MULTICASTING FOR ALL-OPTICAL MULTIFIBER NETWORKS

by

Fatih Köksal

B.S, in Computer Engineering, Boğaziçi University, 1998

M.S, in Computer Engineering, Boğaziçi University, 2000

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy

Graduate Program in Computer Engineering

Boğaziçi University

2007

MULTICASTING FOR ALL-OPTICAL MULTIFIBER NETWORKS

APPROVED BY:

Prof. Cem Ersoy (Thesis Supervisor)	....
Prof. Kuban Altınel	....
Prof. M. Ufuk Çağlayan	....
Asist. Prof. Ayşegül Gençata	....
Assoc. Prof. Can Özturan	....

DATE OF APPROVAL: 20.07.2007

For my father

ACKNOWLEDGEMENTS

The thesis has written with minimalism. Though, it was very hard to keep the same spirit, when it comes to thank people. Minimalism leads to clarity, in which every world tell as William Strunk put in the elements of style, and further lessen the suffering of my advisor, Prof. Cem Ersoy, head of our department, graduate advisor of nine other people like me. I really did not know how to thank him for his efforts that he has put on this work, having fun with us, giving courage, support, friendliness and motivation. Then, I tried to drink less at the perfect party that he organized, when everything was over. I also thank Prof. Lale Akarun for always being kind and helpful, not only to me but also to all students around. Finally, thank you Ayça for sharing your bear costume, but you still owe me a kiss.

The jury significantly improved the thesis. I thank Prof. Kuban Altınel for shaking me when I most needed, Prof. M. Ufuk Çağlayan for making me tough, Asist. Prof. Ayşegül Gençata for being kind and grace, and Assoc. Prof. Can Özturan for helping me with modesty.

My family was always with me and they will be with me too whenever I think of them. Thank you father, mother and my brother to help me become what I want to become again and again, since there is no ”I”, which needs further redefinition, again and again, throughout life. Thank you Pelin, you always helped me when I was suffering. And thank you my friends: Ali, Kerem, Ertan, İlker, Atay, Rabun, Hendrik, Sanem, and all the others whom I forgot. Finally, thanks to Ali Nesin for his beautiful preface in Matematik Dünyası (Kış 2005) and Bart Kosko for his eloquent quote in the preface of Fuzzy Thinking: ”For the young men and women who stick with their training while their youth calls. It’s hard, it will get harder, but it turns the world.”

ABSTRACT

MULTICASTING FOR ALL-OPTICAL MULTIFIBER NETWORKS

We propose to use a layered graph approach, which has been previously proposed for unicasting, 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 all-optical multicasting with sparse light splitting and wavelength conversion restrictions so that it is formulated as an original Mixed Integer Linear Programming (MILP). The MILP formulation is solved by CPLEX which finds the optimal solution within a given precision and it also gives a lower bound by relaxing the integrality constraints. However, it is possible to solve MILP problems to optimality only for small networks and number of sessions, since the problem is NP-hard. Therefore, we also propose three different heuristics (LAMA, SLAM and C-FWA) for larger problems and dynamic multicasting requests. Extensive computational experiments demonstrate that LAMA and SLAM perform close to the optimal and better than their competitor (M-ONLY) for all metrics. However, LAMA and SLAM work better than their alternatives, since we jointly optimize routing and fiber-wavelength assignment phases compared to the other candidates which attack to the problem by decomposing two phases. Experiments show that important metrics (e.g. the session and group blocking probabilities, wavelength and fiber conversions, transmitters) are adversely affected by the separation of routing and fiber-wavelength assignment. SLAM, which is the scalable version of LAMA, performs close or better to LAMA. SLAM can be applied to static or dynamic all-optical multicasting problems of any size. Finally, we also propose a new fiber-wavelength assignment strategy (Ex-Fit in C-FWA) which uses wavelength and fiber conversion resources more effectively than the First Fit.

ÖZET

TÜM-OPTİK ÇOK FİBERLİ AĞLAR İÇİN ÇOĞA GÖNDERİM

Bu tezde daha önce teke gönderim için önerilen çok katmanlı çizge yaklaşımını tüm-optik çok fiberli ağlarda çoğa gönderim için öneriyoruz. Bu yaklaşım daha genel, gerçekci ve esnek bir modelleme sağlamakta ve problemi nadir ışık bölme ve dalgaboyu dönüştürme kısıtlarıyla bir matematiksel formülasyona (MILP) kavuşturmaktadır. Problem CPLEX tarafından çözülüp ya verilen hassasiyette en iyi sonuç yada alt sınır küçük ağlar ve gruplar için elde edilebilir. Fakat büyük problemler ve dinamik çoğa gönderim ihtiyaçları için üç buluşsal metot önerilir (LAMA, SLAM ve C-FWA). Çok sayıda deney LAMA ve SLAM'in en iyiye yakın ve rakibinden (M-ONLY) daha iyi olduğunu bütün metrikler için göstermektedir. LAMA ve SLAM'in iyi çalışmasının sebebi rakipleri gibi rotalama ve fiber-dalgaboyu atama safhalarını ayırmayıp birlikte eniyilemeye çalışmasıdır. Bu sebeple önemli tüm metrikler (kullanıcı ve grup tıkanma olasılıkları, dalgaboyu ve fiber dönüştürme, gönderici sayısı) bu safhaların ayrılmasından negatif bir şekilde etkilenmektedir. LAMA'nın ölçeklenebilir versiyonu olan SLAM LAMA'ya yakın bazen de ondan iyi sonuç verir ve herhangi bir büyüklükteki statik yada dinamik tüm-optik çoğa gönderim problemlerini çözer. Son olarak önerilen yeni fiber-dalgaboyu atama stratejisi (C-FWA'deki Ex-Fit) First-Fit stratejisinden daha az fiber ve dalgaboyu dönüştürme kaynaklarını harcamaktadır.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

c_{ij}	Cost between nodes i and j in the layered graph
D	Average nodal degree
D_{min}	Minimum nodal degree
D_{max}	Maximum nodal degree
E	Number of edges
E'	Set of all links
E''	Set of all links except the ones with zero costs
E'''	Set of wavelength channel links among the same layer
F	Number of fibers
$G(V, E)$	Graph G with vertex set V and the edge set E
H	Average internodal distance
k	Index for the number of multicast sessions
L	Number of bidirectional links
M	Number of multicast nodes
M'_k	k^{th} multicast set excluding the source
M''	Set of multicast session sets
N	Number of nodes
N_{ls}	Number of nodes which have full light splitting property
N_{wc}	Number of nodes which have full wavelength conversion property
P_C	Physical connectivity
R	Network diameter
R_{ls}	Number of full light splitting capable nodes
R_{mn}	Fraction of multicast nodes
R_{wc}	Number of full wavelength conversion capable nodes
R_{fcc}	Fiber conversion cost ratio
R_{tuc}	Transmitter usage cost ratio
R_{wcc}	Wavelength conversion cost ratio
S	Number of multicast sessions

S_S	Set of nodes which have sparse splitting property
S_C	Set of nodes which have sparse conversion property
u_k	First node (source) in the k^{th} multicast set M_k
V'	Set of all nodes (it includes the main and the sub-nodes)
V''	Set of sub-nodes
W	The number of wavelengths

AB	Average Bandwidth
AD	Average Delay
AFC	Average Fiber Conversion
AHWI	Average Highest Wavelength Index
ART	Average Running Time
AT	Average Tree (Transmitter)
AWC	Average Wavelength Conversion
C-FWA	Conservative Fiber and Wavelength Assignment
DLE	Dynamic Lightpath Establishment
FDDI	Fiber Distributed Data Interface
FLAMA	Fast Layered All-optical Multicasting Algorithm
FLS	Full Light Splitting
FWC	Full Wavelength Conversion
GBP	Group Blocking Probability
GPRS	General Packet Radio Service
kEDSP	k Edge-disjoint Degree-constrained Steiner Tree Problem
LAMA	Layered All-optical Multicasting Algorithm
LAN	Local Area Network
LB	Lower Bound
LLS	Limited Light Splitting
LWC	Limited Wavelength Conversion
MC-RFWA	Multicasting version of R-FWA
MILP	Mixed Integer Linear Programming
M-ONLY	Member-ONLY

MST	Minimum Steiner Tree
NLS	No Light Splitting
NWC	No Wavelength Conversion
OBS	Optical Burst Switching
QoS	Quality of Service
R-FWA	Routing and Fiber-Wavelength Assignment
SBP	Session Blocking Probability
SLAM	Scalable Layered All-optical Multicasting
SLE	Static Lightpath Establishment
TC	Total Cost
UMTS	Universal Mobile Telecommunications System
VTD	Virtual Topology Design
VTR	Virtual Topology Reconfiguration
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WIXC	Wavelength Interchange Crossconnects
WLAN	Wireless Local Area Network
WSXC	Wavelength Selective Crossconnects

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) [1,2]. However, these networks are the last category in the evolution of networking: The first generation networks were mainly copper-based in the physical layer and all the switching and transmission issues were solved in the electronic domain. In the second generation, e.g. Fiber Distributed Data Interface (FDDI) and Gigabit Ethernet, copper based wires were replaced by optical fibers, but switching was still realized in the electronic domain, that is, the data in the optical domain should be transferred to the electronic domain and then back to the optical domain and sent through fibers, after performing necessary routing decisions. Thus, it was not possible to fully utilize the power of optical networks, since optical fiber can supply bandwidth on the order of 50 THz, while the peak electronic speed is only a few gigabits per second. Hamad *et al.* [3] state that less than 0.1 per cent of the fiber's 50 THz bandwidth is used. Finally, third generation networks have emerged by dividing the optical fiber bandwidth into many non-overlapping channels so that each channel corresponds to a different wavelength (frequency) and they can operate at peak electronic speed [4]. This approach is called wavelength division multiplexing (WDM).

An optical network topology is single-hop, if data stays on the optical domain without opto-electronic processing at intermediate devices [5]. Similarly, traffic from a source node to a destination node undergoes opto-electronic conversions, possibly more than one, at intermediate nodes in multihop optical networks [6,7]. WDM multicast is currently implemented by using IP layer multicast protocols like DVMRP (Distance-Vector Multicast Routing Protocol), CBT (Core-Based Trees), OSPF (Open Shortest Path First), or PIM (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 O/E/O (optical/electrical/optical) 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. Coding-format and bit-rate transparency are the other advantages of all-optical multicasting [8]. Thus, we specifically worked on all-optical networks, but our problem formulation and solution techniques are also applicable to optical networks.

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 [9]: In Optical Burst Switching (OBS), the data is carried via OBS in a more bursty fashion that is suitable for relatively short duration of dense transportation [10]. In Wavelength-routed WDM, the multicast data is carried over a logical topology (or virtual topology) which is more stable than OBS. Therefore, it is best suited for long duration of dense transportation like in [11].

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. The input of the problem, Virtual Topology Design (VTD) Problem, is an existing physical topology, a description of the average traffic exchanged by sources and sets of destinations, and a multi-hop routing strategy (defined both for unicast and multicast flows), and the output is the logical topology that minimizes a target function or cost [12]. In VTD, the configuration is done once and the topology does not change after this configuration for a very long time. In the dynamic version of the problem, Virtual Topology Reconfiguration (VTR), the current traffic requirements (traffic matrix) may change from time to time and a new configuration should be established [13].

An all-optical channel, a lightpath, is created between the source and the destination for unicast communication [14]. Figure 1.1 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 Figure 1.1 in which the lightpaths share common links with the light-tree, but they are using different wavelengths. The lightpath establishment can be done in two ways in terms of traffic characteristics. If traffic pattern is static then all lightpaths are established together and network continues to operate with these lightpaths. This is called Static Lightpath Establishment (SLE). In the other case, the traffic pattern may change frequently and lightpaths should be established and released dynamically. This is called Dynamic Lightpath Establishment (DLE). Nowadays, traffic demand is highly fluctuating and it is a challenge to develop efficient algorithms and protocols for establishing these lightpaths [15].

The type of traffic for lightpath establishment, Routing and Fiber-Wavelength Assignment, R-FWA, is important for the optimal solution of the problem. Thus, the ratio of unicast to multicast traffic is critical to choose the right algorithm [16]. A point-to-multipoint extension of the lightpath concept, a light-tree, is proposed to better support the multicast and the broadcast traffic [4] (see Figure 1.1 for a light-tree example). Similarly, MC-RFWA is a multicasting version of R-FWA. The difference between static and dynamic MC-RFWA is similar to the difference between VTD and VTR.

The capability of optical elements may severely affect the performance of a network in terms of multicasting. Thus, we review some optical components shortly [17]: There are two types of transmitters: Tunable transmitters are less restricted and they have either lasers whose output wavelength can be tuned as a need arises, or an array of lasers with different wavelengths that can be selectively enabled. Fixed transmitters have lasers whose wavelengths are set during manufacturing. Similarly, receivers can be tunable or fixed in the wavelengths they can receive. Burst-mode receivers can syn-

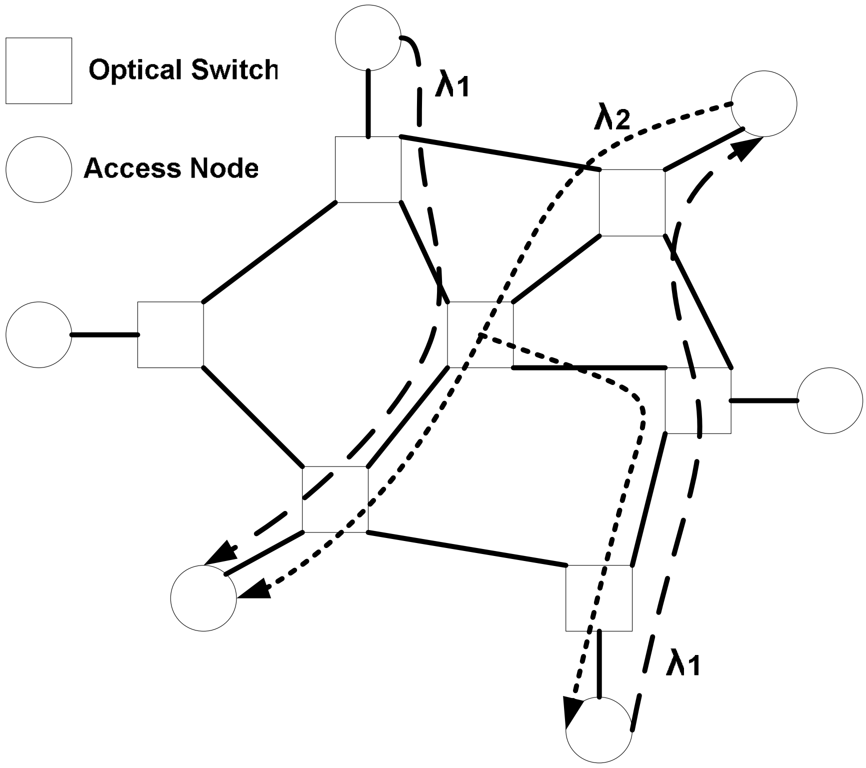

Figure 1.1. An example of a wavelength-routed WDM network with two lightpaths on the first wavelength and a light-tree on the second wavelength established over the physical topology

chronize to a transmitters signal very rapidly, allowing their use with transmitters that send bursts of data (alternating with silences), unlike continuous-mode receivers that have slow synchronization times and hence require the transmitter to send a continuous signal.

The main switching elements are called wavelength interchange crossconnects (WIXCs) and wavelength selective crossconnects (WSXCs) and the difference is that wavelength conversion capability is present for WIXCs which are less restricted and different wavelengths may be used in a lightpath or a light-tree. Another issue related with the capabilities of switching elements is that they may not have full splitting capability, that is, the power loss due to splitting prevent a switch to multiply the incoming packet to more than one outgoing links, if it is not supplied with the necessary equipment. Briefly, a switch may have no, limited or full wavelength conversion

(NWC/LWC/FWC) and light splitting capabilities (NLS/LLS/FLS). 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.

Figure 1.2 demonstrates different examples for the capabilities of switching elements. In Figure 1.2a, 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 Figure 1.2b, since the switch has limited wavelength conversion capability. Moreover, there is no restriction for the converted wavelengths in Figure 1.2c, since the switch has FWC. However, none of the switches has any light splitting capabilities in those examples. In contrast, the switches in Figures 1.2e-f-g-h have full light splitting 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 wavelength conversion capability of the switch and whether the light splitting is after or before the wavelength conversion as exemplified in Figures 1.2f-g-h. If the wavelength conversion is after the light splitting, the wavelength assignment becomes more flexible with the disadvantage of using more wavelength converters. Finally, the switch in Figure 1.2d has limited light splitting 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.

The advances in switching elements, which can perform all switching in purely optical domain nowadays, have increased the available bandwidth, but they have posed some other problems. Since some of the jobs which are easily performed in electronic domains are highly problematic for optical networks. For example, the buffering of incoming data is quite easy for electronic networks but not for optical ones. Thus, it is needed to configure optical devices across a network and establish all optical connections in this wavelength routed WDM network. If it is not possible to use

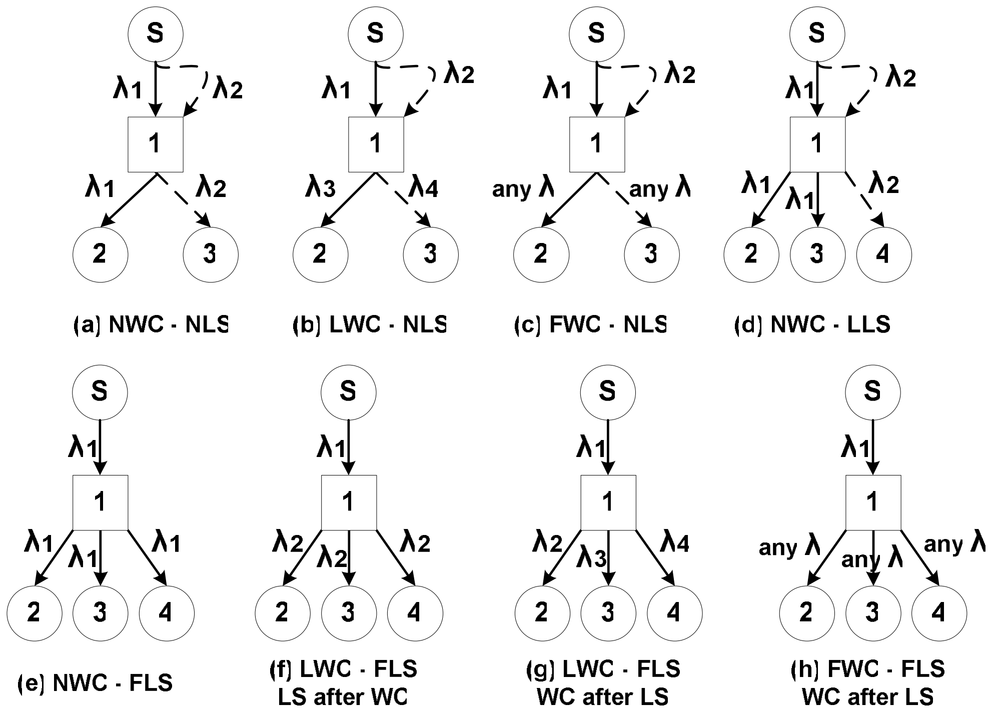

Figure 1.2. Capabilities of switching elements. If Node 1 is LWC, it can do conversion among first four wavelengths, and if Node 1 is LLS, it can split to two output links

wavelength conversion capable switching elements, then the same wavelength has to be used in the fiber links of a lightpath. This problem is called wavelength continuity constraint.

In a general multicasting problem, a sender tries to send the copies of a message to some of recipients in a network by trying to minimize some of the network resources. If the message should be sent to all the members of a network, then the multicasting problem degenerates to a special case that is called broadcasting and it can be solved by applying the minimum spanning tree algorithm in polynomial time. The other degenerate case is that there might be only one recipient in the network and the application of shortest path algorithm gives the minimum cost path between these two nodes. However, the general multicasting problem can be solved to optimality only by constructing the minimal Steiner Tree that includes all the recipients and possibly some other nodes as well, and this problem is known to be one of the NP-complete problems of graph theory [18, 19]. Moreover, the Multicasting to Groups (MG) problem in a WDM optical network is also NP-complete and cannot be approximated within a logarithmic factor [20].

In [21], 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, fairness. Therefore, another important characteristic of a multicast routing algorithm is its dynamic ability to adapt changes in a multicast group, that is, some recipients may actively join in or leave from the multicast group. In this case, construction of a multicast tree for all changes might not be the best thing to do, since there can be big differences between the old and the new tree and the whole group may be affected by these changes. Thus, the new tree should be as close as possible to the old one [22].

1.1. Research Overview and Contributions

After mentioning the motivation behind all-optical networking and the basic terminology in this research area, we examine the main issues related with the characteristic of the multicasting: 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.

New solutions in multicasting domain would usually come from the ideas in unicasting domain. Similarly, we propose to use a layered graph approach, which has been previously proposed for unicasting, 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 multicasting for all-optical multifiber networks with sparse light splitting and wavelength conversion restrictions so that it is formulated as an original Mixed Integer Linear Programming (MILP) as described in Chapter 4.1. The MILP formulation is solved using CPLEX which is a state of the art optimization tool [23]. CPLEX finds the optimal solution within a given precision and it also gives a lower bound by relaxing the integrality constraints. However, it is possible to solve MILP problems to optimality only for small networks and number of sessions, since the problem is NP-hard (Chapter 3). Therefore, we also propose three different heuristics (LAMA, SLAM and C-FWA) for larger problems and dynamic multicasting requests. Extensive computational experiments demonstrate that LAMA and SLAM perform close to the optimal and better than their competitor (M-ONLY) [8] for all metrics. However, the main contribution is to demonstrate that LAMA and SLAM work better than their alternatives, since we jointly optimize routing and fiber-wavelength assignment phases compared to the other candidates which attack to the problem by decomposing two phases. Experiments show that important metrics (e.g. session and group blocking probability, transmitter wavelength and fiber conversion resources) are adversely affected by the separation of routing and fiber-wavelength assignment phases in multicasting. SLAM, which is the scalable version of LAMA, performs close to (or sometimes better than) LAMA. SLAM can be applied to static or dynamic all-optical multicasting problems of any size in terms of fibers and wavelengths. Finally, we also propose a new fiber-wavelength assignment strategy (Ex-Fit in C-FWA) which uses wavelength and fiber conversion resources more effective than the First Fit, if we have to separate two phases.

1.2. Thesis Outline

The rest of the thesis is organized as follows: Chapter 2 covers the related work in the literature. Chapter 3 describes the problem definiton, mathematical formulation and the underlying assumptions. Chapter 4 is devoted to solution techniques and experiment design is explained in Chapter 5. The computational experiments for LAMA and SLAM is covered in Chapters 6 and 7, respectively. The effects of the number of fibers/wavelengths and the wavelength conversion or light splitting properties of the switches are examined in Chapter 8. Finally, Chapter 9 summarizes the conclusions and has a discussion about future works.

2. MULTICASTING OVER WDM NETWORKS

Malli *et al.* [24] suggest that multicasting in all-optical networks should be handled separately instead of dividing it into separate unicast traffic and send it via a unicasting protocol. These issues are studied in a simulation environment and it is concluded that with a reasonably large multicasting group size, multicasting can reduce the bandwidth consumed by around 50 per cent which also motivates our research. However, this work does not consider dynamic multicast groups, multiple fibers, nodes with limited wavelength conversion and/or limited splitting capability, or nodes that have the sparse wavelength conversion and/or the sparse splitting capabilities but are distributed non-uniformly.

2.1. Single and Multi-hop

In WDM local area networks, a passive star coupler (PSC) is used as a broadcast medium to connect all the nodes in the network and any path from source to destination is purely optical, that is, there is no need for electro-optic conversion [25]. These networks are called single-hop networks. In [26], a multicasting protocol is suggested for single-hop optical WDM networks and theoretical and practical performance are measured, but exact theoretical analysis is still an open problem. They also suggest that partitioning large multicasts into a number of smaller multicasts by using multiple receivers per node can increase the parallelism and improve the performance. This idea is realized and the receiver waiting time is decreased, but usage of bandwidth is also increased in [27]. However, it is stated that this idea may not produce the best result and it depends on traffic conditions and some other factors. Thus, a hybrid algorithm is proposed and shown to be working better in [28].

In [29], a new technique for multicasting is proposed and the idea is based on virtual receivers that behave identically in terms of tuning. They also combine both uses of channel bandwidth and wavelength throughput objectives so that partitioning the set of physical receivers into virtual receivers' problem is formulated. Since, it is proved to be an NP-complete problem; a number of heuristics are developed. This formulation is tried to be improved by further applying tabu search to the first solution obtained [30]. Since single-hop networks are quite simple than multi-hop systems in terms of complexity, upper bound analysis on the performance of single-hop optical networks can be studied [31]. The effect of combined unicast and multicast traffic is examined in [32]. The reconfiguration issue for receivers (this is mostly assumed to be negligible) in terms of multicasting is studied in [33]. In [34], the problem of minimizing the number of wavelengths is considered for one multicast session for multi-hop WDM optical networks. Yang and Liao formulated their problem as a static VTD with the objective of minimizing end-to-end delay, then optimal placement of power splitters and wavelength converters are obtained [35]. They allow multi-hop traversing, i.e., electro-optical conversion which is not allowed in our formulation.

Regular topologies have advantages in terms of routing and fiber wavelength assignment strategies and it is easier to have analytical results because of the well determined structure of the network. Thus, Scheutzow *et al.* present an analytical model to investigate the mean hop distance of shortest path routing in bidirectional optical WDM ring networks for multicast traffic [36]. Mukherjee and Tridandapani provides a general method using channel sharing to construct practical multi-hop networks for multicast traffic and the method is applied to a generalized shuffle-exchange based multihop architectures, called GEMNET [37]. Ferrel *et al.* work on finding virtual topologies for multicasting in the WDM network which satisfies the constraints on available resources and they minimize the maximum hop distance for the cases of unidirectional paths and rings [38]. Wang and Yang examine the upper and lower bounds on the minimum number of wavelengths required for all-optical regular topologies and they stress the importance of using light splitting switches to reduce the number of wavelengths for multicasting [39]. In [40], a simple and efficient multicast scheduling algorithm is proposed in an asynchronous WDM optical star network. Finally, Jeyakumar *et al.* suggest to use genetic algorithm for optimal design of delay bounded WDM multicast networks [41]. They first find a virtual topology that can meet the delay constraints, then embedding of virtual rings into physical links is carried out, followed by an assignment of wavelengths to virtual links.

2.2. IP over WDM (OBS)

This group of work in the literature mainly focuses on the development of some protocols to work with multicasting in different network structures. Multicasting in IP over WDM networks can be done via IP multicast, multiple WDM unicast, or WDM multicast. And there are two different WDM multicasting approaches; one based on wavelength routing and the other is based on optical burst switching (OBS) [42]. IP over WDM multicasting issues can be found in [43–50].

2.3. WDM Multicasting

Recent comprehensive surveys on optical multicasting over wavelength-routed WDM networks are given in [51, 52]. The basic formulation for a multicasting problem in all-optical networks is a modification of routing and wavelength assignment (RWA) problem with the consideration of multicasting issues. In [16], Steiner Minimum Tree (SMT) based hybrid algorithms are proposed and results are examined in different traffic combinations (unicast and multicast). The result also stress that the ratio of unicast to multicast traffic is very important for the performance of a multicasting algorithm. Another issue is that there might not be many nodes with splitting capability in the network and a multicast algorithm should consider sparse splitting cases. Thus, wavelength routed multicasting algorithms are compared for these sorts of networks [8, 53]. Lightpath concept can be extended to light-trees to make the virtual topology design problem easier [4].

The static Virtual Topology Design (VTD) problem is examined in terms of multicasting in [54–56]. However, wavelength conversion issues are not examined in [56]. Power loss in WDM networks is an important issue and, [57] and [58] examine multicasting from this perspective. Another static VTD formulation is given in [4], 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 [4]. Yu and Cao study light splitter and wavelength converter placement in all-optical WDM networks to enable optimal provisioning of static and dynamic traffic through efficient multicast connections [59]. A MILP formulation is solved to minimize the total number of wavelength channels required by the multicast requests. Miller *et al.* investigate the problem of finding optimal multicast virtual topologies, with respect to minimizing the maximum hop distance, in wavelength-division multiplexing multicast trees to reduce the complexity of VTD problem [60]. Ali addresses the placement of multicast nodes in wavelength-routed all-optical networks and an analytical model for the approximate blocking probability in multicast networks is developed [61]. He concludes that only a subset of the nodes (50 per cent) need to be multicast capable for acceptable blocking performance. VTD problem is examined in terms of transmission impairments in multi-hop all-optical WDM multicasting networks in [62]. They also propose a multicast capable nodes placement algorithm based on two multicasting routing algorithms called nearest hub first and nearest on tree.

The dynamic multicast routing problem is studied with delay constraints and heterogeneous light splitting capabilities to find an optimal light-forest by Chen et al [63]. Huang *et al.* suggest a new wavelength router architecture with O/E and E/O conversions, which prevent the WDM network being all-optical, for dynamic multicasting [64]. Rammohan and Murty consider to add QoS constraints to the dynamic multicasting problem, but they assume full light splitting and no wavelength converters are available [65]. In [66], Kim *et al.* propose the share index based-dynamic multicast scheduling algorithm to address how to efficiently allocate video transmission channels in wavelength division multiplexed-passive optical network.

In [67], 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 [68]. Their scenario is very similar in terms of setting, but they have only one source that is the video server store and all the other nodes are groups of users. Multicast Routing under Delay Constraint Problem (MRDCP) is defined as Minimal Steiner Tree Problem with different light splitting and delay constraints in [69] for one multicast session. Another approach is given in [70] for efficient use of wavelengths by adding wavelength conversion constraints. In [71], 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 [72], 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 [73], but delay constraints are also added and a distributed algorithm is proposed for the solution. Similar assumptions are also considered in [74] with many fibers and a distributed reinforcement algorithm is proposed.

In traffic grooming, multicast streams that require subwavelength bandwidth groomed on the same wavelength [75]. In our application scenario, we assume that each session occupies one wavelength channel (Section 3.1). Recent advances in traffic grooming can be found in [76–78]. In [79], the sparse splitting case is examined only for one fiber and one multicast (tree) session by minimizing the number of wavelengths used. All nodes have some limited splitting capability without wavelength conversion in [80]. The problem is formulated to optimize mostly quality of service (QoS) based metrics (e.g. maximizing the number of destinations and/or minimizing the wavelength cost), since wavelength conversion and light splitting resources are very scarce in this setting. As a last, Singhal *et al.* [81] also work on traffic grooming and propose a fast heuristic for establishing a set of multicast sessions in a network with or without wavelength converters and with fractional-capacity sessions.

The main difference of our algorithms is that we jointly optimize the routing and fiber-wavelength assignment phases of MC-RFWA problem. However, the general trend is to solve the problem by first finding routes and then deploying a fiber-wavelength assignment algorithm. In this respect, Hashimoto *et al.* [82] prove a min-max theorem on the number of wavelengths necessary for routing a multicast and they propose an algorithm for wavelength assignment part of the problem. Similarly, Pankaj derives asymptotic upper bounds on the number of wavelengths needed to support multicasting capability in an all-optical network [83]. Jia *et al.* [84] still separate the two phases of the problem to minimize the number of wavelengths in the system, but they partly integrate the two phases by rerouting some paths. There are many specific algorithms in the literature which specifically deal with only the wavelength assignment part like [85, 86].

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. Wu and Yang accept that M-ONLY provides the best bandwidth and wavelength usage in the multicast routing construction with sparse splitting constraint, but their algorithm can reduce the power loss significantly compared to M-ONLY [87]. Jo *et al.* [88] also stress that M-ONLY requires the least number of wavelengths and wavelength channel resources. Finally, Murty and Mohan suggest a new all-optical multicast tree algorithm which is different than M-ONLY in terms of using the virtual sources and priority heuristic while constructing the tree [89].

3. ALL-OPTICAL MULTICASTING PROBLEM

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 [90–92] 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 $F.W$ 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 $(F.W+1).N$ nodes in the final directed layered graph and a main node is represented by one node in each $F.W$ layer. If we use a link from a source main node to any one of the corresponding nodes (sub-nodes) 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 (sub-nodes) with bidirectional links. For example, the usage of a link from a main node to its sub-node 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 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. Finally, the sub-nodes of a main node in different fiber-wavelength layers are connected with respect to the wavelength conversion and switching capabilities of the main node of these sub-nodes. For example, corresponding sub-nodes in different fibers are connected to represent wavelength conversion, if the main node of these sub-nodes has full wavelength conversion property. Similarly, corresponding sub-nodes in different wavelengths are connected to represent fiber conversion, if the main node of these sub-nodes has switching property.

There may be different number of fibers between some nodes and we present an example to explain the difference from the homogeneous case. A layered graph example is given in Figure 3.1 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 rather than different fiber types. 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 3.1(a). Node 1 and 2 have only switching capability but Node 3 has both switching and wavelength conversion capabilities in Figure 3.1. 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.

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. There are multiple types of Steiner tree problems. We prefer a generic MILP solver like CPLEX instead of using a specialized Steiner solver, since our problem differs from the basic MST problem in several ways. First, there are more than one MST (k) and the total cost of all MST's are minimized. Second, each MST should be edge-disjoint in the layered graph, since each wavelength in a fiber can only be used by one multicasting session. Third, the representation of sparse splitting capability of nodes also forces us to add degree constraints to the formulation. 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, [93] and [94] summarizes the results. Although it is even possible to solve very big Steiner Tree Problems to optimality [95], the problem is NP-hard [19]. Thus, its generalized version that includes k-edge-disjoint MST's with

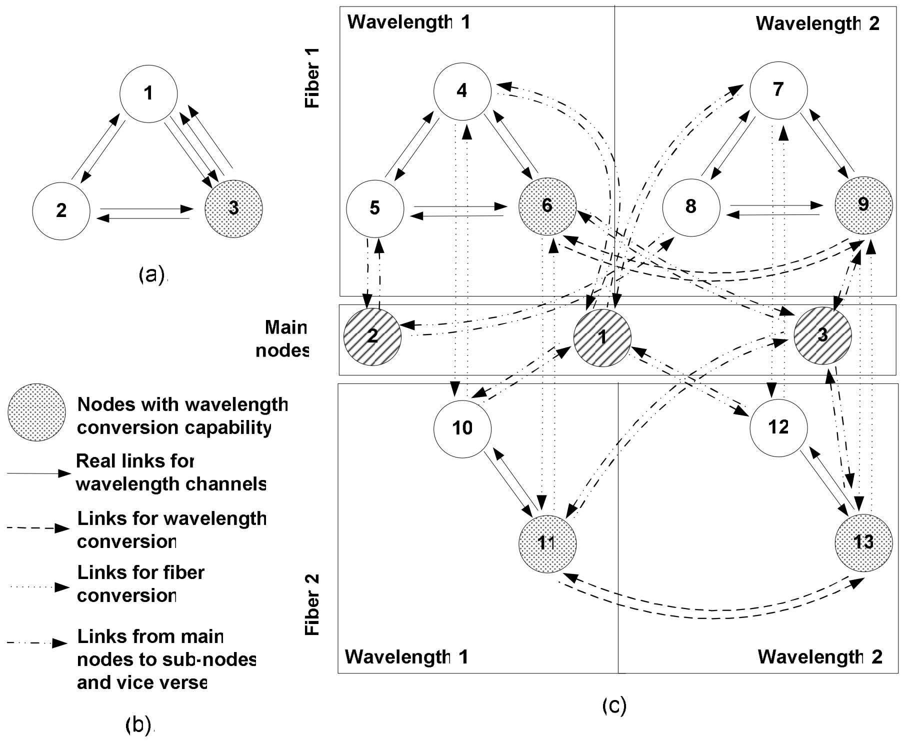

Figure 3.1. (a) A simple WDM network having three nodes, four bidirectional fiber links, two wavelengths on each link, and two heterogeneous fiber layers (b) Notation (c) Layered graph model of (a)

additional degree constraints in our case is even harder to solve.

3.1. Assumptions

- A wavelength on a given fiber between two nodes carries only the data of one multicast session, since the route for one multicast constitutes a tree 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, since one wavelength channel offers very large bandwidth with current technologies and it is quite difficult today to imagine a multicast application requiring a full lambda channel to each destination. 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.

3.2. Notation used in the formulation

$G(V_G, E_G)$: The graph G representing the WDM network with vertex set V_G and the edge set E_G

N : Number of nodes in G

L : Number of bidirectional links in G

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 full light splitting capable nodes

N_{wc} : The number of full wavelength conversion capable nodes

R_{ls} : N_{ls}/N

R_{wc} : N_{wc}/N

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 3.1 in Section 3.3). These c_{ij}'s, which are further explained in Section 4.2, are either given and dictated by the problem, or adjusted to favor different metrics which we demonstrate in Section 6.1 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 3.2 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

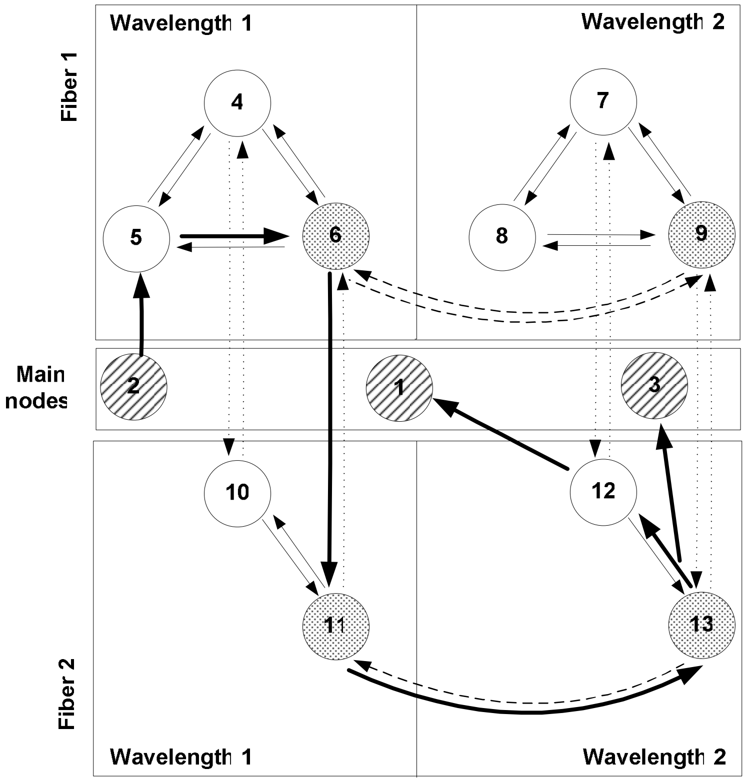

Figure 3.2. The routing and wavelength assignment of a multicast session $\{2\} \rightarrow \{1, 3\}$ which is shown with bold arrows for the network which is given in Figure 3.1

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.

We can adjust c_{ij}'s to be able to reflect the underlying relative cost of using wavelength channels, wavelength and fiber conversions and transmitters so that all four different cost terms 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
M : Number of multicast nodes
R_{mn} : M / N
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
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_{ij}^k : The binary decision variable that determine whether link (i, j) is used by multicast k, $x_{ij}^k \in \{0, 1\}$

3.3. Problem Formulation

The k-edge-disjoint (non-overlapping) degree-constrained Steiner Problem (kEDSP) can be formulated as follows [96]:

Minimize the total cost of served sessions

$$TotalCost : z = \min \sum_k \sum_{(i,j) \in E''} c_{ij}.x_{ij}^k \tag{3.1}$$

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 3.2 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 3.2, 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.

$$x_{ij}^{k} \geq f_{kl}^{ij}, \forall (i,j) \in E^{'}, \forall k, \forall l \in M_{k}^{'} \tag{3.2}$$

$$\sum_{(j,i)\in E'} f_{kl}^{ji} - \sum_{(i,j)\in E'} f_{kl}^{ij} = \begin{cases} 1, & \forall l \in M_{k}^{'}, \forall k, \text{ and } i = l \\ 0, & \forall l \in M_{k}^{'}, \forall k, \text{ and } i \neq l \end{cases} \tag{3.3}$$

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 3.2 and 3.3 ensure that the solution is in the form of a set of trees.

$$\sum_{k} x_{ij}^{k} \leq 1, \forall (i,j) \in E^{'''}, \tag{3.4}$$

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 3.4 makes sure that a link representing a wavelength and a fiber can be used once and all degree-constrained trees should be edge disjoint.

$$\sum_{j\in V'',(i,j)\in E'} -x_{ij}^k + \sum_{i\in V'',(j,i)\in E'} x_{ji}^k \geq 0, \quad \forall i \in S_S \cap V'', \forall k, i \text{ is not a source for multicast } k, \tag{3.5}$$

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 3.5 (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 3.6 is added to the formulation:

$$x_{ij}^k = \begin{cases} 0, & \text{if } i \text{ and } j \text{ represents the same main source node for multicast } k \\ 1, & \text{else} \end{cases} \tag{3.6}$$

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 [19]. Therefore, the problem is solved using CPLEX [23] for smaller networks, and we propose heuristic algorithms for larger problems.

4. SEVEN COMPETITORS FOR ALL-OPTICAL MULTICASTING

4.1. Mixed Integer Linear Programming (MILP) Solution: CPLEX

We solve the MILP formulation, which is given in Section 3.3, with CPLEX [23] 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 LAMA for larger problems.

4.2. Layered All-optical Multicasting Algorithm (LAMA)

A layered graph, which LAMA works on, is created from the graph representing the WDM network as explained in Section 3. 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. It calculates all shortest paths for each multicast destination (while loop in line 4) in each session (for loop in line 1) consecutively. Therefore, the shortest path algorithm is executed $S.M$ times. We use Bellman-Ford all-pairs shortest path algorithm with adjacency matrices implementation that has the complexity of $O(n^3)$, where n is the number of nodes [97]. Thus, the complexity of LAMA is $O(S.M.(F.W.N)^3)$, since there are $(F.W + 1).N$ nodes in the layered graph. In LAMA, the routing paths of node pairs are not pre-computed and fixed. Therefore, LAMA can dynamically change the cost assignment, while joining new multicast members to the group. The common variables and the initialization code of all heuristics are given in Figure 4.1 and the algorithm of LAMA is given in Figure 4.2.

The ability to change different cost terms in the layered graph is an important advantage for LAMA heuristic to support the minimization of different metrics simul-

Common variables and initialization code

Common Variables:

Z: Set of multicast nodes

$RemainingConnectionNumber$ for degree constrained nodes

$MulticastTree$: Links and nodes in a multicast tree

$AllMulticastTree$: Set of $MulticastTree$

Common Initialization Code:

Initialize $RemainingConnectionNumber$ with degree constraints

Initialize $MulticastTree$ by adding the source node

Initialize Z with multicast destinations except the source

Figure 4.1. Common variables and initialization code for algorithms

taneously. If we have an idea about the 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 6.1). 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 terms: the cost of using wavelength channels, wavelength conversion, 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 1) for wavelength resources, one part of the optimization becomes minimizing the average bandwidth (AB). Alternatively, this part of the optimization becomes minimizing the average delay (AD), if we assign the time duration of the communication in these wavelength resources as costs. We can either assign costs with respect to bandwidth or delay and this decision affects all heuristics which are using this information. Therefore, LAMA can optimize a pre-

```
LAMA()
for each multicast session do
    Set transmitter usage, fiber-wavelength conversion and delay costs in
    THE LAYERED GRAPH;
    Initialize multicast session; current path finding is successful;
    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 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 shortest path is found 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
```

Figure 4.2. LAMA Algorithm

ferred metric by changing the type of the cost assignment. Moreover, we also realize that we can balance these two metrics, if we assign the cost of a wavelength resource as the average of the corresponding delay value in this wavelength resource and the mean of all delays in the network. We can also use a weighted average instead of an arithmetic average to favor one metric to another. All algorithms should use the same type of cost assignment to be able to fairly compare all competitors. Therefore, we omit the work related with the effect of the cost assignment on two different metrics, since all heuristics are evaluated fairly, if we use one type of cost assignment for all. 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 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 for different costs of a particular cost term.

LAMA heuristic does not separate routing and wavelength assignment steps and considers both of them jointly: 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: $S_S = \{1, 4\}$ and $S_C = \{4, 5\}$. The original network and the layered graph of that original network are given in Figure 4.3. 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. We assume that the values of R_{wcc} and R_{tuc} are set as 1. Thus, the costs of these links equal to the average delay in the network, since the cost assignment of wavelength resources is done to optimize average delay. We show only delay costs in the demonstrative example for simplicity. Additionally, Nodes 1 and 4 do not have light splitting capability and cannot multiplex the incoming data to transfer to more than one node.

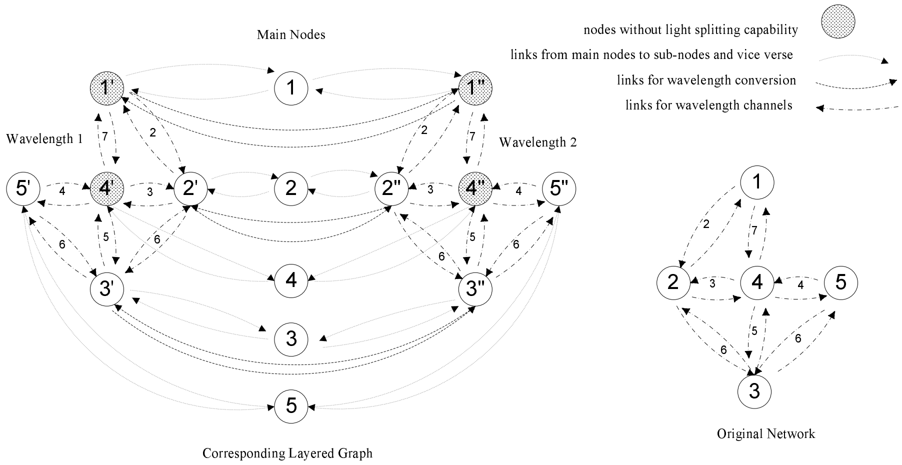

Figure 4.3. The layered graph model of a network having five nodes and one fiber carrying two wavelengths (only delay costs are shown for simplicity)

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 4.4 with bold arrows. The cost assignment of wavelength resources is done with respect to the delay, but it adversely affects the wavelength resources consumed, since the variance of the delay is high in the example. However, we could also minimize the average bandwidth by assigning the cost of wavelength resources consumed equally. In this case, LAMA produces 1-4-5-3 which has 17 units of delay (compared with 15 units of delay of the previous solution), but it also consumes one wavelength resource less than the previous solution.

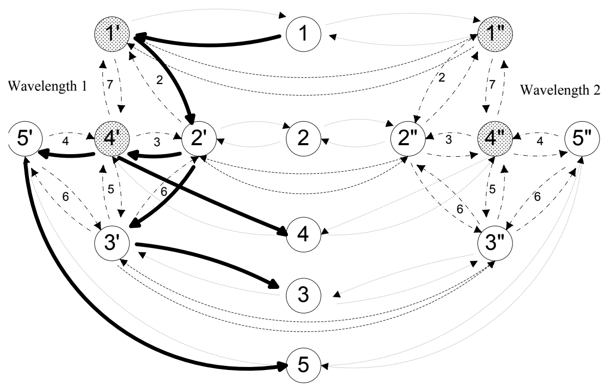

Figure 4.4. Routing on the layered graph for the first multicast session ($\{1\} \rightarrow \{3, 4, 5\}$), which is shown with bold arrows

After routing the first session, we need to remove the links that are used and come up with the layered graph on Figure 4.5. The links representing wavelength and fiber conversion, and transmitter usage are not removed, since we assume that we have enough transmitters, and wavelength and fiber conversion resources are not restricted, if the node has that capability.

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 4.6. 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.

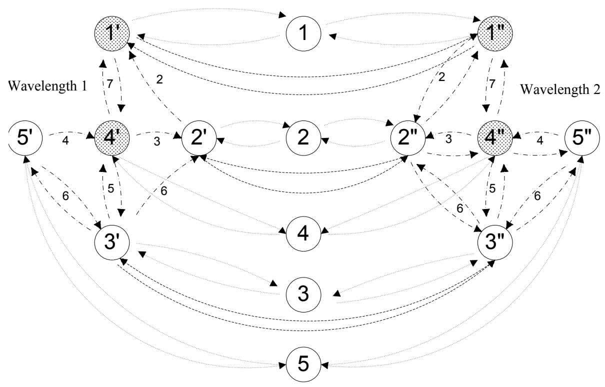

Figure 4.5. Layered graph after routing the first multicast session

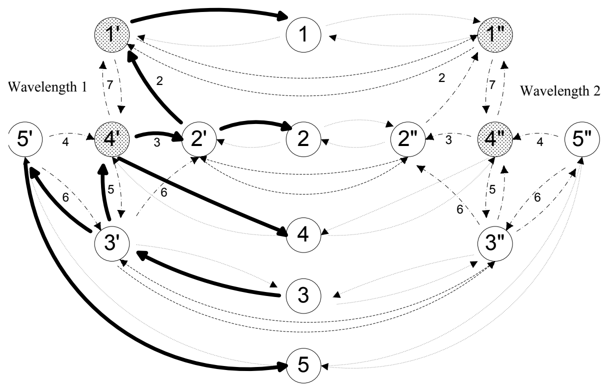

Figure 4.6. Routing on the layered graph for the third multicast session

$(\{3\} \rightarrow \{1, 2, 4, 5\})$

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 channels). The fifth multicast session is $\{4\} \rightarrow \{1, 2, 3\}$ and it is routed as in Figure 4.7 and used links are again removed.

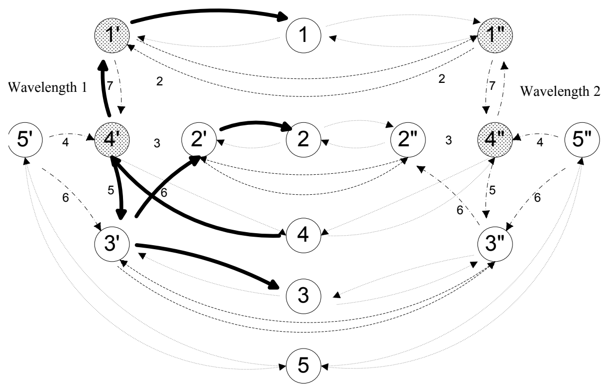

Figure 4.7. Routing on the layered graph for the fifth multicast session ($\{4\} \rightarrow \{1, 2, 3\}$)

The sixth multicast session is $\{5\} \rightarrow \{2, 3\}$ and is routed as in Figure 4.8. 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 $3' \rightarrow 3'' \rightarrow 2'' \rightarrow 2$.

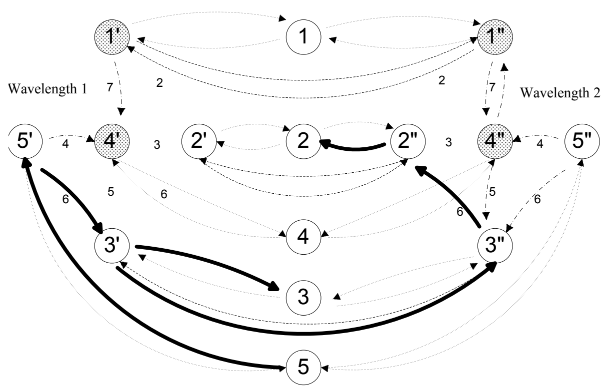

Figure 4.8. Routing on the layered graph for the sixth multicast session ($\{5\} \rightarrow \{2, 3\}$)

The remaining links are shown in Figure 4.9 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.

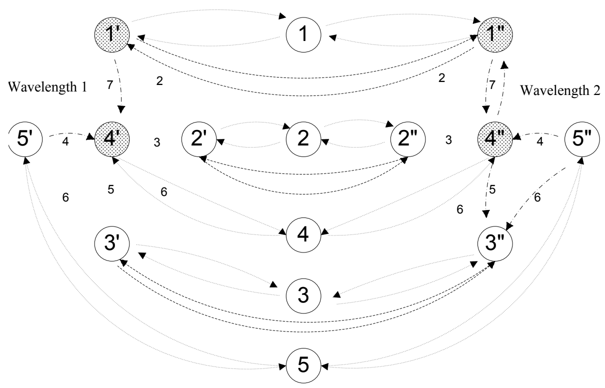

Figure 4.9. Remaining links on the layered graph

4.3. Fast Layered All-optical Multicasting Algorithm (FLAMA)

LAMA is suitable for medium size dynamic problems due to its complexity ($O(S.M.(F.W.N)^3)$). 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 $O(S.(F.W.N)^3)$. However, performance losses in some metrics are expected, since the routing paths of node pairs are pre-computed for one session and FLAMA uses less dynamic information than LAMA. The algorithm of FLAMA is given in Figure 4.10.

4.4. Scalable Layered All-optical Multicasting Heuristic (SLAM)

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 ($F.W+1$). Moreover, LAMA and FLAMA combine all fiber-wavelength layers in a big layered graph, which may not be necessary. Instead of creating one big layered graph,

```
FLAMA()
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; current path finding is successful;
    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 shortest path is found 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
```

Figure 4.10. FLAMA Algorithm

partial layered graphs can be constructed by dividing the layered graph into disjoint segments and removing the wavelength and fiber conversion links among segments. Multicast sessions which are not blocked are routed on the first partial graph, then remaining sessions are routed on the second partial graph, so on so forth. We call this algorithm scalable LAMA (SLAM) [98], since its complexity $O(S.M.F.W.N^3)$ is linearly dependent of the number of layers. We use Bellman-Ford all-pairs shortest path algorithm with adjacency matrices implementation that has the complexity of $O(N^3)$, where $O(N)$ is the order of the number of nodes in partial layered graphs [97] and all-pairs shortest path algorithm is run for each group of layer (for loop in line 2 is executed $F.W$ times) in each multicast session (for loop in line 3 is executed S times) and destinations (while loop in line 6 is executed M times). However, the order of selection of partial graphs is important for SLAM. Figure 4.12(A) shows the LAMA approach for the creation of layered graph and Figure 4.12(B-C-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 ($R_{fcc}/R_{wcc}/R_{tuc}$) for the cost assignment are the other parameters for SLAM. Table 4.1 denotes different versions of SLAM. SLAM is advantageous for limited wavelength conversion, 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 algorithm of SLAM is given in Figure 4.11.

Table 4.1. Different versions of SLAM

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

```
SLAM()
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; current path finding is successful;
      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 shortest path is found 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
```

Figure 4.11. SLAM Algorithm

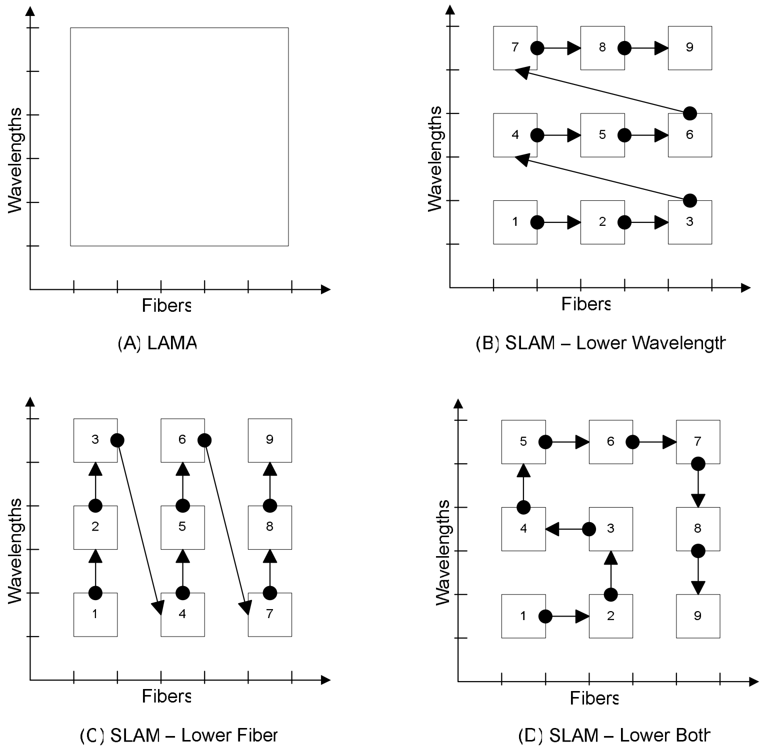

Figure 4.12. Comparing LAMA and SLAM for the layered graph approach

4.5. Member-Only (M-ONLY) Heuristic

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 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 use Bellman-Ford all-pairs shortest path algorithm for finding the shortest paths ($O(N^3)$). 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 $O(S.M.N^3)$. 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 M 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 $O(S.M.N.F.W + S.M.N^3)$. 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.

4.6. 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. We call this new fiber and wavelength assignment strategy as Ex-Fit. The algorithm of C-FWA is given in Figure 4.13.

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 ($O(S.M.N.F.W)$). 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.

4.7. 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 [24]. 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.

```
C-FWA()
Set delay costs in the normal graph;
Calculate all shortest paths on the normal graph;
for each multicast session do
    Initialize multicast session; current path finding is successful;
    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 shortest path is found then
            Do fiber-wavelength assignment with Ex-Fit;
            if Ex-Fit fiber-wavelength assignment is not successful then
                Do fiber-wavelength assignment with First-Fit;
            end if
            if Ex-Fit or First-Fit assignment is not successful then
                current path finding is not successful;
            else
                if all wavelengths in all fibers of a link are used then
                    Remove the link from the normal graph;
                    Calculate all shortest paths on the normal graph;
                end if
                Add this path to MulticastTree;
                Update Z, RemainingConnectionNumber;
            end if
        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
```

Figure 4.13. C-FWA Algorithm

5. EXPERIMENT DESIGN

We performed experiments on various size WDM networks with different characteristics for the comparative evaluation of Cplex solution with those obtained by different heuristics [99]. 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.

5.1. Network Model and Workload

The nodes and the edges among nodes determine the structure of a network, which can be characterized by the following properties:

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)

Realistic random networks with different number of nodes (N) and average nodal degree (D) were created by adjusting a parameter (Alpha=0.20). Therefore, we experimented networks with different size and density from small sparse ($N = 10/D = 3$) to large dense ($N = 30/D = 4$). Table 5.1 compares the characteristics of real [100] and random networks, and an example random graph is given in Figure 5.1.

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 light splitting R_{ls} and wavelength conversion R_{wc} capabilities for nodes. Although each

Table 5.1. Different parameters of real and random networks

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

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 experiment design, the number of layers ($F.W$) 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_{mn}) of multicast nodes to all nodes are chosen as the factors to determine the workload.

5.2. 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 (Section 4.2). 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, the auxiliary graph, to jointly opti-

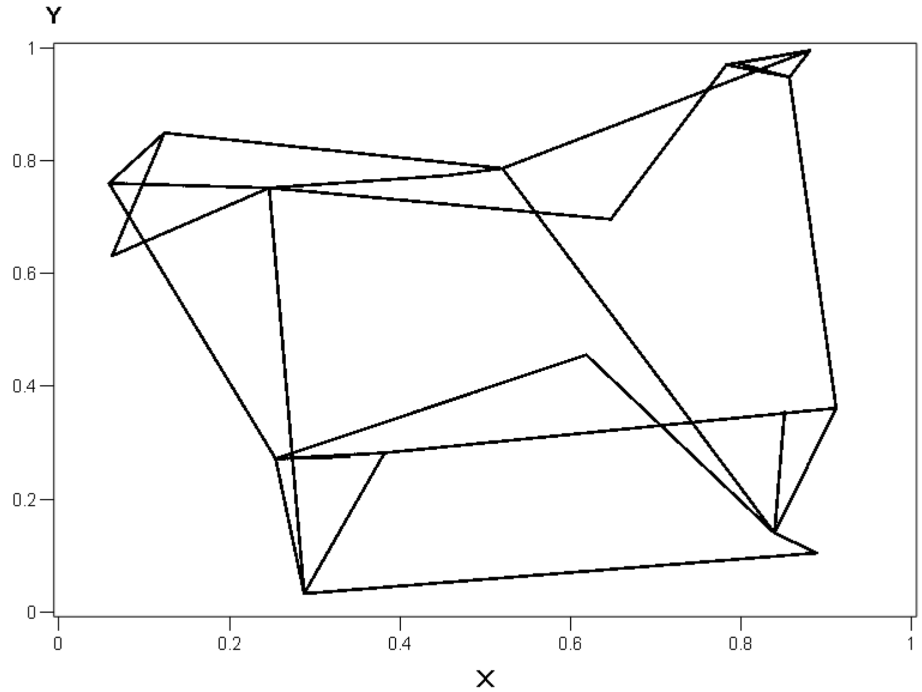

Figure 5.1. A random network topology (Random Network 5)

mize routing and fiber-wavelength assignment problem. C-FWA and M-ONLY only use the cost assignment of the network to determine routes, then a fiber-wavelength assignments 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, wavelength conversion and fiber conversion. The parameters R_{tuc}, R_{wcc}, and R_{fcc}, which are valid for CPLEX, LAMA, FLAMA, and SLAM, represent the relative weight of these terms with respect to the average delay.

CPLEX solves the MILP formulation in Section 3.3 and gives an optimal solution for the problem in terms of total cost and the Lower bound (LB) is derived from the relaxation of the integrality constraints of the MILP formulation. UNICAST (unicasting) is compared only in the first experiments to measure the benefit of multicasting.

5.3. 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. 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. 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: AET=AT-1.
8. Total Cost(TC): It is given in Equation 3.1. 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 terms which are explained in Section 3.2. The parameters R_{tuc}, R_{wcc}, and R_{fcc} are used to normalize different cost terms.
9. Average Running Time(ART): Total running time of the algorithm / S.

10. Group Blocking Probability (GBP-Per cent): 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. CPLEX determines the feasibility of a routing of a group, since if the routing is possible, it finds the solution whatever the cost is.
11. Session Blocking Probability (SBP-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 the group blocking probability, 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.

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

Lower Bound Per cent Gap = (Metric Value - Lower Bound) / Lower Bound

Upper Bound Per cent Gap = (Metric Value - Upper Bound) / Upper Bound

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

Lower Bound Ratio Gap = Metric Value / Lower Bound

Upper Bound Ratio Gap = Metric Value / Upper Bound

6. A FLEXIBLE SOLUTION: LAMA

LAMA is a flexible heuristic, since the cost assignment in the auxiliary graph are controlled by the parameters R_{fcc}, R_{wcc} and R_{tuc}, which are explained in Section 4.2. Therefore, we can balance different metrics by varying these parameters.

6.1. Minimizing Blocking Probability

The group and the session blocking probabilities reflect the quality of the service which is experienced by the user. We search for the best values for R_{fcc}, R_{wcc} and R_{tuc} to minimize the QoS related metrics. 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. Hence, CPLEX uses the same parameter values for R_{fcc}, R_{wcc} and R_{tuc} with LAMA. We designed the following experiment to be able to find the right combination of these parameters to minimize the blocking probability (9 factors):

Experiment Design 1 :
D : $\{3, 4\}$ (2)
N : $\{30\}$ with two different networks (2)
F/W : $\{2/4, 2/8, 4/4\}$ (3)
$R_{wc} = R_{ls}$: $\{0, 0.5, 1\}$ with two different S_S and S_C set for 0.5 (4)
R_{mn} : $\{0.25, 0.50\}$ with two different multicast sets (4)
$R_{fcc}/R_{wcc}/R_{tuc}$: $\{0.01/0.01/0.01, 1/1/1, 100/100/100, 0.01/1/1, 100/1/1, 1/0.01/1,$ $1/100/1, 1/1/0.01, 1/1/100\}$ (9)
Number of experiments : (2.2.3.4.4).9=192.9=1728
Method : LAMA

We determine the base line success for each level with combinations $\{0.01/0.01/0.01,$ $1/1/1, 100/100/100\}$ of $R_{fcc}/R_{wcc}/R_{tuc}$ 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 per cent confidence interval for the 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 6.1. How many times a parameter set is outside the upper and lower 99 per cent 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

Table 6.1 denotes that the most intuitive parameter combination {1/1/1} gives the best results in terms of general performance and all four terms of the total cost (delay, transmitter usage, wavelength conversion and fiber conversion) are equally important. The results of 20 experiments were beyond the upper confidence limits and the results of 10 experiments were below the lower confidence limits. Therefore, 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.

6.2. Minimizing Total Cost

After determining the right parameter set for the minimization of the blocking probability, we designed final tests so that the 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 per cent. 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, less transmitters and less 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 different terms of the total cost separately by examining the average wavelength and fiber conversions, the average number of transmitters (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:

Experiment Design 2 :
D : $\{3, 4\}$ (2)
N : $\{10, 15, 20, 25, 30\}$ with 2 two different networks (10)
F/W : $\{1/4, 2/2\}$ (2)
$R_{wc} = R_{ls}$: $\{0, 0.5, 1\}$ (3)
S : $\{4, 6, 8, 10\}$ (4)
R_{mn} : $\{0.25, 0.50\}$ (2)
Number of experiments : 2.10.2.3.4.2=960
Methods : CPLEX/LB, LAMA, C-FWA, M-ONLY, UNICAST

CPLEX found 204(22.4 per cent) experiments infeasible. The group blocking probability measures how much per cent of 756(960-204) multicast groups which consists of different number of sessions $\{4, 6, 8, 10\}$ are blocked. Similarly, we use these 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 6.2. The TC per cent gap and the ART (in seconds) metrics' mean, lower and upper 95 per cent confidence limits

Metrics		CPLEX	LAMA	M-ONLY	C-FWA	UNICAST
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
Average Running Time	Lower	6.73	0.03	0.01	0.01	0.03
	Mean	**10.45**	**0.03**	**0.01**	**0.01**	**0.03**
	Upper	14.16	0.03	0.01	0.01	0.04

The mean values, the upper and the lower 95 per cent confidence limits of the mean for the total cost per cent gap and average running time metrics are given in Table 6.2. LAMA is statistically better than M-ONLY and C-FWA for this metric. It consumes 2.5 times less total cost than M-ONLY and 1.8 times less total cost than C-FWA. Moreover, LAMA is only 19 per cent worse than the optimal with 95 per cent statistical confidence (it is 20 per cent for 99 per cent statistical confidence).

Table 6.3 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

Table 6.3. The TC per cent gap as a function of F/W, D, and R_{mn}

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

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 per cent 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 6.1. 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 6.2 and 6.3 respectively. It is important to have consistency 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, for that case, LAMA behaves slightly better, but M-ONLY's performance deteriorates.

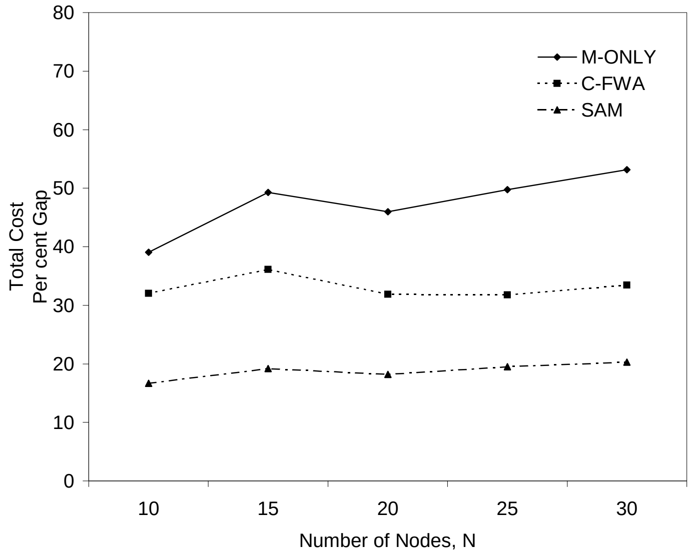

Figure 6.1. The TC per cent gap vs N

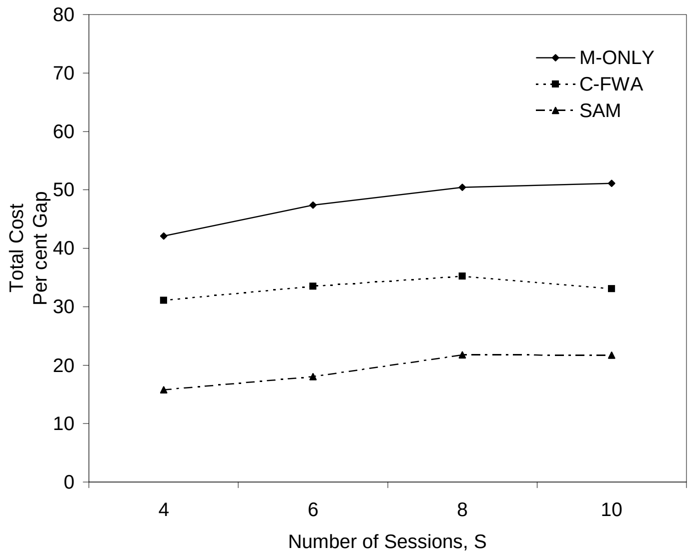

Figure 6.2. The TC per cent gap vs S

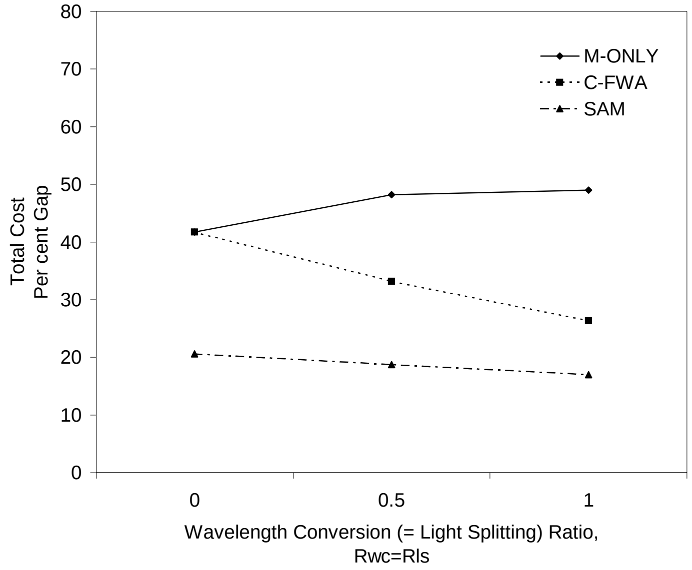

Figure 6.3. The TC per cent gap vs $R_{wc} = R_{ls}$

6.3. Other Metrics

The parameters of LAMA heuristic are optimized to reduce the session blocking probability. Figures 6.4 and 6.5 clearly demonstrate that LAMA is almost as good as CPLEX in terms of both the group and the session blocking probabilities. C-FWA is slightly better than M-ONLY, but they perform very poor against LAMA in terms of both metrics.

The mean values, the upper and the lower 95 per cent confidence limits of the mean for all other metrics are given in Table 6.4. LAMA gives the best results in terms of the average highest wavelength index, which is the only metric that CPLEX does not optimize, 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, and number of trees. It uses 26.9 per cent less wavelength, 7.7 times less wavelength conversion, 3.9 times less fiber conversion, and 13.5 per cent less number of trees (transmitters) than M-ONLY. Similarly, it consumes 27.9 per cent less wavelength, 2.2 times less wavelength conversion, 3.3 times less fiber conversion, and 12.6 per cent less number of transmitters than C-FWA. The difference between M-ONLY and C-FWA is that C-FWA uses nearly

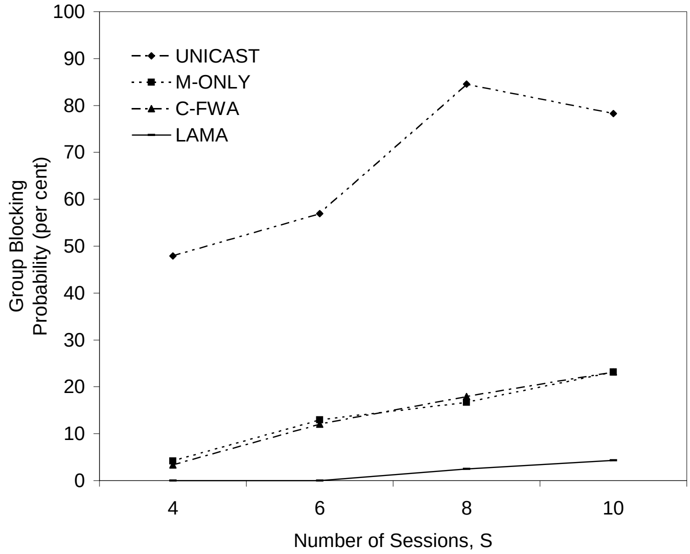

Figure 6.4. The GBP metric vs S

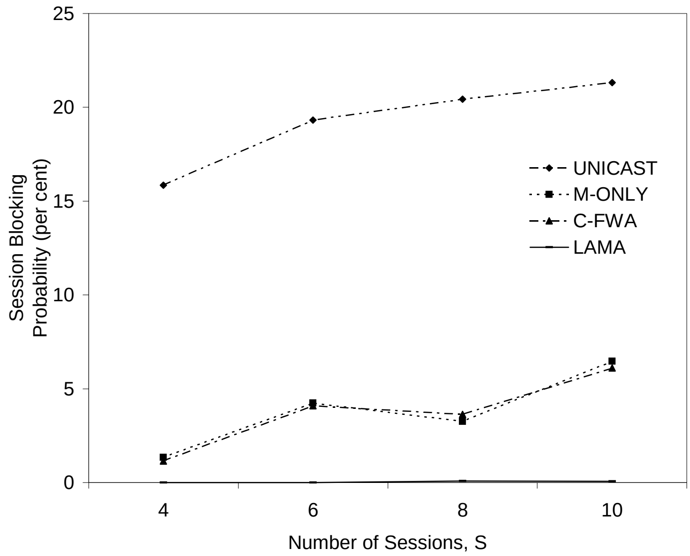

Figure 6.5. The SBP metric vs S

3.5 times less wavelength conversion and 20.7 per cent less fiber conversion and it has slightly better results for the group and session blocking probabilities.

Table 6.4. The AB, AD, AHWI, AWC, AFC, and AT metrics' mean, lower and upper 95 per cent confidence limits

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

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. 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.

6.4. Dynamic vs. Static Multicasting

In dynamic multicasting, session requests are done consecutively and any dynamic algorithm should establish sessions one by one in the order that they are requested. In static multicasting, all session requests are received at once in a batch mode. Therefore, the establishment order for sessions may affect the metrics for LAMA, C-FWA and M-ONLY which are iterative algorithms. We performed all tests many times by only changing the order of destinations at each replication. The results indicate that all metrics almost do not change at all with respect to the order of destinations for all methods. Moreover, we changed both the order of destinations and the sessions, and we repeated these tests with many different random combinations. The results were not almost the same for this time, but there is no statistically significant difference for any metric and any heuristic. However, we also investigated the per cent and absolute differences by spotting the pairs which have the maximum separation in terms of each metric. The performance of LAMA for the average highest wavelength index, wavelength and fiber conversion and number of tree metrics change at most less than 0.01 in terms of absolute difference, the average bandwidth and delay change at most 0.16 and 0.06 respectively. In terms of per cent change, it is at most less than 2.5 per cent for all metrics. Group and session blocking probabilities change at most 0.2 per cent. Although, the performance of C-FWA and M-ONLY deviate more than LAMA, all methods are suitable for both dynamic and static multicasting problems.

The total running time metric is more important for static multicasting, since all sessions are requested and served simultaneously in batch. CPLEX total running time, which are around 18 minutes at average, are affected by the complexity of the problem. The parameters D, N, S and R_{mn}, and also $R_{wc}(= R_{ls})$ determines the number of nonzero integer variables in the MILP formulation. However, CPLEX is more seriously affected by the number of sessions, contrary to LAMA, M-ONLY, C-FWA. LAMA takes only 2 seconds to find high quality solutions for all multicast sessions, and M-ONLY and C-FWA use a very small fraction of a second to run. The average running time metric and its confidence limits are more important for dynamic multicasting, since sessions are established one by one when they are requested. It is shown that LAMA takes only 0.03 seconds which is a suitable response time for dynamic multicasting, since the response time is expected to be in the order of seconds for our application scenarios which have long session duration.

6.5. The Effect of Network Parameters (N/D)

We examine the effect of the number of nodes (N) and the average nodal degree (D) in terms of average delay, highest wavelength index, wavelength and fiber conversion, and tree metrics for LAMA, excluding bandwidth, since bandwidth and delay are related (Section 4.2). Similarly, we examine the same metrics (except AHWI due to bad performance of CPLEX) for CPLEX. All metrics increase for LAMA and CPLEX, while increasing N. In contrast, all metrics decrease for LAMA, while increasing D. Similarly, AB, AD and AFC decrease for CPLEX, while increasing D (AT and AWC do not change).

Table 6.5. The per cent gap of AD, AT, GBP, and SBP metrics vs D for LAMA

Avg. nodal degree(D)	AD	AT	GBP	SBP
3	9.17	6.97	0.35	1.85
4	12.21	3.56	0.14	0.93

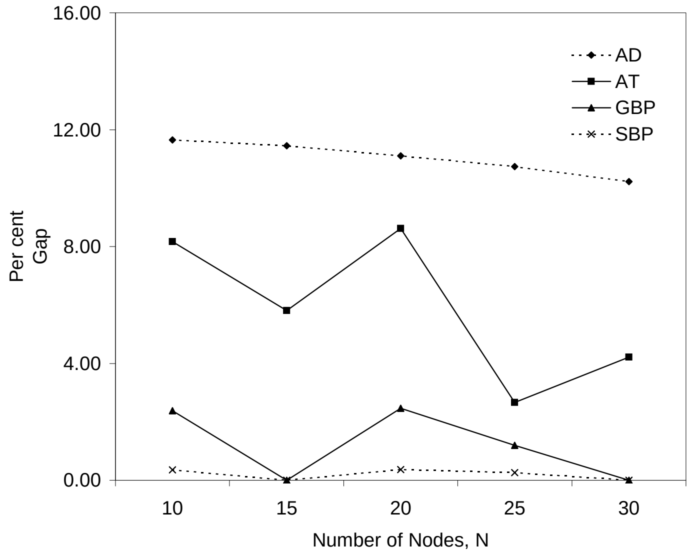

Figure 6.6. The per cent gap of AD, AT, GBP, and SBP metrics vs N for LAMA

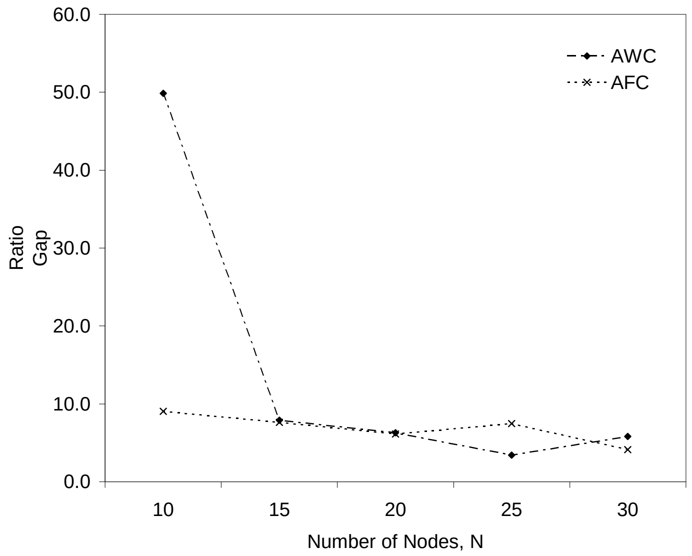

Figure 6.7. The ratio of LAMA to CPLEX for AWC and AFC metrics vs N

Table 6.6. The ratio of LAMA to CPLEX for AWC and AFC metrics vs D

Avg. nodal degree(D)	AWC	AFC
3	7.4	6.6
4	4.4	5.9

The performance of LAMA with respect to CPLEX (per cent gap) is also examined for group and session blocking probabilities (GBP-SBP), average delay, wavelength and fiber conversion, and tree metrics for LAMA, except AHWI, since we do not know the optimal for it. LAMA is compared to the optimal for N in Figures 6.6 and 6.7, and for D in Tables 6.5 and 6.6. While increasing the complexity of the problem (N and D), per cent gap of all metrics demonstrate a decreasing trend (only AD increases, while increasing D), i.e., the performance of LAMA becomes closer to the optimal.

7. A SCALABLE SOLUTION: SLAM

We propose CPLEX for small, LAMA and FLAMA for medium, and SLAM, which is scalable, for large size problems.

7.1. Lower Bounds for All Metrics

The MILP formulation (Section 3.3) minimizes the total cost (Equation 3.1) which consists of delay, wavelength, fiber conversion, and transmitter costs. If a feasible solution (a non-blocking case) exists for the MILP formulation, then CPLEX finds it. Therefore, all CPLEX solutions are optimal in terms of session and group blocking probabilities, 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 they consume less fibers, but few algorithm minimizes both resources simultaneously and equally like SLAM with Lower-Fiber/Wavelength strategy. Average highest wavelength index metric (AHWI) 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 ($R_{wcc}/R_{fcc}/R_{tuc}$) but also the cost assignment strategy of LAMA should be changed to minimize also AHWI in addition to the other metrics (Section 7.2). CPLEX does not minimize AHWI, since it has always zero group and session blocking probabilities.

Average bandwidth (AB) and delay (AD) are also related metrics (Section 4.2) 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. Average bandwidth and delay (AB/AD).
2. Average wavelength conversion (AWC).
3. Average fiber conversion (AFC).
4. Average transmitter (tree) (AT).
5. Average highest wavelength index, session and group blocking probabilities (AHWI/SBP/GBP).

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 LLR (Least Loaded Routing for unicast connections). Therefore, SLAM is a flexible and a scalable solution, since it combines routing and 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 and 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 lower bound 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 $R_{wcc}/R_{fcc}/R_{tuc}$, then we find the lower bound for AD (CPLEX/LB-AD optimized). Similarly, we find the lower bound for

AB, if we set one for wavelength resources and zero for $R_{wcc}/R_{fcc}/R_{tuc}$ (CPLEX/LB-AB optimized). Other lower bounds for AWC ($R_{wcc} = 100/R_{fcc} = R_{tuc} = 0$), AFC ($R_{fcc} = 100/R_{wcc} = R_{tuc} = 0$), and AT ($R_{tuc} = 100/R_{fcc} = R_{wcc} = 0$) 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 till 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.

Initial experiments (Experiment Design 3) 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 could not produce a solution within reasonable time when the number of sessions is 10. 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 lower bounds for AWC, AFC, AT and AHWI together, since we have simulated high traffic load by restricting available wavelength resources. We included the results of Design 2 into Table 7.1, since it was a smaller problem and CPLEX could solve all cases within reasonable time. Moreover, all costs (AB-AD/AWC/AFC/AT) are equally important ($R_{wcc} = R_{fcc} = R_{tuc} = 1$), and we can gain an insight by roughly comparing the base line values of metrics in Design 2 to the lower bounds of them in Design 3, yet both designs are not directly comparable.

Experiment Design 3 :
D : $\{3, 4\}$ (2)
N : $\{30\}$
F/W : $\{1/8, 2/4, 4/2\}$ (3)

$R_{wc} = R_{ls}$: $\{0, 0.5, 1\}$ (3)

S : $\{5, 10, 20\}$ with 30 different multicast sets (90)

R_{mn} : $\{0.2\}$

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, M-ONLY

The lower bounds for AWC, AFC and AT for Design 3 indicate that only less than one wavelength and one fiber conversions, and one extra transmitter are needed for 10 sessions. In Design 2, one wavelength and one fiber conversions for 15 sessions and less than one extra transmitter for 10 sessions are required. Although we treated AB, AWC, AFC and AT equally in Design 2, the performance in these metrics are very close to the lower bounds. Additionally, less than 5 per cent 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 be all minimized and take values which are close to the optimal by using equal cost ratios ($R_{wcc} = R_{fcc} = R_{tuc} = 1$). However, AB is seriously (12-13 per cent) improved, if the cost of using wavelength channels are assigned one for bandwidth minimization.

7.2. Tuning LAMA for Highest Wavelength Index

The parameter tuning of LAMA heuristic to optimize the blocking probability is explained in Section 6.1. Although the group and session blocking probabilities are important metrics, we also want to minimize other important metrics, like the average highest wavelength index without a performance loss in the other metrics. Therefore, we need to differentiate the wavelength conversion and the transceiver usage costs so that LAMA would use the lower wavelengths first and it improves the average highest wavelength index metric. First, we adjust wavelength conversion 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,

Table 7.1. Lower bounds for metrics

Metrics	AD/AWC/AFC/AT Optimized (Design 2)	Only AB Optimized (Design 3)	Only AD Optimized (Design 3)	AWC/AFC/AHWI/AT Optimized (Design 3)
AB	9.91	10.15	11.41	11.48
AD	2.67	3.39	2.80	2.92
AHWI	0.67	x	x	0.56
AWC	0.04	x	x	0.02
AFC	0.02	x	x	0.06
AT	1.09	x	x	1.10

a wavelength conversion from λ_2 to λ_3 costs two times more than the case without adjustment. Similarly, a wavelength conversion 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 sub-nodes (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 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 average bandwidth, delay and highest wavelength index. Figure 7.1 demonstrates that the average bandwidth and delay are positively correlated and the average highest wavelength index 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 ($R_{fcc} = R_{wcc} = R_{tuc} = 0.7$) at which the per cent gap of all three metrics are less than 5 per cent and, the per cent gap of delay and highest wavelength index are equal. We also want to tune the parameters that CPLEX uses and we increase the parameters from 0.1 to 10. However, CPLEX could not manage to produce better results in terms of the average highest wavelength index and we take the values of all parameters as one for CPLEX.

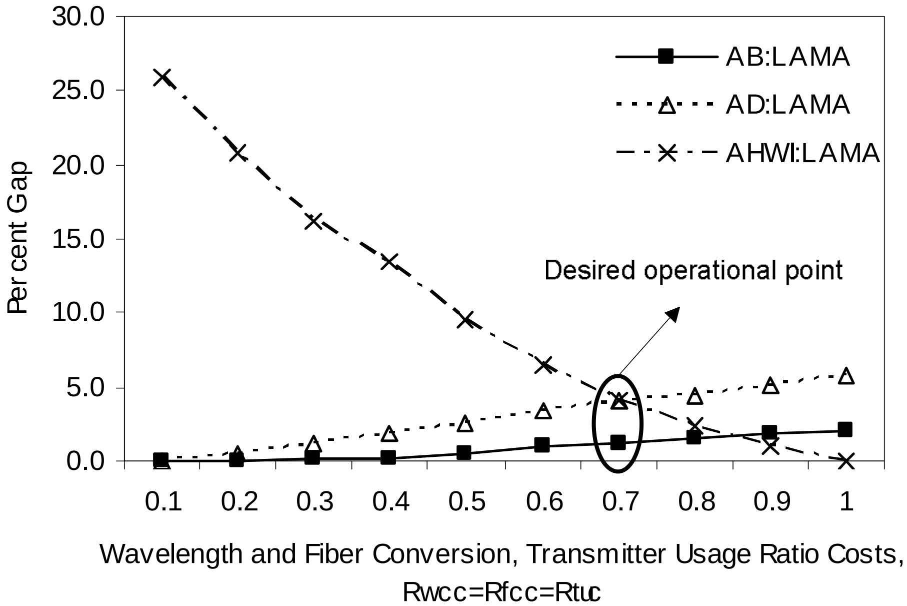

Figure 7.1. The per cent gap as a function of the wavelength and fiber conversion, and the transmitter usage ratio costs, $R_{wcc} = R_{fcc} = R_{tuc}$ for average bandwidth(AB), delay(AD) and highest wavelength index(AHWI) metrics for LAMA heuristic

7.3. How Close SLAM is to The Optimal

We use different traffic loads for batch tuning and online tests to be fair for all competitors. Figures 7.2 and 7.3 show the group and session blocking probabilities (GBP/SBP) for different number of sessions (S). We assume that the routing of all groups ($S = 5/10/20$) are feasible. Although, CPLEX results are not available for higher traffic load($S = 10/20$) in which some cases may not be feasible.

Although, FLAMA is better than M-ONLY and C-FWA in terms of blocking probabilities for $S = 20$, 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 completeness. LAMA is as good as CPLEX for GBP when S is 5, but it

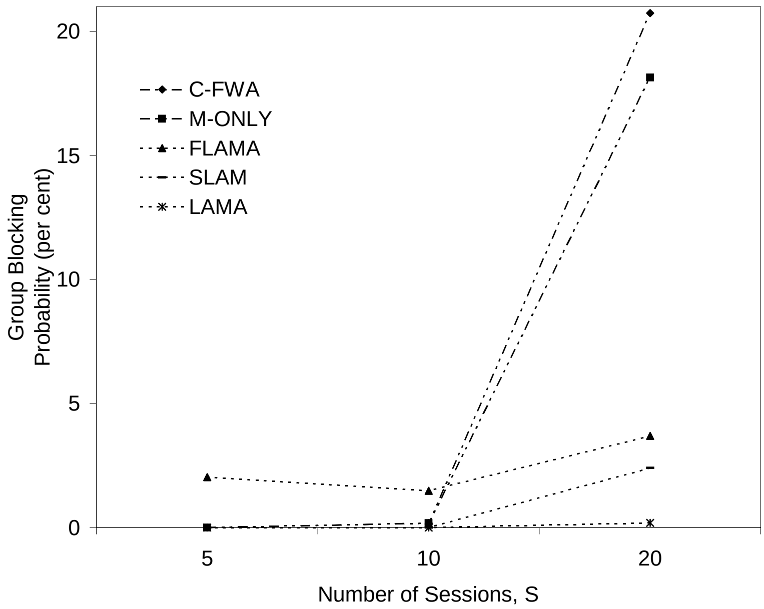

Figure 7.2. GBP vs S

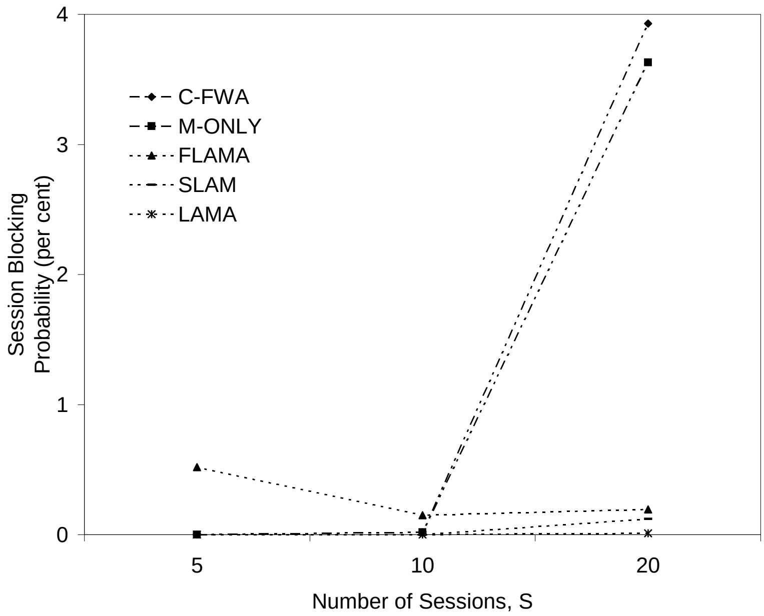

Figure 7.3. SBP vs S

shows its superiority when S is 10 or 20. LAMA almost routes all group requests, but M-ONLY is blocked for 18.1 per cent and C-FWA is blocked for 20.7 per cent of the groups when S is 20. Similarly, the session blocking probability of LAMA is almost zero when S is 20, but it is 3.6 per cent for M-ONLY and 3.9 per cent for C-FWA. SLAM performs almost the same as LAMA in terms of group (0.8 per cent) and session (0.1 per cent) blocking probabilities and it is very close to the optimal solution.

Table 7.2. Means and statistical significances for different metrics and methods (Design 3/All sessions)

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 7.3. Means and statistical significances for different metrics and methods (Design 3/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

The means and statistical significances (if two methods have a common letter in their code, there is no statistically significant difference between them) for all other metrics (Design 3) are given in Tables 7.2 and 7.3 for all sessions and $S = 5$, respectively. CPLEX(LB) is statistically superior to others for all metrics except the average highest wavelength index (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 average delay (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 wavelength conversion for $S = 5/10/20$. C-FWA uses nearly five times less wavelength conversion than M-ONLY.

First, we compare SLAM to the other methods for all sessions ($S = 5/10/20$), then we evaluate SLAM performance against the lower bound when S is 5. 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 3. 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 per cent less wavelength, 14.5 per cent less transmitters, 15.5 times less wavelength conversion, and 4.4 times less fiber conversion than M-ONLY. Similarly, it consumes 11 per cent less wavelength, 14.3 per cent less transmitters, 3.3 times less wavelength conversion, and 4.2 times less fiber conversion than C-FWA. SLAM is less than 5 per cent better than M-ONLY and C-FWA for AB and AD metrics which have least variability among competitors (at most 5 per cent).

In Figures 7.4 and 7.5, SLAM is compared to the lower bound for AT, SBP, GBP, AB, AD, and AHWI in terms of per cent gap, and for AWC, AFC in terms of ratio gap, respectively. The worst competitor is also compared to the lower bound in these figures. Although, SLAM is nearly 25 per cent 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. Moreover, it is also very close to the optimal in terms of AWC and AFC, and it is many times superior to the worst competitor.

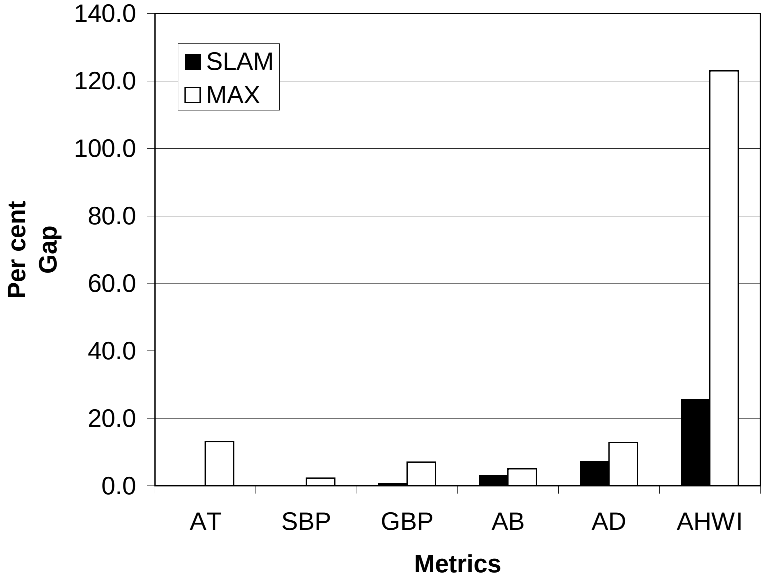

Figure 7.4. SLAM and the worst competitor are compared to the lower bound in terms of per cent gap for AT/SBP/GBP/AB/AD/AHWI

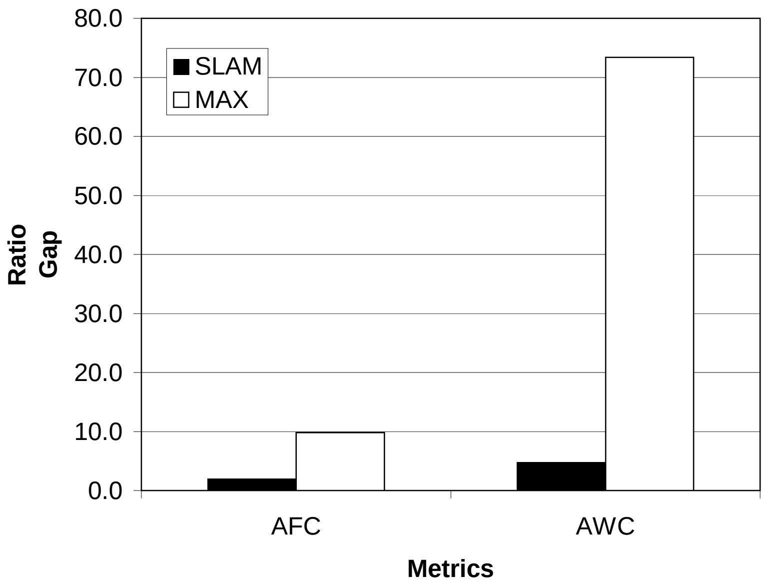

Figure 7.5. SLAM and the worst competitor are compared to the lower bound in terms of ratio for AWC/AFC

7.4. SLAM vs SLAM[4*4]

In Experiment Design 4, 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 that it uses bigger 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 8 layers (F/W: 1/2, 2/2, 4/2). We also compare different versions of SLAM with LAMA, without AHWI optimization (Section 7.2), C-FWA and M-ONLY.

Experiment Design 4 :
D : $\{3, 4\}$ (2)
N : $\{30\}$
F/W : $\{1/32, 2/16, 4/8\}$ (3)
$R_{wc} = R_{ls}$: $\{0, 0.5, 1\}$ 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, M-ONLY

It is not possible for CPLEX to solve medium size problems. Therefore, all upper bounds are determined with respect to the best solution obtained by any heuristic. Figures 7.6 and 7.7 show the group and session blocking probabilities (GBP/SBP) 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 10 times better than M-ONLY which is slightly better than C-FWA.

Table 7.4 denotes the means and the statistical significances (if two methods have a common letter in their code, there is no statistically significant difference between

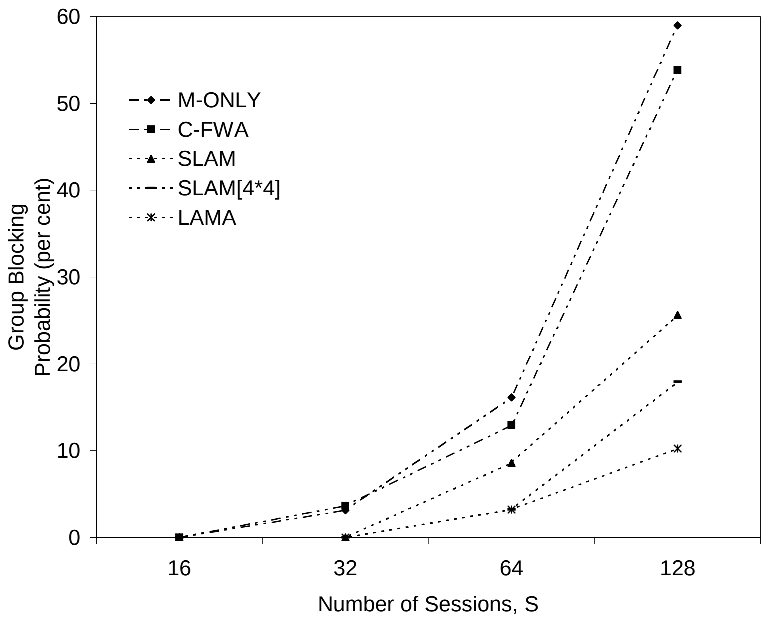

Figure 7.6. GBP for Design 4

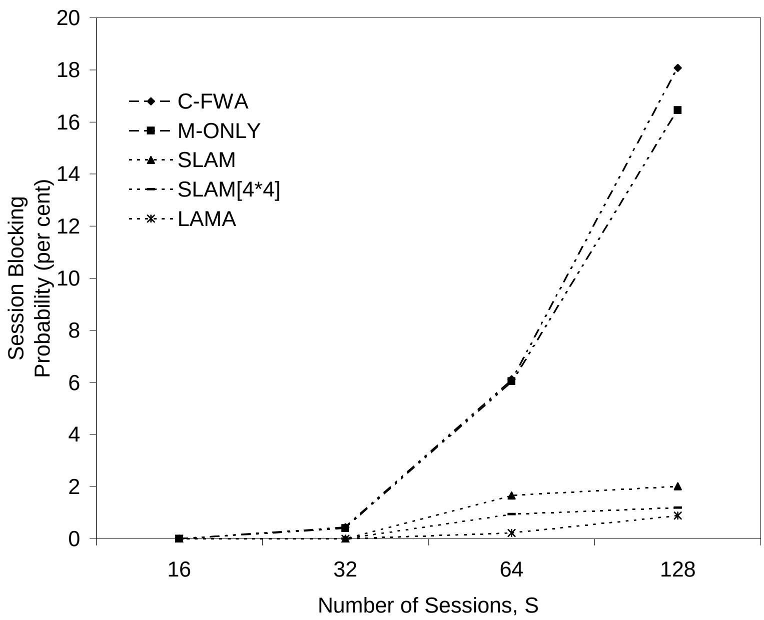

Figure 7.7. SBP for Design 4

them) for other metrics (Design 4). 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.

Table 7.4. Means and the statistical significances for Design 4

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

All methods are compared for AB and AD in Figure 7.8, for AT and AHWI in Figure 7.9, for GBP and SBP in Figure 7.10 in terms of per cent gap. Additionally, all methods are compared for AWC and AFC in Figure 7.8 in terms of ratio gap, since differences are very big to show them in terms of per cent 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 for SBP than SLAM. The same relationship is valid between SLAM and LAMA as well.

7.5. SLAM for Large Problems

In Experiment Design 5, 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

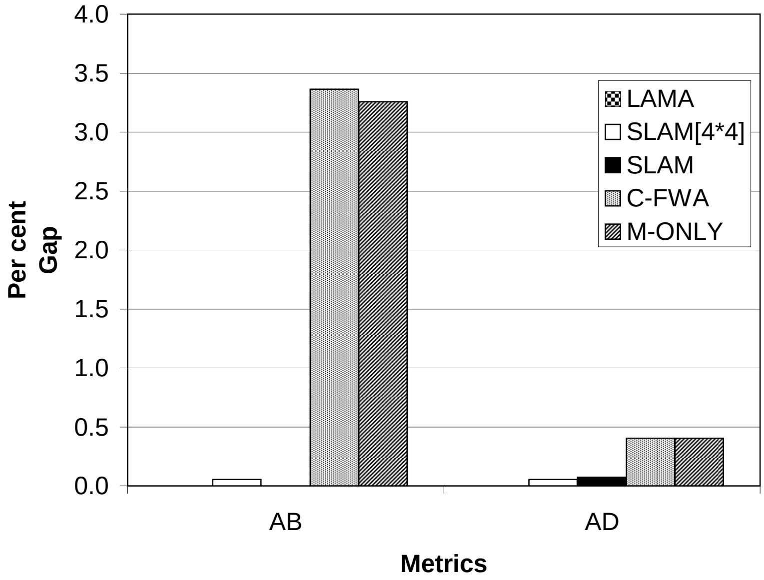

Figure 7.8. AB and AD for Design 4

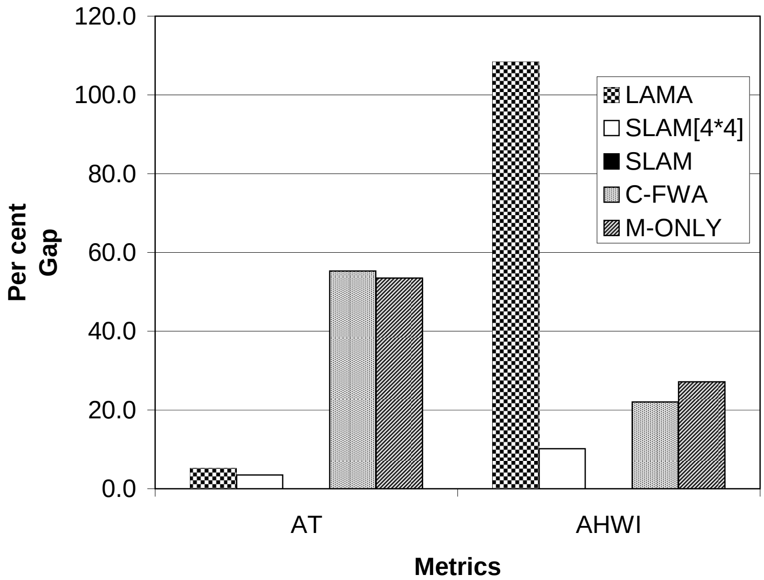

Figure 7.9. AT and AHWI for Design 4

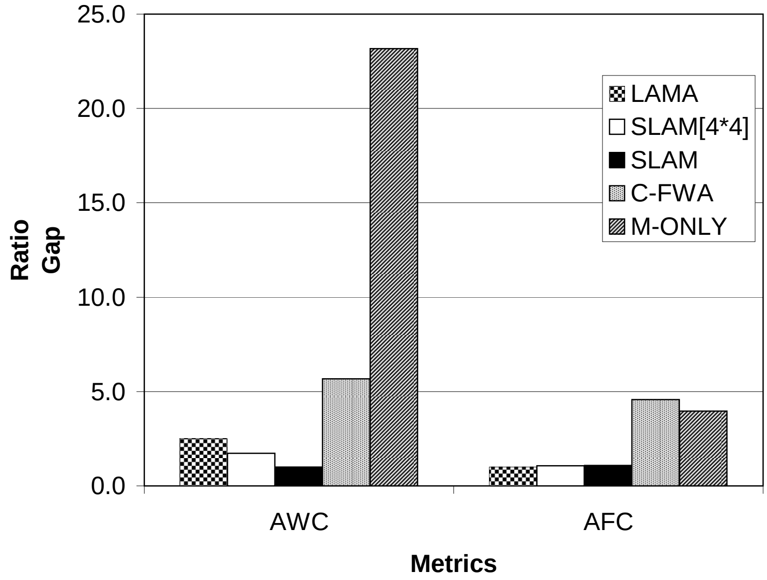

Figure 7.10. AWC and AFC for Design 4

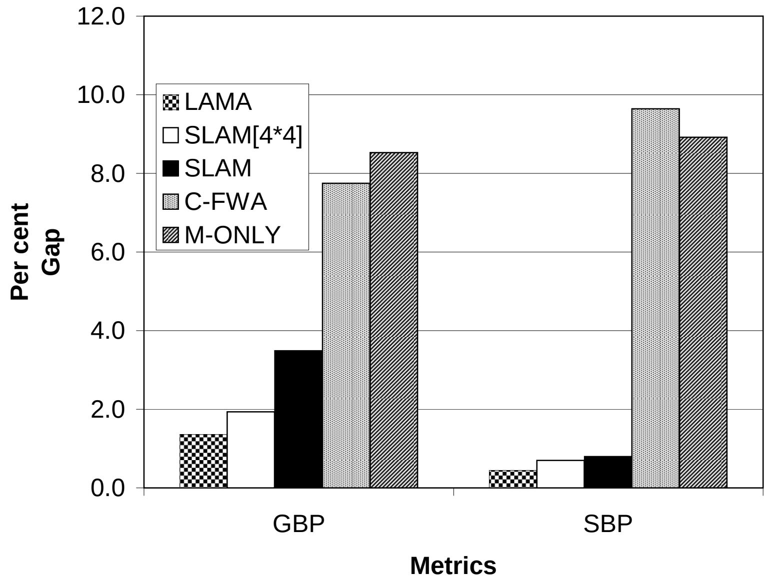

Figure 7.11. GBP and SBP for Design 4

respect to the best solution obtained by any heuristic, similar to Section 7.4.

Experiment Design 5 :
D : $\{3, 4\}$ (2)
N : $\{30\}$
F/W : $\{1/128, 2/64, 4/32\}$ (3)
$R_{wc} = R_{ls}$: $\{0, 0.5, 1\}$ (3)
S : $\{128, 512\}$ with 10 different multicast sets (20)
R_{mn} : $\{0.2\}$
Number of experiments : 2.3.3.20=360
Methods : SLAM, C-FWA, M-ONLY

We already evaluated the effect of the order of session establishment matrix, the order of sessions and destinations, for LAMA in Section 6.4. 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 per cent and it changes at most 3 per cent for AWC and GBP.

Table 7.5. Means and the statistical significances for 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 7.5 shows the means and the statistical significances for all metrics, except 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 significantly better than SLAM for AD, there is no difference for AB and all competitors are very close for these two metrics.

Table 7.6. Means and the statistical significances for 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

When we increase S from 128 to 512, blocking starts to occur. Table 7.6 shows the means and some statistical significances, 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 others when traffic load is high. SLAM is significantly better than M-ONLY and C-FWA for GBP and SBP metrics.

SLAM, C-FWA and M-ONLY are compared for AB, AD, AHWI and AT in Figures 7.12 and 7.13 for S=128 and S=512, respectively. The performance and superiority of SLAM does not change with respect to high or low traffic. Similar to Section 7.4, all methods are compared for AWC and AFC in Figures 7.14 and 7.15 for S=128 and S=512, respectively, in terms of ratio gap, since differences are very big to show them in terms of per cent gap. Finally, Figure 7.16 is for SBP and GBP when S is 512, since there is no blocking for S=128.

SLAM uses 87.7 per cent less wavelength, 17.7 per cent less transmitters, 15.9 times less wavelength conversion, and 1.4 times less fiber conversion than M-ONLY and it consumes 80.9 per cent less wavelength, 19.3 per cent less transmitters, 4.1 times less wavelength conversion, and 2.7 times less fiber conversion than C-FWA when the traffic load is low (S=128). Similarly, SLAM spends 13.1 per cent less transmitters, 17.9 times less wavelength conversion, and 3.6 times less fiber conversion than M-ONLY and it uses 13.8 per cent less transmitters, 4.8 times less wavelength conversion, 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 one second for the routing of one multicast session. Therefore, it is suitable for dynamic multicasting.

7.6. Tuning SLAM for Transmiter Usage, Fiber/Wavelength Conversion

We have examined the relationship between AB and AD in Section 4.2 and the effect of metrics to each other in terms of the optimal solution in Section 7.1. We have also tuned LAMA for the blocking probability in Section 6.1 and for AHWI in Section 7.2. SLAM minimizes the blocking probability by setting $R_{fcc}/R_{wcc}/R_{tuc} = 1$, and it also minimizes AHWI by its strategy to select partial layered graphs (Section 4.4). In Experiment Design 6, we further search for a possibility to improve the number of transmitters, fiber and wavelength conversions without a performance loss in other metrics by changing the cost structure (specifically the values of $R_{fcc}/R_{wcc}/R_{tuc}$).

Experiment Design 6 :
D : $\{3, 4\}$ (2)
N : $\{30\}$
F/W : $\{1/128, 2/64, 4/32\}$ (3)
$R_{wc} = R_{ls}$: $\{0, 0.5, 1\}$ (3)
S : $\{128, 512\}$ with 10 different multicast sets (20)
R_{mn} : $\{0.2\}$

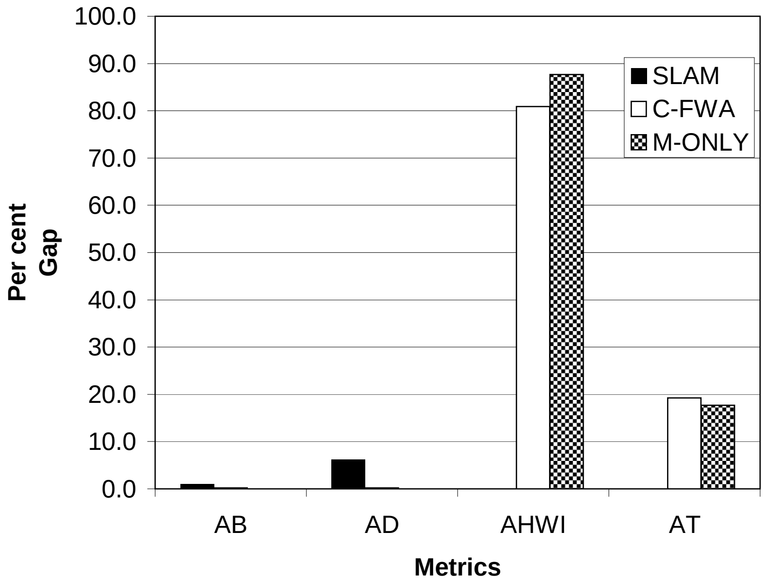

Figure 7.12. AB, AD, AHWI and AT for Design 5/S=128

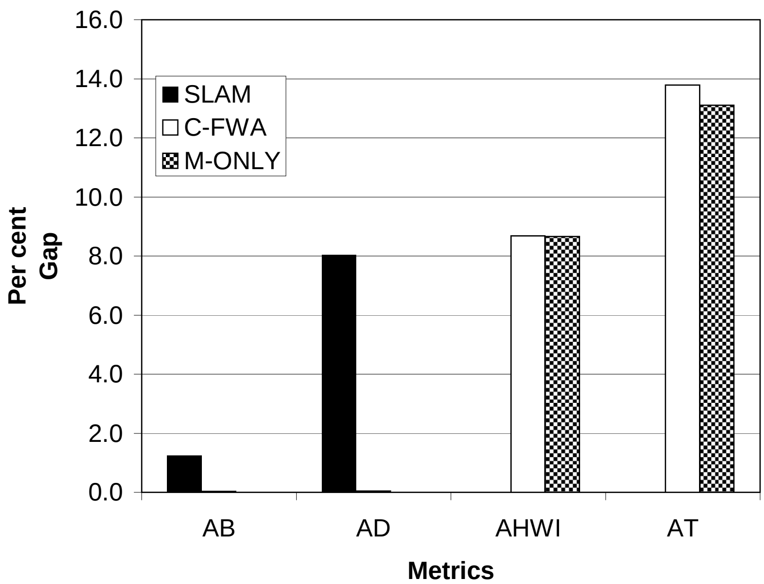

Figure 7.13. AB, AD, AHWI and AT for Design 5/S=512

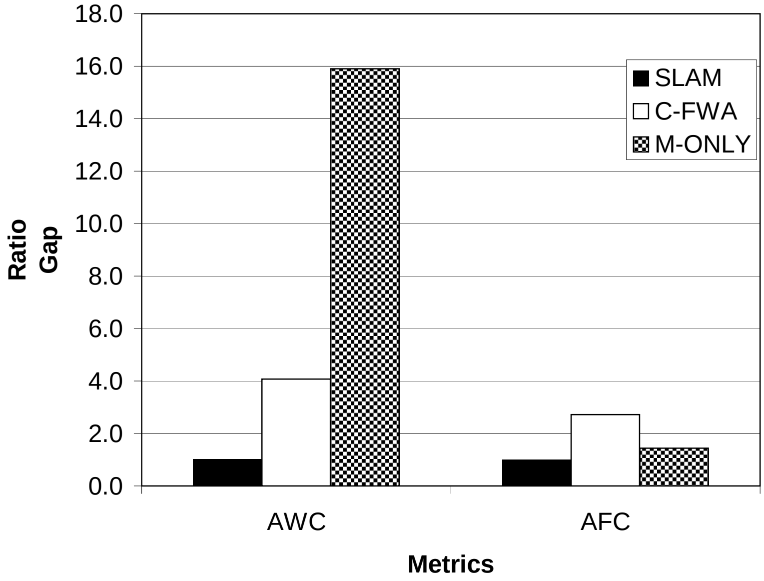

Figure 7.14. AWC and AFC for Design 5/S=128

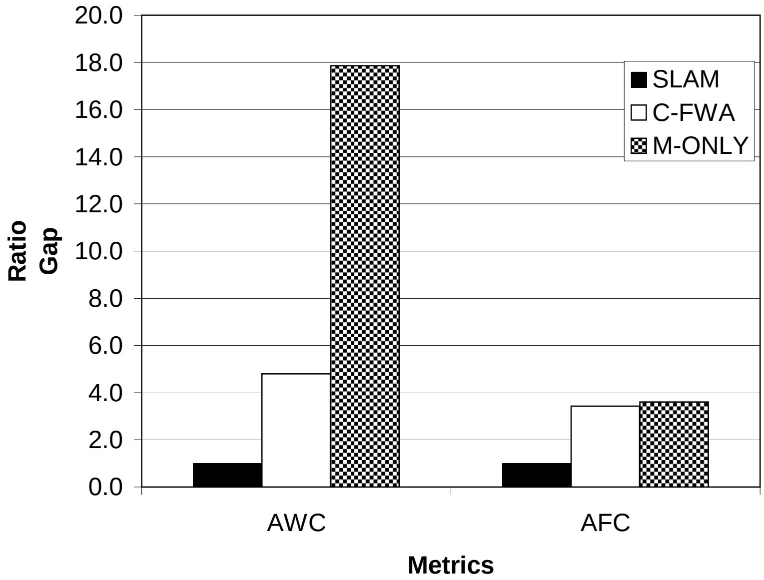

Figure 7.15. AWC and AFC for Design 5/S=512

$R_{fcc}/R_{wcc}/R_{tuc}$: $\{1/1/1, 2/1/1, 1/2/1, 1/1/2, \frac{1}{2}/\frac{1}{2}/\frac{1}{2},$
$4/1/1, 1/4/1, 1/1/4, \frac{1}{4}/\frac{1}{4}/\frac{1}{4},$
$8/1/1, 1/8/1, 1/1/8, \frac{1}{8}/\frac{1}{8}/\frac{1}{8},$
$16/1/1, 1/16/1, 1/1/16, \frac{1}{16}/\frac{1}{16}/\frac{1}{16},$
$32/1/1, 1/32/1, 1/1/32, \frac{1}{32}/\frac{1}{32}/\frac{1}{32}\}$ (21)

Number of experiments : (2.3.3.20).21=360.21=7560

Method : SLAM

If we set one for $R_{fcc}/R_{wcc}/R_{tuc}$, then all four cost terms (delay, transmitters, fiber and wavelength conversions) are equally important. We can favor the average delay metric by a factor of x by setting $R_{fcc}/R_{wcc}/R_{tuc} = 1/x$. Similarly, we can favor the average wavelength conversion metric by a factor of x by setting $R_{fcc} = R_{tuc} = 1/R_{wcc} = x$. In the experiment 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 the number of transmitters, fiber and wavelength conversions metrics do not improve after x is 8. Therefore, specific names are given for these three versions in Section 4.4. Table 7.7 denotes the performances of SLAM, W-SLAM, F-SLAM and T-SLAM for AB, AD and AHWI and Table 7.8 shows the performances of SLAM, W-SLAM, F-SLAM and T-SLAM for AWC, AFC and AET(=AT-1).

Table 7.7. Means for AB, AD, and AHWI

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

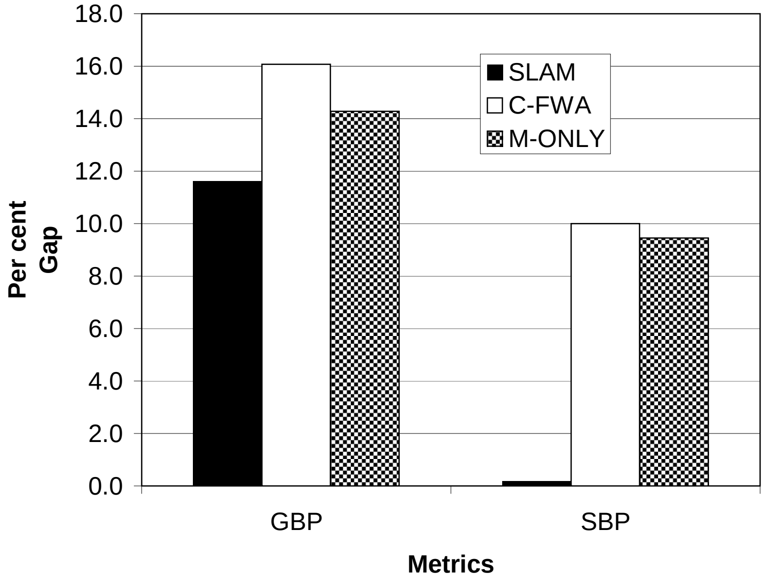

Figure 7.16. GBP and SBP for Design 5/S=512

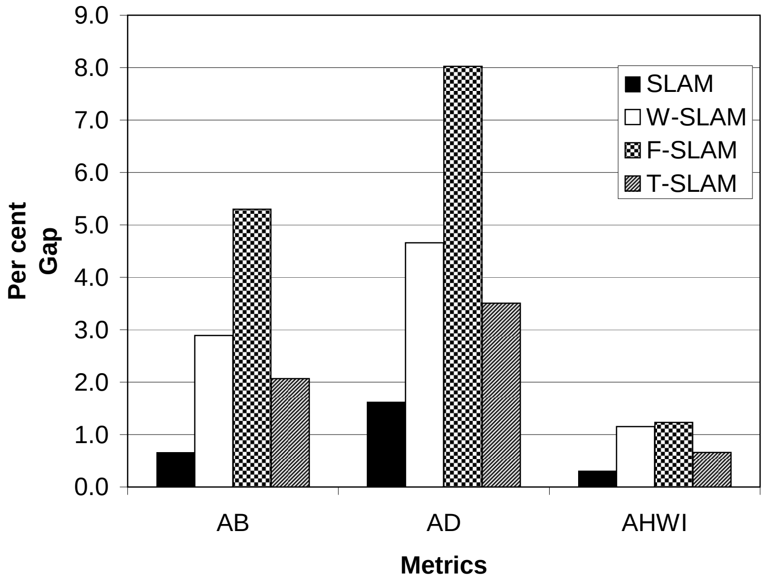

Figure 7.17. AB, AD and AHWI for Design 6/S=128

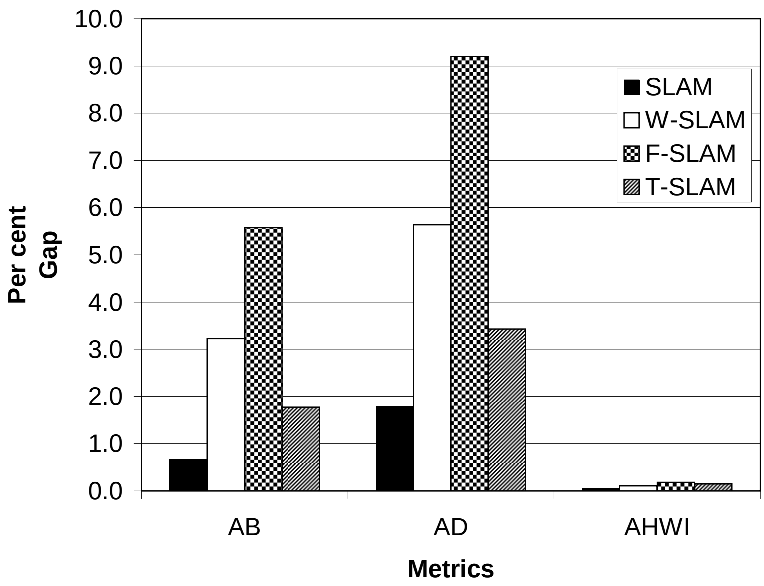

Figure 7.18. AB, AD and AHWI for Design 6/S=512

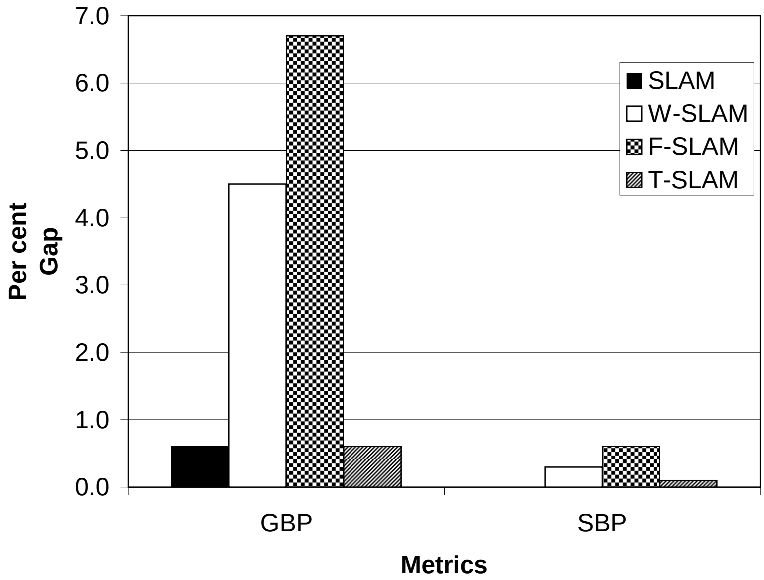

Figure 7.19. GBP and SBP for Design 6/S=512

Table 7.8. Means for AWC, AFC, and AET

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

Figures 7.17 and 7.18 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 less than 2 per cent for AD, 1 per cent for AB, and 1 per cent for AHWI. Similarly, T-SLAM differs from the upper bound 3 per cent for AD, 2 per cent for AB, and 1 per cent for AHWI. Figure 7.19 compare all methods for blocking probabilities. SLAM and T-SLAM perform almost the same for GBP and SBP.

Figures 7.20 and 7.21 are for AWC, AFC and AET metrics. T-SLAM spends from 3-6 times less extra transmitters than SLAM and it only needs one extra transmitter for 12-13 sessions. W-SLAM reduces the number of wavelength conversions from 6-10 times and F-SLAM reduces the number of fiber conversions from 6-8 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.

7.7. The Effect of Workload Parameters (S/R_{mn})

Figures 7.22 and 7.23 demonstrate the effect of S on SLAM for all metrics. Similarly, Figures 7.24 and 7.25 are for the effect of R_{mn}. GBP significantly, SBP slightly increase while the number of sessions (S) and the fraction of multicast nodes (R_{mn}) increase, since the traffic load is increasing for both cases. However, AT decreases

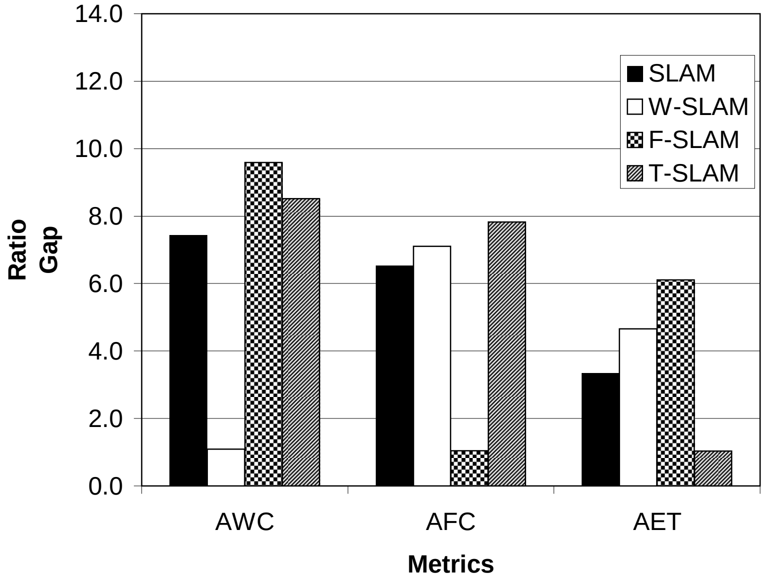

Figure 7.20. AWC, AFC and AET for Design 6/S=128

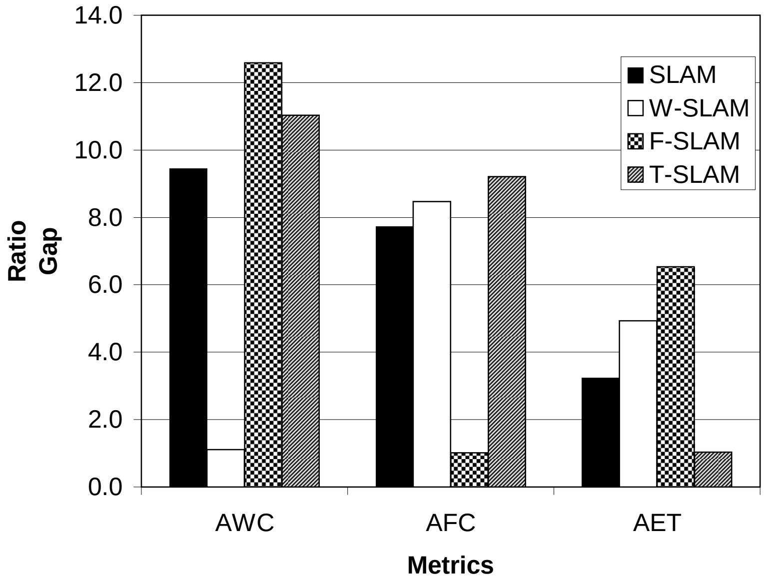

Figure 7.21. AWC, AFC and AET for Design 6/S=512

while R_{mn} increases. Because, this increase creates bigger trees, consequently, less number of trees are needed. AT slightly increases while S increases. AWC and AFC metrics have more variance than the other metrics and it is hard to interpret the behaviour of them. However, they are alternative resources to each other and they are negatively correlated when R_{mn} increases. AHWI, AB and AD significantly decrease while S increases, since they are benefiting from the economy of scale principle. If we route more sessions in the same network, then the sessions are better packed and give better results in terms of these metrics. However, AHWI, AB and AD significantly increase while R_{mn} increases. Because, more destinations require more bandwidth and delay and it is hard to pack them into lower wavelengths.

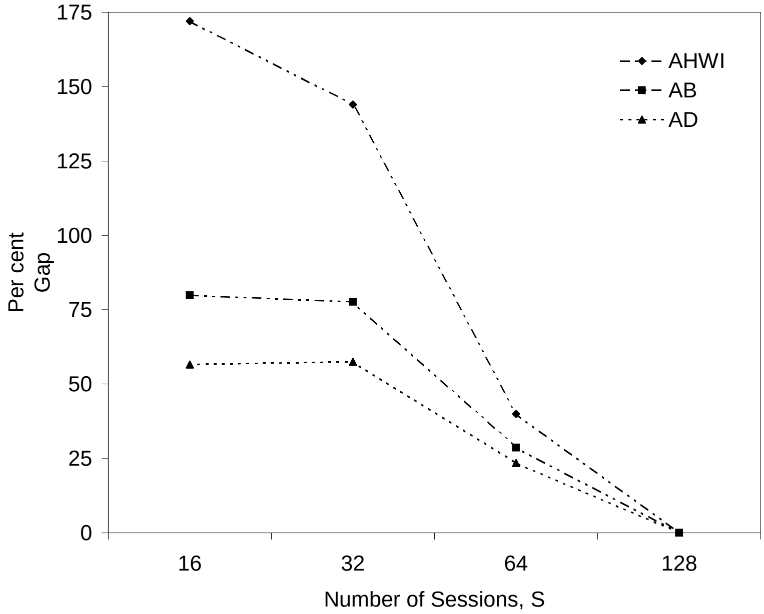

Figure 7.22. The effect of S for AHWI, AB and AD

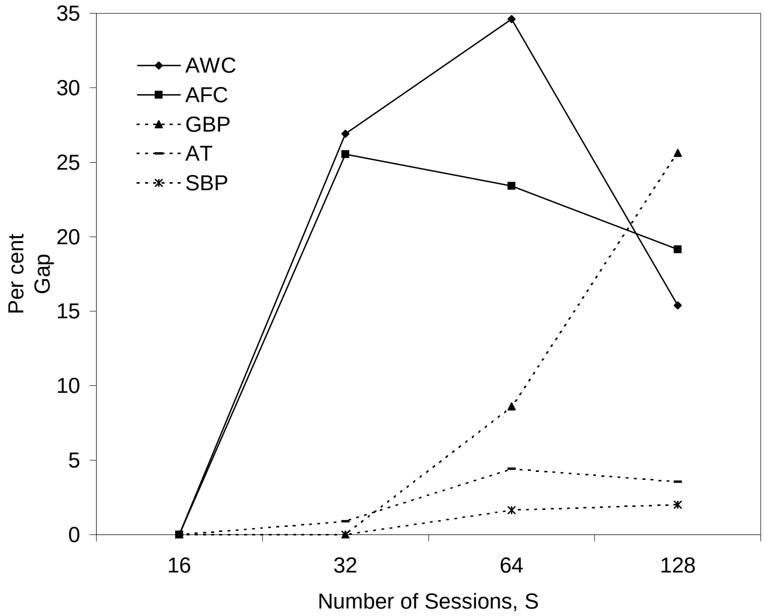

Figure 7.23. The effect of S for AWC, AFC, GBP, SBP and AT

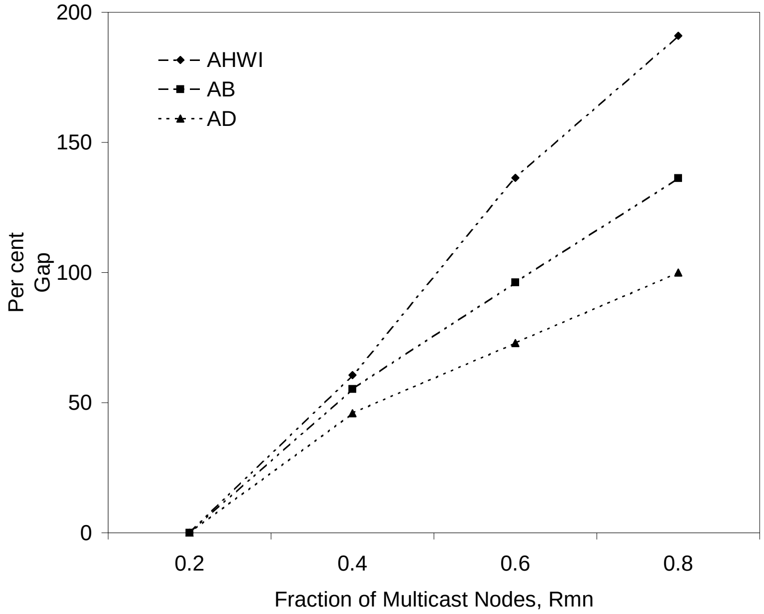

Figure 7.24. The effect of R_{mn} for AHWI, AB and AD

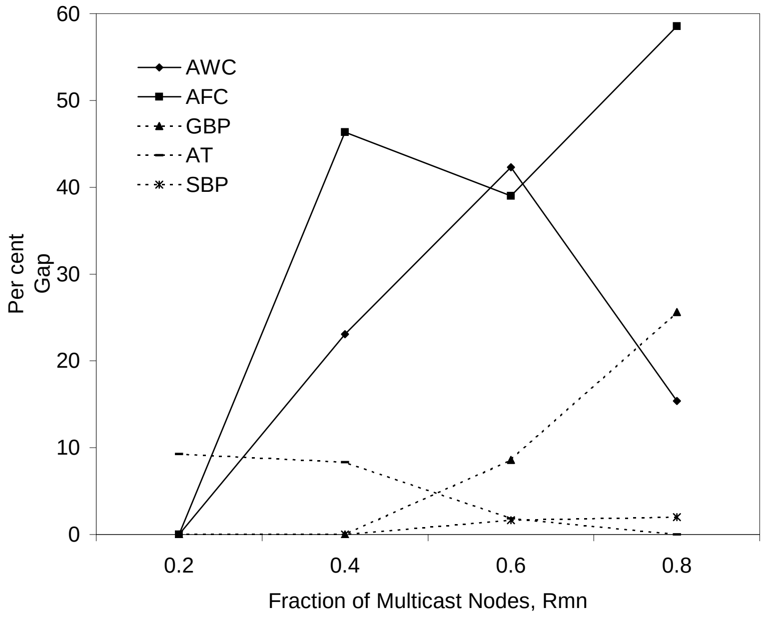

Figure 7.25. The effect of R_{mn} for AWC, AFC, GBP, SBP and AT

8. EFFECT OF FIBER AND SWITCH PROPERTIES

We include all possible parameters and compare different methods with broad ranges of these parameters to be sure that the results are valid, while designing experiments. Moreover, we also examine the effect of network (N/D) and workload parameters (S/R_{mn}) in Sections 6.5 and 7.7, respectively. However, the number of fibers/wavelengths (F/W) and the wavelength conversion (R_{wc}) or light splitting (R_{ls}) properties of the switches are more important to determine while designing a new all-optical network. The following experiment is designed to understand the effect of those parameters:

Experiment Design 7 :
D : $\{3, 4\}$ (2)
N : $\{30\}$
F/W : $\{1/128, 2/64, 4/32\}$ (3)
R_{wc} : $\{0, 0.1, 0.2, ..., 1\} * R_{ls} : \{0, 1\}$
R_{ls} : $\{0, 0.1, 0.2, ..., 1\} * R_{wc} : \{0, 1\}$
with two different groups of S_S and S_C sets (2.(20+20))
S : $\{128, 512\}$ with 2 different multicast sets (4)
R_{mn} : $\{0.2\}$
Number of experiments : 2.3.2.40.4=1920
Methods : SLAM, C-FWA, M-ONLY

8.1. The Effect of Fiber

Any MC-RFWA algorithm that utilizes having more fibers should demonstrate better performance in terms of group and session blocking probabilities, since having more fibers gives more freedom to an algorithm by using fiber conversions. Figures 8.1 and 8.2 compare SLAM, C-FWA, and M-ONLY for group and session blocking probabilities and it is clearly seen that SLAM behaves as expected by improving its performance with increasing number of fibers. In contrast, C-FWA and M-ONLY show no improvement which proves the merit of joint optimization of routing and wavelength assignment phases in MC-RFWA problem. However, all algorithms improve their performances in terms of average bandwidth (AB) and delay (AD) in Figures 8.3 and 8.4 and their improvement rates are similar.

Figure 8.5 denotes that the average highest wavelength index worsens for C-FWA and M-ONLY, while SLAM is quite stable with increasing number of fibers. In Figures 8.6, 8.7 and 8.8 the methods are compared for the average wavelength, fiber and extra number of transmitters metrics. All methods use more fiber conversions as expected while increasing F, but SLAM performs better by using fiber conversion resources more efficiently. Additionally, SLAM uses a small number of wavelength conversions with a slight decreasing trend and it is more economical than its alternatives. It is interesting to note that C-FWA also improves its performance significantly in terms of AWC metric by utilizing the availability of fiber conversions, but M-ONLY consumes many more wavelength conversions and it shows no improvement. Finally, SLAM uses slightly more transmitters with more fibers and C-FWA and M-ONLY use less extra transmitters, while increasing F, but SLAM is still better than the others with respect to the overall extra transmitter consumption.

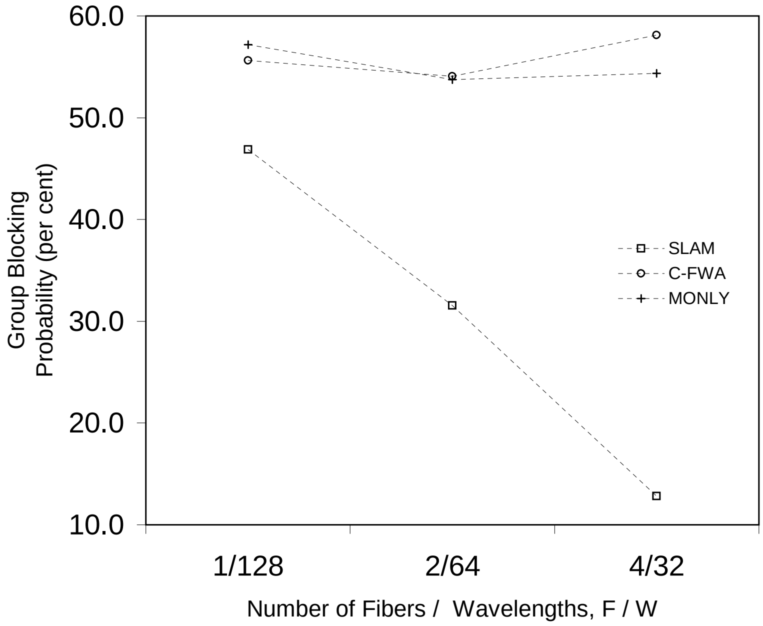

Figure 8.1. GBP vs. F/W for $S = 512$

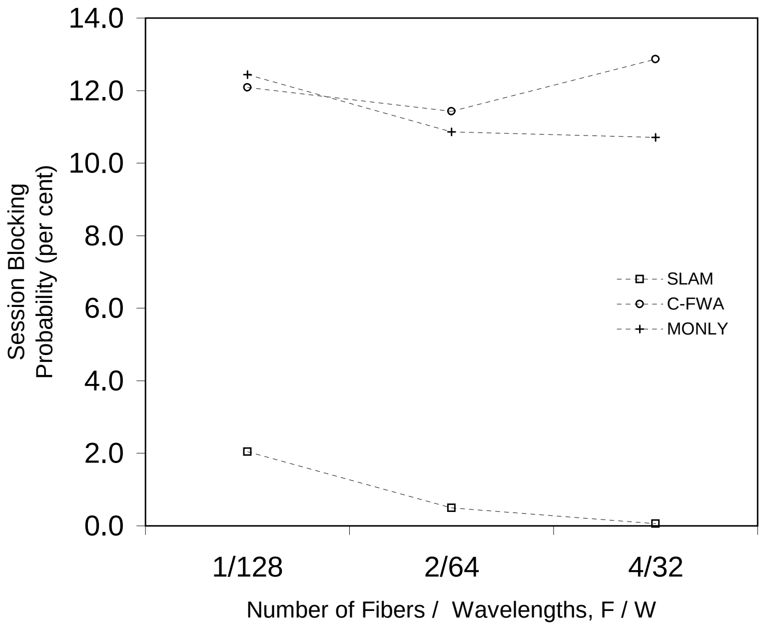

Figure 8.2. SBP vs. F/W for $S = 512$

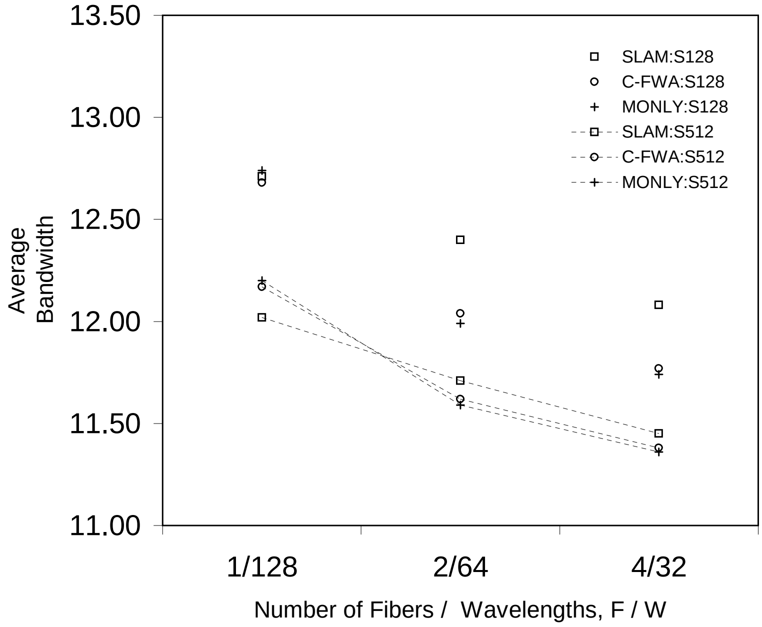

Figure 8.3. AB vs. F/W for $S = 128$ and $S = 512$

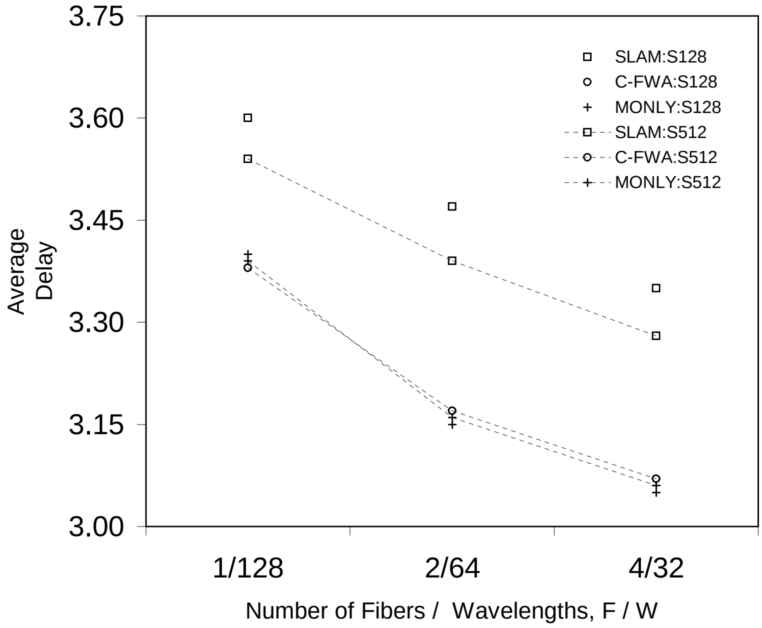

Figure 8.4. AD vs. F/W for $S = 128$ and $S = 512$

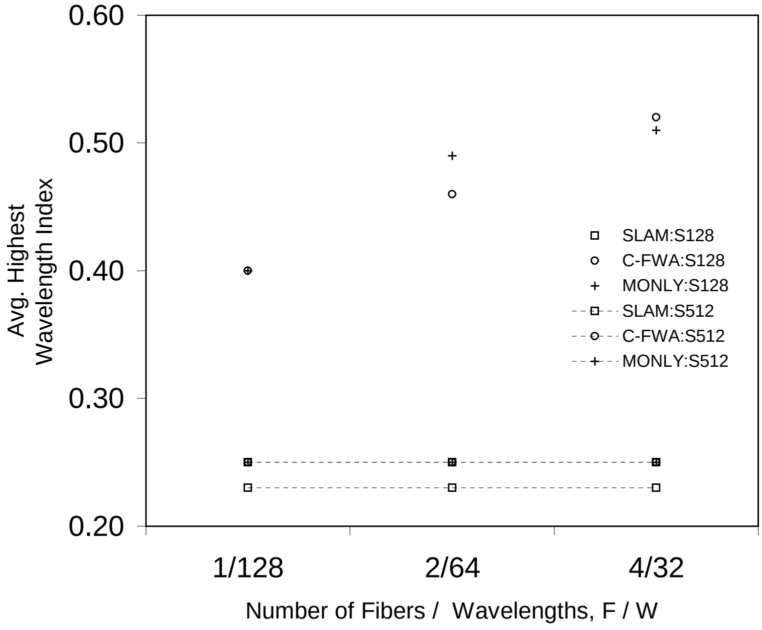

Figure 8.5. AHWI vs. F/W for $S = 128$ and $S = 512$

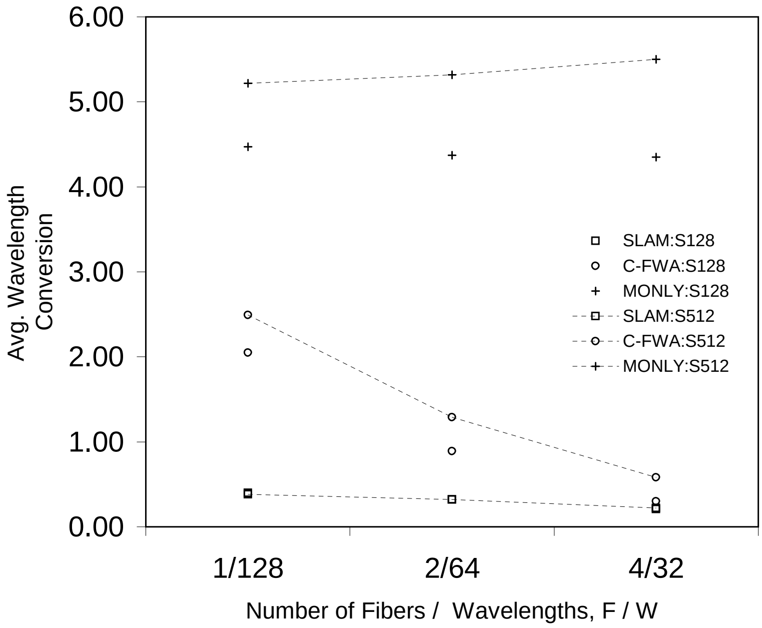

Figure 8.6. AWC vs. F/W for $S = 128$ and $S = 512$

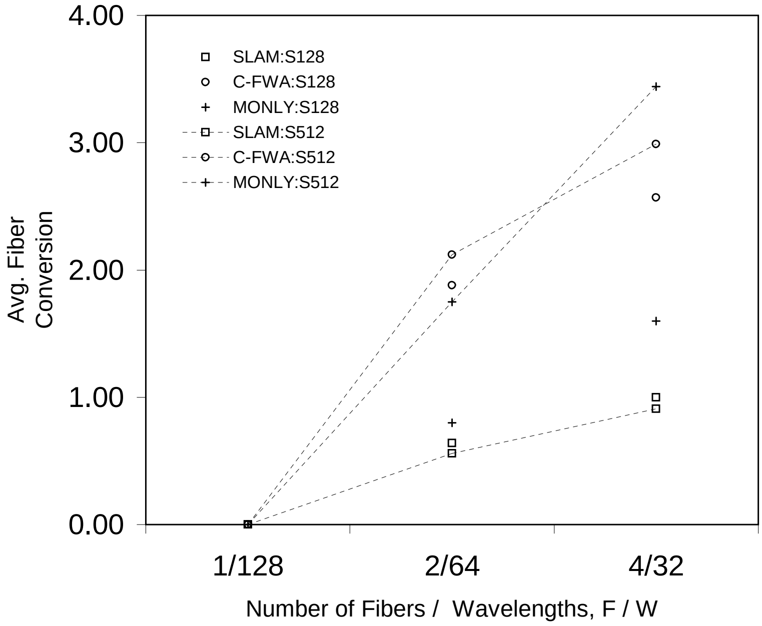

Figure 8.7. AFC vs. F/W for $S = 128$ and $S = 512$

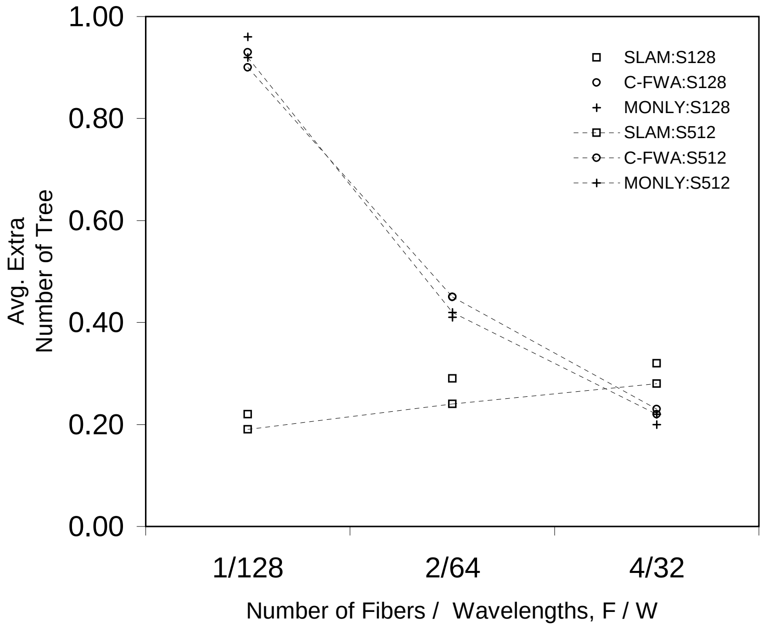

Figure 8.8. AET vs. F/W for $S = 128$ and $S = 512$

8.2. The Effect of Wavelength Conversion

We examine the outcomes of the experiment with respect to two different light splitting conditions which are none ($R_{ls} = 0$) and full ($R_{ls} = 1$), and two different traffic loads which are normal ($S = 128$) and high ($S = 512$) to have better generalizations. Figures 8.9 and 8.10 indicate the average bandwidth metric for normal and high traffic loads, respectively. The performance of SLAM changes around 3-6 per cent for four cases and it is more stable than the others, but the variation doubles while increasing the light splitting capability from 0 to 1 when the traffic load is high. However, this doubling is observed for M-ONLY and C-FWA when the traffic load is both normal and high. It is hard to determine a cutoff point after which there is no improvement for all cases and all algorithms, but $R_{wc} = 0.5$ is a threshold point for SLAM for all cases. If we have restricted amount of wavelength conversion resources, there is no need to deploy wavelength conversion in all of the switches for SLAM which also has the additional advantage of more stability and a small variation for all conditions.

The average delay metric is shown in Figures 8.11 and 8.12. SLAM has a variation of around 5-6 per cent for all cases and it performs similar to the average bandwidth metric. Furthermore, it is more stable, since the optimization is done by assigning the link cost in terms of delay, not bandwidth. The threshold point for SLAM ($R_{wc} = 0.5$) is also similar to threshold point of the average bandwidth metric. SLAM has almost flat curves for the average highest wavelength index metric in Figures 8.13 and 8.14 for all combinations of parameters in contrast to M-ONLY and C-FWA which have quite variations, especially for normal traffic load.

The average extra number of transmitters, wavelength and fiber conversion metrics are denoted in Figures 8.15, 8.16, 8.17, 8.18, 8.19, 8.20. SLAM shows very small variations for all these metrics and almost always better than its competitors. In this respect, it is not appropriate to determine a threshold point for SLAM. Similar comments are also valid for the session blocking probability metric in Figure 8.21. However, the group blocking probability metric varies significantly for all competitors in Figure 8.22, but SLAM performs much better than M-ONLY and C-FWA for GBP.

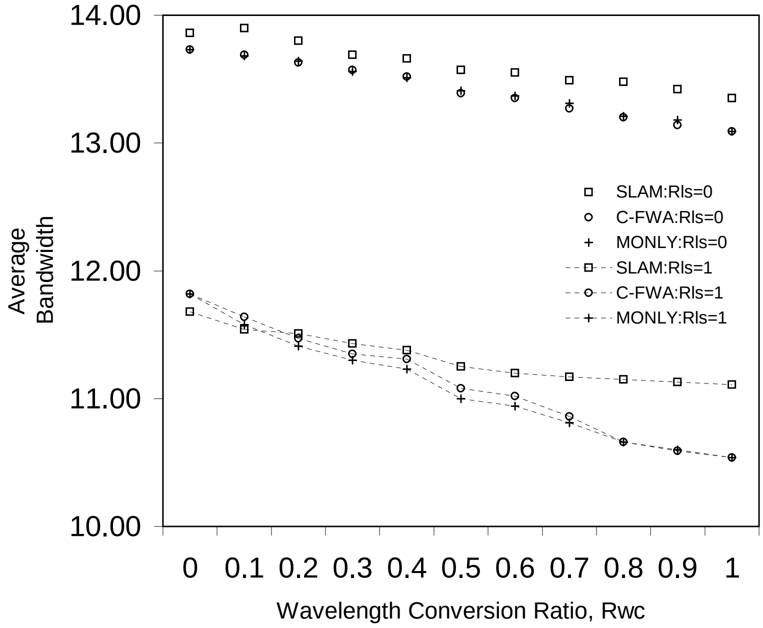

Figure 8.9. AB vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ $(S = 128)$

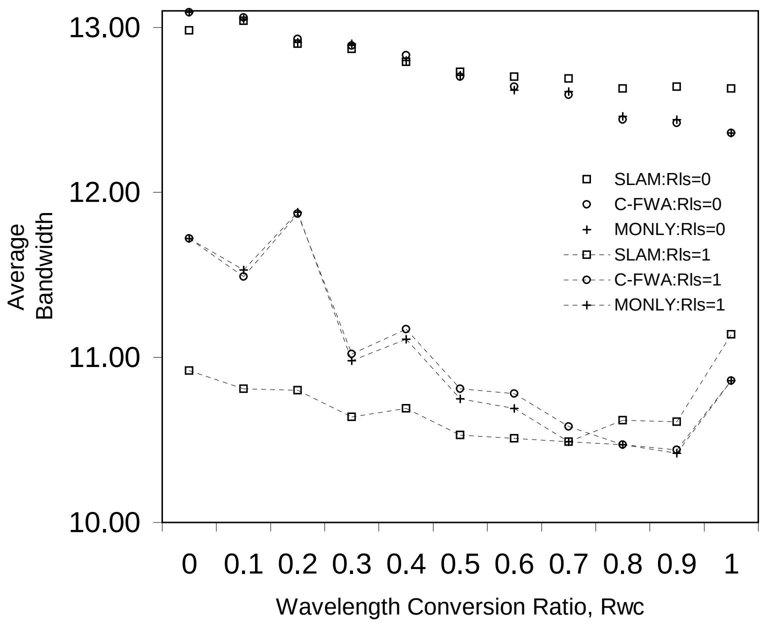

Figure 8.10. AB vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ $(S = 512)$

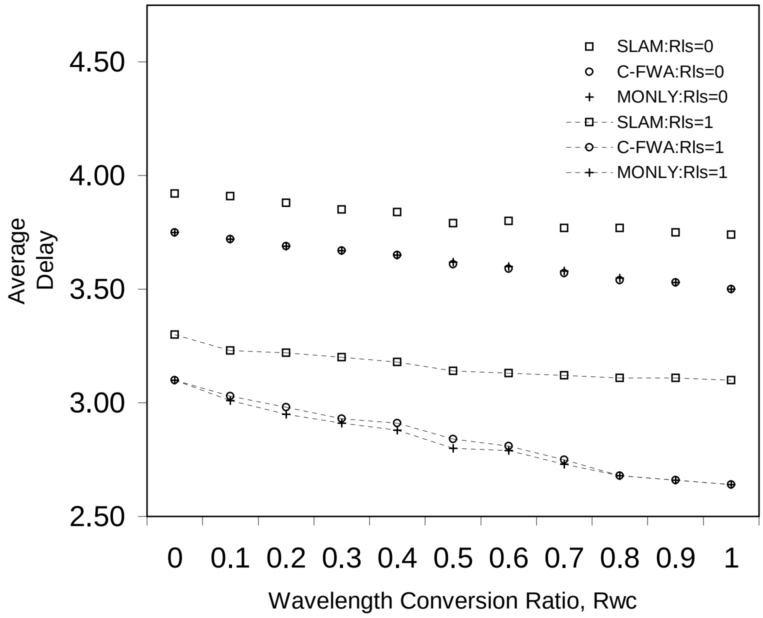

Figure 8.11. AD vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ ($S = 128$)

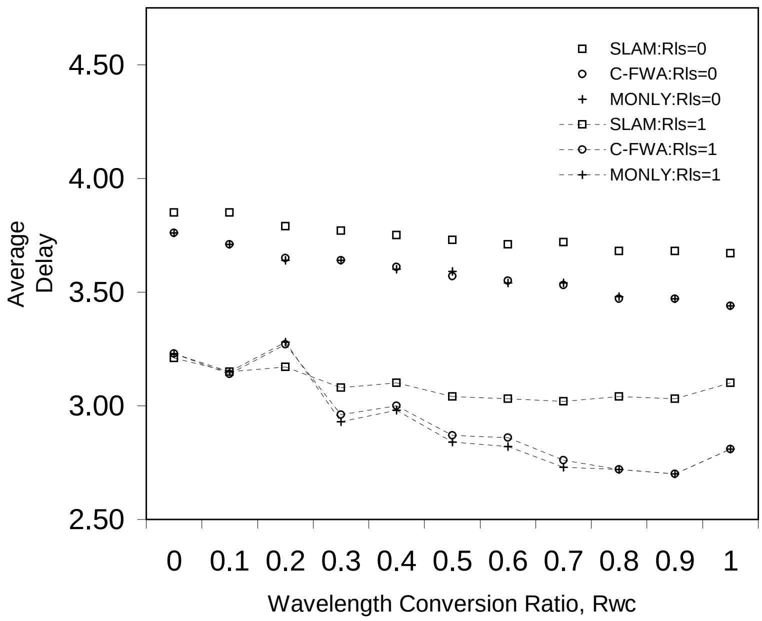

Figure 8.12. AD vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ ($S = 512$)

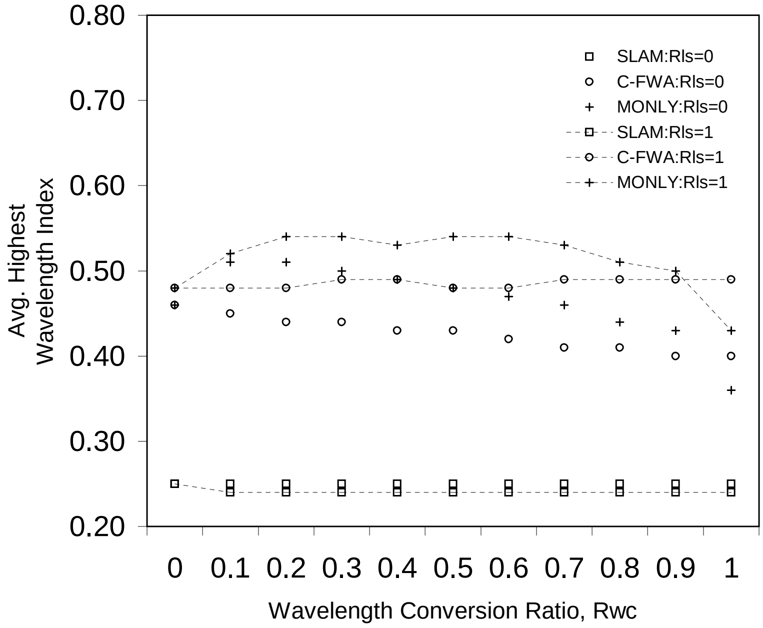

Figure 8.13. AHWI vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ ($S = 128$)

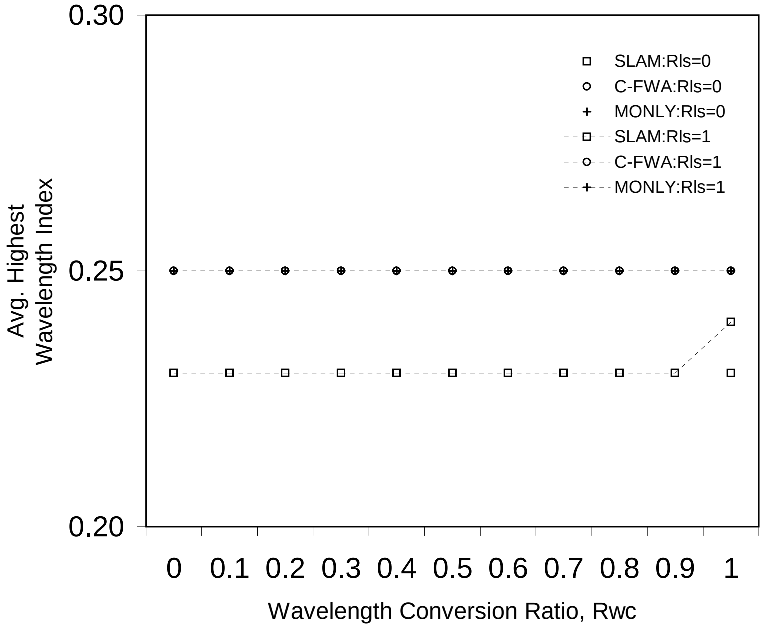

Figure 8.14. AHWI vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ ($S = 512$)

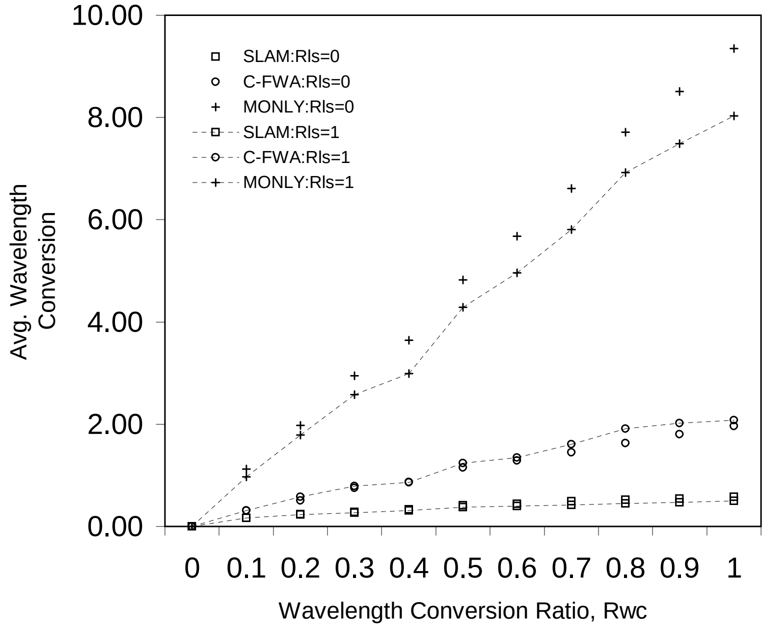

Figure 8.15. AWC vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ ($S = 128$)

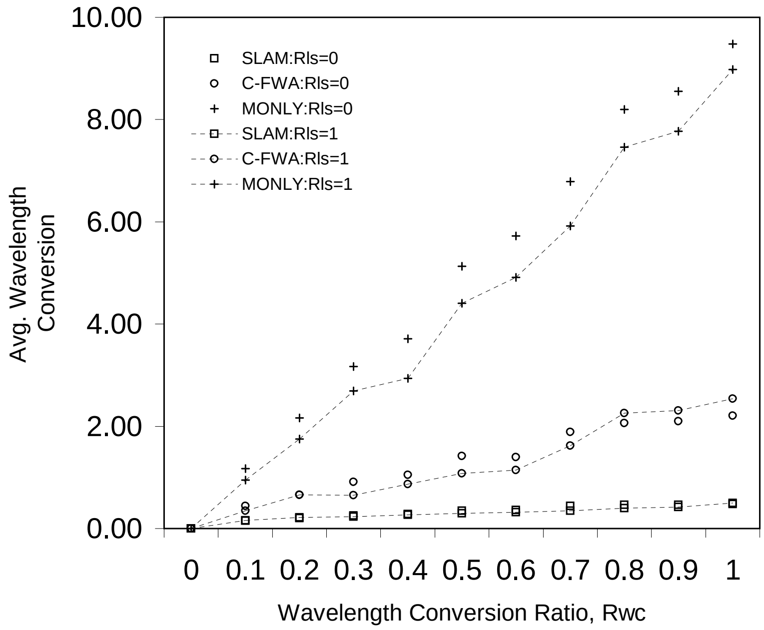

Figure 8.16. AWC vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ ($S = 512$)

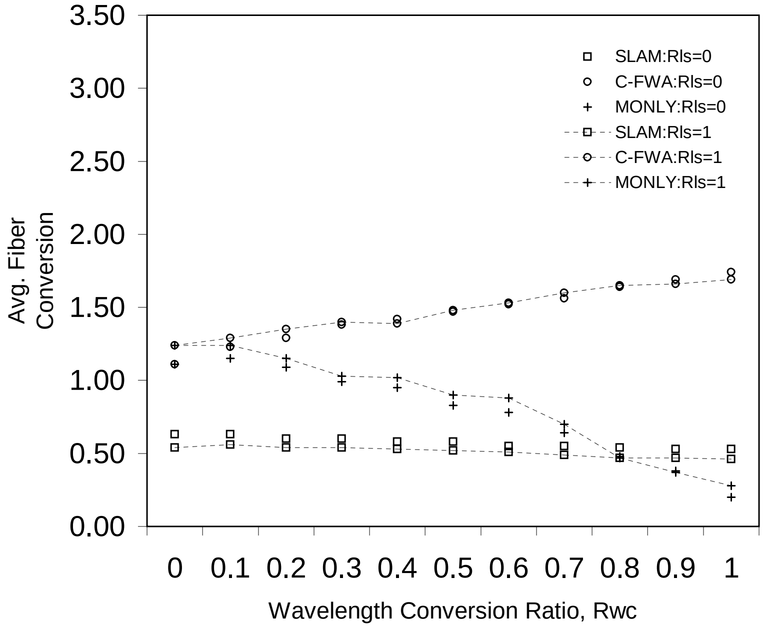

Figure 8.17. AFC vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ $(S = 128)$

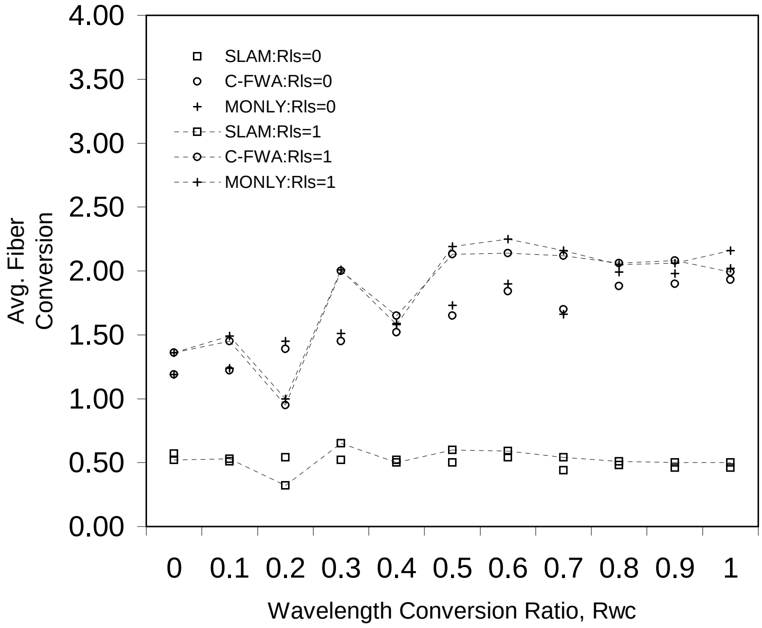

Figure 8.18. AFC vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ $(S = 512)$

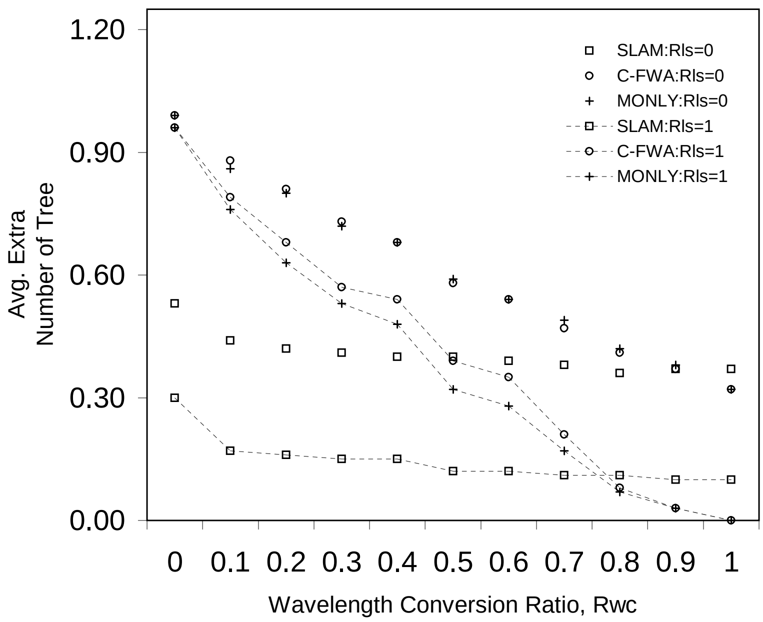

Figure 8.19. AET vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ $(S = 128)$

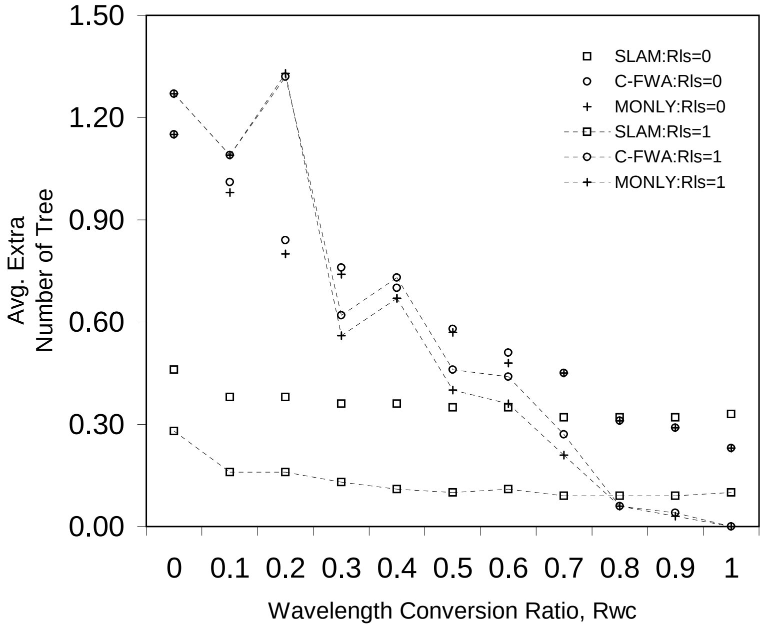

Figure 8.20. AET vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ $(S = 512)$

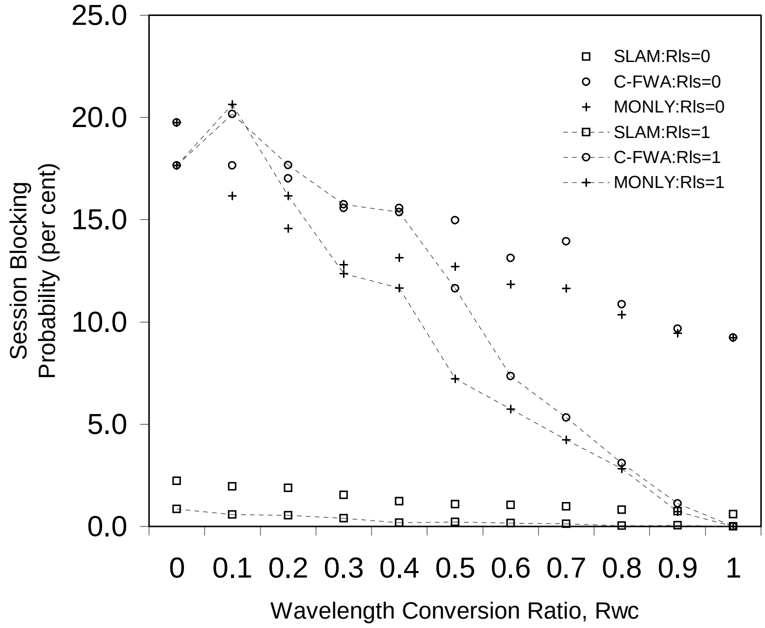

Figure 8.21. SBP vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ ($S = 512$)

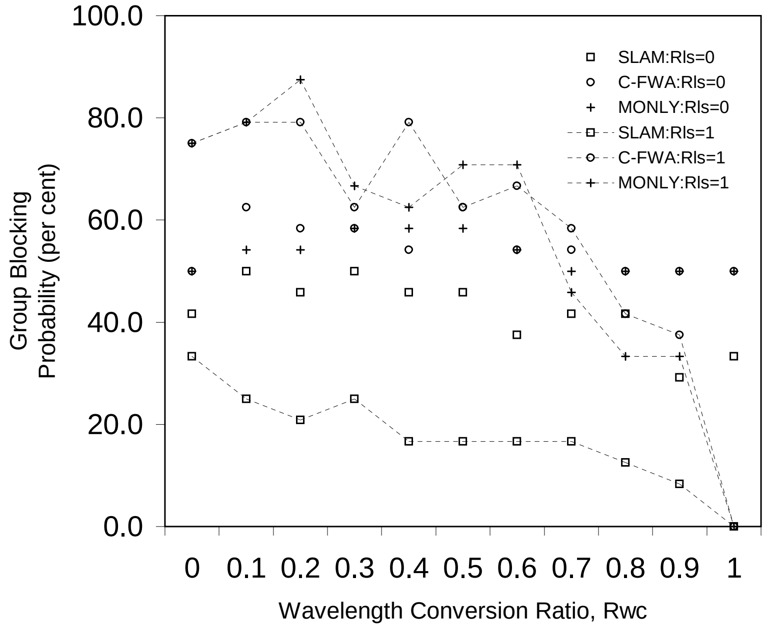

Figure 8.22. GBP vs. R_{wc} for $R_{ls} = 0$ and $R_{ls} = 1$ ($S = 512$)

8.3. The Effect of Light Splitting

The variation of SLAM for the average bandwidth and delay metrics are around four times higher (18-21 per cent) than the variation for wavelength conversion effect and this proves the importance of light splitting capability for building multicasting trees. However, SLAM behaves very similar to the previous case for almost all metrics. The threshold ($R_{ls} = 0.5$) is more obvious for the average bandwidth and delay metrics for SLAM in Figures 8.23, 8.24, 8.25, 8.26 and it is still more stable, since the variation of M-ONLY and C-FWA reaches more than 30 per cent. Figures 8.27, 8.28, 8.29, 8.30, 8.31, 8.32 demonstrate the performance of all methods for the average highest wavelength index, wavelength and fiber conversion metrics. SLAM is still more stable and almost always better than M-ONLY and C-FWA. A slight decreasing trend is observed for the average extra number of transmitters and session blocking probability metrics while increasing the light splitting capability in Figures 8.33, 8.34, 8.35 for SLAM. However, the group blocking probability is much more effected in Figure 8.36.

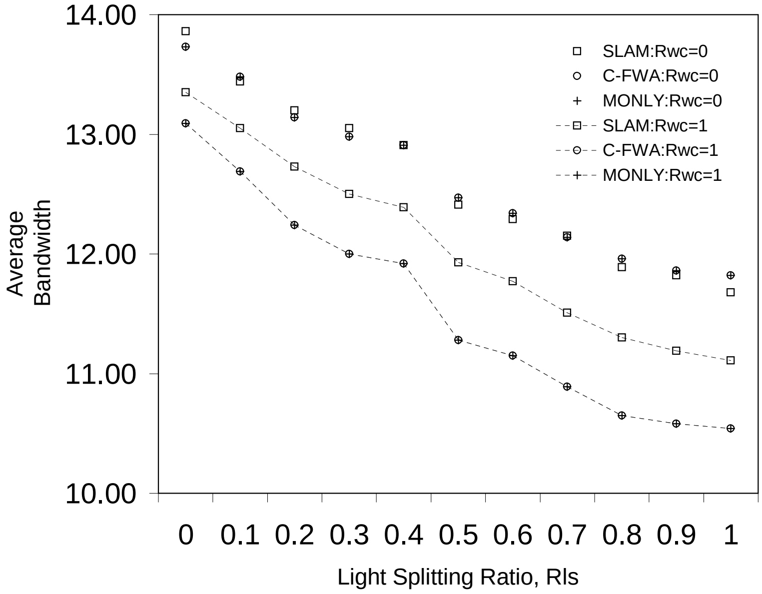

Figure 8.23. AB vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ ($S = 128$)

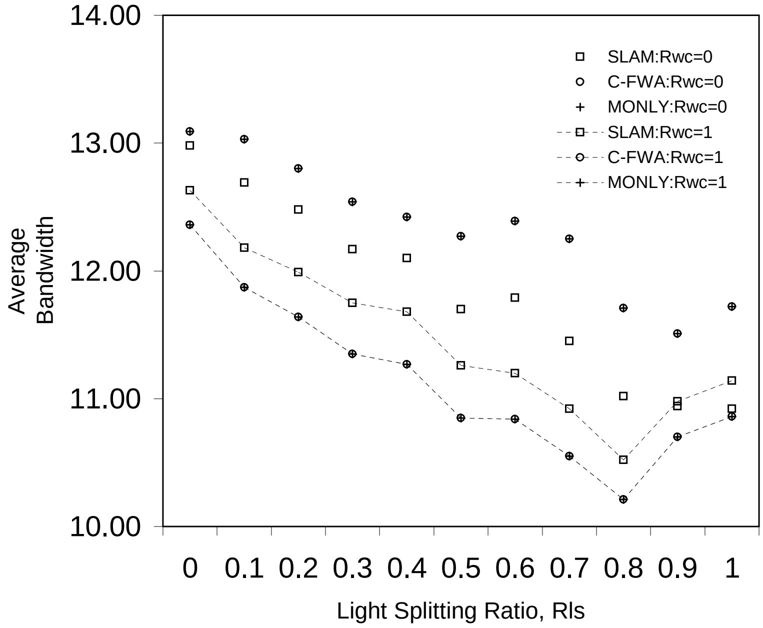

Figure 8.24. AB vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ ($S = 512$)

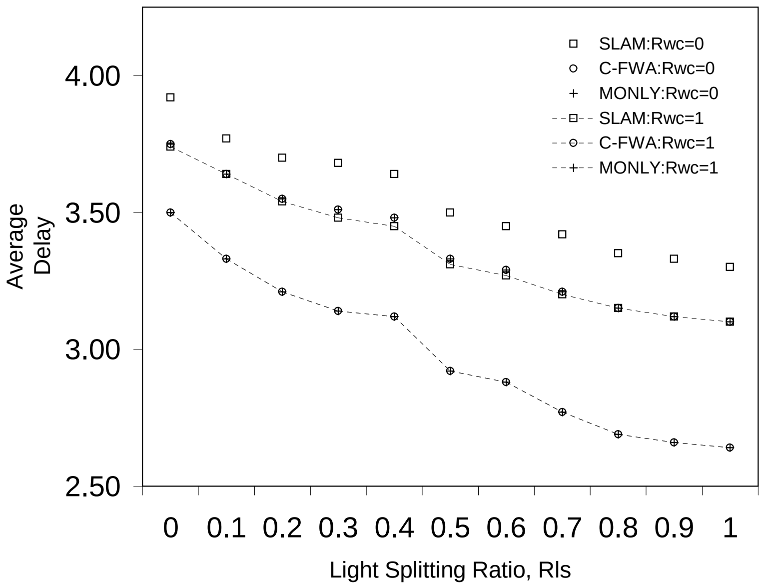

Figure 8.25. AD vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ ($S = 128$)

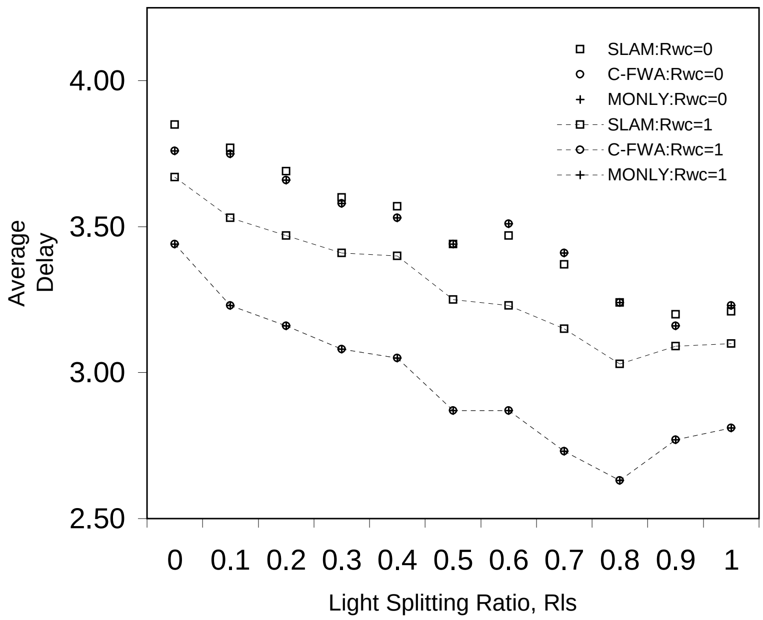

Figure 8.26. AD vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ ($S = 512$)

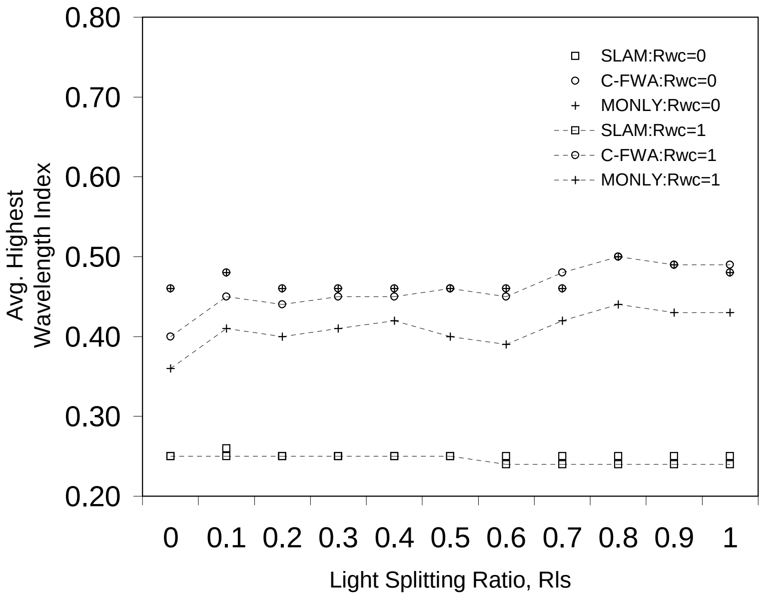

Figure 8.27. AHWI vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ ($S = 128$)

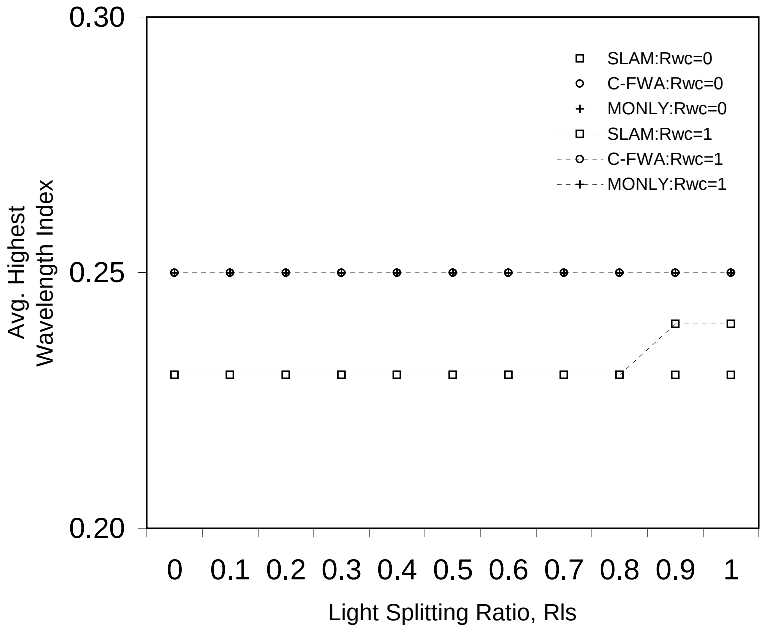

Figure 8.28. AHWI vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ ($S = 512$)

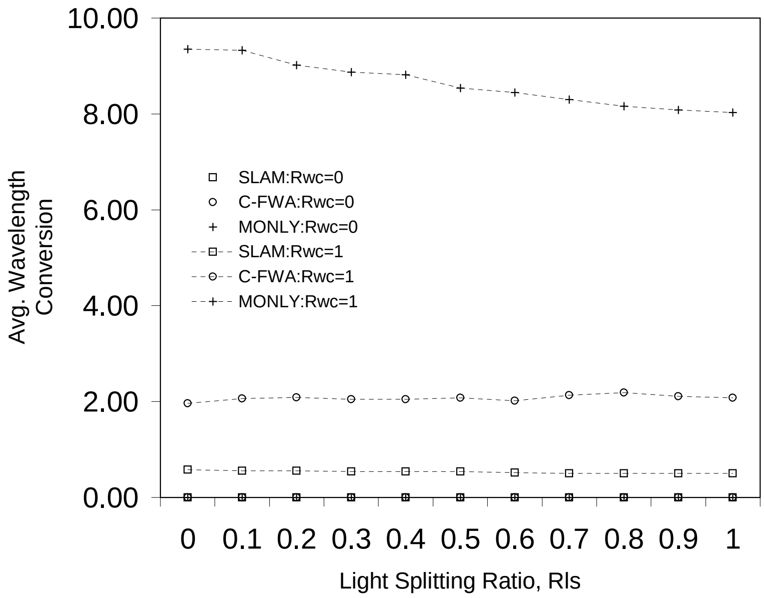

Figure 8.29. AWC vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ ($S = 128$)

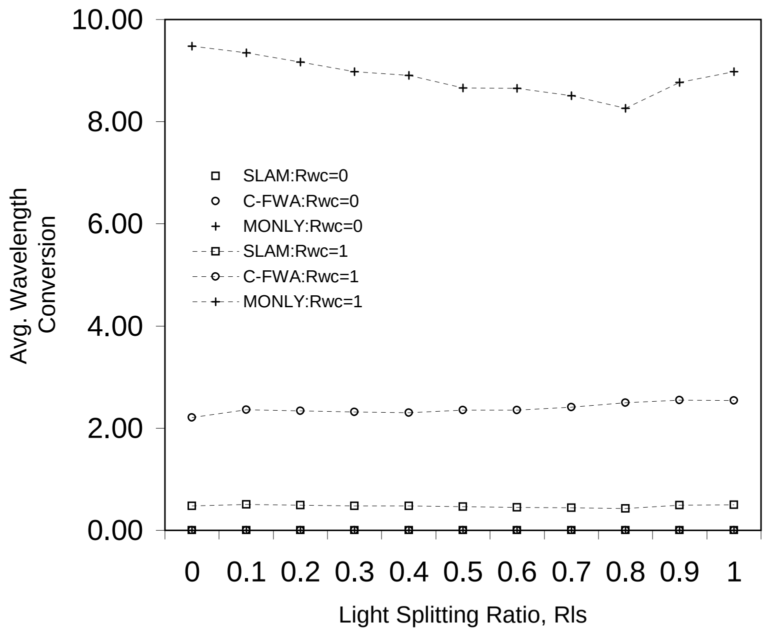

Figure 8.30. AWC vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ ($S = 512$)

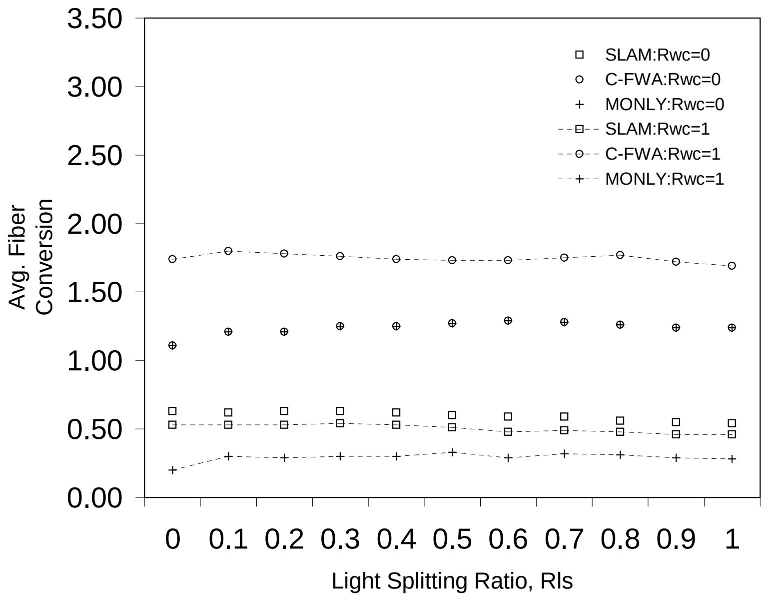

Figure 8.31. AFC vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ ($S = 128$)

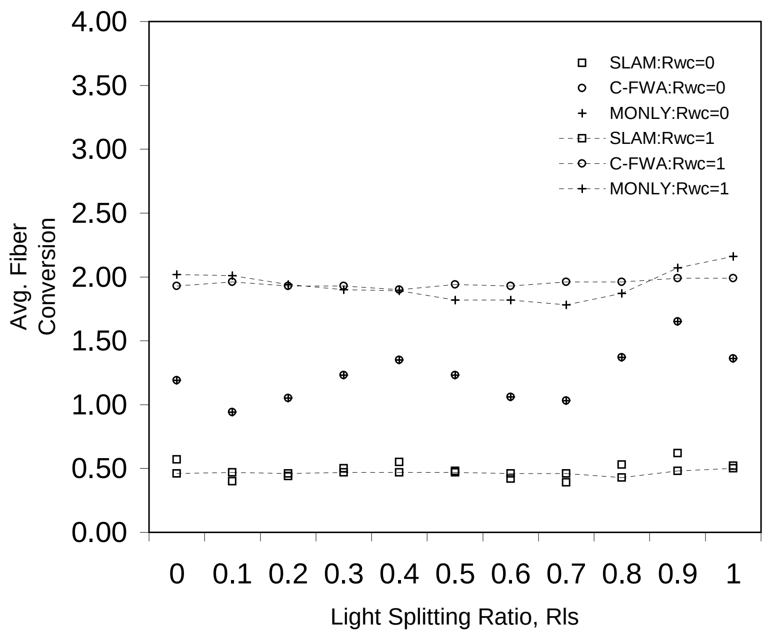

Figure 8.32. AFC vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ ($S = 512$)

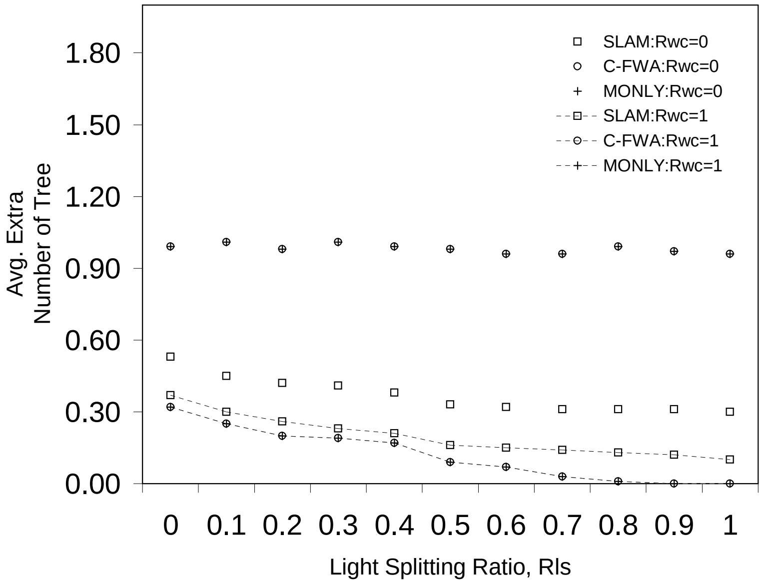

Figure 8.33. AET vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ ($S = 128$)

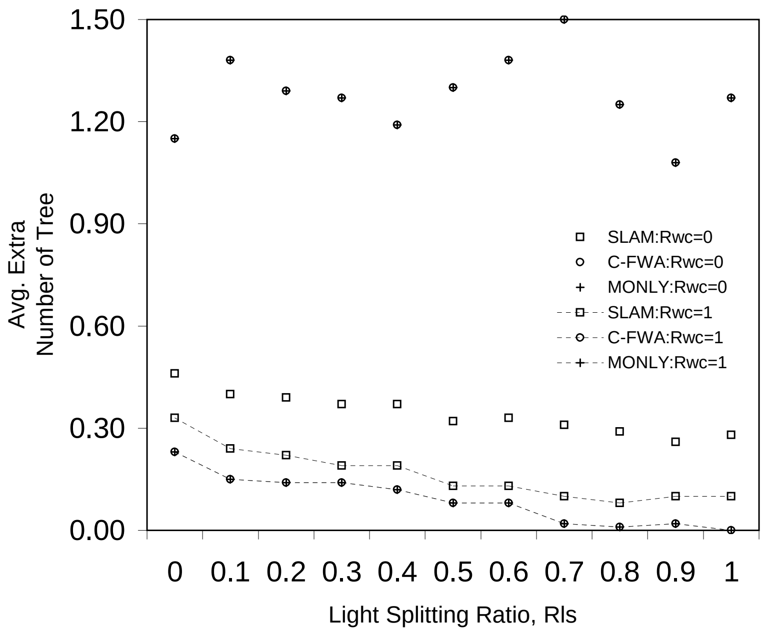

Figure 8.34. AET vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ ($S = 512$)

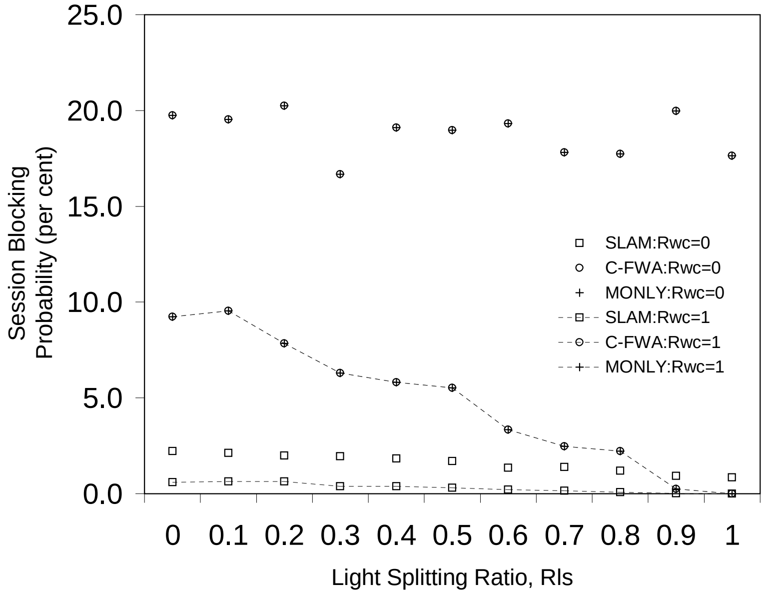

Figure 8.35. SBP vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ $(S = 512)$

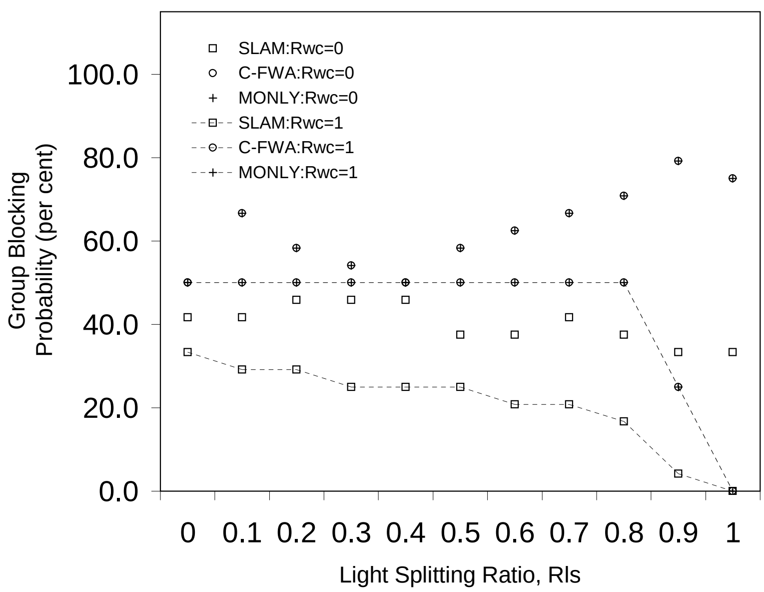

Figure 8.36. GBP vs. R_{ls} for $R_{wc} = 0$ and $R_{wc} = 1$ $(S = 512)$

9. CONCLUSION

The future application scenarios will require long duration of multicast sessions that needs large bandwidth, and all-optical wavelength-routed WDM WANs will be the appropriate infrastructures. In this setting, we proposed a MILP formulation that utilizes a layered graph approach for multicasting in all-optical wavelength routed WDM WAN with multifibers, and sparse wavelength conversion and light splitting 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. Although these parameters can be adjusted to be able to reflect the underlying relative cost of these operations so that all four different cost terms can be minimized simultaneously, LAMA and SLAM can use them to optimize specific metrics. Therefore, the adjustable parameters of LAMA and SLAM make them very flexible to balance different objectives.

In extensive computational experiments, we show that LAMA and SLAM perform very close to the optimal or the lower bound (CPLEX) and significantly better than M-ONLY and C-FWA in terms of nearly all metrics, since they do not separate routing and wavelength assignment steps compared to the other candidates. Experiments also show that important metrics (e.g. the session and group blocking probability, transmitter usage, wavelength and fiber conversion resources) are adversely affected by the separation of routing and fiber-wavelength assignment phases in multicasting. LAMA can be applied to medium size multicasting problems without adjustment and produce partial solutions. Moreover, the running time of LAMA linearly increases with respect to the number of sessions, contrary to CPLEX. However, SLAM, which is a scalable version of LAMA, is appropriate for dynamic multicasting problems. Finally, we also propose a new fiber-wavelength assignment strategy (Ex-Fit in C-FWA) which uses wavelength and fiber conversion resources more effective than the First-Fit.

A very small problem contains up to 4 layers (e.g. F/W: 1/4, 2/2). Similarly, there are at most 8 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 size problems, but it is not suitable for large problems which can only be handled by SLAM or C-FWA.

Table 9.1. Solution methodology for different size and type of problems

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

In general, we propose SLAM for all cases, but SLAM is almost identical to LAMA for small problems. Table 9.1 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 static problems. The running time of SLAM for one session is less than a second and it is suitable for all dynamic problems. However, C-FWA can be used, if extremely fast response is needed.

In all-optical networks, the average number of fiber conversion metric may not be so important in terms of practical reasons, but the average number of transmitters and wavelength conversion are important, since transmitters and wavelength converters are expensive equipments. However, our problem formulation and solution techniques can be applied to optical networks and fiber conversion delay can also be implemented in our general setting. Thus, it is also useful to consider the success in terms of the average number of fiber conversion metric. Moreover, the packing capability of an algorithm which are measured by the average highest wavelength index, session and group blocking probabilities is important for all-optical and optical networks. Therefore, our heuristic solutions are ready to be applied to current optical networks as well as all-optical networks.

WDM multicast is currently implemented by using IP layer multicast protocols like DVMRP (Distance-Vector Multicast Routing Protocol), CBT (Core-Based Trees), OSPF (Open Shortest Path First), or PIM (Protocol-Independent Multicast). However, O/E/O (optical/electrical/optical) conversions cause inefficiencies and processing latencies and this makes all-optical multicasting ideal for bandwidth-intensive applications like distributed computing, database replication, computer-supported scientific collaboration and optical storage area networks. Therefore, our heuristics can be used in those networks with a centralized protocol and they diminish the usage of important resources.

9.2. A search for a background: from top-down to the bottom-up

In an all-optical network, separate routes sharing common links turn to chains or set of chains while moving from unicasting to multicasting without wavelength conversion or light splitting. While wavelength conversion helps to create bigger chains, since more than one wavelength can be used in a path, light splitting converts chains into small trees. Consequently, both capabilities lead to bigger trees so that fewer transmitters are consumed. We have examined all different cases together in a top-down approach with the first six experiments. In the last experiment, we examined each case separately with bottom-up approach, focusing on the performance metrics of the different solution methods for different cases.

We solve MC-RWA problem in which all the constraints and properties are given. When designing a new all-optical network, we also decide on the number of fibers that we lease and the wavelength conversion (WC) or light splitting (LS) properties of the switches so that we minimize the cost while satisfying traffic routing requirements. The last experiment also inspired us to solve this design problem with CPLEX, LAMA or SLAM by an iterative algorithm: A realistic traffic load is created and applied to the network when all nodes have WC and LS capabilities and when no node has these capabilities. If the gaps in terms of desired metrics are significant, then we remove the light splitting or wavelength conversion property of a node with minimal usage of that property. We go on till a serious degradation occurs in one of the important metrics. Similarly, we can decide on the minimum amount of fibers and wavelengths.

9.3. Extending the boundaries

LAMA and SLAM are very flexible heuristics and the current versions can solve multicasting problem on networks having multifiber and nodes with sparse or full wavelength conversion and light splitting capabilities. Moreover, these versions can also handle limited wavelength conversion property of nodes by applying wavelength conversion rules to the layered graph. Similarly, we are using light splitting restrictions for each node. If a node has sparse splitting capability, then the number of its outgoing connections should be one and if it is a full light splitting node, then the number of its outgoing connections should be at least the number of its outgoing links. If we want to solve limited light splitting version of the problem, all we need to do is to update the number of outgoing connections of each node with its limited light splitting capability. Similar adjustments can also be done for CPLEX either by changing the layered graph that it works and/or the constraint 3.5. Moreover, we also evaluated the order of session establishment matrix (the order of sessions and destinations) to generalize from static to dynamic case. Finally, the layered graph approach can be applied to multicasting in next generation wireless systems in which different technologies are employed together like WLAN, GPRS, UMTS, and satellite-based systems.

REFERENCES

1. Brackett, C. A., "Dense Wavelength Division Multiplexing Networks: Principles and Applications", *IEEE Journal Selected Areas in Comm.*, Vol. 8, pp. 948-964, August 1990.

2. Ramaswami, R., "Multiwavelength Lightwave Networks for Computer Communication", *IEEE Communications Magazine*, Vol. 31, pp. 78-88, February 1993.

3. Hamad, A., and A. Kamal, "A Survey of Multicasting Protocols for Broadcast-and-select Single-hop Networks", *IEEE Network Magazine*, 16(4), pp.36-48, 2002.

4. Sahasrabuddhe, L. H., and B. Mukherjee, "Light-Trees: Optical Multicasting for Improved Performance in Wavelength-routed Networks", *IEEE Communications Magazine*, Vol. 36, pp. 67-73, February 1999.

5. Mukherjee, B., "WDM-Based Local Lightwave Networks Part 1: Single-hop Systems", *IEEE Network Magazine 6*, Vol. 3, pp.12-27, 1992.

6. Mukherjee, B., "WDM-Based Local Lightwave Networks Part 1: Multihop systems", *IEEE Network Magazine 6*, Vol. 4, pp.20-32, 1992.

7. Banerjee, S., V. Jain, and S. Shah, "Regular Multihop Logical Topologies for Lightwave Networks", *IEEE Communications Survey*, vol.2, no.1, 1999.

8. Zhang, X., J. Y. Wei, and C. Qiao, "Constrained Multicast Routing in WDM Networks with Sparse Light Splitting", *IEEE Journal of Lightwave Technology*, Vol. 18, No. 12, pp. 1917-1927, December 2000.

9. He J., S. H. G. Chan, and D. H. K. Tsang, "Multicasting in WDM Networks", *IEEE Commun. Surveys and Tutorials*, 2002.

10. Yoo, M., and C. Qiao., "Optical Burst Switching (OBS) - A New Paradigm for An Optical Internet", *Journal of High Speed Networks (JHSN)*, 8(1), pp.69 -84, 1999.

11. Sahin, G., and M. Azizoglu, "Multicast Routing and Wavelength Assignment in Wide Area Networks", *Proceedings of SPIE*, Vol. 3531, pp.196 -208, 1998.

12. Mellia, M., A. Nucci, A. Grosso, E. Leonardi, and M. A. Marsan, "Optimal Design of Logical Topologies in Wavelength-routed Optical Networks with Multicast Traffic", *Proc. IEEE GLOBECOM*, pp.1520-1525, November 2001.

13. Dutta, R., and G. N. Rouskas, "A Survey of Virtual Topology Design Algorithms for Wavelength-routed Optical Networks", *Optical Networks Magazine*, 1(1), pp.73-89, January 2000.

14. Chlamtac, I., A. Ganz, and G. Karmi, "Lightpath Communications: An Approach to High Bandwidth Optical WAN's", *IEEE Transactions on Communications*, Vol.40, pp.1171-1182, July 1992.

15. Zang, H., J. P. Jue, L. Sahasrabuddhe, R. Ramamurthy, and B. Mukherjee, "Dynamic Lightpath Establishment in Wavelength-routed WDM Networks", *IEEE Communications Magazine*, Vol.39, pp.100-108, September 2001.

16. Sun, Y., J. Gu, and D.H.K. Tsang, "Routing and Wavelength Assignment in All-Optical Networks with Multicast Traffic", *Proceedings of International Teletraffic Congress (ITC'16)*, Edinburgh, U.K., June 1999.

17. Veeraraghavan, M., M. Karol, R. Karri, T. Moors, and R. Grobler, "Architectures and Protocols that Enable New Applications on Optical Networks", *IEEE Communications Magazine*, Vol.39, pp.118-127, March 2001.

18. Gilbert, E. N., and H. O. Pollak, "Steiner Minimal Trees", *SIAM Journal of Applied Mathematics*, Vol.16, no.1, pp.1-29, 1968.

19. Karp, R. M., "Reducibility among combinatorial problems", *In Complexity of Computer Computations*, R. E. Miller and, J. W. Thatcher (editors), pp. 85-103, Plenum Press, New York, 1972.

20. Gargano, L., A. A. Rescigno, and U. Vaccaro, "Multicasting to Groups in Optical Networks and Related Combinatorial Optimization Problems", *Proceedings of the International Parallel and Distributed Processing Symposium (IPDPS03)*, 2003.

21. Sahasrabuddhe, L. H., and B. Mukherjee, "Multicast Routing Algorithms and Protocols: A Tutorial", *IEEE Network*, Vol.14, pp.90-102, January/February 2000.

22. Doar, M., and I. M. Leslie, "How bad is Naive Multicast Routing?", *IEEE Infocom*, pp.82-89, 1993.

23. ILOG CPLEX: High-Performance Software for Mathematical Programming and Optimization. http://www.ilog.com/products/cplex/

24. Malli, R., X. Zhang, and C. Qiao, "Benefits of Multicasting in All-optical Networks", *Proceedings of SPIE, All optical Networking*, Vol. 3531, pp.209 -220, November 1998.

25. Thaker, G. N., and D. Rouskas, "Multi-Destination Communication in Broadcast WDM Networks: A Survey", *Technical report: TR-2000-08*, North Carolina State University, Raleigh, July 28, 2000.

26. Borella, M., and B. Mukherjee, "A Reservation-Based Multicasting Protocol for WDM Local Lightwave Networks", *Proceedings of IEEE ICC '95*, pp.1277-1281, June 1995.

27. Jue, J. P., and B. Mukherjee, "The Advantages of Partitioning Multicast Transmissions in a Single-Hop Optical WDM Network", *Photonic Network Communications*, 1:2, pp.111-124, 1999.

28. Lin, H., and C. Wang “A Hybrid Multicast Scheduling Algorithm for Single-Hop WDM Networks”, *Proc. IEEE INFOCOM, 2001*, pp.169-178, April 2001.

29. Ortiz, Z., G. Rouskas, and H. Perros, “Maximizing Multicast Throughput in WDM Networks with Tuning Latencies Using the Virtual Receiver Concept”, *European Trans. on Telecommunications*, Vol.11, pp.63-72, Jan.-Feb., 2000.

30. Bianco, A., G. Galante, E. Leonardi, F. Neri, and A. Nucci, “Scheduling Algorithms for Multicast Traffic in TDM/WDM Networks with Arbitrary Tuning Latencies”, *Computer Networks*, Vol.41, Issue 6, pp.727-742, 2003.

31. Borella, M., and B. Mukherjee, “Multicasting in a WDM Local Lightwave Network”, ITC sponsored seminar on ”Teletraffic Analysis Methods for Current and Future Telecom Networks”, *(To appear)*.

32. Ortiz, Z., G. N. Rouskas, and H. G. Perros, “Scheduling Combined Unicast and Multicast Traffic Broadcast WDM Networks”, *Journal of Photonic Network Communications*, Vol.2, pp.135-154, May 2000.

33. Baldine, I., and G. N. Rouskas, “Traffic Adaptive WDM Networks: A Study of Reconfiguration Issues”, *IEEEJOSA Journal of Lightwave Technology*, 19(4), pp.433-455, April 2001.

34. Wan, Y., and W. Liang, “On the Minimum Number of Wavelengths in Multicast Trees in WDM Networks”, *Networks*, Vol. 45, No. 1, pp. 42-48, 2005.

35. Yang, D., and W. Liao, “Design of Light-Tree Based Logical Topologies for Multicast Streams in Wavelength Routed Optical Networks”, *IEEE Infocom 2003.*, Vol. 1, pp. 32-41, 2003.

36. Scheutzow, M., P. Seeling, M. Maier, and M. Reisslein, “WDM Star Subnetwork Upgrade of Optical Ring Networks for Maximum Spatial Reuse under Multicast Traffic”, *IEEE Journal Selected Areas in Comm.*, Vol. 25, No. 3, pp. 55-67, April 2007.

37. Tridandapani, S. B., and B. Mukherjee, “Channel Sharing in Multi-Hop WDM Lightwave Networks: Realization and Performance of Multicast Traffic”, *IEEE Journal on Selected Areas in Communications*, Vol.15, No.3, p.488, April 1997.

38. Ferrel, I., A. Mettler, E. Miller, and R. L. Hadas, “Virtual Topologies for Multicasting with Multiple Originators in WDM Networks”, *IEEE/ACM Transactions on Networking*, Vol.14, No.1, p.183, February 2006.

39. Wang, Y., and Y. Yang, “Multicasting in a Class of Multicast-Capable WDM Networks”, *Journal of Lightwave Technology*, Vol.20, No.3, p.350, March 2002.

40. Wu, H.-T., K.-W. Ke and S. Huang, “A Novel Multicast Mechanism for Optical Local Area Networks”, *Computers and Electrical Engineering*, Vol. 33, No. 2, pp. 94-108, March 2007.

41. Jeyakumar, A. E., K. Baskaran, and V. Sumathy, “Genetic Algorithm for Optimal Design of Delay Bounded WDM Multicast Networks”, *Conference on Convergent Technologies for Asia-Pacific Region, TENCON 2003*, vol.3, pp.1224-1228, 15-17 October 2003.

42. Jeong, M., C. Qiao, Y. Xiong, Hakki C. Cankaya, and M. Vandenhoute, “Efficient Multicast Schemes for Optical Burst-Switched WDM Networks”, *ICC*, (3), pp.1289-1294, 2000.

43. Jeong, M., C. Qiao, and Y. Xiong, “Reliable WDM Multicast in Optical Burst-Switched Networks”, *Opticomm’00*, Dallas, TX, October 2000.

44. Qiao, C., M. Jeong, A. Guha, X. Zhang, and J. Wei, "WDM Multicasting in IP over WDM Networks", *Proceedings of International Conference on Network Protocols (ICNP)*, pp. 89-96, November 1999.

45. Zhang, X., J. Wei, and C. Qiao., "On Fundamental Issues in IP over WDM Multicast", *IC3N'99*, pp. 84-90, October 1999.

46. Qiao, C., "Labeled optical burst switching for IP-over-WDM integration", *IEEE Communication Magazine*, pp.104 -114, September 2000.

47. Yoo, M., C. Qiao., and S.Dixit, "Optical Burst Switching for Service Differentiation in the Next-Generation Optical Internet", *IEEE Communication Magazine*, pp.98 -104, February 2001.

48. Jeong, M., C. Hakki, and C. Qiao., "On A New Multicasting Approach in Optical Burst Switched Networks", *IEEE Communications Magazine*, pp. 96-103, November 2002.

49. Jeong, M., C. Qiao, Y. Xiong, and M. Vandenhoute, "Bandwidth-Efficient Dynamic Tree-Shared Multicast In Optical Burst-Switched Networks", *Proc. IEEE ICC, 2001*, pp.630-636, June 2001.

50. Jeong, M., C. Qiao, Y. Xiong, H. C. Cankaya, and M. Vandenhoute, "Tree-Shared Multicast in Optical Burst-Switched WDM Networks", *Journal of Lightwave Technology*, Vol.21, No.1, pp.13-24, January 2003.

51. Hamad, A., T. Wu, A. E. Kamal, and A. K. Somani, "On Multicasting in Wavelength-routing Mesh Networks", *Computer Networks*, Vol. 50, pp. 3105-3164, 2006.

52. Zhou, Y., and G. S. Poo, "Optical Multicast over Wavelength-routed WDM Networks: A Survey", *Optical Switching and Networking*, Vol. 2, pp. 176-197, 2005.

53. Yan, S., M. Ali, and J. Deogun, “Route Optimization of Multicast Sessions in Sparse Light-Splitting Optical Networks”, *Proc. of IEEE GLOBECOM’01*, pp.2134-2138, November 2001.

54. Ali, M., and J. S. Deogun, “Power-Efficient Design of Multicast Wavelength-Routed Networks”, *IEEE Journal Selected Areas in Communications*, Vol. 18, No. 10, pp.1852 -1862, October 2000.

55. Ali, M., and J. Deogun, “Allocation of Multicast Nodes in Wavelength-Routed Networks”, *IEEE ICC’01*, Vol. 2, pp. 615-618, 2001.

56. Ali, M., and J. Deogun, “Cost-Effective Implementation of Multicasting in Wavelength-Routed Networks”, *IEEE/OSA Journal of Lightwave Technology*, Vol. 18, No. 12, pp. 1628-1638, December 2000.

57. Hu, X. D., T. P. Shuai, X. Jia, and M. Zhang, “Multicast Routing and Wavelength Assignment in WDM Networks with Limited Drop-offs”, *IEEE Infocom*, Vol. 1, pp. 494-500, 2004.

58. Xin, Y., and G. N. Rouskas, “Multicast Routing Under Optical Layer Constraints”, *IEEE Infocom*, Vol. 4, pp. 2731-2742, 2004.

59. Yu, O., and Y. Cao, “Placement of Light Splitters and Wavelength Converters for Efficient Multicast in All-Optical WDM Networks”, *IEICE TRANS. INF. AND SYST.*, Vol.E89-D, No.2, p.709, February 2006.

60. Miller, E., R. L. Hadas, D. Barnard, W. Chang, K. Dresner, W. M. Turner, and J. R. Hartline, “On the Complexity of Virtual Topology Design for Multicasting in WDM Trees With Tap-and-Continue and Multicast-Capable Switches”, *IEEE Journal on Selected Areas in Communications*, Vol.22, No.9, pp.1601-1612, November 2004.

61. Maher, A., "Optimization of Splitting Node Placement in Wavelength-Routed Optical Networks", *IEEE Journal on Selected Areas in Communications*, Vol.20, No.8, p.1571, October 2002.

62. Peng, Y., W. Hu, W. Sun, X. Wang, and Y. Jin, "Impairment Constraint Multicasting in Translucent WDM Networks: Architecture, Network Design and Multicasting Routing", *Photonic Network Communications*, 13, pp.93-102, 2007.

63. Chen, M., S. Tseng, and B.M.T. Lin, "Dynamic Multicast Routing under Delay Constraints in WDM Networks With Heterogeneous Light Splitting Capabilities", *Computer Communications*, 29, pp.1492-1503, 2006.

64. Huang, N., T. Liu, Y. Wang, and B. Li, "On Multicast Routing for Wavelength-Routed WDM Networks with Dynamic Membership", *Photonic Network Communications*, 4:2, pp.179-190, 2002.

65. Rammohan, N., and C. Siva Ram Murthy, "On-Line Multicast Routing with Qos Constraints In WDM Networks with no Wavelength Converters", *Computer Networks*, Vol.50, No.18, p.3666, 2006.

66. Kim, N., H. Yun, T. Kim, J. Yoo, B. Kim, and M. Kang, "Share Based-Channel Scheduling Algorithm for Multicast Video Delivery in WDM Optical Access Networks", *IEICE Trans. Comm.*, Vol. E90-B, No. 3, pp. 499-507, March 2007.

67. Chen, B., and J. Wang, "Efficient Routing and Wavelength Assignment for Multicast in WDM Networks", *IEEE Journal Selected Areas in Communications*, Vol. 20, No. 1, pp. 97-109, January 2002.

68. He, J., S. H. G. Chan, and D. H. K. Tsang, "Routing and Wavelength Assignment for WDM Multicast Networks", *Proc. IEEE GLOBECOM'01*, pp. 1536-40, 2001.

69. Chen, M. T., and S. S. Tseng, "A Genetic Algorithm for Multicast Routing under Delay Constraint in WDM Network with Different Light Splitting", *Journal of Information Science and Engineering 21*, pp. 85-108, 2005.

70. Honda, H., H. Tode, and K. Murakami, "Optical WDM Multicasting Design under Wavelength Conversion Constraints", *IEICE Transactions on Communications*, Vol. E88-B, No. 5, pp. 1890, May 2005.

71. Sankaranarayanan, S., and S. Subramaniam, "Comprehensive Performance Modeling and Analysis of Multicasting in Optical Networks", *IEEE Journal of Selected Areas in Communications*, Vol. 21, No. 9, pp. 1399-1413, November 2003.

72. Wang, J., B. Chen, and R. N. Uma, "Dynamic Wavelength Assignment for Multicast in All-optical WDM Networks to Maximize the Network Capacity", *IEEE Journal of Selected Areas in Communications*, Vol. 21, No. 8, p. 1274, October 2003.

73. Huang, C., X. Jia, and Y. Zhang, "A Distributed Routing and Wavelength Assignment Algorithm for Real-time Multicast in WDM Networks", *Computer Communications*, Vol. 25, pp. 1527-1535, November 2002.

74. Garcia, P., A. Zsigri, and A. Guitton, "A Multicast Reinforcement Learning Algorithm for WDM Optical Networks", *7th International Conference on Telecommunications-ConTEL*, Zagreb, Croatia, Vol. 2, pp. 419-426, 2003.

75. Kamal, A. E., "Algorithms for Multicast Traffic Grooming in WDM Mesh Networks", *IEEE Communications Magazine*, Vol. 44, No. 11, p. 96, November 2006.

76. Cao, Y., and O. Yu, "QoS-Guaranteed Routing and Wavelength Assignment for Group Multicast in Optical WDM Networks", *Optical Network Design and Modeling Conference*, pp.175-184, Feb. 7-9, 2005.

77. Cao, Y., and O. Yu, "On the Study of Group Multicast in WDM Networks", *ICC 2005*, Vol.3, pp.1625-1630, 16-20 May 2005.

78. Cao, Y., and O. Yu, "Groupcast in Wavelength-Routed WDM Networks", *Journal of Lightwave Technology*, Vol.24, No.11, p. 4286, November 2006.

79. Hsieh, C., and W. Liao, "All Optical Multicast Routing in Sparse-splitting Optical Networks", *Proceedings of the 28th Annual IEEE International Conference on Local Computer Networks (LCN '03)*, p. 162, 2003.

80. Wang, J., X. Qi, and B. Chen, "Wavelength Assignment for Multicast in All-Optical WDM Networks With Splitting Constraints", *IEEE/ACM Transactions on Networking*, Vol. 14, No. 1, pp. 169-182, February 2006.

81. Singhal, N. K., L. H. Sahasrabuddhe, and B. Mukherjee, "Optimal Multicasting of Multiple Light-Trees of Different Bandwidth Granularities in a WDM Mesh Network With Sparse Splitting Capabilities", *IEEE/ACM Transactions on Networking*, Vol.14, No.5, p.1104, October 2006.

82. "On-Line Multicasting in All-Optical Networks", Hashimoto, K., T. Yamada, and S. Ueno, *IEICE TRANS. INF. AND SYST.*, Vol.E86-D, No.2, p.99, February 2003.

83. Pankaj, R. K., "Wavelength Requirements for Multicasting in All-Optical Networks", *IEEE/ACM Transactions on Networking*, Vol.7, No.3, p.414, June 1999.

84. Jia, X. H., D. Du, X. Hu, M. Lee, and J. Gu, "Optimization of Wavelength Assignment for QoS Multicast in WDM Networks", *IEEE Transactions on Communications*, Vol.49, No.2, pp.341-350, February 2001.

85. Hwang, I. S., S. Lee, and Y. Chuang, "Multicast Wavelength Assignment with Sparse Wavelength Converters to Maximize the Network Capacity Using ILP Formulation in WDM Mesh Networks", *Photonic Network Communications*, 12, pp.161-172, 2006.

86. Poo, G., and Y. Zhou, "A New Multicast Wavelength Assignment Algorithm in Wavelength-Routed WDM Networks", *IEEE Journal Selected Areas in Comm.*, Vol. 24, No. 4, pp. 2-12, April 2006.

87. Wu, K., J. Wu, and C. Yang, "Multicast Routing with Power Consideration in Sparse Splitting WDM Networks", *Proc. IEEE Intl. Conf. Commun.*, ICC, 2001.

88. Jo, J.-M., S.-J. Lee, K.-D. Hong, C.-J. Lee, O.-H. Kang, and S.-U. Kim, "Virtual Source-based Minimum Interference Path Multicast Routing in Optical Virtual Private Networks", *Journal Photonic Network Communications*, Vol. 13, No. 1, pp. 19-30, January 2007.

89. Sreenath, N., and C. S. Murthy, "Virtual Source Based Multicast Routing in WDM Optical Networks", *Photonic Network Communications*, 3:3, pp.213-226, 2001.

90. Xu, S., L. Li, and S. Wang, "Dynamic Routing and Assignment of Wavelength Algorithms in Multifiber Wavelength Division Multiplexing Networks", *IEEE Journal of Selected Areas in Communications*, Vol. 18, No. 10, pp. 2130-2137, October 2000.

91. Cinkler, T., 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", *Proceedings of IEEE INFOCOM*, Vol. 2, pp. 1000-1009, 2000.

92. Maier, G., A. Pattavina, L. Roberti, and T. Chich, "Static-lightpath Design by Heuristic Methods in Multifiber WDM Networks", *Proceedings of OPTICOMM*, Vol. 4233, No. 1, pp. 64-75, 2000.

93. Winter, P., "Steiner Problems in Networks: A Survey", *Networks*, Vol. 17, pp. 129-167, 1987.

94. Hwang, F. K., D. S. Richards, and P. Winter, "The Steiner Tree Problem", *Annals of Discrete Mathematics*, 53, North-Holland, Amsterdam, 1992.

95. Koch, T., and A. Martin, "Solving Steiner Tree Problems in graphs to optimality", *Networks*, Vol. 32, No. 3, pp. 207-232, 1998.

96. Köksal, F., and C. Ersoy, "Multicasting for All-optical Multifiber Networks", *Journal of Optical Networking*, Vol. 6, No. 1, pp. 219-238, January 2007.

97. Horowitz, E., and S. Sahni, "Fundamentals of Data Structures in Pascal", *W. H. Freeman and Company*, 41 Madison Avenue, New York, NY10010, 1988.

98. Köksal, F., and C. Ersoy, "A Flexible Scalable Solution for All-optical Multifiber Multicasting: SLAM", *IEEE Journal of Lightwave Technology*, *(To appear).*

99. Jain, R. "The art of computer systems performance analysis"," John Wiley and Sons, 1991.

100. Baroni, S., and Polina Bayvel, "Wavelength Requirements in Arbitrarily Connected Wavelength-Routed Optical Networks", *Journal of Lightwave Technology*, Vol.15, no.2, pp. 242-251, February 1997.