Multicasting for All-Optical Multifiber Networks

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All-optical wavelength-routed WDM WANs can support the high bandwidth and the long session duration requirement of the application scenarios like interactive distance learning or online diagnosis of patients simultaneously in different hospitals. However, multifiber and limited sparse light splitting and wavelength conversion capabilities of switches result in a difficult optimization problem. We attack this problem using a layered graph model. The problem is defined as k edge-disjoint degree-constrained Steiner Tree problem for routing and fiber and wavelength assignment of k multicasts. A mixed integer linear programming formulation for the problem is given and a solution using CPLEX is provided. However, the complexity of the problem grows quickly with respect to the number of edges in the layered graph, which depends on the number of nodes, fibers, wavelengths, and multicast sessions. Hence, we propose two heuristics (LAMA and C-FWA) to compare with CPLEX, existing work and unicasting. Extensive computational experiments show that LAMA's performance is very close to CPLEX and it is significantly better than existing work and C-FWA for nearly all metrics. Although, C-FWA is inferior to LAMA it is also using fiber and wavelength conversion resources more efficiently than its other alternatives.

1. Introduction

In all-optical networks, the network nodes or elements are connected with optical/photonic switches, and data stays on the optical domain using wavelength division multiplexing (WDM). An all-optical channel (lightpath) is created between the source and the destination for unicast communication. A point-to-multipoint extension of the lightpath concept (light-tree) is proposed to better support the multicast and the broadcast traffic [1]. Alternative forms of WDM networks range from small local area networks (LAN), in which single-hop strategy is employed, to wide area networks (WAN) where the fibers may span the whole country like in the NSFNet backbone or even the whole world. There are two current strategies in WDM WAN networks: Wavelength-routed ones like in [1], [2], and [3] and optical burst switching (OBS) based networks like in [4], [5]. In the former case, the multicast data will be carried over a logical(or virtual) topology that we built by using lightpaths or light-trees [1] and in the latter case the data is carried via OBS in a more bursty fashion that is suitable for relatively short duration of dense transportation.

The main issues related with the characteristic of the multicasting are the size of the network, the duration of the session and the amount of information exchanged.

In our application scenarios, the connection should supply large bandwidth to accommodate the multicasting of sessions. Moreover, it may be done in a very broad region and its duration is expected to last many minutes or hours, not seconds. Remote diagnosis and operations in hospitals would be an appropriate example. Thus, our scenario includes relatively long duration of multicast transportation that requires large bandwidth and wavelength-routed WDM WAN is the appropriate environment.

We solve the multicasting problem on the logical topology which is determined by lightpaths and light trees in wide area networks (WAN) [6]. An important parameter is related with the constraints about the capabilities of switching elements. A switch may have no, limited or full wavelength conversion and light splitting capabilities. In limited wavelength conversion, all nodes can convert an incoming wavelength to a subset of available output wavelengths. Similarly, a node with limited light splitting capability can copy incoming data to a subset of output links, if the number of output links is less than the limited splitting capability of that node. Sparse light splitting and wavelength conversion means that not all but some nodes in the network have full wavelength conversion and light splitting capabilities.

In this paper, we propose to use a layered graph approach to have a more general, realistic and flexible model of an all-optical multifiber network for multicasting. This new presentation enables us to state the problem of static multicasting for all-optical multifiber networks with sparse light splitting and wavelength conversion restrictions so that it is formulated as a Mixed Integer Linear Programming (MILP) as described in Subsection 4.A. The MILP formulation is solved using CPLEX which is a state of the art optimization tool [7]. CPLEX finds the optimal solution within a given precision and it also gives a lower bound by relaxing the integrality constraints. We also propose two efficient heuristics (LAMA and C-FWA) and extensive computational experiments demonstrate their performance against CPLEX, unicasting and existing work (M-ONLY) [8].

The rest of the paper is organized as follows: Section 2 covers the related work in the literature. Section 3 describes the problem definiton, mathematical formulation and the underlying assumptions. Section 4 is devoted to solution techniques and computational experiments are given in Section 5. Finally, Section 6 summarizes the conclusions and has a discussion about future works.

2. Multicasting for All-optical Networks

A comprehensive survey on optical multicasting over wavelength-routed WDM networks is given in [9]. Therefore, we only summarize works which are close to our formulation in the literature. Benefits of all-optical multicasting are studied in a simulation environment by Malli et al. and it is concluded that with a reasonably large multicasting group size, multicasting can reduce the bandwidth consumed [3]. However, this work does not consider multifiber, or nodes that have the sparse wavelength conversion and/or sparse splitting capabilities but are distributed nonuniformly.

The static Virtual Topology Design (VTD) problem is examined in terms of multicasting in [10], [11], and [12]. However, wavelength conversion issues are not examined in [12]. Power loss in WDM networks is an important issue and, [13] and [14] examine multicasting from this perspective. Another static VTD formulation is given in [1], but the authors did not consider the sparse splitting cases. If we assume full light splitting, the problem just reduces to finding Minimum Steiner Trees (MST) in a layered graph described in Section 3. Moreover, the objective function is different in [1]. In [15], wavelength assignment of one tree problem is shown to be solvable by a polynomial algorithm. Similarly, the special case of a general multicasting that includes only one source in the formulation with static traffic is given in [16]. Their scenario is very similar to ours in terms of setting, but they have only one source that is the video server store and all the other nodes are group of users. Multicast Routing under Delay Constraint Problem (MRDCP) is defined as Minimal Steiner Tree Problem with different light splitting and delay constraints in [17] for one multicast session. In [18], the problem of minimizing the number of wavelengths is considered for one multicast session and for multi-hop WDM optical networks. Another approach is given in [19] for efficient use of wavelengths by adding wavelength conversion constraints. Yang and Liao formulated their problem as a static VTD [6]. They allow multi-hop traversing, i.e., electro-optical conversion which is not allowed in our formulation, since our network is all-optical. In [20], authors evaluate the tradeoff between capacity and wavelength continuity by developing analytical models and conclude that even a small amount of wavelength conversion capability helps shifting the advantage to the light-tree approach. In [21], the problem of wavelength assignment is studied in order to maximize the network capacity for one multicast in the case of no wavelength conversion. Full wavelength conversion is assumed without mentioning sparse splitting in [22], but delay constraints are also added and a distributed algorithm is proposed for the solution. Similar assumptions are also considered in [23] with many fibers and a distributed reinforcement algorithm is proposed.

In [24], the sparse splitting case is examined only for one fiber and one multicast (tree) session by minimizing the number of wavelengths used. The closest work to our formulation in the literature proposes four different heuristics [8] and we choose to implement M-ONLY heuristic to compare CPLEX, LAMA and C-FWA. Moreover, all nodes have some limited splitting capability without wavelength conversion in [25]. The problem is formulated to optimize mostly QoS based metrics like maximizing the number of destinations and/or minimizing the wavelength cost, since wavelength conversion and light splitting resources are very scarce in this setting.

3. The Problem Definition for All-optical Multicasting

Important issues for the formulation of the problem are how to handle multifiber installations among nodes, representation of different wavelengths in a fiber and how to represent nodes with sparse wavelength conversion capability. We propose to use the layered graph for modeling the WDM network as described in [26] [27] [28] for all-optical multicasting. A layered graph example is given in Figure 1 for a simple WDM network having three nodes, four bidirectional fiber links, two wavelengths on each link, and two heterogeneous fiber layers. WDM network is replicated as different layers corresponding to different fibers and wavelengths. However, the structure of each layer of fibers may be different, because connections among nodes may contain different number of fibers. For example, we have two bidirectional fibers between nodes 1 and 3, but there is only one bidirectional fiber between nodes 1 and 2, and nodes 2 and 3 in Figure 1(a).

The nodes that represent the nodes of the original graph are called main nodes in the layered graph and all others are called sub-nodes. If we use a link from a source main node to any one of the corresponding sub-nodes for the routing of a multicasting request, then a transmitter is used to create a tree originating from the source node. Similarly, the usage of a link from a destination sub-node to the corresponding main node indicates that this destination is reached in the multicasting tree. Therefore, main nodes are used to represent the root and leaves of the multicasting tree, and corresponding sub-nodes are for interior nodes. Thus, sub-nodes are connected to represent the usage of wavelength channels and movements between fibers and wavelengths. Switching and wavelength conversion capabilities of the main node determine these connections. For example, Node 1 and 2 have only switching capability but Node 3 has both switching and wavelength conversion capabilities in Figure 1. Therefore, the sub-nodes of main Node 3 in the same fiber layer are connected to each other to allow conversion among different wavelengths. However, this is not valid for main nodes 1 and 2, since they can only do switching between fibers.

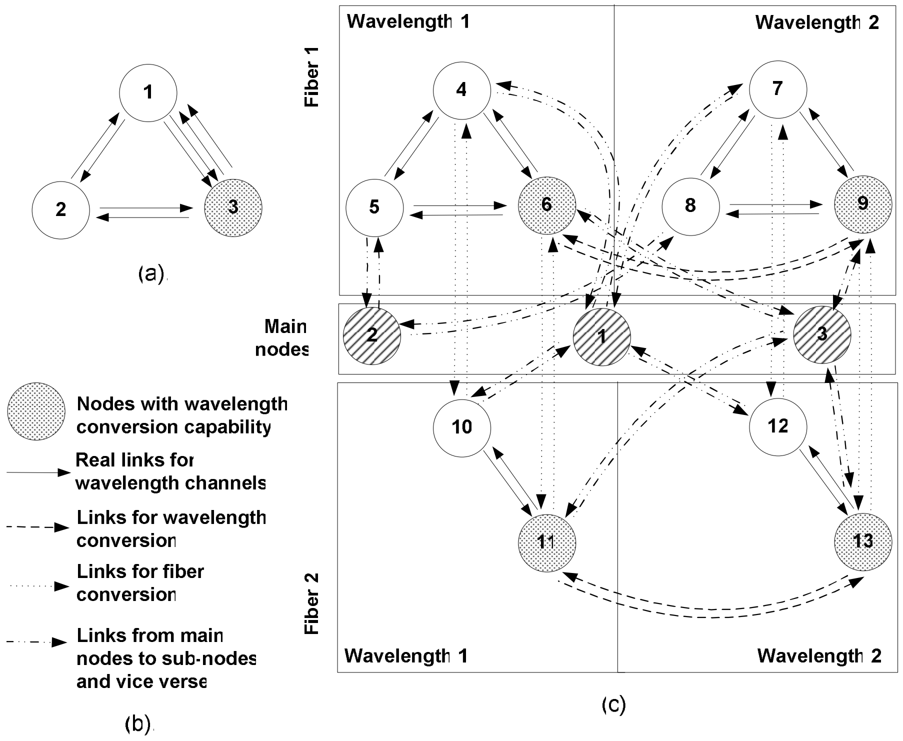

Fig. 1. (a) A simple WDM network having three nodes, four bidirectional fiber links, two wavelengths on each link, and two heterogeneous fiber layers. (b) Notation. (c) Layered graph model of (a).

After establishing the layered graph of a network topology, finding a multicasting tree in the original network turns out to be finding a Minimum Steiner Tree (MST) in the layered graph. Even though we do not consider highly increasing complexity of the problem with respect to the number of fibers or the number of wavelengths, there is another complication, that is, the representation of sparse splitting capability of nodes. In this case, we consider a version of Steiner Tree Problem by adding degree constraints to the formulation. Finally, each tree should be edge-disjoint in the layered graph, since each wavelength in a fiber can only be used by one multicasting session. Thus, our problem can be called k-edge-disjoint (non-overlapping) degree-constrained Steiner Problem in graphs for routing and wavelength assignment of k multicasts in WDM networks.

The Steiner Tree Problem, its variants and heuristic based approaches are mostly examined in the literature and, [29] and [30] summarizes the results. Moreover, it is even possible to solve very big Steiner Tree Problems to optimality [31]. However, the problem is NP-hard [32] and its generalized version that includes additional degree constraints in our case will be even harder to solve.

3.A. Assumptions

- A wavelength on a given fiber between two nodes carries only the data of one multicast session, since the route for one multicast constitute a tree and (it is a tree in the layered graph, but it may be multiple trees generated from the same source in the original graph) and aggregation of more than one multicast session on one wavelength is not allowed, because multi-hopping is not allowed in light trees, that is, all transportation occurs in the optical domain without optic to electronic domain conversion.

- The capacity of one wavelength channel is enough to carry one multicast session. This is a realistic assumption, since one wavelength channel offers very large bandwidth with current technologies. Moreover, we can divide a multicast stream to more than one tree, if the required bandwidth is greater than the capacity of one wavelength channel. Therefore, capacities of the fibers and the required bandwidth for each multicast are not input parameters for the formulation, and each session occupies one wavelength channel.

3.B. Notation used in the formulation

$G(V, E)$: The graph G representing the WDM network with vertex set V and the edge set E. It contains N nodes and L bidirectional links

F : Number of fibers

W : Number of wavelengths

S_S : The set of nodes which have sparse splitting property

S_C : The set of nodes which have sparse conversion property

N_{ls} : The number of nodes which have full light splitting property

N_{wc} : The number of nodes which have full wavelength conversion property

The parameters of the network is used to construct the layered graph and the cost between two nodes is c_{ij} in the layered graph. We minimize the objective of the sum of all c_{ij}'s for the routing and wavelength assignment of k multicast sessions (Equation 1 in Section 3.C). These c_{ij} are either given and dictated by the problem, or adjusted to favor different metrics which we demonstrate in Section 5.B for the blocking probability. Thus, this flexible cost assignment enables us a general framework in which different objectives can be simultaneously achieved or balanced.

A demonstrative example is given in Figure 2 for the routing and wavelength assignment of the multicast session $\{2\} \rightarrow \{1, 3\}$ to clarify what sort of costs are involved. The cost of the link $2 \rightarrow 5$ represents using a transmitter on Node 2. The link $5 \rightarrow 6$ denotes the cost of using the first wavelength channel on Fiber 1 between Nodes 2 and 3. Similarly, the link $13 \rightarrow 12$ is for the cost of using the second wavelength channel on Fiber 2 between Nodes 3 and 1. The link $6 \rightarrow 11$ denotes the fiber conversion cost and the link $11 \rightarrow 13$ denotes the wavelength conversion cost on Node 3. The links $13 \rightarrow 3$ and $12 \rightarrow 1$ are used to ensure that all destinations are reached and they do not add to the objective function.

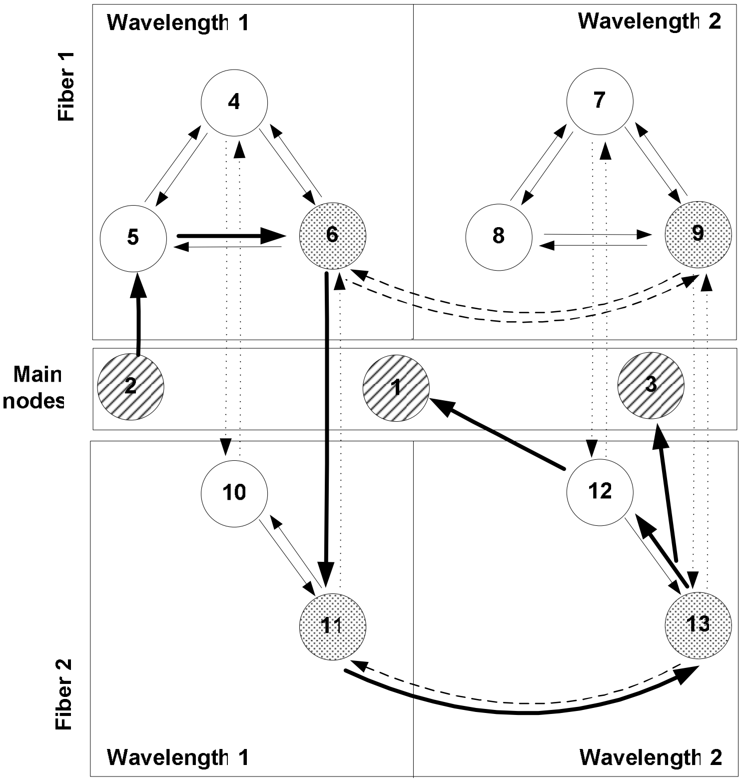

Fig. 2. The routing and wavelength assignment of a multicast session $\{2\} \rightarrow \{1,3\}$ which is shown with bold arrows for the network which is given in Figure 1.

We can adjust c_{ij}'s to be able to reflect the underlying relative cost of these operations so that all four different types of costs can be minimized simultaneously. For example, if the wavelength conversion or the fiber conversion is not costly for us in our routers then we can make the corresponding costs zero. Similarly, we can discourage the creation of more than one tree from the source by setting the cost of using a transmitter to a high value, if we also want to minimize the number of transmitters that are used for multicasting.

We use the following variables for static traffic generation:

S : Number of sessions

R_{mn} : Fraction of multicast nodes

M : Set of multicast session sets, $M = \{M_k | k = 1, 2, \ldots, S\}$

u_k : The first node (source) in the k^{th} multicast set M_k

n : Number of nodes in a multicast group determined by R_{mn}

$M_k^{'}$: K^{th} multicast set excluding the source, $M_k^{'} = M_k - \{u_k\}$

We also have two decision variables:

f_{kl}^{ij} : The flow of multicast k to be sent to node l over the link (i,j), $f_{kl}^{ij} \in \Re^{+} \bigcup \{0\}$

x^k_{ij} : The binary decision variable that determine whether link (i, j) is used by multicast k, $x^k_{ij} \in \{0, 1\}$

3.C. Problem Formulation

The k-edge-disjoint (non-overlapping) degree-constrained Steiner Problem (kEDSP) can be formulated as follows:

Minimize the total cost of served sessions

$$TotalCost : z = \min \sum_{k} \sum_{(i,j)\in E''} c_{ij} * x^k_{ij} \tag{1}$$

where $E^{'}$ contains all types of links (fiber conversion, wavelength conversion, links for wavelength channels, and links for using a transmitter on the source node) and $E^{''}$ contains all types of links except the ones with zero costs:

- The cost for the links from destination sub-nodes to the main nodes are excluded from the objective function. For example, such links 13 → 3 and 12 → 1 in Figure 2 are used to ensure that all destinations are reached. A subtle point should not be missed that if we would assign a cost for this sort of links, then the links that are already included as a cost could be used for the routing of other multicasting sessions to minimize the objective function, since a path from a source to a destination can be completed in any layer (any fiber and any wavelength). Another multicasting session with Node 3 as a destination would have a tendency to use Node 13 to reach the destination Node 3 instead of using nodes 6, 9 and 11 in Figure 2, since this cost is already included by the multicast session which is routed previously.

- The cost for the links from the source sub-nodes to the main nodes and from the main destination nodes to the sub-nodes are also excluded, since they are irrelevant and normally not used for the routing and wavelength assignment of multicast sessions.

$$x^k_{ij} \geq f^{ij}_{kl}, \forall (i,j) \in E^{'}, \forall k, \forall l \in M^{'}_{k} \tag{2}$$

$$\sum_{(j,i)\in E'} f^{ji}_{kl} - \sum_{(i,j)\in E'} f^{ij}_{kl} = \begin{cases} 1 & \forall l \in M^{'}_{k}, \forall k, \text{ and } i = l \\ 0 & \forall l \in M^{'}_{k}, \forall k, \text{ and } i \neq l \end{cases} \tag{3}$$

The multicast data in trees should be non-bifurcated, that is, multicast data in a session cannot be split into two streams in any node of an all-optical network. Constraints 2 and 3 ensure that the solution is in the form of a set of trees.

$$\sum_{k} x^k_{ij} \leq 1, \forall (i,j) \in E^{'''}, \tag{4}$$

where $E^{'''}$ contains only the wavelength channel links among the same layer, and it excludes the links from main nodes to sub-nodes and vice versa, and fiber and wavelength conversion links, since these links can be used more than once. Consequently, this wavelength continuity constraint 4 makes sure that a link representing a wavelength and a fiber can be used once and all degree-constrained trees should be edge disjoint.

$$\sum_{j\in V'',(i,j)\in E'} -x_{ij}^k + \sum_{i\in V'',(j,i)\in E'} x_{ji}^k \geq 0, \quad (5)$$
$$\forall i \in S_S \cap V'', \forall k, i \text{ is not a source for multicast } k,$$

where $V^{'}$ contains all the nodes (it includes the main and the sub-nodes) in the layered graph and $V^{''}$ contains only the sub-nodes.

The degree constraint 5 (in/out degree) forces routes (or specifically trees) to accommodate the sparse splitting restrictions. It should be noted that if a sparse splitting node is a source node then it should not have this restriction, since a source sub-node represents the main source node and it can send as many packets as it wishes, since it is not copying packets, instead it is creating these packets without copying. Moreover, one subtle distinction should not be missed that a main source node should use the link that is coming from the main source node to a sub-node to create a new tree from the same source, instead of using the fiber or wavelength conversion links among the source sub-nodes. Thus, Restriction 6 is added to the formulation:

$$x_{ij}^k \quad = \quad 0, \text{if } i \text{ and } j \text{ represents the same main source node for multicast } k \quad (6)$$

The decision variables x_{ij}^k determines routing and wavelength assignment of the network, that is, a degree constrained Steiner Tree for each multicast session and wavelength assignment in each of these trees. Moreover, the number of decision variables also determines the complexity of the problem. The number of edges in the layered graph is $(2{*}W{*}F{*}L)+(F{*}(F-1){*}N)+(W{*}(W-1){*}N_{wc})+(2{*}W{*}F{*}N)$. Thus, we multiply that number by S to find the number of binary decision variables. If we take F=1, W=1, and S=1, and remove degree constraints due to sparse splitting nodes, the special case (Steiner Tree Problem) would still be NP-hard [32]. Therefore, the problem is solved using CPLEX [7] for smaller networks, and we propose a heuristic algorithm, Layered All-optical Multicast Algorithm (LAMA), for larger problems.

4. Proposed Solutions: LAMA and C-FWA

4.A. Mixed Integer Linear Programming (MILP) Solution: CPLEX

We solve the MILP formulation which is given in Section 3.C with CPLEX [7] and use both the solution of CPLEX and the lower bound which is produced by relaxing the integrality constraints. However, it takes very long time for CPLEX to find the optimal results within a given precision for problems which contain many binary integer variables. Therefore, we propose the LAMA for larger problems.

4.B. Layered All-optical Multicasting Algorithm (LAMA)

A layered graph is created from the graph representing WDM network as explained in Section 3 and LAMA works on this graph. LAMA is a directed degree-constrained Minimum Spanning Tree (MST) heuristic which is based on finding shortest paths from the current spanning tree to the remaining nodes in the multicast session and it uses this method for all multicast sessions consecutively. Bellman-Ford all-pairs shortest path algorithm is run for each multicast destinations in each session [33]. Thus, the complexity of the algorithm is $O(S * n * ((F * W + 1) * N)^3)$, since there are $(F * W + 1) * N$ nodes in the layered graph. Pseudo code for LAMA is given in Algorithm 1.

Algorithm 1 LAMA Algorithm

```
$Z$ = the set of nodes in a multicast session;
$RemainingConnectionNumber$ for degree constrained nodes;
$MulticastTree$ = the links and nodes in a multicast session (a tree);
$AllMulticastTree$ = set of $MulticastTree$;
for each multicast session do
    set the cost of links from source main node to its sub-nodes with $TransmitterUsageCost$;
    initialize $RemainingConnectionNumber$ with degree constraints;
    initialize $MulticastTree$ as empty and add the source node;
    initialize the multicast set $Z$ with multicast nodes except the source;
    current path finding is successful;
    while ($Z$ is not empty) and (current path finding is successful) do
        for all pairs of nodes from the nodes in $MulticastTree$ to the nodes in $Z$ do
            find the shortest path that does not violate degree constraints on the layered graph;
        end for
        if current path finding is successful then
            remove the links corresponding to used wavelengths from the layered graph;
            add this path to the $MulticastTree$;
            update $Z$, $RemainingConnectionNumber$;
        else
            current path finding is not successful;
        end if
    end while
    if the session is successfully created (all path determinations are successful) then
        load all the calculated metrics to an output file;
        add $MulticastTree$ to $AllMulticastTree$;
    else
        undo changes on the layered graph for that session;
    end if
end for
```

The ability to change different types of costs in the layered graph is an important advantage for LAMA heuristic to support the minimization of different costs simultaneously. If we have an idea of relative costs of these operations then we can use LAMA to minimize the ultimate objective function. However, LAMA could also be used for totally different aims. We might not know or care about relative costs, but we might want to minimize a specific metric like, average bandwidth, delay, highest wavelength index, or blocking probability (Section 5.B). Thus, LAMA heuristic could be trained in a batch mode to favor and optimize some metrics for a given network and given workload. In our experiments, we follow the second use of LAMA heuristic to favor and optimize specific metrics. However, we use different traffic loads, which are created randomly, for batch mode training and online tests to be fair for all algorithms.

The total cost which has to be minimized consists of four different types: the cost of using wavelength channels, wavelength conversion, fiber conversion and using transmitters. For the rest of the paper, we interpret the cost of using a wavelength channel as the delay in this wavelength channel and we define all other types of costs with respect to the average delay in the network to normalize different components of the total cost. The relative importance of these costs to the average delay in the network is represented by three ratios, respectively: R_{wcc}(Wavelength conversion cost / Average delay), R_{fcc}(Fiber conversion cost / Average delay), and R_{tuc}(Transmitter usage cost/ Average delay). However, we can heterogeneously assign different values to a particular type of cost.

LAMA heuristic does not separate routing and wavelength assignment steps and considers both of them jointly and, its adjustable parameters on the layered graph make it very flexible. LAMA can be applied to dynamic multicasting without adjustment, since it routes sessions consecutively in a dynamic fashion. LAMA can also produce partial solutions, even if there is not a feasible solution to the problem. For example, LAMA can route 19 out of 20 sessions when CPLEX finds the infeasibility of routing all sessions. Thus, CPLEX cannot give partial solutions and is not applicable to dynamic multicasting. Moreover, the running time of LAMA linearly increases with respect to the number of sessions, contrary to CPLEX.

A demonstrative example is created to clarify how LAMA runs on the layered graph. Network size, number of wavelengths and fibers are kept small to make the demonstration understandable (N=5, F=1, W=2) and the sparse splitting and conversion node sets are given as follows:

$S_S = \{1, 4\}$ $S_C = \{4, 5\}$

The original network and the layered graph of that original network are given in Figure 3. There are two copies of the original network for two wavelengths with sub-nodes $1'$, $2'$, $3'$, $4'$, $5'$ and $1''$, $2''$, $3''$, $4''$, $5''$, and 1, 2, 3, 4, 5 represent the main nodes. The arrows with dots represent the links from main nodes to sub-nodes and vice versa. The links that are shown by small arrows represent the wavelength conversion and Nodes 4 and 5 do not have this capability. Additionally, Nodes 1 and 4 do not have light splitting capability and cannot multiplex the incoming data to transfer to more than one node.

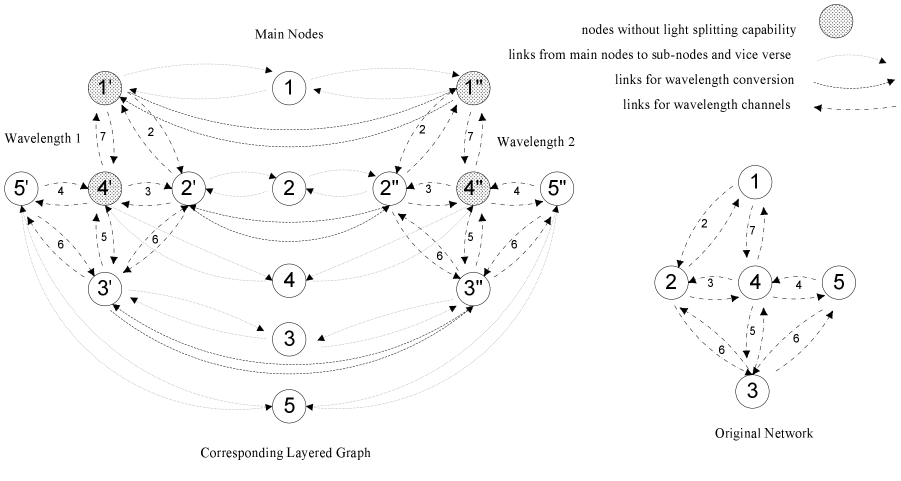

Fig. 3. The layered graph model of a network having five nodes and one fiber carrying two wavelengths.

The first multicast session is $\{1\} \rightarrow \{3, 4, 5\}$. The shortest path, that does not violate degree constraints, from 1 to the multicast destinations is $1 \rightarrow 1' \rightarrow 2' \rightarrow$

$4' \rightarrow 4$. There is another path on the other wavelength's network and one of them is chosen arbitrarily in this setting. However, the transmitter usage costs and the wavelength conversion costs can be differentiated to let LAMA heuristic minimize other metrics like average highest wavelength index (AHWI). The next shortest path to the current tree is $4' \rightarrow 5' \rightarrow 5$ and the last one seems $4' \rightarrow 3' \rightarrow 3$, but it violates the degree constraint on the sparse splitting Node 4. Thus, the next shortest path $2' \rightarrow 3' \rightarrow 3$ is chosen and the first session is routed on the layered graph. The resulting routes are shown on Figure 4 with bold arrows.

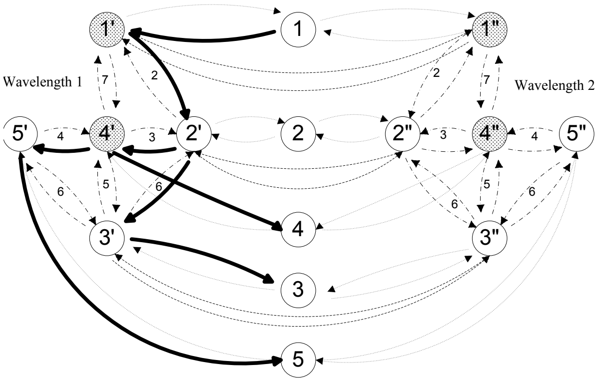

Fig. 4. Routing on the layered graph for the first multicast session ($\{1\} \rightarrow \{3, 4, 5\}$), which is shown with bold arrows.

After routing the first session, we need to remove the links that are used and come up with the layered graph on Figure 5.

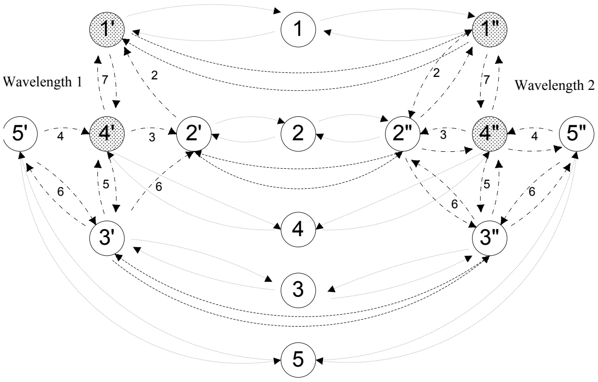

Fig. 5. Layered graph after routing the first multicast session.

The second multicast session is the same as the first one and it is routed similarly on the second wavelengths' network. The used links corresponding to used wavelengths are removed similarly. The third multicast session is $\{3\} \rightarrow \{1, 2, 4, 5\}$ and it is routed as shown in Figure 6. It should be noted that if Node 3 was a sparse splitting node, this routing would not have considered as an illegal one, since the source node can create the copies of the session by using more transmitters.

The fourth session is the same as the third one and it is again routed similarly on the second wavelengths' network and used links are removed (only wavelength

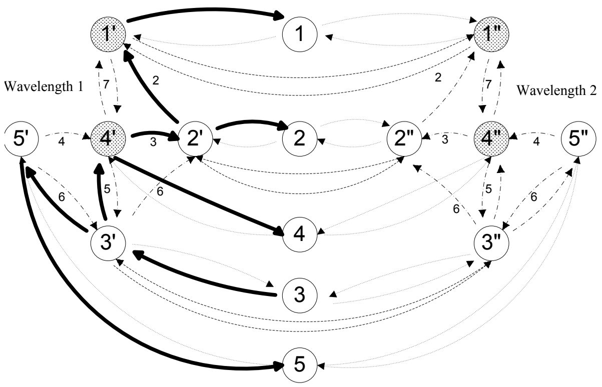

Fig. 6. Routing on the layered graph for the third multicast session ($\{3\} \rightarrow \{1, 2, 4, 5\}$).

channels). The fifth multicast session is $\{4\} \rightarrow \{1, 2, 3\}$ and it is routed as in Figure 7 and used links are again removed.

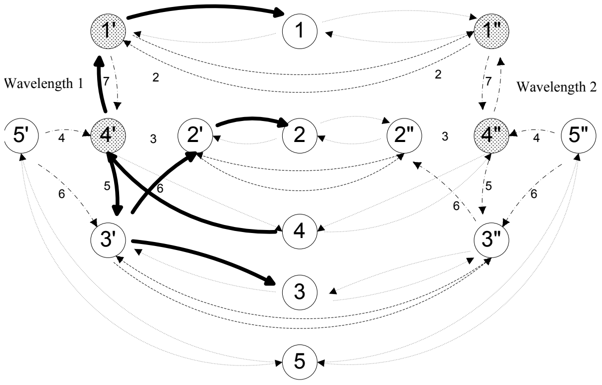

Fig. 7. Routing on the layered graph for the fifth multicast session ($\{4\} \rightarrow \{1, 2, 3\}$).

The sixth multicast session is $\{5\} \rightarrow \{2, 3\}$ and is routed as in Figure 8. It is the first time that routing needs a wavelength conversion via node 3. Since the first shortest path was arbitrarily chosen on the first wavelength's network ($5 \rightarrow 5' \rightarrow 3' \rightarrow 3$) and the second one is $3' \rightarrow 3'' \rightarrow 2'' \rightarrow 2$.

The remaining links are shown in Figure 9 and any multicast session that contains Node 2 as a source or destination will be blocked. However, there are still some other multicast sessions that can be routed on that network like $\{5\} \rightarrow \{1, 3, 4\}$, but the links $4'' \rightarrow 1''$ and $4'' \rightarrow 3''$ cannot be used at the same time, since Node 4 is a sparse splitting node.

4.C. MEMBER-ONLY (M-ONLY) Heuristic [8]

For comparative evaluation, we have also implemented M-ONLY heuristic which was originally proposed in [8] and further modified it to handle multifiber cases with the First-Fit strategy. It separately considers routing and, fiber and wavelength assignment. The first step is to build a forest for routing by adding multicast members consecutively to the current tree. The closest member to the current tree is

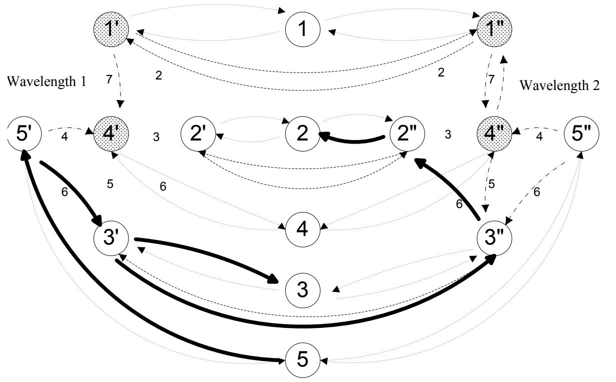

Fig. 8. Routing on the layered graph for the sixth multicast session ($\{5\} \rightarrow \{2,3\}$).

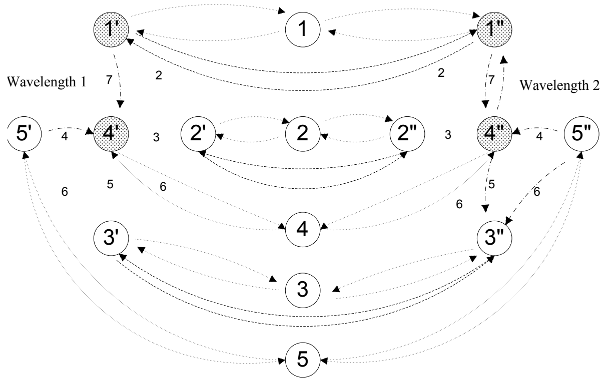

Fig. 9. Remaining links on the layered graph.

added first and it goes on until all multicast members are included. However, nodes with sparse light splitting property in the current tree are not used to connect a new member to the current tree. Additionally, a new tree from the source node is created, if it is not possible to add any remaining multicast members to the current tree. Then, the First-Fit algorithm is preferred to assign fibers and wavelengths for the final forest. If there is more than one fiber, we do not have to find a wavelength assignment in which only one fiber is involved. Thus, we try to find the first available fiber and wavelength for a given segment, which are a part of the tree that should use the same wavelength for routing. The other details can be found in [8].

The complexity of the algorithm is the sum of the complexities of routing and wavelength assignment steps. We used Bellman-Ford all-pairs shortest path algorithm for finding the shortest paths. It should be noted that we do not have to run this algorithm for all sessions and multicast members separately, unless all wavelength channels in all fibers are occupied between any two nodes and this link is removed from the original network. As a result, this algorithm should be run only when a change occurs in the original network, but it can be run for each session and each multicast member at the worst case and the complexity of routing becomes $O(S * n * N^3)$. Similarly, we need to do fiber and wavelength assignment for each link in multicast forests (one forest for each session) with complexity $O(F * W)$. At the worst case, we can have n separate trees each containing at most $N - 1$ edges, since a tree with maximum N nodes can contain at most $N-1$ links. Thus, the total worst case complexity would be $O(S*n*N*F*W+S*n*N^3)$. However, the shortest path calculations seem to dominate in terms of running time in the experiments.

We especially prefer this algorithm to compare with LAMA, since it is easy to show the effect of separating routing and wavelength assignment steps and it also runs very good in practice [8], i.e., it is a strong competitor.

4.D. Conservative Fiber and Wavelength Assignment (C-FWA) Heuristic

The First Fit fiber and wavelength assignment strategy in M-ONLY heuristic is not the only option. Moreover, we also realize that the number of wavelength and fiber conversions can be decreased, if we also try to minimize fiber and wavelength conversions among segments. Therefore, we have also modified the wavelength assignment strategy of M-ONLY [8] and created our own alternative heuristic (C-FWA). The main difference of C-FWA from M-ONLY is that it assigns fibers and wavelengths after a path is added to the current multicast tree in a way that it tries to use the same fiber and wavelength of the link that connects this path to the current tree. If it is not possible to do this assignment, then it uses the First Fit algorithm as in M-ONLY.

The worst case complexity of C-FWA heuristic is the same as M-ONLY, since the complexity of checking the availability of old fiber and wavelength for all segments is much less than the current complexity of fiber and wavelength assignment step ($O(S*n*N*F*W)$). In practice, this algorithm is expected to run in shorter time duration than M-ONLY, since it is expected to do less computation in the fiber and wavelength assignment step. Finally, we call this algorithm C-FWA so that it reflects the fiber and wavelength assignment characteristics, because it first tries to use the old fiber and wavelength in a conservative way. In this respect, we would name M-ONLY heuristic as Greedy-FWA, since it always tries to use the first available fiber and wavelength for assignment.

4.E. Unicasting (UNICAST)

It is possible to route a multicast session by separately routing each request in a unicast manner. However, it wastes resources and using a multicasting solution can reduce the bandwidth that is consumed [3]. During the comparisons, we use CPLEX results as the lower bound. Similarly, we also include unicasting only in the first group of experiments to be able to fully assess the benefit of using multicasting algorithms.

5. Computational Experiments

5.A. Experiment Design

5.A.1. Network Model and Workload

The following characteristics are considered for the creation of random networks that are used in the experiments:

N : Number of nodes

D : Average nodal degree

E : Number of edges $=(N*D)/2$

P_C : Physical connectivity $=E/(N*(N-1)/2)=D/(N-1)$

D_{min} : Minimum nodal degree

D_{max} : Maximum nodal degree

R : Network diameter (max shortest path)

H : Average internodal distance (average shortest path)

We try different values for an adjustable parameter (Alpha) to have artificial random networks that resemble real networks. Table 1 contains the important characteristics of some real life networks and some random networks that are used for the experiments, and an example random graph is given in Figure 10.

Table 1. Different parameters of real and random networks that are created with Alpha=0.20.

Network	N	D	E	D_{min}	D_{max}	P_C	H	R
ARPANet	20	3.10	31	2	4	0.16	2.81	6
UKNet	21	3.71	39	2	7	0.19	2.51	5
EON	20	3.9	39	2	7	0.20	2.36	5
NSFNet	14	3.0	21	2	4	0.23	2.14	3
Network2	10	3.0	15	1	6	0.33	2.00	4
Network7	15	4.0	30	2	6	0.29	1.99	4
Network10	20	3.0	30	1	6	0.16	2.65	6

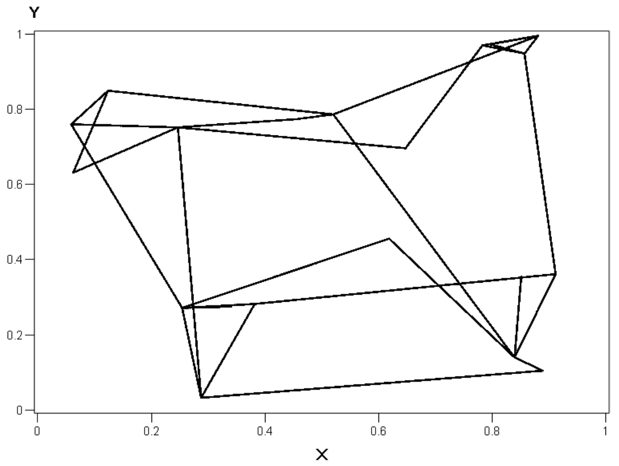

Fig. 10. A random network topology (Random Network 5).

The source and destination nodes of a multicast session are created randomly by using the following parameters:

S : Number of sessions

M : Number of multicast nodes

R_{mn} : M / N

We use the following factors in addition to N and D for the experiment design:

F : Number of fibers

W : Number of wavelengths

R_{wc} : Number of full wavelength conversion capable nodes / N

R_{ls} : Number of full light splitting capable nodes / N

R_{tuc} : Transmitter usage cost / Average delay

R_{wcc} : Wavelength conversion cost / Average delay

R_{fcc} : Fiber conversion cost / Average delay

The total cost consists of four different components: delay, transmitter usage, wavelength conversion and fiber conversion. The parameters R_{tuc}, R_{wcc}, and R_{fcc} represent the relative weight of these components with respect to the average delay.

5.A.2. Evaluation Metrics

All evaluation metrics are strictly dependent on the traffic load (number of sessions, S). Therefore, we prefer to normalize all metrics with respect to the traffic load via dividing them by the number of sessions, but the number of successfully routed sessions can be different for different algorithms because of blocking. We use the per cent gap with respect to the lower bound in terms of different parameter values and algorithms compared: Per cent Gap = (Metric Value - Lower Bound) / Lower Bound. The first three metrics are very similar to the ones used in [8]. We especially include them for comparative evaluation of LAMA, M-ONLY and C-FWA:

1. Average Bandwidth(AB): Total bandwidth / S.
2. Average Delay(AD): Total delay / S.
3. Average Highest Wavelength Index(AHWI): Sum of the highest wavelength index for each fiber / S. This metric is also dependent on the number of fibers (F) and wavelengths (W), but we do not want to normalize this metric by dividing it with the number of fibers, since we are fixing the available wavelength channels for a given experiment design. For example, we use the following combinations for an experiment for F/W: 1/8 - 2/4 - 4/2.
4. Average Wavelength Conversion(AWC): Number of wavelength conversions / S.
5. Average Fiber Conversion(AFC): Number of fiber conversions / S.
6. Average number of Tree(AT): Number of trees in forests / S. It should also be noted that a multicast session may consist of more than one tree routed from the same source. This number exactly equals to number of transmitters used per session (forest).
7. Total Cost: It is given in Equation 1. CPLEX is used to minimize the total cost and we use the per cent gap of this metric with respect to the lower bound which is also found by CPLEX. It consists of four different types which are explained in Section 3.B. The parameters R_{tuc}, R_{wcc}, and R_{fcc} are used to normalize different types of costs.
8. Running time: Running time of the algorithm.

9. Group Success Ratio (Per cent): In the static multicasting problem, a group consists of S number of sessions. If an algorithm fails to route any of these sessions in a group, then it is considered to fail to route this group. Thus, this metric measures the quality of service in terms of the overall group performance. CPLEX determines the feasibility of a routing of a group, since if the routing is possible, it finds the solution whatever the cost is.
10. Session Blocking Probability (Per cent): The whole group performance is not enough to measure the quality of service experienced for each session in a group. Then, we also measure separately the number of sessions that are blocked and divide it by the number of sessions that can feasibly be routed. Similar to group success ratio, CPLEX determines the optimal number of successfully routed sessions for feasible experiments and other heuristics are measured with respect to how many of these sessions are successfully routed.

5.B. Minimization of Blocking Probability and Total Cost

First, we decide to find the best values for R_{fcc}, R_{wcc} and R_{tuc} to minimize the QoS related metrics, that are, the blocking probability and the group success ratio. Thus, the number of sessions that are successfully routed by LAMA before blocking is chosen as a metric to decide for the values of these parameters. If there is a feasible solution for the problem, then CPLEX routes all the sessions in a group. However, it cannot give the maximum number of sessions that can be routed before blocking. Therefore, it is not suitable to find this number and CPLEX uses the same parameter values for R_{fcc}, R_{wcc} and R_{tuc} with LAMA. We performed all experiments on a Pentium IV 3.2 Ghz computer with 1 GB of RAM.

We design the following experiment to be able to find a good combination of the parameter values (9 factors):

1. D: 3, 4 (2)
2. N: 30 with two different networks (2)
3. F/W: 2/4, 2/8, 4/4 (3)
4. $R_{wc} = R_{ls}$: 0, 0.5 with two different S_S and S_C set, 1 (4)
5. R_{mn}: 0.25, 0.50 with two different multicasts (4)
6. $R_{fcc}/R_{wcc}/R_{tuc}$: 0.01/0.01/0.01, 1/1/1, 100/100/100, 0.01/1/1, 100/1/1, 1/0.01/1, 1/100/1, 1/1/0.01, 1/1/100 (9)

Number of experiments: (2*2*3*4*4)*9=192*9=1728

We determine the base line success for each level with combinations 0.01/0.01/0.01, 1/1/1, 100/100/100 and the other six combinations are intended to make each parameter on and off with respect to the base line 1/1/1. For each 192 combinations, we apply 9 different parameter sets and keep track of the maximum number of successfully routed sessions. Then we calculate the 99% confidence interval for number of successfully routed sessions for each 192 combinations. Finally, we record the number of cases in which a particular parameter set (e.g. 0.01/0.01/0.01) is outside the given confidence limits.

Table 2 denotes that the most intuitive parameter combination (1/1/1) gives the best results in terms of general performance and all four parts of the total cost (delay, transmitter usage, wavelength conversion and fiber conversion) are equally important. It is 20 times beyond upper confidence limits and 10 times below lower

Table 2. How many times a parameter set is outside the upper and lower 99% confidence limits.

Parameter Sets					
R_{fcc}	R_{wcc}	R_{tuc}	Upper	Lower	Upper / Lower
0.01	0.01	0.01	12	10	1.2
0.01	1	1	15	19	0.8
1	0.01	1	15	8	1.9
1	1	0.01	15	11	1.4
1	1	1	20	10	2.0
1	1	100	12	10	1.2
1	100	1	8	24	0.3
100	1	1	17	37	0.5
100	100	100	30	38	0.8

confidence limits and the success ratio is two. Moreover, we also examine the effect of R_{mn}, D, $R_{wc}(= R_{ls})$, F and W on the performance and this parameter set almost works best for different values of these factors as well.

After determining the right parameter set, we design online tests so that workload is distributed evenly from very light traffic conditions to very heavy ones that can cause blocking and the blocking rate is kept around 20%. The objective is minimizing the total cost which includes delay, wavelength and fiber conversion costs and the transmitter usage cost. Heuristics try to route most of the requests and they are also expected to use less wavelength and fiber conversions, trees from the source and delay.

The design aims to cover a very broad spectrum of combinations of factors (D, N, F, W, R_{wc}, R_{ls}, S, and R_{mn}), since the per cent gap metric is fair to compare all algorithms for all combinations, if the number of successfully routed sessions are the same. We also examine the components of the total cost separately by examining the average wavelength and fiber conversions, the average number of trees, and the average delay. We fix the parameters R_{fcc}, R_{wcc}, and R_{tuc} to one and there are 8 different factors for the experiment design:

Network:
(1) D: 3, 4 (2)
(2) N: 10, 15, 20, 25, 30 with 2 two different networks (10)
(3) F/W: 1/4, 2/2 (2)
Thus, we have 20 different network instances and two fiber and wavelength combinations for each of them.

Capabilities of Network Nodes:
(4) $R_{wc} = R_{ls}$: 0, 0.5, 1 (3)
There are 3 different restrictions about capabilities of nodes and we have 5 different N (10/15/20/25/30) values. Thus, we have 15 different sparse splitting and sparse conversion node sets.

Workload:
(5) S: 4, 6, 8, 10 (4)
(6) R_{mn}: 0.25, 0.50 (2)
There are 8 different combinations and we have 5 different N (10/15/20/25/30) values. Thus, we have 40 different types of multicasting sessions.

There are total of 960(=2*10*2*3*4*2) groups of sessions in the experiment and 204(22.4%) of them are found to be infeasible by CPLEX. Group success ratio measures how much per cent of 756 multicast groups which consists of different number of sessions (4, 6, 8, 10) can be routed without any blocking. LAMA, M-ONLY, C-FWA heuristics have an important advantage against CPLEX. They may route most of the requests even if a feasible solution does not exist, since they route session requests one by one until blocking occurs. However, we only use the sessions of 756 groups to calculate the session blocking probability. All multicast groups are used for the calculation of running time and all remaining metrics are calculated only for 652 groups, since LAMA, M-ONLY and C-FWA heuristics successfully route all the sessions in these 652 groups. Apart from the other heuristics, unicasting could only route 273 multicast groups and only these are used for the calculation of non-QoS metrics (average bandwidth, delay, highest wavelength index, fiber and wavelength conversion, and number of trees). CPLEX optimizer produces a solution and a gap, and a lower bound (LB) on the problem can be calculated by subtracting the gap from the cost of the current solution. Other metrics are also calculated for the solution found by CPLEX.

Table 3. The group success ratio and session blocking probability metrics for different number of sessions (S) for CPLEX, LAMA, M-ONLY, C-FWA, and UNICAST.

Metrics	Number of Sessions	CPLEX	LAMA	M-ONLY	C-FWA	UNICAST
Group Success Ratio	4	100.00	100.00	95.83	96.67	52.08
	6	100.00	100.00	87.04	87.96	43.06
	8	100.00	97.53	83.33	82.10	15.43
	10	100.00	95.65	76.81	76.81	21.74
	All	100.00	98.68	87.17	87.43	36.11
Session Blocking Probability	4	0.00	0.00	1.35	1.15	15.84
	6	0.00	0.00	4.24	4.09	19.32
	8	0.00	0.08	3.25	3.64	20.44
	10	0.00	0.07	6.47	6.11	21.31
	All	0.00	0.04	4.04	3.96	19.36

The parameters of LAMA heuristic are optimized to reduce the session blocking probability. Table 3 clearly demonstrates that LAMA is almost as good as CPLEX in terms of both group success ratio and the session blocking probability. C-FWA is slightly better than M-ONLY, but they perform very poor against LAMA in terms of both metrics. The average wavelength and fiber conversion performance of UNICAST seem to be better than the other algorithms. The reason is that UNICAST could only route 273 groups and these are the easier ones. Therefore, it consumes less resource for easier problems. The poor performance of unicasting for other metrics shows how much we gain by multicasting.

The mean values, the upper and the lower 95% confidence limits of the mean for all other metrics are given in Table 4. LAMA gives the best results in terms of the average highest wavelength index, but CPLEX is superior to all others for the remaining performance metrics. LAMA is statistically better than M-ONLY and C-FWA for the average highest wavelength index, wavelength and fiber conversions, number of trees, and the total cost per cent gap. It uses 26.9% less wavelength,

Table 4. The average bandwidth, delay, highest wavelength index, wavelength conversion, fiber conversion, number of trees and the total cost per cent gap metrics' mean values and, the lower and the upper 95% confidence limits of the mean for CPLEX, LAMA, M-ONLY, C-FWA, and UNICAST.

Metrics		CPLEX	LAMA	M-ONLY	C-FWA	UNICAST
Average Bandwidth	Lower	9.56	9.98	9.96	9.94	10.67
	Mean	**9.91**	**10.34**	**10.33**	**10.31**	**11.36**
	Upper	10.26	10.70	10.70	10.68	12.04
Average Delay	Lower	2.58	2.90	2.80	2.79	3.39
	Mean	**2.67**	**2.99**	**2.90**	**2.89**	**3.58**
	Upper	2.75	3.09	3.00	2.99	3.78
Avg. Highest Wavelength Index	Lower	0.66	0.47	0.60	0.60	0.66
	Mean	**0.67**	**0.48**	**0.61**	**0.62**	**0.68**
	Upper	0.69	0.49	0.63	0.63	0.71
Average Wavelength Conversion	Lower	0.03	0.19	1.52	0.43	0.03
	Mean	**0.04**	**0.21**	**1.65**	**0.48**	**0.05**
	Upper	0.05	0.24	1.79	0.53	0.07
Average Fiber Conversion	Lower	0.02	0.13	0.51	0.43	0.01
	Mean	**0.02**	**0.15**	**0.58**	**0.48**	**0.02**
	Upper	0.03	0.16	0.64	0.52	0.03
Average Number of Trees	Lower	1.07	1.13	1.27	1.25	4.67
	Mean	**1.09**	**1.15**	**1.30**	**1.29**	**4.87**
	Upper	1.10	1.16	1.33	1.32	5.08
Total Cost Per cent Gap	Lower	3.23	17.85	45.48	31.92	121.60
	Mean	**3.69**	**18.58**	**46.71**	**32.93**	**127.11**
	Upper	4.14	19.31	47.95	33.94	132.61

7.7 times less wavelength conversion, 3.9 times less fiber conversion, 13.5% less number of trees (transmitters), 2.5 times less total cost per cent gap than M-ONLY. Similarly, it consumes 27.9% less wavelength, 2.2 times less wavelength conversion, 3.3 times less fiber conversion, 12.6% less number of transmitters, 1.8 times less total cost per cent gap than C-FWA. The difference between M-ONLY and C-FWA is that C-FWA uses nearly 3.5 times less wavelength conversion and 20.7% less fiber conversion and it has slightly better results for the group success ratio and the session blocking probability.

There is no statistically significant difference among LAMA, M-ONLY and C-FWA in terms of the average bandwidth and delay, but CPLEX is sometimes superior to others in terms of the average delay. Confidence limits seem to be wide for the average bandwidth and delay, but we cover a very broad spectrum of parameters and this increases the standard deviation. Moreover, we also examined the result for each parameter separately, but we did not spot any significant difference.

CPLEX running time is determined mainly by the number of nonzero integer variables which are affected by D, N, S and R_{mn}, and also $R_{wc}(= R_{ls})$. The minimum and the maximum of running times with respect to different number of nodes are given in Table 5 for the cases studied. CPLEX running times are around 18 minutes at average, and it takes only 2 seconds for LAMA heuristic to find high quality solutions. M-ONLY and C-FWA use a very small fraction of a second to run. The running time of CPLEX is more seriously affected by the number of sessions,

Table 5. The running time as a function of the number of nodes in the original network (the minimum and the maximum in seconds) for CPLEX, LAMA, M-ONLY, C-FWA.

Number of Nodes (N)	CPLEX		LAMA		M-ONLY		C-FWA	
	Min	Max	Min	Max	Min	Max	Min	Max
10	0.10	117.93	0.04	0.20	0.01	0.27	0.01	0.02
15	0.31	1076.97	0.16	0.82	0.01	0.14	0.01	0.28
20	0.60	16611.28	0.45	2.64	0.01	0.19	0.01	0.05
25	2.23	170742.86	1.01	5.71	0.01	0.24	0.01	0.08
30	3.17	45261.67	2.28	11.34	0.03	0.32	0.03	0.16
All	0.10	170742.86	0.04	11.34	0.01	0.32	0.01	0.28

contrary to LAMA, M-ONLY, C-FWA and it is also unpredictably affected by the complexity of the problem, since there is a great gap between the maximum and the minimum of running times for CPLEX in Table 5.

Table 6. The total cost per cent gap as a function of the number of fibers(F) and wavelengths(W), the average nodal degree(D) and the fraction of multicast nodes (R_{mn}) for LAMA, M-ONLY and C-FWA.

Parameters	Values	LAMA	M-ONLY	C-FWA
Fiber/Wavelength (F/W)	1/4	22.24	45.87	33.59
	2/2	15.20	47.49	32.32
Avg. nodal degree (D)	3	17.54	45.09	31.33
	4	19.29	47.82	34.02
Fraction of multicast nodes (R_{mn})	0.25	15.29	40.38	28.85
	0.5	23.35	55.91	38.84

Table 6 shows the total cost per cent gap with respect to the number of fibers and wavelengths, the average nodal degree and the fraction of multicast nodes. LAMA performs better while increasing the number of fibers and decreasing the fraction of multicast nodes, since we are increasing resources and decreasing the traffic load (in terms of the number of multicast members) respectively for these two cases. However, an increase in connectivity of the network (average nodal degree) slightly affects the total cost of LAMA. C-FWA always performs better than M-ONLY with 41.9% less total cost at average and it behaves similar to LAMA with respect to the parameter changes.

LAMA performs consistently better and its total cost per cent gap changes slightly in terms of the number of nodes as shown in Figure 11. However, M-ONLY's performance deteriorates when we increase the number of nodes. C-FWA performs closer to LAMA and there is not an increasing trend in terms of the total cost per cent gap as a function of the number of nodes in the network.

The performance of LAMA, C-FWA and M-ONLY with respect to the number of sessions and, percentage of nodes with wavelength conversion and light splitting capability are given in Figure 12 and 13 respectively. It is important to have consis-

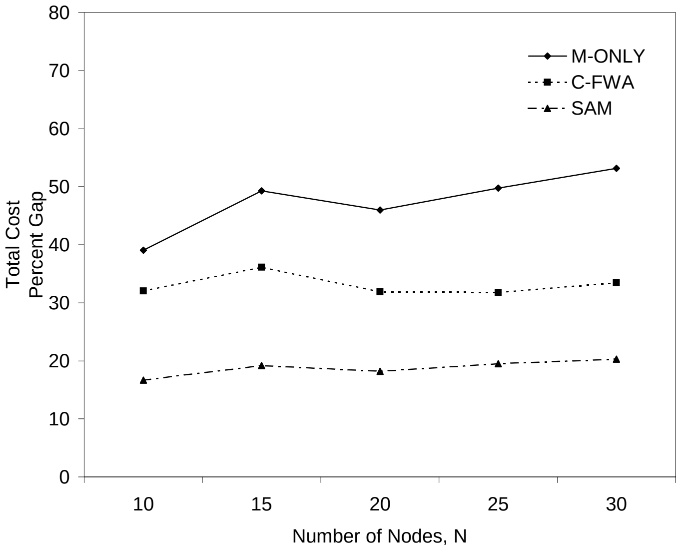

Fig. 11. The total cost per cent gap as a function of the number of nodes in the network(N) for LAMA, M-ONLY, C-FWA.

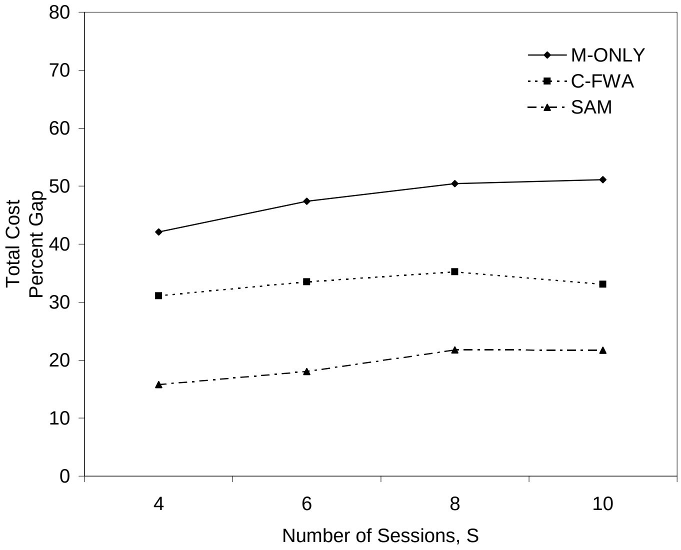

Fig. 12. The total cost per cent gap as a function of the number of sessions in a multicast group(S) for LAMA, M-ONLY, C-FWA.

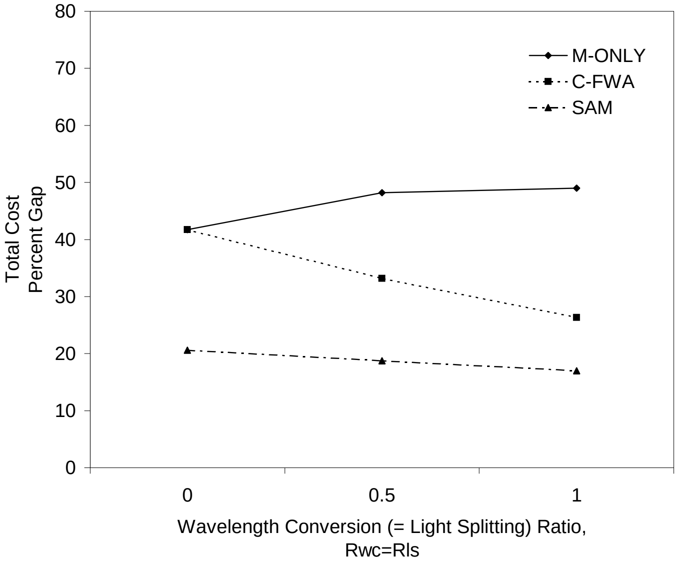

Fig. 13. The total cost per cent gap as a function of percentage of nodes with wavelength conversion and light splitting capability for LAMA, M-ONLY, C-FWA.

tency in terms of broad range of traffic load from very light conditions to conditions with high blocking rate. All three algorithms seem consistent for different number of sessions. C-FWA performs better when we increase the wavelength conversion and light splitting capabilities. Similarly, LAMA behaves slightly better, but M-ONLY's performance deteriorates.

6. Conclusion and Future Work

The future application scenarios will require long duration of multicast sessions that needs large bandwidth, and all-optical wavelength-routed WDM WAN will be the appropriate environment. In this setting, we proposed a MILP formulation that utilizes a layered graph approach for the static multicasting in all-optical wavelength routed WDM WAN with multifiber, and sparse wavelength conversion and light splitting capable routers. The formulation combines four different costs: delay, wavelength and fiber conversion costs and the transmitter usage cost, and we can play with the relative importance of these costs by changing their weights. Although these parameters can be adjusted to be able to reflect the underlying relative cost of these operations so that all four different costs can be minimized simultaneously, LAMA can use them to optimize specific metrics like the blocking probability.

LAMA heuristic does not separate routing and wavelength assignment steps and its adjustable parameters on the layered graph make it very flexible to balance different objectives. LAMA can be applied to dynamic multicasting without adjustment and can produce partial solutions. Moreover, the running time of LAMA linearly increases with respect to the number of sessions, contrary to CPLEX. In extensive computational experiments, we show that LAMA performs very close to CPLEX and significantly better than M-ONLY and C-FWA in terms of nearly all metrics. Finally, we conclude that C-FWA uses fiber and wavelength conversion resources more efficiently than M-ONLY.

The performance of LAMA heuristic is quite satisfactory in terms of quality, but the processing time may be a problem for networks having many fibers and wavelengths. We have recently finished another group of tests with higher number of fibers and wavelengths for the optimization of three different metrics simultaneously (the average bandwidth, delay, highest wavelength index). It takes around 1 minute for LAMA to route one session when the number of nodes (N) is 30 and the number of fibers and wavelengths (F/W) are like 1/32, 2/16, 4/8 (32 layers). An improved version of LAMA uses approximately 1 minute for the routing of a session with 64 layers. Therefore, we currently propose LAMA for medium size problems and C-FWA for large problems. We have also completed the testing of another new version of LAMA so that its complexity is independent of the number of fibers and wavelengths. Layered graph approach is very flexible and we can optimize different metrics by changing the cost assignment. This work includes the optimization of blocking probability and we have finished our last experiment for the optimization of three different metrics simultaneously (the average bandwidth, delay, highest wavelength index). Similarly, we will design an experiment in which we find the minimum number of transmitters used without a performance loss in other metrics. Additionally, another experiment to minimize the number of fibers used is also planned.

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