A Hierarchical Model for Multigranular Optical 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. This algorithm focuses on lowering the number of wavelengths W and ports over the network while being conceptually simple, scalable, and consistent with the way networks are operated and controlled in practice. Our experiments indicate that this algorithm easily scales across different waveband and network sizes.

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. Assuming that the fiber infrastructure exists, the network cost is typically taken as a function of the total number of the switching ports across all network nodes. When all demands are sub-wavelength in size, the network cost is related to the number of *electronic* switching ports required to combine the various traffic components onto wavelength-capacity lightpaths. The area of research concerned with cost-effective transport of sub-wavelength traffic over optical networks is referred to as "traffic grooming." The reader is referred to [10] for a comprehensive survey and classification of research on traffic grooming.

More recently, it has been recognized that combining multiple wavelengths into logical containers called "wavebands" [3] 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 (instead of one port for each of the constituent wavelengths). 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, including single wavelengths, single wavebands, or whole fibers. A discussion of the cost-performance tradeoffs using band aggregation overhead and band contention in MG-OXCs can be found in [16], where an analytical model was also developed to demonstrate the benefits (in terms of port cost) of MG-OXCs over plain OXCs.

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. Variants of this problem

have been studied in several contexts, and it has been found that the number of optical ports required to carry a given traffic matrix is affected by the composition of wavebands and the manner in which lightpaths are grouped into wavebands. The work in [11] establishes an equivalence between the waveband routing and wavelength assignment (RWA) and the logical topology design problems. The effect of uniform vs. non-uniform waveband size on switching cost is studied in [8], while [14] proposes non-uniform wavebands and addresses the issues of waveband size selection and wavelength assignment. A waveband RWA algorithm to minimize wavelength conversion is presented in [17].

Waveband routing heuristics for ring topologies can be found in [12], [15], [21]. A destination-based lightpath grouping mechanism for mesh networks is described in [18], and [4] presents a balanced path routing algorithm for forming wavebands in networks of general topology. According to the study in [19], same-destination-intermediate grouping of lightpaths works slightly better than end-to-end grouping in mesh networks. Waveband routing under dynamic traffic has been studied in [2], [5].

The above studies 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. 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. We base our algorithm on the same principles used in [7] to groom lightpaths into wavebands in a scalable and efficient manner.

Optical fibers carry a number of distinct wavelengths but are limited by the fiber's physical characteristics and state of optical technology to combine wavelengths onto or split them from the fiber [20]. Also, installing and maintaining new optical fibers is prohibitively expensive. Hence, the number of wavelengths used to satisfy traffic demands is an important measure in network design.

The objective of this work is to propose a hierarchical solution which is scalable across different waveband sizes and number of entities while satisfying a given set of traffic demands. We observe our work performs gives lower port cost and comparable wavelength cost considering the balanced path heavy traffic (BPHT) [4] algorithm. We assume uniform waveband size is used throughout the network, all network
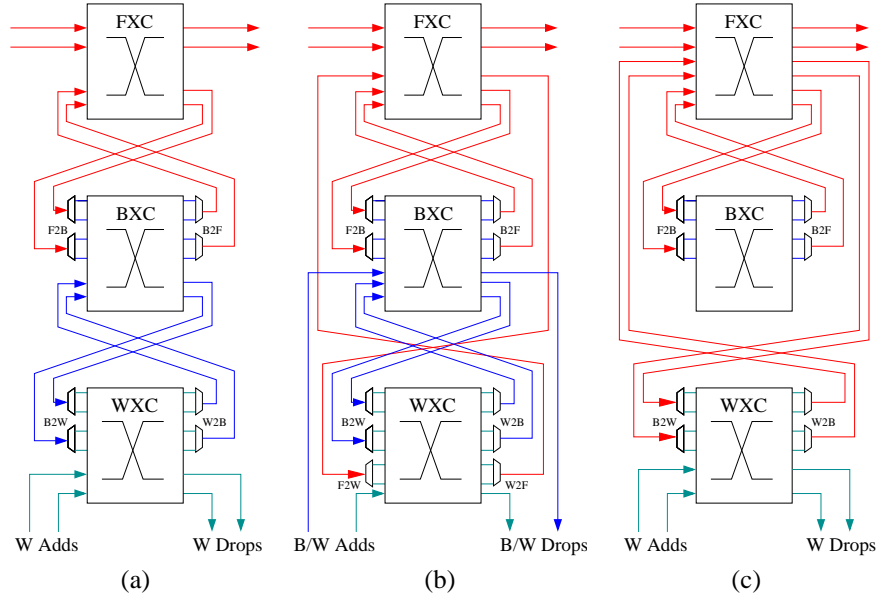
Fig. 1. (a) Waterfall MG-OXC (b) Flexible MG-OXC (c) Band Bypass MG-OXC (F: fiber, B: waveband, W: wavelength)

nodes are MG-OXCs and none of the nodes have wavelength conversion ability.

The paper is organized as follows. In Section II we describe the network and optical switch model we consider in our work. In Section III we present the hierarchical algorithm for lightpath grooming and waveband routing. We present numerical results in in Section IV, and conclude the paper in Section V.

II. NETWORK AND OPTICAL SWITCH MODEL

We consider a general topology network with N nodes interconnected by links consisting of one fiber per direction. Fiber links carry D wavebands, each waveband consisting of L consecutive wavelengths; hence, the total number of wavelengths on each link is $W = D \times L$. We assume the existence of a traffic demand matrix $T = [t^{(sd)}]$, where integer $t^{(sd)}$ denotes the amount of (forecast) long-term traffic, in multiples of the wavelength capacity, to be carried from node s to node d; any changes in the demand matrix take place over long time scales, and, for the purposes of this work, the matrix T is assumed fixed.

Let us define a *bandpath*, a generalization of the lightpath concept, as a (waveband, path) pair that is associated with a number of lightpaths equal to the band size L. The waveband is an integer in the range $1, \cdots, D$, where D is the total number of wavebands in a fiber, and can be thought of as the "color" of the bandpath, while the path may span multiple links. Hence, a bandpath uniquely identifies the path over which the traffic on the associated set of L lightpaths will be carried, as well as the wavelengths of these L lightpaths (since each waveband consists of a unique set of L wavelengths).

Each network node is equipped with an MG-OXC. MG-OXCs are characterized by the switching and grooming capabilities they provide. Specifically, we consider the following capabilities, listed from finer to coarser granularity:

- *wavelength switching* refers to the ability of switching individual wavelengths optically;
- *waveband grooming* is the ability to demultiplex a waveband to its constituent wavelengths, and to add or remove wavelengths from the waveband;
- *waveband switching* is the capability to switch optically individual wavebands, i.e., switch all wavelengths in a waveband as a group;
- *fiber grooming* refers to the ability of demultiplexing a fiber into its constituent wavebands, and adding or removing wavebands from the fiber; and
- *fiber switching* is the capability to switch a whole fiber from an input to an output port.

In general, there is a tradeoff between the switching/grooming granularity and the cost of an MG-OXC [16], with finer granularity implying greater flexibility but also higher cost.

There are three different kinds of MG-OXC we consider. The MG-OXC depicted in Figure 1(a) can switch traffic at the fiber, waveband or wavelength level using the corresponding fiber-, waveband- or wavelength- cross-connects. It is also capable of grooming traffic at the waveband and fiber levels, however traffic can be added(dropped) from(to) the digital cross-connect (DXC), present in the electronic domain through E-O(O-E) conversion, only at the wavelength level. Similarly the waveband cross-connect (BXC) can add (drop) wavebands from(to) the wavelength cross-connect (WXC) and fiber cross-connect (FXC) can add(drop) fibers from the waveband cross-connect. Since traffic demands terminating at a node forces its corresponding fiber, waveband and wavelength to be dropped, this model is called the *Waterfall MG-OXC*.

In addition to having the capabilities of the Waterfall model, *Flexible MG-OXC* depicted in Figure 1(b) can add(drop) wavebands from(to) the digital cross-connect (DXC) at the waveband level. This is useful if waveband sized traffic
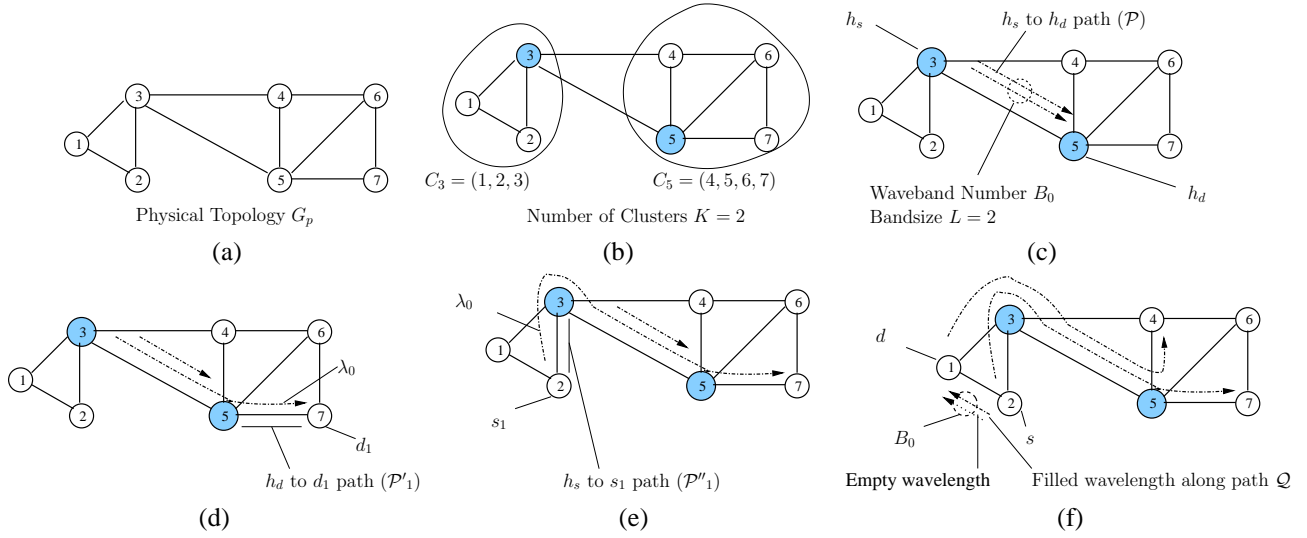
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Fig. 2. (a) Physical Topology (b) Clustering (c) Connection Establishment (d) & (e) Connection Extension - (d) Destination Cluster (e) Source Cluster and (f) Intra Cluster Routing

are routed together over some or all the links till their respective destinations. However, the wavebands still need to be split into(merged from) constituent wavelengths before entering(after leaving) the DXC. This necessitates additional interfaces at the DXC. Also the FXC can add(drop) fibers from(to) WXC. This also adds an additional interface at the wavelength cross-connect.

The *Band Bypass MG-OXC* depicted in Figure 1(c) does not have waveband grooming capability but can switch fibers, wavebands and wavelengths. Traffic can be added or dropped only at the wavelength level. The FXC can add(drop) fibers from(to) waveband and wavelength cross-connect.

Additional interfaces at the DXC and WXC needed by the Flexible and Band Bypass MG-OXC Switches incur additional cost in terms of switch size, equipment and maintenance but if RWA is done intelligently the cross-connect size can be reduced substantially especially in case of Flexible model.

In this work we assume that all the OXCs in the network have exactly the same capabilities (i.e., the network is homogeneous in terms of switching and grooming capability). We also assume that the cost of a node is determined by the cost of the optical ports of its MG-OXC; this is a reasonable assumption that is commonly adopted in the literature.

III. A Hierarchical Approach to Lightpath Grooming and Bandpath Routing

Given the forecast traffic demands $\{t^{(sd)}\}$, our objective is to carry the traffic matrix in its entirety while minimizing the overall total optical port cost and wavelength cost in the network. This problem involves the following conceptual subproblems (SPs):

1) *logical topology SP:* find a set of lightpaths to carry the traffic demands $\{t^{(sd)}\}$;
2) *lightpath grooming SP:* groom the lightpaths into wavebands; and

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Algorithm 1 Routing WaveBand Assignment

Input: Mesh WDM network (G_P), Waveband size L, W wavelengths/link, Traffic Matrix $T = [t^{(sd)}]$.
Output: Waveband sized Set of Connections identified by $\mathcal{P}$ between a source destination pair (s, d) such that $t^{(s,d)} > 0$ and waveband number B.

begin

1) Let $B \leftarrow 0$.
2) Identify a source-destination pair (s, d) which are farthest from each other and $t^{(s,d)} > 0$.
3) Find the shortest path $\mathcal{P}$ over G_P between s and d collectively on the wavelength graphs corresponding to wavelengths $B \times L, \cdots, ((B + 1) \times L) - 1$.
4) If $\mathcal{P}$ is not found, increment B by one and repeat (2-3).
   a) If B exceeds W/L, exit with failure.
5) Remove edges on wavelength graphs corresponding to wavelengths $B \times L, \cdots, ((B + 1) \times L) - 1$ along $\mathcal{P}$.
6) Return $(\mathcal{P}, B, s, d)$.

end

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3) *routing and wavelength assignment SP:* assign a waveband and path over the physical topology to each bandpath; as we mentioned earlier, lightpaths within each bandpath will also be assigned a wavelength as a result.

This is only a conceptual decomposition that helps in understanding and reasoning about the problem; in an optimal approach, the subproblems would be considered together in the solution. Note that, assuming that the first two subproblems above have been solved, the third subproblem reduces to the classical routing and wavelength assignment (RWA) problem [9], with the difference that the entities to be routed and colored are lightpaths considered in units of bandsize at a time hence, the above optimization problem is NP-hard.

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Algorithm 2 Destination Cluster RWA

Input: Mesh WDM network (G_P), Traffic Matrix $T = [t^{(sd)}]$, Source Cluster C_{h_s} with its hub h_s, Destination Cluster C_{h_d} and its hub h_d, Wavelength to be routed on λ.

Output: Lightpath identified by the path $\mathcal{P}'$ from h_d to d and wavelength λ with d having originating traffic in C_{h_s}.

begin

1) Mark all nodes within the destination cluster *not visited*.
2) Consider an unvisited node d farthest away from h_d such that $t^{(s,d)}_{s \in C_{h_s}, d \in C_{h_d}} > 0$.
3) Find the shortest path $\mathcal{P}'$ over G_P from h_d to d on the wavelength graph corresponding to wavelength λ.
4) If $\mathcal{P}'$ is not found mark d visited and repeat (2-3) till either $\mathcal{P}'$ is found to some other node in C_{h_d} or all nodes in cluster C_{h_s} are visited.
5) Return $(\mathcal{P}', d)$.

end

Algorithm 3 Source Cluster RWA

Input: Mesh WDM network (G_P), Traffic Matrix $T = [t^{(sd)}]$, Source Cluster C_{h_s} with its Hub h_s, Destination Node d, Wavelength to be routed on λ.

Output: Lightpath identified by the path $\mathcal{P}''$ from s to h_s and wavelength λ with s having traffic terminating in d.

begin

1) Mark all nodes within the source cluster *not visited*.
2) Consider an unvisited node s farthest from h_s such that $t^{(s,d)}_{s \in C_{h_s}} > 0$.
3) Find the shortest path $\mathcal{P}''$ over G_P from s to h_s on the wavelength graph corresponding to λ.
4) If $\mathcal{P}''$ is not found mark s visited and repeat (2-3) till either a $\mathcal{P}''$ is found to some other node in C_{h_s} or all nodes in cluster C_{h_s} are visited.
5) Return $(\mathcal{P}'', s)$.

end

We now present an extension of the hierarchical model developed in [7] to tackle this lightpath grooming and bandpath routing problem. We assume that all nodes in the network are equipped with a one of the MG-OXCs as shown in Figure 1. All switch models add (or drop) wavelength while the fine granularity model Figure 1(b) can also add (or drop) wavebands.

In our approach, 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 hierarchical algorithm solves the waveband switching

Algorithm 4 Waveband Routing and Wavelength Assignment

Input: A mesh WDM network (G_P) partitioned into m clusters $C_1, \cdots, C_m$ having hubs $h_1, \cdots, h_m$, Waveband size L, W wavelengths/link, Traffic Matrix $T = [t^{(sd)}]$.

Output: Set of Lightpaths in the Logical Topology and routing of the traffic components $t^{(sd)}$, Number of ports used at each network node.

begin

1) Initialize the inter-cluster traffic $H = [h^{(sd)}]$ according to Equation 1.
2) While Inter-Cluster traffic exists do
   a) Set $(\mathcal{P}, B, h_s, h_d)$ by executing the *Routing Wave-Band Assignment Algorithm* on G_P with bandsize L, inter-cluster traffic demands H and W wavelength per link.
   b) For $\lambda = B \times L$ to $((B+1) \times L) - 1$ do
      i) Set $(\mathcal{P}', d)$ by executing *Destination Cluster RWA* on G_P with traffic demands T, source and destination clusters C_s, C_d and wavelength λ.
      ii) If $\mathcal{P}'$ is found then
         A) Remove edges on wavelength graph corresponding to λ along $\mathcal{P}'$.
         B) Set $(\mathcal{P}'', s)$ by executing *Source Cluster RWA* on G_P with traffic demands T, source cluster C_s, destination d and wavelength λ.
         C) If $\mathcal{P}''$ is found, then remove edges on the wavelength graph corresponding to λ along $\mathcal{P}''$ and decrement $t^{(s,d)}, h^{(s,d)}$ by one. Else insert edges on wavelength graph corresponding to λ along $\mathcal{P}'$.
   c) If no connections are extended then free all the connections using B along $\mathcal{P}$.
3) While Intra-Cluster traffic exists do
   a) Set $(\mathcal{Q}, B, s, d)$ by executing the *Routing Wave-Band Assignment Algorithm* on G_P with bandsize L, traffic demands T and W wavelength per link.
   b) If $t^{(sd)} > L$ then, decrement $t^{(sd)}$ by L else decrement it by one.
4) Calculate and print wavelength and number of ports used based on routing information.

end

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problem in two steps as shown in the *Waveband Routing and Wavelength Assignment Algorithm* (Algorithm 4). In the first step, the inter-cluster traffic demands are identified and connections are established between hubs. These connections are extended to originate from (and terminate at) nodes within the source (and destination) clusters. Thus inter-cluster traffic demands are satisfied and lightpaths are established using these connections In the last step, the intra-cluster traffic demands are satisfied.

Our hierarchical model is explained below:

1) **Clustering and hub selection.** In this phase, we use the modified K-center algorithm [6] based on the 2-approximation algorithm [13] for the K-center problem to partition the network into K clusters and select one node having the maximum nodal degree in each cluster as the hub. It is assumed that all-pair shortest paths have been calculated and recorded as input matrix distance.

2) **Routing and Wavelength Assignment** As mentioned before, this phase consists of two steps listed below.

   a) *Inter Cluster Routing and Wavelength Assignment*

   Connection Establishment between Hubs. The inter-cluster traffic $T = [t^{(s,d)}]$ between nodes s and d in clusters C_i and C_j having hubs h_i and h_j repectively are aggregated into $H = [h^{(s,d)}]$ according to equation 1.

   $$h^{(h_i,h_j)} = \lceil (\sum_{s \in C_i, d \in C_j} t^{(s,d)})/L \rceil$$
   $$\forall 1 \le i, j \le K, i \ne j \qquad (1)$$

   A set of bandsize number of connections are established between hubs to help satisfy inter-cluster traffic demands using the *Routing and Waveband Assignment Algorithm* 1. This algorithm uses the shortest path between hubs ($\mathcal{P}$) on the least waveband number (B) available thus minimizing the number of wavelength W.

   Connection Extension within clusters
   Once a set of connections are established, they are extended to non-hub nodes (if required) in the source and destination clusters. For each wavelength λ in the waveband B, *Destination Cluster RWA Algorithm* (in algorithm 2) identifies a node in the destination cluster having traffic originating from the source cluster and farthest from its hub. The connection corresponding to wavelength λ from the set is extended from destination hub h_d to the node d along $\mathcal{P}'$. Similarly, *Source Cluster RWA Algorithm* (in algorithm 3) extends a connection corresponding to wavelength λ from a node s in the source cluster having traffic terminating at d and farthest from its hub h_s on a path $\mathcal{P}''$ between s and h_s.
   If no path is found on wavelength λ in the source cluster, then its equivalent connection in the destination cluster between d and h_d on λ along $\mathcal{P}'$ is freed. If no path is found in the destination cluster, connection extension is performed on the next wavelength in the set. If none of connections in the set established in step 2a are extended, all of them are freed.

   b) *Intra-Cluster Routing and Wavelength Assignment*
   In this step, only intra-cluster traffic demands remain to be satisfied. Bandpaths are established between source and destination nodes using the Rout-ing and Waveband Assignment Algorithm along path $\mathcal{Q}$ on waveband B.

Hub nodes are the only nodes that perform any grooming of lightpaths into waveband. All lightpath grooming is performed in the optical domain without using wavelength conversion.

To further explain the hierarchical model, we use an example depicted in Figure 2. Let us assume single wavelength traffic demands exist from nodes 1 to 4, 2 to 1 and 2 to 7 and no other traffic demands exist. On invoking the *Clustering* algorithm over the network (shown in Figure 2(a)) with $K = 2$ we get a network partitioned into two clusters C_3 and C_5 having nodes 3 and 5 as hubs since they have the maximum nodal degree within their cluster. This resultant network is shown in Figure 2(b).

In the *Connecion Establishment* stage, after $t^{(1,4)} = 1$ and $t^{(2,7)} = 1$ are aggregated into inter-cluster traffic demands H by equation 1, we get $h^{(3,5)} = 2$ implying two traffic demands from cluster C_3 to C_5. As there is no traffic from cluster C_5 to C_3, $h^{(5,3)} = 0$. Nodes 2, 1 belong to the same cluster ($2, 1 \in C_3$), hence $t^{(2,1)}$ will not be represented in H and all other entries in H remain zero. Using the Routing and Waveband Assignment Algorithm we obtain a routed waveband connection of size $L = 2$ along path $\mathcal{P} = (3, 5)$ on waveband number B_0 between nodes $h_s = 3, h_d = 5$. Thus, we establish a bandsized set of connection between the hubs as shown in Figure 2(c).

In the *Connection Extension* stage, we iterate through each wavelength (λ_0, λ_1) belonging to waveband B_0. Initially we consider the destination cluster C_5 and extend a connection from the destination hub 5 to any node (in this case 7 or 4) having originating traffic (not yet satisfied) from source cluster C_3. We choose to extend the connection on wavelength λ_0 along path $\mathcal{P}'_1 = (5, 7)$ as shown in Figure 2(d). Next we consider the source cluster C_3 and extend the connection on wavelength λ_0 and choose any node having terminating at 7. Since only 2 has such traffic the connection is extended along path $\mathcal{P}''_1 = (2, 3)$ as seen in Figure 2(e). We repeat this procedure till $t^{(1,4)}$ is also satisfied.

Lastly, we setup the intra-cluster traffic demands like $t^{(2,1)}$ using Routing and Waveband Algorithm which returns the path $\mathcal{Q} = (2, 1)$ on waveband B_0 and nodes $s = 2, d = 1$. Since $t^{(2,1)} = 1$ and waveband has size $L = 2$, one of the wavelengths is wasted. The resultant routing is shown in Figure 2(f).

IV. NUMERICAL RESULTS

We now present the results of an experimental study to evaluate the performance of the hierarchical lightpath grooming algorithm described in Section III. We conducted our experiments on a 47-node, 96-link network topology in [1]. In order to apply our hierarchical algorithm, we partitioned this network into K clusters, $K = 4, 8, 12$, using the algorithm in [13] for the K-center problem. 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

$0.1t$; if the numbers are greater than t they are rounded up to the next lowest integer otherwise they are rounded down to the next highest integer. Any negative numbers are set to zero. The matrix generated represents the wavelength demands between all source-destination pairs.

We consider two performance metrics in our study: the optical port cost of the network (over all nodes), and the number of wavelengths required to establish all bandpaths and lightpaths. The port cost includes the cost of all fiber, waveband, and wavelength ports at each node in the network. We discuss the performance of our algorithm for all models (Waterfall, Flexible and Band Bypass MG-OXC shown in Figure 1(a)) but primarily concentrate on the Flexible MG-OXC model. All the experiments consider a single fiber scenario except the last experiment (Figure 9) where we considered 40 wavelengths to be contained in a fiber.

For the results presented in this section, we have varied the mean t of each traffic demand ($t = 2, \cdots, 10$). Each point plotted in the figures represents the average over 30 problem instances (i.e., 30 random traffic matrices) for the stated values of the network and traffic parameters. We consider a confidence interval of 95%.

Figure 3 plots the number of optical ports required against the mean value t of the traffic components using Algorithm 4, for various band sizes when the network is partitioned into $K = 8$ clusters. There are two important observations we can make regarding the trend of the curves. First, the number of ports generally increases with the traffic load, as expected. Second, a larger band size implies lower optical port cost; again, this behavior is expected, as larger bands can accommodate more lightpaths, decreasing the number of optical switching ports at intermediate nodes. (*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 $47 \times 46 \times 2 = 4,324$, for average demand $t = 2$ (respectively, $47 \times 46 \times 10 = 21620$, for $t = 10$).)

Figure 4 plot the wavelength cost against the mean value t of the traffic components, for various band sizes. Again the network is partitioned into $K = 8$ clusters. We observe that the wavelength cost generally increases with traffic demands, as expected. Also larger band size implies higher wavelength cost. This can be explained as follows, larger band sizes results in more lightpaths being routed together to use band ports at intermediate nodes. This however requires a contiguous set of wavelengths to be free along the path the lightpaths are routed together, increasing the wavelength number over the links in this path.

The obserations applied for hierarchical approach can be applied for BPHT as shown in Figure 5. BPHT encourages band merges and splits, a number of bands are dropped to the WXC layer before being added back to the BXC layer again. This increases the number of ports needed at the nodes where band merges/spilts take place. In the hierarchical approach, band merges and splits are allowed only at the hubs. The
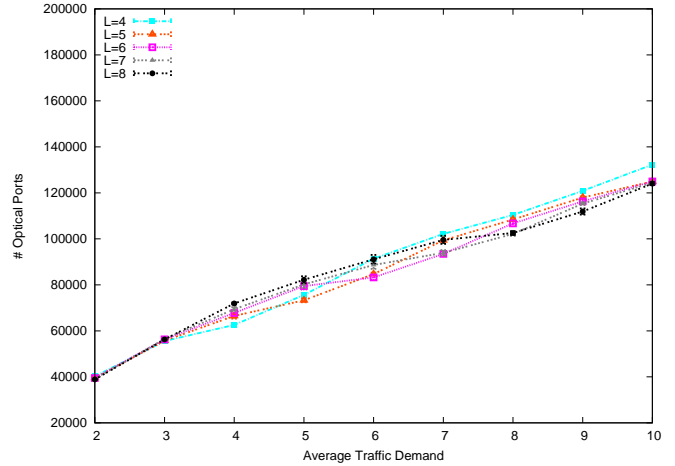

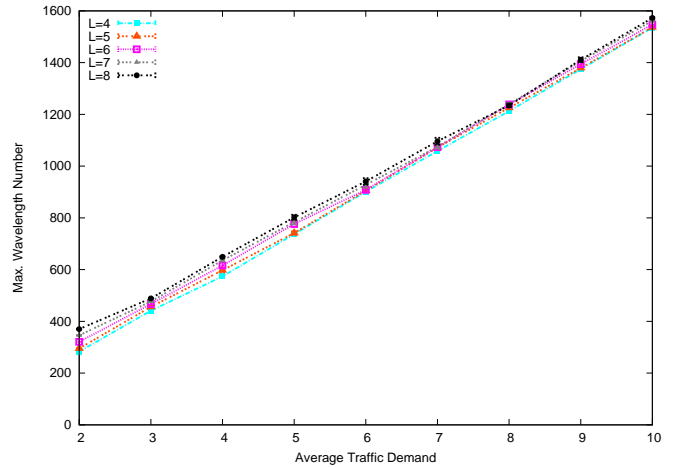Fig. 3. Port Cost, Hierarchical Approach, Varying Bandsize, $K = 8$

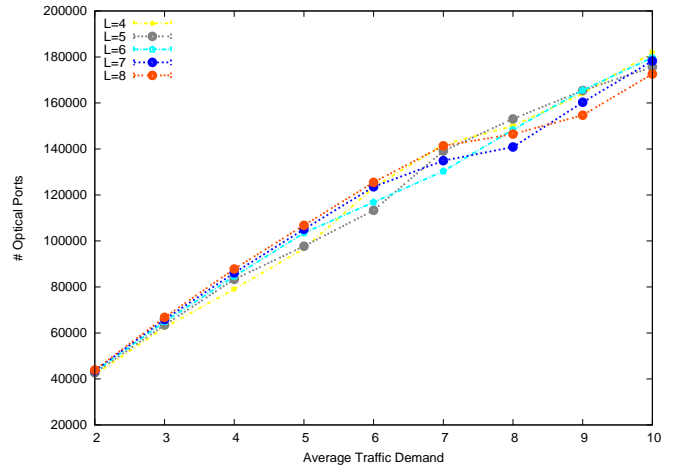Fig. 4. Wavelength Cost, Hierarchical Approach, Varying Bandsize, $K = 8$

Fig. 5. Port Cost, Balanced Path Heavy Traffic, Varying Bandsize, $K = 8$
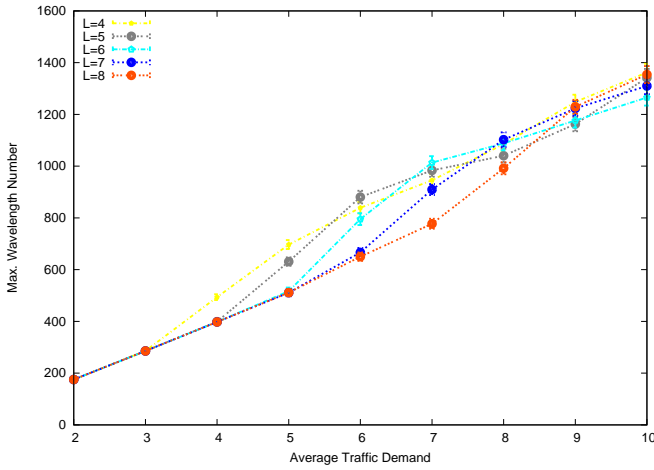
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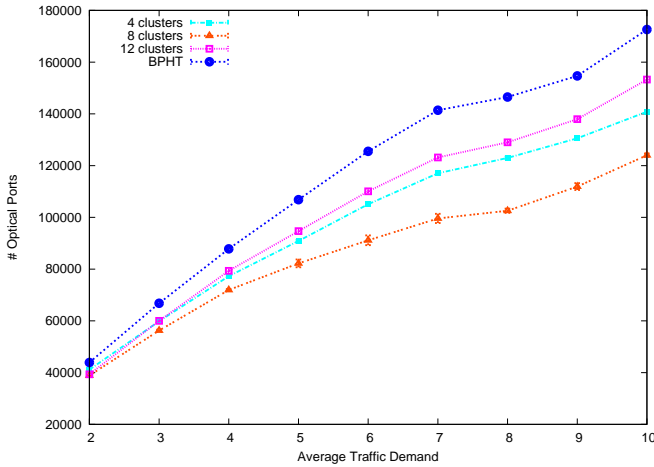Fig. 6. Wavelength Cost, Balanced Path Heavy Traffic, Varying Bandsize, $K = 8$
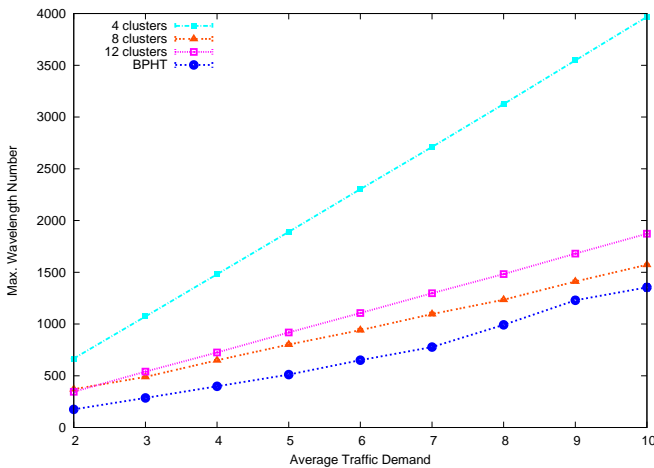

Fig. 9. Port Cost for different Models, $L = 6, K = 8$

Fig. 7. Port Cost, Varying Number of Clusters, $L = 8$

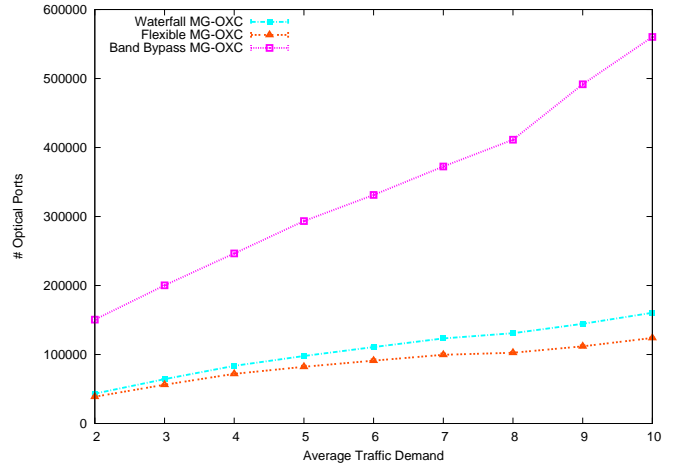Fig. 8. Wavelength Cost, Varying Number of Clusters, $L = 8$

bands are routed between source and destination hubs (from the respective source and destination) without modification. As a result, BPHT uses more ports than hierarchical approach.

Figure 6 shows BPHT using lesser number of wavelengths than hierarchical approach. This can be explained as follows, BPHT encourages band merges and splits in the process tightly packing the lightpaths together as bandpaths. The hierarchical approach on the other hand allows band merger and splits only at the hubs and also wastes wavelengths if there is a wavelength conflict between connection establishment and connection extension phases.

Figure 7 plots the optical port cost against the traffic load when the band size $L = 8$ when the network is partitioned into $K = 4, 8$ and 12 clusters. It is observed that using 12 clusters results in more ports being utlized than the 4 cluster or 8 cluster solution. On analysis we found 12 cluster solution has more wavelength conflicts between hub-to-hub connections established and non-hub nodes to hubs connection extensions. This results in more partially filled wavebands being established, resulting in more waveband adds and drops at hubs increasing the number of ports. The 4 cluster solution uses more ports than 8 clusters primarily due to the longer routes the connections routed through. Again, we observe BPHT requires more ports than hierarchical approach for all the clusters considered.

Figure 8 plots the number of wavelengths as a function of traffic load for $L = 8$. We expect a larger number of clusters requires fewer wavelengths. This is because using smaller number of clusters, each hub has to transmit/receive a larger amount of traffic to/from other hubs; hence, the links directly connected to hubs tend to become congested requiring many wavelengths. With 8 clusters, each hub handles less traffic, alleviating the congestion on its links and leading to fewer wavelengths than 4 clusters solution. However, using 12 clusters results in higher wavelengths being used due to the conflict between hub-hub connections and non-hub node to hub connections. This conflict results in lightpaths being loosely packed into bandpaths as compared to the 8 clusters.

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In this experiment we observe BPHT uses lesser number of wavelengths as compared to hierarchical approach.

Finally, Figure 9 plot the number of optical ports when different models are used for band size $L = 7$ when the network is partitioned into $K = 8$ clusters. We find that Flexible MG-OXC requires the least number of optical ports, this is expected due to the flexibility it offers helping us take advantage of waveband grooming and waveband adds and drops. We note however that entire fibers are rarely dropped to (or added from) the WXC due to large amount of inter-cluster bypass traffic at the nodes. The Waterfall Model can add or drop only wavelengths hence requires more optical ports than Flexible Model. The Band Bypass Model does not have waveband grooming ability forcing entire fibers to be dropped (or added) at either the BXC or the WXC. Fibers are dropped (or added) to BXC only if none of the traffic demands in the fiber require wavelength switching, adds or drops at the concerned node. At all other times they are dropped to the WXC, hence the Band Bypass MG-OXC performs worst and uses significantly more ports. Our studies indicate that all models have identical wavelength costs since the routing and wavelength assignment of traffic demands is independent of the models used in the network.

Overall, these results indicate that the hierarchical algorithm is very scalable in terms of bandsize however the operating minimum with respect to number of clusters needs to be found considering network resources like optical ports and wavelengths.

V. CONCLUDING REMARKS

We have presented a hierarchical approach to grooming lightpath traffic and routing wavebands over a multigranular optical network. In our model, the network is partitioned into clusters and one node in each cluster is designated as the hub. Inter-cluster traffic is routed through the hub in a manner which forms wavebands thus reducing the bypass traffic overhead at the intermediate nodes. Our algorithm easily scales across bandsizes but the operating minimum with respect to number of clusters needs to be found considering network resources like optical ports and wavelengths. Compared to BPHT, our algorithm uses lesser number of ports but uses comparable number of wavelengths.

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