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通信ネットワークの初期トポロジーの設計について

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あらまし　大規模な通信ネットワークの設計において、初期トポロジーは配置、トラフィック、費用などいくつかの制約の下に設計される。その後にできるだけ最適になるように変更される。初期トポロジーの設計に関する種々の問題点と手法を議論し、いろいろな設計目標に関してよりよい候補になるうるネットワークのクラスをいくつか与える。

ON THE DESIGN OF STARTING TOPOLOGY FOR COMMUNICATIONS NETWORKS

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Abstract　In the design of large-scale communication networks, a starting topology is chosen and designed given several constraints such as location, traffic, and cost. The network is then modified so that it would achieve the optimality as much as possible. We discuss the issues and techniques in the design of starting topology and offer some classes of networks which are better candidates according to various design objectives.

1. INTRODUCTION

A cost-effective structure for a large-scale communication network is usually a multilevel hierarchy consisting of a backbone network and a family of local access networks. The cost of a backbone network is mostly dominated by transmission costs. The cost of transmission depends on speed, transmission facility, and the interconnection network. Therefore, it is desirable to use the communication links efficiently. Packet data networks have been developed to increase the utilization of the links in data communication.

A typical backbone design problem is as follows. Given a set of nodes and their locations, and a matrix describing traffic between each pair of two nodes, we want to minimize total transmission (link) costs subject to a set of various constraints. These constraints include a whole spectrum of conditions stipulated by practical environment and simulation study such as maximum node utilization, average packet delay, maximum node-node time delay, maximum node degree, and minimum node-pair connectivity, among others. There are many optimization procedures available for the solution of specific problems (see [1], [3], [4], [8], [10], [11], [12], [14], [16], and [19]). Most of these would start to construct a network (called starting topology) and then optimize it, under the constraints, to obtain a local minimum. The network which can no longer be optimized is then used to design network architecture for the communication system.

The choice of a starting topology plays an important and crucial role in the design and optimization of large-scale communication networks. Since the general problem of network design is NP-complete, the final and revised network topology with local optimum is obtained with a heuristic algorithm. If a poor starting topology is given, the local minimum topology may be still far away from global optimum solution. If the number of nodes in the backbone network is small, one might be able to try alternative starting topology. However, when the network is large in scale and combinatorically complex, it would be costly and computationally impossible to change the starting topology in the design process.

Due to the advent of new technologies such as fiber optic transmission facilities and flexible manufacturing systems, the demand for connection to the backbone network increases rapidly. For example, the intercity Bell System dynamic routing network had 28 nodes in 1981 and a 200-node design problem was projected at that time for the 1990's (see [1]). It is interesting to note that three real-world problems each representing a particular fiber optic network design problem at Bellcore in 1986 are for networks with 100, 116 and 116 nodes respectively. In the same year, randomly generated problem for networks with 200 nodes was studied ([15]). Similarly, the Defense Data Network (DDN) which was based on ARPANET approach and technology has recently grown to a network of 230 nodes and 450 links.

Network designers and practitioners have reported that the choice of starting topology has become one of the fundamental issues in their design process. In this paper, we aim to support this claim and take the first step in studying different issues and techniques in the design of a starting topology for large-scale communication networks. In Section 2, we review previous starting topologies proposed and used by various researchers and designers. In Section 3, we define the class of directed graphs $MG_B(n,d)$ and propose to use these directed graphs as starting topology. These directed graphs have very good combinatorial and graph properties which are natural measures for an optimal network topology.

2. STARTING TOPOLOGY

The topological design of packet switched networks was studied in the early 1970's to optimize ARPANET using "branch exchange" techniques. A starting topology satisfying all constraints is chosen and then exchange methods are used to fine-tune the network until a new network which satisfies all constraints and has lower cost is found. The process is continued until cost can no longer be lowered. The resulting topology has the local minimum property. The whole process is repeated using either a new starting network, a different class of exchange methods, or the same technique in different order. An approach called "cut saturation" which involves a cut set of saturated links was proposed ([3] and [8]) in the late 1970's to optimize the starting network.

Almost all of the proposed network design approaches use trees, especially the Minimum Spanning Tree (MST) as their starting (or initial) topology (see [3], [8], and [14]). A hybrid spanning tree which combines properties from MST and shortest path spanning tree is proposed recently by Kershenbau, Kermani and Grover [12].

The central question now is that what network (or networks) is (are) good candidate(s) for starting topology. The MST, which has been widely used, is a good starting topology because it has the minimum number of links and hence is "optimal" in total transmission cost. However, we claim that using trees as starting topology has at least two basic problems. As we discussed before, no matter how good the optimization techniques and algorithms are used, the final local minimum network may still be far away from global optimum. Sometimes it may even converge to the wrong type of network. The second problem has something to do with the question of "How good a starting topology is good?". One central purpose of this paper is to formally study the measures for and criteria in the design of good starting topology. Other issues such as network optimization, network simulation, and network support systems design will be left for further study and research.

A good starting topology has to be reliable and efficient. These measures can be analyzed and obtained in either deterministic or probabilitic way. In this paper, we only concentrate on deterministic reliability and efficiency measures. We also use graph theory terms to formalize the concepts and notations.

The distance d(u,v) between two nodes u and v is the minimum number of links in a path connecting u and v, i.e., it is the minimum hops between u and v. The diameter D(G) of the network G is the maximum of the minimum hops d(u,v). A set of paths between a pair of nodes is said to be link-disjoint (or node-disjoint) if they do not have links in common (or no nodes in common except the pair itself). A set of link-disjoint (or node-disjoint) paths between two nodes u and v is called a container C(u. v). The width of a container is the number of paths in it. The length of a container is the length of the maximum path in the container. The link connectivity (node connectivity) between two nodes u and v, denoted by k'(u,v) (k(u,v)), is the maximum width of containers between u and v. The link connectivity (node connectivity) of a network G, written as k'(G) (k(G)), is the minimum among all k'(u,v) (k(u,v)).

The hop constraints (on k(u,v) or D(G)) will quarantee the network to have at least a path with minimum hops, but it does not provide the existence of alternate paths between a pair of two nodes. On the other hand, the connectivity constraint (on k'(u,v), k(u,v), k'(G), or k(G)) will ensure a number of communication paths between each pair of nodes, but it will not limit their hops. In Maruyama [14], it was proposed to consider both hop and connectivity constraints in the design of reliable communication networks using the deterministic reliability measures.

Since k'(u,v)=k(u,v)=1 for a pair of nodes u, v in a given tree, the ability of the tree network to communicate after an attack or failure is not very good. This leads naturally to assuring that a good starting topology should have high survivability. This is a particularly important issues for fiber networks since the high capacity of fiber links can support a more sparse network than that for copper facilities (see [15] and [16]). In fact, it was determined in 1989 at Bellcore that a network topology should have at least two deverse paths between certain special offices ([15]). In Monma and Shallcross ([15]), heuristic algorithms are given for constructing an initial feasible network. The initial topology is a two-connected network (k'(u,v)=k(u,v)=2 for u,v in a special subset of nodes) constructed by adding a path, called an ear, to the cycle which connects nodes in the special subset. This technique is called ear composition procedure. Although this approach is shown to be effective on data from both real-world fiber optic communication network problems and randomly generated problems, whether it is optimal with respect to the hop constraints is not known.

3. THE DIRECTED GRAPH $MG_B(n,d)$

The techniqueS used by Monma and Shallcross ([15]) take into consideration the connectivity of a network. In Maruyama ([14]), diameter and connectivity are both considered but the starting topology is a tree (or MST). We propose that the directed graph $MG_B(n,d)$ (or its undirected counterpart) be used as starting topology in the design of large-scale communication networks. This digraph has very good properties such as high connectivity and low diameter.

The directed graph $G_B(n,d)$ has n nodes labeled by the residues of modulo n and the set of nd links $\{i \rightarrow d*i + r \pmod n: 0<=i<=n, 0<=r<=d-1\}$ (see [9] and [17]). The well-known de Bruijn digraph is a special case of $G_B(n,d)$ when n is a power of d. For a d-regular directed graph G with n nodes, the diameter of G has the lower bound;

$$D(G)>=\lceil \log_d(n(d-1)+1)\rceil-1. \quad ------(1)$$

The digraph $G_B(n,d)$ has diameter at most one larger than the lower bound. Moreover, it has $k(u,v)=d-1$ except for some nodes which have self-loops at each node. By removing those self-loops and connecting those nodes by a cycle (or cycles), the resulting digraph $MG_B(n,d)$ has connectivity d for $n>=2d^2$ and $d>= 2$ (see [5] and [7]). Since the modification process does not change the diameter, $MG_B(n,d)$ has diameter one greater than the lower bound. Moreover, $MG_B(n,d)$ has a Hamilitonian circuit except when d=2 and gcd(n,d)=1 ([6]). In this exceptional case, a modified digraph H(n,2) was constructed which possesses maximum connectivity, minimum diameter, and a Hamilitonian circuit ([5]).

For any d-regular digraph G with n nodes, node-connectivity k(G), link-connectivity k'(G), and diameter D(G), the following relations hold:

$$d>=k(G)>=\frac{n(d-1)}{d^D+d^2-d-1} \quad -----(2)$$

and

$$d>=k'(G)>=\frac{n(d-1)}{d^{D-1}+d^2-2} \quad -----(3)$$

Clearly, when D(G) decreases, k(G) and k'(G) increase. Moreover, when D(G) of a d-regular digraph is less than $\log_d(n-d^2+d+1)$, k(G) achieves the maximum value of d. Soneoka, Imase and Okada ([18]) utilized this concept and a construction technique called "digraph overlap" to design CANDY which is a computer-aided network design support system for highly reliable communication networks. The starting topology they used is the digraph $G_I(n,d)$ which has the set of links

$$i \rightarrow (-d)*i - q \pmod n, \; q=1,2,\ldots,d.$$

$G_I(n,d)$ has many properties as good as $G_B(n,d)$ except $k(G_I(n,d))=d-1$. It can not be modified to get a connectivity d digraph because it has connectivity d-1 even without self-loops. Performance study shows that the network model generated by CANDY has about the same average number of transit-links per call as a network designed with a conventional method, while assuring high reliability.

Work is undertaken to use $MG_B(n,d)$ as initial topology in the design and optimization of large-scale communication networks. Heuristic algorithms are being constructed to perform optimization. We note that $G_B(n,d)$ and $G_I(n,d)$ are all special cases of the class of d-circulant digraphs where the adjacent matrix consists of entries with 1's and 0's in the first row and the second and succeeding rows can be obtained by shifting the first row d positions to the right in a circular way (see [13]). This would enable us to represent the network in a simplified way.

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