

# Introduction

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## 1.1 Introduction

In recent years' human beings have become largely dependent on communication networks, such as computer communication networks, telecommunication networks, mobile switching networks etc., for their day-to-day activities [1]. In today's world, humans and critical machines depend on these communication networks to work properly. Failure of these communication networks can result in situations where people may find themselves isolated, helpless and exposed to hazards. It is fact that every component or system can fail and its failure probability increases with size and complexity.

Therefore, it is essential to compute and assure the reliability of these networks, which are growing and becoming complex. Reliability modeling and computation is necessary for reliability and safety assurance of these networks [2]. It also helps to identify weak links. These weak links can be improved cost effectively using reliability design techniques. Recent developments in communication hardware industry has resulted in increasingly reliable and non-repairable (need to be replaced when got bad 1) network components. However new designs involve new components, which tend to be less reliable. A good network design [3] involving fault tolerance and redundancies can deliver better system reliability at lesser cost. This allows new designs to be released faster and works reliably even when components are not mature enough from reliability point of view.

The computation of reliability measures [4] for a large and complex communication network, up to the desired level of accuracy, is time consuming, complex and costly. It has not been realistic to

model and compute the reliability of real-life communication networks, which are quite large, using desktop computer due to large execution time and high memory requirements. Such computations are usually performed on high-end processors for critical systems only. Reliability professionals and researchers have carried out a lot of research and developed techniques to minimize these efforts and develop a practical tool for all the communication network designers [4–6].

This book presents novel and efficient tools, techniques and approaches for reliability evaluation, reliability analysis, and design of reliable communication networks using graph theoretic concepts.

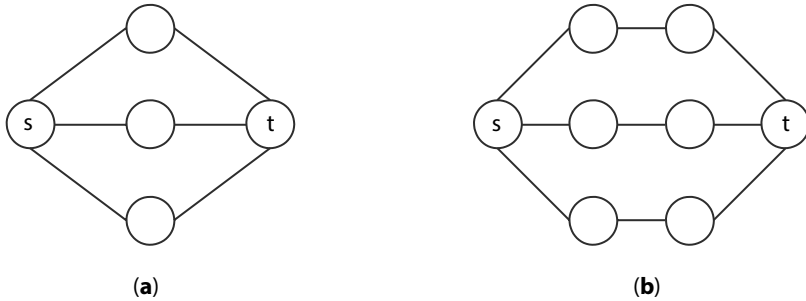
## 1.2 Network Reliability Measures

Earlier attempts to measure network reliability belong to two distinct classes: deterministic and probabilistic [1, 2]. The deterministic measures assumed that the network is subjected to a destructive force with complete knowledge of the network topology. The reliability is measured in terms of the least amount of damage required to make the network inoperative.

Deterministic measures thus provide simple bounds on the reliability of the network, since they are often measured for the network's worst-case environment. For example, in the terminal pair reliability problem, two deterministic measures of reliability are:

1. The minimum number of edges that must be destroyed or removed to disrupt the communication between the specified nodes ( $s$  and  $t$ ), which is simply the number of edges in a minimum cardinality cutset, and
2. The minimum number of nodes that must be destroyed or removed to disrupt the communication between the specified nodes ( $s$  and  $t$ ).

Both of these measures are computable in polynomial time. However, one of the main problems with deterministic measures is these give rise to some counter intuitive notions of network reliability. For example, consider the networks shown in Figure 1.1.

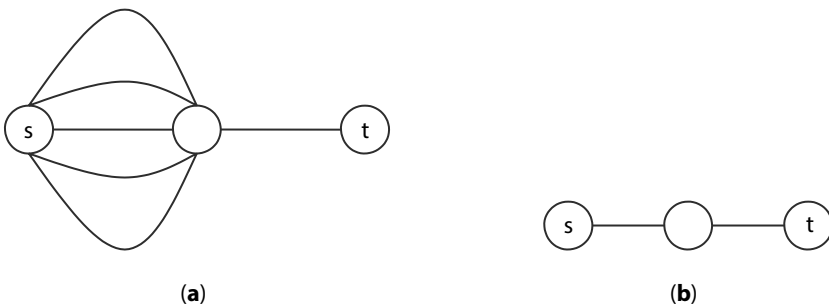


**Figure 1.1** Example networks for deterministic reliability measurement.

According to second deterministic measure of the graph's reliability, the graphs of Figure 1.1 (a) and Figure 1.1 (b) are equally reliable since both of these require minimum three nodes to be destroyed for breaking the  $s$ - $t$  node connectivity.

However intuitively one can easily find out that graph (a) is the more reliable among the two. The same problem arises when the cardinality of a minimum  $(s, t)$ -cut set is used as a measure of unreliability. Consider the graphs shown in Figure 1.2. Both graphs (a) and (b) have a minimum cardinality for  $(s, t)$  cut of size one, which implies both networks are equally reliable.

This clearly shows that deterministic measures of reliability are insufficient to correctly relate network components used in network layout with network reliability. Moreover, failure of network components is probabilistic in nature therefore only probabilistic measures can define system reliability appropriately.



**Figure 1.2** Another set of example networks for deterministic reliability measurement.

Therefore, for evaluating reliability of a network using probabilistic measures, one can associate a statistical probability of failure/success with each component of the network in order to obtain a statistical measure of overall unreliability/reliability of the network. This notion supports an accepted definition of reliability as the probability that a system or device is operational under stated environment for a given mission time. To avoid conflicts that arise with various levels of operation within a network's hierarchy, only the topology of the network is considered. This allows a network to be modeled by a graph where the nodes of the graph represent the communication centers and communication links are represented by its edges.

### 1.3 The Probabilistic Graph Model

Communication networks are generally modeled using network graph [3]. The network graph  $G(V,E)$  consists of a set  $V$  of  $n$  number of nodes (or vertices) and a set  $E$  of  $l$  number of edges (or links). For reliability evaluation, probabilistic graph is used which takes these sets  $V$  and  $E$  of nodes and links as random variables. In probabilistic graph of communication networks, nodes represent the computers/switches/transceivers/routers and edges represent various types of communication links connecting these nodes. For reliability analysis, graphical models of networks are considered to be simple, efficient and effective.

Probabilistic graph models are developed and presented in this book. Depending on the state (working or failed) of nodes (or vertices) and/or links (or edges), the network can be considered either working or failed. A general assumption of statistical independence among nodes and links failures is followed throughout. It implies that the probability of a link or node being operational is not dependent of the states of the other links or nodes in the network. The inherent assumption here is that the link failures are caused by random events which affect all network components individually.

However, this assumption may not be completely correct while modeling a real communication network as more than one component in a particular area may fail due to natural causes such as a major storm or an earthquake. In such cases, dependency analysis

and common cause failure modelling can be used over the analysis performed with assumption of statistical independence. This assumption is often made because of difficulties in obtaining information about the dependencies of link failures and increased modeling and computational rigor. In fact, such dependencies may not be known. Thus, without the assumption of statistical independence the problem becomes much more difficult to solve.

Depending on the connectivity objective of nodes [4–6], the network reliability evaluation problem can be sub-divided into following different cases:

1. Two terminal or terminal pair reliability (TPR) problems:  
The most common communication operation is to send messages from a source node  $s$  to a terminal node  $t$ . The terminal pair reliability of a network is defined as the probability of having at least one operational path between the nodes  $s$  and  $t$ . In case of directed networks, it is usually called  $(s,t)$  connectedness.
2. Global or all terminal reliability (ATR) problems:  
The all terminal reliability of a network is defined as the probability that for every node pair  $(N_i, N_j)$  there exist an operational path to connect them; or equivalently, the probability that there exist a working spanning tree. In the directed case, all terminal reliability is the probability that the directed graph contains at least a spanning tree rooted at the source node  $s$ .
3. K-terminal reliability (KTR) problems:  
The k-terminal reliability ensures that a specified set of k-nodes of the network are able to communicate with each other and it is defined as the probability that a path exists between every pair of nodes belonging to the specified set of k nodes of the network.

Generally, communication network performance is defined not only by the connectivity between nodes but also by the minimum capacity it can transfer between the nodes. The reliability measure considering both capacity and connectivity, as essential performance criterion, is known as capacity related reliability (CRR). It is

defined as the probability that required amount of flow is transferred from source node  $s$  to terminal node  $t$ . Evaluation of above network reliability measures (indices) has attracted a lot of attention from researchers and many approaches have been developed so far. Next section presents a brief summary of these approaches.

## 1.4 Approaches for Network Reliability Evaluation

Misra and Rao [4] developed signal flow graphs: a development recognized as a significant step forward in the evaluation of network reliability. After this, a number of algorithms, techniques and approaches have been suggested in the literature. In fact, today, the use of graph theory has become inseparable from network reliability evaluation. Available literature on reliability evaluation of communication networks, considering only connectivity as performance criterion, can broadly be classified into two paradigms, viz.:

Path sets or Cut sets approaches (POC) paradigm:

These use pathsets or cutsets as the starting point for TPR problems, spanning trees for ATR problems and  $k$ -trees ( $k$ -minimal cutsets) for KTR problems. In this book, the terms path sets and trees are represented by a single term path sets as approaches used for generating them are similar. From the context, whether it is pathset or spanning tree or  $k$ -tree can easily be understood. For example, when the context is TPR problem then it is pathset, when context is ATR it is spanning tree and when the context is KTR it is  $k$ -tree.

Reliability evaluation is generally achieved by enumerating pathsets or cutsets of the network. A pathset is defined to be a set of minimal paths connecting source and destination node. A path is set of components whose functioning ensures that the system functions. A cutset is defined to be a set of minimal cuts that disconnects the source and destination nodes. A cut is a set of components whose failure will result in system failure. A minimal path/minimal cut is a path/cut such that no proper subset of minimal path or minimal cut is a minimal path/minimal cut. In other words, if any element is removed from the set (minimal path/minimal cut) then it no longer remains a path or cut.

Non-Path sets or Cut sets approaches (NPOC) paradigm:

These approaches do not use path sets or cut sets. These apply reduction or decomposition or transformation or a combination of these approaches to solve the reliability evaluation problems. The non-path (or cut) set approaches may be categorized as following: 1) State enumeration methods 2) Topological methods 3) Transformation methods and 4) Decomposition (Factoring theorem) methods.

## 1.5 Motivation and Summary

Main objective of this book is to design new fault tolerant Interconnection network layouts capable of path redundancy among dynamic failures. New INs designs have been proposed and their observed results are found promising when compared with some of the earlier networks.

A summary of problem wise contributions is discussed next:

### 1. *INs Topology Review (Chapter 2)*

Presents an extensive survey of the existing INs topological hardware aspects based on its unexplored Taxonomy of INs performance metrics. In this chapter detailed literature review on interconnection networks has been performed, and an exhaustive taxonomy has been proposed based on the literature review. The chapter also presents advantages and disadvantages of interconnection networks along with a summary of topological characteristics and fault tolerance information of the surveyed interconnection networks in the form of Table.

### 2. *MIN Reliability Evaluation Techniques Review (Chapter 3)*

Presents an overall view of the different reliability measures and their importance in evaluating the reliability can be reviewed with examples. A comprehensive review of the various approaches present for evaluation of different reliability measures is also presented. Based on the literature survey a few shortcomings are identified.

### 3. *Terminal Reliability Analysis of Existing MIN Layouts* (Chapter 4)

Networks such as telecommunication, transportation, power systems, integrated circuitry and computer communication systems are large and it becomes imperative for economic reasons and safety that these have high reliability. Reliability evaluation of such complex systems has not yet been perfected and there is a lot more that needs to be done. System reliability can be measured in terms of various paradigms such as *two terminal*, *all-terminal* and *broadcast* reliabilities.

In this chapter, terminal reliability values of various recent and industrial used MINs topologies are evaluated and compared using existing simple and efficient path-set enumeration method. Path set and cut set techniques are the most widely used techniques for terminal pair reliability evaluation of communication networks as these techniques give a compact reliability expression in sum of disjoint product (SDP) form.

These techniques first enumerate minimal path (or cut) set for the network and then evaluate reliability (or unreliability) expressions in the SDP form. Since enumeration of cut set also requires knowledge of basic paths of the network, the path set enumeration becomes a necessity for these techniques. Available disjoint and redundant paths of various existing MINs are evaluated by a simple and efficient path-set enumeration method based on hybrid multi-variable inversion (MVI) algorithm, which gives accurate reliability values. Present reliability evaluation paves the way of research focus on developing higher disjoint, reliable and highly fault-tolerant MINs than the existing topologies.

### 4. *Comprehensive MIN Reliability Paradigms Evaluation* (Chapter 5)

This chapter has attempted to evaluate comprehensive reliability paradigms of various recent MINs topologies available from literature using path tracing algorithm.

With increasing number of input and output nodes in supercomputer environment reliability evaluation of multi-cast nodes is mandatory. In other words, a network has to transmit a signal or commodity between different pairs of nodes of a network simultaneously. Communication between multiple-sources multiple-destinations offers several advantages like increased performance, improved reliability and decreased costs through resource sharing.

So we have extended the traditional reliability evaluation to include a new reliability measure as multi-source multi-terminal reliability (MSMT). This chapter also evaluate MIN traditional reliability parameters (Two/broadcast/all terminal reliability) using conceptually simple and computationally efficient path tracing algorithm.

5. *Dynamic Tolerant and Reliable Four Disjoint MIN Layouts (Chapter 6)*

This chapter proposes two new fault tolerant and highly reliable multistage interconnection network layouts. Proposed 4-disjoint paths multistage interconnection networks (4DMINs) provide four disjoint paths between any source and destination node pair and provide dynamic rerouting between intermediate stages. Minimal paths of these 4DMIN have been evaluated and MINs performance evaluation has been done by calculating terminal reliability at assumed different switch reliabilities using existing approaches of sum of disjoint products method.

Then a new layout design of fault tolerant reliable interconnection networks (RINs) is proposed. Proposed INs designed with highly adaptive reliable multipath dynamic routing behavior and fault tolerant capability in all the stages with suitable routing techniques. Proposed design can withstand dynamic switch failures in all the stages and provide more redundant paths to tackle such with higher reliability. They provide higher reliability and outperform other MINs.

Recently, research has been undertaken to improve interconnection networks for incoming the next generation of large parallel and distributed systems. Therefore, research focused on designing highly reliable and fault tolerant INs because they provide faster intercommunication capability. This book attempted towards the evaluation of reliability of interconnection networks and concentrates more on reliability evaluation of computer communication networks. But the methods have a good potential to explore new reliability evaluations using the algorithm presented in this work in other fields of interconnection networks systems such as water distribution systems, banking industry, and power distribution systems and any real time interconnection networks.