Clustering Techniques for Traffic Grooming in Optical WDM Mesh Networks[1]

Ding Zhemin and Mounir Hamdi

Department of Computer Science, Hong Kong University of Science and Technology
Clear Water Bay, Kowloon, Hong Kong

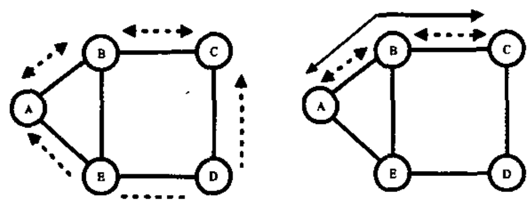
***Abstract*-- In this paper, we are trying to study the traffic grooming problem by minimizing overall network cost that includes the transceivers required as well as the number of wavelengths. A mathematical formulation of the traffic grooming problem in mesh networks is proposed. We also describe a heuristic using Blocking Island (BI) paradigm. Simulations have been carried out to prove effectiveness of our heuristic.**

I. INTRODUCTION

In WDM transmission, each data channel is carried on a unique wavelength (or optical frequency) and a single optical fiber has many different wavelengths. A lightpath (wavelength continuous path without processing in intermediate nodes) is needed to set up for an end-to-end transmission. Because of the lightpath continuity constraint, we need to consider the routing as well as pick up appropriate wavelength when a traffic request arrives. This problem is called routing and wavelength assignment (RWA) problem. When solving RWA problem, people usually simplify the traffic request, assuming each traffic request occupies exactly an entire lightpath capacity. But in practice, the bandwidth requirement of each traffic request is often only some fraction of lightpath capacity. A lightpath typically carries many multiplexed low-speed traffic streams with each stream having its own source and destination. In order to utilize bandwidth more effectively, the problem of allowing several independent traffic streams to "sharing" the bandwidth of a lightpath is called traffic grooming problem.

Most early work on traffic grooming was focused on SONET (Synchronous optical networks) rings. The objective is to minimize the number of SONET ADMs (add/drop multiplexers) used in the ring network. With optical network topologies evolving from rings to meshes, traffic grooming in other topologies is becoming more and more important. A few papers consider traffic grooming in mesh networks. In [4] they formulate the traffic grooming problem as a special case of the multi-commodity flow problem.

[1] This research is supported in part by a grant from the UGC-Hong Kong under the grant AoE/E-01/99.



(a) Solution 1 (b) Solution 2

Fig. 1. The illustrative example of traffic grooming in WDM optical mesh networks

Consider a 5-node mesh network topology as shown in Fig. 1. Assume it is a single fiber WDM optical network with each fiber having one wavelength channel. The capacity of each wavelength channel is 2 units of traffic streams. There are three connection requests: (A, B), (B, C) and (A, C) with each requiring one unit of traffic stream. There are two different ways of aggregating traffic and assigning lightpath. The first assignment is shown in Fig. 1 (a). Three lightpaths AB, BC and AEDC are set up and 6 transceivers are needed. The second solution is to groom the traffic of (A, C) into lightpaths AB and BC, as shown in Fig. 1 (b). Let (A, B) share the lightpath and transceivers with (A, C) from A to B. Similarly, let (B, C) share the lightpath and transceivers with (A, C) from B to C. The second solution requires only 2 lightpaths to be set up, and 4 transceivers are needed. This example shows if we can groom the traffic and assign the lightpath appropriately, the cost of the network will be decreased.

In traffic grooming, we have two parameters to optimize: minimizing the number of wavelengths and minimizing the number of transceivers. We may not be able to always find an optimal solution for both parameters.

This paper is organized into the following sections. A problem statement of the traffic grooming in mesh optical networks and an ILP formulation are presented in section II. The BI paradigm is described in section III. Section IV proposes a heuristic using the BI paradigm for the traffic grooming problem in mesh networks. Numerical results are presented in section VI. Section VII concludes the paper.

II. PROBLEM STATEMENT AND ILP FORMULATION

In [4], an ILP formulation was proposed for the traffic grooming problem in WDM mesh networks. It treats the problem as a special case of a multi-commodity flow problem. However, this model assumes there are always enough number of wavelengths and focuses on the minimization of transceivers.

In this section, an integer linear program (ILP) formulation is developed for the exact solution of the traffic grooming problem in WDM mesh networks, aiming at minimizing the cost of both transceivers and wavelengths. The overall network cost is given by,

$$Cost = C_T\,|T| + C_W\,|W|$$

Where C_T and C_W are the cost of each transceiver and wavelength, respectively. |T| is the number of required transceivers and |W| is the number of required wavelengths. Since the number of transceivers employed in the network only depends on the virtual topology, that is, the number of lightpaths set up on the physical links and a lightpath needs two transceivers for its source node and destination node, we have

$$2\,|LP| = |T|$$

|LP| is the number of lightpaths. So the cost equation we try to minimize can be changed to

$$Cost = 2C_T\,|LP| + C_W\,|W|$$

We extend the formulation in [4] to present a unified ILP framework. We assume a connection can traverse multiple lightpaths before it reaches the destination. Traffic requests can be measured by the number of unit traffic streams. For example, if the unit traffic stream is an OC-1 connection and the lightpath capacity is OC-48, we say the lightpath has 48 unit traffic streams. Notice the lightpath and traffic streams are all full duplex in our model and all the lightpaths have the same capacity.

Let G = G (N, A, W) be the network graph consisting of links $l \in A$, with |A| = L and nodes $n \in N$. |W| is the number of wavelength per fiber. We assume all links in the network have the same number of fibers and wavelengths.

Given:

Node pair $Z = \{(z_1, z_2) \in N \times N\}, \forall z = (z_1, z_2) \in Z$

Traffic Matrix set Traffic requests G are represented by the $|N| \times |N|$ matrix $T = [T_z]$. T_z is the number of unit traffic streams between node pair z.

Connection path set A path is a set of physical links from source node to destination node without any cycles. $P_z = \{p : z_1 \rightarrow z_2\}$ denotes the set of paths connecting the node pair z.

Variables:

Virtual topology matrix $V = [V_z]$, V_z denotes the number of lightpaths set up between node pair z.

Traffic route on lightpaths λ_z^{ij} $\forall i, j \in N$ and $z \in Z$, λ_z^{ij} equals the number of traffic streams of z that are routed through lightpaths from i to j.

Because of the wavelength continuity constraint, a lightpath must occupy the same wavelength on all the fiber links it traverses if there is no converter. Therefore, the number of wavelengths required is equal to the total number of distinguished wavelengths used in the network by at least one lightpath. Here we assume W wavelengths are available at each link. The problem of minimizing the cost of transceivers and wavelengths without wavelength conversion can be formulated as follows:

$$\text{Min: } Cost = 2C_T\,|LP| + C_W\,|W_\lambda|$$

Subject to

$$\beta_{p,w,z} = \begin{cases} 1, \\ 0, \end{cases} \forall z \in Z, \forall p \in P_z, \forall w \in W \qquad (1)$$

$$\sum_{w=1}^{W} \sum_{p \in P_z} \beta_{p,w,z} = V_z, \ \forall z \in Z \qquad (2)$$

$$I(l \in p) = \begin{cases} 1, & if \quad l \in p \\ 0, & otherwise \end{cases} \qquad (3)$$

$$U(w) = \begin{cases} 1 \\ 0 \end{cases} \forall w \in W \qquad (4)$$

$$\sum_{z \in Z} \lambda_z^{ij} \le cV_{ij}, \ \forall i, j \in N \qquad (5)$$

$$\lambda_z^{ij} = \lambda_{z'}^{ij}, \ \forall z, z' \in Z, z = (z_1, z_2), z' = (z_2, z_1) \qquad (6)$$

$$\sum_i \lambda_z^{ik} - \sum_i \lambda_z^{ki} = D_z^k, \ \forall z \in Z, \forall i, k \in N$$

$$D_z^k = \begin{cases} 0, & if \ k \notin z = (z_1, z_2) \\ T_z, & if \quad k = z_1 \\ -T_{z'}, & if \quad k = z_2 \end{cases} \qquad (7)$$

$$|LP| = \sum_{ij} V_{ij}, \ \forall i, j \in N \qquad (8)$$

$$U(w) \ge \beta_{p,w,z}, \ \forall z \in Z, \forall p \in P_z, \in \forall w \in W \qquad (9)$$

$$\sum_{z \in Z} \sum_{p \in P_z} \beta_{p,w,z} I(l \in p) \le 1, \ \forall l \in A, \forall w \in W \qquad (10)$$

Equation (1), if (p, w) is selected as an active lightpath, $\beta_{p,w,z}$ is equal to 1; otherwise it is equal to 0.

Equation (2), given the virtual topology, V_z lightpath(s) will be assigned to each node pair z with different wavelengths.
Equation (3), if l is a link of p, it is equal to 1, otherwise 0.
Equation (4), if wavelength w is used by at least one lightpath, $U(w)$ is equal to 1; otherwise it is equal to 0.
Equation (5), each lightpath can carry at most c unit traffic streams.
Equation (6), lightpath and traffic streams are fully duplex.
Equation (7), For any node k in the network, the traffic flowing into it is equal to the traffic flowing out of it plus the traffic dropped at this node.
Equation (8), |LP| is the total number of lightpaths set up in the network.
Equation (9) is obvious, if wavelength w is used, U(w) must be 1; otherwise, $\beta_{p,w,z}$ must be 0.

Equation (10), any wavelength of any link can at most be used by any lightpath just once.

It is well known that the complexity of optimal traffic grooming in ring networks is NP-Complete. Since ring networks are only a special case of mesh networks, it is easy to see that the optimal traffic grooming problem in mesh networks is NP-Complete as well. Although we have this ILP formulation, it becomes unmanageable even for a very small network because of the exponentially increasing number of the variables and equations as the network size increases. As a result, we have to resort to heuristics to obtain fast and practical solutions. In the next section, we first introduce the Blocking Island Paradigm as an efficient mechanism for resource allocation in communication networks. Then we propose a heuristic using this paradigm to solve the traffic grooming problem in mesh networks.

III. BLOCKING ISLAND PARADIGM

Developed from Artificial Intelligence, namely constraint satisfaction and abstraction and the theory of phase transition, the BI (blocking island) [7] provides an efficient way of abstracting resources (especially bandwidth) available in a communication network. In particular, BI clusters parts of the network according to the bandwidth availability. A b-BI for a node x is the set of all nodes of the network that can be reached from x using links with at least b available bandwidth (Fig. 2).

We assume all demands are unicast and the only QoS parameter taken into account is bandwidth. The network physical topology consists of V nodes arbitrarily connected by L bi-directional links. We model it as a network graph G=(V, L). Fig. 2 depicts such a network graph.

A request is defined by a triple: $d_u=(x_u,y_u,\beta_u)$, where x_u and y_u are distinct nodes of the network and β_u is the bandwidth requirement. β-BI has some very useful properties. Below we list a few without proof (for a proof, see [7]).

Unicity there is one and only one β-BI for a node. Thus if S is the β-BI for a node, S is the β-BI for every node in S.
Partition β-BI induces a partition of nodes in a network.
Route existence give a request $d_u=(x_u,y_u,\beta_u)$, it can be satisfied if and only if the node x_u and y_u are in the same β_u-BI.
Inclusion If $\beta_i<\beta_j$, the β_j-BI for a node is a subset of the β_i-BI for the same node.

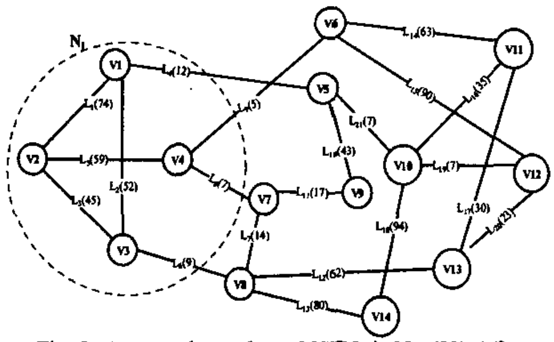


Fig. 2. A network topology (NSFNet). N_1={V1, V2, V3, V4} is the 40-blocking island (40-BI) for node V1.

Using the concept β-BI, we can construct a recursive decomposition of Blocking Island Graphs in decreasing order of βs, e.g., $\beta_1>\beta_2>...>\beta_n$. We call this layered structure of Blocking Island Graphs a Blocking Island Hierarchy (BIH). The most frequent operation in this process is to construct a BIG according to a certain β. It is obtained with a simple greedy algorithm. Starting with an arbitrary node x, we add all the nodes which can be reached by links with at least β available bandwidth to form a β-BI. Then starting with another arbitrary node that is not in the previous β-Bis, we repeat the process until all the nodes in the network are included in one of the β-BIs. The complexity of constructing BIG is O(m) [7], where m is the number of links in the network.

BI is a natural abstraction of network resources. A β-BIG allows us to get a clear picture about the network load as nodes and links with enough resources are hidden behind an abstract node. In particular, bottlenecks are identified by the interlinks between Blocking Islands.

IV. TRAFFIC GROOMING ALGORITHM

In this section, we propose a new traffic grooming heuristic, using the BI paradigm, for mesh networks. The goal of the algorithm is to maximize the throughput subject to the constraint of transceivers and wavelengths.

Before describing the algorithm, we first introduce a BIG (Blocking Island Graph) network model. Define a network topology $G(V, L, W)$ for a given WDM optical network, where V is the set of nodes, L is the set of bidirectional links and W is the set of wavelengths per fiber link. Assume this is a single fiber network without wavelength converters. The set of wavelengths on each fiber link is the same. Each connection request needs to be allocated over a route and assigned one wavelength. The network can be abstracted into $|W|$ blocking island graphs (BIGs). Each BIG starts with one Blocking island (BI) representing a wavelength and has the same topology as the original WDM optical network. So the BIG network model, BIG $(m_1, m_2, \dots m_{|w|})$, can be obtained from a given network topology G as follows. The topology of G is replicated $|W|$ times denoted by $m_1, m_2, \dots m_{|w|}$. Each BIG m_i, which is made of one BI at the beginning, represents a wavelength and the link capacity is 1.

The basic idea behind the proposed approach to traffic grooming and wavelength assignment is as follows: first, we try to group traffic requests for each node pair z to construct as few new requests R_z as possible. The upper bound of R_z is equal to the capacity of a lightpath. Second, given the new request set $\{R''_z\}$, we do the routing and wavelength assignment using the BI_RWA algorithm proposed in [3]. Notice in the original BI_RWA, we only consider the wavelength constraint. So we should add the transceiver constraint into it, judging if there are enough transceivers in a source node and a destination node for each lightpath. Third, we route the rest of the blocked requests on the virtual topology constructed in the second step.

To facilitate the description of the algorithm, we use $T_{ij}=(t^1_{ij}, t^2_{ij}, \dots t^n_{ij})$ to denote the aggregate traffic from node i to node j. t^n_{ij} denotes one connection request from node i to node j.

STEP 1: Traffic Packing

In this step, we try to pack the aggregated traffic requests for each node pair z into as few new requests R_z as possible with each R_z having the capacity of a lightpath. Notice this is actually a Bin-Packing problem:

Input: a set of n traffic requests for node pair z with bandwidth requirement $d_1, d_2, \dots d_n$. A set of bins (new requests R_zs) with the capacity of a lightpath: C.

Problem: how do we pack n traffic requests using the fewest number of $R_z s$.

The Bin-Packing problem is a classical problem. There are many algorithms available. For a detailed description, please refer to [8].

STEP 2: BI_RWA with Transceiver Constraint

After the traffic packing, we get the new request set R_z for each node pair z. Construct a new set $R=\{r \in R_z \mid z \in Z\}$ as the incoming traffic request set.

1. Transform the network topology into a BIG model.
2. Order all the connection requests R in decreasing length of their MNH (Minimum Number of Hops) distance.
3. Select an unallocated request r, $R = R-\{r\}$. If the request set R is empty then go to 7.
4. Use the Route Existence property and the number of transceivers on each node to check if all the requests in R can be satisfied individually. If it can, assign the request r to every blocking island and go to 5. If it can't, put the request r into blocked request list and go to 3.
5. Now we have a set of candidate routes in different BIGs. Compute the splitting number for each route and the most loaded link for each route. Find one with the minimum splitting number and the least "most loaded" link subject to the transceiver availability.
6. Get the route and corresponding wavelength. Reconstruct the BIGs.
7. If the request set is empty, output the result.

The splitting number for a route means the number of blocking islands that will be newly generated if the route is removed from the current blocking island. The "most loaded link" for a route means in a route the most wavelengths in this link have been used. Also here we assume traffic is static. Our goal is to maximize the number of accepted requests given a fixed number of wavelengths per fiber link and a fixed number of transceivers on each node.

If there are enough resources in the network, every connection will be satisfied with a single hop lightpath. If there are not enough resources, we may not be able to meet every connection request. Based on the virtual topology generated in step 2, we carry out the routing using the spare capacity.

STEP 3. Virtual Topology Routing

Update the virtual traffic topology based on the lightpaths set up in step 2. Transform the connection request in the blocked request list into their original form. After ordering the bandwidth requirement of each request, we do the routing on the virtual topology, by trying to fit into as much traffic as possible.

V. NUMERICAL RESULTS

The performance of the proposed algorithm is evaluated on NSFNet shown in Fig 2, which has 14 nodes and 21 links. We employ the random traffic model proposed in [5] to generate our incoming traffic matrices. In our case, we assume the capacity of each lightpath is *OC-48*, and allow the traffic bandwidth requests to be any of *OC-1, OC-3, OC-6, OC-12* and *OC-24*. The traffic matrices are generated as follows: 1) The number of *OC-1* connection requests between each node pair are generated as a uniformly distributed random number between 0 and 48; 2) The number of *OC-3* connection requests between each node pair are generated as a uniformly distributed random number between 0 and 16; 3) The number of *OC-6* connection requests between each node pair are generated as a uniformly distributed random number between 0 and 8; 4) The number of *OC-12* connection requests between each node pair are generated as a uniformly distributed random number between 0 and 4; and 5) The number of *OC-24* connection requests between each node pair are generated as a uniformly distributed random number between 0 and 2.

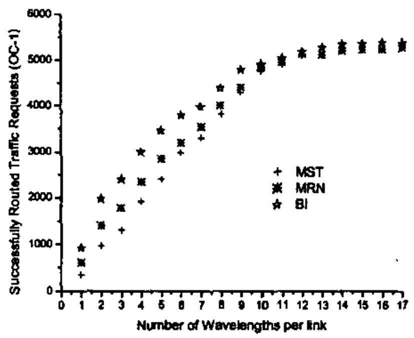


Fig. 3. Network throughput versus the number of wavelengths with 8 transceivers at each node

The other heuristic algorithms used in the simulation are MST (Maximizing Single-hop Traffic) and MRU (Maximizing Resource Utilization) proposed in [5]. MST and MRU consider the problem in two stages. In the first stage, they set up as many lightpaths as possible to accommodate the connection requests. In the second stage, the blocked requests are routed on the virtual topology. The difference is in ordering. MST orders the connection requests according to the aggregate traffic between node pairs. MRU orders the connection requests according to the value of $T(s, d)/H(s, d)$. $T(s, d)$ denotes the aggregated traffic between node s and d. $H(s, d)$ denotes the hop distance on the physical topology between node pair s and d.

Fig.3 compares the results of the three heuristic algorithms BI, MST and MSU. Notice no wavelength conversion is available in our simulation. Given the fixed number of transceivers, Fig.3 shows the relationship between the amount of accepted traffic and the number of wavelengths. The results indicate that the performance of the BI heuristic is the best, followed by MRU and then MST. Since the number of transceivers is limited, when the number of wavelengths reaches certain value (around 12 in the simulation), the number of transceivers becomes the bottleneck and the network throughput stops increasing. Note that BI algorithm can efficiently utilize wavelength, so a request is more likely to be accepted comparing to the other two heuristics.

VI. CONCLUSION

In this paper we studied the problem of traffic grooming in mesh networks. An ILP formulation to minimize the network cost (transceivers and wavelength) is presented. Inspired by a clustering technique called Blocking Island, we propose a new heuristic for traffic grooming in mesh networks. In the Simulation, given there is no wavelength conversion, experimental results demonstrate our algorithm performs better than MST and MRU when the number of transceivers is fixed.

REFERENCES

[1] E. Modiano, P. J. Lin, "Traffic Grooming in WDM Networks," *IEEE Commun Mag.*., pp. 124-129, Jul. 2001.

[2] O. Gerstel, P. Lin, and G. Sassaki, "Combined WDM and SONET Network Design, " *INFOCOM '99*, pp. 734- 743, Mar, 1990.

[3] D. Zhemin and M. Hamdi, "A Simple and Intelligent Routing and Wavelength Assignment Algorithm for All-Optical Networks, " *SPIE Opticom*, 2001, pp. 210-226.

[4] V.R. Konda and T. Y. Chow, " Algorithm for Traffic Grooming in Optical Networks to Minimize the Number of Transceivers," *IEEE 2001 WKshp. High Perf. Swithching and Routing*, pp. 218-221, 2001.

[5] K.Zhu and B. Mukherjee, " Traffic Grooming in an Optical WDM Mesh Network, "*IEEE J. Select. Areas. Commun.*, pp. 122-133, Jan. 2002.

[6] S. Baroni and P. Bayvel. "Wavelength Requirements in Arbitrarily Connected Wavelength-routed Optical Networks." *IEEE/OSA J. Lightwave Technol.*, 15(2):242-251, Feb.1997.

[7] C. R. Frei, "Abstraction Techniques for Resource Allocation in Communication Networks," *PhD thesis*, Swiss Federal Institute of Technology – Lausanne, 2000

[8] S. Martello and P. Toth, "Knapsack Problems: Algorithms and Computer Implementations, " *JOHN WILEY & SONS*, 1990.