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Redundant multicast routing in multilayer networks with shared risk resource groups: Complexity, models and algorithms

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ABSTRACT

This paper presents a redundant multicast routing problem in multilayer networks that arises from large-scale distribution of realtime multicast data (e.g., Internet TV, videocasting, online games, stock quotes). Since these multicast services commonly operate in multilayer networks, the communications paths need to be robust against a single router or link failure as well as multiple such failures due to shared risk link groups (SRLGs). The main challenge of this multicast is to ensure the service availability and reliability using a path protection scheme, which is to find a redundant path that is SRLG-disjoint (diverse) from each working path. The objective of this problem is, therefore, to find two redundant multicast trees, each from one of the two redundant sources to every destination, at a minimum total communication cost whereas two paths from the two sources to every destination are guaranteed to be SRLG-diverse (i.e., links in the same risk group are disjoint). In this paper, we present two new mathematical programming models, edge-based and path-based, for the redundant multicast routing problem with SRLG-diverse constraints. Because the number of paths in path-based model grows exponentially with the network size, it is impossible to enumerate all possible paths in real life networks. We develop three approaches (probabilistic, non-dominated and nearly non-dominated) to generate potentially good paths that may be included in the path-based model. This study is motivated by emerging applications of internet-protocol TV service, and we evaluate the proposed approaches using real life network topologies. Our empirical results suggest that both models perform very well, and the nearly non-dominated path approach outperforms all other path generation approaches.

1. Introduction

Multicast networking has been widely used in many applications in communications systems, including multilocation video conferencing, multimedia broadcasting, wireless/mobile multicast in civil and military applications, web caching, software distribution, video-on-demand, and virtual reality simulation [18,19]. Generally, a multicast network consists of a set of nodes, where some specific data of common interest are transmitted (or broadcasted) from a single source to a set of destinations, called *multicast group*. This feature provides the main difference between multicast networks and unicast networks, where data are sent between pairs of a source node and a destination node. Multicast transmission delivers the information to each node in a multicast group simultaneously over a network, which forms a *multicast tree*. The problem of finding a multicast tree is often called a multicast routing problem. Although there are several multicast routing protocols in the literature including open shortest path first (OSPF) [2] and intermediate system to intermediate system (IS–IS) routing [1], the multicast routing problem is still a hard combinatorial optimization problem [17,21,26].

Recently, a very practical concern about reliability and resiliency issues in provisioning a multicast transmission has been raised [20]. As multicast networks should be protected from and be resilient to network outages or attacks, network operators normally utilize some communication links less than their limit capacity in order to increase the reliability and employ some fast restoration scheme against failures [10]. In an extreme case where the transmission needs to be always-on, network operators often employ a path protection scheme, where network routing finds a backup or redundant path that is disjoint from each working or primary path. Having redundant or multiple multicast trees that are disjoint will protect the multicast transmission from network failures or attacks. The problem of identifying disjoint redundant multicast trees from a single source to a set of destinations that

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can survive any single link failure was well studied in the literature [15]. A protected multicast transmission can also be applied to an existing network infrastructure to maximize the coverage/yeild and minimize the cost and traffic load [3,9].

Today's multicast applications are commonly operated on multilayer telecommunication networks but previous studies did not address the concept of *shared risk resource group* (SRRG) that arises due to a common structure of multilayer networks. SRRG is a set of shared resources that always fail simultaneously. Such resources are often referred to a set of nodes or a set of links. For this reason, SRRG plays a very important role in diverse routing in multilayer networks because a single SRRG failure causes multiple link and node failure [4]. There are two types of SRRG: shared risk link group (SRLG) and shared risk node group (SRNG). Both SRNG and SRLG are special cases of SRRG, where the network contains only a group of nodes or links that are subject to a common risk. Multiple nodes in an SRNG share common resources like channel, power source, or connector (router), whose failure disrupts all nodes in the group. Multiple links in an SRLG share common resources, whose failure disrupts all links in the group, e.g., fiber cuts. In a mathematical modeling sense, the problems of finding redundant multicast trees with SRLG-diverse, SRRG-diverse, or SRNG-diverse constraints are equivalent.

Our study is motivated by emerging applications of internet-protocol TV (IPTV), which deal with finding protected (two or more) redundant multicast trees in multilayer networks. Nowadays several major telecommunications providers around the world are exploring the employment of IPTV as a new revenue opportunity, considering the fact that broadband networks are becoming more and more popular all over the world, especially in Asia and Europe [31]. The results of this study may be used to improve the efficiency and reduce the cost of IPTV employment and provisioning. Specifically, in this paper we consider the problem of IPTV multicast routing from *two redundant multicast sources over a multilayer network*. Our objective is to (a) find two redundant multicast trees, each from one of the two sources to every destination, at a minimum total communication cost, and (b) guarantee that two paths from the two sources to every destination are SRLG-diverse (i.e., links in the same risk group are disjoint). We shall call this problem the redundant multicast routing problem with SRLG-diverse constraint (RMRP-SRLG), which is a generalization of the single-destination SRLG disjoint multicasing problem, which has been studied in Shen et al. [29], Yuan and Jue [34], Guo et al. [7]. To the best of our knowledge, there are a few studies in the literature in this area, and most of them only propose simple heuristic approaches without giving rigorous mathematical modeling of protected multicast routing with the consideration of SRRG. In addition, conventional path protection algorithms that are well studied in the literature (e.g., node/edge disjoint path [23,27,28]) cannot be directly applied to RMRP-SRLG.

In this paper, we prove the NP-completeness of RMRP-SRLG by reducing the well-known NP-complete 3-SAT problem to it. Previously, NP-completeness has been shown for related problems based on a reduction of the maximum bipartite subgraph problem [8]. Our proof provides an alternative and more generalized approach, in which a reduction of the maximum bipartite subgraph problem is proposed. We present for the first time a new edge-based optimization model for RMRP-SRLG, and reformulate it as a path-based model with variables corresponding to paths from a source to a destination. This reformulation arises naturally from the Dantzig–Wolfe decomposition of the edge model. Since there are an exponential number of possible paths in the path-based model for large real networks, we develop a heuristic approach to generate potentially high-quality paths. The idea of this approach is to use a new multi-objective greedy search algorithm to search for high-quality path candidates. We test and compare the performance of both edge-based and path-based models on real world network instances. In addition, we investigate the scalability of the two models by increasing the number of destinations in the network, which is very crucial to service providers for future service expansion.

The rest of this paper is organized as follows. Section 2 provides background on multicast routing and the concept of SRRG. Section 3 investigates the complexity of a special class of this multicast problem. Section 4 formally defines the problem that this paper addresses and present two mathematical programming models: edge-based and path-based. The section also outlines the path generation approaches for the path-based model. Section 5 presents an comprehensive empirical study using real life test cases and the economic interpretation of the results we achieved by applying the described techniques. Section 6 presents a conclusion and discussion about future work.

2. Background

In contrast to unicast systems, multicast routing problems are hard combinatorial problems, which usually require the use of sophisticated solution methods such as approximation algorithms, distributed computing, multi-objective optimization, and mathematical programming. The most widely studied multicast routing problem is the minimum cost multicast routing problem [26], which is to find a multicast tree (a set of links) with a minimum cost from a given source to a set of destination nodes in a network. The problem can be easily seen as a generalization of the Steiner tree problem, which is a well-known NP-hard problem [6,22]. For multicasting in communication networks, additional operational constraints such as capacity, delay, and reliability should be considered and added to the multicast routing research. For example, in most multicast routing problems, operational backbone network owners provision their networks such that the average load on each link and the average end-to-end propagation delay are below a certain threshold. The multicast system considered in this study is motivated by the fast growing internet-protocol TV (IPTV) application. Since identical broadcast TV content is to be distributed across all video hub offices (VHOs) in IPTV networks, it is intuitive to consider the use of multicast to minimize the communication cost (e.g., bandwidth consumed) [21,26].

Operational networks of today's internet applications like IPTV involve physical/data-link layers for optical backbones and network layer for internet protocol (IP) backbones. Extensive research on multicasting and routing in IP networks can be found in [26,30,2]. However, multicasting in multilayer networks (both optical and IP) is a relatively new research area and is in its infancy [5,32]. In order to make practical use of multilayer operations, research studies in multicasting need to invoke up to the network layer architecture of application-dependent network design. The multicasting routing problem in multilayer networks with delay or reliability constraints is in turn very practical, yet extremely challenging. The reliability constraints that are derived by the multilayer structure of operational networks are very intuitive and viable. The concept of shared risk resource group (SRRG) has been introduced to represent a set of communication links and/or nodes that are simultaneously affected due to a single point of failure [12]. For instance, fiber links interconnecting network nodes are often routed over common sections of fiber or conduit [7]. Specifically, in an optical network, a conduit carries a large number of fiber cables, each in turn carrying multiple channels (links). As a result, two diverse connections in the IP