Hierarchical Grooming in Multigranular Networks

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Abstract— **We present a hierarchical algorithm for grooming lightpaths into wavebands, and routing wavebands over a network of multigranular switching nodes. Our approach is conceptually simple, scalable, and consistent with the way networks are operated and controlled in practice.**

I. INTRODUCTION

Future optical networks are expected to carry traffic demands that range in size from sub- to super-wavelength. To ensure that resources are utilized efficiently, traffic demands must be aggregated and carried over the network in a cost-effective manner. It has been recognized that combining multiple wavelengths into logical containers called "wavebands" can lead to a significant reduction in the number of *optical* switching ports in the network, since intermediate nodes only need a single port to switch a waveband. This observation has led to the development of multigranular optical cross-connects (MG-OXCs) which are capable of switching optical signals at a hierarchy of granularities: single wavelengths, single wavebands, or whole fibers. Multi-layer MG-OXCs consist of separate layers of cross-connects that switch traffic at the fiber (FXC), waveband (BXC), or wavelength (WXC) granularity. Single-layer MG-OXCs, on the other hand, consist of a unified layer which understands fibers, wavelengths and wavebands. Studies have concluded that single-layer MG-OXCs provide greater reduction in switch size under a static traffic model, while multi-layer MG-OXCs provide lower blocking probability under a dynamic traffic model.

With the availability of MG-OXCs, a new network design problem has emerged, namely, the problem of grooming wavelength demands onto wavebands and routing these wavebands over a multigranular optical network so as to minimize the number of optical switching ports. Most studies [1], [4] regard the network as a flat entity for the purposes of lightpath grooming, waveband routing, and wavelength assignment. It is well-known, however, that in existing networks, resources are typically managed and controlled in a hierarchical manner. In earlier research we developed a hierarchical approach to grooming sub-wavelength demands that emulates the hub-and-spoke model used by the airline industry to "groom" passenger traffic onto connecting flights [2]. With the increase in the number of entities that need to be controlled, a hierarchical framework for managing wavebands is even more warranted in multigranular optical networks.

II. HIERARCHICAL BANDPATH GROOMING

We extend the hierarchical sub-wavelength grooming algorithm we developed [2] to tackle the lightpath grooming and bandpath routing problem. We assume that each node in the network is equipped with a medium-granularity MG-OXC similar to the one shown in Figure 1. In our model nodes source, sink, and switch traffic at the granularity of a single waveband, or higher. While having a waveband be the unit of carried traffic may seem wasteful for nodes sourcing or sinking an amount of traffic that is a fraction of the waveband capacity, our hierarchical approach does lead to efficient solutions.

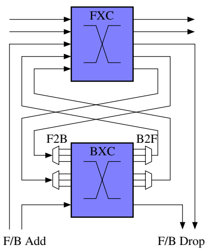

Fig. 1. Medium granularity MG-OXC (F: fiber, B: waveband)

We assume that the network is partitioned into clusters (or islands) of nodes, where each cluster consists of nodes in a contiguous region of the network. The clusters may correspond to independent administrative entities (e.g., autonomous systems), or may be created solely for the purpose of simplifying resource management and control functions. For the purposes of grooming and routing, we designate one node within each cluster as the *hub*. The main idea of the hierarchical strategy is to solve the lightpath grooming problem in two steps. In the first step, all nodes send their traffic to the hub for grooming. In the next step, each hub sends inter-cluster traffic to the appropriate remote hub for grooming and distribution to the remote hub's cluster. Once the inter- and intra-cluster bandpaths have been formed in this manner, we solve the third subproblem, i.e., the bandpath routing and waveband assignment problem, on the underlying physical topology using an existing RWA algorithm. Our approach provisions only a few nodes (the hubs) for grooming lightpaths they do not originate or terminate, and efficiently packs lightpaths among remote clusters onto wavebands between the corresponding hubs.

Our hierarchical algorithm consists of three phases:

1) **Clustering and hub selection.** In this phase, we use the 2-approximation K-center algorithm in [3] to partition the network into k clusters and select one node in each cluster as the hub. Individual clusters form the first level of the hierarchy, while the collection of cluster hubs forms the second level of the hierarchy.
2) **Logical topology design and lightpath grooming into bandpaths.** This phase consists of two parts:

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a) *Intra-cluster lightpath grooming.* Each node n forms a number of bandpaths to its local hub h as required to carry all the traffic it sources; i.e., if node n sources l lightpaths, the number of bandpaths from n to h formed is $\lceil l/L \rceil$, where L is the size of each waveband. In effect, all traffic sourced at non-hub nodes is first routed to the local hub where it is groomed for forwarding to the destination, as explained next.

b) *Inter-cluster lightpath grooming.* At the second level of the hierarchy, each hub h grooms lightpaths it receives into bandpaths as follows. Lightpaths from local nodes carrying traffic for nodes at a remote cluster with hub h', are packed into bandpaths with source h and destination h'. Similarly, lightpaths from local nodes or remote hubs carrying traffic to a local node n, are packed into bandpaths with source h and destination n.

At the end of this phase, the bandpaths to be set up are of one of three types, reflecting our hierarchical model: from a node to its local hub, from a hub to a node in its local cluster, or between two hub nodes.

3) **Bandpath routing and waveband assignment.** In this phase, our objective is to route the bandpaths over the underlying physical topology, and "color" them (i.e., assign to each a waveband) using a minimum number of wavebands. By substituting "lightpaths" for "bandpaths" and "wavelengths" for "wavebands", this problem may be seen as equivalent to the RWA problem that has been studied extensively in the literature. In this work, we adopt the LFAP algorithm [5], which is fast, conceptually simple, and has been shown to produce solutions that are close to the lower bound.

We note that non-hub nodes only add or drop their own traffic, and switch transit traffic, at the granularity of a waveband. Hub nodes are the only nodes that perform any grooming of lightpaths. Since lightpaths arriving on different wavebands may need to be groomed onto new wavebands towards the destination, we assume that hub nodes drop whole wavebands from incoming fibers, perform the grooming electronically, and add the new wavebands onto the outgoing fibers, consistent with the medium-granularity MG-OXC model in Figure 1.

Figure 2 presents representative simulation results for the 47-node, 96-link network topology in [2]. For our hierarchical algorithm, we partitioned this network into K clusters, $K = 4, 8, 12$, using the K-center algorithm in [3]. For comparison, we also implemented the BPHT algorithm [1] which regards the network as a flat entity and does not require any clustering. The traffic matrix T for each problem instance is generated by drawing $N(N-1)$ random numbers (where $N = 47$ is the number of nodes) from a Gaussian distribution with mean t and standard deviation of $0.1t$; all numbers are rounded up to the next integer, while any negative numbers are set to zero. The matrix thus generated represents the wavelength demands between all source-destination pairs. Figure 2 plots the optical port cost against the traffic load when the band size $L = 6$; four curves are shown, one for the BPHT algorithm and three for our hierarchical algorithm when the network is partitioned into $K = 4, 8,$ and 12 clusters. The BPHT curve exhibits a see-saw pattern that reaches a low point at multiples of the band size (plus one), almost identical to the behavior observed by the inventors of BPHT in [1]. However, when the average traffic component is not a multiple of the band size, the number of optical ports can become quite high. This indicates that once the band size has been fixed, the BPHT algorithm is sensitive to changes in the offered traffic, and relatively small changes in the traffic pattern may take the network far away from its optimal operating regime. For the hierarchical algorithm, the number of ports generally increases with the traffic load, as expected. Importantly, our algorithm produces solutions with lower optical port cost than the BPHT algorithm, across all traffic loads shown. We also see that the results of our algorithm depend on the number K of clusters. Specifically, as the number of clusters increases, each node tends to be closer to its local hub, hence carrying the traffic to/from the hub requires fewer ports; on the other hand, the amount of ports required for inter-cluster traffic is not affected significantly, as this traffic is effectively packed into wavebands. (*Note:* the fact that the number of ports is in the order of tens of thousands is due to the large number demands that need to be carried; specifically, the minimum (respectively, maximum) number of wavelength capacity demands that need to be accommodated is equal to $47 \times 46 \times 2 = 4324$, for average demand $t = 2$ (respectively, $47 \times 46 \times 16 = 34,592$, for $t = 16$).)

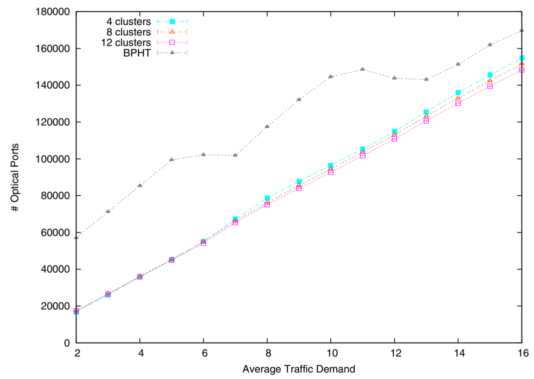

Fig. 2. Optical port cost, hierarchical and BPHT algorithms, band size $L = 6$

Overall, these results and others omitted due to space constraints indicate that the hierarchical algorithm is not only scalable, but also efficient in its use of network resources.

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