Dynamic Hybrid Topology Design for Integrated Traffic Support in WDM Mesh Networks[1] (Invited Paper)

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Abstract

The future Internet will require the transport of a wide range of services including high bandwidth one-to-many applications, with a dynamic interconnection of devices. WDM layer support realizes such services in a transparent, reliable and efficient way. Most of the recent studies have been focused on efficiently building and configuring light-paths for unicast or light-trees for multicast in isolation, and do not take existing traffic demands and configuration into consideration. In this paper we consider a dynamic design problem of integrated traffic in a realistic WDM mesh network. In such a network, new traffic demands of either multicast and/or unicast are supported dynamically in the presence of an existing mixture of traffic. The amount of bandwidth per wavelength is abundant, while the wavelengths and light splitting capabilities on WDM switches are limited. Using subwavelength sharing among traffic demands of unicast and multicast, we build a hybrid virtual topology that exploits both existing light-trees and light-paths. By optimizing WDM resources in addition to resource sharing with existing unicast and multicast demands, we truly maximize the WDM layer capability and efficiently support more traffic demands. We validate the efficiency of our approach with extensive simulations on various network topologies.

Keywords: WDM Networks, Dynamic Topology Design, Unicast, Multicast.

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1. INTRODUCTION

As the Internet traffic continues to grow exponentially and Wavelength Division Multiplexing (WDM) technology matures, the WDM network, with tera-bits per second bandwidth links, becomes a dominant backbone for IP networks. Continuously emerging bandwidth-intensive applications in current and future Internet, however, present the need of efficient and scalable support in an underlying network. Particularly, it is increasingly important for the WDM layer to facilitate, in an efficient and scalable manner, high bandwidth one-to-many applications such as web cache updating, transfer of software upgrade, transfer of video, audio, and text data of a live lecture to a group of distributed participants, whiteboard and teleconferencing [1], [2].

In-network replication or branching of multicast traffic may be done in either an optical WDM domain or an electronic IP domain. In IP over WDM networks, mere IP layer multicasting is not efficient enough without the support of the WDM layer. Enabling multicasting at the WDM layer has clear advantages. First, with the available optical layer resources (e.g. light splitters, wavelength converters and wavelengths) we can utilize a more efficient in-network replication via an optical layer multicast tree than an IP layer multicast tree created without understanding of underlaying physical network. With the inherent light splitting capability of optical switches, it is more efficient to do light splitting than copying IP datagrams in an electronic domain. IP multicasting creates copies of data packets at intermediate routers from an optical into an electronic domain and then converts them into an optical signal, called O/E/O conversion. On the intermediate non-member nodes, this process introduces extra-delays and consumes IP resources unnecessarily. Second, performing multicast in optics is desirable and secure, as it provides consistent support of format and bit-rate transparencies across both unicast and multicast transmissions without requiring the data format to be known to the upper layer.

With no WDM layer multicast support, IP multicast sessions can be realized by having an IP router on a multicast tree make copies of a data packet in an electronic domain and transmit another copy to the downstream routers. However, this requires O/E/O conversion of every data packet at intermediate routers on the tree incurs extra-latency and requires the data format to be known to the upper layer. When IP multicast is supported via light-paths (i.e., WDM multiple unicasts), it avoids the delay of O/E/O conversion at intermediate nodes. However, this scheme is not scalable with a large number of multicast members and number of groups in the network. An ideal approach to supporting multicasting at the WDM layer is to create multicast trees in the optical layer directly. This can be achieved by light-tree [3], which uses optical light splitting at intermediate nodes as needed in order to replicate an optical signal to multiple downstream paths. It minimizes the use of wavelengths and bandwidth as well as O/E/O conversion. The minimal use of physical resources enables us to support larger sessions as compared to other approaches.

In supporting large multicast groups and members, however, the WDM layer multicast using wavelengths only may not be feasible, especially due to the limited number of wavelengths. Based on the observation that a high bandwidth capacity per wavelength is abundant enough to be shared by multiple traffic demands, [4] exploited existing unicast light-path to build light-trees for the WDM layer multicast with the subwavelength sharing approach. However it assumed that there was no multicast session set up initially and only existing unicast light-paths and available physical wavelength were considered to build light-trees.

In this work, we extend the idea of subwavelength sharing to existing multicast demands. We provide a more flexible and practical framework where existing light-trees could be shared as well. A technical challenge in subwavelength sharing of light-trees is that a light-tree is designed for a specific group and a wavelength is not desirable to be shared by different groups with different set of members. It is because the sharing of a light-tree for other multicast groups will cause all the destinations on the tree to receive data packets sent on the tree unnecessarily. We minimize the excess traffic due to light-tree sharing while optimizing all the resources. We bound the degree of sharing in order to meet the QoS of existing traffic. Our solution is aimed for a *dynamic* environment where new traffic demands need to be satisfied without disturbing the service of existing traffic. Our main contribution is that when new traffic demands, either unicast or/and multicast, arrive, they can be supported incrementally, taking available resources and existing traffic demands into consideration. If desirable or physical resources are lacking, we allow the use of existing light-paths or light-trees in conjunction with a possibly new (partial) light-tree. A challenging issue when light-trees are shared, is to minimize excess traffic incurred by the different multicast demand from the existing tree(s). In order to address that, we formulate an optimization problem that includes the overhead of excess traffic. We find that this hybrid (light-trees and light-paths) virtual topology design enables us to establish multicast trees when it would otherwise be impossible. Thus, more traffic demands are supported under practical network condition of limited wavelength constraints. Furthermore, our solution maximally utilizes the available resources of existing light-paths whose traffic demand does not reach full wavelength capacity, but has bounded a degree of sharing for QoS of existing traffic.

The idea of using existing multicast light-trees and/or unicast light-paths gives enormous flexibility in terms of a dynamically integrated future Internet traffic environment, compared to a pure light-tree approach. By optimizing the WDM layer multicast as well as resource sharing with existing mixture of unicast and multicast demands, we truly maximize the WDM layer capability under a practical environment.

The remainder of this paper is organized as follows. In Section 2 we provide the background of our study. We summarize related works in Section 3. In Section 4, we formally state the problem and discuss our approach. The evaluation and validation of our scheme is presented in Section 5. We conclude the paper in Section 6.

2. Background

In Wavelength Division Multiplexing (WDM) networks, each directional fiber optical link is partitioned into multiple data channels, each of which operates on a separate wavelength, permitting high bandwidths. Routers or switches are connected via semi-permanent optical pipes called 'light-paths' that may extend over several physical channels via wavelength routing. At intermediate nodes, incoming channels belonging to in-transit light-paths are transparently coupled to outgoing channels through a passive wavelength router, avoiding the unnecessary IP layer interruption with O/E/O conversion. Meanwhile, at a node terminating light-path, the incoming signal from the channel is converted to the electronic domain so that packets can be extracted and processed and may be retransmitted on an outgoing light-path(s) after electronic IP routing. The concept of a light-tree can be extended using optical light splitters, in order to replicate an optical signal to multiple downstream paths. The light-paths and/or light-trees establish a virtual topology on top of a physical topology made of optical fibers and switches/routers. A virtual topology configuration is constrained by a number of physical resource limitations: 1) The establishment of each light-path requires the reservation of WDM channel on the physical links along the paths and the number of available the WDM channels are limited on a link. 2) The number of transmitters and receivers at each node limits the number of light-path initiating and terminating on the node. 3) The maximum length of a light-path without signal regeneration may be limited by the signal attenuation along the light-path. Therefore, optimizing the use of WDM network resources is a crucial task in order to process traffic demand efficiently.

The concept of wavelength sharing has been proposed before in the context of unicast or multicast individually. The work in [4] was the first that proposed the sub-wavelength resource sharing among unicast and multicast traffic demands and provided a general solution under practical constraints. Traffic grooming concerns grouping of small flows into a single wavelength, that can be processed and routed as one entity. Our work addresses the issue of sub-wavelength sharing with or without traffic grooming. The future Internet will involve interconnections of large number of devices that are aggregated at access networks. High bandwidth WDM mesh networks at the backbone can be better utilized with sub-wavelength sharing in the wavelength assignment and routing. Sub-wavelength sharing can be used in various network business models. Different network business models can be considered as below [5]:

- Model A: An ISP that owns the network from the "ground up" (i.e., to the duct) and only delivers IP-based services.
- Model B: The business owns the layer-one infrastructure and sells services to customers who may themselves resell to others. It serves as the carriers' carrier and offers wholesale services to ISPs
- Model C: An ISP that leases fiber or transport capacity from a third part, and only delivers IP-based services.
- Model D: The business is a bandwidth broker. It provides "match-making" by enabling a variety of ISPs (model 3) to lease bandwidth from a variety of network operators (model 2).

Models B and C are complementary whereas both are integrated in case of model A. Our work can be considered as the issues of model A, B or D.

3. Related work

In recent years, many studies have been conducted in regards to the problem of designing virtual (or logical) topology for WDM networks. The problem of multicasting for IP over WDM networks can be decomposed into two subproblems, namely multicast-tree design, and routing and wavelength assignment (RWA) for the designed multicast-tree. As to the problem of multicast-tree design, two classes of approaches have been taken; namely, optimization and heuristics.

The multicast-tree design problem has been modeled often as a linear optimization problem to minimize the O/E/O conversions, as it is the main bottleneck in utilizing the true potential of optical networks. Other objectives, such as minimizing the average hop count or average number of transceivers used in the network [3] and the total link weight of the light tree [6] have also been used. In [7], the problem of optimal virtual topology design for multicast traffic is studied using light-paths. The authors aim to minimize the maximum traffic flowing on any light-path in the network while designing the logical topology for the multicast traffic. In the same work, the authors have presented several heuristics for topology design such as Tabu search, simulated annealing. Linear optimization techniques have been also used for the unicast single shortest virtual topology design [8], RWA [9], [10], restoration and reconfiguration [11], [12], [13] problems in WDM networks. Several heuristics have been proposed to design the multicast tree in WDM networks. Although a minimum Steiner tree [14] (which is obtained by solving Integer Linear Programming ILP) is more desirable, finding one for an arbitrary network topology is an NP-complete problem [15], thus heuristics are often used to obtain a near-minimum cost multicast tree. Authors in [16] have presented four heuristic algorithms: namely, Re-route-to-Source & Re-route-to-Any, Member-First, and Member-Only, for designing a multicast forest for a given multicast group. The minimum spanning tree (MST) heuristic or the shortest-path tree (SPT) heuristic [14] are also commonly used for designing the multicast tree. Authors in [17] have also presented two such algorithms, Breadth First Search (BFS) and a dynamic and incremental tree construction algorithm. Given an existing multicast tree with a large number of members, new member nodes perform an operation of join/graft similar to CBT [18] and DVMRP [19]. Once a multicast tree is designed, it can be implemented with either wavelength-routing [20], [3] or Optical Burst/Label Switching (OBS/OLS) [21], [22]. In the former case, multicast data will be switched to one or more outgoing wavelengths according to the incoming wavelength that carries it. That is a wavelength needs to be reserved on each branch of a multicast tree. In IP over WDM multicast using label switching, multicast label switched paths are set up first. Afterwards, only the optical labels carried by the bursts need O/E conversions for electronic processing, whereas the burst payload always remains in the optical domain at intermediate nodes. The major disadvantage of the wavelength routing approach is that it may not utilize the bandwidth efficiently in case traffic demand is not up to wavelength capacity. It also has large setup latency and it is not efficient under bursty traffic conditions. Meanwhile, with OBS/OLS, a burst dropping (loss) probability may be potentially significant in a highly loaded OBS network which can lead to heavy overheads such as a large number of duplicate retransmissions in IP layer. In addition, it may take a longer time for an end host to detect and then recover from burst dropping (loss) [23]. In [24], the authors introduced a light-hierarchy graph renewal and distance priority light-tree algorithm (GRDP-LT), which was proposed to improve the light-trees quality for any multicast under light splitting constraints. In a light-hierarchy, cycles are allowed, which is different from the light-tree where no cycle exists in the structure.

In a closely related work [4], a hybrid multicast topology was first designed given only light-paths and physical links. The work is to support better utilize the bandwidths of wavelengths for new multicast traffic; assuming only unicast traffic was supported initially. In this work, we extend the concept of sub-wavelength sharing to existing light-trees as well, in addition to light-paths, and build a hybrid virtual topology which exploits both light-trees and light-paths. We optimize WDM resources for new traffic while keeping the a priori configurations for the existing traffic, so that their performances are not disturbed.

4. Problem formulation

In this section, we formally state the problem of designing hybrid virtual topology for given set of multicast demands using available physical, light-path, and light-tree topologies. The network channel resources are the available wavelengths on the physical links, the available degree of sharing of light-paths, C^v and the available degree of sharing of light-trees, C^t for other traffic demands. The number of available wavelengths is bounded by the physical resources, and the degrees of sharing of light-paths and light-trees are bounded for the QoS of existing traffic. Next, we formulate our objective function and discuss the constraints required for the design problem.

4.1 Objective function

$$min \sum_{s} \sum_{m} \sum_{n} \left(w_{m,n} M_{s,m,n} + \alpha_{m,n} Y_{s,m,n} + \sum_{i} \beta_i T_{s,i,m,n} \right) \quad (1)$$

The objective is to minimize the cost of the selected hybrid topology components, namely physical wavelengths (M), light-paths (Y) and light-trees (T). In the objective function, m and n indicate a source and a destination of the corresponding link, respectively, and s indicates the corresponding multicast session. The cost components, M, Y, and T are binary variables and are weighted by parameters of w, α, and β. New unicast traffic demand can be considered a special type of multicast where it has only one destination. Thus our objective function adds all the cost of physical links, light-paths, and light-trees for each link and each session, for satisfying either unicast or multicast traffic demands. The weights can be assigned depending on the deployment or operational costs. For example, in our evaluations later, we have used the weights of the physical links to reflect the preference to a path with minimum hops. That is, all physical links have the same weights. The weight of a light-path is set to the sum of weights of physical links that were used to design the light-path. Then the weight of a light-tree is the sum of physical links building the tree. The objective function with those weights indirectly minimizes the number of non-destination intermediate nodes between different physical links and light-paths. It also selects light-trees that have a minimum number of fortuitous nodes [25], where a node in a light-tree is a fortuitous destination if it is not a member in that session but receives an excess copy of multicast session packets [26] due to the configuration. Our formulation minimizes the unnecessary excess traffic to fortuitous nodes, since the cost of a light-tree includes the cost of all individual links.

Data Input	Definition
$p_{m,n}^{adjacent}$	Boolean matrix. Represents the adjacency of the physical topology.
$V_{m,n}^{adjacent}$	Boolean matrix. Represents the adjacency of the existing virtual light-path topology.
$tree_{i,m,n}$	Boolean matrix. Represents the adjacency of the existing virtual light-tree topology *i*.
$source_s$	A source node number for the new multicast session *s*.
$session_{s,m}$	Boolean value. Represents if node member *m* belongs to the multicast session *s*.
$w_{m,n}$	Cost of using a physical link *m, n*.
$\alpha_{m,n}$	Cost of using an existing light-path *m, n*.
β_i	Cost of using a existing light-tree for multicast session *i*.
$C_{m,n}^{pavailable}$	The number of available wavelengths on the physical link between node *m* and *n*.
C^v	Degree of sharing on an existing light-path.
C^t	Degree of sharing on an existing light-tree.

Decision variable	Definition
$member_{s,m}$	Boolean value. $member_{s,m}$ =1 if node *m* is a session member or an existing light-tree member, for new session *s*.
$M_{s,m,n}$	Boolean value. $M_{s,m,n}$ = 1 if the physical link m, n is used for the multicast session s.
$Y_{s,m,n}$	Boolean value. $Y_{s,m,n}$ = 1 if the light-path *m*, *n* is used for the multicast session *s*.
$T_{s,i,m,n}$	Boolean value. $T_{s,i,m,n}$ = 1 if the physical link *m, n* in an existing light-tree *i* is used for the new multicast session *s*.
$\gamma_{s,i}$	Boolean value. $\gamma_{s,i}$ = 1 if an existing light-tree *i* is selected to satisfy a new multicast session *s*.
$f_{s,m,n}$	Flow accommodations ($\sum_m member_{s,m}$) from the source node of session *s* over different physical links *m, n*.
$y_{s,m,n}$	Flow accommodations ($\sum_m member_{s,m}$) from the source node of session *s* over different light-paths *m, n*.
$t_{s,i,m,n}$	Flow accommodations ($\sum_m member_{s,m}$) over light-tree *i* to satisfy the multicast demand *s*.

TABLE 1: Data input and decision variable definitions

4.2 Constraints

We discuss a number of constraints to create hybrid topologies in this subsection. We carefully set the constraints so that the number of variables and equations necessary to be minimized, and be solved for a relatively large networks. The constraints can be of three major types, namely, constraints for light-tree design, flow conservation, and resource bounds. Data input and decision variables are defined in Table 1.

1) *Constraints for light-tree generation:*

The following set of equations are to choose light-tree(s) *i* to satisfy a multicast session *s*. They ensure that the variable $T_{s,i,m,n}$ will maintain the topology of the selected light-tree with the necessary nodes. These equations will also ensure that routing of any traffic flowing on the light-tree *i*, $T_{s,i,m,n}$, is feasible.

$$T_{s,i,m,n} \le tree_{i,m,n} \quad \forall\, s,i,m,n \tag{2}$$

$$\sum_{m}\sum_{n} T_{s,i,m,n} = \sum_{m}\sum_{n} v_{s,i}\, tree_{i,m,n} \quad \forall\, s,i \tag{3}$$

$$T_{s,i,m,n} + T_{s,i,k,n} \le 1 \quad \forall\, s,i,m,n,k,k \ne m \tag{4}$$

$$T_{s,i,m,n} + T_{s,i,k,n} + M_{s,m,n} + M_{s,n,m} + Y_{s,m,n} + Y_{s,n,m} \le 1 \quad \forall\, s,i,m,n \tag{5}$$

$$\sum_{i}\sum_{n}\left(T_{s,i,m,n} + T_{s,i,n,m}\right) + session_{s,m} \quad \le member_{s,m}C \quad \forall\, m,s \tag{6}$$

Eq. (2) is to ensure that if a link *m*, *n* is part of the selected existing light-tree *i* to satisfy the new multicast demand *s*, all links in the existing tree should be part of the new multicast tree. Eq. (3) with Eq. (2) guarantees that the variable $T_{s,i,m,n}$ will include all the links of the selected light-tree *i* to support the multicast session *s*. Eq. (4) is to avoid the situation that a node in the light-tree *i* receives more than a packet for the same multicast session *s*. Eq. (5) ensures that different resources (channels) cannot be used more than one time for the same session s on the same link *m*, *n* (or light-path *m*, *n*). It also eliminates the case where the traffic flows on the same link *m*, *n* in different directions (*m*, *n* and *n*,*m*) for the same session *s*. Eq. (6) enables that the members of the new light-tree to include the destinations of used existing light-trees as well as the original destinations of multicast session *s*. *C* is a big positive number.

2) Constraints for light-tree generation:

$$\sum_{n}\left(y_{s,source_s,n} + f_{s,source_s,n} + \sum_{i} t_{s,i,source_s,n}\right) \le \sum_{k} member_{s,k} - 1 \quad \forall\, s\; n \ne source_s \tag{7}$$

$$\sum_{n}\left(y_{s,m,n} - y_{s,n,m} + f_{s,m,n} - f_{s,n,m} + \sum_{i}\left(t_{s,m,n} - t_{s,n,m}\right)\right) \le member_{s,n} \forall\, s\; n \ne source_s \tag{8}$$

$$y_{s,m,source_s} + M_{s,m,source_s} + T_{s,i,m,source_s} = 0 \;\; \forall\, s,i,m \tag{9}$$

$$t_{s,i,m,source_s} = 0 \;\; \forall\, s,i,m \tag{10}$$

First, Eq. (7) makes sure that the source node of each session $source_s$ sends the traffic demand to all the destinations using the virtual and physical links and the light-trees attached with the source node. The destinations are the multicast session *s* members, intermediate nodes and the light-tree members if an existing light-tree is selected to satisfy the demand for the session *s*. Eq. (8) represents the flow balance equation. Eq. (9) ensures that the source node of session *s* will not receive a multicast packet from the same session. The source node has no traffic demand for each multicast session for the light-tree flow as shown in Eq. (10).

3) Constraints for resource bounds:

$$f_{s,m,n} \leq M_{s,m,n}\, C \;\; \forall\, s,m,n \tag{11}$$

$$\sum_{s} M_{s,m,n} \leq \; C_{m,n}^{pavailable} \;\; \forall\, m,n \tag{12}$$

$$y_{s,m,n} \leq Y_{s,m,n}\, C \;\; \forall\, s,m,n \tag{13}$$

$$\sum_{s} Y_{s,m,n} \leq \; C^{v} \;\; \forall\, m,n \tag{14}$$

$$t_{s,i,m,n} \leq \; T_{s,i,m,n}\, C \;\; \forall\, s,i,m,n \tag{15}$$

$$t_{s,i,m,n} \geq \; T_{s,i,m,n} \;\; \forall\, s,i,m,n \tag{16}$$

$$\sum_{s} v_{s,i} \leq \; C^{t} \;\; \forall\, i \tag{17}$$

$$M_{s,m,n} \leq \; P_{m,n}^{adjacent} \;\; \forall\, s,m,n \tag{18}$$

$$Y_{s,m,n} \leq \; V_{m,n}^{adjacent} \;\; \forall\, s,m,n \tag{19}$$

$$\sum_{s} \left(Y_{s,m,n} + M_{s,m,n}\right) \leq \; member_{s,m} C \;\; \forall\, s,m \tag{20}$$

We assume that the maximum number of physical wavelengths of an optical link is *C*. We also assume the degree of sharing of a light-path, and the degree of sharing of a light-tree are limited by C^{v} and C^{t}, respectively, in order to ensure the quality of service of traffic performance.

In Eq. (11), the physical link $M_{s,m,n}$ is used to support the multicast session *s*, multicast traffic can be sent over it. Eq. (12) constrains the number of multicast sessions to number of available channels on the physical link *m*, *n*. Eq. (13) is similar to Eq. (11) but used for light-paths. The number of multicast sessions that can use light-path *m*, *n* is constrained according to the degree of sharing C^{v} in Eq. (14). Eqs. (15) and (16) force the traffic to flow on the links *m*, *n* of the selected light-tree *i* and to be in the proper direction. Eq. (17) constrains number of multicast sessions that can use light-tree *i* to C^{t} where C^{t} is the degree of sharing the light-tree. Eqs. (18) and (19) constrain the selection of a physical link and a light-path between the existing ones. Eq. (20) guarantees that all the intermediate nodes of the selected physical links and light-paths are included in $member_{s,m}$.

In summary, the above constraints of light-tree generation, flow-conservation and resource bounds enable us to use light-trees and light-paths within the resources available and to meet the given multicast demands. Note that the composite objective function of physical and hybrid virtual topology resources given in Eq. (1) provides a generic abstraction for capturing a wide variety of resource and performance optimization such as wavelength, hop count and delays, by controlling the weights of the objective.

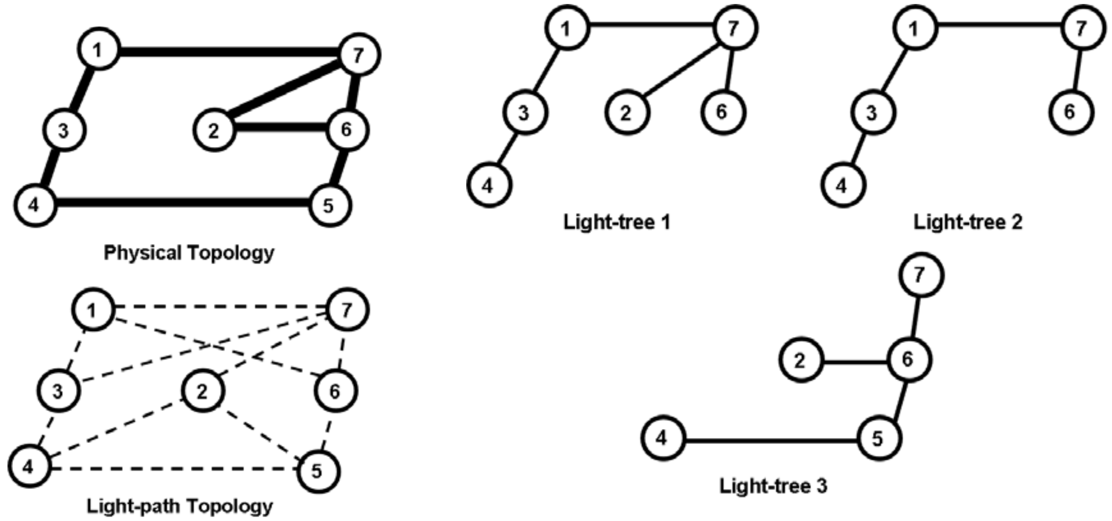

FIGURE 1: A simple network topology (7-node).

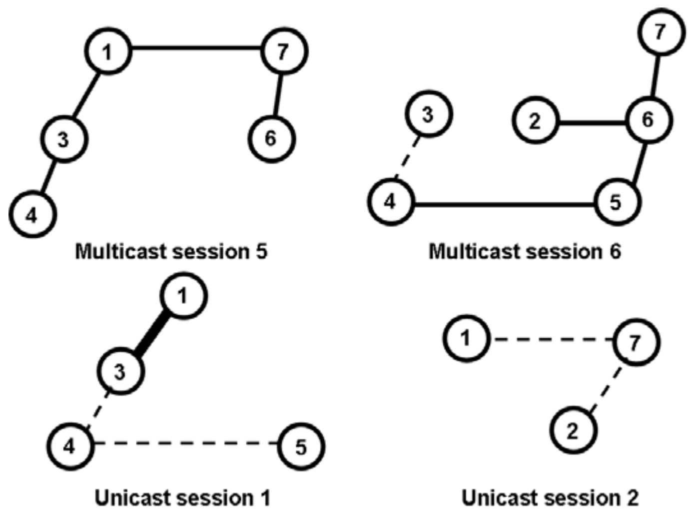

FIGURE 2: Designed hybrid topologies for new unicast and multicast demands (7-node network). (Thick black line: physical link, dashed line: existing light-path, and black line: existing light-tree).

5. Simulation results

Extensive simulations have been conducted to investigate the validity, feasibility and efficiency of our solution. First, we use a simple network topology to explain our solution in detail and validate it. We then apply our solution to a larger network to evaluate the feasibility and efficiency in a real scale network. A simple network topology with 7-nodes is illustrated in Figure 1. Figure 1(a) shows the physical and virtual light-path topologies of the network, and Figure 1(b) depicts the virtual topologies of existing light-trees prior to the arrival of new traffic demands. Each physical link carries a limited number of wavelengths. We assume that the number of available wavelengths on each physical link is $C^p = 5$. First, in order to validate our solution, we suppose the integrated demands of six new multicast sessions and two new unicast demands have been requested. The multicast sessions are S_1={1, 2, 3, 4, 6, 7}, S_2={1, 2, 3, 4, 6, 7}, S_3={1, 2, 3, 4, 7}, S_4={2, 3, 4, 6, 7}, S_5={1, 3, 4, 6, 7} and S_6={3, 4, 5, 6} with source nodes {4, 6, 1, 7, 1, 5}, respectively. Note that S_1 and S_2 have the same set of destinations but different source nodes. Two new unicast traffic demands are requested additionally, and they are U_1={1, 5} and U_2={1, 2} with source nodes {1, 2} respectively.

Figure 2 shows the created hybrid optical topologies with the given new traffic demands, using our ILP formulation. The parameters used are w = 1, β = 0.01, C^v= 2, C^t= 2, and the value of *α* is proportional to the number of used physical links to implement the light-path. Note that for a light-tree, the value of *β* corresponds to each individual link in the tree. We used the homogeneous weights for concise discussions. However, the weights can vary for each link as discussed in the previous section. For example, the weights may be proportional to the actual length of the links, so that it would reflect the delays. The values of w , *α*, and *β* indicate the relative preference of resource components for the new hybrid topology design. Small value of *β* increases the preference of using the light-trees over the light-paths and physical links. In the example scenario, light-trees are weighted least, so that they would be preferred. The result shows that they are all indeed the minimum cost trees that partially exploit existing light-paths, light-trees as well as physical link wavelengths. In Figure 2, which represents session topologies, we can observe that the light-trees are first exploited entirely according to the degree of sharing C^t. The light-paths and particularly physical links are not used extensively due to their high cost coefficients w and *α* with respect to the cost coefficient of the light-tree *β*.

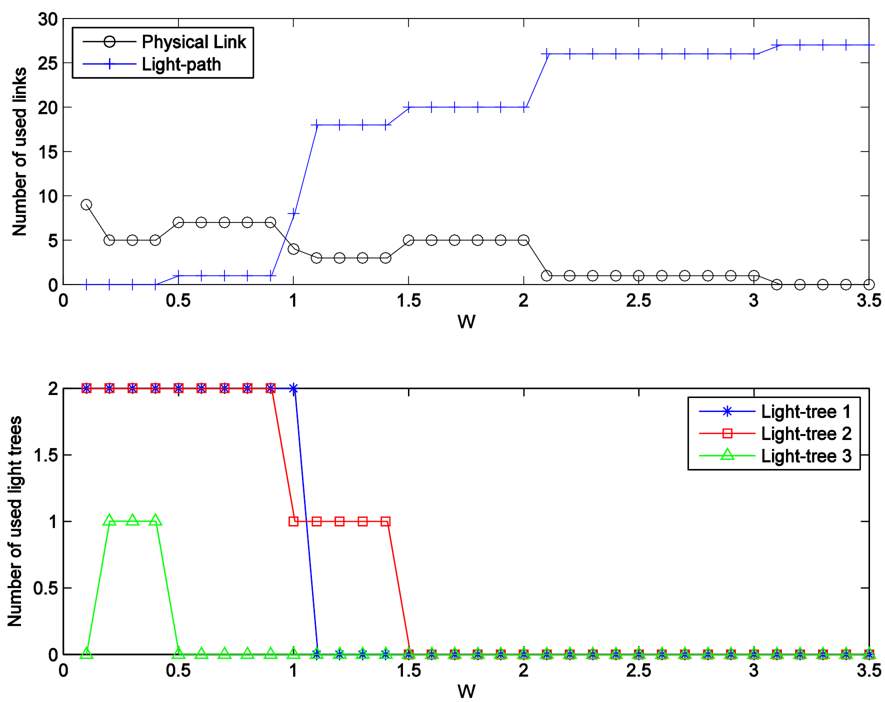

FIGURE 3: w vs. the number of links (top) and light-trees (bottom) used (7-node network).

Next, we investigate the impact of optimization cost weights as shown in Figures 3 and 4. Figure 3 shows the variation of the hybrid topologies when w is changed, while *β* is fixed to be 1 and C^v= C^t = 2. The figure shows that the number of used physical links changes according to the number of used light-trees. The number of used light-paths increases when w becomes more expensive to equalize the decrease in number of light-trees and physical links. Similarly, Figure 4 shows the variation of the hybrid topologies when *β* is changed, while w is constant to be 1 and C^v= C^t = 2.

As β increases, the preference of using the light-trees decreases and the number of used light-paths and physical links increases. When a light-tree is no longer used, light-paths and physical links are used to overcome the shortage of resources to satisfy the traffic demands. We did not vary α, as we set the parameter α to be the sum of physical link weights used for the light-path.

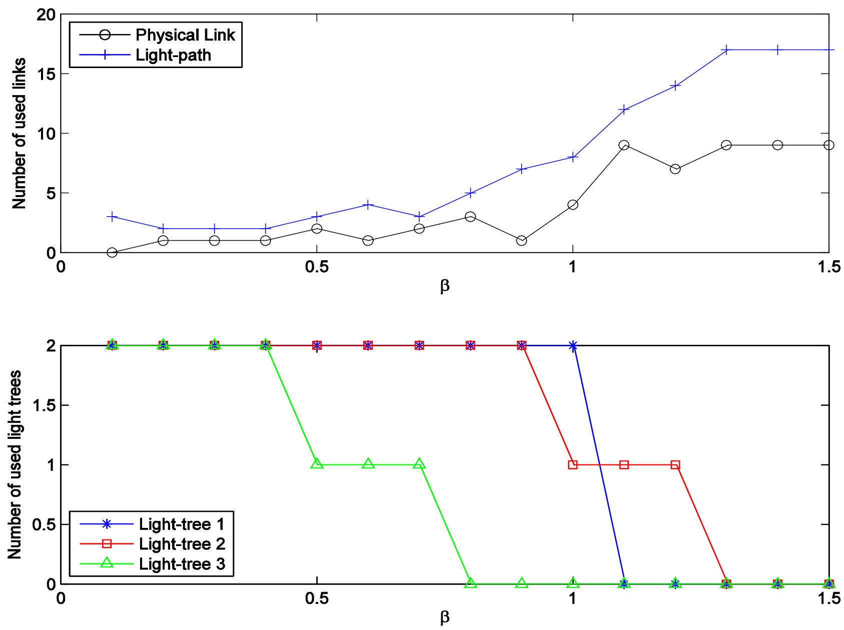

FIGURE 4: β vs. the number of links (top) and light-trees (bottom) used (7-node network).

We now consider a larger network with 14-nodes as illustrated in Figure 5. Figure 5(a) shows the physical and existing light-paths, and Figure 5(b) depicts the existing light-tree topologies. The physical cost coefficient w is equal to 1, while the light-tree cost coefficient β is set to 0.01. The light-path cost coefficient α is proportional to the number of used physical links to implement each light-path. Degree of sharing a light-path C^v and a light-tree C^t are set to 2. The new multicast demands used to evaluate the formulation are S_1 ={1, 3, 4, 6, 9}, S_2={5, 7, 8, 10, 13, 14}, S_3={6, 7, 11, 12, 13}, S_4={9, 10, 11, 12, 14}, S_5={2, 3, 7, 8, 11, 12, 14}, S_6={1, 2, 13, 14}, S_7 ={1, 3 7, 11}, and S_8={3, 4, 7, 14}, with source nodes to be {1, 13, 6, 9, 2, 2, 11, 14}, respectively. In addition, two unicast demands, U_1={1, 8} and U_2={3, 10} are requested with source nodes {1, 10}.

The solution was found successfully for the larger network, and we show the created hybrid topologies for the unicast traffic in Figure 6, and for the multicast traffic in Figures 7. We depict the topologies for the multicast traffic only for the first five demands, for a concise illustration. Figure 7 shows the hybrid topology solutions for individual multicast sessions. Multicast session 1 uses the existing light-tree 1 in addition to two physical links between nodes 3 and 4, and 6 and 9. The new multicast sessions 2 and 3 use the existing light-trees 2 and 4, respectively, in addition to other light-paths, to satisfy their multicast session demand. The new multicast session 4 uses light-trees 3 and 4, and the new multicast session 5 uses a physical link, an existing light-path and the existing light-tree 5.

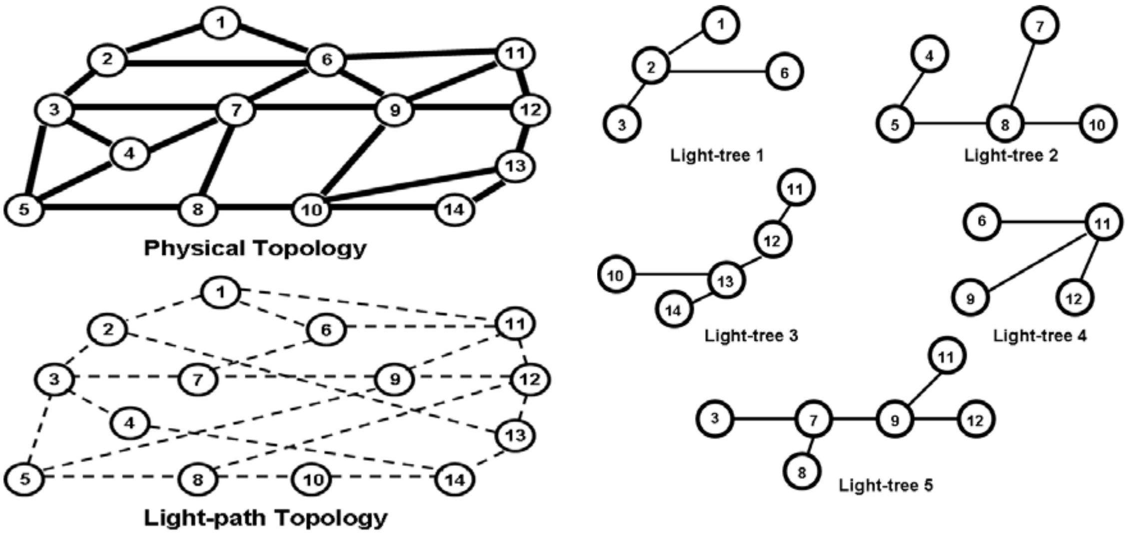

FIGURE 5: A Larger Network Topology (14-nodes).

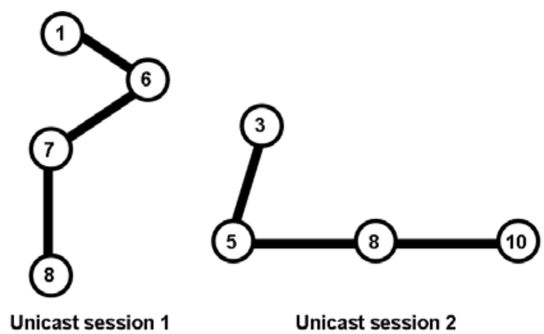

FIGURE 6: Designed hybrid topologies for new unicast demands (14-node network). (Thick black line: physical link)

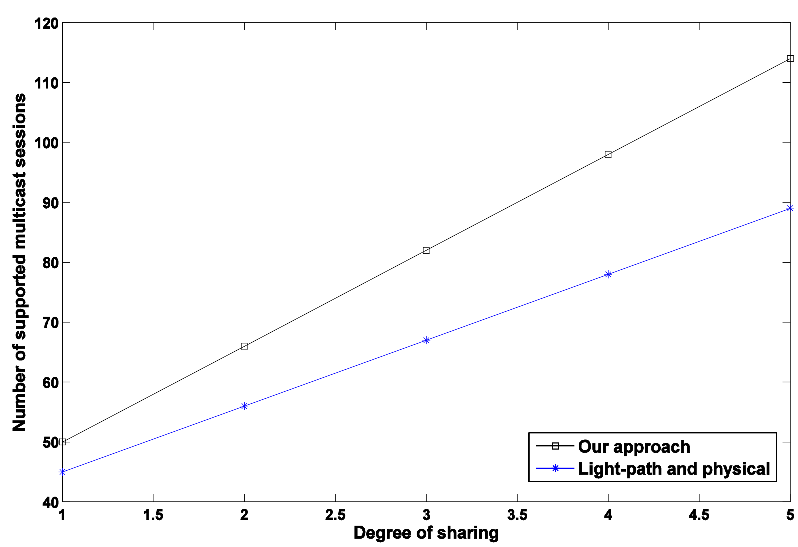

FIGURE 7: Designed hybrid topologies for new multicast demands (14-node network). (Thick black line: physical link, dashed line: existing light-path, and black line: existing light-tree)

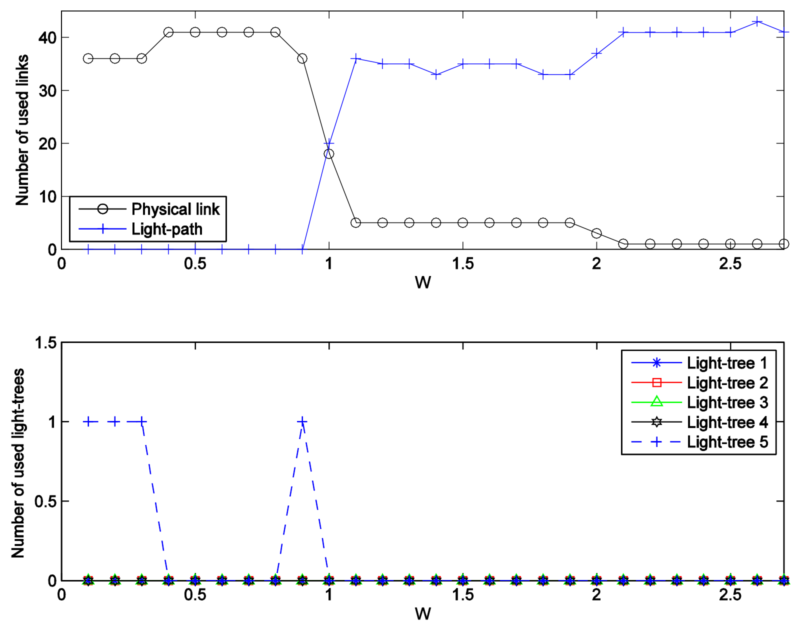

FIGURE 8: Number of links (top) and light-trees (bottom) vs. w (14-node network).

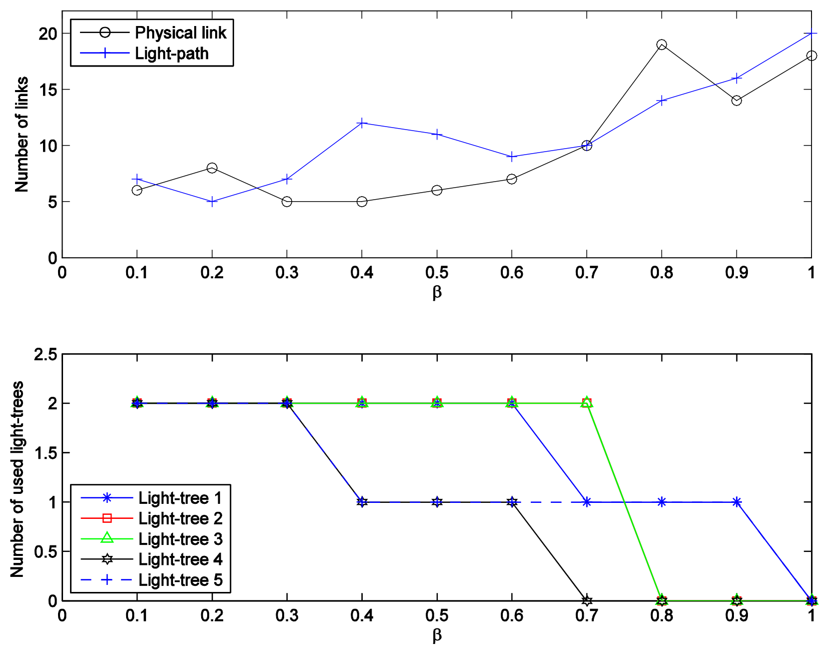

FIGURE 9: Number of links (top) and light-trees (bottom) vs. β (14-node network)

Figures 8 and 9 illustrate the impact of optimization cost weights for the 14-node network. Figure 8 shows the variation of the hybrid topologies when β is changed and w is constant to be 1 where $C^v = C^t$ = 2. For small value of β, all light-trees are used to create hybrid multicasts in addition to some physical links and light-paths. As β increases, more physical links and light-paths are mainly utilized to keep the cost of creating the hybrid multicast topologies low. Similarly, Figure 9 shows the variation of the hybrid topologies when w is changed and β is fixed to 1 where $C^v = C^t$ = 2. The figure shows that the number of light-paths increases while the number of physical links used is decreasing, because physical links become more expensive to transport the multicast traffic demand. In addition, both Figures 3 and 8 show a similar structure of the created hybrid multicast topologies. The figures show that there is a value of w at which the light-trees are no longer used to create the hybrid topologies. This value depends on the network structure as well as the light-trees structure. Similarly, Figures 4 and 9 show similar structure of the created hybrid multicast topologies, and the existence of a value for β at which light-trees are not used to create the hybrid topologies.

We next evaluate the number of supported multicast sessions while varying the degree of sharing of light-paths and light-trees, for this large network. We assumed that C^v and C^t are the same.

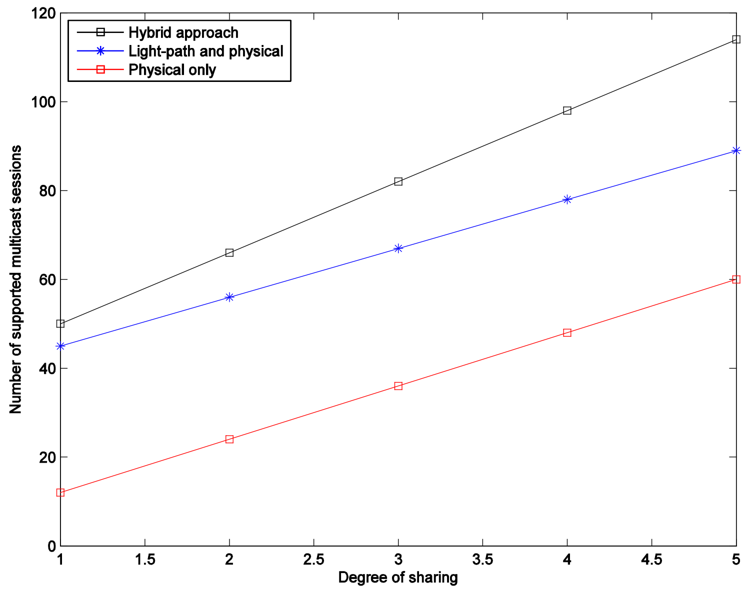

FIGURE 10: The number of supported multicast sessions vs. degree of sharing of the light-paths and the light-trees (14-node network)

Figure 10 shows that the number of supported multicast sessions increases as the degree of sharing increases. Results are compared with no hybrid approach that does not use sub-wavelength sharing. It also compares with the previous work [4], that was the first work that proposed sub-wavelength sharing with existing light-paths but the sharing of multicast trees were not allowed. Figure 10 shows that the number of multicast sessions linearly increases as the degree of sharing increases. The proposed approach clearly satisfies more multicast demands with the sharing of light-trees as well as light-paths.

	7-node network		**14-node network**	
Sharing degree	**# Multicast**	**% increase**	**# Multicast**	**% increase**
1	22	0	50	0
2	36	63	66	32
3	50	127	82	64
4	61	177	114	128

TABLE 2: Effect of sharing the wavelengths

Table 2 compares the small 7-node and large 14-node networks to evaluate the impact of the sharing. It shows the percentage of the increase in the number of supported multicast sessions, with the degree of sharing. The percentage increase is computed comparing with the case of no sub-wavelength sharing. Number of supported sessions increases almost linearly with the degree of sharing for both 7-node and 14-node networks, respectively.

	7-node network		14-node network	
Sharing degree(C^t)	**# Multicast**	**% increase**	**# Multicast**	**% increase**
1	22	0	50	0
2	28	27	55	10
3	31	40	60	20
4	34	54	65	30

TABLE 3: Sharing degree (C^t) vs. number of supported multicast sessions (C^v=1)

	7-node network		14-node network	
Sharing degree(C^v)	**# Multicast**	**% increase**	**# Multicast**	**% increase**
1	22	0	50	0
2	29	31	61	22
3	39	77	72	44
4	49	122	83	66

TABLE 4: Sharing degree (C^v) vs. number of supported multicast sessions (C^t=1)

Tables 3 and 4 show the effect of degree of sharing light-paths and light-trees for both 7-node and 14-node networks. The number of supported multicast sessions increases linearly with the degree of sharing light-paths and light-trees. The degree of sharing light-paths gives more freedom to support more sessions than degree of sharing light-trees. The extensive simulations with small and large mesh networks shown in this section illustrate that the proposed solution creates hybrid topologies for more traffic demands than pure wavelength assignment in an efficient and scalable manner.

6. Conclusions

The future Internet will require the transport of a wide range of services including high bandwidth one-to-many applications, with dynamic interconnection of devices and services. Due to limited wavelengths of WDM networks, an optimal resource management is important for a new set of traffic service demands while keeping services for the existing traffic. We proposed a hybrid optical topology design over constrained WDM mesh network, where both light-paths and light-trees are built. Particularly, existing light-trees as well as light-paths are re-used to create new hybrid multicast virtual topology. It is to increase the number of supported integrated traffic demands of both unicast and multicast for the future Internet, using the excess bandwidth of a wavelength. This sub-wavelength sharing is done within a degree of sharing of light-trees and light-paths. The degree of sharing allows and also bounds the amount of sharing so as to maintain QoS of existing traffic. The problem of creating a hybrid optical topology is formulated using ILP approach, given existing physical, light-path, and light-tree topologies. We formulated the ILP in a compact manner, and the solutions can be reached for a relatively large network in an reasonable time.

Our approach shows how the existing physical, light-path and light-tree topologies are exploited for the newly arriving demands optimally without re-designing all the topologies from the scratch. This approach maximally utilizes the available bandwidth resources from existing light-paths as well as light-trees whose traffic demand does not reach full wavelength capacity. We show this hybrid virtual topology design enables us to establish multicast trees when it would otherwise be impossible with a pure light-tree approach. The proposed solution can be used in a real practical environment where both unicast and multicast demands are supported, and new multicast demands can be realized incrementally and optimally. Extensive simulations are performed over various WDM mesh networks, to show the validity as well as feasibility with relatively large networks. As for a future work, an efficient heuristic approach can be made to speed up a solution.

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