TRAFFIC GROOMING, ROUTING, AND WAVELENGTH ASSIGNMENT (GRWA) IN ALL-OPTICAL DWDM TRANSPORT NETWORKS WITH SPARSE GROOMING RESOURCES

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ABSTRACT

In a wavelength division multiplexing (WDM) all-optical network, the size of a request stream may be less than the maximum capacity of a lightpath. To avoid assigning an entire lightpath to a small request, many researchers have looked at adding traffic grooming to the routing and wavelength assignment (RWA) problem. We consider the RWA problem with traffic grooming (GRWA) problem for mesh networks. Our goal is to provide an optimal (in some sense) solution for a given GRWA problem. In particular we look at either minimizing the cost of the grooming equipment or minimizing the number of hops for all connections. Some of the previous work in this field concentrates on grooming without wavelength conversion or grooming only on the end nodes. We look at the GRWA problem with sparsely located wavelength conversion and grooming capabilities. Furthermore, the grooming and wavelength conversion equipment are collocated in the same nodes. We are proposing an integer linear programming (ILP) model that accurately depicts the GRWA problem. The ILP model can be used to find an optimal solution for a small number of nodes, and can serve as a basis for developing either a heuristic or a genetic algorithm approach to provide near-optimal solutions for larger problems.

.**Keywords:** *Integer Linear Program, All-Optical Network, Traffic grooming, Dense Wavelength Division Multiplexing.*

1. INTRODUCTION

At the present, the service providers of IP and telecommunication backbone networks are heavily invested in optical technology. The reason is the large current and theoretical bandwidth of optical fibers. However, there is a major issue with the optical hardware used today. The problem is the switching and amplifying equipment work in the electrical domain. That is, when a piece of optical equipment at a node receives an optical signal on an input port, it converts the signal to the electrical domain. The signal is processed in the electrical domain, and after processing, it is converted to an optical signal by a transponder on an output port. Equipment that operate in this manner are known as optical-electrical-optical equipment (O-E-O), and are the major drawback of today's optical networks. When upgrading their optical networks, it is in the service providers' interest to develop all optical networks[1], because O-E-O equipment are in general big, expensive, and do not scale well. In addition, O-E-O equipment process in the electrical domain, and there are limits on how quickly a piece of equipment can process an electrical signal. For example, an O-E-O amplifier that was state of the art several years ago may not be able to keep up with the demands in the future. However, an all optical (O-O-O) amplifier does not set any restrictions on the signals that it amplifies. The main advantage of O-O-O equipment over O-E-O equipment is the scalability of the optical network without having to change the O-O-O equipment.

The scalability of O-O-O equipment and the physical security of all optical communication are the main reasons all optical networks are seen as the future networks. The planning and designing of optical networks is in general a more difficult problem than that of electrical networks. The reason is each physical link can carry multiple wavelengths. This means that each connection needs to be assigned a path (route) and have a wavelength assignment on that route. This problem of routing and wavelength assignment is the well-known RWA problem. There is much research on the RWA problem, and a good review/introduction is a paper by Mukherjee, et. al [2].

The RWA problem is generally formulated for all-optical networks using wavelength division multiplexing (WDM). At the present, WDM is classified as coarse WDM (CWDM) with ≈ 40 wavelengths per fiber and as dense WDM (DWDM) with ≈ 160 wavelengths per fiber. However, we do not restrict our model to any type of WDM, and we try to provide a model that is as flexible as possible.

In general we can split the RWA problem into two cases. We can consider the network traffic to be static or dynamic. The static case is called the static lightpath establishment or SLE problem. If the traffic is handled on a first come first serve basis, then we need to model the adding and, possibly, subtracting of connections over time. This method of handling dynamic traffic is known as the dynamic lightpath establishment or DLE problem [2]. In this paper, we focus on the core networks, and we assume that the connections are relatively static.

The general RWA problem can be reduced to only a routing problem if all the nodes have full wavelength conversion capabilities. A side effect is the overall blocking probability is decreased. The problem is the wavelength conversion equipment of today is very expensive, and it has been shown that near-optimal performance can be achieved with sparsely located wavelength conversion equipment. However, the performance of a network with sparse wavelength conversion is very sensitive to the placement of the wavelength conversion equipment. In addition, finding a near-optimal solution to an RWA problem with sparse wavelength conversion is even more difficult than the same RWA problem with no wavelength conversion [2].

Besides the added complexity of sparse wavelength conversion, the RWA problem can be further complicated by allowing traffic grooming. Traffic grooming takes two or more incoming connections and sends the out on the same lightpath. That is, we can think of traffic grooming as allowing multiplexing and demultiplexing of connections as long as they respect the bandwidth constraint of the lightpath. We denote the RWA problem with traffic grooming as the GRWA problem.

The rest of the paper is presented in the following order. First we define and discuss the RWA SLE problem with traffic grooming. Next, an integer linear programming (ILP) model is given for the GRWA problem with sparse wavelength and grooming resources. The model is discussed, and optimal solutions for particular networks and connections are presented. The solutions are compared with those of the general RWA and other grooming methods. Finally, a concise idea is presented and ideas for future work are given.

2. RWA PROBLEM WITH TRAFFIC GROOMING

The routing and wavelength assignment problem with traffic grooming for static lightpaths (GRWA) with (SLE) provides a method to handle connection requests with a wide range of capacities. For example, suppose that we have a backbone network with *OC-N* capacity on each link and switch, and we allow connections with capacity *OC-n* with $1 \leq n \leq N$. If there is no traffic grooming, then an *OC-1* connection request will require a lightpath of size *OC-N*. In this case most of the capacity of the lightpath is unused. This problem can be resolved by allowing the grooming of two or more connections, with capacity less than *OC-N*. Thus, we can see that traffic grooming can increase the utilization of a network.

The GRWA problem can be split into two cases. We can have grooming at the end points (source and destination nodes only); this type of grooming is known as single-hop traffic grooming [3]. If we remove this restriction, then we can have grooming at any node in the network; we denote the general grooming case as multihop traffic grooming [3]. In this paper, we concentrate on the multihop traffic grooming case, and allow for the possibility of on or more nodes having no grooming devices.

The GRWA problem we present is for backbone networks with static connections and full wavelength conversion. The restriction is the grooming and wavelength conversion resources are to be collocated in the nodes, and in the rest of the paper, grooming devices will also imply the (possible) presence of wavelength conversion equipment.

We wish to achieve several (possibly mutually exclusive) network properties with our model. In particular we seek to maximize the utilization of the network and at the same time, minimize the number of wavelengths needed. Another problem we look at is to minimize the cost of grooming hardware, while minimizing the number of wavelengths.

3. ILP MODEL FOR GRWA WITH SPARSE GROOMING RESOURCES

We have been able to model the static GRWA problem with sparse grooming resources as an integer linear programming (ILP) model in a manner that is similar to RWA models [2], [3], [4], [5] presented in the literature. Our formulation relies on several assumptions.

1) The network topology is a mesh with directed fiber connections. At most two fibers (one for each direction) can connect a pair of nodes.
2) The switches in our network may have grooming and full wavelength conversion capabilities. However, it is possible to require that one or more nodes have no grooming and no wavelength conversion capabilities.
3) At any given node, we have the required receivers and transponders for all the used wavelengths (provided the wavelength assignment is valid)
4) Lightpaths do not contain loops. We assume that the routing for a connection can be done using one of the paths given by the K-shortest paths algorithm.
5) The enumeration of all possible lightpaths is done by taking all the routes generated by K-shortest paths for each source destination. After all the routes are generated, we must generate all the possible wavelength assignments for each route. Each unique wavelength assignment on a route is considered as a unique lightpath. We note that the lightpaths cannot change wavelengths on the set of nodes that do not have any grooming devices.

Our formulation requires several items as input. The graph of the network is given as the sets of edges and vertices $(G = (V, E))$. The requested connections are given by a matrix for each desired connection size, with each element specifying the number of connections (of that size) for that source destination pair. If desired, one or more vertices may be forced to not have any grooming equipment. Besides these items, a few others are needed, such as, maximum capacity of a lightpath, etc.

The input is then preprocessed to provide the given network and requested connections as an ILP model. The preprocessing involves setting up many matrices including the lightpath-connection and lightpath-link incidence matrices. In order to find the possible lightpaths, an implementation of K-shortest paths is used to find the K-shortest routes for a given source-destination pair. Given a route, many lightpaths are generated by considering each possible permutation of wavelength assignment as a unique lightpath. Of course, we do take advantage of the fact that all nodes without grooming also have no wavelength conversion resources. After preprocessing, we must then use an ILP solver to solve our given model.

We now give our ILP model for GRWA with sparse wavelength conversion resources.

Notation

- lm and mn : Start-end node pairs for a physical fiber link. In addition, we enforce $l \neq m \neq n$ at all times.
- s, d : Source and destination nodes, respectively, of a requested connection.
- i, j : In general the row and column indices of a matrix.
- w : A particular wavelength.
- c : A particular connection size.
- P : Number of all possible lightpaths between source and destination nodes.

Given

- $C_{\max}$: Capacity of one wavelength on one fiber.
- $C = [1; 3; 12; \ldots; C_{\max}]$: Capacities of connection sizes.
- L : Number of links.
- W : Number of wavelengths per fiber.
- N : Number of nodes.
- N_{sd} : Number of source-destination pairs.
- $D = [d_i]$ Vector of length P, where

  d_i = number of links used by path i.
- $\phi = [\phi_m]$ Vector of length N, where

$$\phi_m = \begin{cases} 1 \text{ if node } i \text{ has no grooming devices} \\ 0 \text{ otherwise} \end{cases}$$

- $\Lambda = [\lambda_{ij}]$: Requested connections matrix of size N_{sd} x $|C|$, where

$$\lambda_{ij} = \begin{cases} n \text{ if } n \text{ conns. of size } c_j \in C \text{ are req.} \\ 0 \text{ otherwise} \end{cases}$$

- $A = [a_{ij}]$: The P x N_{sd} lightpath-connection incidence matrix, where

$$a_{ij} = \begin{cases} 1 \text{ if lightpath } i \text{ is between } sd \text{ pair } j \\ 0 \text{ iflightpath } i \text{ is not between } sd \text{ pair } j \end{cases}$$

- $G^w = [g^w_{ij}]$: A set of W P x L lightpath-link incidence matrices, where

$$g^w_{ij} = \begin{cases} 1 \text{ if light path } i \text{ uses wavelength } w \text{ on link } j \\ 0 \text{ if light path } i \text{ doesnt use } w \text{ on link } j \end{cases}$$

Variables

- $X = [x_{ij}]$: The path variable matrix with size P x $|C|$, where

$$x_{ij} = \begin{cases} n \text{ if lightpath } i \text{ has } n \text{ conns. of size } c_j \\ 0 \text{ if lightpath } i \text{ has no conns. of size } c_j \end{cases}$$

- $S = [s_i]$: Vector of length P, where

$$s_i = \sum_j x_{ij}$$

- y^{wd}_{mn}: Indicator variable for route and wavelength assignment of traffic introduced on the nodes. Given a node m and routing wavelength wd we have for each link.

$$y^{wd}_{mn} = \begin{cases} 0 \text{ if no lp starts at } m \text{ and uses } wd \text{ on } mn \\ 1 \text{ if an lp starts at } m \text{ and uses } wd \text{ on } mn \end{cases}$$

- $y^{ws\ wd}_{lmn}$: Indicator variable for route and wavelength assignment of traffic on the nodes. Given an incoming wavelength ws and outgoing wavelength wd, node m, and incoming link lm, we have for each outgoing link mn:

$$y^{wd}_{mn} = \begin{cases} 0 \text{ if no lp uses ws on } lm \text{ and } wd \text{ on } mn \\ 1 \text{ if lp uses ws on } lm \text{ and } wd \text{ on } mn \end{cases}$$

Optimize Minimize the total number of hops used by all the routed connections.

$$\textbf{Minimize } S.D \qquad (1)$$

Subject to

$$\mathrm{A}^T X \geq \Lambda \tag{2}$$

$$\sum_{1 \leq j \leq |C|} c_j \; col_j(X) \;.\!*\; col_k(G^w) \leq C_{\max} \quad \forall k, w \tag{3}$$

$$S \;.\; (col_{lm}(G^{ws}) \;.\!*\; col_{mn}(G^{wd})) = \psi_{lmn}^{ws\ wd} \tag{4}$$

$$y_{lmn}^{wswd} \leq \psi_{lmn}^{ws\ wd} \tag{5}$$

$$C_{\max}\, y_{lmn}^{wswd} \geq \psi_{lmn}^{ws\ wd} \tag{6}$$

$$S \;.\; (col_{mn}(G^{wd}) - \sum_{l,ws} \psi_{lmn}^{ws\ wd} = y_{lmn}^{wd} \tag{7}$$

$$\phi_m \sum_{mn,wd} y_{lmn}^{wswd} \leq 1 \qquad \forall lm, ws \tag{8}$$

$$\phi_m (y_{lmn}^{wd} + \sum_{lm,ws} y_{lmn}^{wswd}) \leq 1 \qquad \forall mn, wd \tag{9}$$

Explanation of Equations: We desire to minimize the number of hops used by all the nodes in the network. We start by enumerating all the possible lightpaths, and then, impose our desired conditions on the selected lightpaths. The objective function to minimize is (1). Inequality (2) requires the number of routed connections for a given source destination pair to be greater than or equal to the number of requested connections for that pair. (3) requires the sum of the sizes of the connections on any channel to not exceed the channel capacity. We use (4) to substitute for the expression on the left hand side in the next inequalities. (5) and (6) are used to make the y variables boolean and exist for each fixed set of ws, wd, l, m, n. Inequality (7) gives variables that express how many connections were added at a given node and sent out on a given channel and exists for each fixed set of wd, m, n. Nodes without grooming devices cannot demultiplex connections (8) or multiplex connections (9). Wavelength conversion on nodes without grooming devices is precluded by the enumeration of the lightpaths.

Additional Problems: We can solve the end-to-end grooming problem by forcing all nodes that are not a source or a destination node to have no grooming capabilities. Constraints must be added so that all the lightpaths passing through a source or destination node are not added to or subtracted from.

If we wish to have a cost based objective function, one way to do it is the following. We assume the main portion of the additional costs for the grooming enabled switches comes from adding connections, dropping connections, and wavelength conversion. The cost for grooming is α times the number of groomed connections and β times the number of wavelength conversions. The statement of the cost based ILP requires all of the utilization specification except for D and the optimization function. Here we redefine D, give a new optimization function, and provide a few more constraints.

Optimize Minimize the total cost of the grooming and wavelength conversion equipment. We have assumed that $\alpha < \beta$, but it is not required.

- $D = [d_i]$: Vector of length P, where d_i is the number of links plus β times the number of wavelength conversions used by lightpath i.

$$\textbf{Minimize } D.S + \alpha(\sum_{m,n} z_{mn} + \sum_{l,m} j_{lm}) \tag{10}$$

Subject to

$$\sum_{l,ws} y_{lmn}^{ws\ \mathrm{wd}} > u_{mn}^{wd} \tag{11}$$

$$\sum_{l,ws} y_{lmn}^{ws\ \mathrm{wd}} < C_{\max} u_{mn}^{wd} \tag{12}$$

$$\sum_{n,wd} y_{lmn}^{ws\ \mathrm{wd}} > v_{lm}^{ws} \tag{13}$$

$$\sum_{n,wd} y_{lmn}^{ws\ \mathrm{wd}} < C_{\max} v_{lm}^{ws} \tag{14}$$

$$\sum_{l,ws} y_{lmn}^{ws\ \mathrm{wd}} + y_{mn}^{\mathrm{wd}} - u_{mn}^{wd} = z_{mn} \tag{15}$$

$$\sum_{m,wd} y_{lmn}^{ws\ \mathrm{wd}} - v_{lm}^{ws} = j_{lm} \tag{16}$$

Explanation of Equations: (10) is the objective function to minimize and could be changed to follow a network designers specifications. (11) and (12) require the u variables to indicate if any multiplexing has occurred. (13) and (14) cause the v variables to indicate if any demultiplexing has occurred. (15) and (16) are just used to provide a smaller expression for the minimization function.

We believe that our mathematical formulation is very flexible and should be considered by network designers. This would give the option of grooming traffic, and provide benefits in the future. Careful grooming will allow conservation of wavelengths so that more traffic can be added without the addition of new equipment in the nodes. This allows one to keep an existing backbone all-optical network, and increase its capacity over that provided by the RWA problem and grooming at the end points.

4. RESULTS

For figure 1 and figure 2 we have an associated traffic table I of connections that we wish to route. We solve both the utilization and the cost problems for the given traffic table.

	1→4	1→6	2→4	3→5	4→3	5→6	6→4
OC-1	3	0	1	0	0	0	2
OC-12	0	2	0	1	2	1	0
OC-48	2	0	0	0	0	0	1

TABLE I:
THE TRAFFIC TO ROUTE ON THE NETWORK

For our example, we assume that the maximum connection size is OC-48 and that each link has two available wavelengths. The solution for the cost problem does not use any wavelength conversion (because the grooming cost is much less than the wavelength conversion cost, and the connections can be routed without using wavelength conversion). Another observation is that grooming is performed only on two of the nodes in the cost problem.

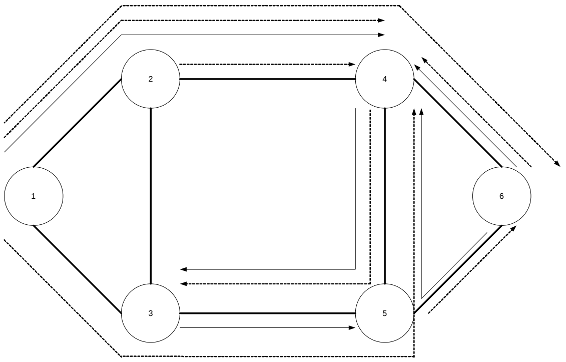

Fig.1. Routing and wavelength Assignment for Cost

On the other hand, the solution for the utilization problem does use wavelength conversion. Unlike the cost problem, in the utilization problem grooming and wavelength conversion are encouraged since we are trying to minimize the total number of hops on the network. We see that the utilization problem does favor grooming over using multiple wavelengths and the cost problem always chooses using multiple wavelengths (when available). Of course, the reason is we have no associated cost for using multiple wavelengths instead of grooming, but grooming does have an associated cost.

To compare our example and solutions with those of others, we need to examine other methods of routing the connections. Since 5 connections have node 1 as their source, we could say that this example requires more than 2 wavelengths unless there is at least end-to-end grooming. However, closer consideration shows that if we stipulate that we have no more than two available wavelengths, then there is contention for both links 2→4 and 3→5. The problem is that node 1 needs at least three connections to node 4 and one connection to node 6, node 2 needs one connection to node 4, and node 3 needs one connection to node 5 (that is we need to route 5 connections over the two links which support only 4 total). We see that our example requires grooming in nodes other than end nodes, and grooming is not required on all of the nodes. In addition, wavelength conversion is not required on all of the nodes, and when the cost of wavelength conversion is higher than the grooming cost, grooming will be chosen over wavelength conversion. Another benefit is the amount of required grooming equipment. In the cost problem for this example we only need grooming equipment at two nodes.

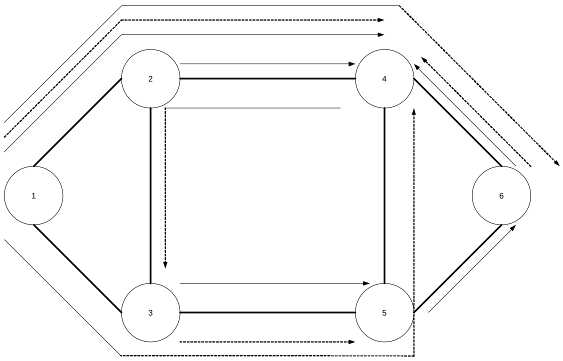

Fig.2. Routing and wavelength Assignment for Utilization

5. CONCLUSION

We have given a mathematical model (ILP) for the WA problem with SLE and parse wavelength and traffic rooming. This model is very powerful and is very flexible. However, because the RWA problem is known to be NP-Complete, we know that the GRWA problem is NP-Complete. Thus, other approaches are needed for large networks and/or a large number of wavelengths.

We expect that as all-optical long-haul networks become the norm, they will require grooming to conserve wavelengths and maximize the utilization of the resources. Also, as mesh networks are seen to be more resilient, flexible, and cost effective (e.g. see [5] and references therein). We expect that SONET rings will be replaced by DWDM meshes, and our model can provide an optimal solution to the GRWA problem.

6. FUTURE WORK

We expect that a genetic algorithm (GA) approach is the best option to solve the GRWA problem for large networks. This may be done by using the K-shortest paths algorithm for each source destination node pair. A GA would be used to find which routes to use and for each selected route, assign a wavelength to each link. After deciding on an encoding scheme, the crossover and mutation operators would need to be defined. In general, we expect that one could use a repair strategy [6] or a hybrid [7] to resolve chromosomes within feasible solutions.

If a GA approach is too difficult or is computationally intensive, a set of heuristics could be proposed.

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