Journal of Computing and Information Technology - CIT 9, 2001, 3, 213–218

On Delay versus Congestion in Designing Rearrangeable Multihop Lightwave Networks*

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We investigate design issues of optical networks in light of two conflicting criteria: throughput maximization (or, equivalently, congestion minimization) versus delay minimization. We assume the network has an arbitrary topology, the flow can be split and sent via different routes, and it can be transferred via intermediate nodes. Tabu search heuristic is used to compare solutions with different weights assigned to each of the two criteria. The approach is tested on a benchmark data set, the 14-dimensional NSFNET T1 network with traffic from 1993. The results suggest that (1) some connectivity matrices are quite robust and desirable regarding both criteria simultaneously; (2) forcing minimization of total delay unconditionally can result with significantly inferior throughput. Some decisions strategies are outlined.

Keywords: heuristic solvability, tabu search, multihop, rearrangeable optical networks, minimal delay, maximal throughput

1. Introduction

Despite a surge in wireless communication, optical networks are still indispensable as a fast and reliable medium for transferring high volume sensitive data. A possibility for reconfiguration by re-tuning node transmitters and receivers to different wavelengths adds to usefulness and economic benefits of optical networks. The underlying assumption is that each network node is equipped with a small number p of transmitters and receivers, and that a spectrum of wavelengths is accessible by and shared among all nodes using Wavelength Division Multiplexing (WDM). In order for traffic to go through a link (i, j), a transmitter of node i and a receiver of node j have to be tuned to the same wavelength. Such a tuning establishes a logical link. Re-tuning results in new paths, making logical connectivity independent of physical architecture. This approach offers possibilities for optimizing logical connections in light of changes in incoming traffic. Depending of input traffic flow, the optical network can be optimized by taking into account different criteria, such as throughput, delay, or total flow. Relevant research considers arbitrary as well as regular network topologies (see Skorin-Kapov and Labourdette, 1996 and 1998). This work deals with arbitrary networks since they are more general and exist for every network size.

A discussion of different design objectives is presented in [Labourdette, 1998]. Previous work always considered one criterion at a time. The exception is the recent work by [Boljunčić, Skorin-Kapov and Skorin-Kapov, 2001] that investigates throughput maximization versus minimization of total network flow. The work presented in this paper deals with joint consider-

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[*] The work was partially supported by the National Science Foundation grant ANI-9814014, by the project 036033- Architectural Elements for Regional Information Infrastructure, funded jointly by the Ministry of Science and Technology of the Republic of Croatia and the Istrian County, and by the project 067010– Models and Methods of Operational Research funded by the Ministry of Science and Technology of the Republic of Croatia.

ation of network delay and congestion. Obviously, in the process of minimizing the maximal congestion the traffic will be re-routed, in turn using longer paths contributing to overall transmission delay. On the other hand, smaller congestion results in smaller queuing delay since the throughput is increased. Hence, it makes sense to investigate the behaviour of the network routing in light of joint consideration of minimal congestion and minimal delay. Regarding congestion, it makes sense to minimize maximal congestion because it increases network scalability and robustness regarding possible bottlenecks. The appropriate consideration of network delay should take into account managerial issues: is it more appropriate to consider minimizing maximal or total delay? (Minimization of average delay is accomplished by minimizing the total delay.) Minimizing total delay leads to overall better network performance. In addition, since the input flow from i to j can be split and sent via different routes using intermediate nodes, it can contribute to a total flow on any link.

This paper investigates different virtual designs and respective routings of optical networks obtained by joint consideration of minimizing congestion and total delay. The heuristic approach based on tabu search follows the strategy proposed by [Skorin-Kapov and Labourdette, 1995]. This requires decomposing the problem into two subproblems: the connectivity and the routing problems. The initial connectivity diagram (i.e. virtual topology) is obtained via a linear assignment problem that seeks a 0/1 solution which maximizes the one hop path traffic. For a given connectivity matrix, a routing problem is a multicommodity flow problem with the objective function that is a weighted sum of both criteria. A local search based on branch exchange and tabu strategy is used to explore different virtual topologies. Computational results presented in this paper include a benchmark network data set of size 14, with $p = 2, 3, 4$ transceivers per node. A 14-node network NSFNET is displayed in Figure 1.

The paper is organized as follows. The formulation of our problem is presented in Section 2, an outline of the tabu search algorithm is given in Section 3, and the computational results are presented in Section 4. Future research is indicated in Section 5.

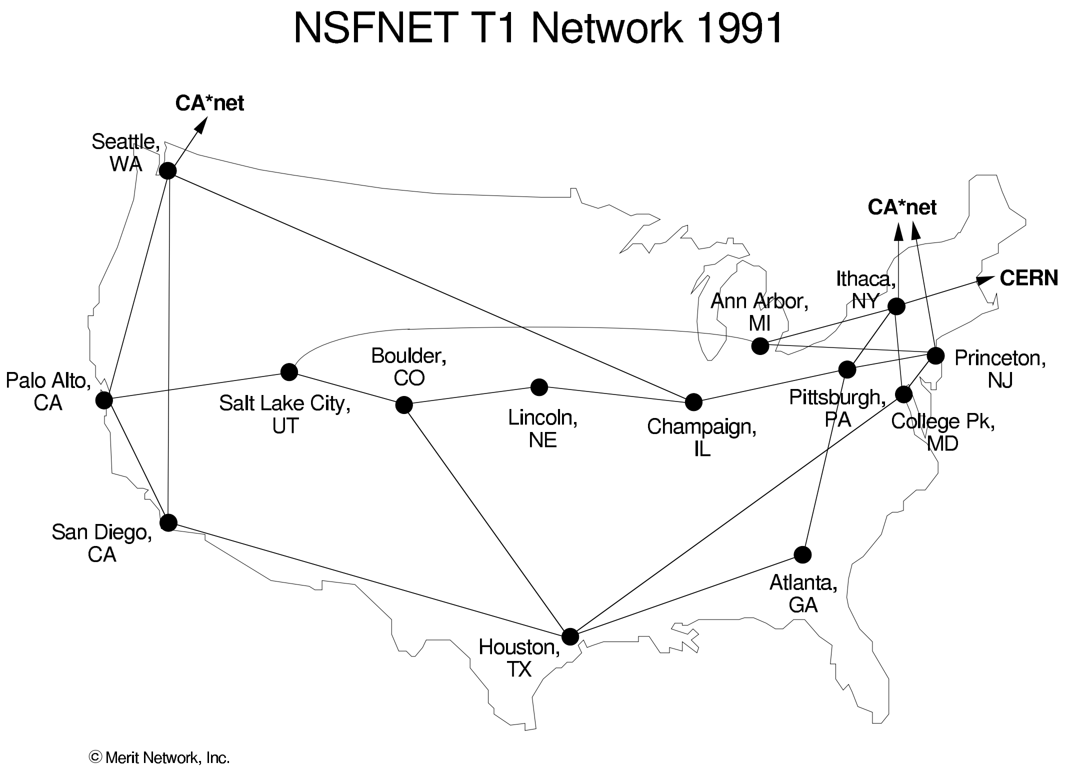

Fig. 1. NSFNET T1 Network.

2. Problem Formulation

Our formulation is a modification of the minimal congestion problem entitled The Flow and Wavelength Assignment (FWA) problem, previously considered in a number of studies including [Labourdette and Acampora, 1991], [Yener and Boult, 1994], [Bienstock and Günlük, 1995], and [Skorin-Kapov and Labourdette, 1995].

The input $N \times N$ traffic matrix T_{st} presents the traffic flow from source s to destination t, while d_{st} represents the distance (in miles) between nodes s and t. For any node, the number of transmitters and receivers is set to p, and the capacity of every link equals C. (For simplicity, the capacities of all channels are assumed to be equal and large enough, so that the feasible solution exists.) The variables include $\{0, 1\}$ variables z_{ij} indicating whether or not a link (i, j) is used in the network, and continuous variables f_{kij} indicating the amount of flow originating at source k, sent through the link (i, j). Our objective is congestion minimization, as well as minimization of the total delay when sending the flow through the network.

The problem is formulated as follows:

$$\min \quad \omega_F F + \omega_D D$$

s.t.

$$\sum_{k,i,j} f_{kij} d_{ij} \le D \tag{1}$$

$$\sum_{k} f_{kij} \le F \quad \text{for all } i, j, i \ne j \tag{2}$$

$$\sum_{k} f_{kij} \le C z_{ij} \quad \text{for all } i, j, i \ne j \tag{3}$$

$$\sum_{i \ne j} f_{kij} - \sum_{i \ne j} f_{kji} = T_{kj} \quad \text{for all } k, j, k \ne j \tag{4}$$

$$\sum_{j \ne i} z_{ij} = p, \quad \text{for all } i \tag{5}$$

$$\sum_{j \ne i} z_{ji} = p, \quad \text{for all } i \tag{6}$$

$$0 \le f_{kij}, \quad z_{ij} \in \{0, 1\}, \text{ for all } k, \ i, \ j, \ i \ne j$$

The equation (1) models minimization of the total network delay using ω_D as the weight in the objective function. The equation (2) models minimization of maximal flow on any link (i.e. congestion) with weight (ω_F) in the objective function. The equation (3) enforces the capacity constraints on links, (4) are conservation of flow constraints, and (5, 6) are assignment type constraints assuring p transmitters and receivers on any node.

In order to get a starting topology, we first solve a *linear assignment problem* maximizing the one hop path traffic (see [Skorin-Kapov and Labourdette, 1995]):

$$\max \quad \sum_{ij} T_{ij} z_{ij}$$

s.t.

$$\sum_{j \ne i} z_{ij} = p, \quad \text{for all } i \tag{7}$$

$$\sum_{j \ne i} z_{ji} = p, \quad \text{for all } i \tag{8}$$

$$0 \le z_{ij} \le 1 \ \text{ for all } i, \ j, \ i \ne j.$$

Sometimes it might be desirable to start with a connectivity matrix known to be good from previous search. In that case we can proceed directly to the routing part of the problem. Namely, the values of the connectivity matrix, $\bar{z}_{ij}$, are used in the formulation of the routing multi-commodity flow problem:

$$\min \quad \omega_F F + \omega_D D$$

s.t.

$$\sum_{k,i,j} f_{kij} d_{ij} \le D \tag{9}$$

$$\sum_{k} f_{kij} \le \bar{z}_{ij} F \quad \text{for all } i, j, i \ne j \tag{10}$$

$$\sum_{i \ne j} f_{kij} - \sum_{i \ne j} f_{kji} = T_{kj} \quad \text{for all } k, j, k \ne j \tag{11}$$

$$0 \le f_{kij}, \quad \text{for all } k, \ i, \ j, \ i \ne j$$

Further improvements in solution quality are obtained via a tabu search heuristic strategy. In this paper we follow the tabu search strategy presented in [Skorin-Kapov and Labourdette, 1995].

3. Tabu Search Heuristic Strategy

Our solution is presented as *(con, rout, F, D)*, where *con* denotes a connectivity matrix, *rout* is the corresponding matrix of flow values, F is the maximal flow value, and D is the total network delay. In order to employ a tabu search heuristic strategy, we need to define a neighborhood of a current solution and ways to evaluate it. For our problem, a neighbor of the current solution *(con, rout, F,D)* is the feasible solution obtained by performing a branch-exchange (BE) operation, and by re-solving the routing problem. Hence, two neighboring connectivity topologies will differ in two branches and the corresponding routing which can be modified throughout the whole network. Due to the combinatorial nature of the connectivity part of the problem, evaluation of the complete neighborhood is computationally intractable. This is the reason behind the restriction to evaluate only a subset of branch exchanges. We elect to evaluate branch exchanges on K least utilized links which will, nonetheless, preserve network connectivity. An iteration of the search is completed when the $K-$neighborhood of a current solution is evaluated, and the non-tabu neighboring solution with the smallest objective value is identified and performed. The tabu list is implemented as an $N \times N$ matrix whose (i, j) entry denotes the iteration at which the link (i, j) is no longer tabu. We start with the matrix of 0's, i.e. all links can be exchanged at first iteration. If at iteration I the old links (i, j) and (k, l) are replaced by the new links (i, l) and (k, j), then, in order to forbid reversal of this branch exchange for the *tabu_size* number of iterations, we update the matrix as follows: *tabu_list* (i, j) = I+*tabu_size*; *tabu_list* (k, l) = I+*tabu_size*. The tabu status of a link is inactive only if the branch exchange including this link leads to a solution better than the best found previously.

Tabu search was enhanced by a diversification strategy employed via a *long term memory* (LTM) function that constructs new initial solutions significantly different from previously visited solutions. The diversification was achieved by modifying the original “flow" entries, but at the same time this strategy had elements of intensification as well, since modifications were geared towards promising solutions (as encountered on the search trajectory). In addition, the tabu search strategy was further enhanced via repeated runs starting with good quality connectivity matrices from previous search.

4. Computational Results

The tabu search algorithm was coded in C, and the routing subproblems were solved using Cplex 7.0 callable library from [ILOG, 2000]. The computational experiments were performed on a PC. The benchmark data set used is the 14-dimensional matrix from [Mukherjee et al., 1996] with $p = 2, 3, 4$ transceivers. This data consists of bytes/sec and is an actual measurement of the traffic on the T1 NSFNET backbone for a 15-minute period (11:45pm to midnight) on January 12, 1993.

We start with the 100% weight given to congestion minimization and 0% weight given to minimization of total delay. The consecutive weights were modified in decrements (resp., increments) of 10% for congestion (resp., total delay). During the first tabu search run, the best connectivity matrix from the previous step was used as a starting solution in the next step. The best connectivity matrix for each pair of weights was saved. The interesting finding revealed that a small number of connectivity matrices repeatedly proved best over a large range of weight pairs. This motivated the second tabu search run, re-started with the connectivity matrix that appeared to be the best in majority of the cases. The results are presented in Table 1. Parameters of tabu search are as follows: K=8, Tabu-size=4, Max-iterations=30, LTM-restart=4. Variable tabu-size with $\delta = [1,4]$ was also applied according to the strategy presented in [Skorin-Kapov and Labourdette, 1995].

Results from Table 1 reveal the following. As the weight for congestion minimization weakens from $\omega_F = 1$ towards $\omega_F = 0$, the congestion *increases* showing some significant jumps. At the same time, as the weight for total delay increases from $\omega_D = 0$ to $\omega_D = 1$, it is causing *decrease* in total delay. The decrease of delay includes less drastic jumps, and for $p = 4$ it is distributed more uniformly. (The increase,

weights		p=2		p=3		p=4	
ω_F	ω_D	% Congestion increase	% Delay decrease	% Congestion increase	% Delay decrease	% Congestion increase	% Delay decrease
1.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
0.9	0.1	2.14	19.02	2.70	8.19	0.00	0.00
0.8	0.2	2.14	19.02	3.19	8.91	0.88	1.29
0.7	0.3	12.57	26.62	10.25	16.82	1.74	2.04
0.6	0.4	24.28	33.24	13.86	18.78	3.27	2.87
0.5	0.5	25.86	33.72	18.69	20.51	7.97	4.48
0.4	0.6	27.48	34.04	22.82	21.51	18.23	6.71
0.3	0.7	28.31	34.16	42.59	24.29	21.51	7.27
0.2	0.8	67.00	37.99	56.01	25.64	27.38	7.84
0.1	0.9	85.74	38.80	64.86	26.02	47.02	8.90
0.0	1.0	110.66	39.08	141.71	26.52	144.71	9.98

Table 1. Results for Infocom94 data set from [Mukherjee at al., 1996].

resp. decrease, is relative to the initial value for the pair $(\omega_F, \omega_D)=(1,0.)$)

The total percent increase in congestion is significantly bigger than the total percent decrease in total delay. The intuition is that the objective of minimizing the congestion allows for less flexibility in attaining it and, hence, forces solutions to change more significantly when its weight is changed. The network manager should decide how much congestion needs to be sacrificed in order to bring down the total network delay. Our analysis can identify points where more drastic changes take place, in turn helping the manager to make an economically justified decision.

5. Conclusions and Directions for Further Research

This paper presents our approach towards designing optical networks with desirable properties regarding congestion minimization as well as total delay minimization. Our future work will emphasize improvements in the basic tabu search strategy employed in order to identify efficient virtual topologies. Furthermore, we will investigate congestion versus delay for networks with regular underlying topologies. Relevant work was done by [Skorin-Kapov and Labourdette, 1996, 1998].

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Received: June, 2001
Accepted: September, 2001

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