Transportation Research Part B 71 (2015) 32–55

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

Regenerator Location Problem and survivable extensions: A hub covering location perspective

Barış Yıldız, Oya Ekin Karaşan *

Bilkent University, Department of Industrial Engineering, Bilkent, 06800 Ankara, Turkey

ARTICLE INFO

Article history:
Received 20 January 2014
Received in revised form 7 October 2014
Accepted 8 October 2014
Available online 12 November 2014

Keywords:
Regenerator location
Hub location
Survivable network design
Branch and cut

ABSTRACT

In a telecommunications network the reach of an optical signal is the maximum distance it can traverse before its quality degrades. Regenerators are devices to extend the optical reach. The regenerator placement problem seeks to place the minimum number of regenerators in an optical network so as to facilitate the communication of a signal between any node pair. In this study, the Regenerator Location Problem is revisited from the hub location perspective directing our focus to applications arising in transportation settings. Two new dimensions involving the challenges of survivability are introduced to the problem. Under partial survivability, our designs hedge against failures in the regeneration equipment only, whereas under full survivability failures on any of the network nodes are accounted for by the utilization of extra regeneration equipment. All three variations of the problem are studied in a unifying framework involving the introduction of individual flow-based compact formulations as well as cut formulations and the implementation of branch and cut algorithms based on the cut formulations. Extensive computational experiments are conducted in order to evaluate the performance of the proposed solution methodologies and to gain insights from realistic instances.

1. Introduction

Campbell (1994a) introduces and formulates a variant of the hub covering location problem under an interesting coverage criterion, namely, that demand nodes are considered covered when served via "close" hubs mutually interconnected in a complete fashion of "close" diameter. Although this specific covering criterion did not receive much attention in the succeeding hub location literature, it is of close kinship to the problem considered in this study. Consider the following generic application setting. There are several nodes spread over a wide geographical area. Some commodity needs to be exchanged between any pair of nodes. This commodity travels in the network via pre-built links. Sent from a node, the commodity cannot travel more than a certain distance without going through a replenishment (regeneration) process, which can only be conducted at the nodes by an expensive piece of equipment called a regenerator. Because it is costly to have a regenerator at all nodes, some nodes must be chosen as centers (hubs) that serve others. Then, the problem is finding the minimum number of regenerators (and their locations) to facilitate transportation of the commodity between any two nodes. In telecommunications literature applications, this version of the hub covering problem is known as the Regenerator Location Problem (RLP) (Chen et al., 2009). In this study, we introduce two new dimensions to it:

* Corresponding author.

http://dx.doi.org/10.1016/j.trb.2014.10.004
0191-2615/

- First, we examine the survivability of a network that hedges against a single failure in the regeneration equipment. In this case, we assume that only nodes with regeneration capabilities (hubs) are susceptible to failure or that the high setup and operating costs of regeneration equipment prohibit employing redundancy strategies as freely as in the case of nodes with no regenerators (non-hub nodes). We thus define the RLP with resilience against regenerator failures (RLPRF) as the problem of finding the minimum number of regenerators (and their locations) that can facilitate transportation of the commodity between any two nodes even if an arbitrary regeneration point fails.
- Second, we extend the previous survivability notion to all nodes in the network. We define the RLP with resilience against node failures (RLPNF) as the problem of finding the minimum number of regenerators (and their locations) that can facilitate transportation of the commodity between any two nodes even if any node (hub or not) in the network fails.

The original practical motivation for the RLP comes from the thriving field of optical networks (Yetginer and Karasan, 2003; Chen et al., 2009). With its vast data transfer capacities, an optical network is the only mature solution able to cope with the explosive growth in mobile communication devices (smart phones, tablets, etc.) that has taken the Internet age to a new stage (Agrawal, 2012). In 2011 global mobile data traffic was eight times the size of the whole Internet in 2000, and is expected to increase 18-fold by 2016 (Index, 2012). Such breakneck growth on the demand side has been met by the vast capacity built over the years on the supply side by fiber optic technologies. From 45 Mb/s in 1980, the data transfer capacities of fiber optic cables jumped by a factor of more than 70,000 by 2003, to reach 3.2 Tb/s. In 2010 the world record for capacity over a single fiber optic cable was set at 64 Tb/s (Agrawal, 2012). Despite their immense capacity to transmit digital data, fiber optic networks suffer from transmission impairments that limit transmission ranges. As globalization connects more people, the need to transfer more data over longer distances becomes more pronounced exacerbating the problem of signal degradation. Therefore, when designing an optical network that spans a wide geographical area, facilitating signal regeneration must be considered. Because regeneration costs make up a significant portion of a network's setup and management costs (Yang and Ramamurthy, 2005b), there is great motivation to design an optical network with few regeneration points. Although they are less costly, sparse networks in general and telecommunication networks in particular are vulnerable to damage and equipment failure. Therefore, survivability is also a big concern for optical networks designers (Monma and Shallcross, 1989; Fortz et al., 2000; Kerivin and Mahjoub, 2005).

Though the motivating application settings for the problems under our scope originate in telecommunications, we shall adopt a hub location perspective in our discussion so as to emphasize the inherent transportation nature of these problems. O'Kelly (1986a,b) and O'Kelly (1987) are seminal works on hub location research. Campbell (1994b), and more recently, Alumur and Kara (2008) provide a comprehensive survey of this literature. Campbell (1994a) studies the hub covering problem that is closely related to the RLP, defines three coverage criteria for hubs and provides the first mixed integer programming (MIP) formulations for the problem. Kara and Tansel (2000) prove that the single allocation hub covering problem is *NP*-hard and provide a linearization for the original quadratic model, which performs better than its previous counterparts. Wagner (2007) provides high-performance preprocessing techniques to reduce the number of the variables and improve the problem formulations. Hamacher and Meyer (2006) delineate facet-defining valid inequalities for the hub covering problem. In all these studies, the underlying hub network is assumed to be complete. Campbell et al. (2005a) relax the fundamental complete hub network assumption and instill a network design perspective to the hub location problems. In a companion study, Campbell et al. (2005b) provide integer programming formulations and optimal solution algorithms. Calik et al. (2009) and Alumur et al. (2009) also address the more general incomplete but connected hub network topologies. We refer the interested reader to Campbell (1993), Racunica and Wynter (2005), Yaman et al. (2007), Alumur et al. (2009), Yaman (2009), Correia et al. (2010), Meng and Wang (2011) for the hub location studies that directly deal with the transportation networks. None of these studies consider system survivability in the case of hub failure or destruction as a significant aspect of the problem. The current study also relaxes the fundamental complete hub network assumption and builds hub networks resilient to hub or node failures.

Kim and O'Kelly (2009) introduce the reliable *p*-hub location problems in hub-and-spoke networks. Using the probabilities of successful edge or hub flow transmissions as reliabilities, the reliability of the network performance can be measured. Kim and O'Kelly (2009) formulate and solve two hub location models namely the *p*-hub maximum reliability and the *p*-hub mandatory dispersion models focusing on maximizing the network performance in terms of reliability based on empirical traffic loss rates among origin destination pairs. Both single and multiple allocation versions of the problem are addressed. Considering hub unavailability and alternative routes in air transportation systems, Zeng et al. (2010) propose different versions of reliable hub location models. Davari et al. (2010) and Zarandi and Davari (2011) design reliable hub networks using fuzzy goal programming. Lei (2013) and Hamidi et al. (2014) utilize a hub interdiction viewpoint and present hub protection and preventive reliable hub location problems, respectively, to the literature. Kim and O'Kelly (2008), An et al. (2011), Kim (2012) and Azizi et al. (2014) bring the survivable network design perspective into the hub-and-spoke networks. With this perspective, backup hubs and alternative routes are designed to provide a continuum of service with a typical objective of minimizing the transportation cost. In our study, the fundamental complete hub network assumption, which is present in the mentioned relevant studies in survivable hub location literature, is relaxed. Moreover, the designs should obey the transport range (optical reach) limitations respecting the edge lengths of an input transportation (optical) network. In particular, for RLP, given an underlying network (typically a sparse one), hubs (regenerators) should be located in such a way that between any origin destination pair, there exists a path visiting perhaps more than two hubs such that each segment of this path is within the transport range. With RLPRF, the hub network design should respect RLP connectivity requirements even if