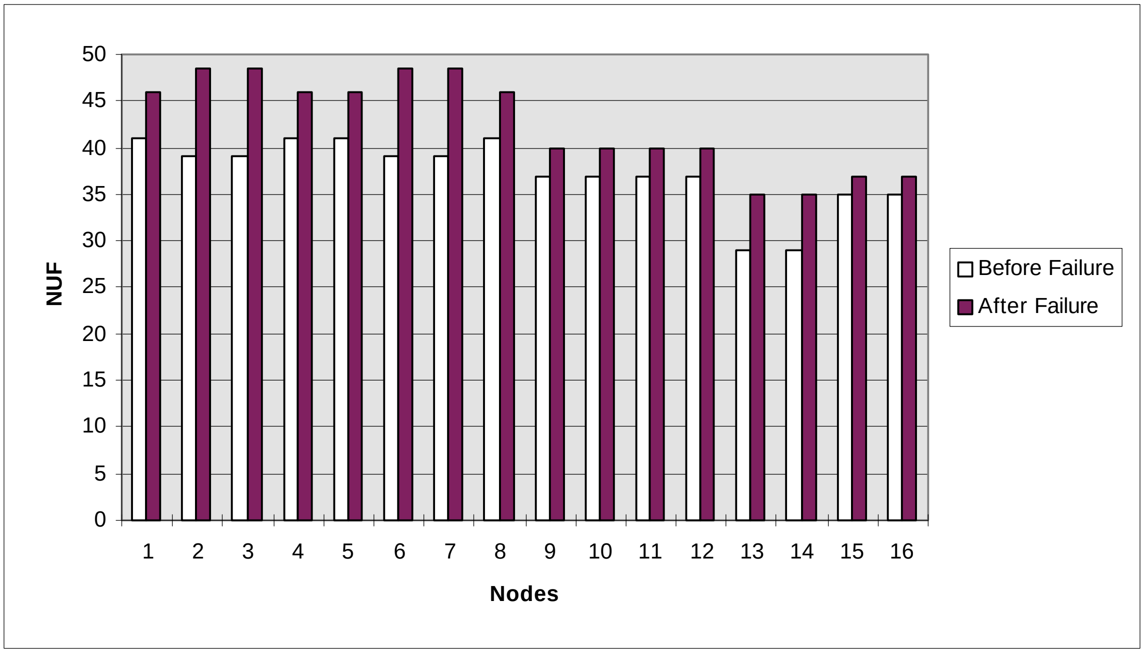

Figure A8.21: Failed Link is A1-A2. Max NUF 48.5 (Nodes 2,3,6 & 7), average NUF 42.625 (37.25 in fault-free case) and S.D. of NUF 4.94 (3.66 in fault-free case). Utilization of nodes 2,3,6 & 7 are 24.36% greater than the fault-free case.

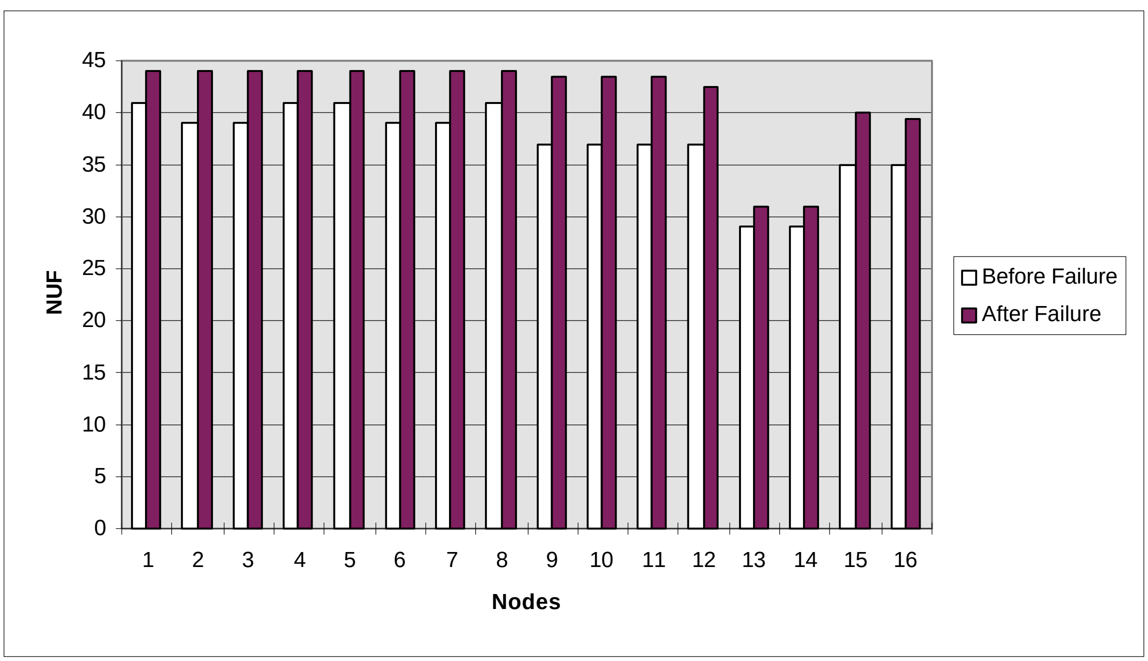

Figure A8.22: Failed Link is D1-D2. Max NUF 44 (Nodes 1 through 8), average NUF 41.66 (37.25 in fault-free case) and S.D. of NUF 4.25 (3.66 in fault-free case). Utilization of nodes 9,10 & 11 are 17.56% greater than the fault-free case.

Appendix I

Definition of links of star-ring topology is given below in Table A9.1.

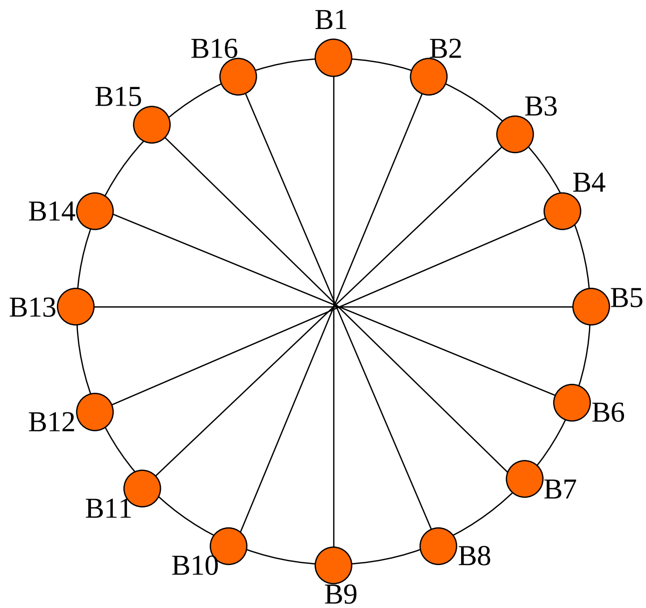

Figure A9: The Star-Ring Topology

Links	Designated Number		Links	Designated Number
B1-B2	1		B13-B14	13
B2-B3	2		B14-15	14
B3-B4	3		B15-B16	15
B4-B5	4		B16-B1	16
B5-B6	5		B1-B9	17
B6-B7	6		B2-B10	18
B7-B8	7		B3-B11	19
B8-B9	8		B4-B12	20
B9-B10	9		B5-B13	21
B10-B11	10		B6-B14	22
B11-B12	11		B7-B15	23
B12-B13	12		B8-B16	24

Table A9: Definition of the links of star-ring topology.

- Nodes are defined according to the number associated with B. That is B3 and B16 are defined as node 3 and 16 respectively.