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# Hierarchical Two-Layer Ring Network Design

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Communication networks are a crucial infrastructure in the modern society today. Helped by advances in optical network technology, modern core networks today carry extreme amounts of data, enabling the networked society. A paramount issue is reliability of the network: The network should be resilient against network errors and a host of different technologies have been developed for dealing with these issues, see Grover [5]. Designing networks which are both resilient to network errors and are cost efficient is the objective in this article.

One of the main technology to protect against network errors today is ring structures. By establishing ring structures, the communication traffic can be redirected in case of an error. Designing such networks is however hard. This paper deals with the design of two-layer ring networks, such that rings of the lower layer is connected through a ring in the upper layer. The upper level ring is referred to as the *federal* ring and the rings on the lower level is denoted *metro* rings, see Figure 1 for an example. In this paper we do not specifically consider the demand of data in the network, but it is assumed that the federal link carries the main load of the data since it acts as the backbone of the network. The individual rings are of a bounded size in order to minimize rerouting times in case of network errors, and to minimize the risk of multiple link failures on the same ring.

## 1 Literature Overview

Because protection of networks using rings is such a standard approach, a number of articles have studied the construction of ring protected networks. In Thomadsen and Stidsen [7] an approximated two-layer ring network was built, consisting of a number of metro rings and an overall connecting federal ring. In the study, the cost of the federal ring was approximated so only the metro rings were designed. A branch-and-price algorithm was used, but the problem proved to be very hard to solve and hence only networks of medium size was solved. In the book Fortz [3], the two-connected network with bounded rings problem (2CNBR) is studied, i.e. design the least cost network such that it is both two-connected and can be covered by rings of bounded size. If no size bound is placed, the cheapest network is a TSP tour. The moment the rings are of bounded size, the problem becomes much harder. No hierarchical issues are considered. In Goldsmith et al. [4] the SONET ring assignment problem (SRAP) is considered. Given a network, a set of rings has to be found which covers all links and where each ring has a capacity limit and where a federal ring binds the metro rings together. An ILP model is formulated and tested. Furthermore theoretical aspects are considered and a heuristic is developed. In Macambira et al. [6] the SRAP is solved using a branch-and-price algorithm and is tested on a number of different networks.

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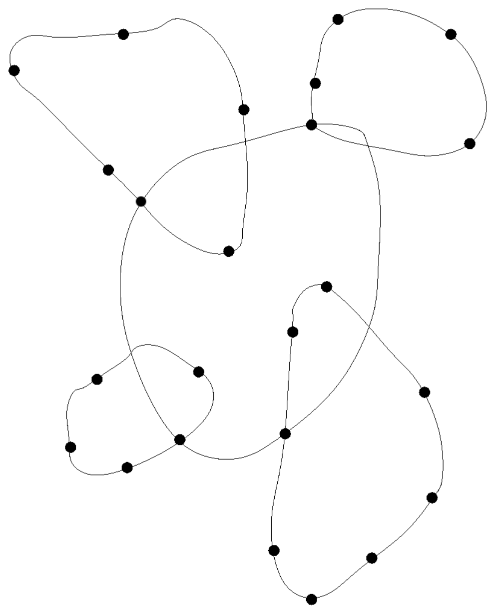

Figure 1: Two-layered ring network. A set of 23 nodes are connected through a two-layer hierarchical network with the federal ring connecting the metro rings.

## 2 Problem Statement

The two-layer ring network design problem is NP-hard. This can be shown by reduction from, e.g., the traveling salesman problem. Consider a set of nodes that may all be connected. Our task is to design a two-layer hierarchical network in order to determine which links to construct. The design network must consist of exactly one federal ring with at least three nodes and a number of metro rings with a given maximal size. The nodes of the network must all be assigned to exactly one metro ring and a metro ring must be connected to the federal ring with exactly one node. The objective is to minimize the cost of the constructing the links used in the ring structures.

## 3 Modelling and Solution Approach

We propose a mathematical model of the two-layer network problem with two binary variables for each link indicating if that link is used on the federal ring or on a metro ring, and a binary variable for each node to indicate if that node is part of the federal link. For each node a constraint conserves flow conservation such that a node is connected with exactly two links for the metro rings and zero or two links for the federal rings. A single constraint bounds the size of the federal ring, and a set of constraints ensure that the federal ring is connected in a single ring. The latter constraint set is similar to the disjoint circuit elimination constraints used in the model for the cardinality constrained circuit problem, see Bauer et al. [2]. Two constraint sets ensure that the metro rings are bounded in length, that they are in fact rings, and that they are connected to the federal ring in exactly one node. The three latter constraint sets are all of exponential size which makes this model intractable to solve out-of-the-box.

Our solution approach is a branch-and-cut algorithm where the three constraint sets of exponential size are relaxed and violated inequalities are separated when violated. All three types of inequalities can be separated in polynomial time by solving a series of max flow problems. The inequalities that bound the size of the metro ring can be strengthened, but results in an NP-hard separation problem. However, experience with similar inequalities used in other problems, e.g., the capacitated m-ring star problem investigated by Baldacci et al. [1], suggests that the harder separation problem is worthwhile for the overall solution process.

## 4 Future Research

Future research includes the integration of more than two layers connected in a hierarchical fashion is an obvious extension to the presented model. Also, the consideration of node-to-node data demand and network capacity would improve the usefulness of the designed network as it will indicate reasonable backbone structures, especially for the federal ring. In this paper we only considered networks design based on complete networks. This setting may not be neither feasible nor wanted in real-life if the links of a current network must be reused. When considering a sparse network it may not be possible to construct a cost efficient two-layer ring structure. Instead, single nodes may be connected to the metro rings with spurs (single links). Obviously, there is no protection on such links, but it may result in much more cost efficient designs where the majority of the nodes are protected by ring structures.

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