A Flexible Scalable Solution for All-Optical Multifiber Multicasting: SLAM

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***Abstract*—We previously proposed a mixed-integer linear-programming formulation, solved by CPLEX, which is a state-of-the-art optimization tool, and two heuristic solutions, layered all-optical multicasting algorithm (LAMA) and conservative fiber and wavelength assignment (C-FWA), for all-optical multicasting in wavelength-routed multifiber wavelength-division multiplexed networks with sparse wavelength conversion and light-splitting restrictions. However, LAMA was not suitable for large and dynamic multicasting problems. In this paper, we evaluate and propose scalable layered all-optical multicasting (SLAM), which is a scalable version of LAMA, for any size static or dynamic multicasting problems. We demonstrate that SLAM performs very close to the optimal (the lower bound/CPLEX) and LAMA, and significantly better than the existing work and C-FWA in terms of nearly all metrics, including the session- and group-blocking probabilities (SBPs and GBPs), since it does not separate routing and fiber-wavelength assignment steps as compared to the other candidates like the existing work and C-FWA. Additionally, transmitter-optimized SLAM, which is a version of SLAM that is specifically tuned to minimize the number of transmitters used, spends three times less extra transmitters than SLAM, without a performance loss in other metrics (one extra transmitter for 12 multicast sessions). Therefore, the adjustable parameters of SLAM make it very flexible to balance different objectives.**

***Index Terms*—All-optic, multicast, multifiber, optic, sparse light splitting, sparse wavelength conversion, wavelength division multiplexing.**

I. Introduction

IN ALL-OPTICAL wavelength-routed wavelength-division multiplexed (WDM) networks, the optical-fiber bandwidth is divided into many nonoverlapping channels so that each channel corresponds to a different wavelength (frequency) and they can operate at peak electronic speed [1]. An all-optical channel, a lightpath, is created between the source and the destination for unicast communication [2]. A point-to-multipoint extension of the lightpath concept is proposed to better support the multicast and the broadcast traffic [1]. WDM multicast is currently implemented by using IP-layer multicast protocols like distance-vector multicast routing protocol, core-based trees, open shortest path first, or protocol-independent multicast. In this type of conventional multicasting, the data cannot stay in the optical domain all the way from source to destination, but optical/electrical/optical (O/E/O) conversions are done in the routers, in which IP multicasting has to duplicate packets electronically. This causes inefficiencies and processing latencies due to replications and O/E/O conversions. However, the data always stays in the optical domain in all-optical networks, and this is the key advantage of all-optical multicasting. This makes all-optical multicasting ideal for bandwidth-intensive applications like distributed computing, database replication, computer-supported scientific collaboration, and optical-storage-area networks. Fig. 1 demonstrates an example of a wavelength-routed WDM network with two lightpaths and a light-tree, which are established over the physical topology. In these lightpaths and trees, O/E/O conversions are not done, but the data stays in the optical domain from source to destinations. Moreover, different paths with different wavelengths can share the same link as in Fig. 1, in which the lightpaths share common links with the light-tree, but they are using different wavelengths. Coding format and bit-rate transparency are the other advantages of all-optical multicasting [3].

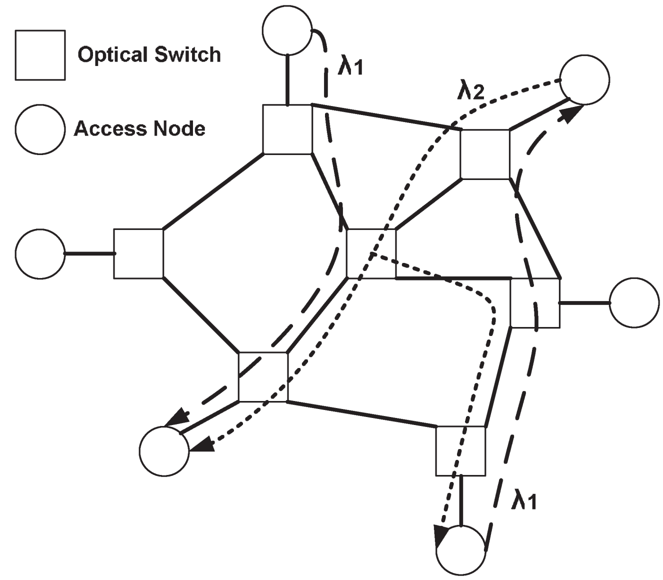

Fig. 1. Example of a wavelength-routed WDM network with two lightpaths on the first wavelength, and a light-tree on the second wavelength established over the physical topology.

A switch may have no wavelength conversion (NWC), limited WC (LWC), or full WC (FWC) and no light splitting (NLS), limited LS (LLS), or full LS (FLS) capabilities. In LWC, a node can convert an incoming wavelength to a subset of available output wavelengths. Similarly, a node with LLS

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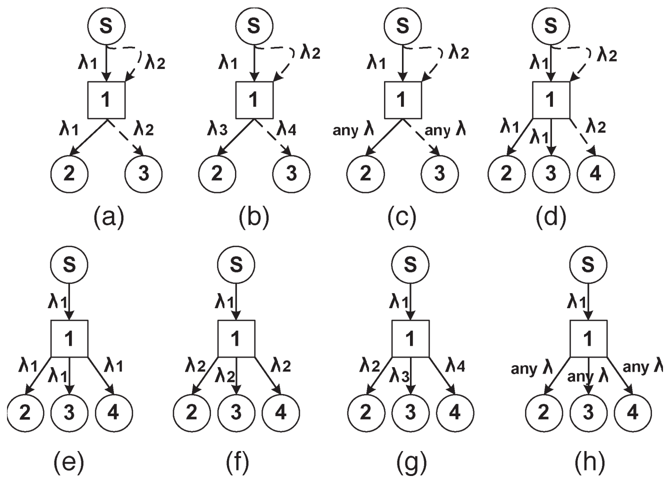

Fig. 2. Capabilities of switching elements. If Node 1 is LWC, then it can do conversion among the first four wavelengths, and if Node 1 is LLS, then it can split to two output links. (a) NWC-NLS. (b) LWC-NLS. (c) FWC-NLS. (d) NWC-LLS. (e) NWC-FLS. (f) LWC-FLS LS after WC. (g) LWC-FLS WC after LS. (h) FWC-FLS WC after LS.

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 LS and WC mean that not all but some nodes in the network have full WC and LS capabilities. Fig. 2 demonstrates different examples for the capabilities of switching elements. In Fig. 2(a), the same wavelengths have to be preserved during switching, since the switch has NWC, but the incoming wavelengths can be converted to one of the first four wavelengths in Fig. 2(b), since the switch has LWC capability. Moreover, there is no restriction for the converted wavelengths in Fig. 2(c), since the switch has FWC. However, none of the switches has any LS capabilities in those examples. In contrast, the switches in Fig. 2(e)–(h) have FLS capabilities, and they can multiply the incoming wavelength to all output links by either preserving the same wavelength or converting it to different wavelengths. This depends on both the WC capability of the switch and whether the LS is after or before the WC, as exemplified in Fig. 2(f)–(h). If the WC is after the LS, the wavelength assignment becomes more flexible with the disadvantage of using more wavelength converters. Finally, the switch in Fig. 2(d) has LLS capability of multiplying the incoming signal to, at most, two output links. Therefore, we need another wavelength to send the incoming data to the third output node.

In [4], a historical look at the emergence of optical networking is taken, and the future of optical networking is discussed. We have recently surveyed all-optical multicasting over wavelength-routed WDM networks in [5], and recent comprehensive surveys on all-optical multicasting are given in [6] and [7]. Therefore, we only examine very recent papers in the field and stress the difference of our approach. In wavelength-routed WDM networks, we identify two levels for the optimization of any type of traffic, like unicast, multicast, or broadcast. The first level consists of all the issues related with the placement of amplifiers, arrangement of tunable lasers, switches, and the links that are made up of fibers, and the most common problem formulation in this domain is the determination of logical topologies on top of the physical one. Ferrel *et al.* [8] study the multicasting problem from this perspective for the cases of unidirectional path and rings. Yu and Cao [9] examine the same problem for mesh networks. However, we aim to solve the multicasting routing and fiber-wavelength assignment (MC-RFWA) problem, which is the establishment of light-trees over wavelength-routed WDM networks. The general approach for MC-RFWA problem is to separate the routing and fiber-wavelength assignment phases [10]–[12]. We previously proposed a mixed-integer linear-programming (MILP) formulation (k-edge disjoint degree constrained Steiner problem), solved by CPLEX [13], and two heuristic solutions, layered all-optical multicasting algorithm (LAMA) and conservative fiber and wavelength assignment (C-FWA), for all-optical multicasting in wavelength-routed multifiber WDM networks with sparse WC and LS restrictions [5]. Our experiments demonstrated that the separation of two phases adversely affects important metrics like the average highest wavelength index (AHWI), the SBPs and GBPs, the number of transmitters, fiber, and WCs. In [14], the properties of a good multicast tree are prioritized and listed as follows: low cost, low delay, scalability, support for dynamic multicast groups, survivability against node and link failures, and fairness. However, LAMA was not scalable, and it could support dynamic multicast groups for small- or medium-size problems, since the worst-case complexity of scalable layered all-optical multicasting (SLAM) is linear on the number of fibers and wavelengths in the network, but the worst-case complexity of LAMA is cubic on the number of fibers and wavelengths. In practical terms, the running time of SLAM is around 1 s for networks having more than 128 fibers and wavelengths, but the running time of LAMA is more than 1 hr.

In this paper, we evaluate and propose SLAM, which is a scalable version of LAMA, for any size static or dynamic multicasting problems. We demonstrate that SLAM performs very close to the optimal (the lower bound (LB)/CPLEX) and LAMA, and significantly better than member only (M-ONLY) [3] and C-FWA in terms of nearly all metrics, including the SBPs and GBPs, since it does not separate routing and fiber-wavelength assignment steps as compared to the other candidates like M-ONLY and C-FWA. Additionally, transmitter-optimized SLAM (T-SLAM), which is a version of SLAM that is specifically tuned to minimize the number of transmitters used, spends three times fewer extra transmitters than SLAM, without a performance loss in other metrics (one extra transmitter for 12 multicast sessions). Wavelength-optimized SLAM (W-SLAM) and fiber-optimized SLAM (F-SLAM) show the same reduction in average wavelength- (AWC) and fiber-conversion (AFC) metrics, respectively. Therefore, the adjustable parameters of SLAM make it very flexible to balance different objectives. SLAM can minimize the average bandwidth (AB) or delay (AD) metrics or both with respect to the cost assignment for the wavelength resources and pack multicast sessions into smaller wavelengths by minimizing the AHWI by its default partial graph selection criteria (lower wavelength). It can also minimize the number of fibers used with the lower fiber strategy. Finally, SLAM is scalable, and it can support dynamic multicast groups for any size of problems.

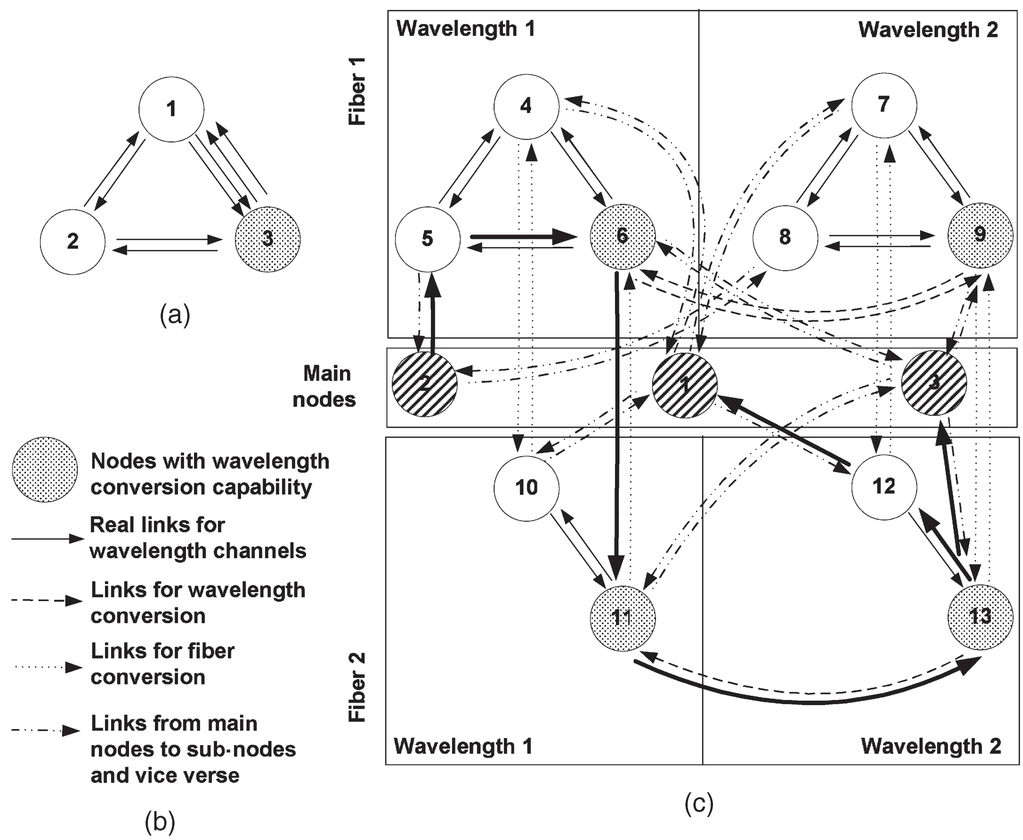

Fig. 3. (a) Simple WDM network having three nodes, four bidirectional fiber links, two wavelengths on each link, and two heterogeneous fiber layers. (b) Notation. (c) Layered-graph model of (a), in which the routing and wavelength assignment of a multicast session $\{2\} \rightarrow \{1, 3\}$ is shown with bold arrows [5].

The rest of the paper is organized as follows. Section II covers the problem definition and explains two heuristic solutions: SLAM and fast LAMA (FLAMA). Section III is devoted to the experimental design. The computational experiments are given in Sections IV–VI for small-, medium-, and large-size problems, respectively. Different versions of SLAM are compared in Section VII. Finally, Section VIII summarizes the conclusions and has a discussion about future works.

II. Problem Definition and Proposed Solutions: SLAM and FLAMA

We have previously defined the all-optical multicasting problem over wavelength-routed multifiber WDM networks with sparse LS and WC restrictions in [5]. For that reason, here, we only briefly describe the problem and the previously proposed LAMA for the sake of completeness. 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 WC capability. We proposed to use the layered graph for modeling the WDM network as described in [15]–[17] for all-optical multicasting. The layered graph in a multifiber WDM network, which has N nodes, F fibers for each pair of nodes in the network, and W wavelengths in each fiber, is constructed by replicating the original directed network $F \cdot W$ times (both nodes and links among them) in addition to adding only one node (main node) for each node of the original network (no link is added). In each replication, the original bidirectional links of the network are preserved, but they represent a specific wavelength channel in the given fiber and wavelength. Thus, we have $(F \cdot W + 1) \cdot N$ nodes in the final directed layered graph, and a main node is represented by one node in each $F \cdot W$ layer. If we use a link from a source main node to any one of the corresponding nodes (subnodes) for the routing of a multicasting request, then a transmitter is used to create a tree originating from the source node. Consequently, a main node is connected to its representative nodes (subnodes) with bidirectional links. For example, the usage of a link from a main node to its subnode in the layer for $F = 2$ and $W = 2$ represents the usage of a transmitter for the second wavelength in the second fiber on the corresponding node of the original network. Similarly, the usage of a link from a destination subnode 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 subnodes are for interior nodes. Finally, the subnodes of a main node in different fiber-wavelength layers are connected with respect to the WC and switching capabilities of the main node of these subnodes. For example, corresponding subnodes in different fibers are connected to represent WC if the main node of these subnodes has FWC property. Similarly, corresponding subnodes in different wavelengths are connected to represent fiber conversion, if the main node of these subnodes has switching property.

A layered-graph example is given in Fig. 3 for a simple WDM network having three nodes, four bidirectional fiber links, two wavelengths on each link, and two heterogeneous fiber layers which indicate differing number of fibers between nodes. The original network and the properties of the nodes (sparse WC) and the edges (the number of fibers and wavelengths) is used to construct the layered graph. A demonstrative example is also given in Fig. 3 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 WC 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. Thus, the total cost, which has to be minimized, consists of four different terms: the cost of using wavelength channels, WC, fiber conversion, and using transmitters.

The cost of using a wavelength channel can be assigned to minimize two different metrics. If we assign equal cost (or simply one) for wavelength resources, one part of the optimization becomes minimizing the AB. Alternatively, this part of the optimization becomes minimizing the AD, if we assign the time duration of the communication in these wavelength resources as costs. All methods should use the same type of cost assignment to be able to fairly compare all competitors. Then, 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 AD in the network to normalize different components of the total cost. The relative importance of these costs to the AD in the network is represented by three ratios, respectively: R_{wcc}(WC cost/AD), R_{fcc} (fiber conversion cost/AD), and R_{tuc}(transmitter usage cost/AD). However, we can heterogeneously assign different values for different costs of a particular cost term.

These terms can be adjusted to reflect the underlying relative cost of these operations so that all four different cost terms can be minimized simultaneously. For example, if the WC 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. Therefore, these costs are either given and dictated by the problem or adjusted to favor different metrics, which we demonstrate for the AHWI (LAMA) in Section IV and the average extra transmitter, wavelength, and fiber conversion (SLAM) in Section VII. Thus, this flexible cost assignment enables us a general framework in which different objectives can be simultaneously achieved or balanced by minimizing the objective of the sum of all different cost terms for the routing and wavelength assignment of k multicast sessions. Not only the previously proposed CPLEX, LAMA, and C-FWA but also currently proposed SLAM and FLAMA have this flexibility.

A. Fast LAMA (FLAMA)

LAMA is a directed degree-constrained minimum-spanning-tree heuristic which is based on finding the shortest paths from the current spanning tree to the remaining nodes in the multicast session on the layered graph. It uses this method for all multicast sessions and destinations consecutively. However, it is suitable for medium-size dynamic problems due to its complexity $[O(S \cdot M \cdot (F \cdot W \cdot N)^3)]$. It can be improved in terms of running time by calculating the shortest paths once for one session, then the complexity of the new algorithm, which is FLAMA, becomes $O(S \cdot (F \cdot W \cdot N)^3)$. However, performance losses in some metrics are expected, since the routing paths of node pairs are precomputed for one session, and FLAMA uses less dynamic information than LAMA. The pseudocode of FLAMA is given in Algorithm 1.

Algorithm 1 FLAMA Algorithm

for each multicast session **do**
  Set transmitter usage, fiber-wavelength conversion, and delay costs in THE LAYERED GRAPH;
  Initialize multicast session;
  CALCULATE SHORTEST PATHS FROM NODES IN *MulticastTree* TO NODES IN Z ON THE LAYERED GRAPH;
  while (Z is not empty) and (current path finding is successful) **do**
    for all pairs of nodes from nodes in *MulticastTree* to nodes in Z **do**
      Find the shortest path that does not violate degree constraints;
    end for
    if current path finding is successful **then**
      Remove links corresponding to used wavelengths from THE LAYERED GRAPH;
      Add this path to *MulticastTree*;
      Update Z, *RemainingConnectionNumber*;
    else
      current path finding is not successful;
    end if
  end while
  if all path findings are successful **then**
    Add *MulticastTree* to *AllMulticastTree*;
  end if
end for

B. SLAM Heuristic

Although FLAMA is faster than LAMA, LAMA and FLAMA can only handle medium-size dynamic problems, since their complexities depend on the number of layers $(F \cdot W + 1)$. Moreover, LAMA and FLAMA combine all fiber-wavelength layers in a large layered graph, which may not be necessary. Instead of creating one large layered graph, partial layered graphs can be constructed by dividing the layered graph into disjoint segments and removing the wavelength- and

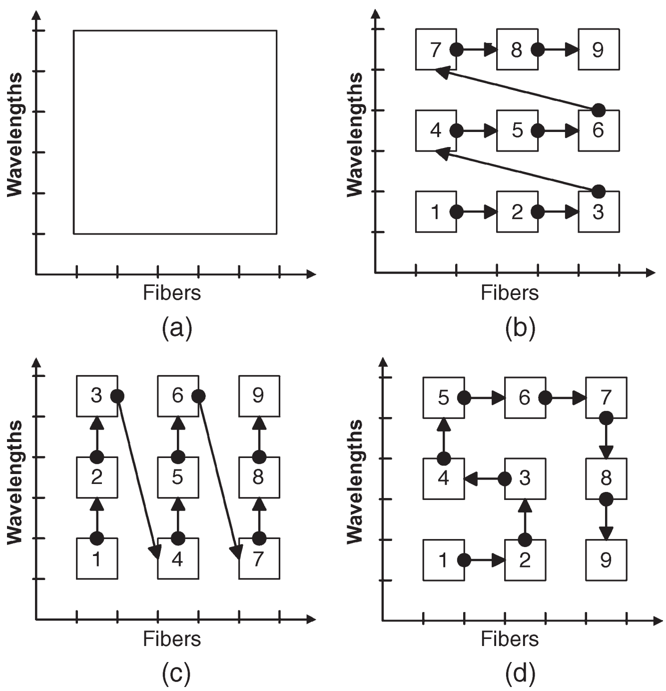

Fig. 4. Comparing LAMA and SLAM for the layered-graph approach. (a) LAMA. (b) SLAM–Lower Wavelength. (c) SLAM–Lower Fiber. (d) SLAM–Lower Both.

TABLE I
DIFFERENT VERSIONS OF SLAM. PRIMARY OBJECTIVE IS TO LOWER WAVELENGTH

Name	Size of partial layered graph (FxW)	Cost assignment $R_{fcc}/R_{wcc}/R_{tuc}$
SLAM	4x2	1/1/1
T-SLAM	4x2	1/1/8
F-SLAM	4x2	8/1/1
W-SLAM	4x2	1/8/1
SLAM[4x4]	4x4	1/1/1

fiber-conversion links among segments. Multicast sessions, which are not blocked, are routed on the first partial graph, then the remaining sessions are routed on the second partial graph and so on so forth. We call this algorithm scalable LAMA (SLAM), since its complexity $O(S \cdot M \cdot F \cdot W \cdot N^3)$ is linearly dependent on the number of layers. However, the order of selection of partial graphs is important for SLAM. Fig. 4(a) shows the LAMA approach for the creation of layered graph, and Fig. 4(b)–(d) shows three different strategies, which are minimizing the number of fibers used, minimizing the highest wavelength index, or both together, for SLAM.

The size of the partial layered graphs in terms of F and W and the value of ratios $(R_{\text{fcc}}/R_{\text{wcc}}/R_{\text{tuc}})$ for the cost assignment are the other parameters for SLAM. In Fig. 4(a), LAMA works on the big layered graph which consists of 36 layers ($F = 6$ and $W = 6$), but SLAM works on nine small layered graphs which have four layers ($F = 2$ and $W = 2$) in Fig. 4(b)–(d). Table I denotes different versions of SLAM which is advantageous for LWC, since each partial layer allows wavelength and fiber conversions within that layer. Moreover, it successfully packs sessions into lower fibers, wavelengths, or both, depending on the strategy used. The pseudocode of SLAM is given in Algorithm 2.

Algorithm 2 SLAM Algorithm

CREATE PARTIAL LAYERED GRAPHS FOR EACH GROUP OF LAYER
for EACH GROUP OF LAYER **do**
  for EACH MULTICAST SESSION THAT IS NOT ROUTED **do**
    Set transmitter usage, fiber-wavelength conversion, and delay costs in THE PARTIAL LAYERED GRAPH CORRESPONDING TO THE GROUP;
    Initialize multicast session;
    while (Z is not empty) and (current path finding is successful) **do**
      CALCULATE SHORTEST PATHS FROM NODES IN *MulticastTree* TO NODES IN Z ON THE PARTIAL LAYERED GRAPH;
      for all pairs of nodes from nodes in *MulticastTree* to nodes in Z **do**
        Find the shortest path that does not violate degree constraints;
      end for
      if current path finding is successful **then**
        Remove links corresponding to used wavelengths from THE PARTIAL LAYERED GRAPH;
        Add this path to *MulticastTree*;
        Update Z, *RemainingConnectionNumber*;
      else
        current path finding is not successful;
      end if
    end while
    if all path findings are successful **then**
      Add *MulticastTree* to *AllMulticastTree*;
    end if
  end for
end for

III. EXPERIMENTAL DESIGN

We performed experiments on various size WDM networks with different characteristics so that all experimental designs cover a broad spectrum of parameter values [18]. We also compared SLAM solutions with those obtained by CPLEX [13] and different heuristics. All experiments were performed on Pentium IV 3.2-GHz computers with 1 GB of RAM. In order to speed up the experiments, multiple computers with identical configurations were also used.

A. Experimental Parameters

The number of nodes (N) and the edges (E) among nodes determine the average nodal degree $(D = (2 * E)/N)$. We have created realistic random networks with different number of nodes (N) and average nodal degree by adjusting a parameter (Alpha) [5].

After setting the structure of the network, which is controlled by the factors N and D, we decide on the number of fibers (F) and wavelengths (W) for edges and the LS (R_{ls}) and WC

TABLE II
WORST-CASE COMPLEXITIES OF DIFFERENT METHODS

Method	Worst-Case Complexities
CPLEX	NP-Complete
LAMA	$O(S.M.(F.W.N)^3)$
FLAMA	$O(S.(F.W.N)^3)$
SLAM	$O(S.M.(F.W).N^3)$
C-FWA / M-ONLY	$O(S.M.N.F.W + S.M.N^3)$

($R_{\rm wc}$) capabilities for nodes. Although each edge may have different number of fibers and each fiber may carry different number of wavelengths, we deploy equal number of fibers in each edge, and the capacity of fibers are the same to easily measure the effect of F/W in the experiments. In an experimental design, the number of layers ($F \cdot W$) is also kept constant to have equal bandwidth for different F/W combinations. We consider a problem with up to 4 layers as very small, 8 layers as small, 32 layers as medium, and 128 layers and above as large. We conducted experiments for all problem sizes. The source and destination nodes of a multicast session are created randomly. The number of sessions (S) and the ratio ($R_{\rm mn}$) of multicast nodes to all nodes are chosen as the factors to determine the workload.

B. Solution Methods

All methods use an auxiliary graph to solve the routing and fiber-wavelength assignment problem and give a solution which is evaluated to measure different metrics. Although different methods can use different cost assignment for wavelength resources in their auxiliary graphs, we interpret the cost of using a wavelength channel as the delay in this wavelength channel. Therefore, all heuristics are evaluated fairly, since we use one type of cost assignment for all. CPLEX, LAMA, FLAMA, and SLAM use the layered graph of a network to jointly optimize routing and fiber-wavelength assignment problem. C-FWA and M-ONLY only use the cost assignment in the original network to determine routes, then a fiber-wavelength assignment strategy is deployed, e.g., first-fit or ex-fit. In addition to delay, there are three more different cost terms in the layered graph: transmitter usage, WC, and fiber conversion. The parameters $R_{\rm tuc}$, $R_{\rm wcc}$, and $R_{\rm fcc}$, which are valid for CPLEX, LAMA, FLAMA, and SLAM, represent the relative weight of these terms with respect to the AD. CPLEX solves the MILP formulation of the problem and gives an optimal solution in terms of total cost, and the LB is derived from the relaxation of the integrality constraints of the MILP formulation. The worst-case complexities of all methods are given in Table II.

C. Evaluation Metrics

All metrics are normalized with respect to the traffic load via dividing them by the number of sessions.

1) AB: Total bandwidth/S.
2) AD: Total delay/S.
3) AHWI: Sum of the highest wavelength index for each fiber/S.
4) AWC: Number of WCs/S.
5) AFC: Number of fiber conversions/S.
6) Average number of Tree (AT): Number of trees in the forests/S. This number exactly equals to number of transmitters used per session (forest).
7) Average Extra number of Tree (AET): At least one transmitter (tree) is needed for one session, then we measure extra transmitters needed by a simple formula: $\text{AET} = \text{AT} - 1$.
8) GBP (in percent): In the static multicasting problem, a group consists of S 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.
9) SBP (in percent): 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.

We use the percent gap with respect to the LB or upper bound in terms of different parameter values and algorithms compared. If CPLEX solutions are available, then the LB percent gap is calculated. Otherwise, the performance of the best algorithm for the given metric is taken as an upper bound, and upper bound percent gap is calculated

$$\begin{aligned}&\text{Lower Bound Percent Gap}\\&\quad = (\text{Metric Value} - \text{Lower Bound})/\text{Lower Bound}\\&\text{Upper Bound Percent Gap}\\&\quad = (\text{Metric Value} - \text{Upper Bound})/\text{Upper Bound}.\end{aligned}$$

If there is a serious gap between the best and the worst competitor, then the ratio gaps are calculated

$$\text{Lower Bound Ratio Gap} = \text{Metric Value}/\text{Lower Bound}$$
$$\text{Lower Bound Ratio Gap} = \text{Metric Value}/\text{Upper Bound}.$$

IV. LBs FOR ALL METRICS

The MILP formulation minimizes the total cost which consists of delay, wavelength, fiber conversion, and transmitter costs. If a feasible solution (a nonblocking case) exists for the MILP formulation, then CPLEX finds it. Therefore, all CPLEX solutions are optimal in terms of SBPs and GBPs, which are zero for SBP and GBP. Although, CPLEX uses fiber and wavelength resources in an arbitrary way, SLAM with lower wavelength strategy assigns wavelength resources from lower indexes to higher indexes so SLAM better packs wavelength resources consumed. Alternatively, SLAM with lower fiber strategy or M-ONLY with first-fit (first available wavelength in first fiber) use fiber resources from lower indexes to higher indexes so that they consume fewer fibers, but few algorithms minimize both resources simultaneously and equally like SLAM with lower fiber/wavelength strategy. AHWI metric is used to compare all methods. AHWI, GBP, and SBP are related metrics. When there is no blocking (light traffic load), GBP and SBP metrics are zero, and AHWI measures the packing of wavelength-fiber resources consumed. If we continue to increase the traffic load after blocking, AHWI stays constant, and GBP and SBP metrics increase to measure this packing performance for blocking cases. SLAM and M-ONLY naturally minimizes AHWI but not only the values of the ratios ($R_{\rm wcc}/R_{\rm fcc}/R_{\rm tuc}$), but in addition, the cost-assignment strategy of LAMA should be changed to minimize AHWI, in addition to the other metrics. CPLEX does not minimize AHWI since it has always zero GBPs and SBPs.

AB and AD are also related metrics and depend on the cost assignment for wavelength resources. If delay values are set, then AD is minimized. Similarly, AB is minimized, if we set equal (simply one) values for wavelength resources. Thus, we have five groups of metrics which may be minimized without deteriorating the performance in the other groups:

1) AB/AD;
2) AWC;
3) AFC;
4) AT;
5) AHWI, SBPs, and GBPs.

The first-fit (specifically the first available wavelength in the first fiber) strategy can be generalized to minimize wavelength resources by selecting the fiber which has an available wavelength with the lowest index. The partitioning and numbering of the whole layered graph with different strategies in SLAM is a further generalization so that fibers and wavelengths are grouped and numbered to be used, instead of directly selecting a specific fiber and wavelength like in first-fit. Moreover, SLAM can utilize other strategies, in addition to the ones we proposed. For example, SLAM can first use the partial layered graph which has the highest number of available wavelength resources by generalizing least loaded routing for unicast connections. Therefore, SLAM is a flexible and scalable solution, since it combines routing and fiber-wavelength assignment phases like FLAMA and LAMA, contrary to M-ONLY and C-FWA, which decompose two phases (shortest path routing with first-fit or ex-fit fiber and wavelength assignment), and generalizes and utilizes fiber-wavelength assignment strategies used both for unicasting and multicasting.

Although, all CPLEX solutions are optimal in terms of SBP and GBP, CPLEX always minimizes the terms of the total cost (AD–AB/AWC/AFC/AT), simultaneously; therefore, it is not optimal for any of them. The LB for each can be found by setting the remaining costs to zero and solving each problem separately. If we set delay for wavelength resources and zero for $R_{\rm wcc}/R_{\rm fcc}/R_{\rm tuc}$, then we find the LB for AD (CPLEX/LB-AD optimized). Similarly, we find the LB for AB, if we set one for wavelength resources and zero for $R_{\rm wcc}/R_{\rm fcc}/R_{\rm tuc}$ (CPLEX/LB-AB optimized). Other LBs for AWC ($R_{\rm wcc} = 100/R_{\rm fcc} = R_{\rm tuc} = 0$), AFC ($R_{\rm fcc} = 100/R_{\rm wcc} = R_{\rm tuc} = 0$), and AT ($R_{\rm tuc} = 100/R_{\rm fcc} = R_{\rm wcc} = 0$) can also be found. MILP formulation does not minimize AHWI, but we can incrementally solve the same problem with one less wavelength at each iteration and continue solving it until blocking to determine the lowest available AHWI (CPLEX/LB-AHWI optimized). Additionally, we can compare the performance loss in the other metrics to quantify the strength of the relationship among AHWI, AB, AD, AWC, AFC, and AT.

TABLE III
LBs FOR ALL METRICS FOR DESIGN 1 AND THE RESULTS OF AN OLD EXPERIMENT [5]

Metrics	Only AB Optimized (Design 1)	Only AD Optimized (Design 1)	AWC/AFC AHWI/AT Optimized (Design 1)	AD/AWC AFC/AT Optimized ([5])
AB	10.15	11.41	x	9.91
AD	3.39	2.80	x	2.67
AHWI	x	x	0.56	0.67
AWC	x	x	0.02	0.04
AFC	x	x	0.06	0.02
AT	x	x	1.10	1.09

Initial experiments (Experimental Design 1) demonstrated that AWC, AFC, and AT are highly related. If we set costs (constrain) for one of them, then CPLEX uses other two resources, and the constrained one attains its theoretical minimum (zero for AWC and AFC and one for AT). Moreover, if we constrain two of them, then both still take their minimum values. Surprisingly, AWC, AFC, and AT still attained their theoretical minimums for lower traffic ($S = 5$) by spreading sessions, instead of packing them when we constrained all together. Therefore, we increased S to further constrain them, but CPLEX crashed most of the time without even producing a solution when the number of sessions is ten. However, the traffic load is an important parameter to examine relationships among metrics, since the characteristics may be different for light or dense traffic load. Thus, we measured the LBs for AWC, AFC, AT, and AHWI together, since we have simulated high traffic load by restricting available wavelength resources. We included the results of an old experiment into Table III from [5], since it was a smaller problem, and CPLEX could solve all cases without crashing. Moreover, all costs (AB–AD/AWC/AFC/AT) are equally important ($R_{\rm wcc} = R_{\rm fcc} = R_{\rm tuc} = 1$), and we can gain an insight by roughly comparing the base-line values of metrics to their LBs in Design 1, yet both designs are not directly comparable.

Experimental Design 1: SLAM versus LBs
D: $\{3, 4\}$ (2)
N: $\{30\}$ (1)
F/W: $\{1/8, 2/4, 4/2\}$ (3)
$R_{\rm wc} = R_{\rm ls}$: $\{0, 0.5, 1\}$ (3)
S: $\{5, 10, 20\}$ with 30 different multicast sets (90)
$R_{\rm mn}$: $\{0.2\}$ (1)
Number of experiments: $2.3.3.90 = 1620$
Methods: CPLEX/LB (AB optimized), CPLEX/LB (AD optimized), CPLEX/LB (AHWI–AWC–AFC–AT optimized), LAMA (AHWI optimized), FLAMA, SLAM, C-FWA, and M-ONLY.

The LBs for AWC, AFC, and AT for Design 1 indicate that only less than one wavelength and one fiber conversions and one extra transmitter are needed for ten sessions. In the old experiment, one wavelength and one fiber conversions for 15 sessions and less than one extra transmitter for ten sessions are required. Although we treated AB, AWC, AFC, and AT equally, the performances in these metrics are very close to the LBs. Additionally, less than 5% (from 2.92 to 2.80)

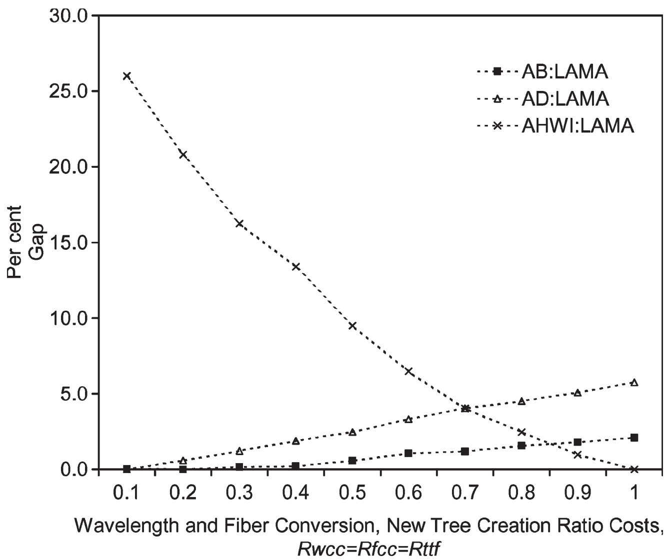

Fig. 5. Percent gap as a function of the wavelength and fiber conversion, and the transmitter usage ratio costs $R_{\mathrm{wcc}} = R_{\mathrm{fcc}} = R_{\mathrm{tuc}}$ for AB/AD and highest wavelength index (AHWI) metrics for LAMA heuristic.

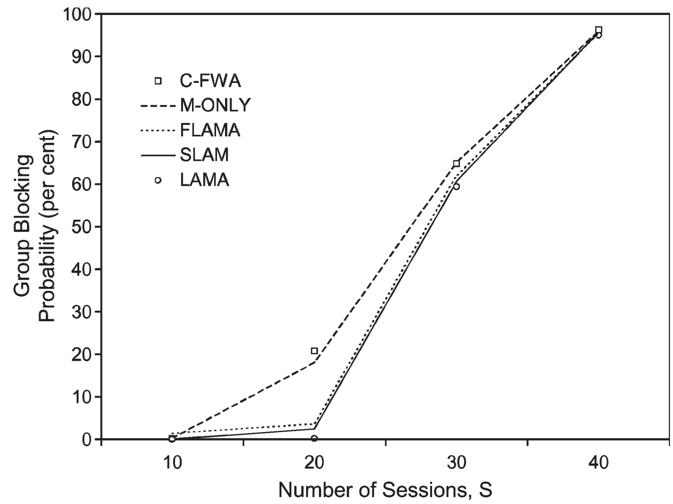

Fig. 6. Comparative evaluation of algorithms in terms of GBP versus S for Design 1.

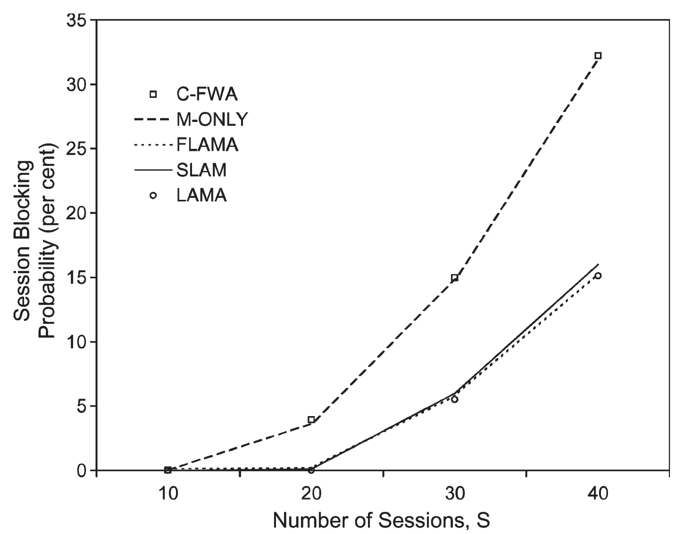

Fig. 7. Comparative evaluation of algorithms in terms of SBP versus S for Design 1.

performance gain is achieved for AD (much less for AB) if we optimize for it. We concluded that AD/AWC/AFC/AHWI/AT do not affect each other significantly, and they can all be minimized and take values which are close to the optimal by using equal cost ratios ($R_{\mathrm{wcc}} = R_{\mathrm{fcc}} = R_{\mathrm{tuc}} = 1$). However, AB is seriously (12%–13%) improved if the cost of using wavelength channels is assigned as one for bandwidth minimization.

Although the GBPs and SBPs are important metrics, we also want to minimize other important metrics like the AHWI without a performance loss in the other metrics. SLAM minimizes AHWI by its default partial-graph-selection criteria (lower wavelength). However, LAMA should be modified to differentiate the WC and the transceiver usage costs so that it would use the lower wavelengths first and it improves the AHWI metric. First, we adjust WC costs in a way that the cost from a lower wavelength to a higher wavelength is multiplied by the positive difference in levels plus one, and the cost from a higher wavelength to a lower wavelength is divided by the positive difference in levels plus one. For example, a WC from λ_2 to λ_3 costs two times more than the case without adjustment. Similarly, a WC from λ_5 to λ_2 costs four times smaller in this new setting. Second, the costs of links from the main nodes to the subnodes (transceiver usage costs) are also adjusted in a similar way. The costs of links from the main nodes to the nodes of the first wavelength's layers stay the same, but all the other transceiver usage costs are multiplied by the index of the wavelength used. Therefore, the cost of using a transceiver for λ_3 is three times more than the cost of using a transceiver for λ_1.

The tuning of LAMA for quality of service (QoS) (blocking probabilities)-related metrics indicates that all four terms of the total cost (delay, wavelength and fiber conversions, and transceiver usage costs) are equally important. Therefore, we keep these ratios equal and change them between zero and one to see the effect on the AB/AD and highest wavelength index. Fig. 5 demonstrates that the AB/AD are positively correlated and the AHWI is negatively correlated with the others. A performance increase in one group causes a decrease in the other. However, there is a desired operational point ($R_{\mathrm{fcc}} = R_{\mathrm{wcc}} = R_{\mathrm{tuc}} = 0.7$) at which the percent gap of all three metrics are less than 5%, and the percent gap of delay and highest wavelength index are equal.

We use different traffic loads for batch tuning and online tests to be fair for all competitors. Figs. 6 and 7 show the GBPs and SBPs for different number of sessions ($S = 10/20/30/40$). The higher number of sessions ($S = 30/40$) are only used to measure GBP and SBP metrics to see the tendency of blocking probability better. Although, CPLEX results are only available when S is five, we assume that the routing of all groups is feasible.

Although FLAMA is significantly better than M-ONLY and C-FWA in terms of blocking probabilities like SLAM and LAMA, FLAMA is blocked for small session sizes ($S = 5/10$). Therefore, FLAMA, which is less dynamic than LAMA, is eliminated, but it is reported in the study for

TABLE IV
MEANS AND STATISTICAL SIGNIFICANCES FOR DIFFERENT METRICS AND METHODS FOR DESIGN 1 AND $S = 5/10/20$

Metrics	AB	AD	AHWI	AWC	AFC	AT
LAMA	11.87 BC	3.11 B	0.47 A	0.27 B	0.32 B	1.23 C
FLAMA	11.72 A	3.00 A	0.83 D	0.16 A	0.19 A	1.15 B
SLAM	11.85 AB	3.07 B	0.54 B	0.14 A	0.21 A	1.12 A
C-FWA	12.00 C	3.16 C	0.60 C	0.46 C	0.88 C	1.28 D
M-ONLY	12.00 C	3.16 C	0.59 C	2.18 D	0.93 C	1.28 D

TABLE V
MEANS AND STATISTICAL SIGNIFICANCES FOR DIFFERENT METRICS AND METHODS FOR DESIGN 1 AND $S = 5$

Metrics	AB	AD	AHWI	AWC	AFC	AT
LB	11.41 A	2.80 A	0.56 A	0.02 A	0.06 A	1.10 A
LAMA	11.78 BC	3.02 B	0.59 A	0.11 B	0.21 C	1.16 B
FLAMA	11.68 B	2.97 B	1.25 D	0.09 B	0.12 B	1.11 A
SLAM	11.77 BC	3.00 B	0.70 B	0.10 B	0.12 B	1.10 A
C-FWA	11.98 C	3.16 C	0.76 C	0.25 C	0.59 E	1.24 C
M-ONLY	11.98 C	3.16 C	0.75 C	1.47 D	0.44 D	1.24 C

completeness. SLAM performs almost as good as LAMA, which is the best, for both metrics, and they are significantly better than M-ONLY and C-FWA, which also perform similarly.

The means and statistical significance for all other metrics (Design 1) are given in Tables IV and V for $S = 5/10/20$ and $S = 5$, respectively. The letters (codes) that are next to the numbers in tables are used to indicate statistically significant differences among different methods. If two methods have a common letter in their codes, there is no statistically significant difference between them. For example, in Table IV, there is no statistically significant difference between FLAMA (A) and SLAM (AB) in terms of AB metric, since they have a common letter in their codes (A), but FLAMA (A) is statistically significantly superior to LAMA (BC), C-FWA (C), and M-ONLY (C), since FLAMA and the others do not share common letters in their codes. CPLEX (LB) is statistically superior to others for all metrics except the AHWI (LAMA is statistically equivalent) and trees (transmitters-AT) for which SLAM is statistically equivalent and optimal. LAMA is statistically better than M-ONLY and C-FWA for the AD, highest wavelength index (AHWI), wavelength (AWC), and fiber (AFC) conversions and trees (transmitters-AT) for $S = 5$ and all sessions. There is a statistically significant difference between C-FWA and M-ONLY for the average WC for $S = 5/10/20$. C-FWA uses nearly five times less WC than M-ONLY.

First, we compare SLAM to the other methods for $S = 5/10/20$, then we evaluate SLAM performance against the LB when S is five. SLAM is statistically better than LAMA for AWC, AFC, and AT, but LAMA is statistically superior to SLAM for AHWI, since LAMA is specifically optimized for AHWI in Design 1. There is no statistically significant difference between SLAM and LAMA for AB and AD. Similarly, SLAM is statistically better than FLAMA for AT and AHWI (FLAMA is not optimized for AHWI like LAMA), but FLAMA is statistically superior to SLAM for AD. Finally, SLAM is statistically superior to M-ONLY and C-FWA for all metrics. SLAM uses 9.5% less wavelength, 14.5% less transmitters, 15.5 times less WC, and 4.4 times less fiber conversion than M-ONLY. Similarly, it consumes 11% less wavelength, 14.3% less transmitters, 3.3 times less WC, and 4.2 times less fiber conversion than C-FWA. SLAM is less than 5% better than M-ONLY and C-FWA for AB and AD metrics, which have least variability among competitors (at most 5%).

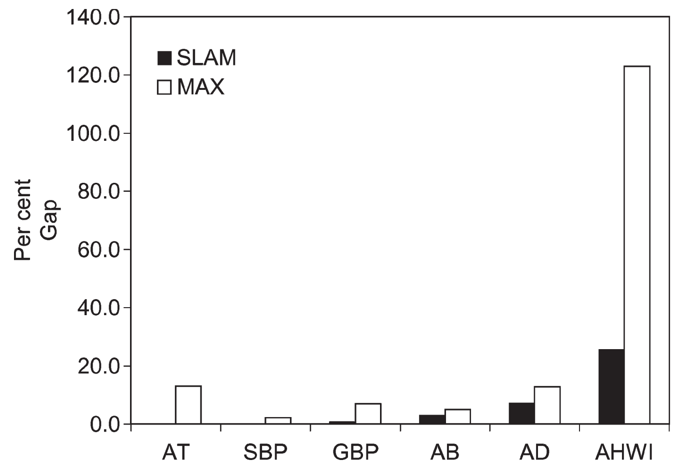

Fig. 8. SLAM and the worst competitor are compared to the LB in terms of percent gap for AT/SBP/GBP/AB/AD/AHWI for Design 1 and $S = 5$.

In Fig. 8, SLAM is compared to the LB for AT, SBP, GBP, AB, AD, and AHWI in terms of percent gap. The worst competitor is also compared to the LB. Although, SLAM is nearly 25% worse than the optimal in terms of AHWI, it is five times better than the worst competitor. All competitors perform closely for AB and AD metrics. Thus, SLAM is very close to the optimal for AB and AD. However, SLAM is almost as good as the optimal for AT, SBP, and GBP metrics. Additionally, SLAM is also very close to the optimal in terms of AWC and AFC, and it is 15 times better for AWC and four times better for AFC than the worst competitor.

V. SLAM FOR MEDIUM-SIZE PROBLEMS

In Experimental Design 2, we compare SLAM with SLAM$[4*4]$ for medium-size problems with 32 layers (F/W: 1/32, 2/16, 4/8). SLAM$[4*4]$ differs from SLAM in that it uses larger partial layered graphs with, at most, 16 layers (F/W: 1/4, 2/4, 4/4), depending on the number of fibers used. In contrast to SLAM (the brief notation for SLAM$[4*2]$) uses, at most, eight layers (F/W: 1/2, 2/2, 4/2). We also compare different versions of SLAM with LAMA, without AHWI optimization (Section IV), C-FWA, and M-ONLY.

Experimental Design 2: SLAM vs LAMA and SLAM$(4*4)$
D: $\{3, 4\}$ (2)
N: $\{30\}$ (1)
F/W: $\{1/32, 2/16, 4/8\}$ (3)
$R_{\text{wc}} = R_{\text{ls}}$: $\{0, 0.5, 1\}$ with two different S_S and S_C set for 0.5 (4)
S: $\{16, 32, 64, 128\}$ (4)
R_{mn}: $\{0.2, 0.4, 0.6, 0.8\}$ with two different multicast sets (8)
Number of experiments: $2.3.4.4.8 = 768$
Methods: LAMA, SLAM$(4*4)$, SLAM, C-FWA, and M-ONLY.

It is not possible for CPLEX to solve medium-size problems. Therefore, all upper bounds are determined with respect to the

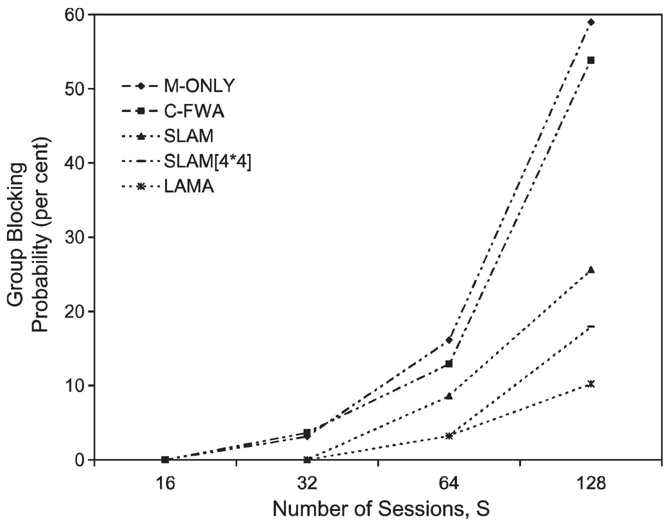

Fig. 9. Comparative evaluation of algorithms in terms of GBP for Design 2.

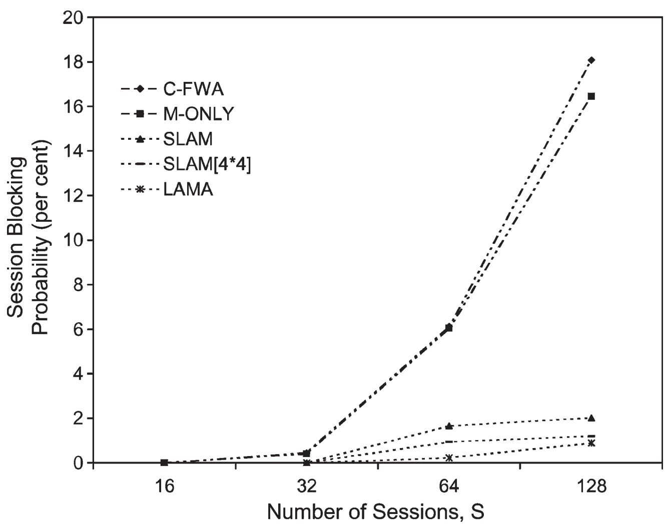

Fig. 10. Comparative evaluation of algorithms in terms of SBP for Design 2.

TABLE VI
MEANS AND THE STATISTICAL SIGNIFICANCES FOR DESIGN 2

Metrics	AB	AD	AHWI	AWC	AFC	AT
LAMA	18.73 A	4.55 A	1.23 D	0.75 C	0.50 A	1.20 B
SLAM[4*4]	18.74 A	4.58 A	0.65 B	0.52 B	0.53 A	1.18 B
SLAM	18.73 A	4.59 A	0.59 A	0.30 A	0.54 A	1.14 A
C-FWA	19.36 A	4.77 A	0.72 C	1.70 D	2.29 B	1.77 C
M-ONLY	19.34 A	4.77 A	0.75 C	6.95 E	1.98 B	1.75 C

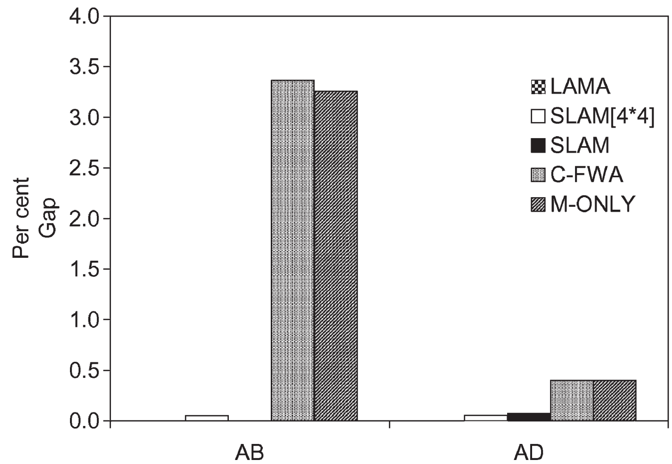

Fig. 11. Comparative evaluation of algorithms in terms of AB and AD for Design 2.

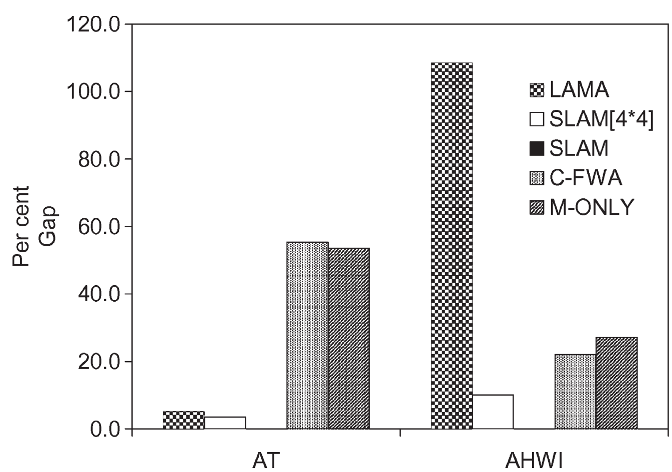

Fig. 12. Comparative evaluation of algorithms in terms of AT and AHWI for Design 2.

best solution obtained by any heuristic. Figs. 9 and 10 show the GBPs and SBPs for different number of sessions (S). LAMA, SLAM, and SLAM$[4*4]$ are significantly better than C-FWA, which perform slightly better than M-ONLY in terms of GBP. LAMA is the best, and SLAM$[4*4]$ is better than SLAM. However, the increase rates for SLAM and SLAM$[4*4]$ from $S = 64$ to $S = 128$ are almost the same. In terms of SBP, LAMA, SLAM, and SLAM$[4*4]$ perform very close and they are more than ten times better than M-ONLY, which is slightly better than C-FWA.

Table VI denotes the means and the statistical significance (if two methods have a common letter in their code, there is no statistically significant difference between them) for other metrics (Design 2). Although, there is no statistically significant difference for AB and AD for all methods, SLAM, SLAM$[4*4]$, and LAMA are very close and better than C-FWA and M-ONLY, which perform almost the same for AB and AD. SLAM is statistically significantly better than all the others for AHWI, AWC, and AT. SLAM, SLAM$[4*4]$, and LAMA are very close and better than C-FWA and M-ONLY for AFC.

All methods are compared for AB and AD in Fig. 11, for AT and AHWI in Fig. 12, for GBP and SBP in Fig. 13 in terms of the percent gap. Additionally, all methods are compared for AWC and AFC in Fig. 14 in terms of the ratio gap, since differences are very big for them to be shown in terms of percent gap.

While comparing SLAM and SLAM$[4*4]$, SLAM is slightly better than SLAM$[4*4]$, except AWC, for which SLAM is significantly better, and blocking probabilities, for which SLAM$[4*4]$ perform better for GBP and slightly better

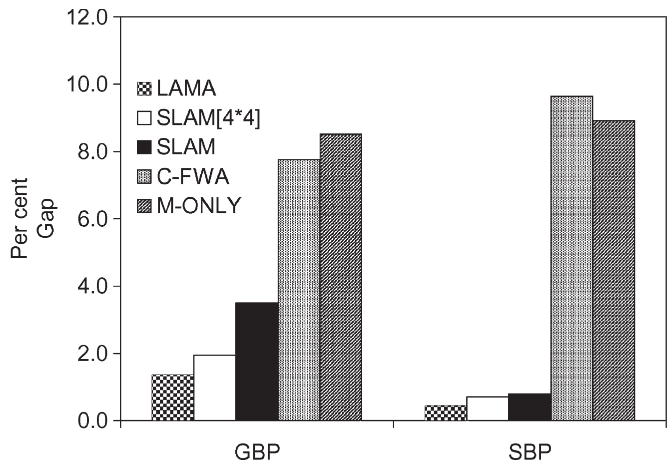

Fig. 13. Comparative evaluation of algorithms in terms of GBP and SBP for Design 2.

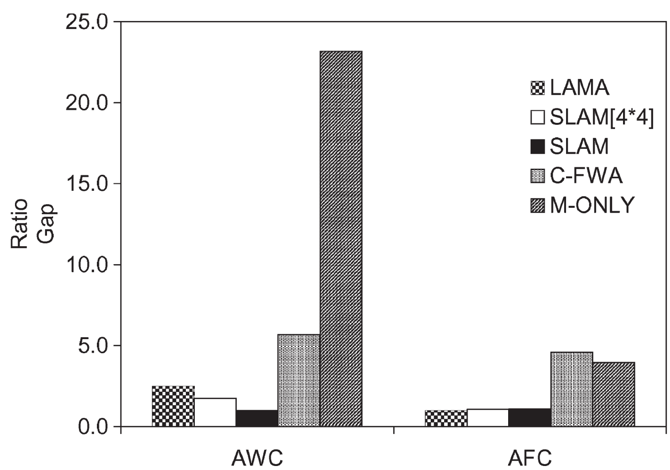

Fig. 14. Comparative evaluation of algorithms in terms of AWC and AFC for Design 2.

for SBP than SLAM. The same relationship is valid between SLAM and LAMA as well.

VI. SLAM FOR LARGE-SIZE PROBLEMS

In Experimental Design 3, we compare SLAM, C-FWA, and M-ONLY for large-size problems with 128 layers (F/W: 1/128, 2/64, 4/32). Not only CPLEX but also LAMA cannot solve large-size problems. Thus, all upper bounds are determined with respect to the best solution obtained by any heuristic.

Experimental Design 3: SLAM versus C-FWA and M-ONLY
D: $\{3, 4\}$ (2)
N: $\{30\}$ (1)
F/W: $\{1/128, 2/64, 4/32\}$ (3)
$R_{\mathrm{wc}} = R_{\mathrm{ls}}$: $\{0, 0.5, 1\}$ (3)
S: $\{128, 512\}$ with ten different multicast sets (20)
R_{mn}: $\{0.2\}$ (1)
Number of experiments: $2.3.3.20 = 360$
Methods: SLAM, C-FWA, and M-ONLY.

We already evaluated the effect of the order of session establishment matrix and the order of sessions and destinations for LAMA in [5]. Similarly, we performed all tests many times by only changing the order of destinations for SLAM, C-FWA, and M-ONLY. All metrics did not change for all methods. Furthermore, we changed both the order of destinations and the sessions; there is no statistically significant difference for any metric and any heuristic. The performance of SLAM for AB, AD, AHWI, AFC, AT, and SBP changes, at most, 0.3% and it changes, at most, 3% for AWC and GBP.

TABLE VII
MEANS AND THE STATISTICAL SIGNIFICANCES FOR DESIGN 3 AND $S = 128$

Methods	SLAM	C-FWA	M-ONLY
AB	12.48 A	12.39 A	12.36 A
AD	3.47 B	3.28 A	3.27 A
AHWI	0.26 A	0.47 B	0.49 B
AWC	0.27 A	1.10 B	4.30 C
AFC	0.53 A	1.44 C	0.76 B
AT	1.26 A	1.50 B	1.48 B

TABLE VIII
MEANS AND THE STATISTICAL SIGNIFICANCES FOR DESIGN 3 AND $S = 512$

Methods	SLAM	C-FWA	M-ONLY
AB	11.67 A	11.53 A	11.53 A
AD	3.35 B	3.10 A	3.10 A
AHWI	0.23 A	0.25 B	0.25 B
AWC	0.31 A	1.49 B	5.54 C
AFC	0.56 A	1.92 B	2.02 B
AT	1.22 A	1.39 B	1.38 B
GBP	11.6	16.1	14.3
SBP	0.2	10.0	9.4

Table VII shows the means and the statistical significance for all metrics, except for GBP and SBP which are zero for light traffic load $(S = 128)$. SLAM performs significantly better than C-FWA and M-ONLY for AHWI, AWC, AFC, and AT. Although C-FWA and M-ONLY, statistically, are significantly better than SLAM for AD, there is no difference for AB, and all competitors are very close for these two metrics.

When we increase S from 128 to 512, blocking starts to occur. Table VIII shows the means and some statistical significance when S is 512. The comparison is exactly the same when we increase the traffic load, except SLAM is slightly better than its competitors for AHWI. Because sessions are blocked, and all wavelength resources are probably consumed. GBP and SBP are the right metrics to quantify the difference of SLAM and the other algorithms when the traffic load is high. For the cases studied, SLAM performs significantly better than M-ONLY and C-FWA for GBP and almost 50 times better for SBP.

SLAM uses 87.7% less wavelength, 17.7% less transmitters, 15.9 times less WC, and 1.4 times less fiber conversion than M-ONLY, and it consumes 80.9% less wavelength, 19.3% less transmitters, 4.1 times less WC, and 2.7 times less fiber conversion than C-FWA when the traffic load is low $(S = 128)$. Similarly, SLAM spends 13.1% less transmitters, 17.9 times less WC, and 3.6 times less fiber conversion than M-ONLY, and it uses 13.8% less transmitters, 4.8 times less WC, and 3.4 times less fiber conversion than C-FWA when the traffic load is high $(S = 512)$. In terms of running time, SLAM spends around 1 s for the routing of one multicast session. Therefore, it is suitable for dynamic multicasting.

TABLE IX
MEANS FOR AB, AD, AND AHWI FOR DESIGN 4

Metric-S	AB		AD		AHWI	
Method	128	512	128	512	128	512
SLAM	12.48	11.65	3.47	3.38	0.265	0.223
W-SLAM	12.76	11.94	3.57	3.51	0.267	0.223
F-SLAM	13.06	12.22	3.69	3.63	0.267	0.223
T-SLAM	12.66	11.78	3.54	3.44	0.265	0.223

TABLE X
MEANS FOR AWC, AFC, AND AET FOR DESIGN 4

Metric-S	AWC		AFC		AET=AT-1	
Method	128	512	128	512	128	512
SLAM	0.27	0.27	0.53	0.52	0.26	0.23
W-SLAM	0.04	0.03	0.58	0.57	0.37	0.36
F-SLAM	0.35	0.36	0.09	0.07	0.48	0.47
T-SLAM	0.31	0.31	0.64	0.62	0.08	0.08

VII. TUNING SLAM FOR THE MINIMIZATION OF TRANSMITTER USAGE, FIBER, AND WC

We have examined the relationship between AB and AD in terms of the optimal solution and tuned LAMA for AHWI in Section IV. SLAM minimizes the blocking probability by setting $R_{\text{fcc}}/R_{\text{wcc}}/R_{\text{tuc}} = 1$, and it also minimizes AHWI by its strategy to select partial layered graphs. In Experimental Design 4, we further search for a possibility to improve the number of transmitters, fiber, and WCs without a performance loss in other metrics by changing the cost structure (specifically the values of $R_{\text{fcc}}/R_{\text{wcc}}/R_{\text{tuc}}$).

Experimental Design 4: Different versions of SLAM
D: $\{3, 4\}$ (2)
N: $\{30\}$ (1)
F/W: $\{1/128, 2/64, 4/32\}$ (3)
$R_{\text{wc}} = R_{\text{ls}}$: $\{0, 0.5, 1\}$ (3)
S: $\{128, 512\}$ with ten different multicast sets (20)
R_{mn}: $\{0.2\}$ (1)
$R_{\text{fcc}}/R_{\text{wcc}}/R_{\text{tuc}}$: $\{1/1/1, 2/1/1, 1/2/1, 1/1/2, (1/2)/(1/2)/(1/2), 4/1/1, 1/4/1, 1/1/4, (1/4)/(1/4)/(1/4), 8/1/1, 1/8/1, 1/1/8, (1/8)/(1/8)/(1/8), 16/1/1, 1/16/1, 1/1/16, (1/16)/(1/16)/(1/16), 32/1/1, 1/32/1, 1/1/32, (1/32)/(1/32)/(1/32)\}$ (21)
Number of experiments: $(2.3.3.20).21 = 360.21 = 7560$
Method: SLAM.

If we set one for $R_{\text{fcc}}/R_{\text{wcc}}/R_{\text{tuc}}$, then all four cost terms (delay, transmitters, fiber, and WCs) are equally important. We can favor the AD metric by a factor of x by setting $R_{\text{fcc}}/R_{\text{wcc}}/R_{\text{tuc}} = 1/x$. Similarly, we can favor the average WC metric by a factor of x by setting $R_{\text{fcc}} = R_{\text{tuc}} = 1/R_{\text{wcc}} = x$. In the experimental design, we increase x by a factor of two each time so that we can determine the threshold after which no significant improvement is observed. The results indicate that delay cannot be improved any further and that the number of transmitters, fiber, and WCs metrics do not improve after x is eight. Therefore, specific names are given for these three versions in Section II-B. Table IX denotes the performances of SLAM, W-SLAM, F-SLAM, and T-SLAM for AB, AD, and AHWI, and Table X shows the performances of SLAM, W-SLAM, F-SLAM, and T-SLAM for AWC, AFC, and AET$(= \text{AT} - 1)$.

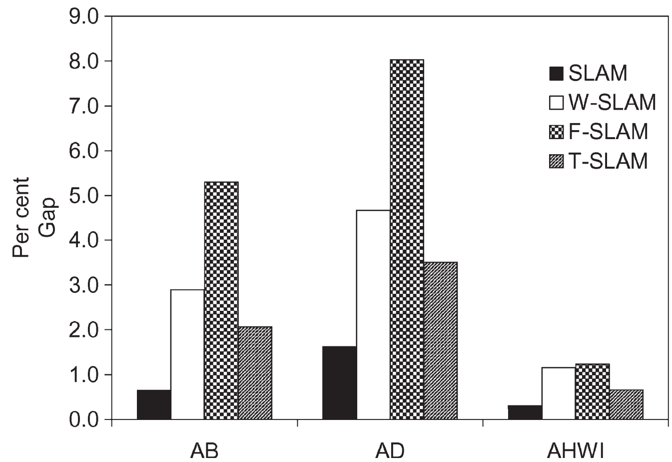

Fig. 15. Comparative evaluation of algorithms in terms of AB, AD, and AHWI for Design 4 and $S = 128$.

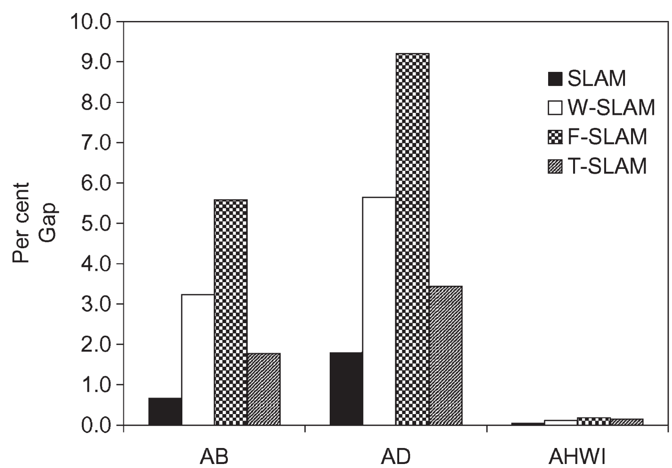

Fig. 16. Comparative evaluation of algorithms in terms of AB, AD, and AHWI for Design 4 and $S = 512$.

Figs. 15 and 16 compare all methods for AB, AD, and AHWI metrics for $S = 128$ and $S = 512$, respectively, with respect to the upper bound (the best SLAM version (out of 21) for this metric). SLAM differs from the upper bound by less than 2% for AD, 1% for AB, and 1% for AHWI. Similarly, T-SLAM differs from the upper bound by 3% for AD, 2% for AB, and 1% for AHWI. Fig. 17 compares all methods for blocking probabilities. SLAM and T-SLAM perform almost the same for GBP and SBP. Figs. 18 and 19 are for AWC, AFC, and AET metrics. T-SLAM spends from three to six times less extra transmitters than SLAM and it only needs one extra transmitter for 12–13 sessions. W-SLAM reduces the number of WCs from six to ten times, and F-SLAM reduces the number of fiber conversions from six to eight times. However, the performances of W-SLAM and F-SLAM in other metrics are adversely affected, but T-SLAM performs very close to SLAM for these metrics.

VIII. CONCLUSION AND FUTURE WORK

We previously proposed a MILP formulation that utilizes a layered-graph approach for multicasting in all-optical wavelength-routed WDM WAN with multifibers and sparse

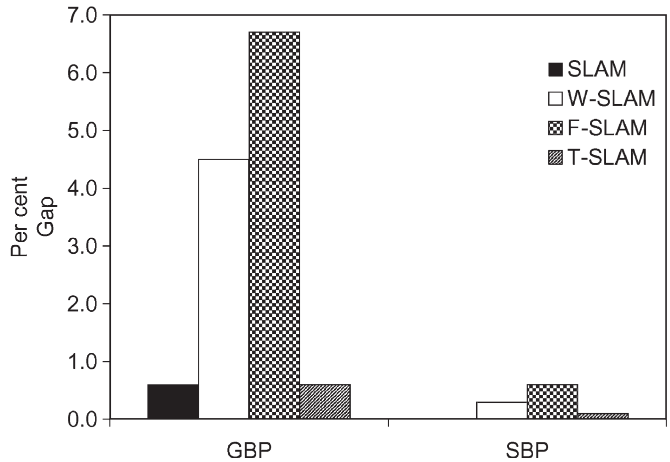

Fig. 17. Comparative evaluation of algorithms in terms of GBP and SBP for Design 4 and $S = 512$.

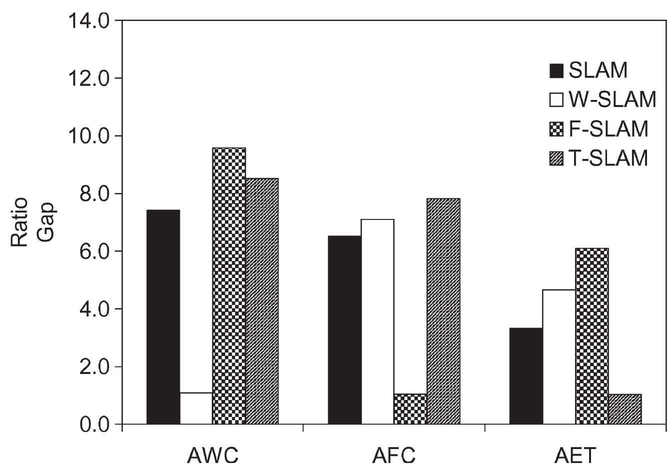

Fig. 18. Comparative evaluation of algorithms in terms of AWC, AFC, and AET for Design 4 and $S = 128$.

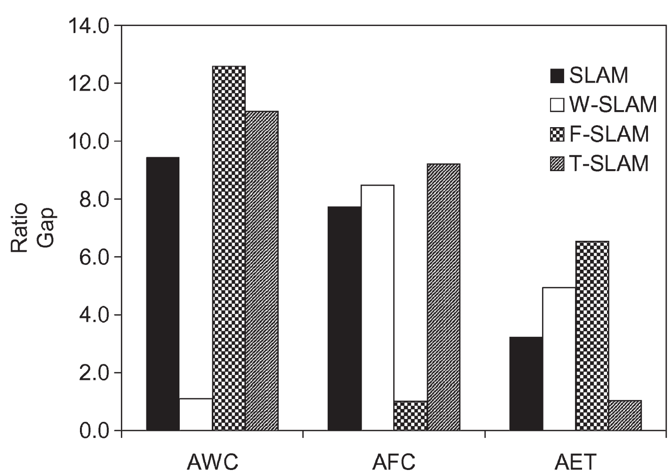

Fig. 19. Comparative evaluation of algorithms in terms of AWC, AFC, and AET for Design 4 and $S = 512$.

WC and LS-capable routers. The formulation combines four different cost terms: delay, wavelength and fiber conversion costs, and the transmitter usage cost, and we can play with the relative importance of these cost terms by changing their weights. Either these parameters could be adjusted to reflect the underlying relative cost of these operations so that all four different cost terms can be minimized simultaneously or they can be used to optimize specific metrics. LAMA and C-FWA heuristics were also proposed for the solution in addition to the CPLEX solutions of the MILP formulation [5]. However, LAMA was not suitable for large and dynamic multicasting problems.

TABLE XI
SOLUTION METHODOLOGY FOR DIFFERENT SIZE AND TYPE OF PROBLEMS

Size/Type	Static	Dynamic
Very small	CPLEX/LAMA	LAMA
Small	CPLEX/LAMA	LAMA
Medium	LAMA/SLAM	SLAM
Large	SLAM	SLAM/C-FWA

In this paper, we show that SLAM performs very close to the optimal (the LB/CPLEX) and LAMA and significantly better than M-ONLY and C-FWA in terms of nearly all metrics, since it does not separate routing and fiber-wavelength assignment steps as compared to the other candidates like M-ONLY and C-FWA. Similar to LAMA, SLAM is very flexible. It can minimize AB, AD, or both with respect to the cost assignment for the wavelength resources. Additionally, T-SLAM can use three times less extra transmitters than SLAM, without a performance loss in other metrics (one extra transmitter for 12 multicast sessions). W-SLAM and F-SLAM show the same reduction in AWC and AFC metrics, respectively. However, they are slightly worse than SLAM in AB, AD, and GBP metrics. SLAM minimizes AHWI by its default partial-graph-selection criteria (lower wavelength). It can also minimize the number of fibers used with the lower fiber strategy. Therefore, the adjustable parameters of SLAM make it very flexible to balance different objectives. Finally, SLAM is scalable and suitable for any size static or dynamic problems.

A very small problem contains up to four layers (e.g., F/W: 1/4, 2/2). Similarly, there are, at most, eight layers for a small problem, 32 layers for a medium problem, and 128 or more (no restriction) layers for a large problem. We currently solve very small problems to optimality using CPLEX for all traffic loads and small problems to optimality or near optimality for light-traffic conditions. Similarly, LAMA can easily solve medium-sized problems, but it is not suitable for large and dynamic problems, which can only be handled by SLAM. In general, we propose SLAM for all cases, but SLAM is similar to LAMA for small problems. Table XI includes a more detailed methodology. We propose to use CPLEX for small static problems, but LAMA and CPLEX can be run together, and the solution of LAMA is used if CPLEX cannot produce a solution. Similarly, LAMA and different versions of SLAM can be used together to choose the best solution in terms of desired metric for medium-sized static problems. The running time of SLAM for one session is around a second, and it is suitable for all dynamic problems. However, C-FWA can be used if extremely fast response is needed.

LAMA and SLAM are very flexible heuristics, and the current versions can solve the multicasting problem on networks having multifiber and nodes with sparse or FWC and LS capabilities. Moreover, these versions can also handle LWC property of nodes by applying WC rules to the layered graph. Similarly, we are using LS restrictions for each node. If a node has no splitting capability, then the number of its outgoing connections should be one, and if it is an FLS node, then the number of its outgoing connections should be equal to the number of its outgoing links. Therefore, we need to update the number of outgoing connections of each node with its LLS capability to solve the LLS version of the problem. Similar adjustments can also be done for CPLEX either by changing the layered graph that it works and/or the sparse-splitting constraint.

We already evaluated the order of session establishment matrix (the order of sessions and destinations) to generalize from static to dynamic case. However, a dynamic simulator module needs to be developed for further dynamic experimentation. Another line of research may be extended to incorporate the QoS issues by adding the delay constraints for the given multicast sessions. The jitter metric will be added to the metric portfolio. All heuristics are dynamic, and we can check the delay of the added destination against the delay of the shortest path. The node is considered to be added to another tree if the gap is above a certain threshold. This could be jitter-aware version of our heuristics. Power-aware versions can limit the number of destinations to at most k as in the multidrop model which allows at most k destinations.

REFERENCES

[1] L. H. Sahasrabuddhe and B. Mukherjee, "Light-trees: Optical multicasting for improved performance in wavelength-routed networks," *IEEE Commun. Mag.*, vol. 36, no. 2, pp. 67–73, Feb. 1999.

[2] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath communications: An approach to high bandwidth optical WAN's," *IEEE Trans. Commun.*, vol. 40, no. 7, pp. 1171–1182, Jul. 1992.

[3] X. Zhang, J. Y. Wei, and C. Qiao, "Constrained multicast routing in WDM networks with sparse light splitting," *J. Lightw. Technol.*, vol. 18, no. 12, pp. 1917–1927, Dec. 2000.

[4] M. J. O'Mahony, C. Politi, D. Klonidis, R. Nejabati, and D. Simeonidou, "Future optical networks," *J. Lightw. Technol.*, vol. 24, no. 12, pp. 4684–4696, Dec. 2006.

[5] F. Koksal and C. Ersoy, "Multicasting for all-optical multifiber networks," *J. Opt. Netw.*, vol. 6, no. 2, pp. 219–238, Feb. 2007.

[6] A. Hamad, T. Wu, A. E. Kamal, and A. K. Somani, "On multicasting in wavelength-routing mesh networks," *Comput. Netw.*, vol. 50, no. 16, pp. 3105–3164, Nov. 2006.

[7] Y. Zhou and G. S. Poo, "Optical multicast over wavelength-routed WDM networks: A survey," *Opt. Switch. Netw.*, vol. 2, pp. 176–197, 2005.

[8] I. Ferrel, A. Mettler, E. Miller, and R. L. Hadas, "Virtual topologies for multicasting with multiple originators in WDM networks," *IEEE/ACM Trans. Netw.*, vol. 14, no. 1, pp. 183–190, Feb. 2006.

[9] O. Yu and Y. Cao, "Placement of light splitters and wavelength converters for efficient multicast in all-optical WDM networks," *IEICE Trans. Inf. Syst.*, vol. E89-D, no. 2, pp. 709–718, Feb. 2006.

[10] I. S. Hwang, S. Lee, and Y. Chuang, "Multicast wavelength assignment with sparse wavelength converters to maximize the network capacity using ILP formulation in WDM mesh networks," *Photon. Netw. Commun.*, vol. 12, no. 2, pp. 161–172, Sep. 2006.

[11] J. Wang, X. Qi, and B. Chen, "Wavelength assignment for multicast in all-optical WDM networks with splitting constraints," *IEEE/ACM Trans. Netw.*, vol. 14, no. 1, pp. 169–182, Feb. 2006.

[12] G. Poo and Y. Zhou, "A new multicast wavelength assignment algorithm in wavelength-routed WDM networks," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 4, pp. 2–12, Apr. 2006.

[13] *ILOG CPLEX: High-Performance Software for Mathematical Programming and Optimization*, 2006. [Online]. Available: http://www.ilog.com/products/cplex/

[14] L. H. Sahasrabuddhe and B. Mukherjee, "Multicast routing algorithms and protocols: A tutorial," *IEEE Netw.*, vol. 14, no. 1, pp. 90–102, Jan./Feb. 2000.

[15] S. Xu, L. Li, and S. Wang, "Dynamic routing and assignment of wavelength algorithms in multifiber wavelength division multiplexing networks," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 10, pp. 2130–2137, Oct. 2000.

[16] T. Cinkler, D. Marx, C. P. Larsen, and D. Fogaras, "Heuristic algorithms for joint configuration of the optical and electrical layer in multi-hop wavelength routing networks," in *Proc. IEEE INFOCOM*, 2000, vol. 2, pp. 1000–1009.

[17] G. Maier, A. Pattavina, L. Roberti, and T. Chich, "Static-lightpath design by heuristic methods in multifiber WDM networks," in *Proc. OPTICOMM*, 2000, vol. 4233, pp. 64–75. No. 1.

[18] R. Jain, *The Art of Computer Systems Performance Analysis*. Hoboken, NJ: Wiley, 1991.

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