On the Design of Fault Tolerant k-Connected Network Topologies

Kamalesh V. N., Shanthala K. V., Chandan B. K., Pavan M. P., and Pradeep P. Bomble

***Abstract*—Designing a cost effective, fault tolerant survivable network, with optimal number of links is of prime importance, especially in the design of adhoc network topologies. Several methods have been proposed in literature for the same. However, the performances of the different methods vary according to the required connectivity and the number of nodes. Hence, a choice has to be made, as to which method is to be employed for the design of a given network. This paper portrays the performance of the different methods, for the node connectivity, number of links used and the geographical position of the nodes.**

***Index Terms*—Computer network, topological design, fault tolerance, k-connected, adhoc network, survivable network.**

I. Introduction

Computers have become incredibly smaller, cheaper and numerous over the last few decades. Interconnecting them results in a computer network. Networks satisfy a broad range of purposes and meet various requirements, such as, facilitating communications, sharing hardware, files, data, information and software are some of the common objectives of computer communication networks.

Applications of computer communication networks are growing in every field of human activity. Computer communication networks have applications in education, business, telemedicine, telesurgery, media, infotainments, multi-time multiplayer computer gaming, etc. All these applications demand the design of efficient fault tolerant survivable computer communication network topology with minimum transmission delay, response time and maximum throughput. Further, in topological design of adhoc networks, energy, memory, transmitting and computing power of a node are limited. The efficient utilization of these resources is influenced by the underlying network topology. Also, the optimization of the link constraints such as line-of-sight interference, length-of-link, signal loss, noise is achieved by designing efficient network topological algorithms.

The topological design of a network assigns the links and link capacities for connecting the network nodes. This is a critical phase of network synthesis, partly because the routing, flow control, and other behavioral design algorithms largely rest on the given network topology. For reliability or security considerations, some networks may be required to provide more than one distinct path for each pair of nodes, thereby resulting in a minimum degree of connectivity between the nodes.

In the design of an interconnection network, one of the most fundamental considerations is the reliability of the network, which can be usually characterized by the node connectivity and edge connectivity of the topological structure of the network.

In designing or selecting a topological structure of an interconnection network for a system, one fundamental consideration is the fault tolerance. There are two types of faults in a system- Hardware failures and software errors. The former can be modeled by a mathematical way and the latter are much more difficult to model.

Aviziens has succinctly defined fault tolerance in a computer communication network as 'The ability of the system to execute specified algorithms correctly regardless of hardware failure and program errors.'

The performance of the fault tolerance system should include two aspects- computational efficiency and reliability. A variety of measures of fault tolerance have been proposed by several researchers. These measures are either deterministic or probabilistic. Researchers have mainly used graph-theoretic concepts to develop deterministic measure of fault tolerance. The notion of connectivity is the key graph-theoretic deterministic measure for fault tolerance.

II. Literature of Existing Methods

One of the most well suited problems in the framework of the survivable network design problem is given a computer communication network with costs on its edges, and a connectivity requirement *rij*. for each pair *i*, *j* of nodes. The goal is to find a minimum cost subset of edges that ensures that there exist rij disjoint paths for each pair *i*, *j* of nodes. Where all *rij* Є {0, *k*}, for some integer *k*, we will refer to these problems as *k*-connectivity of a computer communication network or design of minimum cost fault-tolerant survivable network topologies.

Looking into the research work related to the design of k-connected fault tolerant survivable network topologies, a few methods for generating *k*-connected networks are proposed in the literature.

Steiglitz *et al.* [1] have presented the most widely used heuristics algorithm, called the link deficit algorithm, to design a low cost survivable network. Algorithms have also been presented for producing local improvements in given networks and for testing the redundancy of networks. The heuristic begins by numbering the nodes at random. A pair of nodes which are not adjacent are selected and connected,

Manuscript received February 27, 2015; revised June 5, 2015.

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doi: 10.18178/ijimt.2015.6.5.626

provided that they have the least deficiency.

S. Latha and S. K. Srivatsa [2] have proposed a method for Topological Design of a K-Connected Communication Network. In their nodes are numbered arbitrarily. The decimal number of each node is converted into a k bit Gray code. Thus each node has a Gray code associated with it. There exist a link between any two nodes whose Gray codes differ only in one place are connected. Thus every node gets connected to k nodes and has a degree of k.

S. Latha and S. K. Srivatsa [3] have proposed a method for design of cheapest survivable networks. In this method nodes are numbered arbitrarily and assume that the nodes of the network are equispaced and lie on a circle. Depending upon the nature of n and k, the algorithm operates with three possible cases.

Case i: k is even and n is even or odd. Here every node is directly connected to the nearest $k/2$ vertices in each direction around the circle giving rise to a k-connected graph.

Case ii: k is odd and n is even. Here every vertex is directly connected to the nearest $(k-1)/2$ vertices in direction and in addition, vertices which are diametrically opposite to one another are connected resulting in a k-connected graph.

Case iii: k is odd and n is odd. The circular graph is constructed as indicated above. Every vertex I is directly connected to every vertex $i+(n-1)/2$ for all $0 \leq I \leq (n-1)/2$.

S. Latha and S. K. Srivatsa have proposed a modification of the Steiglitz algorithm where in the minimal spanning tree is determined first and then the link deficit algorithm is applied. They have also shown how to set up a 3 connected network using the algorithm for minimal spanning tree. The heuristic numbers the nodes at random and involves repeated searching of nodes when conflicts occur.

Kamalesh V. N. and S. K. Srivatsa [4] have proposed a method for generating k-connected survivable network topologies using incremental approach. In this method, nodes are numbered in the increasing order of the accumulated costs. Establish link between node number 1 and every other node. This results in 1-connected network. Establish link between node number 2 and every other node (avoid parallel links). This results in 2-connected network. Continuing in this way k number of times, we get a k-connected network.

Kamalesh V. N. and S. K. Srivatsa [5] have proposed a method for the design of minimum cost survivable computer communication networks based on the mathematical concept of bipartite graphs. In this method, nodes are numbered in the increasing order of the accumulated costs. The nodes are then divided into two disjoint sets. The first set–X contains the first k nodes. The second set-Y contains the remaining nodes. The algorithm proceeds to form a complete bipartite graph between the two sets X and Y.

III. Algorithmic Analysis

The algorithms for the existing methods have been analysed. The pros and cons of each method are discussed below.

The method proposed by Steiglitz *et al* is a general method. This involves numbering of nodes at random; this randomization lets the heuristic to generate many topologies from the same input data. Further this method involves repeated searching of nodes when conflicts occur. This demands more computational effort.

The method proposed by S. Latha and S. K. Srivatsa is optimal compared to the method proposed by Steiglitz *et al*. However, the limitation of this method is again arbitrarily numbering of nodes and this method is applicable only when number of nodes in the network is $2k$.

The method proposed by S. Latha and S. K. Srivatsa for the design of cheapest survivable networks is applicable only when the nodes of the network form a regular polygon.

The method proposed by S. Latha and S. K. Srivatsa based on the concepts of minimum spanning tree involves the numbering of nodes at random and involves repeated searching of nodes, which demands more computational effort.

The method put forward by Kamalesh V. N. and S. K. Srivatsa for generating k-connected survivable network topologies using incremental approach is very simple and straightforward. Unlike other existing methods, the proposed method does not make any specific assumption on the position and the number of nodes to generate a network topology. In this method the maximum hops between any two nodes is only two. Hence the transmission delay is minimum. This method will generate all topologies starting from 1-connected to K-connected networks. However, this method is neither cost nor link optimal.

The method proposed put forward by Kamalesh V. N. and S. K. Srivatsa for the design of minimum cost survivable computer communication networks based on the mathematical concept of bipartite graphs does not make any specific assumption on the position and the number of nodes to generate a network topology. Further, in this method the maximum hops between any two nodes is only two. Hence the transmission delay is minimum. This method is link optimal when compared to the previously discussed methods. Also, one of the basic principles of network design as discussed by Bermond and Peyrat is symmetry of the network topology. The network generated by this method satisfies the design principle of symmetry. However, it incurs the overhead of sorting the accumulated costs.

IV. Simulation and Algorithmic Profiling

Programs have been developed for all the existing methods discussed previously, and it has been run extensively for a large number of nodes. Graphs have been plotted for the values thus obtained based on the number of links used and instruction count.

It is apparent, from the bar graph, that the incremental method is not link optimal, compared to any other methods. The other three methods, however, use lesser number of links for generating the same number of nodes and same connectivity.

It can be inferred from the graph that the method proposed by S. Latha and S. K. Srivatsa is the most optimal compared to all the existing methods. However, due to the assumptions discussed in the literature (Section II), it is not practically applicable in almost any network. The Method proposed by Steiglitz *et al.* is a general method applicable to all networks.

However, scalability is an inherent issue. The method put forward by Kamalesh V. N. and S. K. Srivatsa is optimal compared to Steiglitz *et al.* method. Finally, the method put forward by Kamalesh V. N and S. K. Srivatsa is more optimal as compared to the methods proposed by Steiglitz *et al.* and Kamalesh V. N. and S. K. Srivatsa. Hence, in practical the method proposed by Kamalesh V. N. and S. K. Srivatsa can be used. Further, a comparative analysis of all the aforementioned methods is tabulated as shown below.

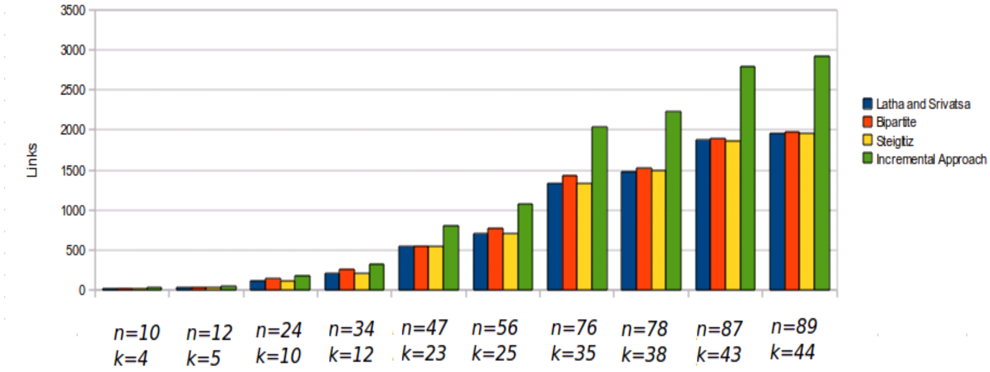

Fig. 1. Performance profiling of algorithms (Number of links used v/s Number of nodes *n*, connectivity *k*).

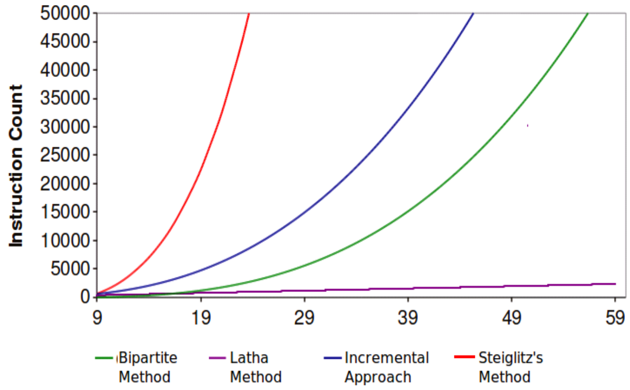

Fig. 2. Performance profiling of algorithms (Instruction count v/s Number of nodes).

TABLE I. COMPARATIVE ANALYSIS FOR LINK OPTIMIZATION

Method	Number of links used to generate k-connected network with n nodes	Remarks
Bipartite Graph method	$k(n-k)$	---
S.Latha's method	$kn/2$	$k(n-k) < kn/2$, for all $k > n/2$. The bipartite method is link optimal compared to method proposed by S. Latha for all $k > n/2$
Incremental Approach	$(n-1) + (n-2) +,...,+ (n-k)$	$k(n-k) < (n-1)+(n-2)+,...,+ (n-k)$, for all n and k. The bipartite is link optimal compared to the Incremental method.
Steiglitz's method	$kn/2$	$k(n-k) < kn/2$, for all $k > n/2$. The bipartite method is link optimal compared to method due to *K.* Steiglitz for all $k > n/2$.

V. CONCLUSIONS

The topological design of a network assigns links and link capacities for connecting the network nodes. This is a critical phase in the design of network synthesis, partly because the routing, flow control and other behavioral design algorithms rest largely on the given network topology. The goal of a computer communication network is to achieve a specified performance at a minimal cost. In this paper, we have presented an in-depth performance analysis of the various existing methods to generate a *k*-connected fault tolerant network. Further, we have also portrayed the link analysis of different methods. It is clear that coming out with a method for the generation of link and cost optimal network topology is still an open research.

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