Rastislav Královič
Ondrej Sýkora (Eds.)

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11th International Colloquium, SIROCCO 2004
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Proceedings

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Preface

The Colloquium on Structural Information and Communication Complexity (SIROCCO) is an annual meeting focused on the relationship between computing and communication. Over its 11 years of existence, SIROCCO has gained considerable respect and has become an acknowledged forum bringing together specialists interested in the fundamental principles underlying all computing through communication.

SIROCCO 2004 was the eleventh in this series, held in Smolenice Castle, June 21–23, 2004. Previous SIROCCO colloquia took place in Ottawa (1994), Olympia (1995), Siena (1996), Ascona (1997), Amalfi (1998), Lacanau-Océan (1999), L'Aquila (2000), Val de Nuria (2001), Andros (2002), and Umeå (2003). The colloquium in 2004 was special in the respect that, for the first time, the proceedings were published in the Lecture Notes in Computer Science series of Springer-Verlag.

SIROCCO has always encouraged high-quality research focused on the study of those factors that are significant for the computability and the communication complexity of problems, and on the interplay between structure, knowledge, and complexity. It covers topics such as distributed computing, mobile computing, optical computing, parallel computing, communication complexity, information dissemination, routing protocols, distributed data-structures, models of communication, network topologies, high-speed interconnection networks, wireless networks, sense of direction, structural properties, and topological awareness. The 56 contributions submitted to this year's SIROCCO were subject to a thorough refereeing process and 26 high-quality submissions were selected for publication. We thank the Program Committee members for their profound and careful work. Our gratitude extends to the numerous subreferees for their valuable refereeing. We also acknowledge the effort of all the authors who submitted their contributions.

We thank the invited speakers at this colloquium, Paul Spirakis (Patras) and Shmuel Zaks (Haifa), for accepting our invitation to share their insights on new developments in their areas of interest. Paul Spirakis delivered a talk about "*Algorithmic Aspects in Congestion Games*" and Shmuel Zaks presented "*Results and Research Directions in ATM and Optical Networks*".

We would like to express our sincere gratitude to the conference chair David Peleg (Rehovot) for his enthusiasm and invaluable consultations, and to the organizing team chaired by Dana Pardubská and Imrich Vrťo.

Our deepest respect belongs to our late friend and colleague Peter Ružička who started the preparation of SIROCCO 2004.

June 2004

Rastislav Královič
Ondrej Sýkora

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Table of Contents

Traffic Grooming in a Passive Star WDM Network

Eric Angel, Evripidis Bampis, and Fanny Pascual

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Abstract. We consider the traffic grooming problem in passive WDM star networks. Traffic grooming is concerned with the development of techniques for combining low speed traffic components onto high speed channels in order to minimize network cost. We first prove that the traffic grooming problem in star networks is NP-hard for a more restricted case than the one considered in [2]. Then, we propose a polynomial time algorithm for the special case where there are two wavelengths per fiber using matching techniques. Furthermore, we propose two reductions of our problem to two combinatorial optimization problems, the *constrained multiset multicover problem* [3], and the *demand matching problem* [4] allowing us to obtain a polynomial time H_{2C} (resp. $2 + \frac{4}{5}$) approximation algorithm for the minimization (resp. maximization) version of the problem, where C is the capacity of each wavelength.

Keywords: star, traffic grooming, WDM network, approximation, algorithm.

1 Introduction

Recently, in order to utilize bandwidth more effectively, new models appeared allowing several independent traffic streams to share the bandwidth of a lightpath. It is in general impossible to setup lightpaths between every pair of edge routers and thus it is natural to consider that traffic is electronically switched (groomed) onto new lightpaths toward the destination node. The introduction of electronic switching increases the degree of connectivity among the edge routers while at the same time it may reduce significantly wavelength requirements for a given traffic demand. The drawback of this approach is that the introduction of expensive active components (optical transceivers and electronic switches) may increase the cost of the network. These observations motivated R. Dutta and G.N. Rouskas [2] to study the traffic grooming problem that we consider in this paper in order to find a tradeoff between the cost of the network and its performance.

We focus on star networks composed by a set of transmitters, a set of receivers and a hub, and the goal is to minimize the *total amount of electronic switching*. This cost function measures exactly the amount of electronic switching inside

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the network (but it only indirectly captures the transceiver cost). Our interest to star networks besides their simplicity, which allows us to provide the first approximation algorithms with performance guarantee for this variant of the traffic grooming problem, is also motivated by their use in the interconnection of LANs or MANs with a wide area backbone.

1.1 Problem Definition

We consider a network in the form of a star with $N+1$ nodes. There is a single *hub* node which is connected to every other node by a physical link. All the nodes, except the hub, are divided into two groups V_1 and V_2: the nodes in V_1 are the transmitters and the nodes in V_2 are the receivers. The hub is numbered 0 and the N other nodes are numbered from 1 to N in some arbitrary order. Each physical link consists of a fiber, and each fiber can carry W wavelengths. Each wavelength has a capacity C, expressed in units of some arbitrary rate. We represent a traffic pattern by a demand matrix $T = [t_{ij}]$, where integer t_{ij} denotes the number of traffic streams (each unit demand) from node $i \in V_1$ to node $j \in V_2$. We do not allow the traffic demands to be greater than the capacity of a lightpath, i.e. for all $(i,j), 0 \leq t_{ij} \leq C$.

The hub has both optical and electronic switching capabilities: it let some lightpaths pass through transparently, while it may terminate some others. Traffic on terminated lightpaths is electronically switched (groomed) onto a new lightpath towards the destination node. A traffic demand (or request) t_{ij} must have its own wavelength from i to the hub and from the hub to j to be optically routed, whereas it can share a wavelength with some other traffic demands if it is electronically switched. The goal we consider in this paper is to *minimize the total amount of electronic switching at the hub.* This problem is often called *the traffic grooming problem.*

R. Dutta and G.N. Rouskas considered in [2] the traffic grooming problem in several network topologies, including a star network. However there are differences between their problem and ours: in [2], each node of the network, including the hub, can be a transmitter and a receiver, and traffic demands between two nodes are allowed to be greater than the capacity of a wavelength (i.e. it is possible that $t_{ij} > C$ for some i, j). To distinguish the two problems, we will call their problem the traffic grooming problem in an active star, and our problem *the traffic grooming problem in a passive star* (see Section 4 for an integer linear programming formulation of the problem). Once we know which traffic demands are optically routed, the wavelength assignment problem is easy in the case of a passive star network.

There are in fact two versions of the traffic grooming problem: either we want to minimize the total amount of electronic switching at the hub (this is the *minimization* version), or we want to maximize the total amount of traffic which is optically routed (this is the *maximization* version). These two versions are equivalent (i.e. an optimal solution for one is also an optimal solution for the other one) because the optimal solution of the maximization problem is equal to the sum of all the traffic demands, minus the optimal solution of the minimization problem.

Our results are as follows. First, we show in Section 2 that the traffic grooming problem in a passive star is NP-Complete, in both the minimization and the maximization versions of the problem. Then we show in Section 3 that these problems are polynomially solvable if there are only two wavelengths per fiber ($W = 2$): we give an algorithm which gives an optimal solution. In Section 4, we show that we cannot deduce a constant approximation guarantee of the maximization (resp. minimization) version from a constant approximation guarantee of the minimization (resp. maximization) version of the problem, and we give two approximation algorithms. The first one concerns the minimization version: we transform our problem in a constrained multiset multicover problem [3], and we get an approximation guarantee of H_{2C}. The second approximation algorithm concerns the maximization version: we transform our problem in a demand matching problem in a bipartite graph [4], and we obtain an approximation guarantee of $(2 + \frac{4}{5})$. We conclude the paper in Section 5.

2 Hardness Results

Let us show in this section that the decision version of the grooming problem in a passive star is NP-Complete.

In order to do this proof, we were inspired by the proof of R. Dutta and G.N. Rouskas in [2]: in this paper they showed that their traffic grooming problem is NP-complete. They reduced the decision version of the Knapsack problem to their problem. We do the same reduction, replacing traffic demands t_{ij} greater than C by several traffic demands of the same weight from i, or to j. They also used traffic demands to the hub (or from the hub). We replace these traffic demands by traffic demands to some new nodes (or from some new nodes) and we force these traffic demands to be switched electronically at the hub.

We reduce the decision version of the Knapsack problem [1] to our grooming problem: let $Q \in Z^+$, is there a solution of our grooming problem in which the amount of optically routed traffic is greater or equal to Q? An instance of the Knapsack problem is given by a finite set U of cardinality n, for each element $u_i \in U$ a weight $w_i \in Z^+$, and a value $v_i \in Z^+, \forall i \in \{1, 2, ..., n\}$, a target weight $B \in Z^+$, and a target value $K \in Z^+$. The problem asks whether there exists a binary vector $X = \{x_1, x_2, ..., x_n\}$ such that $\sum_{i=1}^{n} x_i w_i \leq B$, and $\sum_{i=1}^{n} x_i v_i \geq K$. Given such an instance, we construct a star network using the following transformation: $W = n$, $C = max_i(w_i + v_i) + 1$, $Q = K + \sum_{i=1}^{n}(C - w_i - v_i)$ and the traffic matrix is represented on the Figure 1. In this figure the nodes are the nodes of the star network (the hub is not represented), and the links represent the traffic demands. Traffic demands equal to 0 are not represented, and the value on the link from a node a to a node b is $t_{a,b}$. Nodes from $n + 1$ to $n + 10$ represent each one a node of the network, but nodes $i_\alpha, j_\alpha, k_\alpha, l_\alpha, m_\alpha, p_\alpha$ and q_α represent each one several nodes:

For the nodes i_α, α ranges from 1 to n (i.e. i_α represents the nodes $i_1, i_2, ..., i_n$);
for the nodes j_α, α ranges from 1 to $\lfloor \frac{(n-2)C}{C-1} \rfloor$;
for the nodes k_α, α ranges from 1 to $\lfloor \frac{\sum_{k=1}^{n}(w_k-B)}{C-1} \rfloor$;
for the nodes l_α, α ranges from 1 to $\lfloor \frac{nC-(C-1)}{C-1} \rfloor$;
for the nodes m_α, α ranges from 1 to $\lfloor \frac{nC-((\sum_{k=1}^{n}(w_k-B)) \bmod (C-1))}{C-1} \rfloor$;
for the nodes p_α, α ranges from 1 to $\lfloor \frac{n}{C-1} \rfloor$;
for the nodes q_α, α ranges from 1 to $\lfloor \frac{nC-n((n-2)C \bmod (C-1))}{C-1} \rfloor$;
and for the nodes r_α, α ranges from 1 to $\lfloor \frac{nC-\sum_{k=1}^{n} w_k}{C-1} \rfloor$.

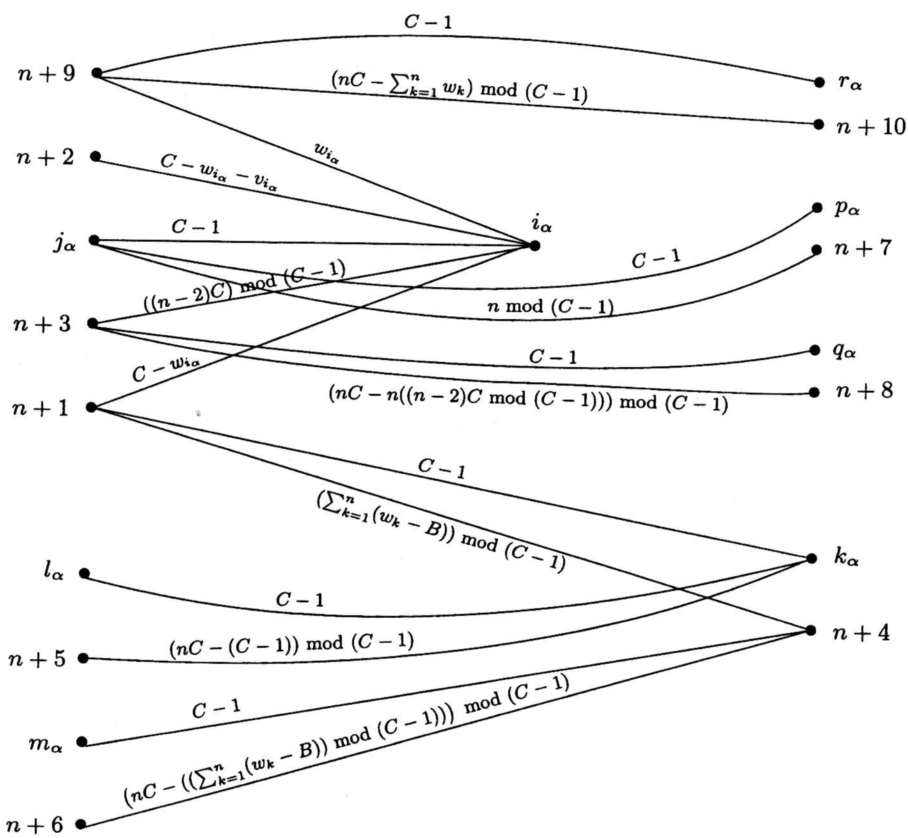

Fig. 1. Illustration of the traffic matrix. Transmitters are on the left and receivers on the right

Lemma 1. *Let a be a transmitter and b a receiver. It is not possible to have a lightpath from a to b, if $(a,b) \neq (n+1, i_\alpha)$ or $(a,b) \neq (n+2, i_\alpha)$.*

Proof. Let us show that each traffic demand different from 0 between each couple (a,b) of nodes in $V_1 \times V_2$ ($(a,b) \neq (n+1, i_\alpha)$ and $(n+2, i_\alpha)$), cannot be optically routed. In order to show that it is not possible to route $t_{a,b}$ optically, we will see that either the sum of the traffic streams from a, or the sum of the traffic streams to b, is equal to nC, and that $t_{a,b}$ is smaller than C.

- $\forall x \in V_2, t_{n+9,x}$ cannot be optically routed. Indeed:
$$\begin{aligned}\sum_{x\in V_2} t_{n+9,x} &= \sum_\beta t_{n+9,r_\beta} + t_{n+9,n+10} + \sum_\beta t_{n+9,i_\beta}\\ &= \lfloor \tfrac{nC-\sum_{k=1}^n w_k}{C-1} \rfloor (C-1) + (nC - \textstyle\sum_{k=1}^n w_k) \bmod (C-1)\\ &\quad + \textstyle\sum_{k=1}^n w_k\\ &= nC\end{aligned}$$
and $t_{n+9,r_\alpha} < C,\ t_{n+9,n+10} < C,\ t_{n+9,i_\alpha} < C$.
- $\forall x \in V_2, t_{j_\alpha,x}$ cannot be optically routed. Indeed:
$$\begin{aligned}\sum_{x\in V_2} t_{j_\alpha,x} &= \sum_\beta t_{j_\alpha,i_\beta} + \sum_\beta t_{j_\alpha,p_\beta} + t_{j_\alpha,n+7}\\ &= n(C-1) + \lfloor \tfrac{n}{C-1} \rfloor (C-1) + n \bmod (C-1)\\ &= nC\end{aligned}$$
and $t_{j_\alpha,i_\beta} < C,\ t_{j_\alpha,p_\beta} < C,\ t_{j_\alpha,n+7} < C$.
- $\forall x \in V_2, t_{n+3,x}$ cannot be optically routed. Indeed:
$$\begin{aligned}\sum_{x\in V_2} t_{n+3,x} &= \sum_\beta t_{n+3,i_\beta} + \sum_\beta t_{n+3,q_\beta} + t_{n+3,n+8}\\ &= n((n-2)C \bmod (C-1)) + \lfloor \tfrac{nC-n((n-2)C \bmod (C-1))}{C-1} \rfloor (C-1)\\ &\quad + (nC - n((n-2)C \bmod (C-1))) \bmod (C-1)\\ &= nC\end{aligned}$$
and $t_{n+3,i_\alpha} < C,\ t_{n+3,q_\alpha} < C,\ t_{n+3,n+8} < C$.
- $\forall x \in V_1, t_{x,k_\alpha}$ cannot be optically routed. Indeed:
$$\begin{aligned}\sum_{x\in V_1} t_{x,k_\alpha} &= t_{n+1,k_\alpha} + \sum_\beta t_{l_\beta,k_\alpha} + t_{n+5,k_\alpha}\\ &= (C-1) + \lfloor \tfrac{nC-(C-1)}{C-1} \rfloor (C-1) + (nC-(C-1)) \bmod (C-1)\\ &= nC\end{aligned}$$
and $t_{n+1,k_\alpha} < C,\ t_{l_\beta,k_\alpha} < C,\ t_{n+5,k_\alpha} < C$.
- $\forall x \in V_1, t_{x,n+4}$ cannot be optically routed. Indeed:
$$\begin{aligned}\sum_{x\in V_1} t_{x,n+4} &= \sum_\beta t_{m_\beta,n+4} + t_{n+6,n+4} + t_{n+1,n+4}\\ &= \tfrac{nC-((\sum_{k=1}^n (w_k-B)) \bmod (C-1))}{C-1}(C-1) + (\lfloor nC - ((\textstyle\sum_{k=1}^n (w_k -\\ &\quad B)) \bmod (C-1))\rfloor) \bmod (C-1) + (\textstyle\sum_{k=1}^n (w_k-B)) \bmod (C-1)\\ &= nC\end{aligned}$$
and $t_{n+1,n+4} < C,\ t_{m_\beta,n+4} < C,\ t_{n+6,n+4} < C$. □

Lemma 2. *Let $\alpha \in \{1, ..., n\}$. Traffic demands t_{n+1,i_α} and t_{n+2,i_α} cannot be optically routed simultaneously.*

Proof. The node i_α receives from the hub a total traffic equal to: $t_{n+9,i_\alpha} + \sum_\beta t_{j_\beta,i_\alpha} + t_{n+3,i_\alpha} = w_{i_\alpha} + \lfloor \frac{(n-2)C}{C-1} \rfloor (C-1) + ((n-2)C) \bmod (C-1) = (n-2)C + w_{i_\alpha} > (n-2)C$.

Since $W = n$, there is at most one wavelength left to have a lightpath to the node i_α. □

Lemma 3. *Let $\alpha \in \{1, ..., n\}$. It is possible to have a lightpath from $n+1$ to i_α, or from $n+2$ to i_α.*

Proof. – Let us show that it is possible to have a lightpath from $n+1$ to i_α: $\sum_{x \in V_1, x \neq n+1} t_{x,i_\alpha} = (n-2)C + w_{i_\alpha} + (C - w_{i_\alpha} - v_{i_\alpha}) = (n-1)C - v_{i_\alpha} \leq (n-1)C$
and, since $\exists i_\alpha \in \{1, ..., n\}, B \geq w_{i_\alpha}$ (otherwise the instance of the Knapsack problem would be trivial) and $C = max_{i_\alpha}(v_{i_\alpha} + w_{i_\alpha}) + 1$, we have $\sum_{x \in V_2, x \neq i_\alpha} t_{n+1,x} = \sum_{k=1}^{n}(w_k - B) \leq (n-1)C$. So there is enough bandwidth to have a lightpath from $n+1$ to i_α.

– Let us show that it is possible to have a lightpath from $n+2$ to i_α: $\sum_{x \in V_1, x \neq n+2} t_{x,i_\alpha} = (n-2)C + w_{i_\alpha} + (C - w_{i_\alpha}) = (n-1)C \leq (n-1)C$ and $\sum_{x \in V_2, x \neq i_\alpha} t_{n+2,x} = 0 \leq (n-1)C$. So there is enough bandwidth to have a lightpath from $n+2$ to i_α. □

Since t_{n+1,i_α} and t_{n+2,i_α} ($\alpha \in \{1, ..., n\}$) are the only traffic demands which can be optically routed (Lemma 1) and since, for each $\alpha \in \{1, ..., n\}$ it is possible to have a lightpath from $n+1$ to i_α, or from $n+2$ to i_α, (Lemma 3) but not both (Lemma 2), we need only to consider solutions in which there is a lightpath from exactly one of the nodes $n+1$, $n+2$, to each node i_α to determine the satisfiability of the instance.

Let X denote a candidate solution of the Knapsack instance. Consider the solution of the grooming problem in which X (respectively, $\overline{X}$) represents the indicator vector of the lightpaths formed from node $n+1$ (resp., $n+2$). Nodes i_α are numbered from 1 to n: let $\alpha \in \{1, ..., n\}$, we have $i_\alpha = \alpha$. Applying the transformation to the satisfiability criteria of Knapsack, we obtain:

$$\sum_{i=1}^{n} x_i w_i \leq B$$
$$\Leftrightarrow \sum_{i=1}^{n} x_i (C - t_{n+1,i}) \leq \sum_{i=1}^{n}(C - t_{n+1,i}) - (t_{n+1,n+4} + \sum_\beta t_{n+1,k_\beta})$$
$$\Leftrightarrow \sum_{i=1}^{n}(\overline{x_i} t_{n+1,i}) + (t_{n+1,n+4} + \sum_\beta t_{n+1,k_\beta}) \leq (n - \sum_{i=1}^{n} x_i)C$$

This inequality means that the amount of electronically routed traffic demands (the left hand side of the inequality) has to be smaller than or equal to the capacity of a link, C, times the number of links available (i.e. n minus the number of traffic demands which are electronically routed).

$$\sum_{i=1}^{n} x_i v_i \geq K$$
$$\Leftrightarrow \sum_{i=1}^{n} x_i (t_{n+1,i} - t_{n+2,i}) \geq Q - \sum_{i=1}^{n} t_{n+2,i}$$
$$\Leftrightarrow \sum_{i=1}^{n} (x_i t_{n+1,i} + \overline{x_i} t_{n+2,i}) \geq Q$$

This inequality means that the total amount of optically routed traffic has to be greater than or equal to Q.

Therefore, a vector X either satisfies both the Knapsack and the grooming instance, or fails to satisfy both. Hence, the grooming instance is satisfiable if and only if the Knapsack instance is.

Theorem 1. *The decision versions of the minimization and the maximization versions of the grooming problem in a passive star are NP-Complete.*