Grooming of Multicast Sessions in WDM Mesh Networks*

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Abstract

Handling "sub-wavelength" traffic demands by cost-effective traffic grooming in WDM networks has become prominent. We, in this paper, address the problem of routing and wavelength assignment of multicast sessions with sub-wavelength traffic demands in the scenario of WDM mesh networks. In order to support multicasting, individual nodes need to have the capability of duplicating traffic. We propose a node architecture which will perform the task of duplication in the optical as well as the electronic domain. This architecture is cost effective as it allows the duplication in optical domain also. The traffic duplication at the electronic level is much more expensive than the optical level. We study the problem of assigning routes and wavelengths to the multicast sessions so as to minimize the electronic copying resources required. We present a non-linear programming (NLP) formulation as an analytical model for the problem. As solving the model for large networks is intractable, we propose the heuristic algorithms namely (k-SPT, GRS, and GCOT). We have studied the performance of the proposed heuristic algorithms by conducting extensive simulation experiments.

Keywords: Optical WDM mesh networks, Multicast routing and wavelength assignment, Optical splitter, Traffic grooming, NLP formulation.

1 Introduction

Wavelength Division Multiplexed (WDM) optical networks have come to stay as the backbone of the Internet. With each optical link capable of carrying traffic on several wavelengths, each one of which supports traffic in the Gbps range, the bandwidth offered by a WDM network is of the order of Tbps. However, traffic requested by individual connection is still in the Mbps range. Hence, to utilize the available bandwidth efficiently, several connections have to be grouped onto the same wavelength. This requires strategic routing and wavelength assignment (RWA) of each connection because the traffic carried on any wavelength needs to be converted from optical to electronic form whenever a part of that traffic needs to be switched to another wavelength or has to be added/dropped at some node. The cost of the equipment involved in this opto-electronic conversion is the dominant cost in setting up the network.

The problem of RWA of sub-wavelength demands with the objective of minimizing the network cost, called "traffic grooming" problem, has been studied widely in the literature. Most of the work in this direction has been focused on ring networks [1], with emphasis on minimizing either the number of wavelengths or the number of Add/Drop Multiplexers (ADMs) required. In the recent past, there have also been efforts towards solving the problem for the case of mesh networks. This issue has been addressed in both the static [2] as well as the dynamic [3] scenarios. Dynamic grooming is the problem of routing and assigning wavelengths for a new demand, given the current state of the network, whereas in static grooming the traffic demands are known a priori and all of them have to be assigned routes and wavelengths to minimize the resources required (wavelengths or ADMs). Static grooming can also be viewed from the angle of maximizing the throughput given the constraints on resources. A survey and review of traffic grooming with several switching architectures is presented in [4].

The growth in traffic demand over the Internet is primarily due to the increasing popularity of multicast services such as video conferencing and distance learning. Multicast is the simultaneous transmission of information from one source to multiple destinations. This is bandwidth-efficient because it eliminates the necessity for the source to send an individual copy of the information to each destination. As WDM provides efficacy to support these high-bandwidth services, there is an increasing need to implement multicasting efficiently at the optical layer [5]. Effi-

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cient designs have been proposed in [6] for the architecture needed at each node to support multicasting in wavelength-routed networks. The concept of *light-tree* was introduced for the multicast scenario, which is analogous to the lightpath idea used in the context of unicast traffic [7]. To support light-trees, individual nodes need to be equipped with the capability to duplicate an incoming optical signal into multiple copies. By applying the concept of light-trees, the problem of designing a logical topology for given set of multicast demands is studied in [8]. In [9], routing and wavelength assignment for multicast traffic is studied in the context of all optical networks. The multicast RWA problem has also been addressed in the case wherein few nodes in the network are equipped with splitting capability [10]. A recent survey of multicasting in WDM networks is given in [11] and [12]. In the recent past, multicast traffic grooming in mesh networks is addressed [13], wherein an ILP formulation is presented along with a heuristic algorithm with an objective of minimizing the number of ADMs. Multicast traffic grooming in the case of ring networks is proposed by the authors in [14], wherein node architectures were proposed with heuristic algorithms to groom the multicast traffic demands with a major goal to reduce the number of electronic ports required for a given set of multicast traffic demands. In [15], the grooming issue in sparse splitting networks is solved with an ILP and heuristic solution for minimizing the number of wavelengths required for a given set of multicast demands.

In this paper, we address the problem of multicast routing and wavelength assignment in WDM mesh networks with sub-wavelength demands. In other words, we address the traffic grooming problem in mesh networks in the multicast scenario. Firstly, we present a node architecture for supporting multicasting demands of wavelength as well as sub-wavelength levels, which is a translucent grooming node architecture for supporting the multi-granularity range of demands. Since the cost of optical layer splitting is negligible in comparison to that of duplication at the electronic level [16], we study the multicast traffic grooming problem with the objective of minimizing cost in terms of electronic ports required across the network. We model this problem as a non-linear programming formulation, which can be solved to obtain an optimal solution. As the complexity of solving NLP increases with increase in number of nodes and number of sessions, we present three heuristic algorithms for solving the multicast traffic grooming problem. In general, to solve the multicast routing and wavelength assignment problem (MCRWA), the first step is to construct a multicast tree spanning from source to all destinations of the given multicast group. This tree construction problem can be formalized as a *steiner tree problem* [17]. The Steiner tree problem is known to be NP-complete, when the multicast group has more than two members [17]. Several heuristics and approximation schemes, such as the shortest path tree (SPT), shortest path heuristic (SPH) and its several variations, and the minimum spanning tree (MST) have been suggested for the Steiner tree problem [17]. After constructing the multicast tree, the next step is to assign a wavelength to each branch of the tree. In our proposed heuristic approaches, we perform routing and wavelength assignment steps at sub-wavelength level traffic demands in an integrated manner and any session is assigned one wavelength. In all the proposed heuristic solutions, route computation for the given session is computed by shortest path tree (SPT) algorithm, where SPT for a session is union of all shortest paths from the source to each destination.

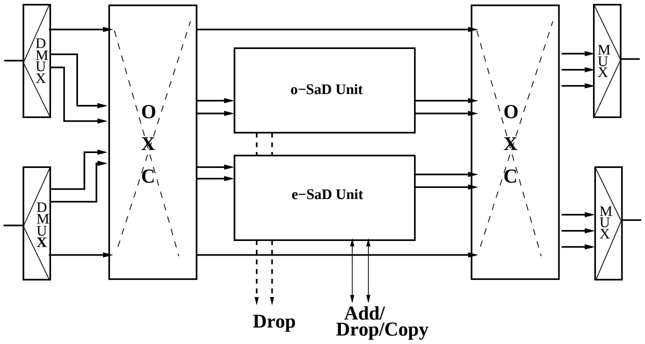

Figure 1. Node Architecture for Grooming Multicast Traffic in WDM Mesh Networks

The rest of the paper is organized as follows. In Section 2, we outline the node architecture required for supporting multicast of sub-wavelength traffic demands in mesh networks. A formal problem definition, is described in Section 3. An NLP formulation for grooming multicast sessions is given in Section 4. Heuristic algorithms proposed for the grooming of multicast sessions are presented in Section 5. Results of the simulation experiments we conducted to measure the performance of our heuristic algorithms are given in Section 6. We finally conclude our work in Section 7 with some future directions.

2 Node Architecture

In the recent past, grooming received significant attention from the research community, which is essential to reduce the overall network cost. There are mainly two ways to groom multicast sub-wavelength level traffic, the first one is an *opaque* way which employs optical-electronic-optical conversion *O/E/O* at each logical hop of the multicast routed tree, and the other is a *translucent* way which employs *O/E/O* conversion as well as optical layer splitting. The first approach to groom the multicast traffic by dropping and regenerating the traffic with *O/E/O* conversion using ADMs was proposed in [13]. The basic limitation of such an approach is the cost of buffers as well as the extremely high duplication complexity required at each node. Since we are addressing the problem of grooming multicast sessions where the streams are ranging from megabits to gigabits, the above approach is not cost effective in terms of either cost of buffer or duplication complexity required at node. So we propose a node architecture shown in Figure 1 which performs grooming in a translucent way, which means that the node architecture supports a range of traffic demands, from low speed streams (Mbps) to wavelength (Gbps) with support of optical as well as electronic switching. The node architecture basically consists of two main units *o-SaD* (optical split and delivery) and *e-SaD* (electronic split and delivery). The basic function of the o-SaD unit is to split the incoming signal on incoming wavelength and deliver on different output wavelength ports, all in the optical domain. The second one is the e-SaD unit, which carries out duplication in electronic domain with functionality such as traffic add/drop/copy with switching to different wavelength ports. The incoming wavelengths are demultiplexed and switched through the OXC to appropriate unit i.e., o-SaD or e-SaD unit, based on a predefined strategy. Here node architecture provides an optical bypass to the traffic on those wavelengths which are not having any local add or drop. The architecture is not equipped with any wavelength converters. If in case wavelength conversion is required, it can be performed by e-SaD unit in the electronic domain.

One important point that can be observed in the above node architecture is that, when all the traffic on the incoming wavelength needs to be duplicated, the e-SaD unit is redundant because there is no necessity to examine the header of each individual packet (since every packet needs to be duplicated). Clearly, in such a scenario, splitting can be done at the optical layer rather than implementing it at the electronic level.

The o-SaD unit is highly cost-effective in comparison with that of e-SaD unit as this obviates the need to examine the header of each packet being added/dropped at a node. In summary, the proposed translucent node architecture is highly cost-effective alternative to groom the multicast traffic in the network. The proposed node architecture reduces buffer requirement as well as duplication complexity, which are the prime issues for broadband multicasting.

3 Problem Definition

We formally define the multicast traffic grooming problem in a WDM mesh network. Given the physical network topology represented as a graph $G(V, E)$ where V is the set of nodes and E is the set of links in the network. Let there be *W* wavelengths per fiber and each wavelength can accommodate up to *g* number of low speed streams. Given a set of multicast traffic demands where i^{th} demand T_i is represented by (s_i, D$_i$, B$_i$) where $s_i \epsilon$ *V* is the source, D$_i \subseteq V$ is the set of destinations, and B_i is the required bandwidth of the connection. The problem is to find a multicast tree for every session request, connecting s_i to all destinations in D_i and route each request on the physical topology with wavelength assigned, so as to reduce total number of e-SaD ports required. Here, a port means a transceiver required to add or drop a wavelength.

4 Non-linear Programming Formulation

In this section, we present an *analytical model* of grooming problem represented as non-linear programming formulation, it finds routes for all given multicast demands with an objective of minimizing the required e-SaD ports. Here, we use tree and flow control constraints proposed in [18].

Notations:

N number of nodes in the network

W number of wavelengths per fiber

g groom factor expressed in terms of number of OC-n streams

S_i = $\{s_i$, $d_{i,1}$, $d_{i,2}$, $d_{i,3}$, $d_{i,4}$, ...$\}$ represents the session i with source s_i and destinations $d_{i,1}$, $d_{i,2}$, $d_{i,3}$, $d_{i,4}$, ...

$D(i)$ is the cardinality of destination set

$AD(j)$ physical adjacency degree of j^{th} node

B_i bandwidth of session i, $B_i \leq g$

$B_d(m)$ physical branching degree of node m

Boolean Variables:

$P_{m,n}$ physical link between node m and node n

$P_{m,n} = P_{n,m}$ which indicates that the, fiber link is bidirectional. The direct physical fiber link between nodes m and n where m,n= 1, 2, 3, ... N

If there is no fiber link between nodes m and n, then $P_{m,n}$=$P_{n,m}$ = 0

$M^{i,w}_{m,n}$- is 1 if session i is routed on wavelength w of link (m, n)

V^i_m- is 1 if node m is either source or destination of i^{th} session , else is 0

$D^w_{m,n}$- is 1, if node n requires a port for dropping any session(s) on wavelength w of link(m, n). $A^w_{n,k}$ is 1, if node n requires a port for adding session(s) on wavelength w of link (n, k).

d_{ij}- is 1 if node j is one of the destinations of session i session, else is 0

C^w_i is 1 if multicast session i is on wavelength w, otherwise, C^w_i is 0. The lighttree for a multicast session can occupy only one wavelength

Integer Flow Variables:

$F^i_{m,n}$- An integer commodity flow variable. Here the assumption is each destination node of a session needs one unit of commodity. Therefore, d_i units of commodity flowing out at source s_i of session i.

Objective function

$$\text{Minimize } (\sum_m \sum_n \sum_w D^w_{m,n} + \sum_n \sum_k \sum_w A^w_{n,k})$$

Constraints

Tree creation constraints :–

$$\forall i, \forall n \neq s_i : \sum_{m,w} M^{i,w}_{m,n} = V^i_n \qquad (1)$$

The above equation ensures that, every node that belongs to a multicast session (except the source) has at least one incoming edge.

$$\forall i : \sum_{w,m} M^{i,w}_{m,s_i} = 0 \qquad (2)$$

The source has no incoming edge, as it is root of the tree.

$$\forall i, j \in S_i : V^i_j = 1 \qquad (3)$$

This constraint ensures that every source node and the destination node of a multicast session belongs to tree.

$$\forall i, m \neq d_{ij}, j \geq 1 : \sum_{w,n} M^{i,w}_{m,n} \geq V^i_m \qquad (4)$$

It ensures that every node (except the destination nodes) belonging to the tree has at least one outgoing edge.

$$\forall i, m : \sum_{n,w} M^{i,w}_{m,n} \leq B_d(m) \times {V^i}_m \qquad (5)$$

It ensures that for every node in the multicast tree for a session, the number of outgoing links in the tree is lesser than or equal to the physical branching degree of the node.

$$\forall m, n : \sum_{i,w} M^{i,w}_{m,n} \leq P_{m,n}.W \qquad (6)$$

This restricts the number of lightpaths between nodes m and n by $P_{m,n}.W$ in each direction.

$$\forall m, n, w : \sum_i B_i \times M^{i,w}_{m,n} \leq g \qquad (7)$$

The grooming constraint which restricts number of sessions groomed on a physical link (m,n) on wavelength w should be less than or equal to the grooming factor.

Commodity flow constraints :–

$$\forall i, m \notin S_i : \sum_n F^i_{m,n} = \sum_n F^i_{n,m} \qquad (8)$$

The above equation ensures that for any intermediate node (which is neither source nor a destination), the incoming flow is same as the outgoing flow. However, outgoing flow at the source node for a session is the number of destinations in the session, and the incoming flow at the source node is zero. These are achieved by equations 9 and 10.

$$\forall i, m \notin S_i : \sum_n F^i_{S(i),n} = D(i) \qquad (9)$$

$$\forall i : \sum_n F^i_{n,S(i)} = 0 \qquad (10)$$

$$\forall i, \forall m = d_{i,j}, j \geq 1 : \sum_n F^i_{n,m} = \sum_n F^i_{m,n} + 1 \qquad (11)$$

Equation 11 ensures that the total outgoing flow is one less than the incoming flow for destination nodes.

$$\forall i, m, n : \sum_w M^{i,w}_{m,n} \leq F^i_{m,n} \qquad (12)$$

$$\forall i, m, n : F^i_{m,n} \leq N. \sum_w M^{i,w}_{m,n} \qquad (13)$$

$$\forall i : \sum_w C^w_i = 1 \qquad (14)$$

$$\forall m, n (n > m) \forall i, w : M^{i,w}_{m,n} + M^{i,w}_{n,m} \leq C^w_i \qquad (15)$$

Equations 12 and 13 ensure that the links occupied by a session have a positive flow and that the links not occupied by a session have no flow. Equation 14 ensures that a session chooses only one wavelength and Equation 15 ensures that no link is occupied by a session on the wavelength not chosen by it and that all links occupied by a session are on the same wavelength.

Ports calculation:-

The following are the equations to compute the number of add/drop ports required at a node subject to the routing of multicast tree, which is constructed using tree and flow constraints. A port is needed on a wavelength in one of the following three cases,

Case I: An add port is required if there exists a session which has to be added on that wavelength of an outgoing link

Case II: A drop port is required if there exists a session which has to be dropped on that wavelength of the incoming link

Case III: An add and drop port is required if all the sessions on the wavelength of an incoming link are not switched onto the same wavelength of some outgoing fiber.

We first restrict the port calculation to an incoming and outgoing link pair, and later extend it to compute number of add and drop ports required on each wavelength of each incoming and outgoing link. Let at node n, (m,n) be an incoming link and (n,k) be some outgoing link. Let $S^{i,w}_{m,n,k}$ be a variable which represents whether session i is present on one of the links (m,n) and (n,k), and is defined as

$$S^{i,w}_{m,n,k} = M^{i,w}_{m,n} + M^{i,w}_{n,k} - (M^{i,w}_{m,n} \times M^{i,w}_{n,k}) \tag{16}$$

Let $B^{w}_{m,n,k}$ represent a variable which equals 1, if an add/drop port is not required on wavelength w on the links (m,n) and (n,k), and is defined as follows.

$$B^{w}_{m,n,k} = \begin{cases} 1 & if\ all\ sessions\ forwhich\ S^{i,w}_{m,n,k} is'1' \\ & \ occupy\ both\ the\ links\ (m,n)\ and\ (n,k) \\ & \qquad\quad \textbf{or} \\ & if\ all\ sessions\ forwhich\ S^{i,w}_{m,n,k} is'1' \\ & \ occupy\ link\ (m,n)\ but\ not\ link\ (n,k) \\ & \qquad\quad \textbf{or} \\ & if\ all\ sessions\ forwhich\ S^{i,w}_{m,n,k} is'1' \\ & occupy\ link\ (n,k)\ but\ not\ link\ (m,n) \\ & \\ 0 & otherwise \end{cases}$$

We represent the three cases of $B^{w}_{m,n,k}$ (where it's value is '1') using the variables $Q^{w}_{m,n,k}$, $Y^{w}_{m,n,k}$, and $Z^{w}_{m,n,k}$ which are defined as follows.

$$Q^{w}_{m,n,k} = \prod_{i} \left[1 - S^{i,w}_{m,n,k} + (M^{i,w}_{m,n} \times M^{i,w}_{n,k})\right] \tag{17}$$

$$Y^{w}_{m,n,k} = \prod_{i} \left[1 - M^{i,w}_{m,n} + (M^{i,w}_{m,n} \times \ (1 - M^{i,w}_{n,k}\ )\ )\ \right] \tag{18}$$

$$Z^{w}_{m,n,k} = \prod_{i} \left[1 - M^{i,w}_{n,k} + (\ (1 - M^{i,w}_{m,n}) \times \ M^{i,w}_{n,k}\ )\ \right] \tag{19}$$

Now, $B^{w}_{m,n,k}$ is defined as,

$$B^{w}_{m,n,k} = Q^{w}_{m,n,k} \bigvee Y^{w}_{m,n,k} \bigvee Z^{w}_{m,n,k} \tag{20}$$

$R^{w}_{m,n,k}$ is 1 if node n needs a port to add session(s) on wavelength w.

$$R^{w}_{m,n,k} = 1 - B^{w}_{m,n,k} \tag{21}$$

But, a drop port is needed at every destination of a session. So, we define variable $X^{w}_{m,n,k}$ as follows,

$$X^{w}_{m,n,k} = \prod_{i} \left[1 - S^{i,w}_{m,n,k} + ((M^{i,w}_{m,n} \times M^{i,w}_{n,k}) \times (1 - D^{i}_{n}))\ \right] \tag{22}$$

where D^{i}_{n} is 1, if n is in destination set of session i.

$P^{w}_{m,n,k}$ is 1 if node n needs a port to drop session(s) on wavelength *w*.

$$P^{w}_{m,n,k} = 1 - \left(X^{w}_{m,n,k} \bigvee Y^{w}_{m,n,k} \bigvee Z^{w}_{m,n,k}\right) \tag{23}$$

$D^{w}_{m,n}$ is 1, if node *n* requires a port for dropping any session(s) on wavelength *w* of an incoming link (m,n).

$$D^{w}_{m,n} = \left[\bigvee_{k} P^{w}_{m,n,k}\right] \bigvee \left[\ \left(\ \prod_{k} Y^{w}_{m,n,k}\right) \bigwedge \left(\bigvee_{i} M^{i,w}_{n,k}\right)\right] \tag{24}$$

$\forall k \in AD_n$ (adjacent link set of node n)

$$A^{w}_{n,k} = \left[\bigvee_{k} R^{w}_{m,n,k}\right] \bigvee \left[\ \left(\ \prod_{k} Y^{w}_{m,n,k}\right) \bigwedge \left(\bigvee_{i} M^{i,w}_{m,n}\right)\right] \tag{25}$$

$\forall k \in AD_m$ (adjacent link set of node m)

5 Heuristic Solutions

Since unicast traffic grooming for mesh networks is NP-complete [2] and as unicast is a special case of multicast with one node in the destination set, the traffic grooming problem in the multicast scenario is also NP-complete. Solving linear or non-linear formulations is practicable only in the case of small sized networks because the computations become intractable as the network size and number of sessions increases. Hence, we resort to heuristic solutions to solve the multicast grooming problem.

We assume that all the nodes in the network are equipped with the proposed node architecture. The heuristic algorithms try to minimize the total number of grooming ports required on the *e-SaD* unit present in the architecture at every node for a given set of traffic demands. We present each heuristic algorithm and illustrate with an example. We propose three heuristic solutions namely k-shortest path tree (k-SPT), grooming by re-routing the session (GRS) and grooming by computing overlapped tree (GCOT). We illustrate each of the heuristic with example in following subsections. We assume that each multicast tree is assigned only one wavelength across entire links. The set S represents the set of input multicast demands.

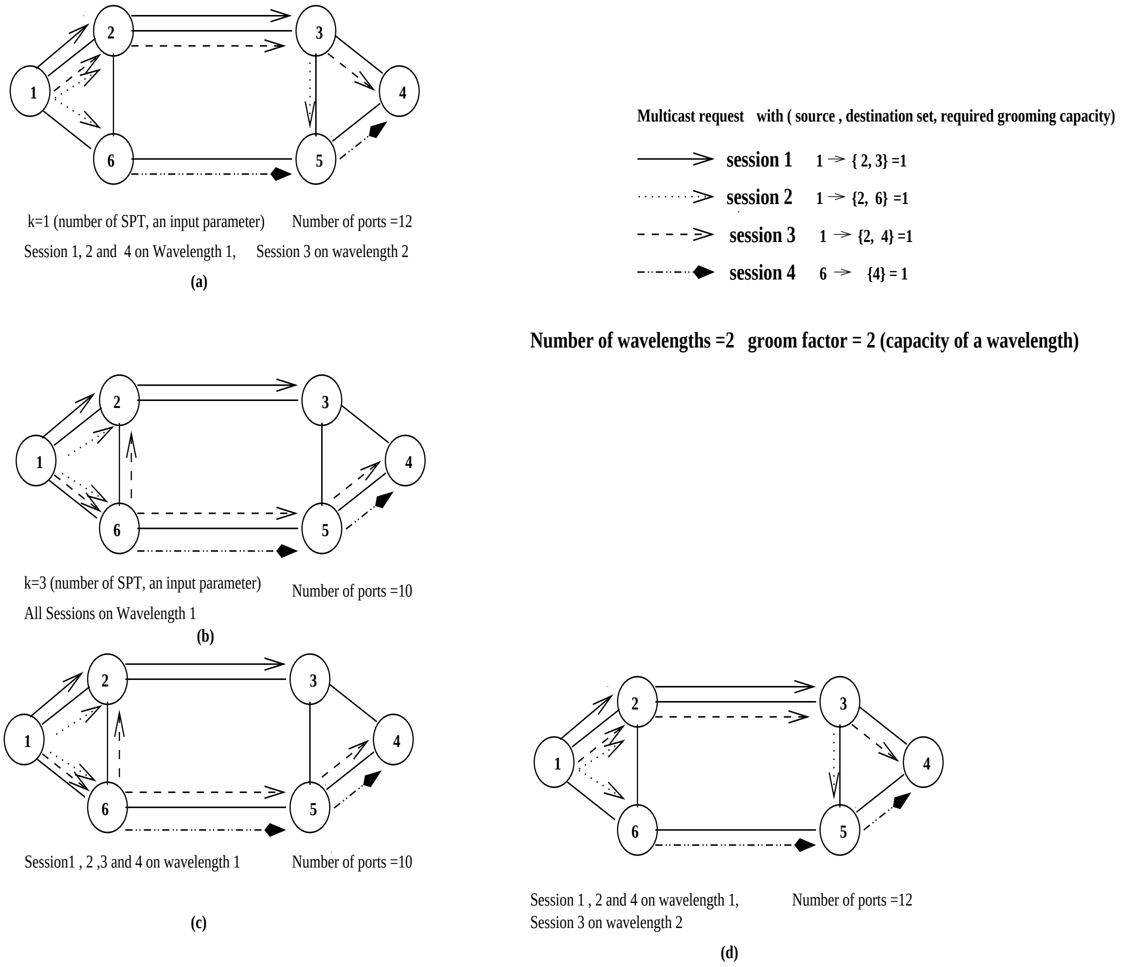

Figure 2. Example showing multicast grooming and requirement of ports and wavelengths

5.1 k-Shortest Path Trees (k-SPT):

The basic logic behind this heuristic is that any multicast session will have more than one route, *k* is an input parameter to the heuristic algorithm. In the first step, the heuristic finds for each session, k number of multicast trees using SPT algorithm. It constructs the first tree by applying the SPT on the physical topology. It then starts removing one link at a time from the first SPT and computes a new SPT tree on the resulting topology until all the k number of trees are constructed (see the *repeat* loop in step-1). The links are removed in the order of indices of nodes on which the link is incident. In the second step, from all such trees of all sessions the one which minimizes the number of e-SaD ports required is selected. The session corresponding to the tree is marked as routed. The process is repeated till all the sessions are routed. We will first elucidate above heuristic steps with an example shown in Figure 2(a) and 2(b), which shows a six node network with two wavelengths on each link and four multicast requests. We will assume here that the input parameter k is 3. Now, let us take the first request 1→{2,3}.

Our first step of the heuristic is to compute the first SPT by setting parameter k=1, the corresponding SPT is computed as: 1→2→3. Similarly by incrementing parameter k=2: 1→6→2→3, and for k=3: 1→2→6→5→3. So for each request based on the input parameter k that many number of SPTs are generated. We compute the shortest path trees for all sessions in the way explained above. After generating the set k trees for each demand, the second phase selects a tree from the k-SPT set which requires the least number of unused ports for routing it. Now in our example let us consider if input parameter k is 1 then one tree for each multicast request is generated. The number of of add/drop ports required are 12. For k=3, the requirement is 10, which is shown in Figures 2 (a) and 2 (b).

Algorithm:

```
1. for each session in the set S do
        Construct SPT. Let it be $T_1$.
        Arrange the links present in the tree into list ordered by node index number
        repeat until all the k-trees are computed
            Remove first link in list from the physical graph
            Apply SPT and construct next tree
            Remove the link from list
        end repeat
   end for
2. repeat till all the sessions are routed or no further routing is possible
        a) From all k number of trees of all the sessions not routed so far, select one tree which can be fit on the existing wavelength.
        b) If more than one tree is selected, choose the one which consumes lesser number of unused ports.
        c) If no tree is selected, choose a new wavelength and route a tree which consumes least number of unused ports.
        d) Mark the session for which the selected tree is one of the k -trees, as routed.
   end repeat
```

5.2 Grooming with Rerouting the Sessions (GRS):

The basic idea behind this heuristic is reroute the current session under consideration in order to find free resources. Initially it selects a session from set S randomly and establishes the session on a wavelength. Then for each un-routed session, it checks whether it can be routed on one of the existing wavelengths. If the un-routed session has some links which we call "bottleneck links", which do not have sufficient capacity to route the session, the heuristic tries to reroute current session on those links, thus trying to accommodate the current un-routed session on it. However, we restrict the number of such links to be rerouted to a maximum of two.

Algorithm:

```
1. for each multicast session in set S do
         find the shortest path tree $T_i$
2. select a session randomly and route it on first wavelength
3. for each un-routed session from set S do
        a) check whether it can be routed on already used wavelengths
        b) If it can be routed, route it on a wavelength and update the capacity of wavelength, consider next session in S and go to step 3
          else find bottleneck links for this route i.e., those links on which the non-availability of free capacity has made the above route failed
        c) If number of bottleneck links on every wavelength is above two, assign next wavelength, goto step 3
        d) If a wavelength exists with at most two bottleneck links,
        e) check whether rerouting of these links for current session which will lead to successful accommodation on the existing wavelength
        f) If yes, reroute the links, assign the wavelength to the current tree, consider next session in S and goto step 3
        g) If it cannot be accommodated even by rerouting, assign the next wavelength
end for
```

We illustrate the heuristic steps by an example shown in the Figure 2(c). The first two requests are routed along their respective shortest paths by constructing SPT, but the third request does not have enough resources available on it's SPT on wavelength 1, which takes the route as $1 \rightarrow 2 \rightarrow 3 \rightarrow 4$. So it will check for the reroute step. Here the number of bottleneck links are less than two (only 1→2 is bottleneck link) and hence the rerouting of path passing through 1→2 link is carried out through $1 \rightarrow 6 \rightarrow 2$ and $6 \rightarrow 5 \rightarrow 4$ route, which is shown in Figure 2(c).

5.3 Grooming by Computing Overlapped Trees (GCOT):

This heuristic tries to pack sessions into wavelengths in a greedy manner. First a session having maximum number of physical links in the tree is selected and assigned the first wavelength. It tries to pick up one of the remaining sessions which has maximum overlap in terms of number of common links. After computing and selecting session which is having maximum overlap with the already sessions marked as routed (set W_i denotes the set of sessions routed on i^{th} wavelength). The granularity constraint is checked i.e. sum of bandwidth routed connections on a wavelength should be less than it's capacity before it is marked as routed and placed in W_i. The process is repeated till all the sessions are routed.

Algorithm:

```
1. for every $j^{th}$ multicast session in set S, find the shortest path tree $T_j$. Let i=1.
2. Pick up one un-routed session which has more number of links in its SPT. Add that session to $W_i$.
3. for each un-routed session $j$,
        a) find the overlap degree with $W_i$ (i.e., number of links common to all in $W_i \cup T_j$).
        b) Arrange sessions in decreasing order of overlapping degree into orderedList
end for
4 a) Take the first session from orderedList.
   b) Check whether it can be assigned wavelength i. (i.e.
```

check whether granularity constraint is satisfied or not)

c) If yes, then add the session to set W_i and remove from *orderedList*.

d) If *orderedList* is not empty, select next session repeat step 4.

e) If all sessions in *orderedList* are considered, increment *i*. Goto step 2.

We illustrate the heuristic steps with an example shown in the Figure. 2(d). The first step is to construct SPT for each request. After construction, select the one which is having maximum number of links. Here in our example sessions 1 and 2 have maximum links in their respective SPTs. Select session 2 and route the session; place it in W_1 set. Now find the overlapped degree of remaining sessions with this set and arrange sessions in decreasing order of overlapped degree which is 1, 3. Now session with highest overlapped degree is selected and checked for placing in the set W_1 which satisfies for session 1; route it and place it in W_1 set. Next session 3 will be routed on the second wavelength due to lack of capacity on link 1-2 and session 4 is routed on wavelength 1. Figure 2 (d) illustrates the final state of routing and port calculation for the above heuristic.

6 Simulation Results

We conducted several simulations to study the performance of all proposed heuristic algorithms. The objective of our simulations were two-fold:

1) Compare the results yielded by all these heuristic algorithms with the optimal solution obtained by solving the NLP formulation.

2) Compare the performance of all these heuristic algorithms among themselves.

6.1 Comparison with NLP

We first evaluated the near-optimality of all the proposed heuristic algorithms by comparing their results with that obtained by solving the NLP formulation provided in Section 4. Since an NLP formulation can be solved in reasonable time only for small networks, the comparison with NLP was performed over a 6 node mesh network (used for illustration in Figure 2). We have written a C++ program to formulate NLP and experimented by conducting simulation on a six node network with several groom factor variations. The overall number of e-SaD grooming ports consumed was determined with the value of groom factor varying from 1 to 4. The results of these simulations are shown in Table 1, which mainly indicates number of e-SaD ports required. The optimal solution the difference is reasonable compared to the solving complexity of the NLP.

Table 1. Comparison of performance of heuristics with that of NLP (grooming factor vs number of e-SaD ports)

g	NLP	k-SPT	GRS	GCOT
1	6	10	10	9
2	6	6	6	7
3	8	10	12	12
4	8	9	10	11

6.2 Performance of Heuristic Solutions

In order to study the performance of the heuristic algorithms, we conducted simulations on the NSFNET topology. We studied the performance by varying the grooming factor for various number of sessions. The performance of all heuristics was evaluated in terms of the overall network cost, measured in terms of the total number of e-SaD grooming ports and number of wavelengths.

6.2.1 Generation of Sessions

While generating a multicast session, each of the 14 nodes of the NSFNET, was given equal probability of being the source node for the session. The size of the destination set was generated as a uniformly distributed random number in the range 2 to 13. After the size of the destination set was determined to be d, the nodes in the destination set were then chosen such that every subset of size d of remaining 13 nodes was equally probable of being the destination set.

6.2.2 Analysis of the Results

The performance of the heuristics in terms of *number of ports* (**P**) and *number of wavelengths* (**W**) consumed is shown in Tables 2, 3 and 4.

Table 2 discusses the results of all the proposed heuristics when the traffic generated for multicast sessions is integer multiples of OC-1 chosen randomly from the set $\{1, 3, 9, 12, 18, 24, 36, 48\}$. The wavelength capacity in this case is OC-48. As per the results shown in the Table 2, the performance of all three heuristics is similar when number of sessions is less. But it varies as the number of sessions increases. The k-SPT heuristic will perform better compared with other two, due to ability of k-SPT heuristic to find more number of routing trees for a session which gives more sharing of e-SaD ports with increase in k. GRS also performs close to k-SPT but we kept the upper bound of not more than two links to be rerouted which restricts its performance compared to k-SPT.

Table 3 summarizes the results obtained when the session

Table 2. Performance of heuristics at g=48

Sessions	GCOT		GRS		k-SPT (k=2)		k-SPT (k=5)		k-SPT (k=10)	
	P	W	P	W	P	W	P	W	P	W
50	401	12	410	12	375	12	364	11	344	10
100	760	22	805	22	713	21	712	20	673	18
150	1080	30	1147	32	1019	29	1019	29	943	25
200	1447	40	1527	41	1362	41	1343	38	1263	33
250	1806	49	1914	50	1669	50	1654	47	1591	41
300	2102	60	2257	57	1957	60	1946	56	1873	48
350	2428	68	2384	60	2284	66	2280	63	2173	56
400	2793	76	3095	80	2553	74	2545	71	2441	60

Table 3. Performance of heuristics at g=98

Sessions	GCOT		GRS		k-SPT (k=2)		k-SPT (k=5)		k-SPT (k=10)	
	P	W	P	W	P	W	P	W	P	W
50	325	9	356	9	327	8	318	8	295	6
100	651	17	703	18	597	17	586	16	559	14
150	873	21	963	22	818	22	807	20	771	17
200	1177	29	1300	30	1079	28	1060	27	1003	22
250	1421	36	1594	37	1287	35	1286	33	1213	28
300	1652	41	1894	42	1532	40	1513	39	1428	32
350	1827	45	2080	46	1777	48	1671	43	1601	36
400	2115	53	2440	47	1938	53	1919	50	1836	42

set was generated from {1, 3, 9, 12, 18, 24, 36, 48, 98} and Table 4 shows the results when the set was {1, 3, 9, 12, 18, 24, 36, 48, 92, 192}.

7 Conclusion

In this paper, we addressed the problem of routing and wavelength assignment of sub-wavelength multicast sessions in the scenario of WDM mesh networks. We proposed a node architecture, wherein a translucent grooming approach is adopted. The proposed node architecture is capable of performing the duplication of multicast traffic in either electronic domain or optical domain. We also presented an NLP formulation towards an analytical model along with three heuristic approaches (k-SPT, GRS, GCOT) to solve the multicast traffic grooming problem. Finally, we provided extensive simulation results to demonstrate and compare the performance of each heuristic approach.

In the future, we intend to extend this work in the case where only a few nodes in the network are equipped with this architecture, in other words a sparse grooming case. We are also studying the architecture in the dynamic scenario, with the objective as maximization of throughput when resources such as number of wavelengths and ports are fixed.

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Table 4. Performance of heuristics at g=192

Sessions	GCOT		GRS		k-SPT (k=2)		k-SPT (k=5)		k-SPT (k=10)	
	P	**W**	**P**	**W**	**P**	**W**	**P**	**W**	**P**	**W**
50	235	6	282	7	233	6	224	6	213	5
100	480	12	556	13	464	11	439	11	410	9
150	712	18	844	19	662	17	645	16	580	13
200	903	23	1052	24	849	22	842	21	776	17
250	1124	29	1316	30	1076	28	1059	27	951	21
300	1358	34	1516	35	1271	34	1224	31	1138	26
350	1624	41	1874	42	1500	40	1442	38	1371	32
400	1753	43	2205	48	1615	43	1594	40	1449	33

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