On Management of Optical Networks: Utilization versus Cost

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As telecommunications go through an unprecedented growth due to consumers' demands for high bandwidth applications such as video-on-demand, digital home applications, and transfer of data-rich documents, new issues and challenges guide the management of telecommunication networks. Despite the allure of wireless networking, fiber-based networks present the choice for high-speed transferring of data over longer distances. The two conflicting criteria, maximizing utilization and minimizing cost, should be jointly taken into account when designing and managing such networks. We present a framework for an optimization approach based on formal mathematical modeling. A model can be used to provide guidelines for network administrators when deciding on the appropriate weight given to each of the two conflicting criteria. The approach is tested on a benchmark data set.

INTRODUCTION

Today's requirements for telecommunications involving high bandwidth necessitate the use of optical fiber as a physical medium and lead to proliferation of optical networks, both opaque and transparent. The proliferation of web applications and the technological capabilities of huge data transfer create the main trends in telecommunications: (1) increased demand for high bandwidth, (2) increased demand for speed, and (3) decreased equipment cost. These trends lead to the issues of security, utilization, and cost effectiveness. Despite a surge in wireless communication, optical networks are still indispensable as a fast and reliable medium for transferring high volume sensitive data. Due to the nature of optical fibers, data transfer is more secure than in a wireless environment prone to ears-dropping. However, optical networks are certainly vulnerable, either with respect to a failure (equipment malfunctioning) or to an attack generated purposely. Regarding utilization, the issue is how to make efficient use of the huge data transfer capacity. Current technology allows transmission with up to 160 wavelengths per fiber, and packing of more than 800 fibers in one cable. Each wavelength can carry up to 10 - 40 Gbps of data. (Bandwidth adopting fiber to the home (FTTH) strategy is designed to deliver the 100 Mbit/s capability. A comprehensive overview of optical access networks and FTTH is provided by Lin(2006).) When there are many different requests for transmission over a certain channel, it becomes mandatory to group together low-speed requests, for example using the time-division multiplexing scheme, in order to better utilize the high-speed channel. This gives rise to the challenge of traffic grooming and many researchers are trying to devise efficient schemes for it.

Hence, due to their high capacity, speed and better privacy protection, optical networks are aggressively replacing the older copper-wired networks. In addition, optical networks are inherently scalable since optical infrastructure supports technological developments and additional bandwidth can be obtained with better node equipment, without necessitating additional physical fiber cables. In telecommunications there is distinction between the so-called transport network, and the access network. The transport (or core, or backbone) network is used for transferring data over longer distances, and for transporting amalgamated traffic originated from various customers. The earliest usage of fiber cables and optical technology was in the domain of transport networks, while the access network (leading to end customers) was still implemented via copper wires. However, the catchword nowadays is FTTH, or Fiber-To-The-Home, the trend to bring possibilities of huge bandwidth to the end user by providing optical access networks.

When presenting taxonomy of optical networks, we can distinguish between opaque and transparent (all-optical) networks, between broadcast-and-select and wavelength routed networks, and between regular topologies and arbitrary topologies. Opaque networks require electric-optical conversions along the transfer path and present earlier generations of optical networking. The electric-optical conversion allows better data monitoring but slows down the transfer. With improved optical components such as optical add/drop multiplexers, converters, and amplifiers, the transfer speed was highly improved by designing all-optical (transparent) networks. In such networks the electric-optical conversion is restricted to the incoming signal, while the opposite optic-electronic conversion occurs only when the signal reaches its destination; the path in between is entirely optical. The challenge is to locate optical components efficiently so that the cost is minimized and, yet, the required routing and the quality of the transferred signals is maintained. Skorin-Kapov, Skorin-Kapov and Boljunčić (2006) provide a survey of various location problems occurring in the design of optical networks.

Broadcast-and-select networks based on a passive star coupler allow any two nodes to communicate and are well suited for shorter distances, while wavelength routed networks support bypassing some of the nodes in reaching a destination. They are better suited for long-haul and wide area networks. With respect to the topology of connections in an optical network, there are regular or arbitrary topologies. The current trend is the usage of mesh topologies since they are more scalable.

DESIGN CHARACTERISTICS AND NETWORK CONFIGURATION

Let us now present some relevant design characteristics of optical networking. The physical network consists of fiber links through which data is sent as light in the form of electro-magnetic waves. The waves can have different wavelenghts (a distance between repeating wave patterns) and data sent over different wavelengths will not interfere with one another. Sending many different wavelengths over a single fiber increases the capacity (the bandwidth) of this fiber link. This is possible with the wavelength-division-multiplexing (WDM) technology. It was first presented in 1970, combining two waves; nowadays up to 160 different wavelengths can be sent over a single fiber link.

If the network nodes are equipped with re-tunable transmitters (lasers) and re-tunable receivers (filters), then a virtual topology consisting of established node-to-node lightpaths can be superimposed on the physical topology. Further, a possibility for reconfiguration by re-tuning node transmitters and receivers to different wavelengths adds to usefulness and economic benefits of optical networks. It 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 patterns.

Depending of input traffic flow, an optical network can be optimized by taking into account different criteria, such as throughput, cost or delay. The work presented in this paper deals with joint consideration of network utilization and network cost.

With respect to utilization, we would like to maximize throughput so that network resources are utilized as fully as possible. Throughput maximization leads to congestion minimization, and this can be achieved by trying to balance the usage of network links and prevent bottlenecks. The Theory of Constraints (TOC) is a well-known operations management technique designed to manage capacity, utilization and performance in order to avoid bottlenecks (Krajewski, Ritzman and Malhotra, 2007). Regarding congestion, it makes sense to minimize the maximal congestion on a link because that increases network scalability and robustness regarding possible bottlenecks. A simple way to avoid such bottlenecks is to minimize the maximal load on a network link. In our model, minimization of a maximal traffic flow on any network link will be one of the criteria for optimization.

Obviously, in the process of minimizing the maximal congestion the traffic will be re-routed, in turn using longer paths, contributing to higher overall usage of network resources. This brings us to the issue of network cost. Assessing network cost is a complex issue since there are many different components of costs: the fixed cost of design and buildup of a network, and a variable cost of managing the traffic sent over the network. It is not our current intension to provide a detailed study of network cost, including a fair cost allocation scheme for establishing appropriate users' rates. Instead, we propose a framework for comparing network utilization versus cost. For that reason, it seems appropriate to provide a certain estimation of network cost, say per unit of distance of existing physical fiber cables. For longer distances there will be a need to include amplifiers and repeaters to maintain the quality of the signal, and this certainly adds to the overall cost of the network. Sending data over longer routes and re-routing it more frequently incurs additional cost. Hence, for the purposes of our model framework, it seems appropriate to implement the minimization of network cost by minimizing the weighed total flow on the network. The weights given to the amalgamated traffic on a network link will be proportional to the length of such a link, i.e. to the physical distance between its end-points. The minimization of total weighted network flow will be the other criteria of optimization in our model. We next proceed with the description of our framework for managing optical networks.

NETWORK DESCRIPTION

Let us assume that there are N nodes in the network connected via fiber links. Each fiber supports up to W wavelengths (channels) by using the Wavelength Division Multiplexing (WDM) technique. Also, each node i has T_i available transmitters and R_i available receivers. The physical topology consisting of available fiber cables is described by the NxN matrix P where $P(m,n) = 1$ if there is a physical link between nodes m and n, and $P(m,n) = 0$ otherwise. The cost of a physical link (m,n) is proportional with the distance of that link and it is denoted by $D(m,n)$. Let C denote the capacity of each channel. The traffic matrix consisting of connection requests is depicted as the NxN matrix Λ where $\Lambda(s,d)$ denotes the traffic sent from source s to the destination d. The matrix is non-symmetric, i.e. the traffic from s to d can be different from the traffic from d to s.

Using the above network parameters, our task is to create an efficient virtual topology by re-tuning transmitters and receivers of network nodes in order to create lightpaths through which traffic from all the sources can be sent to all the destinations. This gives rise to three different sub-problems. First, we need to establish a virtual topology described by the usable lightpaths connecting all source-destination pairs. Second, we need to route the required traffic over the lightpaths, making sure that channel capacity is taken into account. Third, we need to provide a physical embedding of the virtual topology by establishing the actual routes over the existing fiber links and making sure that no more than the available number of wavelengths on each fiber link is used. Finally, a feasible solution to this complex problem needs to be evaluated in light of our objective of minimizing the maximal flow on a link (corresponding to congestion) and the total weighted flow (corresponding to total network cost). To this end, we need to devise an algorithmic strategy for improvements of the initial feasible solution. This should result with some guidelines for a decision maker concerned with both utilization and cost of the network.

MODEL DESCRIPTION

In order to provide a mathematical formulation appropriate for the above network description, we need the following variables:

- v_{ij} , $i, j = 1,\ldots,N$ is a binary variable with the following values: $v_{ij} = 1$ if there is a lightpath (a virtual link) from node i to node j ; $v_{ij} = 0$ otherwise.
- $f_{s,ij}$, $s, i, j = 1,\ldots,N$ denotes the traffic from source s sent via the virtual link (i,j).
- $p_{mn,ij}$, $m, n, i, j = 1,\ldots N$ is a binary variable with the following values: $p_{mn,ij} = 1$ if the virtual link v_{ij} uses the physical link $P(m,n)$; $p_{mn,ij} = 0$ otherwise.
- F denotes the maximal traffic flow on a virtual link (corresponding to congestion)
- T denotes the total weighted traffic flow in the network (corresponding to total network cost)

Using the above variables, the objective function of joint minimization of congestion and cost, with different emphasis on each of the criteria, can be written as follows:

$$\text{Min} \quad \omega_F F + \omega_T T \qquad (1)$$

The weight given to congestion is ω_F and the weight given to cost is ω_T . The constraints defining the variables used in the objective function are:

$$\sum_{s} f_{s,ij} \le F, i \ne j \qquad (2)$$

$$\sum_{s,i,j} d(i,j) \times f_{s,ij} \le T \qquad (3), \text{ where}$$

$$d(i,j) = \sum_{m,n} D(m,n) \times p_{mn,ij}, i \ne j \qquad (4)$$

Constraint (2) assures that F denotes the maximal flow on any link. Constraint (3) establishes the total cost of network usage by multiplying traffic flows on virtual links by the costs of such links. Since the cost is assumed to be proportional with the physical length, we need equation (4) to define the cost of a virtual link as the sum of costs of the physical links used by the virtual link.

Next, constraints specifying the virtual topology are as follows:

$$\sum_{j} v_{ij} \le T_i \quad \forall i \qquad (5)$$

$$\sum_{i} v_{ij} \le R_j \quad \forall j \qquad (6)$$

Due to a limited number of transmitters and receivers at a node, constraint (5) assures that not more than T_i lightpaths originate at node i, while constraint (6) specifies that not more than R_j lightpaths end at node j.

The routing of traffic requests is modeled with the following constraints:

$$\sum_{i \ne l} (f_{s,il} - f_{s,li}) = \Lambda_{sl} \quad s \ne l \qquad (7)$$

$$\sum_{s} f_{s,ij} \le C \times v_{ij} \quad i \ne j \qquad (8)$$

Constraint (7) assures that the amount of traffic from source s staying at node l equals the traffic requirement Λ_{sl}. Constraint (8) allows sending traffic only through established virtual links, making sure that the capacity is taken into account. (For simplicity we assume equal capacities on all virtual links.)

Finally, the physical embedding of virtual topology requires the following constraints:

$$\sum_{i,j} p_{mn,ij} \le W \times P(m,n) \quad m \ne n \qquad (9)$$

$$\sum_{n} p_{in,ij} = v_{ij} \quad i \ne j \qquad (10)$$

$$\sum_{m} p_{mj,ij} = v_{ij} \quad i \ne j \qquad (11)$$

$$\sum_{m} p_{ml,ij} = \sum_{n} p_{\ln,ij} \quad l \ne i \ne j \qquad (12)$$

Constraints (9) make sure that virtual paths can use only existing physical links, and a physical link can accommodate not more than W lightpaths. Constraints (10)-(12) represent the so-called conservation of flow: if the virtual link v_{ij} has been established, then the path is constructed from node i to node j, possibly passing through intermediate nodes l.

The model (1) – (12) is quite general and it can be further specified by providing more accurate characterization of network cost, by incorporating different channel capacities, and by requiring that virtual paths can use only one wavelength along the whole path. This last consideration is known as the "wavelength continuity constraint" and it would significantly modify the formulation by adding a nonlinear constraint that at any physical link (*m,n*) employed by the lightpath (*i,j*) the same wavelength has to be used. Podnar and Skorin-Kapov (2002a, 2002b) considered such a model on arbitrary as well as regular topologies when the sole criterion was to minimize congestion. For the arbitrary topology they proposed an efficient heuristic algorithm based on genetic search and were able to improve the scalability of a benchmark data set consisting of 14 nodes in the NSFNET backbone network. (The same data set will be used in this study and it will be presented in the DATA section.)

Due to the cost factor in the objective function, the current model is also nonlinear, and the non-linearity is present when constraint (4) is substituted in constraint (3):

$$\sum_{s,i,j}(\sum_{m,n} D(m,n)\times p_{mn,ij})\times f_{s,ij} \leq T$$

However, due to declining cost of optical equipment, we can assume that each network node is equipped with a converter, allowing wavelength conversion. In that case the "wavelength continuity constraint" can be relaxed, and virtual paths can then be composed of virtual links between two nodes. We can redefine the virtual topology variables v_{ij} to equal 1 if the transmitter of node *i,* and the receiver of node *j,* are tuned to the same wavelength. The cost weight applicable to the variable $f_{s,ij}$, i.e. the length of the virtual link (*i,j*), can be approximated by the cost of the shortest physical path between nodes *i* and *j*. Of course, we need to allow that traffic from source to destination can pass many different links (the so-called multihop network). In addition, we allow that the traffic from a source to a destination can be split and can use different routes.

Now, considering wavelength conversion at each node allows effectively decomposing model (1) – (12) into two separate parts. First, we need to establish the virtual topology along constraints (5) and (6). Next, we need to route the traffic over virtual links in order to minimize the objective function. Then, using an effective heuristic strategy, we try to find improved virtual topology and its corresponding traffic. Upon reaching the best sub-optimal solution according to a stopping criterion of our algorithm, we can solve the physical embedding problem by using the shortest path algorithm. The number of times a certain physical link occurs in shortest paths will indicate the required number of channels (or wavelengths) used by that link. If the number is bigger than the prescribed number of available wavelengths, we would need to re-route the traffic on a somewhat longer path. However, due to current capacity of fiber links accommodating up to 160 wavelengths, and assuming that the number will increase in the future, we leave aside the physical embedding problem and concentrate on virtual topology design and traffic routing over virtual links.

In the earlier generation of optical networking, there was a need to perform optic-electronic and electronic-optical conversion when changing the wavelength. This type of conversion slowed the traffic. Current developments of optical technology allow all-optical wavelength conversion. A good reference for introduction to optical technology is Kolimbiris (2004). With technological improvements and declining equipment cost it becomes possible to use various optical node equipments (e.g. reconfigurable optical add/drop multiplexers, optical crossconnects) for designing transparent networks satisfying the ever-increasing demands for speed and bandwidth.

SOLUTION STRATEGY

The virtual topology and routing model (1)-(8) adapted to wavelength routed networks with converters was solved using the *tabu search* heuristic strategy. Tabu search is a meta-heuristic strategy proposed by Glover (1989, 1990) and used successfully in various business applications modeled via combinatorial optimization. In such applications we try to improve the initial solution by exploring the feasible space through appropriately defined neighborhood structure. Progressing from a solution to its neighbor in order to improve the objective function would stop when a locally optimal solution is encountered. Tabu search provides ways to continue the search even after encountering a local optimum. In the process, information regarding the search trajectory is kept and used in attempts to improve the search by intensifying it in promising regions of the search space, and by diversifying it to escape locality of the neighborhood.

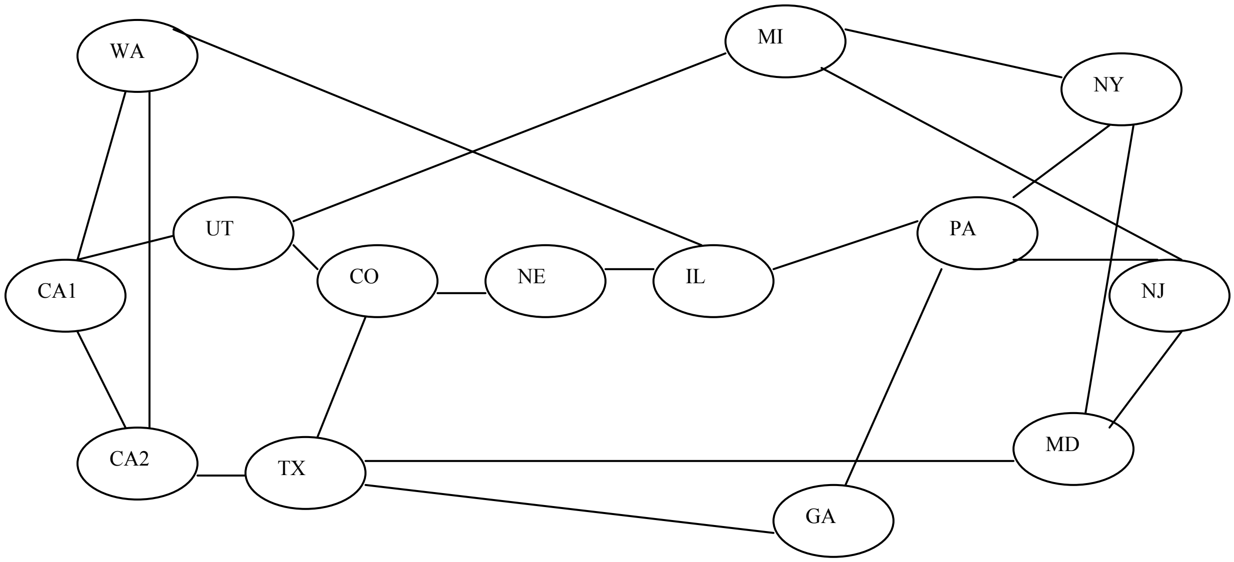
The earlier tabu search adaptations to the problem of wavelength assignment and routing in arbitrary as well as regular topologies include Skorin-Kapov and Labourdette (1995, 1997, 1996, 1998). In all their works Skorin-Kapov and Labourdette considered minimizing only the maximal flow on a link, regardless of network cost. Boljunčić, Skorin-Kapov and Skorin-Kapov (2001) developed a model for joint consideration of congestion and total delay. In a later study, Boljunčić, Skorin-Kapov and Skorin-Kapov (2004) improved on their heuristic strategy and considered minimizing both congestion and total network flow. In the present work we use their heuristic strategy in a model incorporating consideration of total network cost.

The outline of the algorithm is as follows. First, the virtual topology design problem is solved as a linear assignment problem by maximizing the one-hop traffic. Hence, we attempted to create the initial virtual topology by making adjacent those nodes that communicate the most. By fixing the 0/1 virtual topology variables v_{ij}, we can then solve the routing problem and get the continuous $f_{s,ij}$ variables by optimally solving the routing multi-commodity flow problem with the objective function as given by (1). For technical details of the algorithm we refer to Boljunčić et al. (2001, 2004). The algorithm was run with consecutive set of weights, starting with 100% weight given to congestion minimization (i.e. without taking into account the total network cost), then in 10% increments reducing the weight for congestion and increasing the weight for cost, until the 100% weight was given to cost minimization. The task was to see whether there are pairs of weights that would lead to good decision-making. Namely, we wanted to discourage using pairs of weights for considering congestion and cost such that decrease in cost brings a disproportionate increase in congestion. That would slow the efficiency of the network and might result with loss of customer goodwill, translating into tangible losses. Those pairs of weights should be avoided, and the most promising strategy appears to be the one whereby we minimize the network cost, but not regardless of congestion.

DATA AND DISCUSSION OF COMPUTATIONAL RESULTS

The proposed model is illustrated on a benchmark data set, used in previous studies. The physical topology consists of 14 US cities comprising the NSFNET backbone network and is represented in Figure 1.

FIGURE 1
NSFNET NETWORK COMPOSING THE PHYSICAL TOPOLOGY *P(m,n)*



The traffic matrix used is a widely used benchmark traffic matrix (Mukherjee et al., 1996) and is here reprinted for completeness in Table 1.

TABLE 1
THE NSFNET TRAFFIC MATRIX *Λ(s,d)* AND THE SYMMETRIC COST MATRIX *D(s,d)* PROPORTIONAL WITH DISTANCES

Flow (cost)	WA	CA1	CA2	UT	CO	TX	NE	IL	PA	GA	MI	NY	NJ	MD
WA	5.30 (0)	26.82 (8.35)	11.70 (12.55)	2.71 (8.40)	19.65 (13.23)	0.87 (23.65)	5.38 (16.80)	24.90 (21.15)	3.42 (25.24)	1.85 (26.71)	31.17 (23.04)	9.67 (27.37)	4.41 (28.55)	19.14 (27.62)
CA1	71.91	3.90 (0)	61.00 (4.76)	30.12 (7.63)	58.63 (12.95)	26.17 (19.01)	39.87 (16.51)	154.97 (21.86)	11.44 (26.12)	21.41 (24.54)	79.93 (23.91)	103.13 (28.25)	55.24 (29.43)	77.58 (28.50)
CA2	10.91	47.56	0.03 (0)	46.61 (7.49)	8.50 (10.89)	36.37 (14.68)	8.65 (15.61)	85.67 (20.29)	10.03 (24.52)	4.62 (21.40)	51.63 (23.01)	6.20 (27.35)	13.91 (27.68)	21.57 (26.75)
UT	7.01	6.20	13.64	0 (0)	1.90 (5.24)	0.60 (14.81)	0.70 (8.81)	2.88 (14.17)	2.00 (18.42)	3.26 (18.73)	13.11 (16.21)	12.15 (20.55)	2.39 (21.73)	6.97 (20.80)
CO	122.77	159.99	19.02	3.43	0.35 (0)	4.03 (10.61)	10.77 (4.92)	62.22 (10.27)	24.02 (14.53)	17.92 (14.25)	72.10 (12.32)	118.56 (16.66)	13.18 (17.82)	21.75 (16.88)
TX	1.84	16.53	3.42	5.52	3.40	0 (0)	2.61 (8.77)	2.68 (9.57)	0.87 (13.39)	3.87 (7.92)	6.05 (12.59)	4.82 (16.24)	1.54 (15.88)	6.95 (14.21)
NE	37.00	62.00	102.31	4.47	22.03	7.90	0 (0)	114.17 (5.39)	19.82 (9.65)	21.95 (9.93)	154.02 (7.43)	93.32 (11.78)	23.66 (12.96)	163.87 (12.02)
IL	14.95	234.54	210.34	8.52	28.21	2.66	97.08	0.31 (0)	43.95 (4.81)	33.00 (6.22)	90.05 (3.42)	71.15 (7.62)	20.20 (7.97)	88.90 (7.04)
PA	84.93	19.94	37.35	6.00	24.99	6.81	25.06	61.02	0 (0)	39.62 (6.86)	110.68 (2.84)	147.61 (3.11)	45.67 (3.37)	63.13 (2.43)
GA	1.86	41.92	10.26	3.73	22.34	9.48	4.98	57.08	6.84	0.14 (0)	36.32 (6.99)	26.17 (9.19)	12.69 (8.17)	14.36 (6.46)
MI	11.16	37.61	58.29	5.06	9.44	12.99	18.79	37.89	20.47	25.12	45.49 (0)	59.67 (4.51)	32.27 (6.14)	37.19 (5.21)
NY	31.22	131.83	19.87	14.62	42.99	7.15	17.32	57.32	39.60	29.42	211.63	74.24 (0)	27.99 (2.21)	65.97 (3.40)
NJ	39.37	55.34	18.60	7.53	8.41	0.85	4.49	24.39	117.68	35.69	69.17	79.21	7.06 (0)	52.19 (1.72)
MD	81.90	227.00	54.28	22.96	89.27	31.82	32.70	91.85	30.60	1.66	129.69	137.59	62.74	121.623 (0)

It represents the traffic on the NSFNET backbone for a 15-minute period on January 12, 1993.We also include the cost matrix used, which is proportional to distances among the included US sites. We tested the network with the same number of transmitters and receivers for each node. Hence, we used $p = T_i = R_i$ for every i, and set this value to 2,3, and 4. The current technology supports much larger number of transmitters and receivers per node, but we wanted to use a number of transceivers appropriate for the network size of our data set. Larger values of p would result with a less constrained network regarding the congestion and one of our tasks was to evaluate network cost and performance with increasing number of transceivers per node.

Since we wanted to test different weights given to minimization of congestion and network cost, we started with 100% weight given to minimizing congestion, and 0% weight given to cost minimization; hence cost minimization was not taken into account. Then, we decreased the weight for congestion and increased the weight for cost in increments of 10%, until we reached 100% weight given to cost, while completely disregarding congestion. For each set of weight pairs we run a tabu search algorithm resulting with a sub-optimal virtual topology and the corresponding flow variables, i.e. we solved the problem described by formulation (1)-(8).

In Table 2 we display the ratio $\frac{Cost}{Congestion}$ for all the weight pairs and the three values of p. By plotting the results in Figure 2 we wanted to observe whether there are sudden drops in this value. Sudden drops might indicate that congestion increases disproportionately with respect to cost. The points where this occurs indicate weighting ratios that put too much emphasis on cost, resulting with substantially increased congestion. Not surprisingly, with p=2 transceivers congestion jumps even when smaller weights are given to cost minimization (20%), while with more transceivers there are more paths possible for transferring data. Hence congestion is less volatile and the decision maker can push for higher consideration of network cost.

In order to evaluate the results further, for each value of p we graphed the % of congestion increase and the relevant % of cost decrease as we progressed in our weighting scheme of 1.0-0.0 (indicating 100% weight for congestion minimization and 0% weight for cost minimization) towards 0.0-1.0 (indicating 0% weight for congestion minimization and 100% weight for cost minimization). The results are displayed in Figure 3 a,b,c. It is clear that the line indicating "% of congestion increase" dominates the line indicating "% of cost decrease" earlier in the weighting scheme for p=2, followed by p=3, and finally p=4. This is a consequence of having more freedom to route the traffic when there are more transceivers. With more transceivers per node we can more easily keep congestion under control.

To get yet a different view of the results, we graphed the ratio between "% Cost increase" and "% Congestion increase". For weight pair "1.0-0.0" (i.e. ω_F=1, ω_T=0) we do not have "congestion increase", and for weight pair "0.0-1.0" there is no "Cost increase". Hence, we plotted only values for the remaining pairs. When the ratio of "% Cost increase" divided with "% Congestion increase" is close to 0, it implies that the denominator dominates the numerator, i.e. there is much bigger percent of congestion increase relative to the corresponding percent of cost increase. For the data used, it appears that in all three networks the proper consideration of weights could be about 80 % towards minimizing congestion and 20% towards minimizing cost. However, larger values of p result with more routing flexibility and make congestion less volatile, i.e. they make throughput more robust. This is evident for p = 4 where the ratio between "% Cost increase" and "% Congestion increase" approaches zero for the "0.4-0.6" pair of weights. Hence, we can push more aggressively for cost minimization, without significantly increasing congestion.

TABLE 2
THE RATIO BETWEEN COST AND CONGESTION FOR DIFFERENT WEIGHT PAIRS AND DIFFERENT p VALUES

Cost / Congestion Weights	p=2	p=3	p=4
1.0 - 0.0	287.21	403.57	436.71
0.9 - 0.1	227.71	360.78	436.71
0.8 - 0.2	227.70	356.25	427.29
0.7 - 0.3	187.22	304.46	420.45
0.6 - 0.4	154.28	287.87	410.75
0.5 - 0.5	151.26	270.28	386.37
0.4 - 0.6	148.60	257.91	344.59
0.3 - 0.7	147.38	214.27	333.28
0.2 - 0.8	106.65	192.35	315.96
0.1 - 0.9	94.64	181.09	270.59
0.0 - 1.0	83.06	122.69	160.65

FIGURE 2
RATIOS BETWEEN COST AND CONGESTION FOR DIFFERENT VALUES OF p

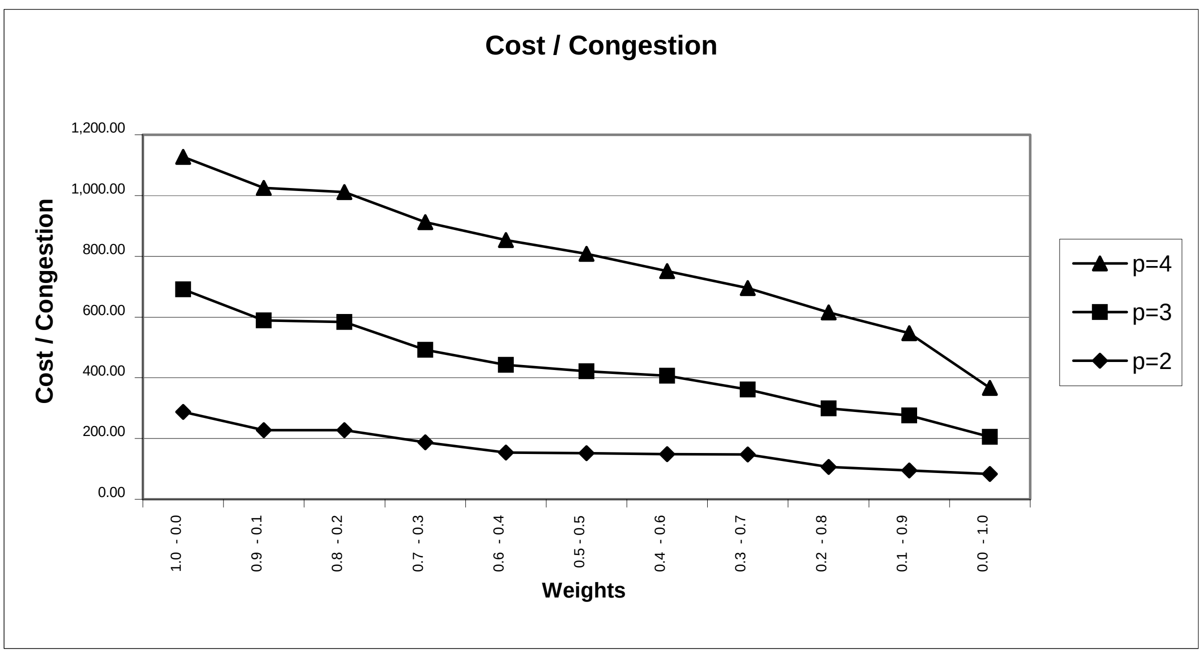
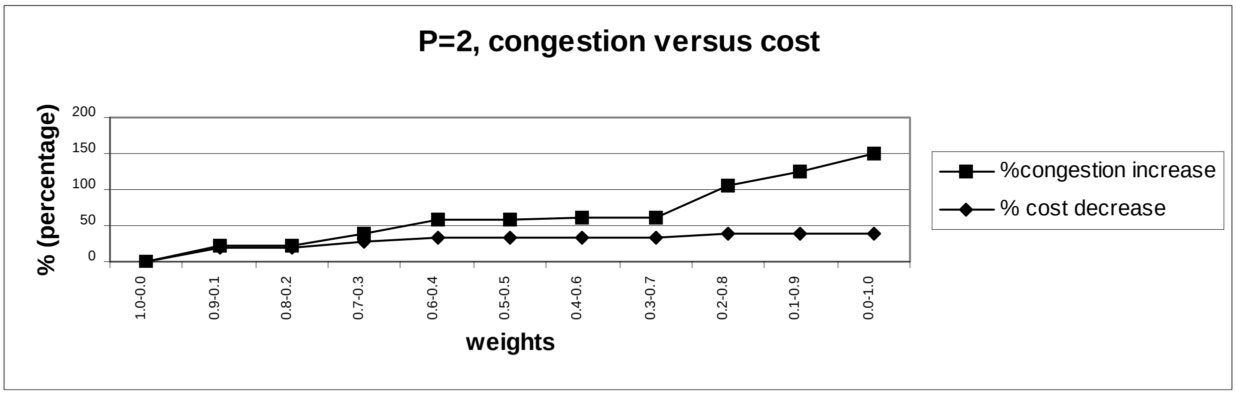
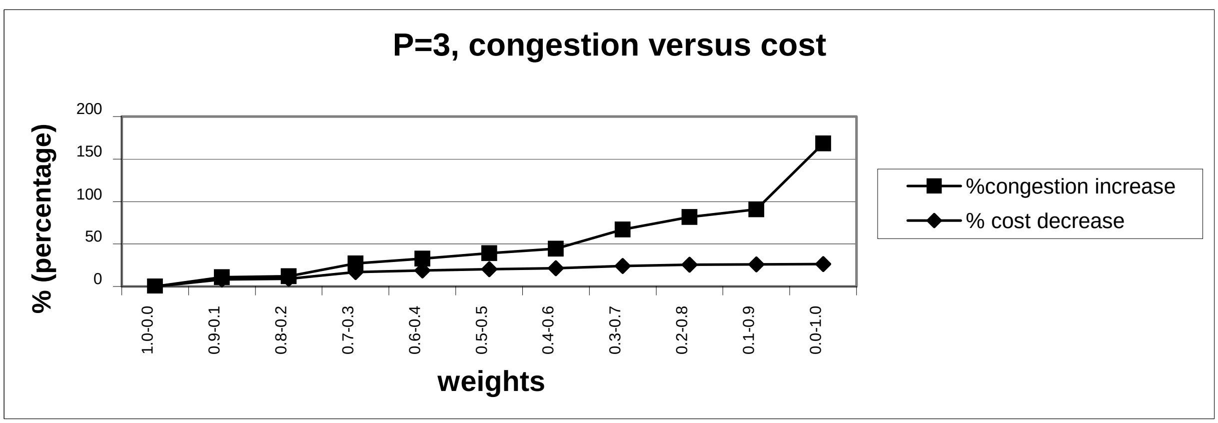


FIGURE 3
IMPACTS OF THE WEIGHTING SCHEME TO THE PERCENTAGE OF CONGESTION INCREASE AND THE PERCENTAGE OF COST DECREASE: a) p=2; b) p=3; c) p=4

a)



b)



c)

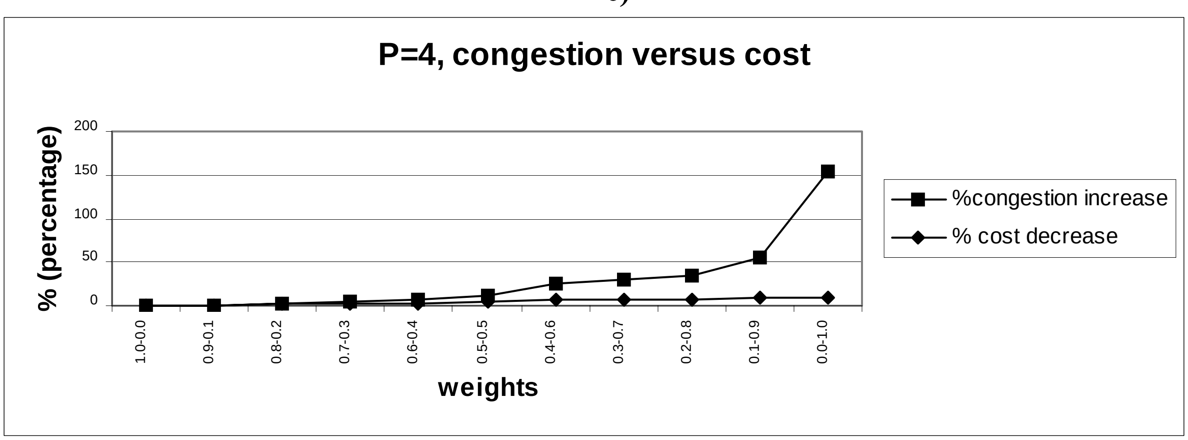
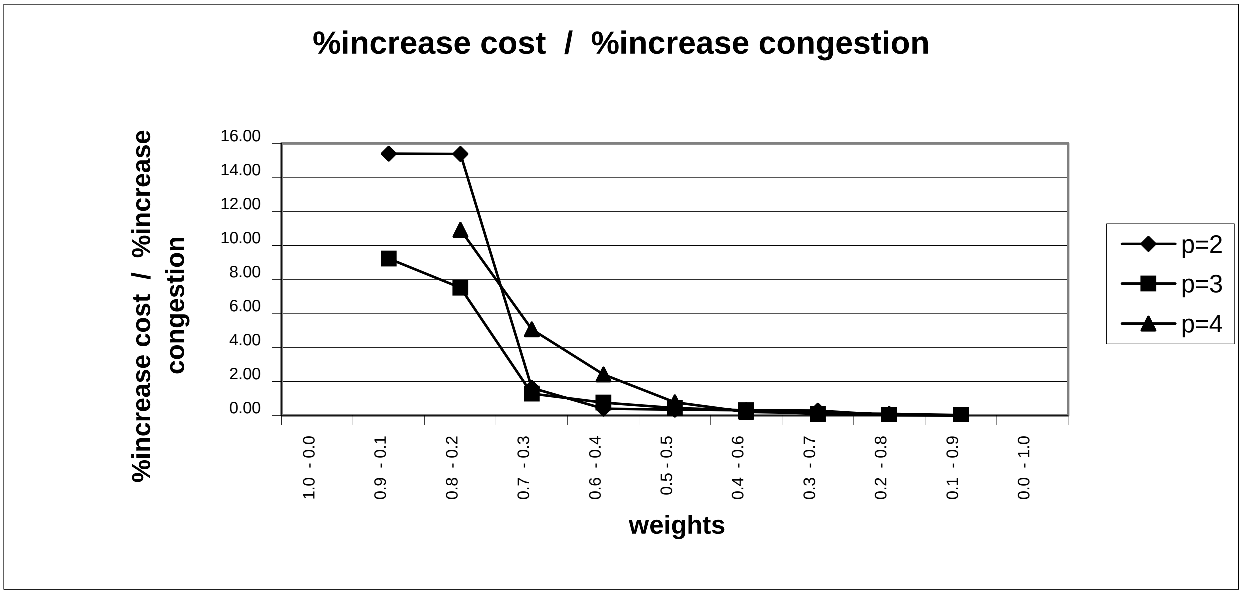


FIGURE 4
THE RATIOS OF "THE PERCENTAGE COST INCREASE" VERSUS "THE PERCENTAGE CONGESTION INCREASE" FOR p=2,3,4



CONCLUSIONS

We presented a framework for joint consideration of network cost and congestion in management of optical networking. Due to the complexity of the environment and due to the aggressive technological developments of optical components, our model provides a simplified scheme for considering costs and utilization. Certainly, more elaborate models are needed and could be developed by building on the existing ones. We attempted to provide some insight into the conflicting nature of minimizing congestion (or, equivalently, maximizing throughput) and minimizing network cost assumed to be proportional with physical network distances. A tabu search heuristic strategy was applied to a benchmark data set and the results are displayed graphically. The results suggest that forcing minimization of total network cost unconditionally can result with significantly inferior throughput. Some decisions strategies are outlined.

REFERENCES

Boljunčić, V., D. Skorin-Kapov, J. Skorin-Kapov (2004). A Tabu search Approach Towards Congestion and Total Flow Minimization in Optical Networks. Journal of Systems Science and Systems Engineering, *Vol.13(2)*, 180-201.

Boljunčić, V., D. Skorin-Kapov and J. Skorin-Kapov. (2001). On Delay versus Congestion in Designing Rearrangeable Multihop Lightwave Networks. Journal of Computing and Information Technology, *Vol. 9(3)*, 213-218.

Glover, F. (1989). Tabu Search: Part I, ORSA Journal on Computing, *Vol.1, No.3*, 190-206.

Glover, F. (1990). Tabu Search: Part II, ORSA Journal on Computing*, Vol.2, No.1*, 4-32.

Kolimbiris, H. (2004). Fiber Optics Communication. Upper Saddle River: Pearson Prentice Hall.

Krajewski, L., L. Ritzman and M. Malhotra. (2007). Operations Management: Processes and Value Chains. Upper Saddle River: Pearson Prentice Hall.

Lin, C. (2006). Broadband: Optical Access Networks and Fiber-to-the-Home, Chichester: John Wiley & Sons Ltd.

Mukherjee, B., S. Rammamurthy, D.Banerjee and A. Mukherje. (1996). Some Principles for Designing a Wide-Area WDM Optical Network. IEEE/CM Transcations on Networking*, Vol. 4, No. 5*, 684-696.

Podnar H. and J. Skorin-Kapov. (2002a). An Application of a Genetic Algorithm for Throughput Optimization in Non-broadcast WDM Optical Networks with Regular Topologies. Mathematical Communications *Vol. 7*, 45-59.

Podnar H. and J. Skorin-Kapov. (2002b). A Genetic Algorithm for Optimizing Throughput in Non-Broadcast WDM Optical Networks. Hybrid Information Systems (Eds. A. Abraham and M. Koeppen)*, Physica Verlag, Heidelberg,* 323-338.

Skorin-Kapov, D., J. Skorin-Kapov and V. Boljunčić (2006). Location Problems in Telecommunications. *Handbook* of Optimization in Telecommunications*, Chapter 20*, 518-544 (ed. P.M. Pardalos and M.G.C. Resende), Springer.

Skorin-Kapov, J. and J.-F. Labourdette. (1998). On Minimum Congestion Routing in Broadcast Optical Networks with Regular and Arbitrary Topologies. DIMACS Series in Discrete Mathematics and Theoretical Computer Science*, Vol. 46*, 143-155.

Skorin-Kapov, J. and J.-F. Labourdette (1997). Rearrangeable Multihop Lightwave Networks: Congestion Minimization on Regular Topologies. Telecommunication Systems *Vol. 9*, 113-132.

Skorin-Kapov, J. and J.-F. Labourdette (1996). On Throughput Optimization in Optical Networks With Regular and Arbitrary Topologies. Journal of Computing and Information Technology*, Vol. 5(4)*, 219-230.

Skorin-Kapov, J. and J.-F. Labourdette (1995). On Minimum Congestion Routing in Logically Rearrangeable Multihop Lightwave Networks. Journal of Heuristics*, Vol.1(1)*, 129-145.