Multicast Routing and Wavelength Assignment in WDM Networks: A Bin Packing Approach

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This paper addresses the problem of multicast routing and wavelength assignment (MC_RWA) in wavelength routed WDM optical networks. Multicast requests are facilitated in WDM networks by setting up so-called *light-trees* and assigning wavelengths to them. Objectives of the MC_RWA problem include minimizing the number of distinct wavelengths used to establish a set of multicast requests and minimizing the cost of the corresponding light-trees. This cost can represent the physical length, delay or actual cost of a tree. Applications that require QoS multicasting can impose additional constraints on light-trees, such as a bounded end-to-end delay. Proposed are heuristic algorithms based on bin packing methods for the general MC_RWA problem, which is NP-complete. These algorithms can consider unicast, multicast and broadcast requests with or without QoS demands. Computational tests indicate that these algorithms are very efficient, particularly for dense networks.

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1. Introduction

Due to the rapid development of advanced network services and applications, network traffic has been growing exponentially in the past several years. WDM technology is a promising solution for satisfying the ever increasing capacity requirements in telecommunication networks. Namely, WDM networks can exploit the large bandwidth of optical fibers by dividing it among different wavelengths. In addition to high capacity requirements, the development of several multimedia applications has created an increasing need for point-to-multipoint and multipoint-to-multipoint communication. This type of communication is referred to as multicasting. WDM optical networks can efficiently support multicasting since splitting light is inherently easier than copying data into an electronic buffer. Applications of multicasting include multimedia conferencing, distance education, video distribution, distributed games and many others. Many of these applications require packets of information to be sent with a certain Quality of Service (QoS). In this paper we will consider the QoS demand of a bounded end-to-end delay. This constraint is particularly important for real-time applications such as video-conferencing or distance education.

In wavelength routed WDM networks, a virtual topology is established over the physical optical network by setting up all-optical connections, called *lightpaths*, between pairs of nodes. Although lightpaths can traverse multiple physical links, information sent via a lightpath does not require any opto-electronic conversion at intermediate nodes. Demands to set up lightpaths can be known *a priori* and established 'semi-permanently' (static lightpath demands) or arrive unexpectedly with random holding times (dynamic lightpath demands). Lightpaths can also be set up and released according to an *a priori* known schedule (scheduled lightpath demands). To set up a virtual topology, lightpaths must be routed over the physical network and assigned wavelengths. This problem is known as the *Routing and Wavelength Assignment* (RWA) problem and has been proven to be NP-complete [2]. Examples of heuristic algorithms which solve the RWA problem for static, dynamic and scheduled lightpath demands can be found in [3], [4], and [5], respectively.

A generalization of a lightpath, called a *light-tree*, was proposed in [6] to facilitate multicasting in wavelength routed WDM optical networks. Light-trees logically connect a source node to a group of destination nodes. Thus, these trees enable all-optical point-to-multipoint communication, i.e. entirely in the optical domain. A survey of optical multicasting in WDM networks is given in [1]. To establish a light-tree, nodes in the network must be equipped with multicast capable switches [7] which increases network cost. However, it has been shown that setting up a virtual topology composed of a set of light-trees, as opposed to lightpaths, substantially reduces the average packet hop distance and the number of tranceivers required in a network for unicast, multicast *and* broadcast traffic [6].

To establish a virtual topology composed of a set of *light-trees*, we must solve the *Multicast Routing and Wavelength Assignment* (MC_RWA) problem. In this paper, we consider *static* multicast requests, i.e. all the the requests are known *a priori* and the virtual topology is established 'semi-permanently'. Given is a network and a set of multicast requests. For each multicast request, it is necessary to find a multicast tree, i.e. a light-tree, which connects the source node to all the destination nodes. Optimization problems in multicast tree construction are discussed in [8]. Multicast routing is often reduced to the minimum Steiner tree problem in graphs. Generally, for a given graph $G = (V, E)$, where V is a set of nodes and E is a set of edges, and a given subset of nodes, $D \subseteq V$, a Steiner tree is one which connects all the nodes in D using a subset of edges in E. This tree may or may not include nodes in $V \setminus D$. A *minimum* Steiner tree is such a tree which is of minimum weight in a weighted graph. Several applications of Steiner Trees can be found in [9].

In addition to finding a feasible multicast tree, in order to solve the Multicast Routing and Wavelength Assignment problem it is necessary to assign wavelengths to these trees subject to the following constraints. If no wavelength converters are available, the same wavelength must be assigned along the entire tree. This is called the *wavelength continuity constraint*. In addition, light-trees that share a common physical link cannot be assigned the same wavelength. This is called the *wavelength clash constraint*. Depending on the power splitters available at each node, the optical signal may only be split into a bounded number of signals [10]. This imposes a constraint on the degree of the established multicast trees. The objective of the MC_RWA problem is often to minimize the number of wavelengths used, or to maximize the number of light-trees successfully set up subject to a limited number of wavelengths. The problem of Routing and Wavelength Assignment of *unicast* demands has been shown to be NP-complete [2]. Multicast demands make the problem even harder. In fact, multicast routing, i.e. the minimum Steiner tree problem, itself is NP-hard [11]. Several variations of the MC_RWA problem and their solutions have been proposed in [12], [13], [14], [15], and [16].

We develop heuristic algorithms for the routing and wavelength assignment of multicast requests by efficiently applying bin packing based algorithms. These heuristics are motivated by concepts used by RWA algorithms for unicast demands from [3]. They also apply a heuristic for the delay constrained multicast routing problem from [17]. The objective of the proposed heuristic algorithms for the

MC_RWA problem is to minimize the number of wavelengths used. We also consider a second objective, which is to minimize the costs of the established light-trees. The cost of a light-tree can represent various values such as the actual cost, the total number of hops, the total length or the maximum transmission delay in the tree. Delay constrained multicasting, where each multicast request has an end-to-end delay bound associated with it, is also considered.

The algorithms were tested on random networks and on a benchmark problem set for the Steiner tree problem from [18]. Comparison with lower bounds indicates that the proposed algorithms obtain solutions of good quality both with respect to the number of wavelengths used and average light-tree cost, particularly for denser networks. These algorithms are highly flexible and can consider unicast, multicast and broadcast requests with or without QoS constraints.

The rest of the paper is organized as follows. In Section 2 we informally define the MC_RWA problem and discuss related work in Section 3. In Section 4 we introduce classical bin packing and suggest heuristic algorithms for the MC_RWA problem. Lower bounds are briefly discussed in Section 5. Numerical results and concluding remarks are given in Sections 6 and 7, respectively.

2. Problem Specification

The physical optical network is modelled as a graph $G = (V, E)$, where V is the set of nodes and E is the set of edges. Edges are assumed to be bidirectional (each representing a pair of optical fibers, i.e. one fiber per direction). On graph G we define the functions $c(i, j)$ and $d(i, j)$, where $c(i, j)$ can represent the cost of using edge $(i, j) \in E$ and $d(i, j)$ can represent the length or propagation delay along edge $(i, j) \in E$. The cost of an edge is not necessarily proportional to its delay. Given is a set of multicast requests $\tau = \{(s_1, S_1, \Delta_1), \ldots, (s_n, S_n, \Delta_n)\}$, where $\{s_i \cup S_i\} \subseteq V, i = 1, \ldots, n$. Each multicast request is defined by a source node $s_i \in V$, a group of destination nodes $S_i \subseteq V$, and an upper bound on the delay from s_i to any node in S_i denoted as Δ_i. If we are considering multicasting with no QoS demands, Δ_i is set to ∞. If we are considering multicasting with a bounded end-to-end delay, Δ_i is set to the desired bound.

The Multicast Routing and Wavelength Assignment problem consists of finding a set of trees $T = \{T_1, \ldots, T_n\}$ in G, each corresponding to one multicast request, and assigning wavelengths to them. We assume that the trees are bidirectional, i.e. that data is transmitted between the source and destination nodes in both directions. Each tree $T_i = (V_{T_i}, E_{T_i})$, where $V_{T_i} \subseteq V$ and $E_{T_i} \subseteq E$, is subject to the following constraints. $s_i \cup S_i \subseteq V_{T_i}$ and $D(s_i, v) \leq \Delta_i$ for every $v \in S_i$ where $D(s_i, v) = \sum_{(j,k)} d(j, k)$ for all edges $(j, k) \in E_{T_i}$ on the path from s_i to v in T_i. The cost of tree T_i is $c(T_i) = \sum_{(j,k) \in E_{T_i}} c(j, k)$. Trees T_i and T_j where $i \neq j$, $i, j = 1, \ldots, n$, cannot be assigned the same wavelength if they share a common edge. We assume no bound on the degree of a multicast tree, i.e. the optical signal can be split into an arbitrary number of signals. The objective is to minimize the number of wavelengths required to successfully route and assign wavelengths to all the multicast requests in τ. We also consider a second objective which is to minimize the average cost of the established trees, i.e. $min \frac{\sum_{i=1}^{n} c(T_i)}{|\tau|}$.

3. Related Work

Previous works regarding the MC_RWA problem consider various problem models and solution approaches. In [12], the authors decompose the MC_RWA problem into two subproblems, routing and wavelength assignment, solved subsequently. For multicast routing, a heuristic is suggested which minimizes the cost of the multicast trees. The authors consider cost to include not only the bandwidth cost, but the cost of wavelength conversion and light splitting as well. Furthermore, the authors prove that wavelength assignment for a given routing scheme is not NP-hard and propose a polynomial optimal wavelength assignment algorithm. In [13], wavelength assignment for dynamic multicasting, i.e. where multicast sessions are dynamically set up and released over time, was also shown to be solvable in linear time if the number of wavelengths per link, transmitters and receivers per node, and switch degree are constants.

In [19] and [14], the authors explore multicast routing under the *multi-tree* model. In such a model, one multicast request is realized with a collection of light-trees where each light-tree can have at most a specified number of destinations. A 4-approximation routing algorithm is proposed which minimizes the cost of the established trees. A wavelength assignment algorithm is also suggested.

QoS multicast routing and wavelength assignment is studied in [15]. The QoS demand considered is a bounded end-to-end delay from the source node to any destination node in a multicast session. Heuristic algorithms with the objective to minimize the number of wavelengths using two different approaches are proposed. The first approach reduces the maximal link load in the system, while the second tries to free the least used wavelength.

Multicasting in all-optical networks where each node can receive only one signal at a time, referred to as the *single reception constraint*, is studied in [20]. Using some properties of expander graphs, the authors obtain an upper bound on the number of wavelengths required to support such multicasting. Protective MC_RWA, where back-up trees are reserved to protect multicast sessions, is studied in [16]. The authors give a mathematical formulation for this problem, along with an expanded formulation for protective MC_RWA in sparse splitting networks.

Since multicasting in WDM networks requires multicast-capable switches, their cost and design have been widely studied [21] [7]. Multicasting in optical networks where some switches in the network are incapable of splitting light due to evolutional and/or economic reasons is studied in [22]. The authors propose heuristic algorithms for multicast routing in such networks by constructing a so-called 'light-forest' consisting of a collection of multicast trees for each multicast session. A low cost architecture, referred to as *Tap-and-Continue*, for multicasting in WDM networks along with a 4-approximation algorithm for multicast routing was proposed in [23].

4. Heuristic algorithms for the MC_RWA problem

In order to solve the MC_RWA problem we propose fast and simple heuristic algorithms developed by applying concepts used for bin packing. The bin packing problem is a classical combinatorial NP-complete optimization problem. Given is a list of n items of various sizes and identical bins of limited capacity. To solve the bin packing problem, it is necessary to pack these items into the minimum number of bins, without violating the capacity constraints, so that all items are packed. Since this problem is NP-hard [11], a vast array of approximation algorithms have been proposed and studied. Four well-known classical bin packing algorithms are the First Fit (FF), Best Fit (BF), First Fit Decreasing (FFD) and Best Fit Decreasing (BFD) algorithms. The FF algorithm packs each item, in the order in which they are given, into the first bin into which it fits. The BF algorithm packs each item into the bin which leaves the least room left over after packing the item. The FFD and BFD algorithms sort the given items in nonincreasing order of their corresponding sizes, and then perform packing in the same manner as the FF and BF algorithms, respectively. These algorithms perform significantly better than FF and BF. Surveys of bin packing algorithms can be found in [24] and [25].

We apply these classical bin packing methods to help solve the Multicast Routing and Wavelength Assignment problem. Since each link in the physical network G can support multiple wavelengths, we can consider G to be a multilayered graph where each layer represents one wavelength. Our main objective is to 'pack' a set of multicast requests into this graph using the least number of layers, i.e. using the minimum number of wavelengths. As a result, we consider multicast requests to represent the 'items' in bin packing, while copies of graph G (individual layers) represent 'bins'. Each copy of G, referred to as bin $G_i, i = 1, 2, 3, \ldots$, corresponds to one wavelength. The capacity of each bin is limited by the edges in G since light-trees routed on the same layer cannot traverse any of the same edges due to the *wavelength clash constraint*.

Since the FFD and BFD bin packing algorithms sort 'items' in decreasing order of their corresponding sizes, we must define the size of a multicast request. Herein, we suggest two evaluation functions.

- $|S_i|$: The first evaluation function considers the size of a multicast request to be the number of destination nodes, i.e. the cardinality of set S_i. This size is easy to calculate but may not be a good representative of the actual size of the multicast tree. Namely, if all the destination nodes are set close to each other in the network, the multicast tree may be much smaller than a tree whose destination nodes are spread out over the graph even though they are fewer in number. Also, this measure may not be relevant if all the multicast sessions have a similar number of destination nodes.

- MCT_j: The second evaluation function considered for the size of a multicast request is an approximation of the corresponding minimum cost multicast tree. As already mentioned, finding a multicast tree, i.e. multicast routing, reduces to the minimum Steiner tree problem in graphs. Since this problem itself is NP-hard [11], there is no polynomial time algorithm known which can guarantee the optimal minimum cost Steiner tree. Therefore, we consider the size of each multicast request $(s_j, S_j, \Delta_j) \in \tau$ to be the length of the suboptimal minimum cost tree, MCT_j, in graph G found using the multicast routing heuristic algorithm, called GRASP-CST, from [17]. However, it is important to note that multicast requests will not necessarily be routed on these found suboptimal trees. This measure is used only by the algorithms in order to sort the 'items' or multicast requests in nonincreasing order of their corresponding sizes.

A description of the proposed heuristics for the MC_RWA problem follows. Their corresponding pseusocodes are shown in Fig. 1. Algorithms referred to as FF_MC_RWA and BF_MC_RWA are based on the classical bin packing algorithms FF and BF, respectively. Two algorithms, FFD_MC_RWA and FFTD_MC_RWA, are suggested which correspond to the bin packing FFD algorithm. The two differ with respect to the evaluation of the size of a multicast request. Analogously, algorithms BFD_MC_RWA and BFTD_MC_RWA correspond to bin packing algorithm BFD.

4..1. *FF_MC_RWA*

The First Fit Multicast Routing and Wavelength Assignment algorithm, referred to as FF_MC_RWA, runs as follows. Layers of G, or bins, are created as needed

```
FF_DCMC_RWA (FFD_DCMC_RWA; FFCD_DCMC_RWA)
Input:
G = (V, E);//physical network
τ = {(s_1, S_1, Δ_1), ..., (s_n, S_n, Δ_n)}; //multicast requests
Begin:
-----------------
ONLY FOR FFD_DCMC_RWA:
Sort and renumerate demands τ in nonincreasing order of the
number of destination nodes in each request, |S_i|, i = 1, ..., n
-----------------
ONLY FOR FFCD_DCMC_RWA:
for i = 1 to n do
  Run GRASP-CST(s_i, S_i, Δ_i; G) to obtain Steiner tree
  MCT_i;
end for
Sort and renumerate demands τ in nonincreasing order of the cost
of the obtained Steiner trees c(MCT_i), i = 1, ..., n.
-----------------
T = {}; //The final trees
Create 1 copy (bin) of G : G_1;
BINS := {G_1};
while τ is not empty do
  for j = 1 to |τ| do
    T_j = ∅;
    for i = 1 to |BINS| do
      Find Steiner tree T_j^i by running
            GRASP-CST(s_j, S_j, Δ_j; G_i);
      if feasible then
        T_j = T_j^i;
        Assign wavelength i to tree T_j;
        Delete edges in T_j^i from G_i;
        i = |BINS|;
      end if;
    end for;
    if T_j = ∅ then
      New := |BINS| + 1;
      Create copy of G: G_New;
      BINS := BINS ∪ {G_New};
      Find Steiner tree, T_j^New, by running
            GRASP-CST(s_j, S_j, Δ_j; G_New);
      T_j = T_j^New;
      Assign wavelength New to path T_j;
      Delete edges in T_j^New from G_New
    end if;
    T = T ∪ T_j;
    τ = τ \ (s_j, S_j, Δ_j);
  end for;
end while;
return T;
End
```

```
BF_DCMC_RWA (BFD_DCMC_RWA; BFCD_DCMC_RWA)
Input:
G = (V, E);//physical network
τ = {(s_1, S_1, Δ_1), ..., (s_n, S_n, Δ_n)}; //multicast requests
Begin:
-----------------
ONLY FOR BFD_DCMC_RWA:
Sort and renumerate demands τ in nonincreasing order of the
number of destination nodes in each request, |S_i|, i = 1, ..., n)
-----------------
ONLY FOR BFCD_DCMC_RWA:
for i = 1 to n do
  Run GRASP-CST(s_i, S_i, Δ_i; G) to obtain Steiner tree
  MCT_i;
end for
Sort and renumerate demands τ in nonincreasing order of the cost
of the obtained Steiner trees c(MCT_i), i = 1, ..., n.
-----------------
T = {}; //The final trees
Create 1 copy (bin) of G : G_1;
BINS := {G_1};
while τ is not empty do
  for j = 1 to |τ| do
    T_j = ∅, c(T_j) = ∞;
    BestBin := 0;
    for i = 1 to |BINS| do
      Find Steiner tree T_j^i by running
            GRASP-CST(s_j, S_j, Δ_j; G_i);
      if feasible and c(T_j^i) < c(T_j) then
        BestBin = i;
        T_j = T_j^i;
        Assign wavelength i to tree T_j;
      end if;
    end for;
    if T_j ≠ ∅ then
      Delete edges in T_j^BestBin from G_BestBin;
    else
      New := |BINS| + 1;
      Create copy of G: G_New;
      BINS := BINS ∪ {G_New};
      Find Steiner tree, T_j^New, by running
            GRASP-CST(s_j, S_j, Δ_j; G_New);
      T_j = T_j^New;
      Assign wavelength New to tree T_j;
      Delete edges in T_j^New from G_New
    end if;
    T = T ∪ T_j;
    τ = τ \ (s_j, S_j, Δ_j);
  end for;
end while;
return T;
End
```

Fig. 1. Pseudocodes of the FF_MC_RWA, BF_MC_RWA, FFD_MC_RWA, BFD_MC_RWA, FFTD_MC_RWA, and BFTD_MC_RWA algorithms.

and sequentially indexed. The algorithm begins by creating one layer of G, called G_1. Multicast requests (s_j, S_j, Δ_j) are selected at random and routed on the lowest indexed layer of G in which there is room. Bin G_i is considered to have room for multicast request (s_j, S_j, Δ_j) if we can find a multicast tree, using the GRASP-CST algorithm, connecting s_j to all the nodes in S_j in G_i. This tree is denoted as T_j^i. If we are considering delay constrained multicasting, this tree must satisfy the delay constraint. If a multicast request is routed in bin G_i, the request is assigned wavelength i and the edges along tree T_j^i are deleted from G_i. If all the edges from bin G_i are deleted, the bin no longer needs to be considered. If no existing bin can accommodate multicast request (s_j, S_j, Δ_j), a new bin is created.

4..2. BF_MC_RWA

The Best Fit Multicast Routing and Wavelength Assignment algorithm, BF_MC_RWA, runs as follows. Multicast requests are routed on the layer of G

in which they fit 'best'. We consider the best fit to be the layer on which we can find the least cost feasible multicast tree. In other words, if at some point in running the algorithm, there are B bins created, bin G_i, $1 \leq i \leq B$, is considered to be the best bin for multicast request (s_j, S_j, Δ_j) if $c(T_j^i) \leq c(T_j^k)$, for all $k = 1, \ldots, B$. This is not necessarily the suboptimal minimum cost tree, MCT_j, found on the original graph G, since it is possible that none of the existing bins have this tree available. If there is no feasible tree available in any of the B bins, a new bin is created.

The benefit of such a 'best fit' approach is that it attempts to minimize the cost of the established multicast trees which is the second objective we consider for the MC_RWA problem. Of course, we could route each multicast request (s_j, S_j, Δ_j) strictly on its suboptimal minimum cost tree, MCT_j, but this would in most cases lead to using a larger number of layers, which in turn means using a larger number of wavelengths.

4..3. *FFD_MC_RWA*

The First Fit Decreasing Multicast Routing and Wavelength Assignment algorithm sorts the multicast requests in nonincreasing order of their corresponding number of destination nodes, i.e. $|S_j|$. Requests with an equal number of destination nodes are placed in random order. The rest of the algorithm runs as FF_MC_RWA. Sorting the requests in this order may establish multicast trees using less wavelengths. The reasoning behind this is that routing requests with a large number of destination nodes is in most cases more demanding than routing multicast requests with fewer destination nodes. Therefore, if we route the requests which are more demanding first, i.e. when there are more edges available on low indexed layers of G, routing on these layers will most likely be successful. We then may be able to fill up the remaining space on these already used layers with less demanding requests and thus eliminate the need for creating higher indexed layers. This may lead to a routing and wavelength assignment using less wavelengths.

4..4. *BFD_MC_RWA*

The Best Fit Decreasing Multicast Routing and Wavelength Assignment algorithm sorts the multicast requests in nonincreasing order of their corresponding number of destination nodes, i.e $|S_j|$, and then runs as BF_MC_RWA.

4..5. *FFTD_MC_RWA*

The First Fit Tree Decreasing Multicast Routing and Wavelength Assignment algorithm sorts the multicast requests in nonincreasing order of the cost of the suboptimal multicast trees in G, MCT_j, found for each request using the GRASP-CST algorithm from [17]. The algorithm then proceeds as FF_MC_RWA. This method of sorting requests is more complex than that in FFD_MC_RWA but seems a better indicator of multicast request size and thus may help obtain better solutions for some instances.

4..6. *BFTD_MC_RWA*

The Best Fit Tree Decreasing Multicast Routing and Wavelength Assignment algorithm sorts the multicast requests in nonincreasing order of the cost of the suboptimal multicast trees in G, MCT_j, and then runs as BF_MC_RWA.

5. Lower bounds

To assess the quality of the solutions obtained by the proposed algorithms, we suggest lower bounds for the number of wavelengths used and the average cost of the established light-trees. A lower bound on the number of wavelengths needed to establish a given set τ of multicast requests in network $G = (V, E)$ is

$$LB_W = \max_{i \in V} \lceil \frac{\Delta_l(i)}{\Delta_p(i)} \rceil. \tag{1}$$

This is similar to the lower bound on the number of wavelengths for the routing and wavelength assignment problem for unicast demands used in [3]. $\Delta_l(i)$ represents the logical degree of node i, while $\Delta_p(i)$ represents the node's physical degree. The logical degree of a node is the number of multicast requests for which the node is the source or destination node. Recall that the established multicast trees are bidirectional so trees which terminate and originate from the same node cannot be assigned the same wavelength if they traverse the same edge adjacent to the node. This is due to the *wavelength clash constraint.* Since node i has $\Delta_p(i)$ adjacent physical links and is the source or destination node for $\Delta_l(i)$ multicast trees, at least one physical link will have $\lceil \frac{\Delta_l(i)}{\Delta_p(i)} \rceil$ multicast trees routed over it. Since trees routed on the same physical links cannot be assigned the same wavelength, at least $\lceil \frac{\Delta_l(i)}{\Delta_p(i)} \rceil$ wavelengths are needed to route the corresponding multicast requests. The highest such ratio among all the nodes in the network is a lower bound on the number of wavelengths needed to solve the MC_RWA problem.

A lower bound on the average cost of the established multicast trees can be found in the following manner. Since finding the minimum cost multicast tree is itself NP-hard, we need to find a lower bound for the minimum cost multicast tree for each request. A simple lower bound for a multicast request with one source node and $|S_i|$ destination nodes is the sum of the $|S_i|$ cheapest edges in G. It follows that a lower bound on the average cost of the multicast trees corresponding to requests in $\tau = \{(s_1, S_1, \Delta_1), \ldots, (s_n, S_n, \Delta_n)\}$, is the average of the lower bounds corresponding to each of the n requests. We refer to this lower bound as LB_C. If we sort edges (i, j) in $|E|$ in increasing order of their costs, $c(i, j)$, and rename them as $\{e_1, \ldots, e_{|E|}\}$, the bound is as follows.

$$LB_C = \frac{\sum_{i=1}^{n} (\sum_{j=1}^{|S_i|} c(e_j))}{n}. \tag{2}$$

6. Numerical Results

The FF_MC_RWA, BF_MC_RWA, FFD_MC_RWA, BFD_MC_RWA, FFTD_MC_RWA, and BFTD_MC_RWA algorithms were implemented in C++ and run on a PC powered by a P4 2.8GHz processor. We generated a series of random 50-node networks using a method similar to that used in [26] and [3]. Namely, the probability of there being a link between two nodes was set to 0.06, 0.08, 0.10 and 0.12. Thus, we obtained test networks with average degrees (5 networks per average degree) of approximately 3, 4, 5, and 6, respectively. Next, we generated random sets of multicast requests, consisting of 50, 100, 150, 200 and 250 requests, for each test network. Each request was generated by selecting a random source node and a random number (ranging from 1 to 49) of destination nodes . This way, unicast and broadcast traffic was also included since they are special cases

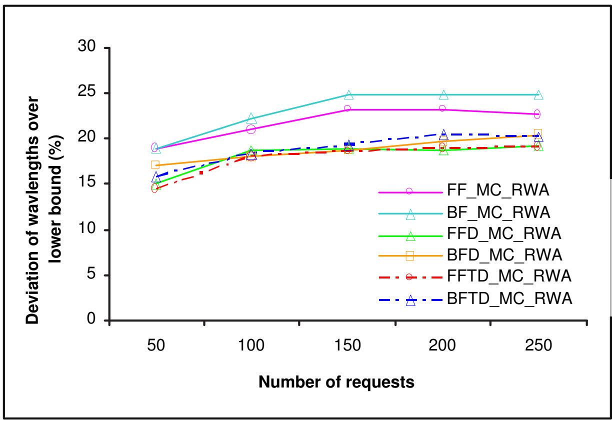
Table 1. The average number of wavelengths required by the FF_MC_RWA, BF_MC_RWA, FFD_MC_RWA, BFD_MC_RWA, FFTD_MC_RWA, and BFTD_MC_RWA algorithms and the lower bound, LB_W, for random networks with 50 nodes.

Avg. Degree	*No. Of Requests*	LB_W	*FF_MC_RWA*	*BF_MC_RWA*	*FFD_MC_RWA*	*BFD_MC_RWA*	*FFTD_MC_RWA*	*BFTD_MC_RWA*
	50	30.6	36.4	36.4	35.2	35.8	**35.0**	35.4
	100	55.6	67.2	68.0	66.0	**65.6**	**65.6**	65.8
3	150	82.4	101.4	102.8	98.0	97.8	**97.6**	98.2
	200	109.6	135.0	136.8	**130.0**	131.2	130.4	132.0
	250	135.8	166.6	169.6	162	163.4	**161.8**	163.2
	50	24.2	28.4	28.7	27.4	27.4	**27.2**	27.4
	100	46.0	51.8	52.0	**50.8**	**50.8**	**50.8**	**50.8**
4	150	70.6	79.6	80.6	78.4	78.8	**78.2**	78.6
	200	92.6	105.4	106.0	**103.6**	104.4	103.8	104.2
	250	115.8	131.4	132.4	**130.0**	130.6	130.2	130.4
	50	16.6	19.2	19.4	**18.8**	19.2	**18.8**	19.2
	100	33.2	37.8	39.0	36.6	36.4	**36.2**	36.8
5	150	49.8	57.8	59.4	**55.4**	55.6	55.6	**55.4**
	200	67.8	76.6	79.2	74.0	75.0	**73.4**	74.2
	250	84.4	95.6	98	93.2	93.6	**92.0**	93.4
	50	17	18.4	18.6	18.4	18.2	18.4	**18.0**
	100	33.4	36.0	37.0	35.6	35.6	35.8	**35.4**
6	150	49.8	54.0	55.2	53.6	53.6	**53.2**	**53.2**
	200	66.8	71.6	72.8	**70.4**	70.6	**70.4**	70.8
	250	83.4	88.4	89.8	88.4	88.0	88.2	**87.6**

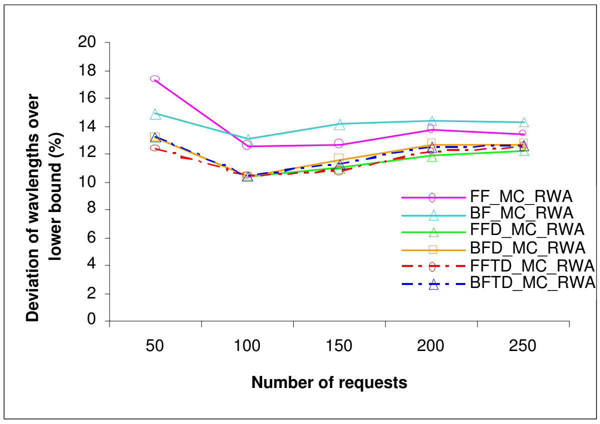
of multicast traffic. Functions $c(i,j)$ and $d(i,j)$ were both set to 1 if there was an edge between nodes i and j, and 0 otherwise. In other words, instead of the actual cost, the algorithms try to minimize the number of hops in a multicast tree. The upper bound on the end-to-end delay from the source node to any destination in a multicast session was set to $\max(diam(G), \sqrt{|E|})$ as used for unicast RWA algorithms in [26] and [3]. The input parameters chosen for the delay constrained multicast routing algorithm GRASP-CST are those used in [17].

The average number of wavelengths needed to successfully perform Multicast Routing and Wavelength Assignment by each of the algorithms for the 50-node test networks are shown in Table 1. The lower bound, LB_W, is also shown. The best obtained solution for each test case is marked in bold. The FFD_MC_RWA algorithm performed best in 7 cases, the BFD_MC_RWA algorithm in 2 cases, the FFTD_MC_RWA algorithm in 13 cases and the BFTD_MC_RWA algorithm in 6 cases. The FF_MC_RWA and BF_MC_RWA algorithms did not obtain the best solution in any of the cases. For easier visualization of the obtained results, the deviation of the number of wavelengths required by the solutions obtained by each of the algorithms over the lower bound are shown in Fig. 2 for networks with an average degree of (a) 3, (b) 4, (c) 5, and (d) 6.

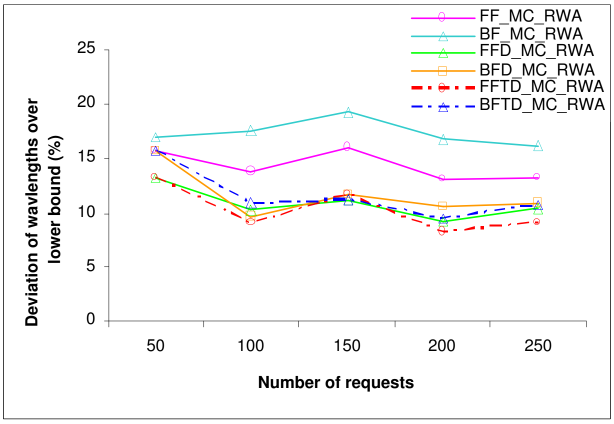
We can see from the results that the gap between the obtained solutions and the lower bound decreases as the density of the network increases. This may be due to the fact that RWA can be solved using less wavelengths in denser networks since more links are available (i.e. the wavelength clash and continuity constraints are



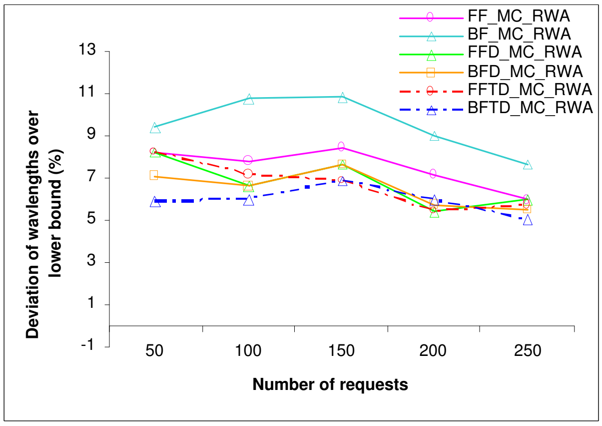
(a)



(b)



(c)



(d)

Fig. 2. The deviation of the number of wavelengths required by the FF_MC_RWA, BF_MC_RWA, FFD_MC_RWA, BFD_MC_RWA, FFTD_MC_RWA, and BFTD_MC_RWA algorithms over the lower bound, LB_W, for random networks with 50 nodes with average degrees (a) 3, (b) 4, (c) 5, and (d) 6.

easier to meet). As a result, the optimal solution is closer to the ratio of the logical to physical degree in the network and, thus, the lower bound as it is defined in this paper may be closer to the optimal solution. Furthermore, we can see that sorting multicast requests in decreasing order of either the number of destination nodes or the suboptimal multicast trees leads to better solutions, particularly in dense networks. Since more resources are available in denser networks, more requests can be packed into a single 'bin' (i.e. copy of graph G) and thus the advantage of sorting the requests becomes more evident.

Routing demands according to the 'best fit' strategy leads to solutions inferior to those obtained using the 'first fit' strategy with respect to the number of wavelengths for the cases tested. However, these algorithms obtain solutions which consistently establish lower cost multicast trees. The average cost of the multicast trees established by the FF_MC_RWA, BF_MC_RWA, FFD_MC_RWA, BFD_MC_RWA, FFTD_MC_RWA, and BFTD_MC_RWA algorithms and the lower bound, LB_C, are shown in Fig. 3 for the 50-node test networks with an average degree of (a) 3, (b)

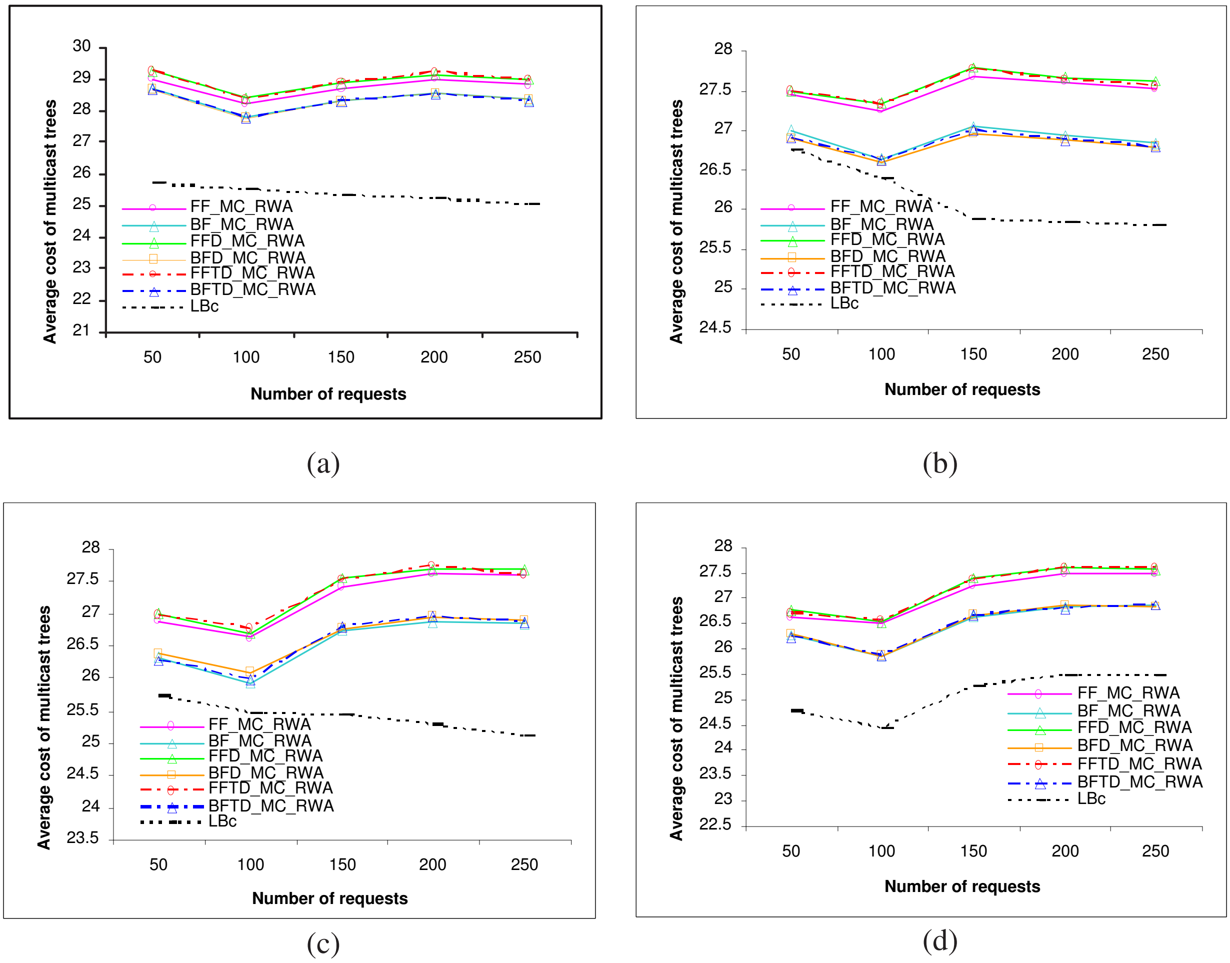


Fig. 3. The average cost of the multicast trees established by the FF_MC_RWA, BF_MC_RWA, FFD_MC_RWA, BFD_MC_RWA, FFTD_MC_RWA, and BFTD_MC_RWA algorithms and the lower bound, LB_C, for random networks with 50 nodes with average degrees (a) 3, (b) 4, (c) 5, and (d) 6.

4, (c) 5, and (d) 6. Here we can see the gain of using the 'best fit' strategy.

Furthermore, we tested the algorithms on a set of 18 benchmark network topologies from problem set B from SteinLib [18]. Steinlib is a publicly available library of test data for Steiner tree problems. The characteristics of the networks are shown in Table 3. The costs, $c(i,j)$, of the edges in each network topology are those given in [18]. The delay of an edge, $d(i,j)$, was set to the same value as the cost. To limit the delay from the source to each destination node we set the delay bound to a value proportional to the maximum delay of the shortest delay path in G between the source and any destination node included in the multicast request. In other words, for multicast request (s_i, S_i, Δ_i), $\Delta_i \equiv \beta \cdot max\{SD(s_i,v)|v \in S_i\}$ where $SD(s_i,v) = \sum_{(j,k)} d(j,k)$ for all edges (j,k) on the shortest delay path between nodes s_i and v in G. Such a delay bound was suggested in [15]. β was set here to 2. For each network, we generated 5 random sets of 30 multicast requests with the number of destination nodes ranging from 1 to 29.

Table 2. The average number of wavelengths and cost of the multicast trees established by the proposed algorithms and the lower bounds for the B network data set from [18] for cases with 30 multicast requests and $\beta = 2$.

Networks	*Lower bounds*	*FF_ MC_ RWA*	*BF_ MC_ RWA*	*FFD_ MC_ RWA*	*BFD_ MC_ RWA*	*FFTD_ MC_ RWA*	*BFTD_ MC_ RWA*
			Wavelengths Used				
B1,B2,B3	18.93	27.13	27.13	**27.07**	27.20	27.20	27.13
B4,B5,B6	17.6	21.47	21.40	**20.93**	21.00	21.00	**20.93**
B7,B8,B9	19.6	29.93	**28.00**	**28.00**	28.33	28.33	28.47
B10,B11,B12	17.27	21.3	21.73	20.87	**20.73**	21.00	21.00
B13,B14,B15	18.87	27.47	27.53	**27.27**	27.87	27.33	27.80
B16,B17,B18	18.47	23.40	23.47	23.47	**23.33**	23.67	**23.33**
			Average Cost of Established Light-trees				
B1,B2,B3	84.49	145.43	145.28	145.39	**145.05**	145.32	145.06
B4,B5,B6	52.47	115.74	114.81	117.52	113.21	117.48	**112.82**
B7,B8,B9	111.07	212.57	212.40	212.50	211.84	212.17	**211.65**
B10,B11,B12	101.12	169.20	166.50	172.10	**165.30**	171.57	165.48
B13,B14,B15	157.24	285.46	285.28	286.08	**284.66**	286.09	284.76
B16,B17,B18	93.23	204.43	203.08	206.08	**199.65**	206.11	200.57

Table 3. B network data set from [18]

Networks	*Nodes*	*Edges*	*Avg. Degree*
B1, B2, B3	50	63	1.26
B4, B5, B6	50	100	2
B7, B8, B9	75	94	1.2533
B10, B11, B12	75	150	2
B13, B14, B15	100	125	1.25
B16, B17, B18	100	200	2

The average number of wavelengths and the average cost of the multicast trees obtained by each of the algorithms and the lower bounds are shown in Table 2. Here, FFD_MC_RWA seemed to perform best. The gain of sorting multicast requests is not as prominent since these networks are fairly sparse. Still we can see that at least one of the 'decreasing' algorithms obtained the best solution in all of the cases tested. The 'best fit' strategy here again consistently obtained lower cost multicast trees.

We can see from the obtained results that sorting multicast requests in nonincreasing order, with respect to either of the evaluation functions presented in this paper, often helps to obtain solutions using fewer wavelengths. Sorting with respect to the number of destination nodes is simpler and yet seems a good measure of size for the cases tested. This seems logical since the number of nodes in the multicast sessions varied significantly. If multicast groups are primarily composed of a similar number of destination nodes, and more so if they are spread out across the network, sorting according to the cost of their corresponding suboptimal trees may perform better. With respect to the method of routing the requests, the algorithms that route light-trees using the 'best fit' strategy, as we define it in this paper, help to consistently reduce the cost of the multicast trees. The 'first fit' strategy, however, in more cases obtains solutions using fewer wavelengths. As a result, if wavelengths are very scarce, it is probably better to use FFD_MC_RWA or FFTD_MC_RWA. If the cost metric is critical, BFD_MC_RWA or BFTD_MC_RWA should be used. Since all these algorithms are one-pass greedy algorithms, running both methods of sorting and choosing the better solution seems reasonable.

Another point which should be mentioned is that in addition to efficiently solving the *static* MC_RWA problem, the FF_MC_RWA and BF_MC_RWA algorithms can be used for *dynamic* MC_RWA. Namely, for the *dynamic* MC_RWA problem, multicast requests arrive dynamically and must therefore be established in a specific order. To solve the dynamic MC_RWA problem using the FF_MC_RWA and BF_MC_RWA algorithms, multicast requests in τ are simply established in the specific order in which they arrive according to the corresponding 'first fit' or 'best fit' strategies.

7. Conclusion

In this paper, heuristic algorithms are proposed for the Multicast Routing and Wavelength Assignment problem in wavelength-routed optical networks. These algorithms are extended to solve delay-constrained multicasting as well. All the suggested heuristics are greedy algorithms based on classical bin packing algorithms. Proposed are methods for sorting multicast requests according to two different evaluation functions in order to minimize the number of wavelengths used. A method of routing multicast trees on specific wavelengths, referred to as the 'best fit' strategy, is suggested to minimize the cost of the established trees. The algorithms were tested on random networks and a set of test networks from [18] and the results were compared with analytical lower bounds. Both methods of sorting multicast requests proved efficient with respect to the number of wavelengths used, while using the 'best fit' strategy consistently lowered the cost of the multicast trees. The encouraging results indicate that further research in this field is worthwhile. Further work will include developing heuristics for Multicast Routing and Wavelength Assignment with multiple QoS demands. Networks with limited splitting capabilities will also be studied.

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