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AN EFFICIENT HEURISTIC FOR TRAFFIC GROOMING AND LIGHT-PATH ROUTING IN WDM RING NETWORKS WITH HOP-COUNT CONSTRAINT

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Abstract This paper deals with a traffic grooming and light-path routing problem in WDM-ring networks, where the number of light-paths to be used for each traffic demand is restricted. With a network augmentation by adding a dummy node and a set of dummy arcs, we formulate the comprehensive problem as a mixed Integer Programming problem. Owing to the computational complexity, it is hard to find an optimal solution for a large-scale network within a reasonable computation time. Hence, we develop a heuristic algorithm to solve it with easy. Our heuristic generates good feasible solutions within a few second in computation time even for large-scale networks. The computational experiments show that the performance of the proposed heuristic is satisfactory in both the speed and the quality of the solutions generated.

Keywords: Telecommunication, traffic grooming, light-path routing, WDM-ring network, heuristic

1. Introduction

As a result of technological advancements in computing and communication systems, it is possible to provide a lot of broadband applications with high-speed network operation. In such networks, the optical fiber and an advanced optical transmission technology are required to transport a traffic at a high speed. The recent emergence of Wavelength Division Multiplexing (WDM) technology has resulted in the ability to transport a high speed traffic on a single fiber pair. The use of WDM allows aggregation of many wavelengths being used to transport light-paths onto a single fiber. The number of wavelengths multiplexed onto a single fiber plays a major role and currently varies between 4 and 32, but is expected to increase up to 100 ([12]). Since each wavelength has a capability of transmitting at *Gbps*, the total transmission capacity of a single fiber can be reached up to *Tbps*. This is the reason why WDM can be about to play a major role in the broadband networks.

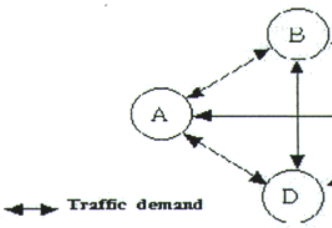
In WDM networks, given the traffic demand to be transported for each node pair, we should first decide a light-path to transmit the demand, and each light-path requires a wavelength to transport the optical signal. Since the equipment cost of WDM depends on the number of wavelengths, it is necessary to reduce the number of wavelengths to be used in the network. As WDM systems start being deployed in commercial contexts, the allocation of wavelengths to light-paths becomes of crucial importance to reduce the total network cost.

The problem of designing a WDM network has been considered in [2,13, 21]. Baroni and Bayvel [2] considered a problem defining the paths on which the traffic is routed and the number of fibers and channels for each link. Mukherjee [13] proposed a heuristic for embedding a hypercube logical topology with the objective of minimizing the average weighted propagation delay. Zhang and Acampora [21] proposed a heuristic based on sequentially assigning a single wavelength to all possible light-paths in order of decreasing traffic before proceeding to the next wavelength. For given a set of light-path demands, there are some studies to minimize the number of wavelengths [8, 13, 16, 21].

In recent years, there has been an increasing amount of research activity on the traffic grooming problem, which is how low-speed traffic streams are packed into higher-speed streams, and how wavelengths are used to carry the traffic ([12]). There is a significant advantage to groom the traffic ([10, 12]). If each demand requires a light-path exclusively, we need a lot of wavelengths to be allocated. Even though users have full wavelength connections to transport their traffic demand, it may be more economical to have sub-wavelength capacity connections. This can be accomplished through the use of multiplexing equipment aggregating low rate traffic on to a high rate channel. When the traffic demands are groomed on to light-paths which will be assigned wavelengths using their full capacities later, the number of light-paths becomes minimal in the network. Hence, a traffic grooming method can result in a significant reduction in the number of wavelengths, and a good grooming algorithm has the potential of minimizing network costs in terms of efficient use of wavelengths [10].

Due to the importance of the traffic grooming, several researches have been reported in the literature [4, 5, 6, 9, 18, 20, 22]. Simmons *et.al.* [18] considered traffic grooming for a bi-directional ring with uniform traffic. Wang *et.al.* [20], for given traffic matrix and a set of pre-defined circles needed to accommodate all the traffic, formulated the traffic grooming problem as a mixed Integer Programming model, and developed a simulated annealing based heuristic. Gerstel *et.al.* [6] proposed a cost-effective traffic grooming method in WDM rings. Chiu and Modiano [4] developed traffic grooming algorithms for unidirectional SONET/WDM ring networks. The objective is to minimize the total cost of electronic equipments. They showed that the general traffic grooming problem is NP-complete. Recently, Modiano [9] gives an overview of the traffic grooming problem and survey some representative works. Owing to the problem complexity of the traffic grooming problem, most of all research proposed a greedy approach to get some results, which are close to the optimal solution for reasonable size networks.

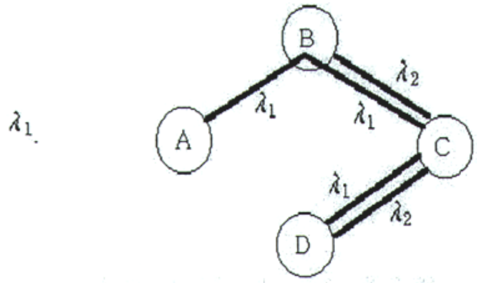
Once a set of light-paths is defined by appropriate traffic grooming, one of challenging problems in WDM networks is to determine the routes over which these light-paths should be setup to minimize the number of wavelengths being assigned to them ([9, 12, 16]). Even the traffic grooming and the light-path routing should be considered within a single framework, the computational complexity makes the whole problem divided into two sub-problems in conventional approaches. In this paper, we are concerned with the integrated problem of the traffic grooming and the light-path routing in WDM-ring networks. We suggest an optimization model for it in a single framework, and develop an efficient heuristic to solve it. A typical traffic grooming and light-path routing is shown in Figure 1. The network has 4 nodes and the traffic demand between WDM nodes are given with an unit of OC-1. We assume each wavelength has a transmission capacity of OC-48 ($2.4Gbps$). Figure 1-a denotes the existence of traffic demand. If we assign a light-path for each traffic demand, i.e., we do not groom the traffic demand, 6 light-paths are required in the network and 3 wavelengths can be allocated on the ring. Figure 1-b shows the results of the traffic routing, which is corresponding to a single light-path, and the wavelength assignment on the light-path. On the other hand, if we allow the traffic grooming, only 4 light-paths and two wavelengths are



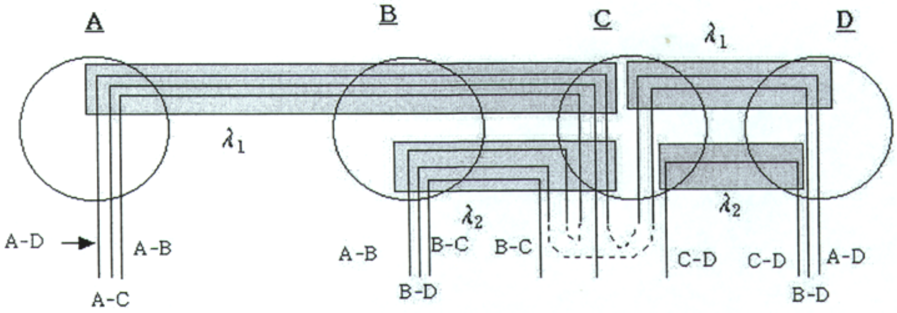
k	o(k)	d(k)	r_k
1	A	B	15 OC-1
2	A	C	10 OC-1
3	A	D	20 OC-1
4	B	C	5 OC-1
5	B	D	20 OC-1
6	C	D	30 OC-1
Transmission capacity for each wavelength = OC-48			

(a) Traffic demand and transmission capacity for each wavelength

(b) Light-path routing and wavelength assignment without traffic grooming



c) Wavelength assignment with traffic grooming



d) Light-path routing and demand routing with traffic grooming

Figure 1. An example of traffic grooming and light-path routing

enough for allocation. Figure 1-c depicts the result of the traffic grooming and the light-path routings. The details of them are given in Figure 1-d, where three different traffic demands, A-B, A-C, A-D are groomed into the light-path A-C being allocated with wavelength λ_1. It is worth noting that node A and B are not directly connected by a light-path, but the traffic demand A-B can be transported by a virtual connection via light-path A-C with wavelength λ_1 and light-path B-C with wavelength λ_2. As can be seen from Figure 1, the traffic grooming can reduce the number of light-paths. Once the number of wavelengths per fiber is defined, the planning consists of defining the light-paths on which the traffic is routed, and defining the number of light-paths for each link to minimize the number of wavelengths. Since the number of wavelengths are limited, the connection graph whose links are light-paths may not be fully connected. Therefore, multihopping between light-paths may be necessary, and each traffic may be transmitted along subsequent light-paths. In WDM network, we can employ multi-hopping connections as many as possible to reduce the number of light-paths. However, information forwarding from light-path to light-path is performed in the electronic domain. Therefore, a frequent opto-electronic transformation results in the worse of grade of service(GOS) for transmission networks such as delay and throughput. To guarantee a certain level of GOS, it need to restrict the number of opto-electronic transformations for a traffic in traffic grooming process. In this paper, we consider such a constraint in the traffic grooming and light-path routing.

Our problem is now specifically described: (1) Given is the ring containing WDM nodes and the traffic to be transported between two nodes in the ring. We allow the traffic can be routed on multiple light-paths, and each light-path should be allocated a wavelength exclusively. (2) We assume there is no wavelength conversion, and each wavelength has a transmission capacity. There is no limit on the number of wavelengths aggregated into a single fiber. As a hop-count constraint, we consider the restriction on the number of light-paths being used to transport a traffic demand. (3) The objective is to groom the traffic on to light-paths, and to route light-paths on the ring in order to minimize the number of wavelengths being allocated.

The rest of this paper is organized as follows: The next section shows an optimization model for our complex problem. We describe the process of formulating our problem as a mixed Integer Programming model. Section 3 describes a heuristic algorithm to solve our problem. Computational results with randomly generated problems are reported in section 4, and some concluding remarks and extensions of our research are given in the last section.

2. Design Model

Consider an undirected ring network $G_0 = (N_0, E_0)$ where N_0 and E_0 represent a set of nodes and links respectively. Each traffic demand corresponds to an individual commodity k, and $o(k)$ and $d(k)$ denote its origin and destination nodes respectively. Let r_k be the demand of each commodity, and K be the set of commodities in G_0. In order to discriminate link types, the undirected and directed links are represented as $\{i, j\}$ and (i, j) respectively. To make the model tractable, we consider an augmented network by introducing dummy nodes and a set of dummy arcs as follows:

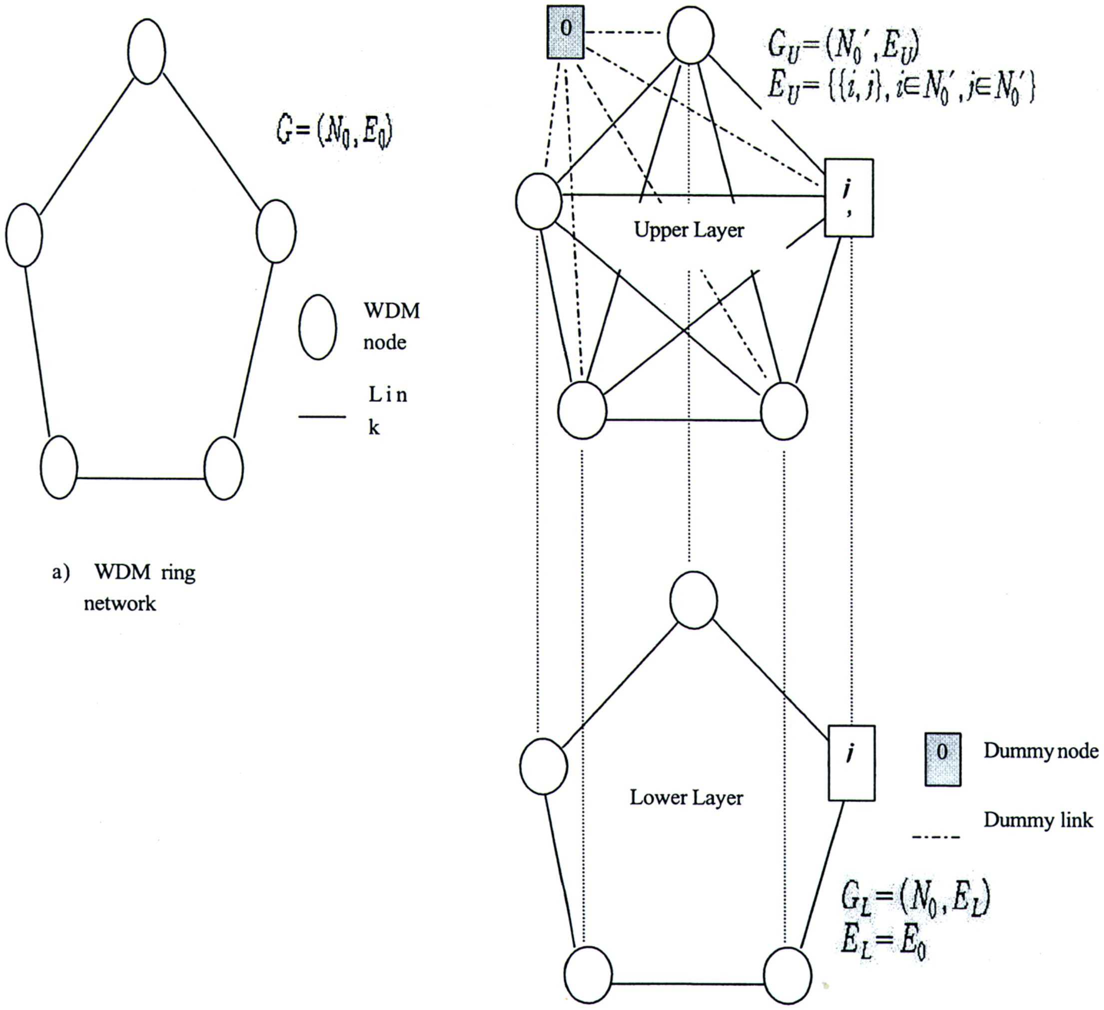
- Associate each node $j \in N_0$ with a dummy node j'. Let N_0' be the set of those dummy nodes. Also, add an additional dummy node 0 and define $N = N_0 \cup N_0' \cup \{0\}$.
- Add dummy arcs connecting each node and the corresponding dummy node. And add dummy arcs connecting all the dummy nodes. Then define $E = E_0 \cup \{\{j, j'\}, j \in N_0\} \cup \{\{j, 0\}, j \in N_0'\} \cup \{\{l', m'\},\ l', m' \in N_0'\}$.

The augmented network can be represented as a two-level layered network : the dummy plane at the upper level, and the real plane at the lower level. Then arcs on the real plane are all real, while those on and above the dummy plane and between the two planes are all dummy. Let $G_U = (N_0', E_U)$ and $G_L = (N_0, E_L)$ denote the upper and the lower networks respectively, and E_U and E_L denote a set of links in the upper and the lower layer networks respectively: $E_U = \{\{l, m\}, l \in N_0', m \in N_0'\}, E_L = E_0$. An illustration of the augmented network is given in Figure 2. In Figure 2, each link in the upper layer corresponds to the light-path to transport traffic demand directly. Let L be the set of light-paths, and $o_l(l)$ and $d_l(l)$ denote the origin and the destination nodes for each light-path respectively. The upper layer is for a traffic grooming which is to decide a path for each traffic demand and to aggregate the traffic into light-paths. The lower layer is for selecting light-path paths along the ring to minimize the total number of wavelengths to be assigned. We define the set of directed links A_U by associating each undirected link in E_U with two directed links having the opposite directions.

For each k in the upper layer, let h_k be a hop-count for k which is the maximum number of light-paths being used to transport the demand r_k. r_k may be shipped from $o(k)$ to $d(k)$ through several transmission paths among alternatives. Let $P(k)$ be an index set of alternative paths for transporting the demand for k. Hence, the path corresponding to each index in $P(k)$ should be made of consecutive light-paths within a hop-count h_k. Once the traffic grooming is completed in the upper layer, we can obtain the set of paths for each commodity k which is composed of a single light-path or a consecutive set of light-paths. A light-path determined in the upper layer should be assigned a wavelength along the ring in the lower layer. To facilitate the problem formulation, consider the following notations:

y**:** the number of wavelengths required to the ring,
z_{ij} **:** the 0-1 variable denoting a light-path on link $\{i, j\}$,
y_{ij}^l**:** the 0-1 variable concerning the establishment of a wavelength l on the link $\{i, j\}$,
x_{ij}^{kp}**:** the variable denoting the demand fraction of p-th path for commodity k transported on light-path (i, j),
H_{ij}^{kp} **:** the 0-1 variable denoting the flow of p-th path for commodity k on the link (i, j),
Q_{ij} **:** the traffic capacity of a light-path on link (i, j).

Using this notation, we formulate our problem as a 0-1 mixed integer programming problem. The objective function of P denotes to minimize the number of wavelengths required in a WDM ring network. Constraints (1) and (2) represent the flow conservation constraints for each commodity k. Note that the traffic demand r_k for commodity k can be divided into several paths from $o(k)$ to $d(k)$. Constraints (2) describe that r_k should be sent to some of out-going links at the origin, and come to the destination via some of incoming links. The incoming demand on the p-th path have to be sent on the same path. Constraints (2) denote these restrictions. Constraints (3) force that flow on the light-path in the upper network be allowed in both directions within the capacity limit only if the light-path is needed to open. (4) indicates the existence of p-th path on link (i, j) for commodity k, and (5) describes the hop-count constraints for each commodity k. The flow conservation constraints for light-paths (6) enforce the network connectivity for each light-path. For each light-path l, constraints (6) state that there should be one connection starting from node $o_l(l)$ and terminating to node $d_l(l)$. If the light-path (i, j) is needed to transport demands in the upper network, the wavelength assigned to it should be installed along the ring in the lower network. On the other hand, if the light-path (i, j) does not need in the upper network, the associated wavelength in the lower network should be assigned along the dummy links.



a) WDM ring network

b) Augmented network with dummy nodes and links

Figure 2 Augmented Network

These restrictions are represented in (7) and (8). Constraints (9) denote the number of wavelengths on each link in the lower network.

$$(P) \quad \text{Min} \;\; y,$$

s.t.

$$\sum_{p\in P(k)}\sum_{j\in N_0'} x_{ij}^{kp} - \sum_{p\in P(k)}\sum_{j\in N_0'} x_{ji}^{kp} = \begin{cases} 1, i=o(k), \\ -1, i=d(k), \end{cases} \quad i\in N_0',\; k\in K \tag{1}$$

$$\sum_{j\in N_0'} x_{ij}^{kp} - \sum_{j\in N_0'} x_{ji}^{kp} = 0, \quad i\neq o(k), i\neq d(k),\; k\in K, p\in P(k), i\in N_0', \tag{2}$$

$$\sum_{k\in K}\sum_{p\in P(k)} r_k(x_{ij}^{kp}+x_{ji}^{kp}) \;\leq\; Q_{ij}z_{ij}, \quad \{i,j\}\in E_U, \tag{3}$$

$$x_{ij}^{kp} \;\leq\; H_{ij}^{kp}, \quad (i,j)\in A_U,\; k\in K,\; p\in P(k), \tag{4}$$

$$\sum_{(i,j)\in A_U} H_{ij}^{kp} \;\leq\; h_k, \quad k\in K, p\in P(k), \tag{5}$$

$$\sum_{j\in N_0\cup\{0\}} y_{ij}^l - \sum_{j\in N_0\cup\{0\}} y_{ji}^l = \begin{cases} 1, i=o_l(l), \\ -1, i=d_l(l), \\ 0, \text{otherwise}, \end{cases} \quad i\in N,\; l\in L \tag{6}$$

$$y_{i0}^l + z_{ij} \;\leq\; 1, \quad i,j\in N_0', l\in L, o_l(l)=i, d_l(l)=j, \tag{7}$$

$$y_{0j}^l + z_{ij} \;\leq\; 1, \quad i,j\in N_0', l\in L, o_l(l)=i, d_l(l)=j, \tag{8}$$

$$\sum_{l\in L} y_{ij}^l \;\leq\; y, \quad \{i,j\}\in E_L, \tag{9}$$

$$x_{ij}^{kp}, x_{ji}^{kp} \;\geq\; 0,\;\; H_{ij}^{kp},\; z_{ij} \;\in\{0,1\}, \quad \{i,j\}\in E_U, p\in P(k), k\in K,$$

$$y_{ij}^l, y_{ji}^l \;\in\{0,1\}, \quad \{i,j\}\in E\backslash E_U, l\in L,$$

$$y \;\geq\; 0, \text{ integer}.$$

The problem (P) is a mixed integer linear programming problem, which contains a light-path routing problem as well as a traffic grooming problem. When we relax constraints (3), the remaining problem can be a kind of hop-count constrained shortest path problems having NP-hard computational complexity. Owing to the problem complexity, it is hard to find an optimal solution for (P). Instead, it is more effective to get a good feasible solution by an heuristic algorithm than to find an optimal solution. In this paper, we are concerned with a heuristic algorithm to solve our complex problem with easy.

3. Solution Method

Since the MILP (P) becomes computationally intractable for large networks, we need some efficient heuristic to solve our problem effectively. Our heuristic has two stages. The first, traffic grooming for each demand, aggregates some demands onto a light-path being correspond to a wavelength. Since each wavelength has a transmission capacity, the number of demands to be aggregated onto a single light-path are restricted by the capacity. This stage is to reduce the number of light-paths required for transmitting all demands in the network. The second stage, routing for each light-path along the ring, is to route physical path of each light-path. Since a light-path needs a wavelength, we should consider assigning wavelengths. With the light-path to be routed, we apply the algorithm developed to solve a ring loading problem by Myung *et.al.* [14] with some modifications in order to minimize the total number of wavelengths used in the network.

In traffic grooming stage, we assume that each demand is transported by a dedicated light-path which is the direct connection between the origin and the destination nodes for each demand. Assume that each traffic demand r_k for k is allocated into the link denoting a direct connection in G_U. Noting the link in G_U and the transmission capacity of a wavelength, we can see the utilization of each light-path loaded with only one demand is very low. Let s_l^k and $K(l)$ be the amount of demand for commodity k and the set of commodities loaded on light-path l respectively. The utilization of light-path l, ρ_l, is calculated as follow: $\rho_l = \sum_{k \in K(l)} s_k^l / Q_l$ where Q_l is the traffic capacity of light-path l. When we select the light-path l^* having minimum utilization, we have to consider an alternate path from $o_l(l)$ to $d_l(l)$ to transport demands assigned to l^*. To find the alternative path for $k \in K(l^*)$, define $G_U^* = (N_0, L^*)$ where L^* denotes the set of light-paths defined as follow: $L^* = \{l : \rho_l \leq 1, l \in L \backslash \{l^*\}\}$. In G_U^*, we assume each link weight be $1 - \rho_l, l \in L^*$. We try to find a path for $k \in K(l^*)$ from $o_l(l)$ to $d_l(l)$ in G_U^*, which is composed of links denoting light-paths and for which the total number of links are limited within a hop-count h_k. Let $PA(k)$ be the set of arcs constituting the path. The available capacity of the path, Δ_k can be defined as follow: $\Delta_k = min\{1 - \rho_l, l \in PA(k)\}$. If $\Delta_k \geq 0$, the demand for k loaded on l^* should be transmitted to the path $PA(k)$. The amount of transition for k is calculated as $\Delta = min\{\Delta_k, s_k^{l^*}\}$, and we adjust the demand on l^* and the links in $PA(k)$ as follows:

$$s_k^{l^*} \leftarrow s_k^{l^*} - \Delta, \quad s_k^l \leftarrow s_k^l + \Delta, l \in PA(k).$$

After the adjustment of demand for all $k \in K(l^*)$, if $\rho_{l^*} = 0$, l^* is deleted from L. If $PA(k) = \phi$, it means there is no alternative path having a hop-count h_k for $k \in K(l^*)$. Thus, l^* is the essential one regardless of its utilization, and we delete it from L in order to consider no more. This procedure is terminated when there are no ones to be deleted from L. The procedure is stated more formally as follows:

```
[Traffic Grooming Procedure]
Step 1 [Initialization]
    For a given $G = (N, E)$, set $E, L, T$ as follows: $L = K, E = L, T = L$. If $k = l$ for $k \in K$
    and $l \in L$, set $s_k^l = r_k$ and $K(l) = \{k\}$. Otherwise, set $s_k^l = 0$ and $K(l) = \phi$.
Step 2 [Candidate light-path selection]
    1) Calculate utilization for each light-path; $\rho_l = \sum_{k \in K(l)} s_k^l / Q_l, l \in L$
    2) Select one from the set of light-paths having minimum utilization $l^* : \rho_{l^*} = min\{\rho_l \, ; l \in L\}$
Step 3 [Alternate path selection and demand adjustment]
    1) For $k \in K(l^*)$, select $PA(k)$,
    2) If $PA(k) = \phi$, delete $l^*$ from $L$,
    3) If $PA(k) \neq \phi$, calculate $\Delta_k = min\{1 - \rho_l \, ; l \in PA(k)\}$.
        i) If $\Delta_l \leq s_k^{l^*}$, update $s_k^l$ and adjust $\rho_l$ among $PA(k)$ as follows:
            $s_k^l \leftarrow s_k^l - \Delta_k, \ l = l^*$ ,    $s_k^l \leftarrow s_k^l + \Delta_k, \ l \in PA(k)$,
        ii) If $\Delta_l \geq s_k^{l^*}$, update $s_k^l \leftarrow 0, \ l = l^*$ ,
            $s_k^l \leftarrow s_k^l + s_k^{l^*}, \ l \in PA(k)$, and adjust $\rho_l \ l \in PA(k)$.
    4) If $\rho_{l^*} = 0$, delete $l^*$ from $L$ and $T$.
Step 4 [Termination]
    If $L = \phi$ , terminate the process. Otherwise, return to Step 2.
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When terminating Traffic Grooming Procedure, there exists the set of arcs T which contains the necessary ones from the original L to transport demand. Each arc in T represent a light-path and is assigned a dedicated wavelength in WDM ring network. For given the set of light-paths to be placed in a WDM ring network, we have to assign a wavelength to each light-path. The second stage is to assign a wavelength for each light-path in T in order to have the minimum number of wavelengths required in the network. To assign the wavelengths with minimum, we apply the concept of the algorithm for a ring loading problem developed by Myung *et.al.* [14]. Based on the concept, we develop an heuristic algorithm to select a route for each light-path.

We define each light-path in T as an individual commodity k on a WDM ring network. d_k denotes the amount of transmission demands for each commodity k.For $k \in T$, the light-path associated with k can be routed along the clockwise or the counter-clockwise direction paths with a dedicated wavelength. Let x_t^k be the amount of demand assigned to the route along the clockwise direction for k at iteration t. For each $k \in T$, let L_k^+ and L_k^- be the set of links in the clockwise and the counter-clockwise direction paths respectively. For a link $r \in E_0$, let T_r^+ and T_r^- be the set of commodities routed along the clockwise and the counter-clockwise direction paths respectively. In the initialization, we have every commodity taken the route along the clockwise direction path. Thereby, we can set $T_r^- = \phi$ in the initial iteration. For $r \in E_0$, let $g(\mathbf{x^t}, r)$ be the total amount of demand loaded on link r at iteration t:

$$g(\mathbf{x^t}, r) = \sum_{k \in T_r^+} x_k^t + \sum_{k \in T_r^-} (d_k - x_k^t)$$

For each $k \in T$, since the demand of k can be loaded on the clockwise or the counter-clockwise direction paths, we can calculate the maximum load of each direction as follows: $\delta_k^+ = max_{r \in L_k^+}\{g(\mathbf{x^t}, r)\}$, $\delta_k^- = max_{r \in L_k^-}\{g(\mathbf{x^t}, r)\}$. If $\delta_k^+ \geq \delta_k^-$, the demand of commodity k can be routed to the counter-clockwise direction path for balancing the loads of both directions. This procedure is terminated when the load balance does not adjusted any more. The formal procedure is listed as follows:

[Lightpath Routing]

```
Initialization
  for each $k \in T$ do
    $x_k^0 := d_k$;
Rerouting
  for $k = 1, .., |T|$ do
  begin
    $\delta^+ := max_{r \in L_k^+} g(\mathbf{x^{k-1}}, r)$  $\delta^- := max_{r \in L_k^-} g(\mathbf{x^{k-1}}, r)$;
    if $(\delta^+ > \delta^-)$ then
    begin
        $\Delta := min\{\lceil \delta^+/2 \rceil, x_k^{k-1}\}$;
        $x_k^k := x_k^{k-1} - \Delta$;
        for $i \in T$ and $i \neq k$ do
            $x_i^k := x_i^{k-1}$;
    end;
    if $(\delta^+ < \delta^-)$ then
    begin
        $\Delta := min\{\lceil \delta^-/2 \rceil, d_k - x_k^{k-1}\}$;
        $x_k^k := x_k^{k-1} + \Delta$;
        for $x_i^k := x_i^{k-1}; i \in T$ and $i \neq k$ do
            $x_i^k := x_i^{k-1}$;
    end;
  end;
```

(where, x_i^k denotes the amount of demand i assigned to the clockwise path at iteration k, and $\lceil a \rceil$ represents the maximum integer not over a.)

4. Computational Results

The solution procedure in the previous section was implemented in C, and a series of computational experiments were performed on a PC(Pentium III/450 MHz) to evaluate its efficiency. To obtain the optimal solution of our problem, we use a commercial Mixed Integer Programming solver, CPLEX program.

The test problems were generated with differing levels of demands. We first assumed that every node pairs have transmission demands which are given by OC-1 unit, and each wavelength has a same transmission capacity. Even each demand is given by OC-1 unit, we transformed it into the ratio for the transmission capacity of wavelength. Thereby, each demand is given the fraction less than 1, and generated from the range of [a, b] randomly. Three kinds of demand types are considered : large, medium and small scale demands. The range of demand for each type is given as follow:

Demand Type	Ranges
small (A)	0.01 - 0.15
medium (B)	0.20 - 0.40
large (C)	0.40 - 0.50

We solved a total of 54 test problems and each problem is grouped into 6 different subsets by the problem size, i.e., the number of wdm nodes and links. Each subset is divided by the demand types and hop limits. Table 1 lists the summary of the test problems ranging from 4 nodes to 10 nodes. The details of the associated computational results for randomly generated problems are also summarized in Table 1. As seen in Table 1, the number of wavelengths for applying traffic grooming method is saved up to 80% for non traffic grooming. For example, consider 8 node wdm ring network with small-scale demand. Once we apply our traffic grooming method having a hop limit 4, it is enough to have only 2 wavelengths for transporting demand. However, applying non traffic grooming method, 10 wavelengths are required for transporting the same demand. It is an extreme case of the efficiency for the traffic grooming method considered in this paper.

For small-sized networks, i.e., 5 nodes or less, CPLEX can find the optimal solution in a reasonable time for small scale of demands. When the network size grows beyond 6 nodes or the demand becomes larger, CPLEX could not find an optimal solution within 5 hours. When we give CPLEX a time limit of 1 hour for each test problem, it usually fails to find even one feasible solution when network size is 10 nodes. The best incumbent solutions are obtained from CPLEX within 1 hour. Comparing the heuristic solution with the best incumbent one, we can see the heuristic algorithm requires more wavelengths, but the computation time is remarkably short. Note that the heuristic provides the feasible solutions within one second on PC.

There exists a few difference for the number of wavelengths required to transport the demand between the optimal and the heuristic solutions. The difference may increase as the number of nodes becomes larger, and cause that our heuristic is two-phase approach and the local optimum may be found in the traffic grooming stage. Since we can't sure that we have an optimal solution by using CPLEX within a day on PC as the network becomes larger, an efficient heuristic algorithm generating a good feasible solution in a short computation time is required for the real-world application. The reader's attention is again called upon to the fact that our problem is so complex. We are unfortunately unable to find any other

Table 1 Computational Results

|N|	|K|	Demand Type	Hop Limits	Light-path routing with traffic grooming				Light-path routing without traffic grooming
				Best Incumbent Solution*		Heuristic Solution		Number of Wavelength
				Number of Wavelength	Computation Time (Sec.)	Number of Wavelength	Computation Time (Sec.)	
4	6	A	2	1	6.34	1	0.01	3
			3	1	8.74	1	0.01	3
			4	1	8.83	1	0.01	3
		B	2	1	4.15	2	0.01	3
			3	1	5.12	2	0.01	3
			4	1	3.89	2	0.01	3
		C	2	2	**	2	0.01	3
			3	2	**	2	0.01	3
			4	2	**	2	0.01	3
5	10	A	2	2	**	2	0.01	3
			3	1	60.09	2	0.01	3
			4	1	56.74	1	0.01	3
		B	2	3	**	3	0.01	3
			3	2	**	2	0.01	3
			4	2	**	2	0.01	3
		C	2	2	**	3	0.01	3
			3	2	**	3	0.01	3
			4	2	**	3	0.01	3
6	15	A	2	2	**	4	0.01	6
			3	2	**	1	0.01	6
			4	2	**	2	0.01	6
		B	2	6	**	3	0.01	6
			3	5	**	3	0.01	6
			4	6	**	4	0.01	6
		C	2	4	**	4	0.01	6
			3	4	**	4	0.01	6
			4	4	**	4	0.01	6
7	21	A	2	4	**	4	0.01	6
			3	4	**	3	0.01	6
			4	4	**	2	0.01	6
		B	2	3	**	5	0.01	6
			3	3	**	4	0.01	6
			4	3	**	4	0.01	6
		C	2	4	**	5	0.01	6
			3	4	**	5	0.01	6
			4	4	**	5	0.01	6
8	28	A	2	8	**	4	0.01	10
			3	8	**	3	0.01	10
			4	8	**	2	0.01	10
		B	2	8	**	5	0.01	10
			3	8	**	6	0.01	10
			4	8	**	5	0.01	10
		C	2	8	**	7	0.01	10
			3	8	**	6	0.01	10
			4	8	**	7	0.01	10
10	45	A	2	***	**	6	0.01	15
			3	***	**	5	0.01	15
			4	***	**	5	0.01	15
		B	2	***	**	8	0.01	15
			3	***	**	8	0.01	15
			4	***	**	10	0.01	15
		C	2	***	**	10	0.01	15
			3	***	**	10	0.01	15
			4	***	**	10	0.01	15

|N| : Number of WDM nodes |K| : Number of commodities

* : The optimal or best feasible solution obtained from CPLEX program within 1 hour.

** : Computation time limit (1 hour).

*** : Not available to find a feasible solution within 1 hours by using CPLEX program.

published study on the same subject as ours for comparison of performance. Despite the absence of comparison with other works and the excessive computational burden expected for such complex problems, the performance of our heuristic is found so remarkable to generate solutions within few second.

5. Conclusions

In this paper we have dealt with a traffic grooming and light-path routing problem in WDM-ring networks, where the number of intermediate light-paths in the path for each traffic demand is restricted. An attempt was made to model the comprehensive problem as a mixed Integer Programming problem. Owing to the computational complexity, it is hard to find an optimal solution for a large-scale networks within an appropriate computation time. Hence, we develop an heuristic algorithm to solve the problem efficiently.

The computation time of our heuristic is remarkable. It means that the heuristic algorithm can be applied to the topological design of WDM-ring networks as well as the network operation. Once the traffic demands are given, the traffic grooming plan and the light-path routes should be decided under the current network status such as available light-path capacities and topologies. To operate networks efficiently, the traffic grooming and light-path routes have to be frequently changed according to the traffic patterns (volume and duration) and the transmission capacity. For the network operation with flexibility, we can apply our heuristic to support the decision for such a operation plan.

The performance of the proposed heuristic was shown to be satisfactory in both speed and quality of the solutions generated. Though effective even for large-scale real-world network problems in its present form, the whole design process may be improved further by devising a wavelength assignment, and/or other types of network topologies. The other interesting extension would be to consider the more practical version of our model encompassing the survivability and expandability issues.

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