

Design of WDM Mesh Networks with Sparse Grooming Capability

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Abstract – In a WDM optical network, the bandwidth requirement of a customer's connection can vary over a wide range, and many of these connections could have a capacity that is much lower than the capacity of a wavelength channel. Efficiently grooming low-speed connections onto high-capacity wavelength channels can significantly improve the bandwidth utilization and minimize the network cost. Our research shows that it is not necessary to have traffic-grooming capability at every network node. We call a network which has only a few grooming nodes to be a *sparse-grooming network*. Through proper network design and traffic engineering, it is possible for a sparse-grooming network to achieve similar network performance as a network which has grooming capability at every node. We investigate the problem of designing such a sparse-grooming WDM mesh network. The problem is mathematically formulated and several design schemes are proposed. Illustrative numerical results from the mathematical formulation as well as heuristics show that, by properly choosing the grooming nodes, a network with sparse-grooming capability can achieve good network performance and the network cost can be significantly reduced.

I. INTRODUCTION

Wavelength-division multiplexing (WDM) technology provides huge amount of link bandwidth to today's telecom networks. As WDM technology keeps maturing, there is a bandwidth gap between a wavelength channel's transmission speed (over a gigabit per second (Gbps)) and the capacity requirement of customers' connections, which may vary in range from STS-1 (51.84 Mbps) (or lower), up to full wavelength-channel capacity. In order to ensure the most efficient utilization of network resources, and to maximize revenue from existing capacity, the low-speed traffic streams need to be efficiently "groomed" onto high-capacity optical channels (commonly referred to as lightpaths).

Most previous research on traffic grooming was conducted on SONET/WDM ring networks (e.g., [1] - [4]). It is well accepted that WDM mesh networks are more scalable, flexible, and resource efficient than WDM/SONET ring networks. Hence, WDM mesh networks are very suitable for long-haul backbone networking applications, and they are the focus of our current research. With the emergence of grooming optical crossconnects (G-OXC), traffic grooming in WDM mesh networks becomes an extremely important problem and it has been

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gaining more attention in industry and academe [5] - [8]. In all previous research on traffic grooming in WDM mesh networks, it is assumed that every network node has traffic-grooming capability, which may not be practical or cost-effective in a nationwide WDM backbone network.

Figure 1 shows a sample G-OXC architecture. There are two switching fabrics in this OXC, a wavelength-switching fabric (W-Fabric) and a grooming fabric (G-Fabric). Because a grooming OXC may be more costly than an OXC without grooming capability (i.e., the OXCs which only have the W-Fabric), and the G-OXCs from different vendors may have different grooming capability, in a multi-vendor inter-operational WDM mesh network, only a few network nodes may have traffic-grooming capability. We call this type of network a "sparse-grooming network", and we call a node which has traffic-grooming capability to be a *grooming node* (G-Node).

Hence, the problem of designing a sparse-grooming WDM mesh network is a very important and practical problem. To the best of our knowledge, no previous work has addressed the sparse-grooming problem in the literature. In this study, we investigate the problem of efficiently designing a sparse-grooming WDM mesh network for a given set of traffic requests via theoretical formulation as well as simulation experiments. The results from our research indicate that, through careful network design, a sparse-grooming WDM network can achieve similar network performance as a full-grooming network, while significantly reducing the network cost.

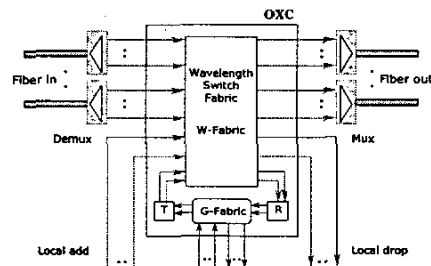


Fig. 1. A sample architecture of a G-OXC. Note that the G-Fabric is present only in a grooming node, while the W-Fabric is present in all nodes.

Figure 2 shows an example of designing a sparse-grooming WDM mesh network. Figure 2(a) shows a six-node network, where each edge represents a pair of unidirectional fiber links. For simplicity of illustration, let us assume that each fiber supports one wavelength channel, which can carry two low-speed

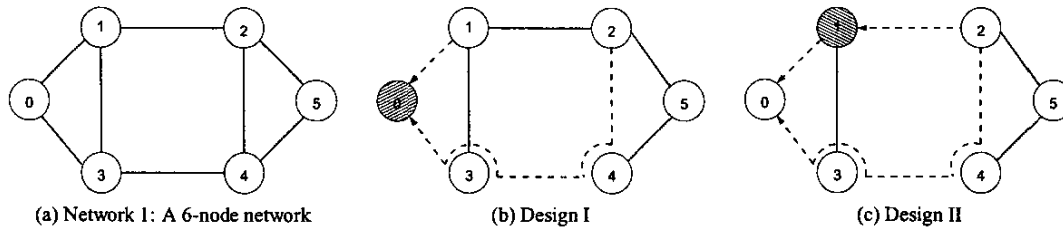


Fig. 2. A sample network and two sparse-grooming network designs.

connection requests. And only one G-OXC is allowed to be used in the network. Assume that there are four low-speed requests, among which three are between node pair (2, 0) and one between node pair (1, 0). Two network designs are shown in Fig. 2. The shaded nodes represent the G-Nodes, and the dashed lines represent established lightpaths.

In Design I (Fig. 2(b)), node 0 is the G-Node. Two lightpaths – (1, 0) and (2, 0) – are established. Three requests can be satisfied by these lightpaths: two between (2, 0), and one between (1, 0). In Design II (Fig. 2(c)), three lightpaths are set up: (2, 0), (1, 0), and (2, 1). Note that in Design II all requests can be satisfied. Thus, this simple example illustrates that improved performance can be achieved by carefully choosing the G-Node and engineering the traffic in the network.

In this paper, we study the problem of how to efficiently design such a sparse-grooming WDM mesh network. Section II gives the formal problem statement. Then, mathematical formulations for two objective functions are presented. Fast heuristic algorithms, which can be used to handle large network topologies, are proposed in Section III. Then, illustrative numerical results from mathematical formulations as well as heuristics are shown and analyzed in Section IV. Finally, Section V concludes the study.

II. PROBLEM STATEMENT AND MATHEMATICAL FORMULATION

We formally define the problem as follows: given a network topology $G(V, E)$, where V represents the node set and E represents the link set of the network; given traffic matrix Λ , where each element represents the number of low-speed requests between a node pair; assume that each wavelength channel can support g low-speed requests (where g is known as *grooming ratio*); design the network such that either one of following two objectives can be optimized:

- 1) For a given certain amount of network resources (number of G-OXCs N_g , and number of wavelengths W on each fiber), maximize the network throughput.
- 2) Carry all traffic requests, while simultaneously minimizing the overall network cost, which is determined by the number of wavelength channels and G-OXCs used in the network.

Figure 3 shows a WDM network in which two low-speed requests ($C1$ and $C2$) are being carried. Both requests are from node 1 to node 5. In Fig. 3, nodes 2 and 3 are G-Nodes, and only their G-Fabrics are shown. Nodes 1, 4, and 5 are equipped with OXCs without grooming capability. Figure 3 shows that,

in a sparse-grooming mesh network, a low-speed request can be carried either by a single lightpath ($C1$) or by traversing multiple lightpaths and G-Nodes ($C2$).

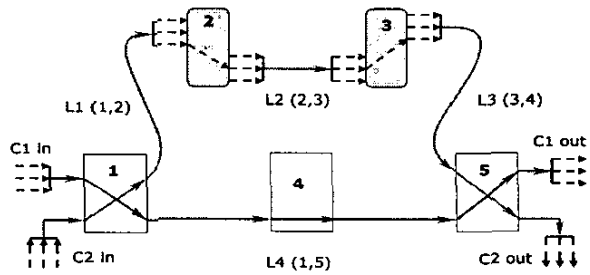


Fig. 3. A sample sparse-grooming WDM network which carries two requests using four lightpaths.

We formulate the problem mathematically and it turns out to be an integer linear program (ILP). Due to space limitations, only the most important equations of the formulation are presented here. The following notations and variables are used:

- (m, n) , (i, j) , and (s, d) denote the end nodes of a fiber, a lightpath, and a low-speed request, respectively.
- There are four types of lightpaths, represented by (i, j) , (i', j) , (i, j') and (i', j') . (i, j) denotes a lightpath which does not connect with any G-Fabric at its end nodes, e.g., $L4(1, 5)$ in Fig. 3. (i', j) , (i, j') , and (i', j') denote the lightpaths which are connected to G-Fabrics at the source node, the destination node, and both nodes, respectively, e.g., $L3$, $L1$, and $L2$ in Fig. 3(b). We use V_{ij} , $V_{i'j}$, $V_{ij'}$ and $V_{i'j'}$ to denote the number of each type of lightpaths.
- P_{mn}^{ij} , $P_{mn}^{i'j}$, $P_{mn}^{ij'}$, and $P_{mn}^{i'j'}$ denote the number of wavelengths which have been used to support each type of lightpaths, on fiber (m, n) . P_{mn} denotes the number of fiber links between node pair (m, n) .
- T_{ij}^{sd} , $T_{i'j}^{sd}$, $T_{ij'}^{sd}$, and $T_{i'j'}^{sd}$ denote the total amount of traffic between node pair (s, d) , which are being carried by the lightpaths (i, j) , (i', j) , (i, j') , and (i', j') , respectively. T_{sd} denotes the successfully carried traffic between (s, d) . Λ_{sd} denotes the total offered traffic between (s, d) . Note that $T_{sd} \leq \Lambda_{sd}$.
- $M_i = 1$ if node i is a G-Node; otherwise, $M_i = 0$.

A. Maximize Network Throughput

Given W wavelengths per fiber link and N_g as the number of G-OXCs which can be used in the network, the problem can be formulated as follows:

- Objective Function:

$$\text{Maximize: } \sum_{s,d} T_{sd} \quad (1)$$

- Constraints:

$$\sum_m P_{mk}^{ij} = \sum_n P_{kn}^{ij} \quad (2)$$

$$\sum_{i,j} (P_{mn}^{ij} + P_{mn}^{i'j} + P_{mn}^{ij'} + P_{mn}^{i'j'}) \leq W \times P_{mn} \quad (3)$$

$$T_{sk'}^{sd} + \sum_i T_{i'k'}^{sd} = T_{k'd}^{sd} + \sum_j T_{k'j'}^{sd} \quad (4)$$

$$\sum_{s,d} T_{i'j'}^{sd} \leq g \times V_{i'j'} \quad (5)$$

$$T_{sd}^{sd} + T_{s'd}^{sd} + T_{s'j'}^{sd} + T_{s'j'}^{sd} = T_{sd} \quad (6)$$

$$T_{sd}^{sd} + T_{sd'}^{sd} + T_{i'd}^{sd} + T_{i'd'}^{sd} = T_{sd} \quad (7)$$

$$\sum_j (V_{ij} + V_{ij'} + V_{j'i} + V_{j'i'}) \leq M_i \times D \quad (8)$$

$$\sum_i M_i \leq N_g \quad (9)$$

Equation (2) is the flow-conservation equation at node k for establishing lightpaths (i, j) , which may use node k as an intermediate node. There are similar equations for lightpaths (i', j) , (i, j') , and (i', j') . Equation (3) is the resource-constraint equation for a fiber link (m, n) , i.e., the total number of lightpaths (four types) carried by fiber (m, n) cannot exceed the total number of wavelength channels in fiber (m, n) . Equation (4) is the flow-conservation equation at any intermediate node k for routing the requests between (s, d) , which may use node k as an intermediate G-Node. Equation (5) is the resource-constraint equation for lightpaths (i', j') , i.e., the total number of low-speed connections carried by the lightpath (i', j') cannot exceed the overall capacity of lightpath (i', j') . There are similar equations for lightpaths (i, j) , (i', j) , and (i, j') . Equation (6) guarantees that, for a given node pair (s, d) , the amount of traffic successfully flowing out from the source node should be equal to the amount of traffic that can be successfully carried between (s, d) . Equation (7) captures the similar constraint at the destination side. Equation (8) ensures that node i is a G-Node if there is a lightpath connected to its G-Fabric (i.e., node i initiates or terminates a lightpath at its G-Fabric). D is a large constant, which can be the upper bound on the maximum number of lightpaths that can originate from any node. Equation (9) ensures that there are at most N_g G-Nodes in the network.

B. Minimize Network Cost

Let C_w denote the cost of supporting one wavelength channel in the network, and C_g denote the extra cost of employing a G-OXC instead of an OXC without grooming capability. The second network design objective can be achieved using the following formulation. Most equations are the same as those in Section II-A, and we only present the different ones below:

- Objective Function:

$$\text{Minimize: } W \times C_w + N_g \times C_g \quad (10)$$

- Constraints:

$$T_{sd} = \Lambda_{sd} \quad (11)$$

III. HEURISTIC APPROACHES

The computational complexity makes the ILP formulations only suitable for designing small or moderate-sized WDM networks. When the network size is large, i.e., there are about several tens of network nodes (e.g., Fig. 4), efficient heuristics are needed to solve the problem.

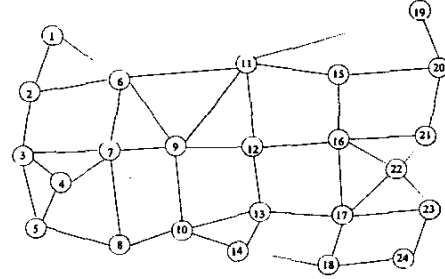


Fig. 4. Sample network topology used in this study.

For a given network topology and given values of N_g and W , we design a heuristic $\delta(N_g, W)$ which chooses G-Nodes and routes the traffic requests to maximize the network throughput (for the first objective function). The second objective function can be achieved by starting with small values of N_g and W , and gradually increasing N_g and W until all the traffic requests are satisfied. In this section, we concentrate on the development of such a heuristic $\delta(N_g, W)$ for the first objective function.

Given a WDM network topology $G(V, E)$ and a list of traffic demands Λ , the heuristic $\delta(N_g, W)$ is composed of the following two steps.

- 1) Choose N_g nodes as G-Nodes from V , based on certain cost function $F_c(v)$ for a given node v (to be elaborated below).
- 2) Route the traffic requests on the network subject to the network resource constraints. Let $F_r(\delta)$ denote the algorithm to be used to route the traffic requests. When the traffic is static (known a priori), the algorithm may contain some backtracking procedure; when the traffic is dynamic or incremental, no backtracking is allowed, and the requests will be carried in a first-come first-served manner. In this study, we consider static traffic.

A. Grooming-Node-Selection Schemes

We propose and study the characteristics of three different cost functions for selecting G-Nodes, namely nodal-degree selection, bypass-traffic selection, and random selection. Note that some ideas on these node-selection schemes are borrowed from sparse-wavelength-converter-placement studies [9], [10].

- **Nodal-Degree Selection:** In this scheme, the first N_g nodes which have the maximum nodal degree are picked to be G-Nodes. If several nodes have same nodal degree and only some of them can be chosen, random selection is used to break any ties.
- **Bypass-Traffic Selection:** For a given node v , $F_c(v)$ is computed as the total amount of traffic which may bypass the node, assuming each traffic request is routed on the physical network topology using a standard shortest-path routing algorithm. The N_g nodes which have maximum amount of bypass traffic can be selected as the G-Nodes. Instead of routing the traffic requests between a node pair (s, d) using a single shortest-path route, it may be also possible to compute $K (K \geq 2)$ alternate paths between (s, d) and bifurcate the traffic among these K alternate paths.
- **Random Selection:** In this scheme, N_g nodes are randomly picked to be G-Nodes.

One can also design other schemes to select the G-Nodes. Similar heuristics exist in the study of sparse wavelength conversion in WDM networks [9], [10].

B. Traffic Routing Scheme

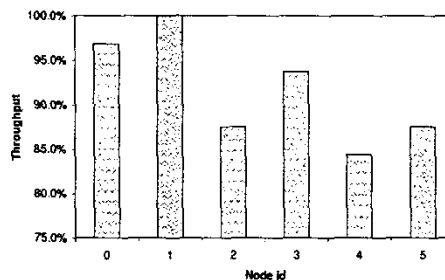
A simple algorithm is used in our study to perform traffic routing after the network resources have been determined and allocated. Given a set of traffic requests, a request list is generated based on a random permutation of all the requests. The requests are then served sequentially following their order in the list. L such random lists can be generated and tried. The best one among these L results will be taken as the final result. In our study, we choose $L = 50$. If L is equal to 1, the traffic pattern is equivalent to incremental traffic where connection requests arrive one at a time.

IV. ILLUSTRATIVE NUMERICAL EXAMPLES

Figure 5 shows an illustrative numerical example based on a sample network shown in Fig. 2(a). For simplicity of exposition, let each fiber in this example support two wavelengths ($W = 2$), each wavelength can carry two low-speed connection requests ($g = 2$), and there is one G-OXC which needs to be placed in the network ($N_g = 1$). Figure 5(a) shows a randomly-generated traffic matrix, in which each element represents the number of low-speed connection requests between a node pair. The total number of low-speed requests is 32 in this example. We use "CPLEX", a commercial optimization software package, to solve the ILP formulation. For this example, our study shows that node 1 is the best candidate node to be the G-Node. Then, we force our formulation to artificially select each of the other nodes separately to be the G-Node and compare the network throughput with that of the best design (i.e., selecting node 1). The performance comparison is shown in Fig. 5(b). The horizontal axis in Fig. 5(b) represents the node chosen as the G-Node. The vertical axis in Fig. 5(b) shows the optimal network throughput (obtained via ILP formulation) by choosing the corresponding node as the G-Node. It is observed that 100% network throughput can be achieved if the G-Node

	NODE 0	NODE 1	NODE 2	NODE 3	NODE 4	NODE 5
NODE 0	0	1	1	1	0	0
NODE 1	1	0	1	1	0	2
NODE 2	0	1	0	2	1	0
NODE 3	2	0	2	0	2	0
NODE 4	1	2	0	2	0	1
NODE 5	1	1	2	2	2	0

(a) Traffic Matrix



(b) Network Throughput vs Grooming Node Id

Fig. 5. Illustrative Result from ILP Formulation for Topology 1 assuming only one node has grooming capability.

is node 1; at the other performance extreme, if node 4 is chosen as the G-Node, the network throughput is below 85%. The results indicate that a network operator can increase the network throughput as well as reduce the network cost (using less grooming equipment in the network) by carefully designing a sparse-grooming WDM mesh network.

When a network has several tens of nodes, the ILP approach becomes computationally intractable; hence, heuristic will need to be used. Figures 6 and 7 show the results obtained on the network topology of Fig. 4, using the heuristic algorithms proposed in Section III. The network contains 24 nodes and 43 bidirectional fiber links. Traffic demands are randomly generated between each node pair with uniform distribution between $(0, 3)$. Each fiber link can support eight wavelength channels ($W = 8$). Different values of the grooming ratio g will be investigated below.

Figure 6 shows the performance comparison between different G-Node selection schemes. It can be observed that random selection does not perform as well as the others. Selecting the G-Node by bypassing traffic achieves better performance than selecting the G-Node by nodal degree in most cases. This is because the Bypass-Traffic-Selection Scheme considers the network topology as well as the traffic intensity at each node. We can also observe that, if the grooming ratio is equal to eight ($g = 8$), when the number of G-Nodes exceed a certain bound ($N_g = 16$ in this case), no additional performance gain can be achieved by having more grooming nodes in the network. We can also observe that, when the grooming ratio is large (e.g., $g = 8$), having more grooming nodes will achieve better network performance than the case when the grooming ratio is small (e.g., $g = 4$).

Figure 7 shows different network costs based on different

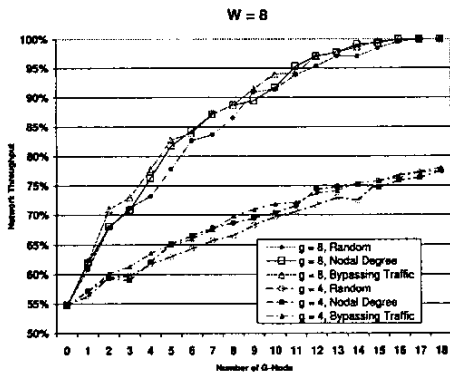


Fig. 6.P Performance comparison between different G-Node selection schemes applied to the network in Fig. 4.

values of the cost ratio R , which is defined as follows:

$$R = C_w / C_g \quad (12)$$

where C_w denotes the cost (equipment cost, operational cost, etc.) to support one wavelength channel in the network, and C_g denotes the cost to employ grooming capability in a network node. The network cost C_n can be represented as:

$$C_n = N_g \times C_g + W \times C_w = (N_g + R \times W) \times C_g \quad (13)$$

The horizontal axis (W, N_g) in Fig. 7 represents, for a given number of wavelength channels on each fiber link (W), how many G-Nodes (N_g) are needed to satisfy all the requests. By normalizing the cost C_g to be one unit, the vertical axis represents the overall network cost computed using Eqn. (13).

We can observe in Fig. 7 that, for a given cost ratio R , an optimal design with minimal overall network cost can be achieved. This optimal configuration reflects the cost trade-off between a grooming node and a wavelength channel. When the cost of a wavelength channel is cheaper compared to the cost of a grooming node (for $R = 0.1$, and $R = 0.5$), more wavelength channels and less grooming nodes should be used, and vice versa (for $R = 2$). Note that, although the cost of a wavelength channel will decrease as WDM technology keeps maturing, supporting more wavelength channels in a nationwide WDM backbone network may still be expensive because of the large geographic distance between the network nodes, the number of fiber links a backbone network may have, and the cost for network monitoring, maintenance, and management.

V. CONCLUSION

This study is devoted to the problem of designing a WDM mesh backbone network with sparse traffic-grooming capability. The mathematical formulations (ILPs) for two design objective functions were presented. Due to the large computational complexity of ILPs, three heuristic algorithms were also proposed to solve large instances of the problem. Our results from both the mathematical formulations and heuristics show

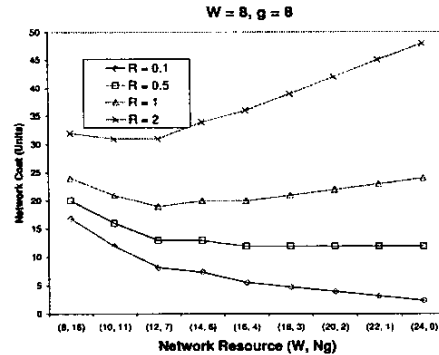


Fig. 7. Network cost vs. network resources based on different cost ratio R .

that, by employing a limited number of grooming nodes, the network capacity can be used more efficiently and the network performance can be improved significantly. We also showed that it is possible to find a balance between the number of wavelength channels and the number of grooming nodes used in the network. This balance will eventually reduce the network cost. Further study is needed on the effect of sparse grooming on dynamic traffic, and more intelligent heuristic algorithms could also be developed.

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