An Efficient Mechanism for Dynamic Multicast Traffic Grooming in Overlay IP/MPLS over WDM Networks

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Abstract

This paper proposes an efficient overlay multicast provisioning (OMP) mechanism for dynamic multicast traffic grooming in overlay IP/MPLS over WDM networks. To facilitate request provisioning, OMP jointly utilizes a data learning (DL) scheme on the IP/MPLS layer for logical link cost estimation, and a lightpath fragmentation (LPF) based method on the WDM layer for improving resource sharing in grooming process. Extensive simulations are carried out to evaluate the performance of OMP mechanism under different traffic loads, with either limited or unlimited port resources. Simulation results demonstrate that OMP significantly outperforms the existing methods. To evaluate the respective influences of the DL scheme and the LPF method on OMP performance, provisioning mechanisms only utilizing either the IP/MPLS layer DL scheme or the WDM layer LPF method are also devised. Comparison results show that both DL and LPF methods help improve OMP blocking performance, and contribution from the DL scheme is more significant when the fixed routing and first-fit wavelength assignment (RWA) strategy is adopted on the WDM layer. Effects of a few other factors, including definition of connection cost to be reported by the WDM layer to the IP/MPLS layer and WDM-layer routing method, on OMP performance are also evaluated.

Keywords: IP/MPLS over WDM network, multicast, overlay model, traffic

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1. Introduction

As wavelength division multiplexing (WDM) networks are taking over the dominant role in the Internet backbone [1], it is widely believed that IP over WDM networks will be a key component of the next-generation Internet [2, 3]. The emerging networking technologies, such as Multi-Protocol Label Switching (MPLS) [4], Generalized MPLS (GMPLS) [5], User Network Interface (UNI) [6], path computation element (PCE) [7], etc., are also paving the way for such network revolution.

An IP/MPLS over WDM network has two different layers. The IP/MPLS layer consisting of label switching routers (LSRs) and label switched paths (L-SPs) is the carrier network, and it delivers requests between its end users; the WDM layer consisting of optical-cross-connects (OXCs) and fiber links is the transport network, and it provides dynamic connectivity services to the upper-layer client(s) in the form of *lightpath*s [8]. A lightpath may span several optical links, and it has to be assigned the same wavelength along its route if all OXCs do not have wavelength conversion capability.

For the interconnection between the IP/MPLS layer and the WDM layer networks, three architectural alternatives, namely, overlay, peer and augmented models, have been proposed [9]. In the overlay model, the two network layer-s are independent of each other, and the only information exchange between them is for service requests and responses. While in the peer model, a unified control plane is maintained, in charge of all network control and management. The augmented model tries to make a compromise between the two by allowing certain information to be shared between the two layers; however, there is still no consensus on what kind of information should be shared. Adapting a peer-model approach allows the network transmission provisioning problem to be conveniently mapped into a network flow problem with complete topology and capacity information on both layers. In practice, however, since the

IP-layer and the WDM layer networks are usually owned by different network operators, overlay model is widely accepted as the most practical one for near-term deployment [9]. The emergence of service oriented optical networks further demonstrates the feasibility of such model [10]. While extensive work has been done on transmission provisioning in peer model networks [11–16], studies on overlay network model are still relatively limited, and mostly only for handling unicast traffic [17–20].

Multicast is an efficient way of disseminating information from one source to multiple destinations simultaneously [21]. In recent years, as Internet applications, such as multi-player gaming, video conferencing and interactive distance learning, etc., are becoming increasingly popular, multicasting becomes one of the essential capabilities in modern networks. In the traditional IP networks, multicast is realized relying on the IP router's copying capability; while in WDM networks, it relies on the OXCs' light-splitting capability. To support physical-layer multicasting in WDM networks, a generalized lightpath concept, named *light-tree*, was proposed [22].

The bandwidth required for a typical multicast session is on the order of megabits per second (Mbps), which is much smaller compared to the $2.5 - 40$ gigabits per second (Gbps) capacity that can be steadily provided by a single wavelength channel in today's WDM networks. To efficiently utilize the wavelength capacity, several multicast sessions are usually packed together onto wavelength channels for transmission. Such a process is known as *multicast traffic grooming* [23].

The early-stage work on multicast traffic grooming mainly focused on the static scenario where traffic is known a prior [24–26]. As more agile networking technologies are being adopted in optical networks, however, multicast traffic tends to show its dynamic nature. Hence dynamic multicast traffic grooming problem becomes an important research issue. Different algorithms utilizing either lightpath, or light-tree, or both for dynamic multicast traffic grooming have been proposed [27–37].

Compared to the extensive interests received in peer model networks, dynamic multicast traffic grooming in overlay IP over WDM networks, however, has not received much attention in the past years. Since the two layers of the network are managed by independent owners with very limited information exchanges in between, routing decisions made on one layer may lead to inefficient resource utilizations on the other layer. To the best of our knowledge, up till now only two methods have been proposed for tackling this problem. Both methods, which will be reviewed in Section 2, are easy to be implemented, yet not free from the inherent limits caused by limited information exchanges between the two layers.

Our previous study [20] on *unicast* traffic grooming in overlay networks shows that, by letting the two layers agree on a definition of the cost for setting up a new lightpah and allowing the IP/MPLS-layer operator to keep record of the recent service requests that have been supported by the WDM layer network, the IP/MPLS-layer owner can make better routing decisions and improve network performance significantly [20]. To extend such results to multicast traffic grooming, however, requires nontrivial work. The issues to be studied include the definition of the cost for setting up new connections (not necessarily new lightpaths), the routing method, and more. Further, how to improve the efficiency of WDM-layer network resource sharing is also an important issue.

This paper addresses the dynamic multicast traffic grooming problem in overlay IP/MPLS over WDM networks. To help relax the constraint imposed by limited information exchanges in overlay networks while improving resource sharing in traffic grooming process, an efficient overlay multicast provisioning (OMP) mechanism is proposed. By jointly utilizing a historical data learning (DL) scheme on the IP/MPLS layer for link cost estimation, and a lightpath fragmentation (LPF) based method on the WDM layer for improving resource sharing, OMP aims to minimize the *bandwidth blocking ratio* (BBR), which is defined as

$$BBR = \frac{\sum \text{Blocked request bandwidth}}{\sum \text{Bandwidth of all requests}}$$

Extensive simulation results show that OMP significantly outperforms the existing methods under different traffic loads, in networks with limited or unlimited optical port resources. It is also found that the IP-layer DL contributes more to improve network performance than the WDM-layer LPF method. Effects of other factors, including definition of new connection cost and WDM-layer routing method, on OMP performance are also evaluated.

The remainder of the paper is organized as follows. Section 2 presents the network model, the definition of the problem, and some most closely related existing results. Section 3 describes the proposed OMP mechanism. Performance evaluations are carried out in Section 4. Section 5 concludes the paper.

2. Network Models, Previous Work and Problem Statement

2.1. Overlay IP/MPLS over WDM Network Model

A typical overlay IP/MPLS over WDM network as shown in Fig. 1 is considered in the paper. With the overlay architecture, the operations and management of the two layers' networks are independent of each other; the IP/MPLS layer is an integrated service provider (ISP) delivering the service requests between its end users, while the WDM layer is the bandwidth provider providing the required connectivity services to its upper layer client(s).

In such an overlay network, the operator of each layer keeps all the information of its own layer, and sends its management commands to all its network elements via a centralized control system. Based on their service contracts, the two operators can also work cooperatively to provide the desired service fulfilling each arriving request. Specifically, upon the arrival of a multicast request, the IP-layer ISP firstly tries to find a route tree for it using only the existing logical links with sufficient residual bandwidths. If such effort fails, it then figures out the LSR pairs between which new lightpaths may need to be set up, and enquires the WDM layer operator for the costs of setting up such lightpaths. After receiving the set up costs reported by the WDM layer, the IP-layer ISP finally decides the lightpaths to be purchased. Note that whether to enquire the

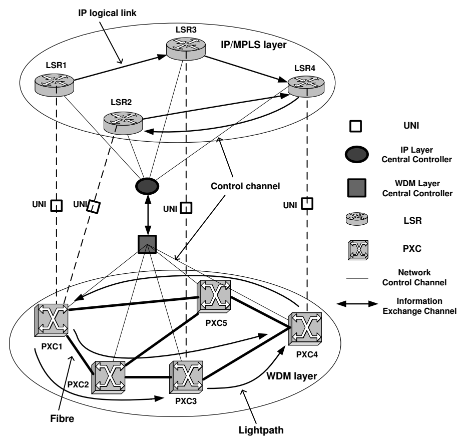


Figure 1: A typical overlay IP/MPLS over WDM network considered.

WDM layer for lightpath set up costs is decided by the IP layer operator, while whether a new lightpath can be set up or not is decided by the WDM layer operator. In the cost enquiring process, the necessary information exchanges between the two layers are performed through well-defined network interfaces, i.e., UNIs, but not necessarily through the information exchange channels as shown in Fig. 1.

In this paper, we assume that there is only one ISP, and it has exact information of the IP/MPLS-layer network. We also reasonably assume that such IP-layer ISP can keep records of the lightpaths that have been supported by the WDM layer, their corresponding setup costs, as well as the time when such costs were reported. We extend the historical data learning (DL) scheme proposed in [20] from unicast to multicast case.

On the WDM layer network, we assume that the fixed minimum hop routing and first-fit wavelength assignment policy is adopted for lightpath routing. Note that a lightpath route could be very long and the long lightpaths may degrade resource sharing in traffic grooming process. As our previous results showed that splitting long lightpaths into shorter ones helps improve resource sharing in dynamic traffic grooming process [34], we assume that a lightpath fragmentation (LPF) based method is adopted in the lightpath routing process. With the LPF method, long lightpaths may be fragmented into shorter ones upon set up. We also assume that an established lightpath with ongoing transmission cannot be fragmented or rerouted.

Detailed DL scheme and the LPF method will be presented later in Section 3.

2.2. Node Architecture

A typical network node in overlay IP/MPLS over WDM networks is an OXC interconnected with zero, one or more LSRs through UNI [9]. By utilizing OXC, a node is able to transmit data traffic transparently from an input port to an output port at the wavelength level granularity. While through LSR(s), a node is also able to receive/transmit data traffic from/to the high-speed wavelength channels.

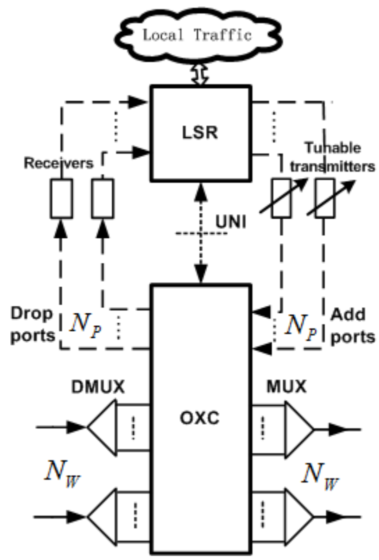


Figure 2: A typical switch architecture utilized in this paper.

Without loss of generality, we assume that each network node in this paper is an OXC interconnected with a single LSR, and all OXCs have no wavelength conversion capability. Figure 2 shows the node architecture utilized. For each node, the number of transmitters/receivers on it equals the number of add/drop ports on the OXC. Due to the existence of high-speed processing units, however, the add/drop ports are typically of high costs. To save network cost without sacrificing network performance, an OXC is usually equipped with a limited number of add/drop ports shared by all incoming/outgoing wavelengths. We use *add/drop ratio* that is defined as below to represent the port resources on a network node:

$$r = N_P/N_W, (0 < r \leq 1) \quad (1)$$

where N_P is the number add/drop port pairs and N_W is the number of incoming/outgoing wavelengths the OXC has. If $r < 1$ for a node, we call it as port-limited; and port-unlimited, otherwise.

2.3. Previous Work

To the best of our knowledge, only two methods have been proposed in literature for dynamic multicast traffic grooming in overlay IP/MPLS over WDM networks [28]. We term these methods as logical-path-tree (LPT) method and saturated cut (SC) method, respectively.

The main idea of both methods is to utilize the IP layer existing logical links to serve as many destinations as possible before setting up any new lightpaths. Specifically, LPT tries to find a route using existing logical links with enough residual bandwidth for the request, and if such a step fails, it then tries to set up new lightpaths to connect the remaining destinations to the partial route found.

Compared to LPT, SC achieves better performance: it firstly identifies some islands, which contains either the source node s and nodes can be reached from s, or at least a destination node d_i and nodes which can reach d_i, using existing logical links with sufficient residual bandwidth, and then connects such islands using new lightpaths when necessary.

These methods are easy to be implemented, yet are suffering from the limited efficiency in resource utilizations. An example is illustrated in Fig. 3. Assume that at the time when multicast request $R\{s \rightarrow \{d_1, d_2, d_3\}\}$ arrives at the network, there are three logical links with enough residual bandwidth on the

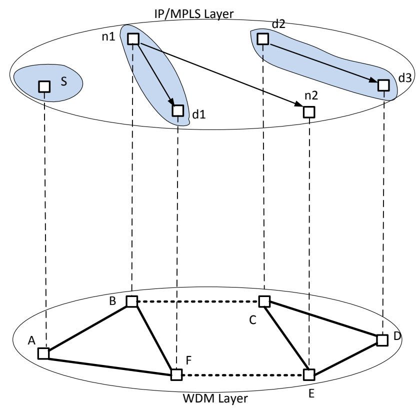


Figure 3: An example of serving multicast request $R\{s \rightarrow \{d_1, d_2, d_3\}\}$ with LPT and SC methods.

IP/MPLS layer, while on the WDM layer, all links have idle wavelengths except for the links BC and FE. When the LPT method is adopted, no route can be found for this request either on the IP layer or the WDM layer. While when the SC method is adopted, three islands as shown in Fig. 3 can be found. However, although the two islands containing s and d_1 respectively can be connected via a new lightpath, the one with d_2 and d_3 cannot be connected to s, and thus the request has to be blocked.

By observing Fig. 3 closely, we may note that if there is any chance to utilize the IP layer existing logical link between nodes n_1 and n_2, the request in fact can be served. To handle such issue, the OMP mechanism is proposed. Specifically, by estimating the cost of each IP layer logical link and then setting up two new lightpaths from s to n_1 and n_2 to d_2 respectively, OMP is able to fulfill the request.

2.4. Problem Statement

Denote the network as $G(V, E)$ with V and E being the sets of network nodes and fiber links respectively. Each WDM layer link consists of two fiber links in opposite directions, each of which carrying W wavelengths. A multicast request is represented as $R\{s, D, b\}$, where s, D and b are the request source, destination set and required bandwidth, respectively. A request is served only when all its destinations can be served; otherwise, it is blocked. Since our previous study showed that the lightpath scheme achieves better blocking performance over light-tree in dynamic traffic grooming process [34], we adopt the lightpath scheme to support multicast transmission in this paper.

The dynamic traffic grooming problem in the overlay IP/MPLS over WDM networks can be defined as follows. Given an overlay IP over WDM network with certain network resources and dynamically arriving/leaving multicast request-s, a request provisioning mechanism, which requests only limited information exchanges between the two different layers is to be devised to optimize the net-work BBR performance. For that purpose, network resource sharing must be enhanced on both of the two layers as much as possible. As aforementioned, any established lightpath cannot be interrupted when there is still any ongoing transmission using it.

3. Overlay Multicast Provisioning (OMP) Mechanism for Dynamic Multicast Traffic Grooming

This section describes the proposed OMP mechanism. First, we present the historical data learning (DL) scheme for logical layer link cost estimation, followed by description of the multiple tree heuristic (MTH) for finding a number of candidate route trees. Then we discuss the lightpath fragmentation (LPF) method for WDM layer routing. Finally, we present the OMP mechanism.

3.1. IP/MPLS layer historical data learning (DL) scheme

When requests arrive at the network, an auxiliary graph which represents the IP/MPLS layer network is generated. Edges of the graph consist of both existing logical links with sufficient residual bandwidth and potential new lightpaths to be set up. We term those existing lightpaths as *existing links*, and those new ones to be set up as *candidate new lightpath*s (CNLs).

Once the auxiliary graph is obtained, OMP assigns each graph edge an appropriate cost, and then finds a number of candidate routes. Hence, a candidate route for a request may consist of only existing links, or CNLs, or both. For simplicity, we further categorize those CNLs into *cost unknown* links and *cost enquired* links: if cost of a link has never been reported by the WDM layer, it is a cost unknown link; otherwise, it is cost enquired. Below we briefly describe the link cost estimation process with DL scheme.

As discussed in [20], for a cost unknown CNL between LSR i and j, it is reasonable for the WDM layer operator to provide the upper layer ISP a default link cost at the beginning of network operation. The default value calculated as below helps achieve satisfactory results:

$$M_{ij} = \left(\frac{1-r}{p \times r \times (\overline{H}+1)} - H_{ij} \ln \left(1 - \frac{1}{\omega + 1} \right) \right) \times amp \tag{2}$$

where amp is an amplification factor; H_{ij} is the minimum number of optical hops between the two OXCs that are connected to LSRs i and j; $\overline{H}$ is the average path length of the WDM network; $\omega = W/2$ is a representative value of the average number of idle wavelengths along a WDM link at a typical network status (As discussed in [20], network performance is not very sensitive to the value of ω); p is the average number of idle optical ports on a network node at a typical network status considered, and it can be calculated as

$$p = \max \left(W \times \delta \times r - \frac{1}{\overline{H}+1} \times \delta \times \left(W - \omega \right), 1 \right) \tag{3}$$

with δ being the average nodal degree of the network.

For a cost enquired CNL, its cost can be estimated using the data learning scheme proposed in [20]. Specifically, for any request arriving at time T^m, the cost of a cost-enquired CNL can be estimated as follows,

$$C_{ij}^{est} = \begin{cases} C_{ij}^{n} - d_{ij} \Delta \left| C_{ij}^{n} - M_{ij} \right| \times \min \left(\frac{1}{\Delta}, \left\lfloor \frac{T^m - T^n}{\delta t} \right\rfloor \right), & \delta t \neq \infty \\ M_{ij}, & \delta t = \infty \end{cases} \tag{4}$$

and the expiration time of the above estimated cost can be calculated using the equation below,

$$T_{ij}^{cal} = \begin{cases} T_{ij} + \left\lfloor 1 + \frac{T^m - T^n}{\delta t} \right\rfloor \times \delta t, & C_{ij}^{est} \neq M_{ij} \\ \infty, & C_{ij}^{est} = M_{ij} \end{cases} \tag{5}$$

Each time a new request arrives at the network, the expiration time of all CNLs are compared to the request arriving time. If a link cost is regarded as being expired, its cost and expiration time will be updated by the new values, C_{ij}^{est} and T_{ij}^{cal} , respectively. Note that although some other schemes can also be devised for link cost estimation, we adopt this scheme for its simplicity. The results to be shown later in this paper demonstrate that the simple scheme steadily leads to satisfactory performance. Detailed equation derivation can be found in [20].

With the above described cost estimation process, the costs of the different types of auxiliary graph edges can be defined as follows,

$$L_{ij} = \begin{cases} 1 & \text{an existing logical link} \\ M_{ij} & \text{a cost unknown CNL} \\ C_{ij}^{est} & \text{a cost enquired CNL} \\ 2M_{ij} & \text{failed lightpath between LSR } i \text{ and } j \end{cases} \tag{6}$$

Once the costs of auxiliary graph edges are known, a desired number of routes can be found using appropriate multicast routing methods. Below we present the heuristic method adopted in this paper to find a desired number of logical trees for a multicast request.

3.2. Multiple tree heuristic (MTH) for IP/MPLS layer routing

Multicast traffic grooming is well-known to be an NP-complete problem, and heuristic methods, e.g., the *minimum cost path heuristic* (MPH) [38], are usually adopted for calculating multicast route. If MPH is directly adopted for multicast grooming, however, only a single tree can be found for a request. In an overlay network, the only tree found by MPH may not be good, or even feasible, for the request. We modify the MPH algorithm to find multiple candidate trees for an arriving request. We term the modified method as *multiple tree heuristic* (MTH).

The main idea of the MTH is to iteratively find one multicasting tree after another, until the required number of trees are found, or until no tree can be found. In each iteration, for CNLs that are already included in multicasting trees found in earlier iteration(s), if any, we assign them with higher costs to discourage (but not strictly prevent) them from being used in the later multicasting trees again. Such an approach encourages MTH to include more CNLs in candidate trees and to enquire their costs, while avoiding the risk of missing some good candidate routes by strictly preventing CNLs from being included in multiple trees.

Procedure I summarizes the main steps of MTH. We see that in Step 2, MTH adds all the existing logical links with sufficient residual bandwidth onto auxiliary graph; and then adds those CNLs that are involved in previous trees and assign them costs at Steps $5-7$; CNLs that are already in VL are assigned with higher costs. Step 8 assigns costs to the other edges of the auxiliary graph; Steps $9-13$ find a logical tree for the current iteration. Note that MTH gives using an existing logical tree a higher priority: when a tree is found at the end of each iteration, MTH checks each of its links in Step 14. If the tree consists of only the existing logical links, it will be used to fulfill the request and the iterations stop; otherwise, the CNLs included in this tree will be recorded in a virtual link set. As aforementioned, these CNLs will be assigned with higher costs while being considered to be included in other trees in later iterations.

At the end of the algorithm, MTH either returns a tree consisting of only the existing logical links, or a CNL set VL. The costs of CNLs included in VL are to be enquired.

3.3. Lightpath fragmentation (LPF) for WDM layer routing

As discussed, if all the candidate IP/MPLS layer multicast trees found for a multicast request contain CNLs, the WDM layer operator needs to report the set up costs of such lightpaths to its IP layer counterpart based on their service

Procedure I: Multiple Tree Heuristic (MTH)

input : The current network $G(V, E)$, request $R\{s, D, b\}$ and a number T.

output: A CNL set, or a tree route for the request.

Clear the link set VL and auxiliary graph AG;

Add all existing logical links with residual bandwidth $\geq b$ onto AG;

for *tree number* $t_N = 1$ *to* $t_N = T$ **do**

    Node set $S = \Phi$; add node s into S, let D be request's destination set;

    for *each candidate new lightpath* VL_{ij} **do**

        Add VL_{ij} onto AG; if VL_{ij} is not in VL, set its link cost to be its estimated link cost; otherwise, set its cost to be t_N times that of its estimated cost;

    end

    Assign costs to the other links on AG according to Eq. (6); compute all-to-all shortest paths on AG;

    while $D \neq \Phi$ **do**

        Choose the minimum cost path P connecting a certain node in S to a certain node d in D; add P onto tree route t;

        Check each link of P, if it is a CNL, add it into VL;

        Add all intermediate nodes along P into S; $D = D \backslash d$;

    end

    If set VL is empty, i.e., there exists a tree consisting of existing logical links only, save and return the logical tree t;

end

Return CNL set VL.

contract. To fulfill such a purpose, a straightforward method is to adopt the lightpath cost definition used in [20], which is shown below:

$$C_{ij} = \begin{cases} \left(\frac{(1-r)}{p\times r\times(\overline{H}+1)} - H_{ij}\ln\left(1-\frac{1}{\omega_{ij}+1}\right)\right)\times amp, & \text{if } \omega_{ij} > 0 \text{ and } p > 0 \\ \infty, & \text{if } \omega_{ij} = 0 \text{ or } p = 0 \end{cases} \tag{7}$$

where all parameters have the same meanings as those defined in Eq. (2) except for p and ω_{ij}. Here p is the smaller one among the number of transmitters at the source and the number of receivers at the destination of the lightpath; ω_{ij} is the number of idle wavelengths along the lightpath route. Such a definition tries to balance the consumptions of WDM layer wavelength and optical port resources: when both resources are abundant, the costs of consuming them should be low and not so different from each other; while if any of them becomes scarce, the cost of consuming it becomes higher.

After receiving the cost reported from the WDM layer, the IP layer ISP will re-calculate the minimum-cost multicast tree and decide the lightpaths to be purchased. The WDM layer operator would then set up these lightpaths. Note that some lightpaths may be long, which may degrade the utilization of WDM layer resources. To improve resource sharing in the grooming process, a lightpath fragmentation (LPF) method [34] is adopted in the WDM layer lightpath routing process. Below we briefly describe the LPF method.

Suppose n_i is an intermediate node along a new lightpath L that the IP layer operator wants to order. Denote the fan-out degree of n_i as d_i; and the numbers of transmitters and receivers on n_i as T_i and R_i, respectively. To determine whether L should be fragmented at node n_i, two parameters are defined as follows,

$$\alpha_m = \min\left(\frac{T_i}{d_i\times W_{out}}, \frac{R_i}{d_i\times W_{in}}\right) \tag{8}$$

$$\alpha = \frac{1}{H_i} \tag{9}$$

where W_{out} and W_{in} are the numbers of idle wavelengths on the incoming and outgoing links that L goes through respectively, and H_i is the average number of optical hops from n_i to the other OXCs along the shortest paths on the WDM layer.

To determine whether a lightpath L should be fragmented at a node n_i, the main idea of LPF is to estimate whether the wavelength or the transceiver resources at n_i are more limited. A lightpath is fragmented at n_i only if the wavelength resources are regarded as more limited. Specifically, while α_m reflects the smaller one among the currently available add and drop ratios at n_i, α is the add/drop ratio required for n_i to support lightpaths from itself to each of the other nodes to be initiated from it. Thus, when $\alpha_m \geq \alpha$, we regard the transceiver resources as being more redundant and let the lightpath L be fragmented at n_i; otherwise, we let L bypass n_i to avoid taxing on the limited transceiver resources. More detailed discussions can be referred to [34].

The main steps of the LPF method are presented as follows.

Procedure II: Lightpath-fragmentation (LPF) method

input : A network $G(V, E)$, a lightpath L
output: A set of new lightpaths.

while *any node of L has not been checked* **do**
    for *each intermediate node (if any) n_i along L* **do**
        Calculate α_m for n_i ;
        if $\alpha_m > \alpha$ *at* n_i **then**
            Fragment L at n_i, and get two new lightpaths L_a and L_b;
            $L = L_b$;
        end
    end
end

When a new lightpath is ordered, LPF method is adopted on the WDM layer to process it accordingly, and a lightpath may be fragmented into several segments. However, note that Eq. (7) does not take into account the possibility of lightpath fragmentation when calculating the cost of a lightpath. This helps simplify the calculation and keep fragmentation operations, if any, transparent to the IP layer operator.

Equation (7) can be easily revised to take into account the effects of lightpath fragmentation in lightpath cost calculations. One possible way is to calculate the default link cost and the new lightpath set up cost as follows:

$$M_{ij} = \left(\sum_{seg} \left(\frac{1-r}{p \times r \times (\overline{H}+1)} - H_{seg} \ln \left(1 - \frac{1}{\omega + 1}\right) \right) \right) \times amp \tag{10}$$

$$C_{ij} = \left(\sum_{seg} \left(\frac{1-r}{p_{seg} \times r \times (\overline{H}+1)} - H_{seg} \ln \left(1 - \frac{1}{\omega_{seg} + 1}\right) \right) \right) \times amp \tag{11}$$

where $\omega = W/2$ which, as discussed in Section 3.1, is a representative value of the average number of idle wavelengths along a WDM link; p is the number of idle optical ports; p_{seg} is the smaller one among the number of transmitters at source and the number of receivers at the destination of a segment after fragmentation; and H_{seg} and ω_{seg} are the hop length and the number of idle wavelengths along the new lightpath, respectively.

Equation (11) defines the cost of a new lightpath as the sum of all fragmented new lightpath segments. To differentiate, we call CNL cost defined in Eq.(7) as a *rough* report, and the cost in Eq.(11) as an *accurate* report. Effects of using these two different definitions on the OMP performance will be evaluated in Section 4.

3.4. Overlay Multicast Provisioning (OMP) Mechanism

OMP utilizes the IP layer DL scheme for logical link cost estimation and the WDM layer LPF method for improving resource sharing. The main working steps of the OMP method are presented below as Algorithm I.

Steps $1-2$ generate the logical layer auxiliary graph, and find a desired number of logical layer candidate trees for the request using the MTH heuristic; if there exists one logical tree consisting of existing logical links only, OMP adopts this tree to serve the request in Step 3. If no such tree exists, however, the IP layer ISP then enquires the WDM layer operator for the costs of all CNLs in *VL*. Based on the lightpath setup costs reported from the WDM layer, OMP runs the MPH algorithm once again at the logical layer to find one logical tree

Algorithm I: OMP for Dynamic Multicast Traffic Grooming

input : A network $G(V, E)$ and multicast request $R\{s, D, b\}$.

output: A tree route to serve $R\{s, D, b\}$.

1 Update the costs of all CNLs of which estimated costs are expired;
2 Call Procedure I;*// logical-layer grooming*
3 If set VL is empty, go to Step 13; otherwise, continue;
4 **for** *each link in set* VL **do**
5   Enquire the WDM layer for the set up cost of the link;
6   Update the IP/MPLS layer cost record for the link;
7 **end**
8 Based on the enquired link costs, run minimum cost path heuristic (MPH) algorithm again on the IP layer to find a logical tree t for the request; if any request destination cannot be connected, block the request, return;
9 **for** *each CNL on tree route* t **do**
10   Call Procedure II, and return a set of new lightpath routes;
11   For each new lightpath, allocate both wavelength and port resources;
12 **end**
13 Serve the request; update the IP/MPLS layer network status;

for the request at Step 8; Steps $9-12$ fragment the new lightpaths to improve resource sharing, and establish them after processing. Finally, Step 13 updates the network status.

Note that once the set up cost of a CNL is reported by the WDM layer network, its upper layer cost record will be updated accordingly.

Finally, we have a brief discussion on the complexities of the heuristic algorithms. Both LPT and SC adopt the MPH algorithm to find the multicast tree for a request [28]. Their complexities can be calculated as $O\left(|D|\,|V|^2\right)$ and $O\left(|D(D+2)|\,|V|^2\right)$, where $|D|$ and $|V|$ denote the numbers of multicast destinations and network nodes, respectively. The OMP method also adopts the MPH algorithm to find the multicast trees. Since it firstly finds K candidate trees and then finds among them the one with the minimum cost, its complexity can be calculated as $O\left((K+1)\,|D|\,|V|^2\right)$. Note that OMP requires additional storage space for recording the historical data, the complexity of which is

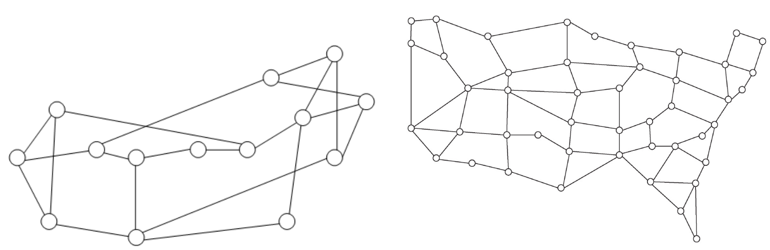
$O\left(|V|^2\right)$. Overall, we see that the complexity of the OMP method remains at a reasonably low level.

4. Simulation Results and Discussions

Extensive simulations have been carried out to evaluate the performance of OMP mechanism in different cases. Below we firstly present the simulation environment and performance metrics. Then we shall compare the performance of OMP with *rough* report against that of an existing algorithm. We will also evaluate the influences of both IP layer DL and WDM layer LPF methods on OMP performance, respectively. Finally, we will assess the influences of WDM layer lightpath cost report (*rough* vs. *accurate*) and WDM layer routing methods (fixed vs. dynamic shortest path) on OMP performance.

4.1. Simulation Environment and Performance Metrics

Two typical network topologies are used in our simulations. As shown in Fig. 4, they are 14-node, 21-link NSFnet and 24-node, 43-link USnet topologies, respectively. NSFnet has an average nodal degree of 3 and an average shortest path length of 2.18. For USnet, the two parameters are 3.58 and 2.99, respectively.



(a) (b)

Figure 4: The network topologies utilized for simulations. (a) The 14-node 21-link NSFnet. (b) The 24-node 43-link USnet topology.

The following are some assumptions adopted in simulations:

(1) Each fiber link carries $W = 32$ wavelengths, the capacity of each wavelength channel is $B = 16$ units;

(2) Requests arrive/leave the network dynamically as a Poisson process with a mean rate λ; their holding time follows a negative exponential distribution with mean $\mu = 1$; bandwidth requirement of each request is an integer uniformly distributed in $[1, 16]$;

(3) Source and destination nodes of all requests are randomly chosen among all network nodes; the number of destination nodes of each request is an integer uniformly distributed in $[2, 4]$ for NSFnet, and in $[2, 7]$ for USnet;

(4) The cost of utilizing a new lightpath is about 5 times [39] that of using an existing logical link; thus, the parameter *amp* is set to be 40 and 25 for NSFnet and USnet, respectively;

(5) For the IP/MPLS layer historical data learning scheme, the parameters are the same as those adopted in [20].

The BBR Performance of OMP is compared to that of the existing saturated cut (SC) method proposed in [28]. Results shown in each figure are averaged from at least five independent implementations, each of which running 10^5 requests or more. Since all conclusions hold for both topologies, unless otherwise stated, we present only the results on NSFnet for comparisons and discussions.

4.2. Performance Comparisons between OMP and SC Method in Different Cases

4.2.1. Comparisons under different traffic loads

We compare OMP and SC methods in networks with either limited or unlimited optical ports under different traffic loads. As can be seen in Fig. 5, OMP outperforms SC within the whole range of traffic loads in port-unlimited NSFnet. Specifically, when under low traffic loads, e.g., around 450 Erlangs, OMP outperforms SC by more than two orders of magnitude; while under higher traffic loads, e.g., around 600 Erlangs, OMP still outperforms SC by about 50%.

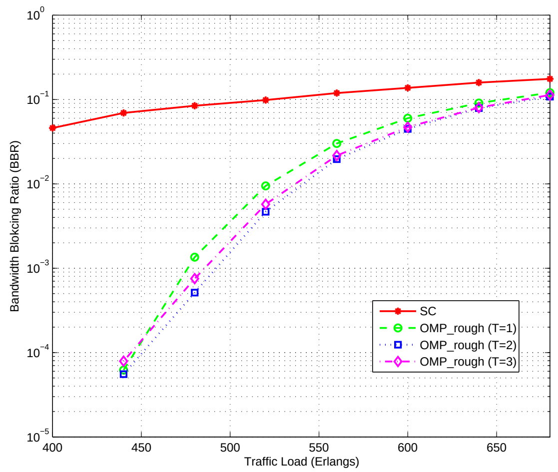


Figure 5: Comparison between OMP and SC methods under different traffic loads in port-unlimited NSFnet ($r = 1.0$).

Figure 6 compares OMP with SC in port-limited NSFnet topology where $r = 0.6$ for all OXCs, under different traffic loads. As we can see, OMP again significantly outperforms SC under different traffic loads: when under low traffic loads, e.g., $\rho = 310$ Erlangs, OMP outperforms SC by more than an order of magnitude, while when under heavier traffic loads, e.g.., $\rho = 360$ Erlangs, OMP outperforms SC by more than 50%.

Together, Figs. 5 and 6 convincingly demonstrate the satisfactory BBR performance of OMP in overlay IP/MPLS over WDM networks. Such satisfactory performance is due to a combined contribution of the IP/MPLS layer DL scheme and the WDM layer LPF method. Contributions of each of them will be further evaluated in Sections 4.3 and 4.4, respectively.

Another interesting observation in Figs. 5 and 6 is that having a larger number of logical layer candidate routes does not always lead to significant improvement in the BBR performance. Such an observation is different from that for dynamic LSP routing as reported in [20], wherein the network performance improves with an increasing number of candidate routes. Many reasons con-

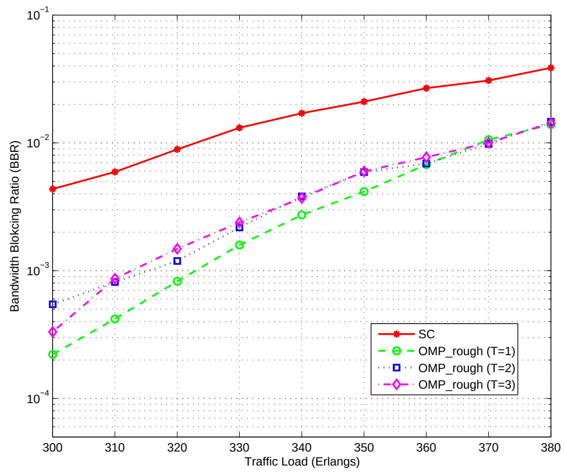


Figure 6: Comparison between OMP and SC in port-limited NSFnet network under different traffic loads ($r = 0.6$).

tribute to this observation, and the main one among them is that the logical layer link cost estimation process rather steadily leads to a reasonably good choice of route for the connection request, even when we try to find only a single candidate route. Specifically, our simulation results show that the first candidate route found by MTH has a high chance ($\geq 95\%$) to be chosen as the final route for the request.

Below we evaluate the influences of optical port resource availability on OMP performance.

4.2.2. Comparisons in networks with different port resources

Figure 7 compares OMP versus SC with different add/drop ratios. The traffic load is fixed at $\rho = 300$ Erlangs. As can be seen, when the add/drop port resource is too limited, e.g., $r < 0.4$, there is no obvious winner between the two methods; once the add/drop ratio is large enough, e.g., $r \geq 0.5$, however, OMP significantly outperforms SC. Specifically, when $r \geq 0.6$, OMP outperforms SC by more than an order of magnitude. Such observation can be understood: when the port resources are too limited, different algorithms cannot make significant differences while subject to the serious bottleneck constraint; once the port resources are reasonably abundant, the one that is capable of utilizing network resources more efficiently easily stands out. Note that, when port resources are more than sufficient, the BBR performance of SC does not further improve, while the performance of OMP steadily improves with add/drop ratio.

It is worth noting that, in Fig. 7, the OMP performance once again does not make significant improvements with an increasing number of IP/MPLS layer candidate routes, due to the same reason as explained earlier.

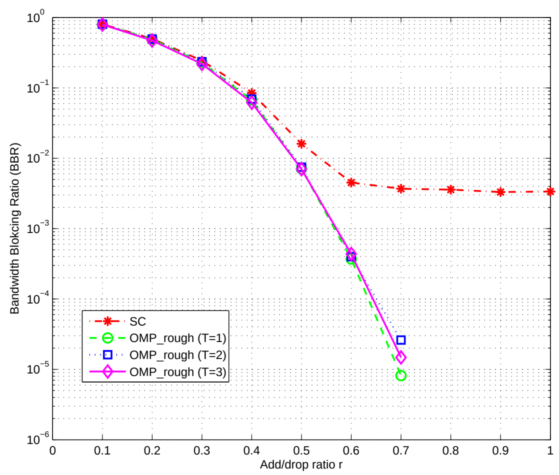


Figure 7: Comparison between OMP and SC versus add/drop ratio in NSFnet network under traffic load $\rho = 300$ Erlangs.

To figure out whether OMP leads to too many intermediate OEO conversions for each connection request, which is not favorable since extensive OEO conversions may lower transmission speed while increasing transmission cost, Fig. 8 compares the average number of intermediate OEO conversions experienced by each multicast request for both the SC and OMP methods. As can be seen, when $r < 0.6$, the average number of OEO conversions experienced by each request decreases with an increasing value r in the SC method, while when $r > 0.6$, this number stays almost unchanged. The observations however are very different for the OMP method: when $r < 0.2$, the average number decreases with an increasing value of r; for $r > 0.2$, the average number increases with r. Specifically, for $r < 0.45$, a request served by OMP usually experiences a smaller number of OEO conversions, while for $r > 0.5$, OMP has a higher number of OEO conversions for each connection request. The highest value of about 2.6, however, appears to be acceptable for most applications.

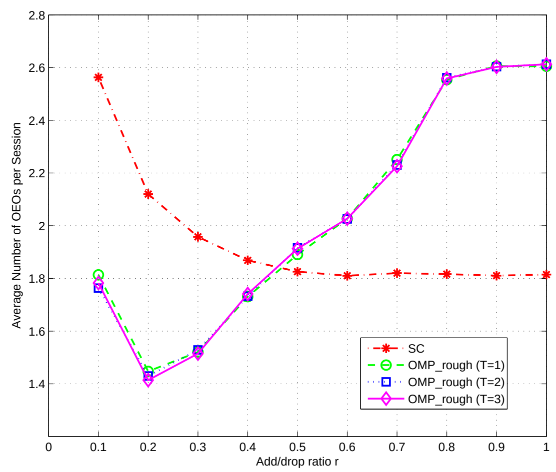


Figure 8: Average number of OEO conversions experienced by each multicast request served with SC and OMP ($\rho = 300$ Erlangs).

Such observations can be understood: when the port resources are too limited, e.g., $r < 0.2$, only a few short lightpaths can be set up between each LSR pair, and most of the admitted requests are served by these lightpaths, which leads to a larger average number of intermediate OEO conversions for both methods. With more abundant add/drop port resources, more end-to-end lightpaths can be set up between each LSR pair, intermediate OEO conversions hence decrease for both algorithms. For SC, once the number of intermediate OEO conversions reaches its lowest value, it will not be further changed. For OMP, however, since the algorithm is designed to make best use of the more abundant resources to improve the network BBR performance as much as possible, some new lightpaths will be fragmented, which leads to an increasing number of intermediate OEO conversions.

Putting Fig. 7 and Fig. 8 together, we see that for a moderate add/drop ratio of $r = 0.6$, the OMP methods, by increasing the average number of intermediate OEO conversions for about 13% (from 1.81 to an acceptable value of 2.04), improves the BBR performance to be more than an order of magnitude better than that of the SC method.

Since increasing the number of candidate routes seldom leads to any significant improvements in BBR performance, hereafter we shall only present the results obtained with a single logical layer candidate route for each connection request.

4.3. Influences of IP/MPLS Layer Data-Learning (DL) Scheme

In this section, we evaluate the influences of IP/MPLS layer historical data learning (DL) scheme on OMP performance. For comparison purpose, we devise an "OMP without data learning" (OMP_No_DL) method. Specifically, the method is nearly the same as the OMP method except that for the IP layer auxiliary graph edge cost assignment, instead of using the DL scheme, it assigns a cost of 1 to using existing logical links and a cost of 5 to using CNLs.

Figure 9 compares OMP_No_DL against SC and OMP in port-limited NSFnet under different traffic loads. Results show that without the IP layer DL scheme, OMP_No_DL performs the worst within the full range of traffic loads: SC outperforms OMP_No_DL by more than 60% in average; while OMP is more than an order of magnitude better under light traffic loads, e.g., when $\rho = 310$ Erlangs, and about 80% better under heavy traffic loads, e.g., when $\rho = 370$ Erlangs.

To further demonstrate the significant effects of the DL scheme, Fig. 10 compares OMP_No_DL against SC and OMP in NSFnet with different port resources. Results show that when the port resource is too limited, e.g., $r \leq 0.3$, there is no obvious winner among the three methods; when $r > 0.3$, however, OMP_No_DL again performs the worst. Specifically, OMP outperforms

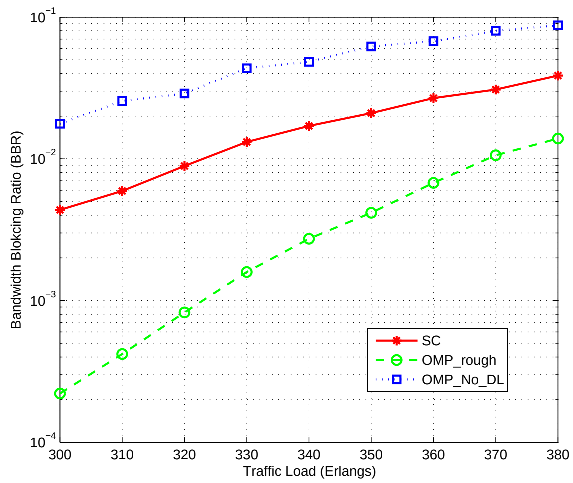


Figure 9: Performance of OMP_No_DL compared to OMP and SC methods under different traffic loads in port-limited NSFnet ($r = 0.6$).

OMP_No_DL by more than one order when $r > 0.55$, while SC outperforms OMP_No_DL once $r > 0.4$.

The above comparisons clearly illustrate the major impacts of the IP layer DL scheme on network BBR performance: by estimating the cost of each logical link using historical data, the DL scheme helps choose the right route for each incoming request, which improves the BBR performance by one, even two or three orders of magnitude.

4.4. Influences of WDM Layer Lightpath Fragmentation (LPF) Method

To evaluate the effects of WDM layer LPF method on OMP performance, similarly as above, we devise an "OMP without LPF method" (OMP_No_LPF), which is nearly the same as OMP yet without using the LPF method on the optical layer.

Figure 11 compares OMP_No_LPF against OMP and SC under different traffic loads in port-limited NSFnet where $r = 0.6$ for all OXCs. As can be seen, OMP_No_LPF steadily outperforms SC within the full range of traffic loads. But it performs nearly the same as OMP when under moderate and high traffic loads;

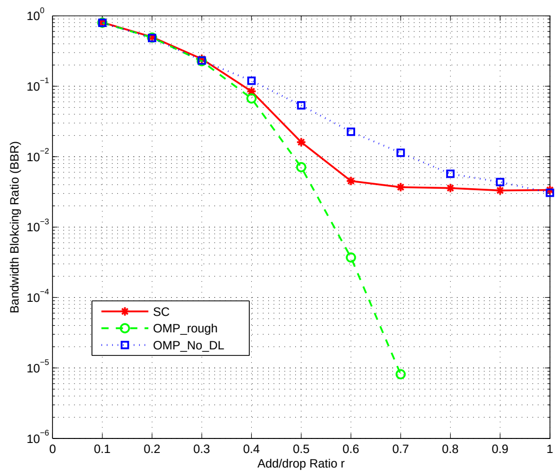


Figure 10: Performance of OMP_No_DL compared to OMP and SC in NSFnet with different optical port resources ($\rho = 300$ Erlangs).

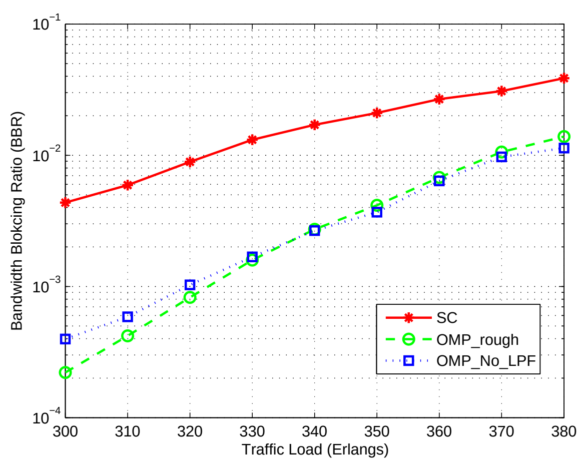


Figure 11: Performance of OMP_No_LPF is compared to OMP and SC under different traffic loads in port-limited NSFnet ($r = 0.6$)

it is only outperformed by OMP when under light traffic loads. Such observation can be explained: while under light traffic loads, most connection requests can be served using the existing lightpaths. Lightpath fragmentation, by enhancing wavelength resources sharing, leads to better performance. Under heavy traffic loads, more lightpaths need to be set up. The limited port resources soon get exhausted, mainly for supporting these new end-to-end lightpaths. The portion of fragmented lightapths among all the lightpaths quickly decreases; the impacts of lightpath fragmentation consequently diminish.

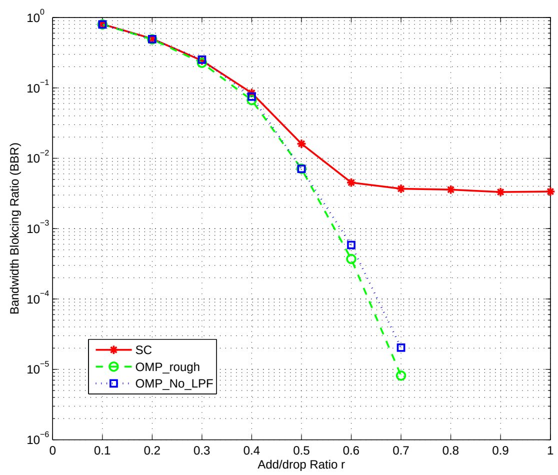


Figure 12: Performance of OMP_No_LPF is compared to OMP and SC schemes in NSFnet with different add/drop ports ($\rho = 300$ Erlangs).

Figure 12 further compares OMP_No_LPF against SC and OMP in NSFnet with different port resources. As can be seen, when the port resources are limited, e.g., $r < 0.4$, the three methods perform nearly the same; while when the port resources are more abundant, OMP_No_LPF and OMP outperform SC. More redundant port resources also lead to bigger differences between the performances of OMP and OMP_No_LPF. Such results again demonstrate that LPF helps improve network performance, especially when the port resources are abundant.

4.5. Influences of WDM Layer Lightpath Set up Cost Definition

In the earlier subsections, Eq. (7) was adopted to define the cost for setting up a new lightpath. As discussed, such a definition does not take into account the lightpath fragmentation effect. It would be of research interest to figure out the impacts on BBR performance when Eqs. (2) and (7) are replaced by Eqs. (10) and (11) respectively in order to reflect the lightpath segmentation on WDM layer.

Figure 13 compares OMP (with rough and accurate reported lightpath costs) against SC in NSFnet network with different optical port resources. As discussed earlier, when port resources are reasonably abundant, e.g., when $r > 0.4$, OMP with either rough or accurate reported link cost performs much better over SC. As to the performances of OMP with two definitions of lightpath cost respectively, we can observe they are quite similar to each other. Specifically, OMP with accurate reports only slightly outperforms OMP with rough report when $r > 0.5$. Such an observation is not difficult to be understood: when port resources is too limited, few lightpaths are fragmented; hence rough and accurate reports typically report the same value; while as port resources increase, more lightpaths are fragmented, accurate reports thus give more accurate cost information. However, since even under such case the fragmented lightpaths count for only a small fraction of all lightpaths, the performance differences remain to be insignificant.

To verify the above discussions, Fig. 14 presents the fragmentation ratio, which is defined as the number of fragmented lightpaths versus the total number of lightpaths, when the two OMP lightpath cost definitions are adopted respectively. As can be seen, when add/drop ratio $r < 0.4$, virtually no lightpath is fragmented. Therefore, the performances of OMP with rough and accurate lightpath costs are nearly the same. When the add/drop ratio $r > 0.4$, though some new lightpaths can be fragmented, i.e., $\alpha_m \geq \alpha$ on a certain node along a new lightpath, the fragmentation ratio is still quite low; hence the differences of BBR performances based on two different cost definitions remain to be insignificant.

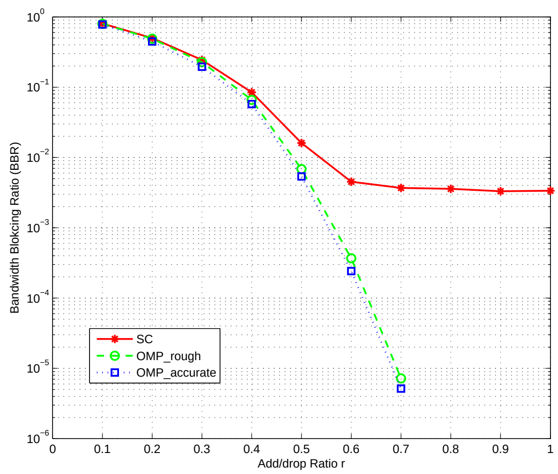


Figure 13: Performance of OMP (with rough and accurate reported link costs) compared to SC in NSFnet with different port resources ($\rho = 300$ Erlangs).

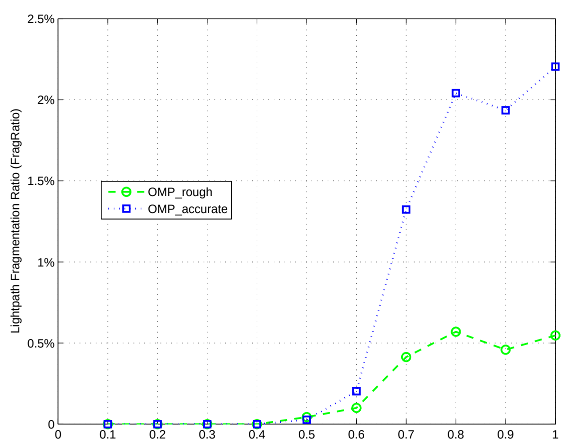


Figure 14: The ratio of new lightpath that are fragmented to the total number of new lightpaths in NSFnet with different port resources ($\rho = 300$ Erlangs).

Similar observations hold in the USnet topology: the fragmentation ratios are 0.3% and 1.6% for add/drop ratio $r = 0.5$ and $r = 1.0$ respectively under a traffic load of $\rho = 200$ Erlangs. The two different cost definitions therefore do not lead to significant differences in BBR performance.

Note that the above results are obtained when the fixed minimum hop routing and first-fit wavelength assignment policies are adopted on the WDM layer. We have also tested the case of adopting the dynamic minimum cost path routing and first-fit wavelength assignment, and found that the conclusions stated above hold.

4.6. Influences of the WDM Layer Routing Strategies

In this section, we evaluate the influences of WDM layer RWA policies on OMP performance.

For comparison purpose, we devise a new scheme which adopts the same IP layer routing method as that of OMP, yet the dynamic minimum-cost path routing and first-fit wavelength assignment policies on the WDM layer. We term such a method as OMP (dynamic). To further assess the influences of LPF on OMP performance, OMP (dynamic) without LPF method is also included in comparisons. Note that for OMP (dynamic), the enquired cost of a CNL is the cost of the dynamic shortest path calculated in the WDM layer network. Also note that we adopt Eq. (7), i.e., rough report of lightpath cost, to define the lightpath set up cost since, as discussed earlier, the two different definitions of lightpath cost lead to nearly the same performance.

Figure 15 compares OMP with different routing strategies against SC in NSFnet with different port resources. As can be seen, with an increasing add/drop ratio, OMP with either dynamic or static WDM layer routing method outperforms SC within the full range of add/drop ratio; while for OMP itself, results illustrate that performances while adopting different routing methods remain nearly the same when $r < 0.5$; when $r > 0.5$, OMP with dynamic RWA starts to perform better. Such results are reasonable: when the port resources are the resource bottleneck, OMP with either dynamic or static RWA scheme,

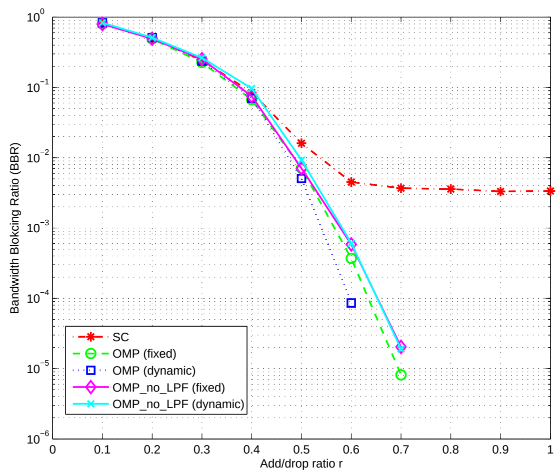


Figure 15: Performances of OMP with different WDM layer routing strategies compared to SC in NSFnet with different port resources ($\rho = 300$ Erlangs).

though different in their capabilities of exploring wavelength resources, cannot lead to significantly different performances. With more abundant port resources, OMP with dynamic WDM layer RWA scheme is able to find more appropriate lightpaths for a request, and consequently leads to better performance.

Figure 15 also shows that LPF on WDM layer leads to, relatively, more significant improvements when dynamic RWA policy is adopted and port resources are abundant ($r > 0.6$).

5. Conclusion

In this paper, we investigated the dynamic multicast traffic grooming problem in overlay IP/MPLS over WDM networks. An efficient overlay multicast provisioning (OMP) mechanism which jointly utilizes an IP/MPLS layer historical data learning (DL) scheme and a WDM layer lightpath fragmentation (LPF) based method was proposed. Simulation results demonstrated that OMP significantly outperforms the existing methods under different traffic loads, in networks with limited or unlimited optical port resources. We assessed the respective influences of DL and LPF methods on OMP performances, and showed that both DL and LPF method help improve OMP performance, and contributions by the DL scheme are much more significant. Influences of the different definitions of WDM layer lightpath cost and different WDM layer routing strategies on OMP performance were also evaluated.

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