

Online Broadcasting and Multicasting in WDM Networks with Shared Light Splitter Bank

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Abstract—In this paper we deal with online broadcasting and multicasting in a WDM optical network with shared light splitter bank. Our objective is to maximize the network throughput. Since light splitting and wavelength conversion switching in WDM optical networks is cost expensive and fabrication difficult, we assume that only a fraction of network nodes are equipped with limited number of light splitting and/or wavelength conversion switches, and they are shared by all incoming and outgoing signals at each installed node. We first propose two cost models of realizing a broadcast or multicast request to model the consumption of network resources, particularly in modelling the light splitting and/or wavelength conversion resources consumption. We then show that under either of the two proposed cost models, finding a cost-optimal broadcast or multicast tree for a broadcast or multicast request is NP-complete, and instead devise approximation and heuristic algorithms for it. We finally conduct experiments to evaluate the performance of the proposed algorithms.

I. INTRODUCTION

Optical networks with Wavelength-Division Multiplexing (WDM) are now widely regarded as the most promising candidates for next-generation Internet due to their ability to meet ever-increasing huge bandwidth demands. A WDM optical network consists of nodes and fiber links, in which nodes are connected by optical fiber links. On each fiber link there are multiple distinct wavelengths carrying different data. Nodes are equipped with optical switches. An optical switch at a node is usually responsible for receiving optical signals from the incoming links and forwarding them to the outgoing links of the node. If optical signals from two incoming links of a node are forwarded to one of its outgoing links using the same wavelength, it will cause a wavelength collision, which can be resolved by either dropping one of the signals or converting one of them to a different wavelength using a wavelength converter. It is obvious that the benefit of using wavelength conversion is that the blockage probability can be reduced by eliminating or reducing the effects of so called *wavelength continuity constraint*. To accommodate the unicast function in optical layer, some nodes in the network are equipped with optical crossconnect (OXC) devices, which can optically switch a optical signal from any input link to any output link, and make it possible to establish a *lightpath* between any pair of nodes. To accommodate the multicast function in optical layer, the *light-tree* concept was proposed [16], which requires that an incoming optical signal at an internal node in the tree can be split into multiple outgoing optical signals along the

tree links. Thus, to support multicasting in an optical network, a fraction of the nodes in the network need to be equipped with Multicast-Capable OXC (MC-OXC) devices that can split an incoming optical signal into multiple identical outgoing optical signals. However, it is predicted that the cost associated with OXC and MC-OXC devices will still be expensive in the near future [15]. Thus, in the design of an optical network, not only the number of nodes equipped with MC-OXCs and/or OXCs but also the number of MC-OXCs and/or OXCs installed at the nodes must be taken into account. Given such a WDM optical network, it is typically assumed that only a fraction of its nodes are installed with MC-OXCs and/or OXCs. Furthermore, each of these installed nodes has only a limited number of light splitters and/or wavelength converters.

A *multicast request* typically involves the transport of information between a single sender (source) and multiple receivers (terminals). A special case of a multicast request is *broadcast* where the set of receivers consists of all the nodes in the network except the source. Multicast applications includes video conferencing, entertainment distribution, remote educations, distributed data processing [14], [19]. The most popular solution to multicast communication is the construction of a multicast tree. The multicast problem in WDM optical networks is referred to as the *one-to-many routing and wavelength assignment problem* (RWA), which aims at finding a set of physical links consisting of a tree and wavelengths on these links to establish the connection from the source to the destination nodes. In WDM optical networks not only the number of available wavelengths on links is the most crucial resource, but also whether an incoming light signal can be splittable and whether wavelength conversion at nodes is available play important roles in the design of efficient multicast routing protocols.

There are several studies on different MC-OXC switching architectures for multicasting in WDM optical networks with various objectives like minimizing the cost of establishing a network or maximizing the network throughout [1], [15], [24]. The previous research focusing on the dedicated splitter switching (MC-OXC) requires a large number of light splitters and optical amplifiers, resulting in a network that is cost expensive and fabrication complex [15]. Instead, a new switching architecture called *light splitter-sharing bank* is proposed [1], [15], as shown in Fig. 1, which is designed for low cost and power loss. The splitters are shared by all incoming signals. The information on incoming link is

first demultiplexed into separate wavelength signals, which then are switched to outgoing links. Signals that do not need multicast are sent directly to the corresponding outgoing links by an optical subswitch OSW1, while those signals that need multicast are sent to another optical subswitch OSW2 - the light splitter bank. The signals sent to the light splitter bank may be enhanced by signal amplification. The splitters then route different copies of an incoming signal to their outgoing links respectively. Due to splitter sharing, this architecture significantly reduces the cost of routing multicast requests and simplifies the fabrication complexity of splitter switches. In this paper we will adopt this splitter sharing switching architecture and further assume that the MC-OXC and OXC nodes have also wavelength conversion ability.

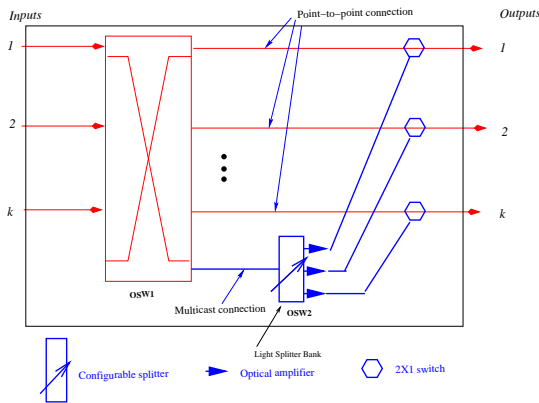


Fig. 1. The Light Splitter-sharing Switch [1]

A. Related work

Consider a multicast request with the terminal set D in a WDM optical network. The objective is to find a cost-optimal multicast tree under different cost models to realize the request. Much effort on this problem has been taken in the past decade. For example, several studies have been carried out under the cost model in which the cost of a multicast tree is defined as the cost sum of wavelength conversion at nodes and wavelengths used at links, where different conversion costs are applied to different pairs of wavelengths at nodes, and different costs are charged by using different wavelengths to reflect the bandwidth consumption as well as the communication delay on links [4], [10]. Sometimes, the routing congestion factor on links is also incorporated into the cost. Liang and Shen [10] proposed the very first approximation algorithm for the problem. Sahasrabudde and Mukherjee [16] approached the problem by formulating it into a mixed-integer linear programming. Chen and Wang [4] provided an exact solution to the problem in a very special network – the tree network, using dynamic programming. Znati et al [27] dealt with the problem by decoupling the delay cost from the other cost of network resources, and presented several heuristic algorithms for finding a multicast tree meeting both delay and cost optimization objectives. Jia et al [8] considered the routing congestion issue in a single hop (all-optical) network by proposing two heuristic algorithms for a multicast problem that aims to minimize the total cost of a multicast tree under the end-to-end delay constraint. Libeskind-Hadas

and Melhem [12] investigated multicast communication in circuit-switched multi-hop networks by showing that it is polynomially solvable when the optimization objective is the wavelength assignment only, despite the fact that the general multicast problem is NP-Hard. In addition, there have been several other studies for constructing constrained multicast trees in WDM optical networks. For example, Bermond et al [2] investigated routing and wavelength assignment in WDM optical networks with only unicast-capable switches. Libeskind-Hadas [11] extended the unicast communication (point-to-point communication model) by proposing a multi-path routing model, in which the multicast problem is to find a set of paths from the source to the destination nodes such that each path contains a subset of destination nodes, the nodes in the set of destination nodes are included by these paths, and the cost sum of these paths is minimized. Another cost model is to minimize the number of wavelengths in the multicast tree. Li et al [9] considered the problem by showing the problem being NP-complete and claiming an approximation algorithm for it, while Wan and Liang [20] later pointed out that their approximation algorithm is unbounded, and proposed a truly approximation algorithm.

There are also several studies focusing on the physical constraints on optical switches like light splitting ability. Sahin and Azizolgu [17] considered the multicast problem under various fanout polices and Malli et al [13] dealt with the problem under a sparse splitting model. Zhang et al [24] considered it by focusing on the limited splitting power of optical switches, and provided several heuristic solutions. Xin and Rouskas [22] studied the splitting power loss in the signal propagation path by introducing the *split ratio of a node* concept, which represents the residual power of a light signal received at a node after the splits along the path, and a Balance-Light-Tree (BLT) algorithm for finding a multicast tree that meets the minimum power threshold is proposed. Zhang and Yang [25] considered the problem in a tree network with an objective of minimizing the number of wavelength conversions by providing an approximation algorithm for it. In addition, Rouskas [15] and Zhou and Poo [26] provided excellent surveys on the optical multicast problem under various cost models including the light splitter switching model.

B. Motivations

Motivated by recent works on unicasting and multicasting in WDM optical networks with shared light splitter bank by Ali and Deogun [1], Zhang et al [24], Zhang et al [23], Rouskas [15], and Zhang and Yang [25], we here consider the online optical multicast problem in a WDM optical network where light splitters and/or wavelength converters at each MC-OXC or OXC node are shared by all incoming links of the node. Due to the nature of online traffic routing, most of such requests are real-time requests, the response time by the system to them is thus critical. Routing algorithms for realizing these requests in such a dynamic traffic environment must be simple and fast. Since it is a hard problem to combine routing and wavelength assignment together, the most adopted strategy is to decouple the problem into two separate subproblems:

the light-tree routing problem and the wavelength assignment problem [1], [15], [25]. The former is to build a routing tree for each multicast request, while the latter is to assign available wavelengths to the links in the tree. It is well-known that there are efficient algorithms for wavelength assignment in tree structures [4], [25]. We thus focus on the former problem - the light-tree routing problem by finding an economic routing tree for a multicast request under the shared light splitter bank switching architecture. It is great challenging to design efficient routing algorithms for the problem by considering various constraints, particularly the constraints on the availability of MC-OXCs, the number of wavelength converters at each node, and the splitting and/or wavelength conversion ability at each node, etc [15]. Meanwhile, to maximize the network throughput, the realization of a request needs to consider the multiple physical constraints imposed by the network, for example some nodes and/or links in the network may be overloaded by existing traffic while others may be idle. More specifically, in this paper we consider the following online optical multicast problem.

Given a WDM optical network with shared light splitter bank, there is a sequence of multicast requests that is unknown in advance and the requests arrive one by one. Once a request arrives, the response by the system is to either realize the request by building a multicast tree for it or reject the request due to lack of network resources to accommodate the request. The objective is to realize as many multicast requests as possible until the rejection rate is very high. In other words, the objective is to either maximize the system throughput or minimize the blockage probability of requests. To approach the problem, we propose different cost metrics for a multicast tree. Due to unknown pattern of future requests to network resources, we focus on realizing each individual multicast request by building an economic multicast tree in terms of the consumption of network resources under various cost metrics, and maximizing the network throughput by the cost savings on each individual request.

C. Contributions

In this paper we consider online broadcasting and multicasting in a WDM optical network in which the light splitter bank at each node is shared by its incoming signals, with an objective to maximize the network throughput. Our major contributions are as follows.

We first propose two cost models that model the cost of a broadcast or multicast tree by utilizing the network resources including light splitting and/or wavelength conversion abilities at nodes and traffic load at links. We then show that under either of the two proposed cost models, finding a cost-optimal broadcast or multicast tree for a broadcast or multicast request is NP-Complete, instead devise approximation and heuristic algorithms for finding such a tree. In contrast to the previous solutions, we here provide the first approximation and heuristic algorithms that incorporate the physical constraints of the network like the splitting and/or wavelength conversion ability at nodes and wavelengths on links into the design of algorithms. A generic methodology of designing routing protocols for optical multicast in a WDM optical network with shared splitter bank is derived.

D. Paper organization

The rest of the paper is organized as follows. In Section 2 we introduce the network model and problem definition. In Section 3 we propose two cost metrics for WDM optical networks with shared splitter and/or wavelength converter bank to model the physical constraints on network resources. In Section 4 we devise approximation algorithms for finding cost-optimal multicast trees under the node-link cost model, and in Section 5 we devise heuristic algorithm for the cost-optimal multicast problem under the refined node-link cost model. We conclude the paper in Section 6.

II. PRELIMINARIES

A. Communication networks

The optical network is modelled by an *undirected graph* $G = (V, E, \Lambda)$, where V is a set of nodes (vertices), E is a set of bidirectional optical fiber links (edges), and Λ is a set of wavelengths in G , $n = |V|$, $m = |E|$, and $|\Lambda| = K$. Let $\Lambda = \{\lambda_1, \lambda_2, \dots, \lambda_K\}$. Some of the nodes in the network are installed with MC-OXC or OXC devices. Associated with each MC-OXC or OXC node, a light splitter bank is shared by all its incoming links. The light splitting and/or wavelength conversion ability of a node is determined by the following factors: whether any MC-OXC and/or OXC switches are installed at the node. If yes, how many MC-OXC and/or OXC are installed? In the dynamic routing (online setting), the light splitting and/or wavelength conversion ability of a node is also determined by the current traffic load at the node. That is, how many splitters and/or wavelength converters are still available at this moment? We here use a weight $w(v)$ to represent the splitting and/or wavelength conversion ability of node $v \in V$, where a larger value $w(v)$ of v means that the light splitting and/or wavelength conversion ability of v is weak, otherwise, a smaller value $w(v)$ of v indicates that the light splitting and/or wavelength conversion ability of v is quite high. Associated with each link $e \in E$, there is a set $\Lambda(e) (\subseteq \Lambda)$ of wavelengths available on e initially.

B. Problem definition

Given a WDM optical network $G(V, E, \Lambda, w)$ with shared light splitter and/or wavelength converter bank at some of its nodes, assume that there is a sequence of multicast requests, which is unknown in advance. The requests arrive one by one. Once a request $(s; D)$ arrives, the response by the system to the request is either accepting the request by building a multicast tree for it, or rejecting the request immediately due to lack of available resources, where s is the source and D is the terminal set and $D \subset V$. The *online multicasting problem* is to realize as many requests as possible in the request sequence until the system is unable to deal with any further requests. In other words, the objective is to minimize the blockage probability of multicast requests.

Due to the nature of unforeseen future requests, it is very difficult to provide an exact solution to the problem. Instead, in this paper we focus on finding a nearly ‘‘cost-optimal’’ multicast tree for each request, where the cost of a tree is defined by a cost metric that models the cost of utilizing the network resources.

III. COST MODELLING OF NETWORK RESOURCE UTILIZATION

In this section we model the utilization of network resources including not only the light splitting and wavelength conversion abilities at nodes but also the existing traffic load at links. We first propose a node-link cost model, which takes into account the light splitting and/or wavelength conversion ability of a node and traffic flow continuity from the node. We then enhance the node-link cost model by incorporating the existing traffic load on the outgoing links of a node into consideration.

A. Node-link cost model

Given a WDM optical network $G(V, E, \Lambda, w)$ with shared light splitter bank and a multicast request $(s; D)$ ($D \subset V$), where w is a weight function on the nodes $w : V \mapsto \mathbb{R}^+$. We assume that $w(v) \geq 1$, which is used to model the light splitting and wavelength conversion ability of v , i.e., a large value of $w(v)$ means that v is heavily loaded by existing traffic and the splitting and/or wavelength conversion ability of v for future traffic is very limited; otherwise, there is still a plenty of splitters and/or wavelength converters at v for further requests. We observe that the number of outgoing links $d'(v)$ of node v in a multicast tree is proportional to its splitting and/or conversion ability. That is,

$$d'(v) \propto \frac{1}{w(v)}. \quad (1)$$

If node v works at its full splitting and/or conversion ability ($w(v) = 1$), then all its $d_v - 1$ outgoing links are available, where d_v is the physical degree of v in the network G . Otherwise, the splitting and/or conversion ability of v , in some extent, is limited if $w(v) > 1$, the number of outgoing links of v in the multicast tree should be fewer than that when v works at its full capacity. Specifically, the number of outgoing links of node v in the multicast tree is bounded by $d'(v)$, which is defined as follows.

$$d'(v) = \min\{\lceil \frac{k_v}{w(v)} \rceil, d_v\}, \quad (2)$$

Clearly, k_v is the initial splitting and/or conversion capability of node v . If there is no restrictions imposed on v , $k_v = d_v$ when v is at its full splitting and/or conversion capacity; otherwise k_v is set to be a value no greater than d_v .

Motivated by the above observation, a cost metric of a multicast tree is proposed. Given a multicast request $(s; D)$, we aim to find a degree-constrained multicast tree in $G(V, E, w)$ rooted at s and spanning the nodes in D such that the degree of each node v in the tree is no more than $d'(v)$, where $d'(v) = \min\{\lceil \frac{k_v}{w(v)} \rceil, d_v\}$. The constrained-degree of a node in the multicast tree reflects the splitting and/or conversion ability of the node at that moment, and a low capability node will have fewer outgoing links. We refer to this optimization problem as *the degree-constrained multicast tree problem*. When the terminal set contains all the other nodes except the source, the problem is referred to as *the degree-constrained broadcast tree problem*.

B. Refined node-link cost model

Although the node-link cost model models the splitting and/or wavelength conversion ability of a node accurately, it suffers the following deficiencies.

Given a node v with node degree constraint $d'(v)$, there is no restriction in the choice of which $d'(v)$ outgoing links of v to be included by the multicast tree, during the construction of a degree-constrained multicast tree. In fact, any $d'(v)$ outgoing links of v among its d_v outgoing links can be included by the multicast tree. Now consider a worst scenario where the $d'(v)$ chosen outgoing links in the multicast tree have been heavily loaded already by the existing traffic (due to the nature of online routing) and run out of their capacities, then any future traffic flow might not be unable to go through from v , even if the splitting and/or wavelength conversion ability of v is still quite high at this moment. Meanwhile, those unchosen outgoing links of v might have plenty of available traffic load left. To reduce the blockage probability of future requests, a weight function on links w_2 is introduced: $w_2 : E \mapsto \mathbb{R}$. For each $e \in E$, an associated weight $w_2(e)$ is defined: $w_2(e) = \frac{|U(e)|}{|\Lambda(e)|}$, where $U(e)$ is the number of wavelengths on link e being in use at the moment. Following this definition, when the weight of a link is large, it implies that the traffic load on the link is heavy and there is not much room left at the node for future traffic requests. As a result, the link should be excluded from the multicast tree if there is another better link that is not heavily loaded. Consequently, an obvious optimization metric for finding a multicast tree is to minimize the weighted sum of the nodes and links in the tree, and there is a heuristic algorithm for finding such a multicast tree [18]. However, we argue that such a simple metric is inappropriate for the problem of concern, because the weight functions associated with nodes w and links w_2 in the network are different. The weight of a node determines the number of its outgoing links in the multicast tree, while the weight of a link is the utilization ratio of the existing traffic load on the link. Thus, we introduce another optimization metric on the multicast tree, which takes both node's ability and link's load into consideration. First, we can see that the weight $w(v)$ of each node v is used to bound its degree $d'(v)$ in the multicast tree. Then, we need to choose $d'(v)$ outgoing links of v such that the incoming traffic to v would not interrupted at v . To do so, the best way is to include the first $d'(v)$ smallest weighted outgoing links of v into the tree. However, consider a link (v, u) with the smallest weighted outgoing link of v but the largest weight of u , if the link is included into the multicast tree, clearly this is the best choice at v but the worst choice at u . To resolve this dilemma, instead of focusing on outgoing links of each node, we use the weighted sum of links in the tree as the *edge metric* of the multicast tree. We thus have the following *refined node-link cost model*.

Given the current status of a WDM optical network $G(V, E, \Lambda, w, w_2)$ with shared light splitter bank and a multicast request $(s; D)$, *the degree-constrained, link-load balanced multicast tree problem* is to find a multicast tree in G rooted at s and spanning the nodes in D such that i) the degree of each node v in the tree is no more than $d'(v)$. This metric is

referred to as the *node metric*; and ii) the weighted sum of the links in the tree is minimized. This latter metric is referred to as the *link metric*, where w and w_2 are the weighted function of nodes and links with $w : V \mapsto \mathbb{R}^+$ and $w_2 : E \mapsto \mathbb{R}$, $w(v)$ models the light splitting and/or wavelength conversion ability of node v and $w_2(e)$ represents the utilization ratio of traffic load on link e . When the terminal set D contains all other nodes except the source, the problem is referred to as the *degree-constrained, link-load balanced broadcast tree problem*.

IV. APPROXIMATION ALGORITHMS BASED ON THE NODE-LINK COST MODEL

In this section we focus on devising approximation algorithms for the degree-constrained broadcast or multicast tree problem, based on the node-link cost model by first showing its NP-Completeness, followed by proposing an approximation algorithm for it.

A. NP-hardness of the degree-constrained broadcast tree problem

It can be seen that the Hamiltonian path problem can be reduced to the degree-constrained broadcast tree problem by finding a degree-constrained spanning tree with degree constraint $d'(v) \leq 2$ for each $v \in V$, while the former is a well-known NP-complete problem [6]. The decision version of the degree-constrained broadcast tree problem is thus NP-Complete, which is stated by the following theorem.

Theorem 1: The degree-constrained broadcast tree problem in a WDM optical network $G(V, E, \Lambda, w)$ with shared light splitter bank is NP-Complete.

Consequently, the degree-constrained multicast tree problem is NP-complete since the degree-constrained broadcast tree problem is a special case of it.

B. Approximation algorithm for degree-constrained broadcast trees

Given an undirected graph $G(V, E, d')$, each node $v \in V$ is bounded by an integer $1 \leq d'(v) \leq d_v$, the problem is to construct a spanning tree in G if it does exist, such that the degree of each node v in the tree is no more than $d'(v)$.

The proposed algorithm consists of a number of iterations. Within an iteration an auxiliary bipartite graph based on the results in previous iterations is constructed and a maximum matching in the auxiliary graph is then founded. The algorithm continues until the subgraph induced by the union of the maximum matchings so far is connected. A degree-constrained spanning tree can be found from the induced subgraph, which will be an approximate, degree-constrained broadcast tree. The rest thus is how to construct the auxiliary bipartite graph at each iteration, which is explained in the following.

Initially, a bipartite graph $H(X, Y, E_{XY})$ is constructed as follows: $X = \{v_1, v_2, \dots, v_{d'(v)} \mid v \in V\}$, i.e., there are $d'(v)$ corresponding nodes in X for each node $v \in V$. $Y = V$. There is an edge $(v_i, u) \in E_{XY}$ if there is an edge $(v, u) \in E$ and v_i is derived from v . Let M_0 be the maximum matching in $H_0 = H$. Denote by M_i the maximum matching in the auxiliary bipartite graph H_i with

$i \geq 0$. Now, we assume that the algorithm proceeds iteration i , $i > 0$. Let G_i be the subgraph of G induced by the edges in $\cup_{j=0}^{i-1} M_j$. We further assume that G_i is disconnected; otherwise, we are done already. Let $CC_1, CC_2, \dots, CC_{k_i}$ be the k_i connected components in G_i . The auxiliary bipartite graph $H_i = (X_i, Y_i, E_i)$ is constructed, where $X_i = X$ and $Y_i = \{CC_1, CC_2, \dots, CC_{k_i}\}$. Edge $(v_i, CC_j) \in E_i$ if there is an edge $(v, u) \in E$ such that v_i is derived from $v \in V$, $v \notin CC_j$ but $u \in CC_j$. The detailed algorithm is described below.

Algorithm Degree_Constrained_Tree(V, E, d') begin

1. $H'(X', Y', E') \leftarrow H(X, Y, E_{XY})$;
2. $M = \emptyset$; /*the union of sets of matching edges*/
3. $counter \leftarrow 0$;
4. $G'(V, M)$ is the induced subgraph of G by M ;
/* let k be the number of CC in G' */
5. while $(k > 1)$ or $(counter \neq \lfloor \log n \rfloor)$ do
6. find a maximum matching M' in H' ;
7. $M \leftarrow M \cup \{(v, u) \in E \mid (v_i, C) \in M',$
 v_i is derived from node $v \in V,$
 C is the CC in G' containing node $u\}$
8. update $G'(V, M)$;
9. $counter \leftarrow counter + 1$;
10. update $H' = (X', Y', E')$ as follows.
 $X' = X,$
 $Y' = \{ C \mid C \text{ is a CC in } G'\},$
 $E' = \{ (v_i, C) \mid v_i \text{ is not derived from}$
 $\text{any node in } C, \text{ but there is an edge}$
 $\text{in } H \text{ between } v_i \text{ and a node in } C\}.$
- endwhile;
11. find a spanning tree in G' ;

end

Note that the degree of each node in G' is at most $\lfloor \log n \rfloor (d'(v) + 1)$, because there are at most $\lfloor \log n \rfloor$ iterations and each node v as the endpoints of matching edges appears at most $d'(v) + 1$ times in H' within each iteration. Among the matching edges, v in X' is the endpoints of $d'(v)$ matching edges and v in Y' is the endpoint of a matching edge.

Lemma 1: Given $G(V, E, w)$ and a degree constraint $d'(v)$ for every $v \in V$, if there is a degree-constrained spanning tree in G , then, (i) there is always a perfect matching in the auxiliary graph $H' = (X', Y', E')$ covering all the nodes in Y' within each iteration. (ii) There is an approximation algorithm for finding a degree-constrained spanning tree in G , and the degree of each node v in the spanning tree delivered by the algorithm is no more than $\lfloor \log n \rfloor (d'(v) + 1)$. The algorithm takes $O(\log nt_{match}(\max_{v \in V} \{d_v\}n, \max_{v \in V} \{d_v\}m)) = O(mn^2 \log n)$ time, where $t_{match}(x, y) = O(\sqrt{xy})$ is the time complexity of finding a maximum matching in a bipartite graph with x nodes and y edges [5], $|V| = n$ and $|E| = m$.

Proof: We show claim (i) by induction. We assume that $H'_t = (X'_t, Y'_t, E'_t)$ is the auxiliary graph H' obtained after the first t rounds of finding perfecting matchings. When $t = 0$, $H'_0 = H$, it is easy to verify that there is a perfect matching in auxiliary graph H'_0 covering all the nodes in $Y'_0 = Y = V$ if such a degree-constrained spanning tree exists, which is shown

as follows. Given a node v in the degree-constrained spanning tree with $d'(v)$ children, let $(v, u_1), (v, u_2), \dots, (v, u_{d'(v)})$ be the list of tree edges incident to v , where $u_i \neq v$ and $u_i \in V$, $1 \leq i \leq d'(v)$. Then, it can be seen that the edges $(v_1, u_1), (v_2, u_2), \dots, (v_{d'(v)}, u_{d'(v)})$ are the matching edges, and all the nodes in Y'_0 are covered by the corresponding edges of the tree edges, because the tree is a spanning tree, where $v_i \in X'_0 = X$ and $u_i \in Y'_0$, $1 \leq i \leq d'(v)$. Thus, the matching edges induced by the tree edges form a perfecting matching in H'_0 .

Suppose that claim (i) holds for H'_{t-1} for $t \geq 1$. We now show the claim also holds for H'_t , i.e., there is a perfecting matching in H'_t covering all the nodes in Y'_t . Following the construction of H'_t , each node in Y'_t is a CC in the subgraph G' of G induced by the matching edges so far. We construct another auxiliary graph $G[Y'_t]$ consisting of nodes in Y'_t as follows. Each node in Y'_t is a *supernode*, which is a CC in G' . There is an edge between two supernodes if there is an edge between two nodes in the degree-constrained spanning tree in G while the two nodes are in the two supernodes. If there are multiple edges between them, just one of the edges is chosen and it will serve as the *representative* of these edges. As a result, $G[Y'_t]$ is connected because there is a spanning tree in G . Let $T[Y'_t]$ be a spanning tree in $G[Y'_t]$. Then, there is a corresponding tree edge e in the spanning tree in G for every tree edge in $T[Y'_t]$. Furthermore, there is a corresponding edge in H'_t for each tree edge e , which is also a matching edge, because for a node $v \in V$, there are exactly $d'(v)$ nodes in $X'_t = X$, and all the nodes in the Y'_t are covered by the matching edges due to the fact that $T[Y'_t]$ is a spanning tree in $G[Y'_t]$ which includes all the nodes in Y'_t . Thus, it is a perfecting matching in H'_t .

We then show that claim (ii) holds as well. Note that although the subgraph induced by the matching edges in a perfect matching may not be connected, the two endpoints of each matching edge are in two different connected components in G' . Also, all the nodes in Y'_t are covered by the matching edges after each round. Thus, the number of connected components in G' induced by the matching edges at each round will be reduced by at least a half. In other words, let Y'_t be the set Y' of nodes at iteration t and Y'_{t+1} the set Y' of nodes at iteration $t+1$, then $|Y'_{t+1}| \leq \lfloor |Y'_t|/2 \rfloor$, following the claim (i). Therefore, if there is a degree-constrained spanning tree in G , then there is only one node in $Y' = Y'_{\lfloor \log n \rfloor}$ after $\lfloor \log n \rfloor$ iterations, which means that there is only one connected component in G' after $\lfloor \log n \rfloor$ iterations, i.e., an approximate, degree-constrained spanning tree is found and the degree of each node v in the tree is no more than $\lfloor \log n \rfloor (d'(v) + 1)$.

We finally analyze the running time of the proposed algorithm. Since the number of connected components in G is reduced by at least a half within each iteration if there is such a degree-constrained spanning tree. There is only one connected component in G' left after $\lfloor \log n \rfloor$ iterations. The auxiliary graph H contains $|X| + |Y| \leq \max_{v \in V} \{d_v\} |V| + |V| = (\max_{v \in V} \{d_v\} + 1)n$ nodes and $|E_{XY}| \leq \max_{v \in V} \{d_v\} |E| = \max_{v \in V} \{d_v\} m$ edges. Note that the degree of node v in the subgraph G' of G induced by the edges in M is at most $\lfloor \log n \rfloor (d'(v) + 1)$, so the degree of v in a spanning tree in G'

is no more than $\lfloor \log n \rfloor (d'(v) + 1)$. The running time of the algorithm then follows. \blacksquare

Theorem 2: Given the current status of the WDM optical network $G(V, E, \Lambda, w)$ with shared light splitter bank, there is an approximation solution for the degree-constrained broadcast tree problem, which is $O(\log n)$ times of the optimum.

C. Approximation algorithm for degree-constrained multicast trees

Given the approximate, degree-constrained spanning tree in the previous subsection, prune the branches that do not contain any node in D from the tree, the resulting tree is a multicast tree, which is an approximation solution to the degree-constrained multicast tree problem. We thus have the following theorem.

Theorem 3: Given the current status of the WDM optical network $G(V, E, \Lambda, w)$ with shared light splitter bank and a multicast request $(s; D)$, there is an approximation algorithm for the degree-constrained multicast tree problem, which delivers a solution within $O(\log n)$ times of the optimum.

V. ALGORITHMS BASED ON THE REFINED NODE-LINK COST MODEL

It can be seen that the degree-constrained, link-load balanced broadcast or multicast tree problem is NP-Complete too, since the degree-constrained broadcast or multicast tree problem is a special case of this general setting.

A. Approximation algorithm for degree-constrained, link-load balanced broadcast trees

The algorithm for the degree-constrained, link-load balanced broadcast tree problem is similar to the one for the degree-constrained broadcast tree problem except the following differences.

Within an iteration of the algorithm, the edges in the auxiliary bipartite graph are now assigned weights. Specifically, given a supernode y that represents a connected component of an induced subgraph G' of G by the edges in the union of maximum matchings obtained by all previous iterations. Assume that there is such an edge $(v, u) \in E$ that u is a node in y but v is not, then there is an edge (v, y) in the auxiliary bipartite graph with weight $w_2(v, y) = \min\{w_2(v, u) \mid u \in y\}$. A maximum matching with the minimum weighted sum of the matching edges in the auxiliary bipartite graph then is found. We thus have the following theorem.

Theorem 4: Given the current status of the WDM optical network $G(V, E, \Lambda, w, w_2)$ with shared light splitter bank, there is an approximation algorithm for the degree-constrained, link-load balanced broadcast tree problem, which delivers a solution within $O(\log n)$ times of the optimum in terms of both node and link metrics.

Proof: Following Lemma 1, the node degree of each node v in the broadcast tree is no more than $\min\{\lfloor \log n * d'(v) \rfloor + 1, d_v\}$. The rest is to show that the weighted sum of the links in the broadcast tree is no more than $\log n$ times of the optimum.

Assume that T_{opt} is the degree-constrained, link-load balanced broadcast tree. Following the construction of the auxiliary graph $H(X, Y, E_{XY})$, there is a matching M_{opt} in H

containing the corresponding edges in T_{opt} such that all nodes in Y are covered, while the maximum matching in H delivered by the proposed algorithm is such a maximum matching that the weighted sum of the edges in the matching is the minimum one, i.e., the weighted sum of the matching edges in it is no more than $\sum_{e \in M_{opt}} w_2(e)$. Within each subsequent iteration, it can be seen that the weighted sum of the edges in the maximum matching delivered by the proposed algorithm is no more than the weighted sum of the edges in M_{opt} . Following Lemma 1, it is known that there are no more than $\lceil \log n \rceil$ iterations. Thus, the weighted sum of the edges in the spanning tree delivered by the proposed algorithm is no more than $O(\log n)$ times of the optimum. ■

B. Heuristic algorithm for degree-constrained, link-load balanced multicast trees

The heuristic for the degree-constrained, link-load balanced multicast tree problem is similar to the one for the degree-constrained multicast tree problem. That is, a degree-constrained, link-load balanced spanning tree is found first, then those branches of the tree will be pruned if they do not contain any terminal nodes. The resulting tree is a multicast tree for the multicast request. We thus have the following theorem.

Theorem 5: Given the current status of the WDM optical network $G(V, E, \Lambda, w, w_2)$ with shared light splitter bank and a multicast request $(s; D)$, there is a heuristic algorithm for the degree-constrained, link-load balanced multicast tree problem.

VI. PERFORMANCE EVALUATION

In this section we evaluate the performance of the proposed algorithms through experimental simulations. We refer the algorithms for finding a degree-constrained tree and degree-constrained, link-load balanced tree to as DCT and DCTLB respectively. We use the network throughput that is the percentage of the number of realized requests in an unknown sequence of broadcast or multicast requests as the main metric. In our simulations, we use an algorithm for a single source node-weighted shortest path tree SPT as the benchmark for the purpose of performance comparison. The following symbols are used in the simulations.

- K: initial wavelength capacity
- γ : initial light splitting and/or wavelength conversion capacity
- θ : percentage of terminals in a multicast request
- ρ : percentage of MC-OXC or OXC nodes in the network

A. Simulation environment

We assume that the WDM optical network consists of $n = 100$ nodes that are deployed randomly in a region of $10 \times 10 m^2$ using the NS-2 simulator. For each pair of nodes u and v , a random value $r_{u,v}$ is generated, where $r_{u,v}$ is equal to or greater than 0 but less than 1. Whether or not u and v are connected is determined by $r_{u,v}$ and the edge probability $P(u, v)$ that is defined as follows [21], [3].

$$P(u, v) = \beta e^{-\frac{d(u,v)}{L\alpha}},$$

where $d(u, v)$ is the Euclidean distance between u and v , L is the maximum distance between any two nodes, and α and β

are the parameters governing the edge density in the network, $0 < \alpha, \beta \leq 1$. There is an edge between u and v if and only if $r_{u,v} < P(u, v)$. Different values of α and β result in different network topologies even for the same node distribution. Large value of α implies the number of long edges is increased, and large value of β results in more edges incident to each node. In our simulations, both α and β are set to be 0.5.

We also assume that there are $K = |\Lambda|$ wavelengths available in the WDM optical network, and the initial wavelength capacity on each link is identical with the value of K . We further assume that only a fraction of nodes in the WDM optical network are MC-OXC or OXC nodes. Initially, the number of the light splitters and/or wavelength converters installed at each MC-OXC or OXC node is identical and the light splitting and/or wavelength conversion capacity at each MC-OXC or OXC node is γ . We use $R(v)$ to represent the number of the available light splitters and/or wavelength converters at node v . When the value of $R(v)$ is 0, there is no light splitting and/or wavelength conversion ability at v . If the value of $R(v)$ is γ , i.e., the light splitting and/or wavelength conversion ability at v is full, the fanout of the node can be as large as its physical degree in the network. For a MC-OXC or OXC node, the weight assigned to it is the ratio of its initial light splitting and/or wavelength conversion capacity to the number of its available light splitters and/or wavelength converters at that moment, i.e.

$$w(v) = \frac{\gamma}{R(v)}.$$

It is obvious that the weight of a MC-OXC or OXC node is 1 initially. For a node that is neither MC-OXC nor OXC node, the weight assigned to it is a sufficiently large number. We use $d'(v)$ as the measure of the light splitting and/or wavelength conversion ability at node v , where $d'(v)$ is defined as follows.

$$d'(v) = \frac{d_v}{w(v)}$$

In our simulations, the sequence of broadcast or multicast requests consists of 100 requests that are generated randomly. Each multicast request is composed of a source node, a terminal set, the arrival time and the duration. Each multicast request occupies network resources only for a certain period of time and will release the resources after its multicast session ends. For a given multicast request $(s; D)$, we say that the multicast request is realized by an algorithm if the multicast tree T built for it by the given algorithm satisfies the following two conditions. (i) If v is an internal node in T , there is enough light splitting and/or wavelength conversion ability at node v , i.e. there are light splitters and/or wavelength converters available at node v and the number of its children is no greater than $d'(v)$; (ii) If e is an edge in T , there are wavelengths available on edge e . The node weight and edge weight change dynamically. Initially, $R(v) = \gamma$ for a MC-OXC or OXC node and $R(v) = 0$ otherwise, and $U(e) = 0$ for each edge e in the network. Suppose that T is the multicast tree built for a multicast request $(s; D)$, v is an internal node in T and has $R(v)$ light splitters and/or wavelength converters available, and e is an edge in T and has $U(e)$ wavelengths being used before

the multicast request arrives. Then $R'(v) = R(v) - 1$ and $U'(e) = U(e) + 1$ if $(s; D)$ is realized, where $R'(v)$ and $U'(e)$ are the number of residual light splitters and/or wavelength converters at node v and the number of wavelengths being used on edge e after $(s; D)$ is accommodated.

We simulated various algorithms on 10 different randomly generated network topologies for different problem size. For each size of the network instance, each value shown in all charts and tables is the mean of 10 individual values obtained by running each algorithm on these 10 randomly generated network topologies.

B. Comparison of various algorithms

In the following we study algorithm DCTLB against algorithms DCT and SPT. For multicast requests, we consider different sizes of terminal sets that are θ percentage of the network size, where $\theta = 10\%$, 25% , 50% , or 75% . We vary the value of the density ρ of MC-OXC or OXC nodes in the network, the light splitter and/or wavelength converter capacity γ , and the wavelength capacity K for performance evaluation. We also evaluate the performance of various algorithms for the case of broadcast requests.

1) *Comparison of various algorithms for multicast requests:* We first compare the performance of various algorithms when $K = 10$ and $\rho = 80\%$ and $\gamma = 10, 25$, or 50 . As shown in Fig. 2, among the algorithms, algorithm DCTLB outperforms the other two significantly for various sizes of terminal sets and various values of light splitter and/or wavelength converter capacities. When 10% of the network nodes are terminals, the network throughput delivered by algorithm DCTLB is around three times or twice of that delivered by algorithm DCT or algorithm SPT respectively. When the percentage of terminals reaches 75% of the network nodes, the network throughput delivered by algorithm DCTLB is one and a half times as great as those delivered by the other two algorithms if $\gamma = 25$ or 50 . When $\gamma = 10$ and $\theta = 75\%$, the performance of algorithm DCTLB is still better than that of algorithms DCT and SPT. The reason behind can be observed from Tables I, II and III. There are two ways

TABLE I
BLOCKAGE PERCENTAGE WHEN $\gamma = 50$, $K = 10$ AND $\rho = 80\%$

θ	Splitting blockage			Traversing blockage		
	DCT	DCTLB	SPT	DCT	DCTLB	SPT
10%	0.00	0.02	0.00	0.77	0.38	0.64
25%	0.00	0.03	0.00	0.72	0.38	0.70
50%	0.00	0.14	0.00	0.71	0.34	0.70
75%	0.00	0.16	0.00	0.74	0.46	0.74

TABLE II
BLOCKAGE PERCENTAGE WHEN $\gamma = 25$, $K = 10$ AND $\rho = 80\%$

θ	Splitting blockage			Traversing blockage		
	DCT	DCTLB	SPT	DCT	DCTLB	SPT
10%	0.00	0.04	0.00	0.77	0.34	0.64
25%	0.00	0.12	0.00	0.72	0.33	0.69
50%	0.00	0.17	0.00	0.71	0.36	0.71
75%	0.03	0.25	0.18	0.74	0.44	0.71

TABLE III
BLOCKAGE PERCENTAGE WHEN $\gamma = 10$, $K = 10$ AND $\rho = 80\%$

θ	Splitting blockage			Traversing blockage		
	DCT	DCTLB	SPT	DCT	DCTLB	SPT
10%	0.08	0.07	0.00	0.71	0.34	0.64
25%	0.36	0.33	0.00	0.46	0.20	0.70
50%	0.62	0.60	0.34	0.32	0.04	0.58
75%	0.72	0.72	0.67	0.22	0.03	0.24

that contribute the failure to realize a multicast request. One is the splitting blockage, where there are some internal nodes in the multicast tree built for the multicast request that have no light splitters and/or wavelength converters available or have not enough light splitting and/or wavelength conversion ability. The other is the traversing blockage, where there exist some edges in the multicast tree that have no wavelengths available. The data in the tables represent the percentages of the multicast requests that are not realized and caused by either splitting blockage or traversing blockage respectively. For the case where $\gamma = 50$, the critical constraint is the available wavelengths on edges for various algorithms, which can be seen from Table. I. Since algorithms DCT and SPT do not take into account the wavelength constraint on edges, all those multicast requests that have not been realized are caused by the exhaustion of wavelengths on some edges in the multicast tree for the multicast request, whereas algorithm DCTLB can tradeoff the traffic load among edges in terms of the number of wavelengths available on different edges at a small cost of splitting blockage and thus increases the network throughput. Similar observations can be noticed when $\gamma = 25$ from Table. II. For the case where $\gamma = 10$, the performance of algorithm DCTLB is much better than that of algorithms DCT and SPT, although the constraints are imposed on both light splitting and/or wavelength conversion ability at nodes and the wavelength availability on links as indicated in Table. III.

We then explore the impact of the sparsity of the MC-OXC or OXC nodes on the performance of various algorithms. We reduce the density ρ of MC-OXC or OXC nodes in the network from 80% to 50%. We here consider the same environment as that in Fig. 2(a) except $\rho = 50\%$. For algorithms DCT and SPT, there is not much difference of network throughput, when ρ varies from 80% to 50%, which can be seen from Figures 2(a) and 3. In comparison with the case where $\rho = 80\%$, the network throughput delivered by algorithm DCTLB drops but keeps constantly greater than those delivered by algorithms DCT and SPT for each size of terminal sets in the simulations when $\rho = 50\%$, as shown in Fig. 3. The reason behind is that algorithm DCTLB consider the light splitting and/or wavelength conversion ability at nodes and the wavelength availability at edges jointly. The variation on the number of the nodes with light splitters and/or wavelength converters impacts the performance of algorithm DCTLB.

We finally analyze the impact of wavelength capacity on the network throughput of various algorithms. We consider the same network environment as that in Fig. 2(a) except $K = 25$. Compared with Fig. 2(a) when $K = 10$, the network throughput of various algorithms increases significantly and algorithm DCTLB still outperforms algorithms DCT and

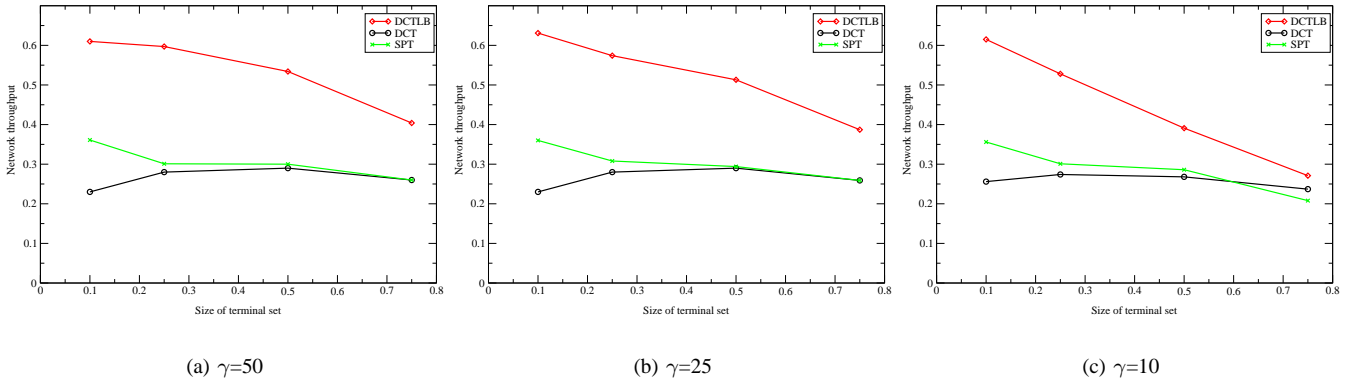


Fig. 2. Comparison of the network throughput of various algorithms with $K = 10$ and $\rho = 80\%$.

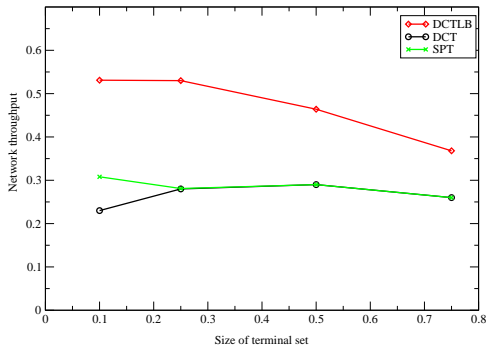


Fig. 3. Comparison of the network throughput of various algorithms with $\gamma = 50$, $K = 10$ and $\rho = 50\%$.

SPT. This is because algorithm DCTLB can employ these wavelengths efficiently and reduce the blockage on links in building a multicast tree when there are plenty of wavelengths available on edges. In addition, algorithm DCTLB reduces the percentage of traversing blockage to zero and maximizes the network throughput, as shown in Fig. 4 and Table. IV. For the other two algorithms DCT and SPT, the traversing blockages are much higher than that of algorithm DCTLB even if there are plenty of wavelengths available on edges.

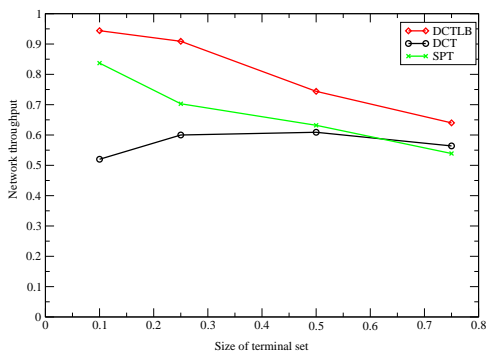


Fig. 4. Comparison of the network throughput of various algorithms with $\gamma = 50$, $K = 25$ and $\rho = 80\%$.

2) *Evaluation on various algorithms for broadcast requests:* We compare the performance of various algorithms when all the requests are broadcast requests. We consider the similar

TABLE IV
BLOCKAGE PERCENTAGE WHEN $\gamma = 50$, $K = 25$ AND $\rho = 80\%$

θ	Splitting blockage			Traversing blockage		
	DCT	DCTLB	SPT	DCT	DCTLB	SPT
0.10	0.00	0.06	0.00	0.48	0.00	0.16
0.25	0.00	0.09	0.00	0.40	0.00	0.30
0.50	0.00	0.26	0.00	0.39	0.00	0.37
0.75	0.04	0.36	0.29	0.41	0.00	0.22

network environment as the case of multicast requests, where $\gamma = 10, 25$, or 50 , $K = 10$ or 25 , and $\rho = 80\%$. As shown in Table. V, both the light splitting and/or wavelength conversion ability at nodes and the traversing ability on edges are limited when $K = 10$ and $\gamma = 25$ or 50 . When $K = 25$, there are sufficient wavelengths on edges and the constraints of network resources are imposed on the light splitting and/or wavelength conversion ability at nodes. All those not realized broadcast requests are caused by the deficit of the light splitting and/or wavelength conversion ability at nodes, which can be seen in Table. VI. However, no matter how the constraints are imposed, Fig. 5 clearly indicates that algorithm DCTLB still outperforms algorithms DCT and SPT.

TABLE V
BLOCKAGE PERCENTAGE FOR BROADCAST REQUESTS WHEN $K = 10$ AND $\rho = 80\%$

γ	Splitting blockage			Traversing blockage		
	DCT	DCTLB	SPT	DCT	DCTLB	SPT
10	0.92	0.56	0.91	0.00	0.28	0.00
25	0.76	0.23	0.71	0.07	0.60	0.20
50	0.38	0.10	0.39	0.43	0.68	0.43

TABLE VI
BLOCKAGE PERCENTAGE FOR BROADCAST REQUESTS WHEN $K = 25$ AND $\rho = 80\%$

γ	Splitting blockage			Traversing blockage		
	DCT	DCTLB	SPT	DCT	DCTLB	SPT
10	0.93	0.83	0.91	0.00	0.00	0.00
25	0.83	0.66	0.79	0.00	0.00	0.00
50	0.66	0.53	0.64	0.00	0.00	0.00

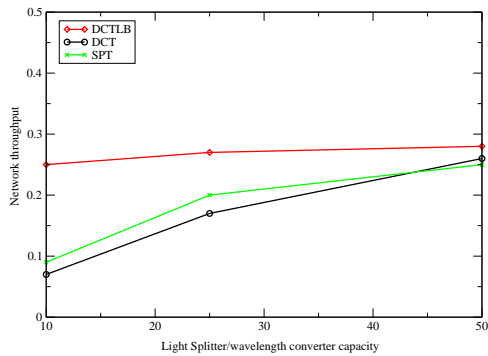
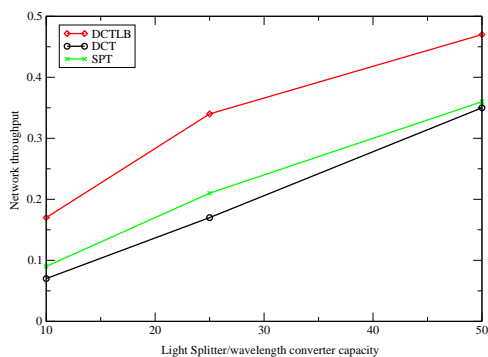
(a) $K=10$ (b) $K=25$

Fig. 5. Comparison of the network throughput of various algorithms for broadcast requests with various γ when $\rho=80\%$

VII. CONCLUSIONS

In this paper we have studied online broadcasting and multicasting in WDM optical networks with shared splitter bank with an objective to maximize the network throughput. To do so, we first proposed two cost models that model the consumption of network resources like splitting and/or wavelength conversion abilities at nodes and traffic load at links. We then showed that under either of the two proposed cost models, finding a cost-optimal broadcast or multicast tree is NP-Complete. Instead, we devised approximation and heuristic algorithms for each broadcast or multicast request. We finally conduct extensive experiments to evaluate the performance of the proposed algorithms against an existing algorithm with various cost metrics. To the best of our knowledge, these are the first approximation algorithms for the optical multicast problem that incorporate the physical constraints on networks like light splitting and/or wavelength conversion ability at nodes into the design of algorithms, and a generic design methodology of optical multicast routing protocols is provided for WDM optical networks with shared light splitter bank.

Acknowledgment. It is acknowledged that the work by the authors is fully funded by a research grant No:DP0449431 by Australian Research Council under its Discovery Schemes.

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