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Chapter 10

Design of Survivable Networks

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1. Overview

This chapter focuses on the important practical and theoretical problem of designing survivable communication networks, i.e., communication networks that are still functional after the failure of certain network components. We motivate this topic in Section 2 by using the example of fiber optic communication network design for telephone companies. A very general model (for undirected networks) is presented in Section 3 which includes practical, as well as theoretical, problems, including the well-studied minimum spanning tree, Steiner tree, and minimum cost k-connected network design problems.

The development of this area starts with outlining structural properties in Section 4 which are useful for the design and analysis of algorithms for designing survivable networks. These lead to worst-case upper and lower bounds. Heuristics that work well in practice are also described in Section 4. Polynomially-solvable special cases of the general survivable network design problem are summarized in Section 5.

Section 6 contains polyhedral results from the study of these problems as integer programming models. We present large classes of valid and often facet-defining inequalities. We also summarize the complexity of the separation problem for these inequalities. Finally we provide complete and nonredundant descriptions of a number of polytopes related to network survivability problems of small dimensions.

Section 7 contains computational results using cutting plane approaches based on the polyhedral results of Section 6 and the heuristics described in Section 4. The results show that these methods are efficient and effective in producing optimal or near-optimal solutions to real-world problems.

A brief review of the work on survivability models of directed networks is given in Section 8. We also show here how directed models can help to solve undirected cases.

2. Motivation

In this section we set the stage for the topic of this chapter by considering an application to designing communication networks for telephone companies based on fiber optic technology. We will use this to introduce the concept of survivability in network design and to motivate the general optimization models described in the next section. It will become clear later that our models capture many other situations that arise in practice and in theory as well.

Fiber optic technology is rapidly being deployed in communication networks throughout the world because of its nearly-unlimited capacity, its reliability and cost-effectiveness. The high capacity of new technology fiber transmission systems has resulted in the capability to carry many thousands of telephone conversations and high-speed data on a few strands of fiber. These advantages offer the prospect of ushering in many new information networking services which were previously either technically impossible or economically infeasible.

The economics of fiber systems differ significantly from the economics of traditional copper-based technologies. Copper-based technologies tend to be bandwidth limited. This results in a mesh-like network topology, which necessarily has many diverse paths between any two locations with each link carrying only a very small amount of traffic. In contrast, the high-capacity fiber technologies tend to suggest the design of sparse 'tree-like' network topologies. These topologies have only a few diverse paths between locations (often just a single path) and each link has a very high traffic volume. This raises the possibility of significant service disruptions due to the failure of a single link or single node in the network. The special report 'Keeping the phone lines open' by Zorpette [1989] describes the many man-made and natural causes that can disrupt communication networks, including fires, tornados, floods, earthquakes, construction or terrorist activities. Such failures occur surprisingly frequently and with devastating results as described in this report and in the popular press [e.g., see Newark Star Ledger, 1987, 1988a, 1988b; New York Times, 1988, 1989; Wall Street Journal, 1988].

Hence, it is vital to take into account such failure scenarios and their potential negative consequence when designing fiber communication networks. Recall that one of the major functions of a communication network is to provide connectivity between users in order to provide a desired service. We use the term 'survivability' to mean the ability to restore network service in the event of a catastrophic failure, such as the complete loss of a transmission link or a facility switching node. Service could be restored by means of routing traffic around the damage through other existing facilities and switches, if this contingency is provided for in the network architecture. This requires additional connectivity in the network topology and a means to automatically reroute traffic after the detection of a failure.

A network topology could provide protection against a single link failure if it remains connected after the failure of any single link. Such a network is called 'two-edge connected' since at least two edges have to be removed in order to disconnect the network. However, if there is a node in the network whose removal