Dynamic Multicast Traffic Engineering in WDM Groomed Mesh Networks [*]

Girish V. Chowdhary and C. Siva Ram Murthy[†] [†]
Department of Computer Science and Engineering
Indian Institute of Technology Madras
Chennai - 600036, India
gvc@cs.iitm.ernet.in, murthy@iitm.ac.in

Abstract

As the popularity of the Internet and new multicast based services like video conferencing and distance learning is gaining significant attention, the network operator's concern to provide such services in an on-line and cost effective manner is also increasing rapidly. In this paper, we address provisioning of online multicast services in the case of WDM groomed mesh networks with the objective of increasing the resource utilization and minimizing the blocking probability for the future arriving requests. We propose a grooming node architecture to perform duplication of traffic in optical as well as in electronic domain. We present a heuristic solution called maximizing the minimum freeload (MMFL) to route the dynamically arriving connections. We compare our algorithm with Fixed and Adaptive Shortest Path Tree algorithms by conducting extensive simulation experiments and present the results.

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

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 connections 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 recent past, there have also been efforts towards solving the traffic grooming problem for mesh networks. This issue has been addressed in both the static [2] as well as the dynamic [3] scenario. 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 required resources (wavelengths and 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.

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[††] Author for correspondence

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]. Efficient 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 two or more copies. By applying the concept of light-trees, the problem of designing a logical topology for given set of multicast demands [8] and, routing and wavelength assignment [9] of these sessions have been studied. The multicast RWA problem has also been addressed in the case wherein few nodes in the network are equipped with splitting capability [10]. A survey of multicasting in WDM networks is given in [11] and [12]. In recent past, static multicast grooming was addressed in mesh networks in [13], wherein an ILP formulation is provided along with heuristic algorithm with objective to minimizing the number of ADMs. In [14], multicast traffic grooming problem is solved in sparse splitting networks by providing ILP with heuristic solution for minimizing number of wavelengths required for given set of multicast demands. In [15], a dynamic multicast routing and wavelength assignment (MC-RWA) is addressed in case of all optical WDM networks wherein an adaptive heuristic is proposed and studied with full blocking and partial blocking of destination. In [16], the issue of maximization of network capacity using dynamic wavelength assignment is addressed in all optical WDM ring network for multicast traffic, wherein the problem of wavelength assignment is proved as NP-hard and two greedy heuristic solutions are presented for wavelength assignment. In [17], traffic engineering (TE) through dynamic traffic grooming is addressed in the WDM groomed networks in unicast scenario. Here, heterogeneous networks consisting of different grooming capable switches are considered. The network is modeled as an auxiliary graph. An adaptive routing algorithm is proposed based on different grooming policies. Traffic grooming and traffic engineering are jointly applied so as to improve the network throughput.

In this paper, we address the problem of multicast routing and wavelength assignment in WDM mesh networks with sub-wavelength demands in dynamic scenario. In other words, we address the dynamic traffic grooming problem in mesh networks in the multicast scenario with traffic engineering objective as maximizing the resource utilization as well as call acceptance ratio. Firstly, we propose a node architecture for supporting multicasting of wavelength as well as sub-wavelength demands, which is a translucent grooming node architecture to support the multi granularity range of demands. Since the optical layer splitting is more efficient in comparison with electronic counterpart [18], we study the dynamic multicast traffic grooming problem with the objective of maximizing call acceptance for future arriving request. In general, to solve the multicast routing and wavelength assignment problem (MCRWA), the first step is to construct a multicast tree spanning the source and all destinations of the given multicast group. This tree construction problem can be formalized as a *steiner tree problem* [19]. The steiner tree problem is known to be NP-complete, when the multicast group has more than two members [19]. 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 [19]. In general, the multicast routing algorithms *Fixed SPT* and *Adaptive SPT* are used to route the multicast traffic demands [15]. In case of fixed SPT, multicast routes will be computed without considering the current status of the network resources. The tree is the union of shortest paths from the source to all destinations of the session. The other way of routing is an adaptive SPT, where the tree is constructed based on the available network resources. After constructing the multicast tree, the next step is to assign a wavelength to the tree. In multicast traffic grooming, we perform routing and wavelength assignment steps in an integrated manner.

The rest of the paper is organized as follows. In Section 2, we outline the motivation behind this proposed work. In Section 3, we outline the node architecture required for supporting multicasting of sub-wavelength demands in mesh networks. The issues involved in grooming of multicast sessions in mesh networks with formal problem definition, are described in Section 4, and heuristic algorithms proposed for the grooming of multicast sessions is presented in Section 5. Results of all the simulation experiments we conducted to measure the performance of our heuristic algorithm are given in Section 6. We finally conclude our work in Section 7 along with some directions for future work.

2 Motivation

In the recent past, traffic engineering (TE) has become an important issue in the IP/MPLS networks for provisioning the quality of service (QoS) or balancing the load on the network. In general, TE scheme is applied based on application's required QoS parameter like delay, reliability etc. based on which, an explicit routing or constraint based routing (CBR) is carried out on the network. In case of WDM optical networks, the basic goal of traffic engineering in dynamic scenario is relatively different to that of MPLS networks. Here the objective is to optimize the network resource utilization at lower blocking rate to the offered load [20].

In recent past, many organizations like Internet Engineering Task Force (IETF), Automatic Switching Optical Networks (ASON) are putting efforts for seamless integration of IP and optical layers. These forums are extending the Multi Protocol Label Switching (MPLS) technology to Generalized Multi Protocol Label Switching (GMPLS) [21] which deals with all the types of switches ranging from packet switching capable to fiber OXC.

Currently there are several proposals to support IP multicasting using MPLS/GMPLS framework by using the traffic engineering extensions to multicast routing protocols. In [22] the issue of scalability of multicast is addressed, which basically discusses the number of states a router has to keep as the number of sessions increases. In [23], label aggregation is proposed as solution to the scalability problem for the IP multicasting over MPLS networks. In [24] new approach is proposed to construct multicast tree for MPLS networks, which mainly keeps the forwarding state information only at branching points to reduce the forwarding states so to increase the scalability of multicast. In a recent paper [25], which proposes edge router multicasting (ERM), the authors proposed a mechanism which shifts the task of duplication of packets from intermediate branching points towards the edge router. Here, this simplifies the task of setting up of label switched paths (LSPs), flow assignment and aggregation of LSPs. The major gain achieved by performing duplication at edges is the subsequent reduction of the forwarding complexity at the Label Switch Routers (LSRs). The intermediate LSRs takes the forwarding of packets as normal unicast packets, hence the multicast forwarding boils down to unicast forwarding.

All the research work, in general is stressing the strong requirement to aggregate the control information to reduce the number of multicast states at routing nodes. The reduction in states in turn increases the scalability of multicasting which is very much essential. In case of WDM groomed optical networks where *optical bypass* [1] is available at each node, hence the total number of states will drop substantially. Here the session(s) state information is required to be kept only at router if and only if the switch/router is either source, destination or branching point. Apart from scalability issue, multicasting adds complexity of duplication of packets to the routing node. This adds additional burden to the routing node apart from control domain overheads such as routing information collection, updating the multicast states. Hence utilizing network resources such as grooming ports effectively also becomes an important issue. In reality, the duplication of packets at high data rate is not a trivial task. We feel a strong need to have routing node architecture to duplicate the packets at high data rate. Hence we propose a node architecture to duplicate packets at high data rate with an objective of maximizing the call acceptance ratio.

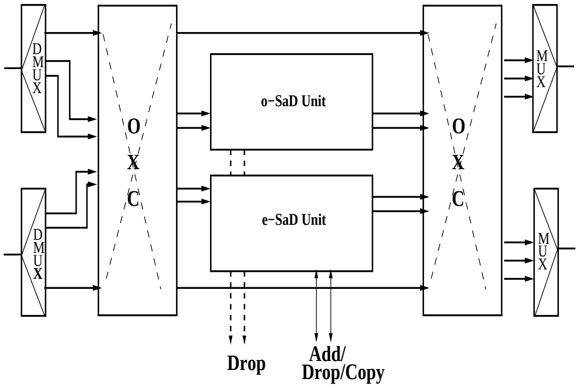

Figure 1. Node Architecture for Multicast Grooming in WDM Mesh Networks

3 Multicast Grooming Node Architecture

In the recent past, grooming received significant attention from the research community which is essential so as to improve the channel utilization. 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 do not have 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 from duplication complexity as which 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. It reduces buffer requirement as well as duplication complexity, which are the prime issues for broadband multicasting.

4 Problem Definition

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 wave lengths per fiber and each wavelength can accommodate up to g number of low speed streams. Multicast connection requests are dynamically arriving. The i^{th} request T_i is represented by (s_i, D_i, B_i, H_i) where $s_i \epsilon V$ is the source, $D_i \subseteq V$ is the set of destinations, B_i is the required bandwidth, and H_i the holding time 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 with the main objective as minimizing the maximum load on a link and thus increase the call acceptance ratio.

5 Solution Approach to The Problem

To approach the solution to the multicast traffic engineering problem in WDM groomed mesh network scenario, first we explain the fundamental difference between IP/MPLS multicast traffic engineering issues to that of the WDM optical networks. Basically in IP/MPLS networks, the issues of multicast TE were either related to scalability or network congestion, out of the former one we have already described in Section 2 the later issue especially in IP multicasting [26], where reduction in network congestion is carried out by changing OSPF weights based on per hop behavior (PHB) (which is computed based on network state). The routing process selects the path based on PHB, which in turns selects the route for the multicast request. But the case where we are discussing TE issue is in WDM groomed mesh networks, the basic objective is lesser blocking at greater resource utilization to that of IP/MPLS networks [27]. Here in case of WDM the problem is different from normal IP/MPLS networks, since here link definition is different compared to normal IP/MPLS networks. As many lightpaths are active on a physical link at a given instant, many parallel links are available for routing the request. We can call them as *virtual links* between the nodes. But for simplicity from here onward we will call them as links instead of virtual links. Here, our objective is to find route for arriving request on each of wavelength link currently active by checking with the available freeload on each one of them, so as to experience less blocking for the future arriving requests.

All the nodes are assumed to be equipped with the node architecture discussed in section 3. At any particular node, the cost involved in grooming depends on the number of ports required on the *e-SaD*/*o-SaD* unit at that node. The cost of the *o-SaD* unit is negligible compared to the *e-SaD* unit. Hence, we consider only the number of grooming ports required on the e-SaD unit as a measure of the network utilization cost.

5.1 Maximizing Minimum Freeload Heuristic (MMFL):

The MMFL heuristic makes use of the concept of *freeload* in order to route the multicast demands dynamically. The *freeload* on a wavelength link is defined as the available free bandwidth on that link i.e., a wavelength link can be part of the route for a connection having bandwidth requirement at most the freeload on that link.

The heuristic algorithm, before finding the route for the multicast connection, finds a freeload graph which reflects the current freeloads on each wavelength link. A freeload graph is a W-layer graph, (where W is the total number of wavelengths available on each fiber) and on each layer a link between nodes u and v exists if and only if the wavelength corresponding to that layer is having enough capacity on the physical link between u and v to carry the connection. Then Shortest Path Trees are computed on each layer of the graph. So at most W multicast trees are computed. The advantage of constructing the multicast tree on top of the freeload graph is that, the SPT algorithm considers only the links having the necessary free bandwidth in computing the multicast route.

The SPT generates the multicast tree by finding the individual paths from source to each destination. The path is constructed between the source and the destination using the Dijkstra's algorithm with the objective that the average freeload per link is maximum. If more than two paths have the same average freeload per link then the path with less number of links (hop count) is selected. Out of all the W trees one tree will be selected for the multicast session with an aim of maximizing minimum freeload. We calculate the *minimum freeload* in the network (MFN) as follows. The minimum freeload on a wavelength (MNW) is defined as the minimum freeload available on all the links on that wavelength plane. Like that we get W number of MNW values, each corresponding to one wavelength. The MFN is the minimum of these W values. Now the MFN is calculated for each multicast tree assuming that it is routed on the network. Finally, the multicast tree which results in the maximum MFN is selected as the required multicast route. The following notation is used in the algorithm presentation. $G(V, E)$ represents the physical network topology, $c_{i,j}$ represents the bandwidth available on the link connecting node i and node j where $i, j \epsilon V$ and $ij \epsilon E$. $G'_w(V'_w, E'_w)$ represents the present network state for the wavelength w. G''_w represents freeload graph constructed based on whether the current request is on that wavelength layer w. c'_{ij} represents the free bandwidth on the link connecting node i and node j where $i, j \epsilon V'_w$ and $ij \epsilon E'_w$. c''_{ij} refers to the freeload on link (i, j) if the current request is routed on some wavelength layer w.

MMFL Algorithm:

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1. for each wavelength $w$ do
        a) Generate the freeload graph $G''_w$ from $G'_w$ such that $c''_{ij} = \frac{(c'_{ij}-g)}{c_{ij}}$ where $c''_{ij}$ denotes the freeload on the link if the current request is routed on it.
        b) On this network find the paths from source to each destination. The path is constructed using Dijkstra's algorithm such that the average freeload per link along the path is maximum. If the average freeload per link is same for two paths then the path having lesser number of links (hop count) is taken into consideration. All these individual paths from source to destinations together constitute the multicast tree.
   end for
        /* We will get a maximum of p trees if p wavelengths are available. One tree should be selected for the request. */
2. for each multicast tree do
        a) Assume that the multicast tree is routed
        b) Calculate the minimum freeload in the network (MFN)
   end for
3. Select the tree which maximizes the MFN and route it.
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The figures 2 and 3 gives an illustration for how the *Adaptive* SPT method [15] and the *Freeload (MMFL)* method works respectively. Here in the example, we assumed the number of available wavelength is 1. The traffic requests are $1 \rightarrow \{2, 3, 4\}$, $1 \rightarrow \{2, 5\}$, $1 \rightarrow \{2, 4\}$ and the required granularities are 24, 12, 12 respectively. In adaptive SPT method, the tree is generated using Shortest Path Tree Method (SPT). In this method, the multicast tree for the request is built on top of the physical network. So, the generated tree may or may not get routed on a wavelength. In the example, after the three requests got routed, the free bandwidth on the link $1 \rightarrow 2$ becomes zero as shown in figure 2. So, now if some request comes whose SPT contains the link $1 \rightarrow 2$ then the request will get blocked. In the freeload (MMFL) method, the tree is generated taking the current network state into consideration. First, the freeload graph is generated using the formula $\frac{free-required}{total}$. In the example, for the first request the freeload graph is generated as shown in the figure 3. Consider the link $1 \rightarrow 2$. The total bandwidth on this link is 48, the free bandwidth is 48, and the required bandwidth is 24. So, the freeload on this link is 0.5. In this way the freeload graph is calculated. Now the

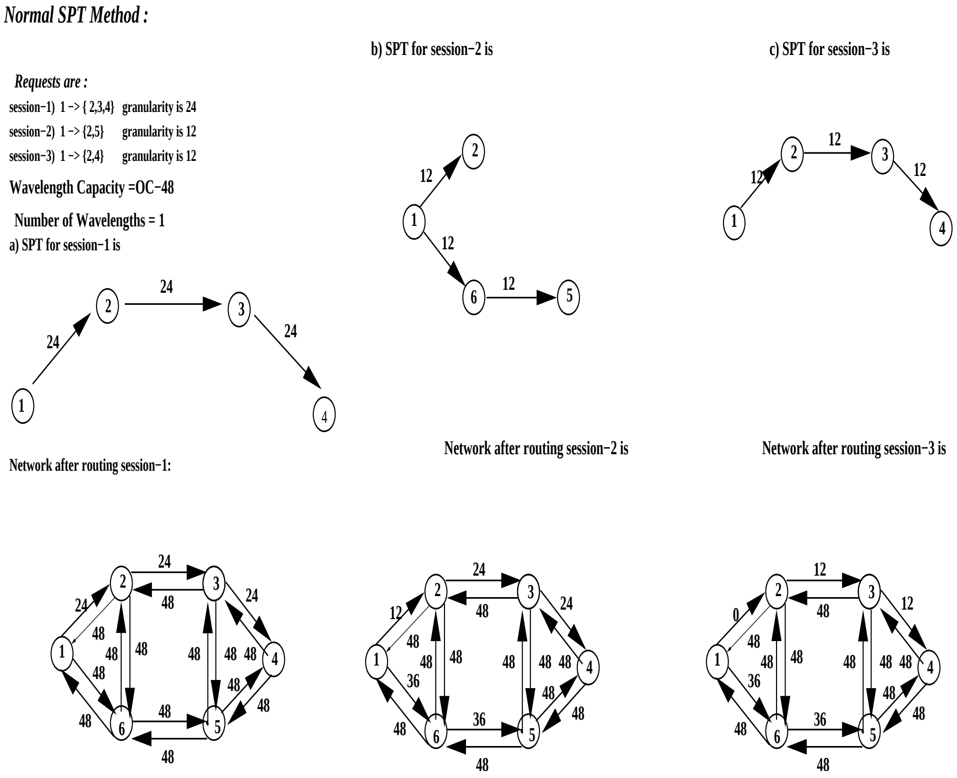

Figure 2. Example showing how SPT heuristic works

multicast tree is generated by finding the paths between source and each destination with the objective that the average freeload per link is maximum. If the average freeload per link is same then we consider the path with less number of links. In the example, in order to find the multicast tree for the first traffic request the paths are constructed for the source-destination pairs $(1, 2)$, $(1, 3)$, $(1, 4)$. These individual paths together constitute the multicast tree. Now take the source-destination pair $(1, 2)$. For this pair, we get different paths $1 \rightarrow 2$, $1 \rightarrow 6 \rightarrow 2$, etc., having the same average freeload per link. But we will consider the path $1 \rightarrow 2$ since the number of links in the path is one (less than the links in other paths). Similarly the paths for remaining source-destination pairs are found. Finally, after routing all the requests, a free bandwidth of 24 is available on the link $1 \rightarrow 2$. So, unlike in the fixed SPT method the future request will not get blocked if its multicast tree contains the link $1 \rightarrow 2$.

6 Simulation Results

We conducted several simulation experiments to study the performance of proposed heuristic algorithm. We compared the performance of MMFL heuristic with the heuristics Fixed SPT and Adaptive SPT. The performance of the heuristic is compared in terms of the *call acceptance ratio*, which is the ratio of total number of calls accepted to the number of calls generated. The other performance metric is *average resource utilization*, which is the number of ports consumed while grooming the arrived requests. Note that we assume that the node architecture is present at all the nodes of the network and ports will be available on all the wavelengths. We have conducted the simulation on NSFNET topology.

6.1 Generation of Sessions

The connections are generated with arrival times following a Poisson process with rate parameter λ and whose durations are exponentially with mean $1/\mu$. While generating a multicast session, each of the nodes of the NSFNET graph, 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

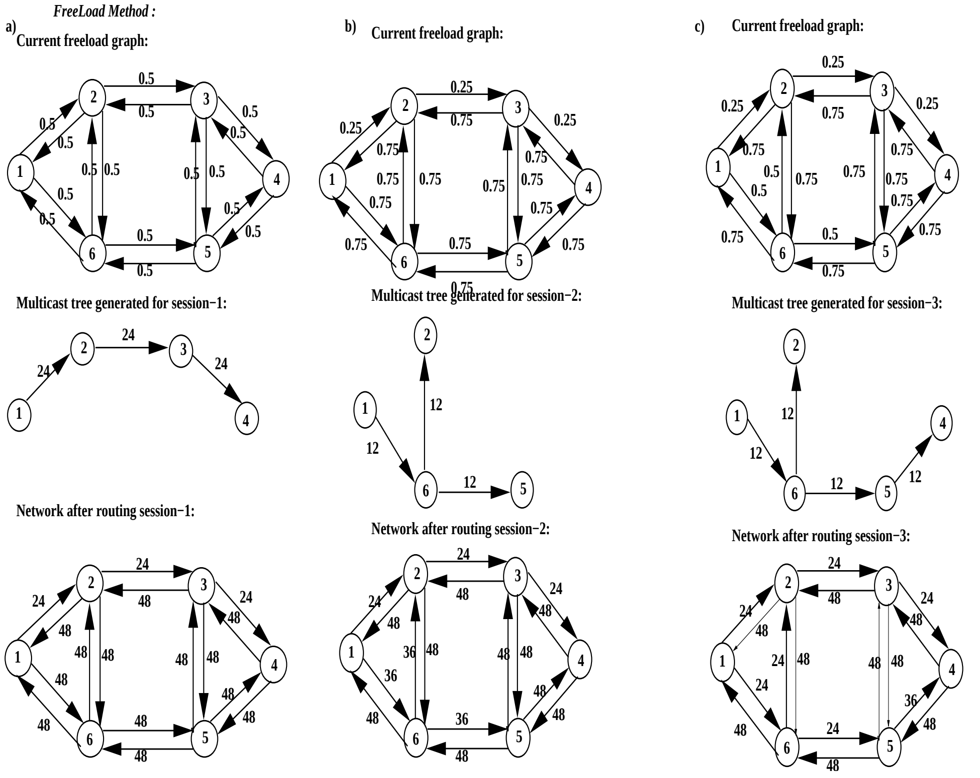

Figure 3. Example showing how MMFL heuristic works

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. Here we assumed for simulation the number of wavelengths available to be five on each fiber and same number of ports available at each node. We have varied the load by varying the duration $1/\mu$ for each simulation run.

6.2 Comparison of Heuristic Algorithms

We found that the MMFL heuristic performs better than adaptive heuristic and fixed SPT in terms of call acceptance ratio and average resource utilization. Figure 4 shows the simulation experiment where bandwidth of sessions is the integer multiples of OC-1 chosen from set $\{1, 3, 9, 12, 18, 24, 36, 48\}$ where the wavelength capacity is OC-48, It is clear that MMFL performs better than other heuristics. We have carried out more simulation experiments by changing the session set generated from $\{1, 3, 9, 12, 18, 24, 36, 48, 92\}$ and $\{1, 3, 9, 12, 18, 24, 36, 48, 92, 192\}$ where the wavelength capacity is OC-92 and OC-192 respectively. From all these simulation experimentation we found the performance of MMFL heuristic is consistent and better than the adaptive heuristic across the wide variation in the granularity. There is an average increase of 10% in the call acceptance ratio when compared to Adaptive SPT method. We have also measured the performance of heuristic in terms of resource utilization shown in figure 5. The MMFL is showing better resource utilization compared to the other heuristics.

In general, in case of IP/MPLS domain the requirement of granularity specified in continuous range (for e.g. 1 Mbps to 1 Gbps range then the request can take any value in this range). We have conducted similar set of experimentation for different wavelength capacities (OC-48, OC-96 and OC-192) for which figure 6 shows the performance, which demonstrates the consistent and better performance of MMFL heuristic.

7 Conclusion

In this paper, we addressed the problem of dynamic multicast traffic engineering in WDM groomed mesh network through a scheme called maximize the minimum freeload (MMFL). We proposed a node architecture along with heuristic solution for supporting dynamic multicasting of sub-wavelength demands,

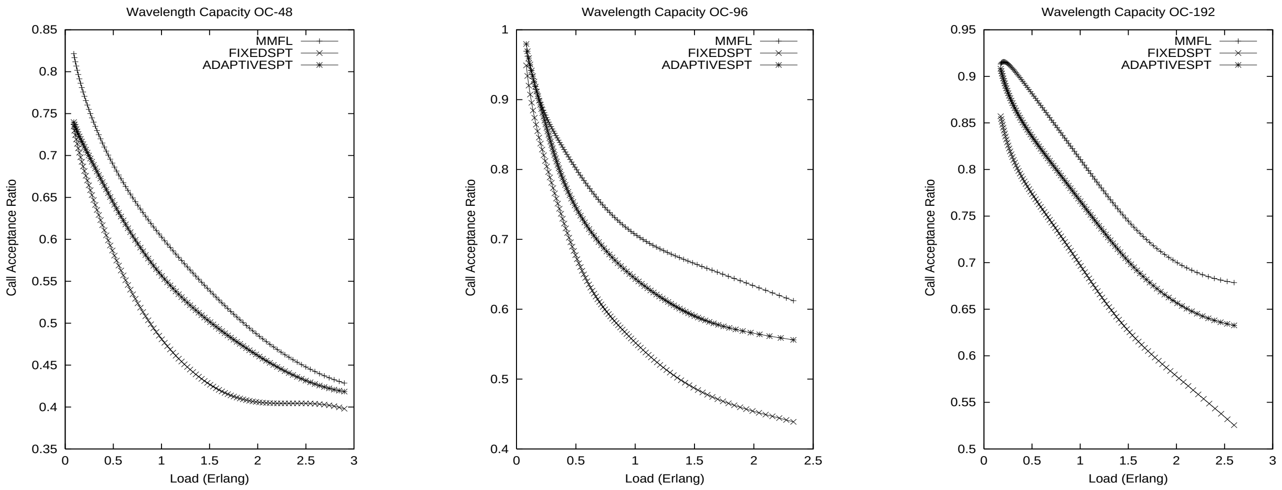

Figure 4. Performance of Heuristics Measured in terms of Call Acceptance Ratio

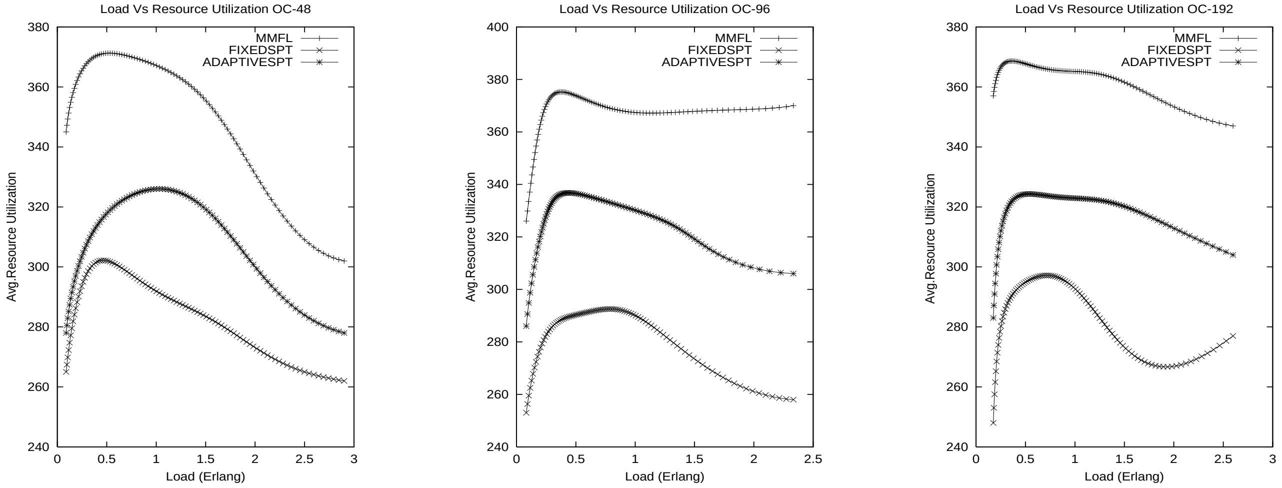

Figure 5. Performance of Heuristics Measured in terms of Resource Utilization

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 have extensively studied the performance of MMFL by conducting simulation experiments to compare the performance with adaptive shortest path tree (SPT) and fixed SPT.

In the future, we intend to extend this work for GMPLS networks, where only ingress and egress nodes in the network are equipped with this architecture. Also we are currently studying the distributed protocol implementation required to support in the case of GMPLS networks where nodes have different grooming capabilities and switching architectures.

References

[1] E. Modiano and A. Chiu, “Traffic Grooming Algorithms for Reducing Electronic Multiplexing Costs in WDM Ring Networks,” *IEEE/OSA Journal of Lightwave Technology*, vol. 18, no. 1, Jan. 2000, pp. 2-12.

[2] Keyao Zhu and B. Mukherjee, “Traffic Grooming in an Optical WDM Mesh Networks,” *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 1, Jan. 2002, pp. 122-133.

[3] Hongyue Zhu, Hui Zang, Keyao Zhu and B. Mukherjee, “Dynamic Traffic Grooming in WDM Mesh Networks Using a Novel Graph Model,” in *Proc. IEEE Globecomm 2002*, vol. 3, Nov. 2002, pp. 2681-2685.

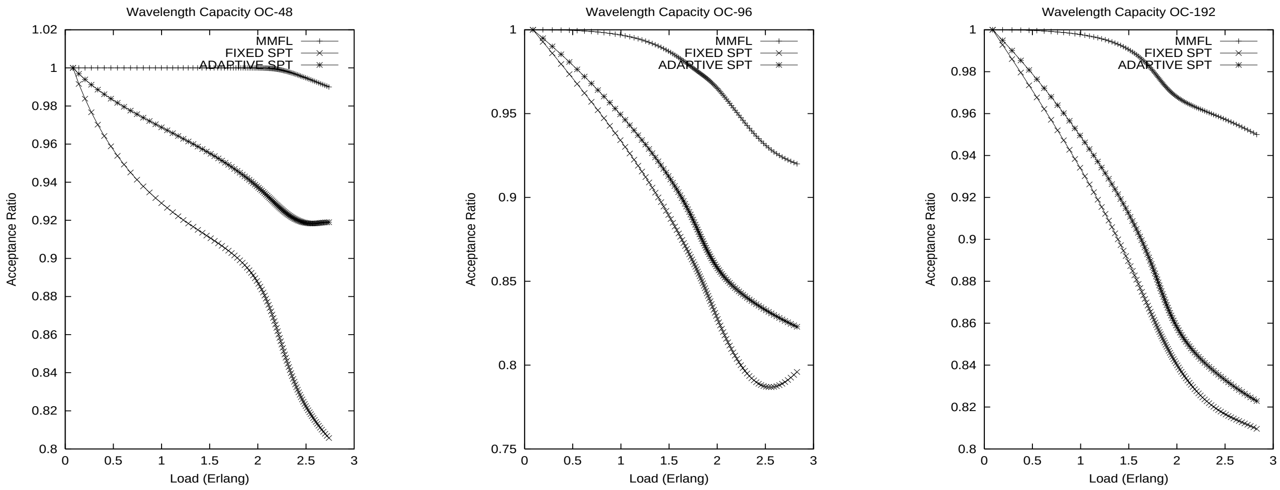

Figure 6. Performance of Heuristics Measured in terms of Call Acceptance Ratio (continuous granularity)

[4] K. Zhu and B. Mukherjee, “A Review of Traffic Grooming in WDM Optical Networks: Architectures and Challenges,” *Optical Networks Magazine,* vol. 4, no. 2, Mar. 2003, pp. 55-64.

[5] R. Malli, X. Zhang, and C. Qiao, “Benefit of Multicasting in All-Optical Networks,” in *Proc. of SPIE All Optical Networking*, Nov. 1998, pp. 209-220.

[6] M. Ali and J. S. Deogun, “Cost-Effective Implementation of Multicasting in Wavelength Routed Networks,” *IEEE/OSA Journal of Lightwave Technology*, vol. 18, no. 12, Dec. 2000, pp. 1628-1638.

[7] L. H. Sahasrabuddhe and B. Mukherjee, “Light-Trees: Optical Multicasting for Improved Performance in Wavelength Routed Networks,” *IEEE Communications Magazine*, vol. 37, no. 2, Feb. 1999, pp. 67-73.

[8] M. Mellia, A. Nucci, A. Grosso, E. Leonardi, and M. A. Marsan, “Optimal Design of Logical Topologies in Wavelength-Routed Optical Networks with Multicast Traffic,” in *Proc. IEEE Globecomm 2001*, Nov. 2001, pp. 1520-1525.

[9] G. Sahin and M. Azizoglu, “Routing and Wavelength Assignment in All-Optical Networks with Multicast Traffic,” *European Transactions on Telecommunications*, vol. 11, no. 1, Jan. 2000, pp. 55-62.

[10] X. Zhang, J. Wei, and C. Qiao, “Constrained Multicast Routing in WDM Networks with Sparse Light Splitting,” *IEEE/OSA Journal of Lightwave Technology*, vol. 18, no. 12, Dec. 2000, pp. 1917-1927.

[11] Jingyi He, S. H. Gary Chan, and Danny H. K. Tsang, “Multicasting in WDM Networks,” *IEEE Communications Surveys*, vol. 4, no. 1, Dec. 2002, pp. 2-20.

[12] Aijun Ding and Gee-Swee Poo, “ A survey of optical multicast over WDM networks,” *Computer Communications,* vol. 26, no. 2 Feb. 2003, pp. 193-200.

[13] Ahmed Kamal and Raza Ul-Mustafa, “Multicast Traffic Grooming in WDM Networks,” in *Proc. Opticomm 2003.* vol. 5285, Oct 2003, pp. 25-36.

[14] Abdur R.B. Billah, Bin Wang and Abdul A.S.Awwal, “Multicast traffic Grooming In WDM Optical Mesh Networks,” in *Proc. IEEE GLOBECOM* , vol.5, Dec. 2003, pp. 2755-2760.

[15] G. Sahin and M. Azizoglu, ”Multicast Routing and Wavelength Assignment in Wide Area Networks,” *Proc. SPIE,* vol. 3531, 1998, pp. 196-208.

[16] Jianping Wang, Biao Chen, and Uma R.N., “Dynamic wavelength assignment for multicast in all-optical WDM networks to maximize the network capacity” *IEEE Journal Selected Areas in Communications* , vol. 21, no. 8, Oct. 2003, pp.1274-1284.

[17] Keyao Zhu, Hongyue Zhu, and B. Mukherjee , “Traffic Engineering in Multigranularity Heterogeneous Optical WDM Mesh Networks Through Dynamic Traffic Grooming,” *IEEE NETWORK* vol. 17, no. 2, Mar/Apr. 2003, pp. 8-15.

[18] Xiao Hua Jia, Ding Zhu Du, Xiao Dong Hu, Man Kei Lee, and Jun Gu, “Optimization of Wavelength Assignment for QoS Multicast in WDM Networks,” *IEEE Transactions on Communications*, vol. 49, no. 2, Feb. 2001 pp. 341-350.

[19] M. R. Garey, R. L. Graham, and D. S. Johnson, “The Complexity of Computing Steiner Minimal Trees,”

SIAM Journal of Applied Mathematics, vol. 32, no. 4, Jun. 1977, pp. 835-859.

[20] Iovanna, P., Sabella, R., and Settembre M., " A traffic engineering system for multilayer networks based on the GMPLS paradigm" *Network, IEEE,* vol. 17, no.2, Mar/Apr 2003, pp. 28-37.

[21] S.J.Ben Yoo "Optical-label switching, MPLS, MPLambdaS, and GMPLS," *Optical Networks Magazine,* vol. 4, no.3, May 2003, pp. 17-31.

[22] Young-Kyu Oh, Dong-Keun Kim, Hun-Je Yoen, Mi-Sun Do, and Jaiyong Lee, "Scalable MPLS Multicast using Label Aggregation in Internet Broadcasting System", in *Proc.ICT2003,*Tahiti, vol.12003 pp 273 - 280.

[23] Aiguo Fei, Jun-Hong Cui, Mario Gerla, and Michalis Faloutsos "Aggregated Multicast: an Approach to Reduce Multicast State," in *Proc. IEEE Globecom 2001,* Texas, USA, vol 3, Nov.2001 pp. 1595 - 1599.

[24] A. Boudani, and B. Cousin. "A New Approach to Construct Multicast Trees in MPLS Networks," in *Proc. IEEE ISCC,* Taormina, Italy, 2002, pp. 913-919.

[25] Baijian Yang, and Prasant Mohapatra, "Edge Router Multicasting with MPLS Traffic Engineering," in *Proc. IEEE international conference on networks(ICON) 2002.* Aug.

[26] C. Jacquenet and C. Proust, "An Introduction to IP Multicast Traffic Engineering," *Proc. ECUMN 2002.*, April 2002, pp. 263-267.

[27] Xu Shao, Tee Hiang Cheng, and Kumaran Veerayah, " Requirements for MPLS over GMPLS-based Optical Networks," *IETF Internet draft*, Work in Progress, draft-xushao-ipo-mplsovergmpls-02.txt, May 2004.