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A traffic grooming problem considering hub location for synchronous optical network-wavelength division multiplexing networks

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ABSTRACT

In this paper, we deal with a traffic demand clustering problem for designing SONET-WDM rings. The objective is to minimize the total cost of optical add-drop multiplexers (OADMs) and inter-ring hub equipments, while satisfying intra-ring and inter-ring capacities. Also, the minimum number of nodes, for example three, for each ring should be satisfied. We develop an integer programming (IP) formulation for the problem and develop some valid inequalities that provide a tight lower bound for the problem. Dealing with the inherent computational complexity of the problem, we also devise an effective tabu search procedure for finding a feasible solution of good quality within reasonable computing time. Computational results are provided to demonstrate the efficacy of the lower and upper bound procedures for solving the problem.

1. Introduction

Optical transport system such as the synchronous optical network (SONET) has been widely deployed in current telecommunication networks to meet the rapid growth in demand of telecommunication services. The SONET technology supports several network architectures providing enhanced network survivability, for example, self-healing rings (SHRs), dual homing and point-to-point diverse protection scheme. In recent years, traditional SONET based optical networks are being upgraded to SONET-WDM (Wavelength Division Multiplexing) based optical networks due to the increased demands of telecommunication services. The WDM technology enables us to stack multiple wavelengths on a single optical fiber, by which we can economically upgrade the existing SONET based networks to SONET-WDM based networks. Thus, the combination of SONET and WDM technologies can be an attractive choice for network planners since the capacity of optical networks with survivability can be increased economically.

For deploying SONET-WDM rings, we consider some technical constraints such as the maximum number of nodes on a ring and the capacity of a ring. For example, SONET supports up to 16 nodes on a ring since 4-bit addressing field is used as a node identifier. However, network planners usually set a smaller bound than 16 as the maximum number of nodes on a ring to limit the restoration time. Also, the capacity of a ring is determined by the capacity of the optical add-drop multiplexer (OADM) placed at each node of the ring. The capacity of an OADM is usually expressed as $n \times$ STM-1 (equivalent to OC-3: 155Mbps), where n denotes the maximum number of channels (equivalent to wavelengths) the core fabric of OADM supports.

OADMs located at each node add and drop the traffic to and from the ring, and we can use an optical cross-connect (OXC) system serving as a hub node of a ring in order to connect several rings. This is shown in Fig. 1(a). By using OXCs, we can reduce the total number of OADMs required to cover all the traffic demands as intra-ring traffic. That is, unless we use OXCs, we should install two OADMs at the node that connects two rings as shown in Fig. 1(b).

The problem considered in this study can be described as follows. Given a set of demand pairs between nodes in the network, we partition a set of demand pairs to a number of metro rings and a regional ring, and determine the hub node location of each metro ring such that the total cost of OADMs and OXCs is minimized, while satisfying the metro ring cardinality constraint and the capacity constraints of OADM and OXC. Here, note that not all the metro rings have to be connected to the regional ring by way of OXCs placed at the hub nodes. That is, some metro rings can be connected each other by installing two OADMs at some common node of the metro rings as shown in Fig. 1(b). Also, note that the total demands carried as intra-ring traffic may change depending on the hub node location (OXC site) in a metro ring.

Fig. 2 illustrates an example network design using OXCs. Fig. 2(a) displays the demands (wavelength requirements) between nodes. In Fig. 2(b) and (c), we present two examples of traffic demand partitioning with inter-ring traffic, where demand pairs {(2, 5), (3, 5)} are carried as inter-ring traffic. As displayed in Fig. 2(b), if hubs are located at nodes 2 and 5 of rings 1 and 2,

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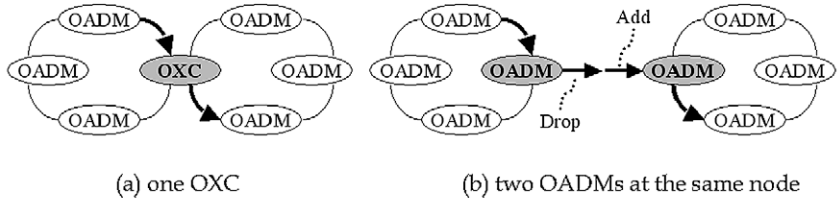

Fig. 1. Connecting rings with and without OXCs.

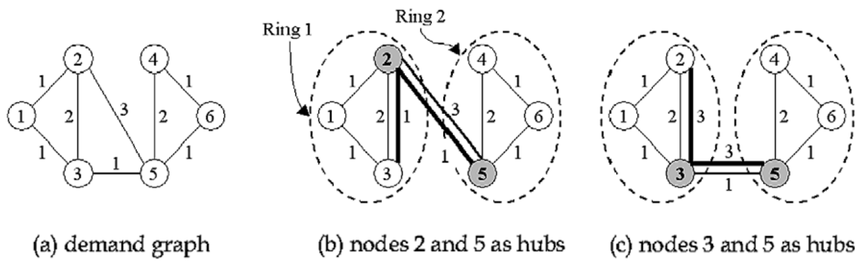

Fig. 2. Traffic grooming dependent upon hub locations.

respectively, demand pair (3,5) consumes the OADM (intra-ring) capacity of ring 1 and the OXC (inter-ring) capacities of rings 1 and 2. While, if hubs are located at nodes 3 and 5 of rings 1 and 2, respectively, demand pair (3,5) does not consume the OADM capacity of ring 1. This is shown in Fig. 2(c). However, by moving the hub location of ring 1 from node 2 to node 3, the required OADM capacity of ring 1 increases from 5 to 7, while the required OXC capacity of ring 1 (and of ring 2) remains the same, 4.

A number of research efforts for SONET design problems have been reported over the last 10 years. Lee, Sherali, Han, and Kim (2000) Sherali, Smith, and Lee (2000) considered a demand partitioning problem that minimizes the ADM cost for SONET rings without permitting inter-ring traffic subject to the capacity and cardinality constraints of a ring. Goldschmidt, Laugier, and Olinick (2003) addressed a SONET/SDH ring design problem that assigns ADM sites to rings in order to minimize the total number of rings subject to the capacity constraint of a ring. They developed three heuristic algorithms, and two of them find feasible solutions satisfying that the total cost is at most twice that of an optimal solution. Aringhieri and Dell'Amico (2005) developed a tabu search algorithm for solving the same problem considered by Goldschmidt et al. (2003). They used a variable objective function for move evaluation. Also, they implemented several intensification and diversification schemes such as path relinking, scatter search (Glover, Laguna, & Marti, 2000), and tabu search. Thomadsen and Stidsen (2005) solved a node-disjoint demand clustering problem using branch-and-price procedure. Kang, Lee, Park, Park, and Kim (2000) developed a column generation approach for solving the ring network design problem, where predetermined hub nodes should be shared by all rings. However, they do not consider the cardinality constraint of a ring and inter-ring capacity constraints at hub nodes. Fortz, Soriano, and Wynants (2003) considered a unidirectional self-healing ring design problem with different capacities per ring and split-routing of traffic demand. Also, there are several studies on the demand clustering (or partitioning) problem for designing SONET-WDM rings allowing inter-ring traffic such as Han, Lee, and Kim (2005), Wang, Cho, and Mukherjee (2001), Cho, Wang, and Mukherjee (2001), Gerstel, Ramaswami, and Sasaki (2000) Chung, Kim, Yoon, and Tcha (1996).

The remainder of the paper is organized as follows: in Section 2, we present an integer programming (IP) model for the SONET-WDM ring design problem with hub. In Section 3, we develop strong valid inequalities that exploit the polyhedral structure of the problem. In Section 4, we propose an effective tabu search procedure for finding high quality feasible solutions for large scale problems. In Section 5, we present computational results that demonstrate the efficacy of the proposed solution procedure. Section 6 concludes the paper.

2. Problem formulation

Define N as a set of nodes and E as a set of traffic demands d_{ij} (>0), equivalent to the channel requirement, between nodes i and j ($>i$) $\in N$. And, define K as a set of rings. Now, we define decision variables. Let $x_{ik} = 1$ if node $i \in N$ is assigned to ring $k \in K$, in which case OADM cost α arises, and 0 otherwise. Let $v_{ik} = 1$ if node $i \in N$ on ring $k \in K$ is selected as a hub node of the ring, in which case additional cost β ($\geqslant 0$) for upgrading the OADM to OXC arises, and 0 otherwise. Let $f_{ijkk} = 1$ if traffic demand d_{ij} is carried as intra-ring traffic on ring $k \in K$, which forces that $x_{ik} = 1$ and $x_{jk} = 1$. Also, let $f_{ijkl} = 1$ if traffic demand d_{ij} is carried as inter-ring traffic between rings k and l $(\neq k) \in K$, which forces that $x_{ik} = 1$ and $x_{jl} = 1$. We limit the maximum cardinality of a ring by R. That is, at most R OADMs can be placed on a ring. To calculate the total intra-ring traffic on a ring, we define additional variables. For each $(i,j) \in E$, let $u_{ijk} = 1$ if $\sum_{l(\neq k)\in K} f_{ijkl} = 1$ and $v_{ik} = 0$, and 0 otherwise. Similarly, let $u_{jik} = 1$ if $\sum_{l(\neq k)\in K} f_{ijlk} = 1$ and $v_{jk} = 0$, and 0 otherwise. If $u_{ijk} = 1$ (or $u_{jik} = 1$), traffic demand d_{ij} handled as inter-ring traffic between rings k and a certain ring $l(\neq k) \in K$ consumes OADM capacity of ring $k \in K$ since node i (or j) $\in N$ is not the hub node of ring $k \in K$. Thus, total traffic demands that should be handled by OADMs on a ring $k \in K$ is calculated as $\sum_{(i,j)\in E} d_{ij}(f_{ijkk} + u_{ijk} + u_{jik})$, which is limited by the channel capacity of an OADM (b^A). Also, we define b^C as the channel capacity of an OXC. The total traffic demands that should be handled by an OXC on a ring $k \in K$ is calculated by $\sum_{(i,j)\in E} d_{ij} \sum_{l(\neq k)\in K} (f_{ijkl} + f_{ijlk})$.

We assume that there is no isolated subgraph in the demand graph $G(N,E)$. Then, we can formulate the SONET-WDM ring design problem with hub (P) as follows:

$$\mathrm{P}: \quad \text{Minimize} \sum_{i\in N} \sum_{k\in K} (\alpha x_{ik} + \beta v_{ik})$$

Subject to

$$\sum_{k\in K} \sum_{l\in K} f_{ijkl} = 1 \qquad (i,j) \in E, \tag{1}$$

$$f_{ijkl} \leqslant x_{ik} \qquad (i,j) \in E, k, l \in K, \tag{2}$$