Low-Cost, Delay-Bounded Point-to-Multipoint Communication To Support Multicasting Over WDM Networks

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Abstract

The confluence of technical advances and multimedia service needs is intensifying the need for high throughput and low latency. Future communication networks will face an increase in traffic driven by multimedia requirements with stringent delay and jitter requirements. *Wavelength Division Multiplexing* (WDM) optical networks have the potential for meeting these goals by offering unprecedented high bandwidth and low latency. One very important aspect of the emerging Internet services is the need to support multicasting. This is crucial if WDM networks were to play an efficient role in the next generation Internet.

Multicasting in WDM networks supporting multimedia applications can be viewed as the process of taking a group communication request and selecting a multicast tree that satisfies the quality of service (QoS) requirements, in terms of bandwidth and end-to-end delay, of the underlying application. In this paper, we present a new class of low-cost, bounded-delay multicast heuristics for WDM networks. The heuristics use various techniques to establish a tree of semi-lightpaths between a source and a group of destination nodes. The unique feature of these heuristics is that they decouple the cost of establishing the multicast tree from the delay incurred by data transmission due to light-wave conversion and processing at intermediate nodes along the transmission path. A simulation study shows the performance of the proposed heuristics.

I. Introduction

The Next Generation Internet (NGI) technology will, for the most part, be driven by the increasing need for high throughput and low latency [27]. Optical networks have the potential for achieving these two goals by offering unprecedented bandwidth in a medium that is free from inductive and capacitive loadings, thus relaxing the limitations imposed on the bandwidth-distance product [10], [15]. Optical fibers may be used for transmitting terahertz signals in low attenuation pass-bands while maintaining low error rates and low sensitivity to noise [21], [11].

Although different types of photonic switching networks have been reported and demonstrated, Wavelength Division Multiplexing (WDM) has emerged as one of the most attractive approaches for data transfer in interconnection networks [5], [11], [7], [19]. WDM is a technology that allows multiple optical signals operating at different wavelengths to be multiplexed onto a single fiber so that they can be transported in parallel through the same fiber. An incoming wavelength in one input port can be routed to one or more output ports. Due to electro-magnetic interference, however, the same wavelength coming from two separate input ports cannot be routed to the same output port.

In *single-hop* WDM networks, the optical layer provides a *lightpath* to the higher layers. A lightpath is an all-optical transmission path between a source and a destination which uses the same wavelength between the intermediate nodes along the path. Each lightpath provides a full wavelength's worth of bandwidth to the higher layer. Light-paths enable an efficient utilization of the optical bandwidth since data transmission through a lightpath does not require wavelength conversion or electronic processing at intermediate nodes. Therefore, an all-optical path between two access nodes can exploit the large bandwidth of optics without the overhead of buffering and processing at intermediate nodes.

In optical networks, however, the number of wavelengths available at the intermediate nodes and the tuning of the optical transceivers at these nodes are both limited. These constraints, combined with the fact that optical networks are usually large in size, make all-optical networks practically infeasible [4]. To increase the probability of successfully establishing a connection between a source and a destination, *multi-hop* WDM networks allow conversion between different wavelengths to take place at the intermediate nodes[1]. The resulting path is referred to as *semi-lightpath*.

Despite the renewed popularity of WDM, it has not been easy to bridge the gap between the Internet and optical networks. Much of the focus of optical communications research has been on transmission, a link property, rather than on networking. The feasibility of economical all-optical wide band amplifiers and multi-channel links has been demonstrated, thus proving WDM to be an effective transmission solution. However, optical networking, a property of the overall system and its dynamics, still remains a challenge to the research community. Addressing this challenge requires the identification of the synergy between the two technologies that will enable the wide deployment of Internet protocols and services on advanced optical networks. One very important aspect of the new Internet services is multicasting [28], [23].

Multicasting, which is currently supported in most common commercial operating systems and routers, is expected to play a major role in the Internet. It provides the means to deliver messages to multiple destinations as a network service without requiring message replication by the end systems. As such, support for *native* WDM multicast is essential if WDM networks are to play an effective role in the next generation Internet.

Multicasting requires building a *point-to-multipoint tree* of paths between the source node and a *group* of destination nodes. The focus of the early research work on multicasting aimed at extending the LAN-style multicasting across a wide area network by developing heuristics for approximate solutions to the Steiner problem. In this context, the objective was to find a minimum cost tree that connects all the multicast nodes. The heuristics developed aimed at finding a low cost multicast tree, given a connectivity graph and single cost metric; the goal was to minimize the sum of link metrics in the tree.

The primary limitation of using the previous approaches for multimedia applications rests with their sole consideration of low cost. In addition to low cost, multimedia applications have different demands in terms of bandwidth, reliability, delay and jitter. A key property of multimedia data is its time dependency. The support of sustained streams of multimedia objects, over a period of time, requires the establishment of reliable, low delay and low cost source to destination routes. Nevertheless, the objective is not to develop a strategy which produces the lowest possible end-to-end delay, but a strategy to ensure that the data traffic arrives within its delay bound, thereby allowing a tradeoff between delay and cost. Thus the objective is to produce a minimal cost tree which guarantees bounded end-to-end delay between all source-destination pairs.

Finding the minimum delay paths from a source to a set of destination nodes can be achieved in polynomial time using one of the well-known shortest path algorithms. However, finding a delay-

[1]The physical realization of wavelength conversion can be either opto-electronic or fully optical.

bound, minimum cost multicast tree is at least as complicated as the classical Steiner Minimum Tree (SMT), which is known to be NP-hard. Finding an approximation solution for the SMT problem has been the focus of research in multicasting and several algorithms for constructing multicast trees have been developed for traditional networks.

It must be mentioned, however, that there is a fundamental difference between the traditional networks and the WDM networks regarding the multicasting issue. This difference reflects in their optimization objectives. Multicasting in traditional networks has focused on bounding the end-to-end delay while keeping the cost minimum. In WDM networks, wavelengths constitute critical resources and the cost of wavelength conversion plays an important factor in the optimization objectives. Furthermore, the optimization objectives in WDM networks involve more than one cost metric. The tradeoff between the desire to reduce wavelength conversion to a minimum and the need to increase the likelihood of successfully establishing a multicast tree brings about challenges that are unique to WDM networks.

This paper focuses on the algorithmic issues related to establishing trees of semi-Lightpaths between a source node and a group of destinations nodes. More specifically, we propose a set of heuristics that can be used to build minimum-cost, delay-bounded multicast trees in WDM networks. Contrary to many solutions proposed in the literature, our approach decouples the cost of building the multicast tree from the data transmission delay due to wavelength conversion and processing at intermediate nodes along the semi-lightpath.

The rest of this paper is organized as follows: We first review the research work related to multicasting in traditional and WDM networks. We then formalize the multicast problem in WDM, in terms of minimizing the cost and bounding the delay, and describe a graph model to characterize this problem. In the following section, we describe three heuristics that can be used to build minimum-cost, bounded-delay multicast trees. In the last section, we summarize the contributions of this paper and discuss future work.

II. Related Work

The minimum-cost, delay-bounded multicast tree problem, thereof referred to as *Delay-Bounded Steiner Minimum Tree* (DBSMT), can be viewed as a derivative of the Steiner Minimal Tree (SMT) problem in which the delay from the source to the destinations is bounded [12]. Both problems are NP-hard and several heuristics have been proposed to address these problems.

Based on their design objectives, the multicast heuristics proposed in the literature can be viewed as members of one of three possible classes. The first class includes heuristics which are designed to accommodate the Internet environment. The second class includes heuristics which aim at reducing the cost of the multicast tree, while bounding the end-to-end delay. The third class of heuristics focuses on multicasting in WDM networks.

The Internet community proposed different algorithms to create multicast trees, including Distance Vector Multicast Routing Protocol (DVMRP), Multicast Open Shortest Path First (MOSPF), Protocol Independent Multicasting (PIM), and Core Based Trees (CBT) [22], [18], [9], [1]. These protocols are designed to work specifically with the IP environment and take advantage of the IP routing protocols such as RIP and OSPF. They focus on issues related to scalability and reduced communication overhead. These protocols do not address the performance requirements of the underlying applications and may not be directly applicable to WDM networks.

The second class of multicast algorithms aims at achieving good approximations to DBSMT problem. These heuristics include Least Delay Heuristic (LDH), Least Cost Heuristic (LCH), Dynamic Programming Heuristic (DPH), Bounded Shortest Multicast Algorithm (BSMA), and Kompella, Pasquale, and Polyzos (KPP) Heuristic. They differ in terms of their objectives and the techniques used to achieve them.

The KPP heuristic finds the minimum cost constrained paths between any two multicast nodes [12]. KPP assumes that the link delay, $\delta(u, v)$, between any two nodes u and v, and the delay-bounds, Δ_i, are integers. The heuristic first computes the minimum cost constrained delay path between any two multicast nodes using a dynamic programming approach. Using the least-constrained paths the heuristic then builds the closure graph, a fully connected graph consisting of the multicast nodes. The cost and delay of an edge in the closure graph are the same as the cost and delay of the minimum-cost constrained path. Using the closure graph, the heuristic computes the minimum-spanning tree to produce the final delay-constrained tree. The approach used to build the spanning tree is similar to the one used by the Distance Network Heuristic [13]. The heuristic accuracy and complexity depend on the granularity of the delay values. If the granularity of the delay values is very small, KPP complexity is high. On the other hand, a large delay value granularity reduces the computation time but results in poor performance.

LDH builds the shortest delay path tree, using Dijkstra's sink shortest path tree algorithm, without any consideration of the cost [6]. Therefore, the heuristic's time complexity is $O(n^2)$. LDH finds a solution to the multicast problem, if one exists. The tree total cost, however, is not optimal.

LCH is similar to LDH except that it tries to reduce the tree cost by building the least cost tree instead of the least delay tree [29]. In the worst case, this heuristic requires finding the minimum cost tree as well as the minimum delay tree. If there are no delay violations then in the worst case the cost of the tree produced by LDH does not exceed $|D|$ times the cost of the optimal tree, where D is the size of the multicast group. The time complexity in this case is $O(n^2)$.

DPH finds the minimum cost constrained paths between any two multicast nodes [12]. DPH assumes that the link delay, $\delta(u, v)$, between any two nodes u and v, and the delay bounds, Δ_i, are integers. The algorithm first computes the minimum cost constrained delay path between any two multicast nodes using a dynamic programming approach. Using the least constrained paths, the algorithm then builds the closure graph, a fully connected graph consisting of the multicast nodes. The cost and delay of an edge in the closure graph are the same as the cost and delay of the minimum cost constrained path. Using the closure graph, the algorithm computes the minimum spanning tree to produce the final delay-constrained tree. The approach used to build the spanning tree is similar to the one used by the Distance Network Heuristic [13]. The algorithm accuracy and complexity depend on the granularity of the delay values. If the granularity of the delay values is very small, DPH complexity is high. On the other hand, a large delay value granularity reduces the computation time but results in poor performance.

BSMA starts initially with a minimum delay path tree and incrementally reduces the tree cost by iteratively replacing high cost relay-paths with lower cost paths [29]. A relay-path is a path on which all internal nodes are relay-nodes. Relay-nodes are nodes of degree two which are not multicast nodes, excluding the end nodes. This iterative process terminates when no relay-paths can be replaced. The resulting tree represents the final delay-bounded multicast tree. The time complexity of the heuristic is $O(n\, log(n) * k\, n^2) = O(k\, n^3\, log(n))$, where k is the number of shortest paths to be explored when a relay-path is removed.

The above heuristics deal with DBSMT from different perspectives. The simple heuristics, LDH and LCH, use the shortest path tree algorithm to build the multicast tree. Due to the fact that they perform very limited cost optimization, these heuristics do not produce "good" approximations. On the other hand, DPH and BSMA use more elaborate approaches to find a low cost tree but incur a much higher time complexity. DPH may lead to a good approximation if the granularity of the delay bound is large. However, if the granularity of the delay bound is fine, the time complexity of the algorithm may be very high, thereby limiting its practical implementation. BSMA results in a feasible least-cost, delay-bounded tree, if one exists. The algorithm also has high complexity making its implementation impractical for large networks. Most importantly, these heuristics do not consider the cost of wavelength conversion which limits their applicability to WDM networks.

The third class of heuristics focuses on routing and channel assignment in WDM networks. For a given number of routing requests, the objective is to minimize the number of wavelengths used to satisfy the routing requests [8], [3]. Most of this work focused on point-to-point routing in single-hop and multi-hop WDM networks. More recently, the focus has shifted to point-to-multipoint routing [20], [17], [16]. The metric used in building point-to-multipoint paths must take into consideration the cost of using a specific wavelength on a given link, the cost of converting an incoming wavelength into one or more outgoing wavelengths, and the time required to convert an incoming wavelength into one or more outgoing wavelengths. Most of the proposed solutions that address WDM multicast communication combine these costs to produce a weighted cost structure which is then used to produce a multicast tree. The DBSMT problem, however, consists of two sub-goals, namely minimizing the multicast tree cost and bounding the delay due to switching and wavelength conversion. Our approach decouples the cost optimization from bounding the delay. Furthermore, given that in WDM networks, the need for wavelength conversion is expected to be low and must be avoided as much as possible, our approach is first to build a close-to-optimal minimal cost tree and deal with delay violations whenever they occur.

III. Network Model

The network model considered in this paper consists of routers attached to an optical core network and connected to their peers over dynamically established switched lightpaths. The optical network is assumed to consist of multiple optical sub-networks interconnected by optical links in a general topology.

In such a network, an all-optical path between two network nodes can exploit the availability of a large bandwidth, without the overhead of buffering and processing at intermediate nodes. In general, however, it is worth noting that WDM links are affected by several factors that can introduce impairments into the optical signal path. These factors include the serial bit rate per wavelength, the amplification mechanism and the type of fiber being used. Furthermore, the number of wavelengths on a single fiber are often limited which in turn limits the number of all-optical paths connecting a source to a destination. However, it has been shown that the ability of converting between wavelengths along the same path increases the probability of successfully establishing a connection [24].

Unfortunately, current technology does not allow wavelength conversions to be performed efficiently and cost effectively in the optical domain. Hence, it is often the case that the switching fibers of many optical networks are not capable of performing wavelength conversions. In such networks, semi-optical paths may still be established if intermediate nodes are used as relays to receive a message on one wavelength and retransmit it on another. A typical intermediate node in a network with two wavelengths is shown in Figure 1 In this simple example, the node is connected to its neighbors by two input links and two output links. The optical input and output signals to the local node are either multiplexed (Figure 1a) or demultiplexed (Figure 1b).

When the node receives several signals, coming from different links at the same wavelength, which need to be transmitted over their respective output ports, the incoming wavelength must be converted to a number of desirable outgoing wavelengths. Due to speed and other physical limitation of electronic wavelength converters, the time required by the last conversion to wait for its turn may be

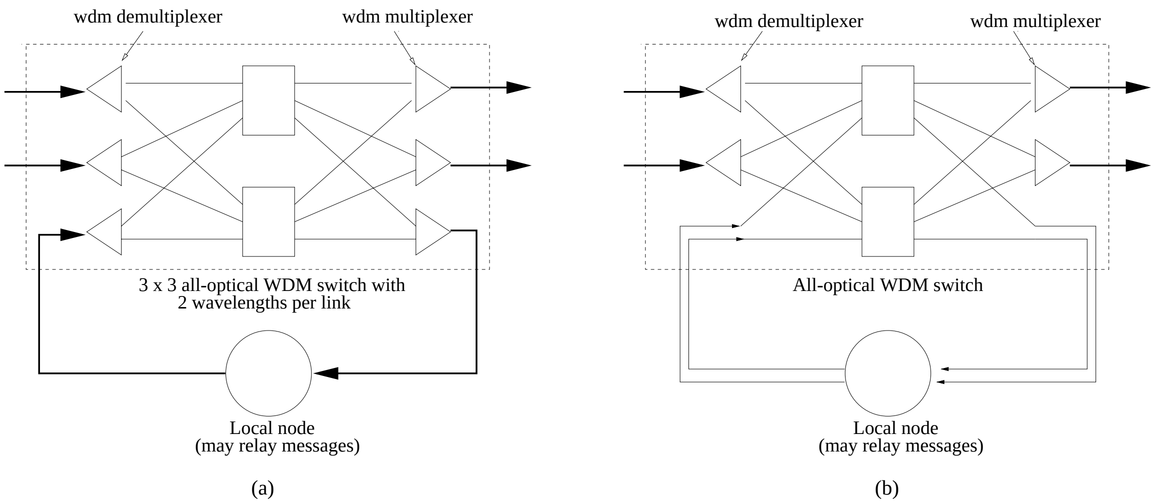


Fig. 1. Node Model in a WDM Network with All-Optical Switches

significant. Consequently, a message that is relayed at such a node may suffer a relatively large delay because of buffering, processing, and optics/electronic conversion.

Thus, wavelength conversion in networks with all-optical switches introduces delays at intermediate nodes which affect the quality of service on the connections. For this reason, it is desired to minimize the number of wavelength conversions along a given connection. Moreover, if certain quaility of service guarantees are required in terms of delay and jitter, then a limit on the number of wavelength conversions need to be imposed on a connection in order to meet these requirements. The multicast heuristics proposed in this paper aim to achieve this goal.

IV. DBSMT Problem Formulation

What makes the problem of building WDM multicast trees fundamentally different from the multicasting problem in traditional networks is the cost structure associated with the underlying network. The metrics used in building point-to-multipoint paths in WDM networks must take into consideration the cost of using a specific wavelength on a given link, the cost of converting an incoming wavelength into one or more outgoing wavelengths, and the delay required for wavelength conversions.

Consider a WDM optical network with N nodes, M optical links, and K wavelengths. This network can be modeled by a graph $G = (V, E, \Omega)$ where:

- V denotes a set of vertices, corresponding to the network nodes,
- E denotes a set of edges, corresponding to the network optical links. A link incident from node $u \in V$ onto node $v \in V$ is denoted as (u, v).
- $\Omega = \{\nu_1, \nu_2, \cdots, \nu_K\}$ represents the set of all available wavelengths in the network.

Each link $l = (u, v) \in E$, connecting node $u \in V$ to $v \in V$, is associated with a set $\Omega_l \subseteq \Omega$ of available wavelengths. Furthermore, each link $l = (u, v) \in E$, is associated with the following costs and delays:

- a *wavelength usage cost*, $\omega_l(\nu)$, for each $\nu \in \Omega_l$, which represents the cost of using ν on link l.
- a *wavelength conversion cost*, $c_l(\nu_i, \nu_j)$, representing the cost of converting a wavelength, ν_i, on some incoming link $e = (x, u)$ into a wavelength ν_j on the outgoing link $l = (u, v)$, where $\nu_i \in \Omega_e$ and $\nu_j \in \Omega_l$. This cost is infinity if such a conversion is not possible at u , and is reduced to zero if $\nu_j = \nu_i$. Furthermore, we assume that $c_l(\nu_i, \nu_j) = c_{l'}(\nu_i, \nu_j)$ for all l and l'.
- a *wavelength conversion delay*, $\delta_l(\nu_i, \nu_j)$, representing the time required to convert a wavelength,

ν_i, on incoming link $e = (x, u)$ into a wavelength, ν_j, on outgoing link $l = (u, v)$, where $\nu_i \in \Omega_e$ and $\nu_j \in \Omega_l$. This delay is reduced to zero if $\nu_j = \nu_i$.

The wavelength usage cost can be used to enforce a specific wavelength assignment strategy. The First-Fit policy, for example, selects the wavelength with the lowest index to assign to a new connection request [14]. The MaxSum policy, on the other hand, assigns the wavelength that maximizes the wavelength path capacity (WPC), defined as the capacity of the most congested link along the path, over all potential paths and all wavelengths [2]. The wavelength usage cost can be used to enforce either of these two policies. In the case of the First-Fit policy, the cost of available wavelengths on a given link can be assigned in a way such that the wavelength with the lowest index bears the lowest cost. Similarly, setting the cost of the wavelength that maximizes the WPC to be the lowest enforces the MaxSum wavelength assignment policy.

The wavelength conversion cost can be used to minimize the number of wavelength conversions along a path. In some cases, it can also be used to discourage wavelength conversion at nodes that perform critical functionalities within the network, such as nodes interconnecting different networks, or at nodes that are heavily loaded. The wavelength conversion cost can be also used to adapt to changing network environments and to reflect the availability of wavelengths at a given node. Links incident from interconnection nodes, heavily loaded nodes, or nodes with a reduced number of available wavelengths incur higher wavelength conversion costs.

The wavelength conversion delay reflects the significance of the time required to convert an incoming wavelength into an outgoing wave length in comparison to the time required to transmit the signal over the optical link. Furthermore, in multicast configuration, wavelength conversion can take place between an incoming wavelength on a given input port and a number of outgoing wavelengths on several output ports, as required by the underlying multicast tree. Unless the wavelength conversions proceed in parallel, the required wavelength conversion delay can become even more significant in comparison with the transmission delay.

The cost structure proposed in this paper decouples the conversion cost from the conversion delay. This is necessary to account for the fact that in a multicast tree two connections from the source to two different destinations which share some nodes along the path face conversion jointly at the shared node but suffer the conversion delays separately. Therefore, the conversion cost must be accounted for only once, while the end-to-end delay requirement must be verified for each connection separately. Consequently, the DBSMT problem can be viewed as consisting of two sub-goals, namely minimizing the multicast tree cost and bounding the delay. Given a source and a set of predefined multicast nodes, the DBSMT problem consists of finding the minimal cost tree which contains all selected multicast nodes. In addition to finding the optimal multicast tree that satisfies the delay requirements, a procedure to assign a specific wavelength $\nu_i \in \Omega_l$ on each link $l = (u, v)$ along the path is required. More specifically, the DBSMT problem can be stated as follows:

Let $\mathcal{G}$ be a multicast group composed of a source $s \in V$ and a set of multicast nodes $D \subseteq V$. Every destination node $d \in D$ has a delay bound Δ_d. The objective is to find:
1. a multicast tree $T = (V', E')$, $V' \subseteq V$ and $E' \subseteq E$, connecting s to all $d \in D$, and
2. a wavelength assignment function, $\nabla_P : E' \longrightarrow \Omega$, which assigns a wavelength, $\nabla_P(l) = \nu \in \Omega_l$ to link, l for each path, $P(s, d)$, connecting source s to a given destination $d \in D$,
such that the total cost of the tree is minimum and the delay from the source s to any multicast node $d \in D$ does not exceed Δ_d.

In order to formalize the cost of the multicast tree and the delay on a given path, define $P(s, d)$ as the sequence of links $(s, v_1), \cdots, (v_i, v_{i+1}), \cdots, (v_k, d)$ forming the multicast tree path from source s to node d. Furthermore, let $Pred(l) = (v_{i-1}, v_i)$, be the predecessor of link $l = (v_i, v_{i+1})$ on path $P(s, d)$.

Note that if two paths, $P(s, d_1)$ and $P(s, d_2)$, share the same link, l, the $Pred(l)$ on $P(s, d_1)$ is the same as $Pred(l)$ on $P(s, d_2)$. This follows directly from the tree property of the multicast graph.

Further, define $\nabla(l) = \{\nabla_P(l) | l \in P(s, d)\ \forall d \in D\}$ to be the set of all wavelengths currently used on link l by all the source to destination paths which include l. Finally, let $\mathcal{W}_l = \{\ (\mu, \nu) \mid \exists P \supseteq l\ :\ \nabla_P(Pred(l)) = \mu\ and\ \nabla_P(l) = \nu\ \}$ be the set wavelength pairs used on link l and its predecessor, respectively, along the same path. The following observations can be made regarding paths of a multicast tree in WDM networks:

- Two paths, $P(s, d_1)$ and $P(s, d_2)$, can share some link, l, without necessarily sharing the same wavelengths on l. This may be required if at one node along either one of the two paths, further conversions are no longer possible without violating the delay requirements.
- If two paths share the same wavelength on a given link, l, then they share the same wavelength on $Pred(l)$. This is required to eliminate unnecessary wavelength conversions which can only increase the cost and delays of the final multicast tree.

Based on the above, the DBSMT problem can be formalized as follows:

Find:

A multicast tree $T(V', E')$ and a wavelength assignment function, ∇_P for each each path P, such that:

$$Cost(T) = \sum_{l \in E'} \sum_{\nu \in \nabla(l)} \omega(l, \nu)\ +\ \sum_{l \in E'} \sum_{(\mu,\nu) \in \mathcal{W}_l} c_l(\mu, \nu) \quad \text{is minimum} \tag{1}$$

Subject to:

$$Delay(P(s, d)) = \sum_{l \in P(s,d)} \delta_l(\nabla_P(Pred(l)), \nabla_P(l)) < \Delta_d \quad \forall d \in D \tag{2}$$

The DBSMT problem can be viewed as a derivative of the Steiner Minimal Tree (SMT) problem in which the delay from the source to the destinations is bounded. Minimizing the tree cost is inherently NP-hard, while bounding the delay can be achieved in polynomial time. When the two parameters are combined, the problem is NP-hard and, therefore, has to be approached by a heuristic method. What makes the DBSMT problem in WDM networks inherently more complex than in traditional networks is that path selection in WDM networks is compound with wavelength assignment along the path. Heuristics for WDM networks, which take delay, cost and wavelength assignments into consideration, are discussed next.

V. Multicast Heuristics for WDM Networks

Given that in a WDM networks, the number of delay violations is expected to be low, an efficient approximation approach to the DBSMT problem is to first build a close-to-optimal least-cost tree and deal with delay violations as a special case. In the following, we show how we transform the original graph representing the network into an expanded graph to facilitate route computation and wavelength assignment. We then describe three new heuristics which can be used to build a low-cost, bounded-delay multicast tree for WDM networks.

A. Graph Transformation

Route selection and wavelength assignment are difficult to achieve based on the original graph. This is mostly due to the fact that the cost metrics and the delay computation must be considered dynamically during the path selection process. To make path selection and delay computation more

tractable, an expanded directed and weighted graph, $\mathcal{A}(\mathcal{M},\mathcal{L},\Omega)$, derived from the original graph is used [4]. The expanded graph, $\mathcal{A}(\mathcal{M},\mathcal{L},\Omega)$, is defined as follows:
• $\mathcal{M}$ represents a set of *nodes*, (m,ν), where $m \in V$ is a node in the original graph, and $\nu \in \Omega$ is a wavelength in the network.
• $\mathcal{L}$ represents a set of links connecting pairs of nodes in M.
• Ω represents a set of all available wavelengths in the network.
• an edge between two nodes (m_1,ν) and (m_2,ν) exists in the expanded graph, $\mathcal{A}(\mathcal{M},\mathcal{L},\Omega)$, only if there exists a link l from node m_1 to node m_2 in the original graph, $G(V,E,\Omega)$, and the wavelength ν is available on link l.
• an edge between (m,ν_1) and (m,ν_2) exists only if wavelength conversion from ν_1 to ν_2 is available at node m.

The costs and delay associated with the links of the original graph, namely wavelength usage cost, wavelength conversion cost and wavelength conversion delay, are directly mapped into the corresponding costs and delay of the links of the expanded graph. Figure 2(a) shows the expanded graph resulting from the original graph in Figure 2(b).

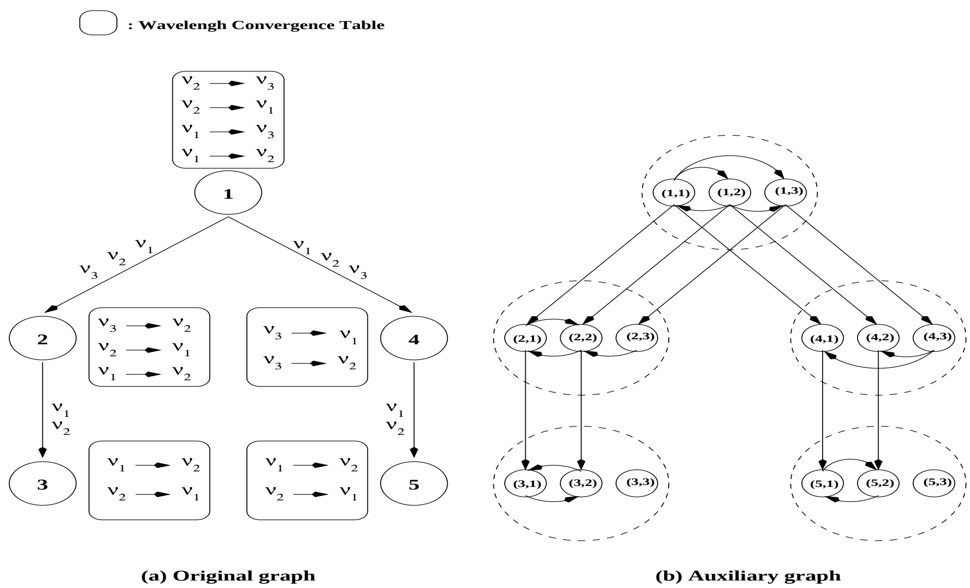


Fig. 2. Graph transformation

Using the expanded graph, we describe three new heuristics, *Least Delay Replacement*, *Immediate Least Delay Replacement* and *Least Delay First*. The first heuristic decouples the cost optimization from bounding the delay by first building a low cost tree and then handling any delay violations that may occur in the tree. The other two heuristics incorporate delay bound checking into the process of building the minimum cost tree. That is, if any delay violation occurs, it is dealt with immediately. This is achieved by searching for a new delay-bounded path with the lowest cost. The two heuristics differ in the way they select low-cost paths which may result in different low-cost multicast trees.

B. Least Delay Replacement (LDR) Heuristic

The basic idea of the LDR is to first build a least-cost tree using a Shortest Path Heuristic (SPH) based approach [30]. Using the resulting least-cost tree, delay bounds are checked for every multicast node in the tree and delay violations are removed accordingly. In the following, we first describe the SPH procedure used to compute the least-cost tree. We then describe the LDR heuristic.

B.1 SPH description

The SPH based procedure to compute the least-cost tree is described in Algorithm 1. In the SPH heuristic, the link cost takes into consideration both the cost of wavelength conversion and the cost of using a specific wavelength on the link.

Algorithm 1 PROCEDURE Shortest Path Heuristic

INPUT:
G : Network Graph.

OUTPUT:
T : Least-Cost Multicast Tree

Shortest Path Heuristic (G , T)
Let $PATH(d, T)$ represent the least-cost path from a multicast node $d \in D$ to a tree T.
Step 1:
Set $i = 1$ and $M_1 = \{\emptyset\}$.
Construct a subtree, $T_1 = \{s\}$, consisting of the source node s.
Step 2:
Set $i = i + 1$.
Find the least-cost node, d_i, to T_{i-1} such that $d_i \in (D - M_{i-1})$ (ties are broken arbitrarily).
Step 3:
Construct a new subtree, T_i, by adding all edges and nodes in $PATH(d_i, T_{i-1})$ to T_{i-1}.
Set $M_i = M_{i-1} \cup \{d_i\}$.
Step 4:
if $|M_i| < |D|$
Go to **Step 2**
else
DONE: $T = T_i$ is the final least-cost multicast tree.
end if

The SPH heuristic is similar to Prim's Minimum Spanning Tree algorithm. The time complexity of SPH is $O(n^2\ log(n))$, where n is the number of nodes in the network. However, the need to compute the least-cost path at each stage raises the total complexity of the algorithm to $O(|Z| \times n^2)$, where $Z = D \cup \{s\}$, s is the source node and D is the set of multicast nodes. It was shown by simulation that on average the additional cost of the trees produced by this algorithm is no more than 5% above the cost of the corresponding optimal Steiner trees [26]. However, in the worst case, the cost of this algorithm is $(2 - 2/|Z|) \times C(T_{opt})$, where $C(T_{opt})$ is the cost of the corresponding optimal Steiner tree[2].

B.2 LDR basic steps

The LDR heuristic uses the expanded graph, $\mathcal{A}(\mathcal{M}, \mathcal{L}, \Omega)$, and invokes SPH to produce a least-cost multicast tree. The SPH, however, does not guarantee that the end-to-end delays on all paths of the least-cost tree meet the delay bounds required by the multicast nodes. To address potential delay bound violations, LDR identifies each node, v, whose delay exceeds its end-to-end delay bound, and replaces its current path with a new least-cost path that meets the end-to-end delay requirement of

[2]This bound only applies to graphs with symmetric, undirected edges. For directed graphs, the bound can be worse [25].

node v, if such a path exists. Notice, however, that adding the new path to the tree may cause nodes to have two incoming paths. This is undesirable as it causes the same information to be transmitted twice to the same node over different paths[3]. To illustrate this case, consider Figure 3, where S is a source node and M, R and L are multicast nodes, which depicts the least-cost tree produced by SPH. Assume, however, that in this tree the path from S to R, namely $((S,E), (E,H), (H,R))$ does not satisfy the end-to-end delay requirement of R. LDR finds a new least-cost path, from S to R, which meets the delay-bound requirement of node R. The addition of this path to the tree causes R to have two incoming paths. LDR removes the path with the higher delay up to the closest intermediate node of degree three or greater, as depicted in Figure 4 (Link (H,R) is removed in this case). The resulting tree satisfies the delay requirements of all multicast nodes. The addition of this new path to the tree, however, causes an intermediate node, N in this case, to have two incoming paths. This is again undesirable as node N receives the same information over two different paths. Furthermore, the presence of two incoming paths may unnecessarily increase the overall cost of the tree.

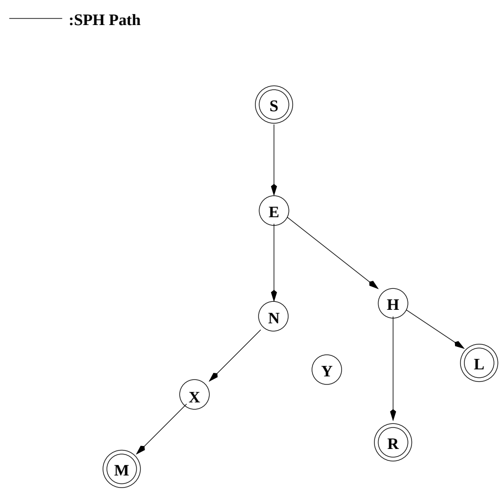


Fig. 3. SPH low-cost multicast tree

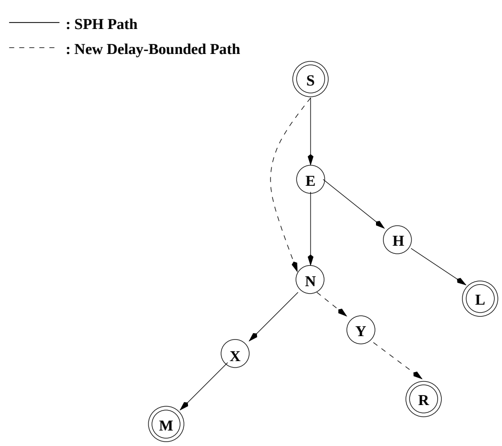


Fig. 4. Resulting tree after removal of the path with larger delay

In general, the problem of intermediate or multicast nodes with two incoming paths can be resolved

[3]It may be acceptable to have a node with two incoming paths if the main objective is to find a path from the source to all multicast nodes. The final multicast graph, however, will not be a tree

by removing the *relay-path* on the larger-delay path. A relay-path is characterized by the following two properties: (i) all internal nodes on the path are neither multicast nor source nodes and are exactly of degree two; (ii) the end nodes of the relay-path are either a source node, a multicast node or a node of degree three or higher[4]. In Figure 4, the relay-path, namely link (E,N), is redundant and may be removed. Notice, however, that because of potential wavelength conversions that can take place between the incoming link to node N on the new path and the outgoing links from node N along the paths to the multicast nodes attached to N, the removal of link (E,N) may not be feasible. For example, the removal of relay-path, (E,N), is only feasible if the end-to-end delay on the new path to multicast node M does not exceed M's delay bound

Based on the above, one possible way to verify the feasibility of removing a *redundant relay-path* at a given node, N, is by checking that its removal does not cause the end-to-end delay requirement of any multicast node attached to N to be violated. This, however, may increase the time complexity of the algorithm since it requires revisiting all nodes in the subtree attached to N. In the following, we derive a *sufficient* condition which can be used to verify the feasibility of removing a *redundant relay-path* without causing any multicast node to violate its end-to-end delay requirements. The condition involves quantities that can be obtained locally at the node and its verification can be achieved in a constant amount of time.

B.3 Relay-path removal feasibility condition

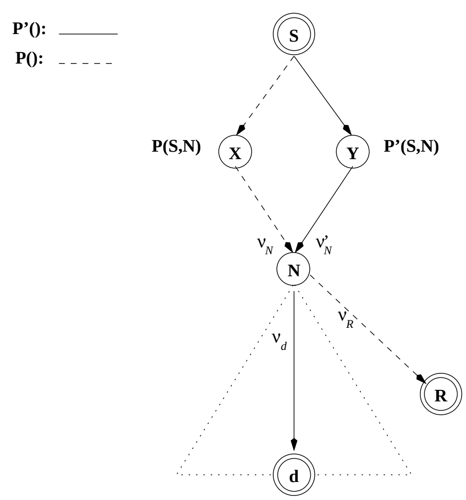


Fig. 5. Redundant Relay Paths

Consider an intermediate node, N, and let $D_N = \{d \in D \mid \exists P(N,d)\}$ represent the set of multicast nodes of the subtree rooted at node N, as depicted in Figure 5. Let l_N, and l'_N represent the incoming link to node N on $P(S,N)$ and $P'(S,N)$, respectively. We use ν_N and ν'_N to denote the respective wavelengths associated with l_N and l'_N. Further, denote the wavelength associated with the outgoing link, l_R, at node N along $P(S,R)$ through node X as ν_R. Finally, let ν_d, $\forall\ d \in D$, denote the wavelength associated with the outgoing link, l_d, at node N along $P(N,d)$, to multicast node d.

Assume, without loss of generality, that $P(S,R)$ meets the delay requirements of node R, while the delay on $P'(S,R)$), denoted as $Delay(P'(S,R))$, exceeds the delay bound of node R. Then the following expression holds:

[4]Notice that according to the above definition, a relay-path can be composed only of one edge

$$Delay(P(S,N)) + c_{l_R}(\nu_N, \nu_R) < Delay(P'(S,N)) + c_{l_R}(\nu'_N, \nu_R) \quad (3)$$

which can be rewritten as:

$$Delay(P(S,N)) - Delay(P'(S,N)) < c_{l_R}(\nu'_N, \nu_R) - c_{l_R}(\nu_N, \nu_R) \quad (4)$$

where $c_{l_R}(\nu_N, \nu_R)$ represents the conversion cost on link l_R along $P(S,R)$, and $c_{l_R}(\nu'_N, \nu_R)$ represent the conversion cost on link l_R along the concatenated path $P'(S,N) \cup P(N,R)$. Notice, however, that the relay-path on $P'(S,N)$) can be removed if :

$$Delay(P(S,N)) + c_{l_d}(\nu_N, \nu_d) < Delay(P'(S,N)) + c_{l_d}(\nu'_N, \nu_d) \quad (5)$$

which can be rewritten as:

$$Delay(P(S,N)) - Delay(P'(S,N)) < c_{l_d}(\nu'_N, \nu_d) - c_{l_d}(\nu_N, \nu_d) \quad (6)$$

where $c_{l_d}(\nu_N, \nu_d)$ and $c_{l_d}(\nu'_N, \nu_d)$ represent the conversion cost on link l_d along $P(S,d)$, and $P'(S,d)$, respectively. Combining Equation 4 and Equation 6, a sufficient condition for a relay-path removal can be expressed as follows:

Relay-path $P'(S,N)$ can be removed if:

$$c_{l_R}(\nu'_N, \nu_R) - c_{l_R}(\nu_N, \nu_R) \leq c_{l_d}(\nu'_N, \nu_d) - c_{l_d}(\nu_N, \nu_d) \quad (7)$$

B.4 LDR basic steps

The basic idea of the LDR heuristic is to decouple cost optimization from delay bounding. This is achieved by first building a minimum cost multicast tree and then dealing with any possible delay violations.

Using the SPH heuristic, LDR first builds a low cost tree. It then handles any delay violations that may have occurred in the process of building the tree by finding a new delay-bounded path to the delay-bound violating node, if such a path exists. Finally, the LDR heuristic removes redundant relay-paths which may cause a node to have more than one incoming edge. The basic steps of the LDR heuristic are described in Algorithm 2.

The DCP procedure searches for the least-cost, delay-bounded path that connects the delay violating node, $v \in D$, to the current tree, T. This is achieved by building a new graph G', obtained by reversing the links of G while keeping all its nodes. DCP then builds a set of paths composed of the shortest delay paths from v to the tree nodes and the shortest cost paths from v to nodes in T' in that order. Prior to computing the shortest cost paths, T's links are removed from G' to create different independent least-cost paths. This is necessary to avoid creating paths that are mutually derived from each other. Using this set of paths, DCP selects the path which meets the following three criteria (i) the end-to-end delay on the path meets the delay bound of the multicast node, and (ii) the addition of this path to the tree and the removal of the redundant relay-path associated with v do not cause any other multicast node currently attached to the tree to violate its delay bounds, and (iii) the path is the least-cost path that meets criteria (i) and (ii). The basic steps of the DCP procedure are described in Figure 3.

The LDR heuristic uses the shortest delay paths, therefore, it finds a solution if one exists. Furthermore, if there is no violation, or the number of violations is low, then the cost of the resulting tree is close to the cost of the SPH tree. The complexity of the algorithm is bounded by the complexity

Algorithm 2 PROCEDURE Least Delay Replacement

INPUT:
$\mathcal{A}(\mathcal{M}, \mathcal{L}, \Omega)$: Extended graph.

OUTPUT:
T : Minimal-cost, delay-bounded multicast tree.

Least Delay Replacement ($\mathcal{A}(\mathcal{M}, \mathcal{L}, \Omega)$, T)
Step 1:
Find the minimum cost multicast tree, T, using SPH.
Step 2:
Let $P_\delta(s, d)$ be the end-to-end delay on $Path(s, d)$ connecting node s to d on the tree.
Find $W = \{ d \in D, \mid P_\delta(s, d) > \Delta_d \}$.
Step 3:
for each node $v \in W$
Invoke the *Delay Constrained Path* procedure, $DCP(\mathcal{A}, T, v)$, described in Algorithm 3, to find the minimal-cost, delay-bounded path from s to v, whose addition to the tree and the removal of the resulting redundant relay-path do not cause any tree node to violate its delay bound.
if such a path exists
Attach node v to the tree using this new path and remove the redundant relay-path to node v;
else
Node v cannot be attached to tree. Exit.
end if
end for
Step 4:
Output $T = T_i$ as the final minimal-cost, delay-bound multicast tree.

of SPH which is $O(|Z| * n^2)$, where n is the total number of nodes in the graph. When there is a delay violation, then for each violating node the shortest delay path can be found in $O(n^2)$. In the worst case, we have $|D|$ violating nodes. Hence, the total time complexity of LDR is $O(|Z| * n^2)$.

C. Immediate Least Delay Replacement (ILDR)

The $ILDR$ heuristic incorporates the delay bound check as an integral part of the multicast tree construction algorithm to find the least constrained path to any delay-bound violating node. This approach differs from the one used in the LDR procedure where delay violations are dealt with after the entire tree is built.

The algorithm builds the tree starting from the source node. Tree construction is performed by iteratively finding the node, $v \in D$, with the least-cost path. If the path to v satisfies the delay bound then that path is added to the tree. On the other hand, if the path fails to satisfy the delay bound, the DCP procedure, described in Figure 3, is used to find the least-cost, delay-bounded path to v. The basic steps of the $ILDR$ heuristic are described in Algorithm 4.

The time complexity of $ILDR$ is similar to LDR, which is dominated by the need to compute the least-cost path to all multicast nodes. Therefore the time complexity is $O(|Z| * n^2)$.

Algorithm 3 PROCEDURE Delay Constrained Path

INPUT:
G : Network graph,
T : Current multicast tree, and
v : Delay-violating node.

OUTPUT:
$p(u, v)$: Bounded-delay path, if one exists.

Delay Constrained Path (G, T, v)
Create a new graph G' consisting of G's nodes and G's edges reversed.
Using G', create, P, the set of the least-cost delay paths, $p(u, v)$, from v to each node u in $T \in G'$.
Remove the edges of T from G'.
Using G', find the set of the least-cost paths from v to each node in T and add them to P.
Out of all paths in P select path, $p(u, v)$, such that:

- $Delay(p(u, v)) < \Delta_v$,
- $Cost(p(u, v))$ is minimum, and
- addition of $p(u, v)$ to the tree only creates a redundant relay-path (i.e., the removal of the redundant relay-path does not cause any other node to violate its delay bound.

if no such path exists **then**
  return "no solution"
else
  return $p(u, v)$.
end if

D. Least Delay First (LDF)

The LDF heuristic is similar to $ILDR$ algorithm except that it uses a more efficient method to add a node to the tree. $ILDR$ does not take into consideration the delay when it tries to select the next node to add to the tree. This approach may unnecessarily increase the number of delay bound violations. LDF attempts to address this problem by taking the delay into consideration when selecting the next destination node to add to the tree.

LDF first finds the least-cost paths to the destination nodes. Then out of these paths, it selects the path whose delay is the minimum. The heuristic takes both cost and delay constraints into consideration when selecting the next node to add to the tree. The basic steps of the heuristic are described in Algorithm 5.

The time complexity of LDF is similar to the time complexity of $ILDR$. In this case, again the complexity is dominated by the need to compute the least-cost path to all multicast nodes. Therefore the time complexity is also $O(|Z| * n^2)$. Table I summarizes the time complexity of the heuristics discussed in this paper.

VI. Simulation Results

To evaluate the proposed heuristics, a simulation program has been developed and implemented in C++. The heuristics were run over a large number simulated network graphs. The network topologies selected reflected current and future Internet optical backbones. Each network node has, on average, a relatively low number of adjacent nodes, as is typically the case in Internet optical

Algorithm 4 PROCEDURE Immediate Least Delay Replacement

INPUT:
$\mathcal{A}(\mathcal{M},\mathcal{L},\Omega)$: Extended graph.

OUTPUT:
T : Minimal-cost, delay-bounded multicast tree.

Immediate Least Delay Replacement ($\mathcal{A}(\mathcal{M},\mathcal{L},\Omega)$, T)
Let $PATH(d,T)$ represent the least-cost path from a multicast node $d \in D$ to a tree T.
bf Step 1:
Initially, set $i = 1$. Construct a subtree $T_1 = (s, \emptyset)$, consisting of the source node.
Set $M_1 = \emptyset$.
Step 2:
Set $i = i + 1$.
Find the closest node, d, to T_{i-1} such that $d \in (D - M_{i-1})$ (ties are broken by choosing the node with the smallest delay path).
Step 3:
if the delay from s to d on $PATH(T_{i-1}, d)$ does not exceed Δ_d **then**
Construct a new subtree, T_i, by adding all edges and nodes in $PATH(T_{i-1}, d)$.
Set $M_i = M_{i-1} \cup \{d\}$.
Go to Step 5.
else
Find a different path $PATH(T_{i-1}, d)$ using the DCP procedure described in Algorithm 3.
Construct a new subtree, T_i, by adding all edges and nodes in $PATH(T_{i-1}, d)$ and removing any relay-path to node d.
Set $M_i = M_{i-1} \cup \{d\}$.
end if
Step 5:
if $|M_i| < |D|$ **then**
Go to Step 2
else
DONE: T_i is the final least-cost, delay-bounded tree.
end if

backbone topologies.

The model used to generate the network graphs is based on the network model proposed by Waxman [31]. The cost of a link is set to a uniform random number between times the delay over the link. The existence of link (u, v) implies the existence (v, u). However, the cost on each direction can be different. The average number of outgoing (or incoming) links for each node on the simulated optical backbone network, was 4, on average. The delay bound, Δ, was expressed in terms of the number of conversions allowed, assuming a fixed delay amount for each wavelength conversion encountered by a connection through the routing path.

The objective of the simulation was twofold: perform a sensitivity analysis of both LDR and ILDR and conduct a comparative study to assess the performance of ILDR with respect to other heuristics, including KPP, SPH and BSMA. Two metrics were used to compare the performance heuristics, namely the cost of the multicast trees produced by each heuristic and the the computational cost

Algorithm 5 PROCEDURE Least Delay First

INPUT:
$\mathcal{A}(\mathcal{M},\mathcal{L},\Omega)$: Extended graph.

OUTPUT:
T : Minimal-cost, delay-bounded multicast tree.

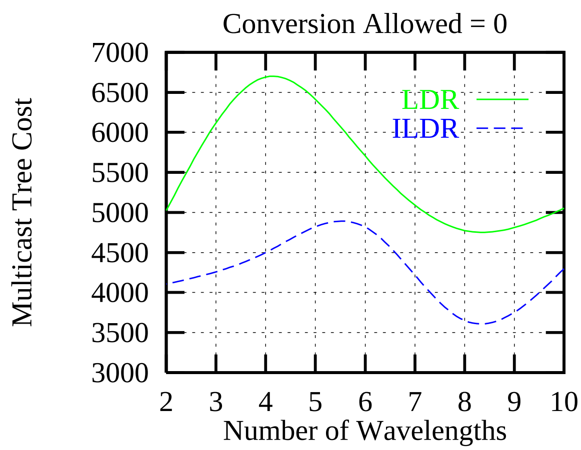
Least Delay First ($\mathcal{A}(\mathcal{M},\mathcal{L},\Omega)$, T)
Let $PATH(d,T)$ represent the least-cost path from a multicast node $d \in D$ to a tree T.
Step 1:
Initially, set $i = 1$.
Construct a subtree $T_1 = (s, \emptyset)$, consisting of the source node.
Set $M_1 = \emptyset$.
Step 2:
Set $i = i + 1$.
Find the least-cost paths from T_{i-1} to the nodes in $D - M_{i-1}$.
Select the node $d \in (D - M_{i-1})$ whose least-cost path has the minimum delay.
Step 3:
if the delay from s to d on $PATH(T_{i-1}, d)$ does not exceeds Δ_d **then**
Construct a new subtree, T_i, by adding all edges and nodes in $PATH(T_{i-1}, d)$.
Set $M_i = M_{i-1} \cup \{d\}$.
Go to Step 5.
else
Find a different path $PATH(T_{i-1}, d)$ using the DCP procedure described in Figure 3.
Construct a new subtree, T_i, by adding all edges and nodes in $PATH(T_{i-1}, d)$ and removing any relay-path to node d.
Set $M_i = M_{i-1} \cup \{d\}$.
end if
Step 5:
if $|M_i| < |D|$ **then**
Go to Step 2
else
DONE: T_i is the final least-cost, delay-bounded tree.
end if

required by the heuristic to produce the multicast tree. Furthermore, several experiments were designed where different network environments and system parameters were varied. In this discussion, the network load, ρ, was kept at 50%. Similar trends have been observed for different loads and are not reported in this discussion for lack of space.

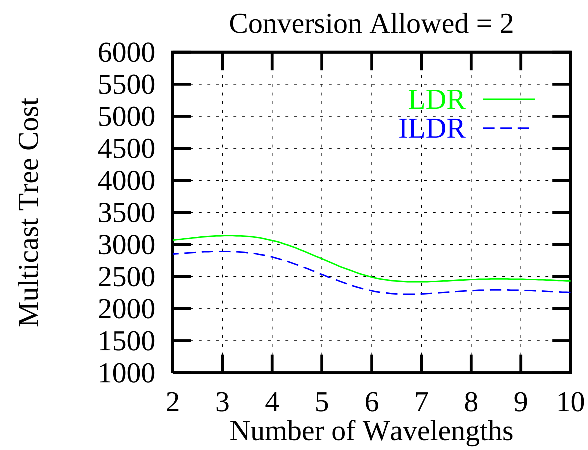
A. LDR and ILDR Performance Comparison

The first set of experiments focused on a performance comparison between LDR and ILDR. The objective was to study the effect of wavelength conversion and multicast size group on the overall cost of the multicast trees produced by each heuristic. In the first experiment, the multicast group size, G, was set to 12, or 30% of the total number of nodes in the network, and the number of wavelengths in the network was varied from 0 to 10.

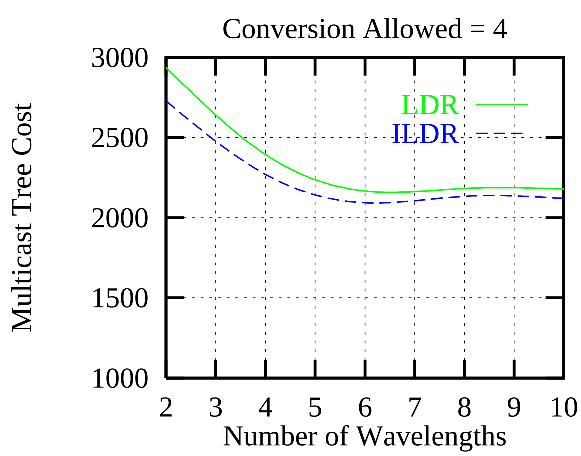
Based on the above, four scenarios were simulated, whereby the number of wavelength conversions allowed by the application (i.e. conversion delay bound) was set to 0, 2, 4 and 6, respectively. The results of this scenario are depicted in Figure 6



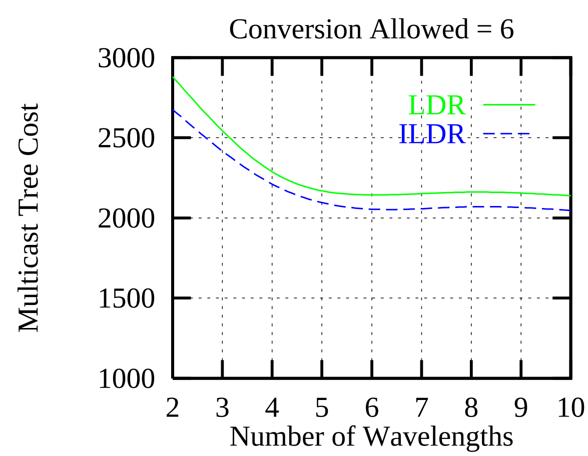
(a) $G = 12$; $\rho = 0.5$



(b) $G = 12$; $\rho = 0.5$



(c) $G = 12$; $\rho = 0.5$



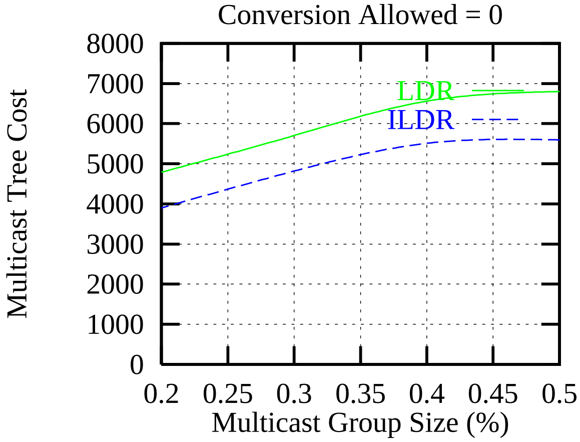
(d) $G = 12$; $\rho = 0.5$

Fig. 6. Wavelength Conversion Effect

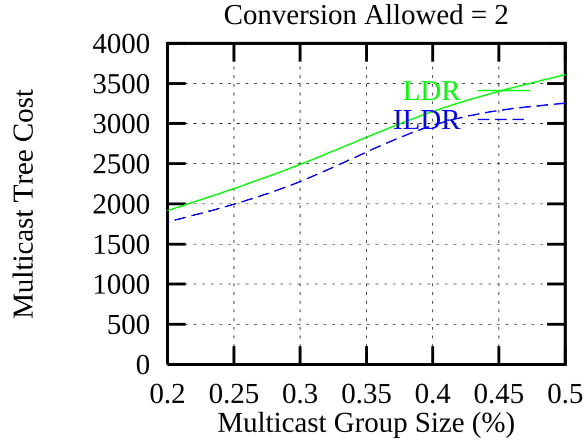
As expected, ILDR always produces multicast trees with smaller cost than the cost of the trees produced by LDR. The difference in cost reached its highest when the number of allowed wavelength conversions was small. As the number of allowed conversions increased, the difference in cost is reduced.

In the second scenario, the objective was to assess the impact of the group size on the cost of the multicast trees produced by ILDR and LDR, respectively. In this case, the number of wavelengths was set to 6 and the multicast group size was varied as a percentage of the total number of network nodes. The results of the experiments are depicted in figure 7.

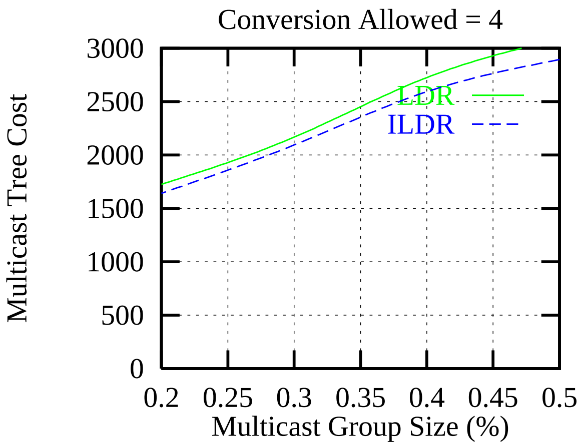
The results show a trend similar to what was observed in the first scenario. In all cases, the performance of ILDR, in terms of multicast tree cost, was better. The difference in cost is the



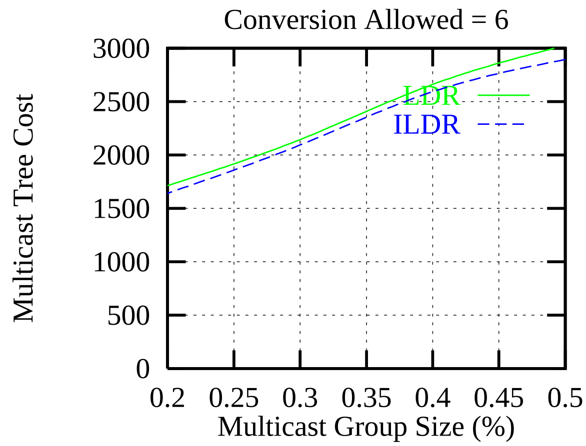
(a) $W = 6$; $\rho = 0.5$



(b) $W = 6$; $\rho = 0.5$



(c) $W = 6$; $\rho = 0.5$



(d) $W = 6$; $\rho = 0.5$

Fig. 7. Multicast Group Size Effect

highest when the number of conversions allowed by the application is 0. As the conversion delay requirements of the application are relaxed, the difference of the cost of the multicast trees produced by both heuristics narrows and is reduced to less than 10% when the number of wavelength conversions allowed is the highest. This trend was also observed for various other network settings and parameter values under different network load conditions. In all simulated cases, ILDR outperforms LDR.

B. Heuristics Performance Comparison

The objective of the second set of experiments was to compare the performance of ILDR to other heuristics, namely, un-bounded delay SPH, KPP and BSMA. The selection of these heuristics was based on the fact that they are representative of the spectrum of tradeoffs between optimality of performance and complexity of operation. While KPP is a low overhead heuristic, it does not use extensive path searching mechanisms to optimize the cost of the tree. BSMA, on the other hand, seeks to produce low cost multicast trees by exploring a large number of path selections. Finally, the unbounded delay SPH does not constrain the delay to the specified bound (i.e., number of wavelength allowed along the path) and focuses only on minimizing the cost of the multicast tree. Since the multicast tree problem is NP-Complete, the results produced by SPH can serve as a "pseudo-lower" bound on the dual-metric multicast tree problem for the network in consideration.

Two types of studies were conducted. In the first study, the metric to compare the heuristics was the average cost of the multicast trees produced by each heuristics. In the second study, the metric used was the computational cost required by each heuristic to produce the multicast tree. Each study involved multiple experiments in different network settings.

Case of the multicast tree cost metric: The first set of experiments of the multicast tree cost based study aimed at comparing the performance of each heuristic, with respect to the cost of the multicast trees produced, in networks with different number of wavelengths. Four scenarios were run, whereby the number of allowed wavelength conversions varied from 0 to 6. As stated earlier, the number of wavelength conversion reflects the delay requirements of the underlying application. The results of the experiments are depicted in Figure 8. In this case, the size of the multicast group size is 30% of the total number of network nodes and the number of wavelength conversions allowed varied from 0 to 6.

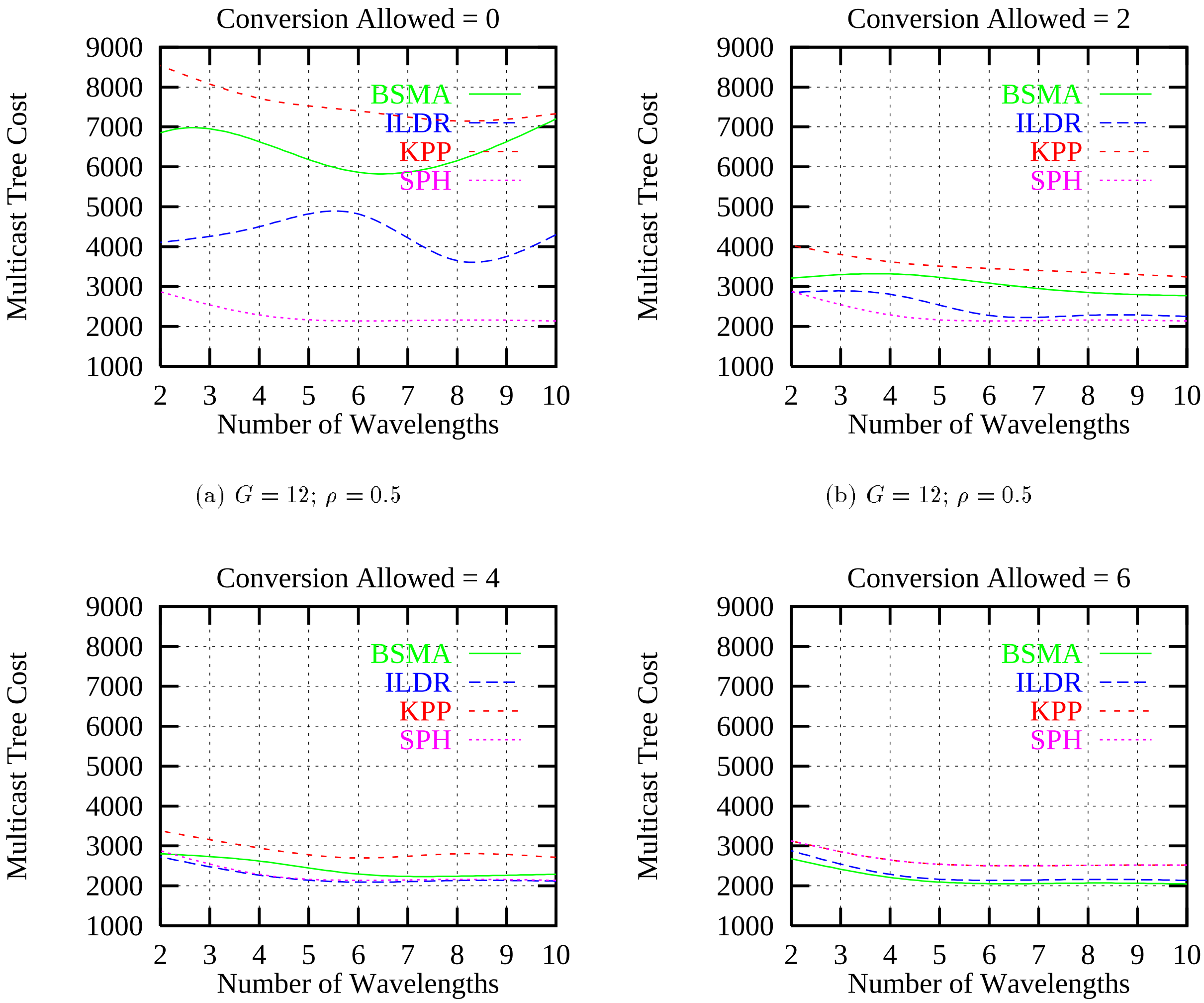
The results show that on average KPP's cost was higher than ILDR's cost by and BSMA's cost and reaches its largest value as the delay bounds become more stringent. BSMA's average cost is higher than ILDR's multicast tree cost by 4% to 5% on average. That is mainly due to the difference in the way BSMA and ILDR build their initial trees. The initial tree built by BSMA is the sink least-delay tree to the multicast nodes with no cost optimization. However, ILDR optimizes the cost of the initial tree before performing the iterative relay-path switching. This initial optimization allows ILDR to produce, on average, smaller cost multicast trees than those produced by BSMA.

The results also show that, as expected, the cost of the unbounded-delay SPH was lower than the cost of the trees produced by ILDR, BSMA and KPP, respectively. When the number of wavelength conversions is small, the difference in cost is the highest. As the number of allowed wavelength conversions increases, the difference in the average cost of the multicast trees produced by BSMA and ILDR decreases. This is mainly due to the fact that when the number of allowed conversions increases, fewer delay-bound violations occur. Finally, the cost of the multicast tree produced by KPP remains high even when the number of allowed wavelength conversions is increased.

The second set of experiments in this study, aimed at assessing the effect of the multicast group size on the performance of ILDR, BSMA, KPP and SPH. In this cae, the number of wavelengths available in the network, W, was set to 6 and the group size, G, expressed as a percentage of the total number of nodes in the network varied from 0.2 to 0.5. The results of the experiments are depicted in Figure 9

The results show that the cost of the multicast trees produced by SPH is the smallest. Among the remaining three heuristics, however, ILDR produces trees with the smallest cost. Furthermore, the difference of ILDR's multicast tree cost and SPH's cost is small and reduces further as the number of wavelength conversions allowed increases. When the number of of wavelength conversions allowed is 6, the difference in cost between SPH and ILDR becomes negligible.

Case of computational cost metric: The second comparative study focused on the computational cost required by each heuristic to compute the multicast tree. Two sets of experiments were conducted. The objective of the first set of experiments was to study the effect of the number of wavelengths available in the network on the cost of the multicast trees for each heuristic. The results of the study are depicted in Figure 10. In this case, the multicast group size is set to 30% of the total number of network nodes. Four scenarios were considered, whereby the number of wavelength conversions



(a) $G = 12$; $\rho = 0.5$ (b) $G = 12$; $\rho = 0.5$

(c) $G = 12$; $\rho = 0.5$ (d) $G = 12$; $\rho = 0.5$

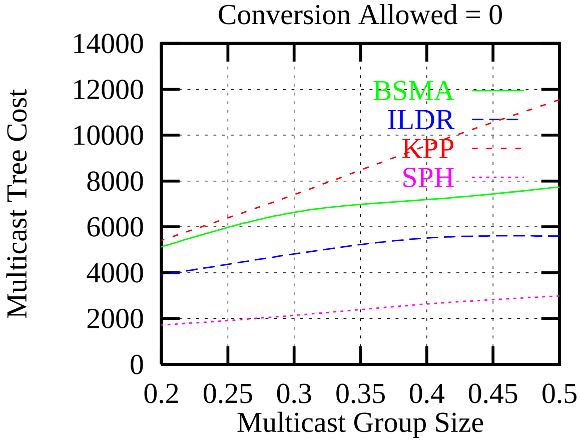
Fig. 8. Wavelength Conversion Effect

allowed varied from 0, meaning no conversion allowed, to 6.

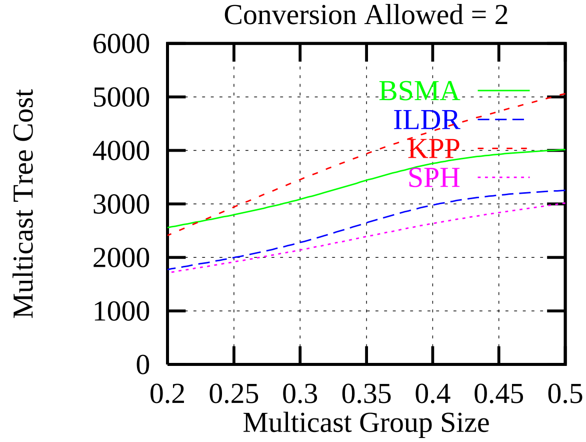
The results show that the cost of SPH remains the lowest in all cases, while the cost of KPP is the highest. The results also show that when the number of wavelength conversion allowed is small, ILDR performed better than BSMA. The difference between the computation cost of the two heuristics becomes higher as the the number of conversion allowed increases. This confirms the fact that optimizing the cost of the initial tree before performing the iterative relay-path switching leads to less expensive multicast trees on average.

The last set of experiments conducted in this study focused on varying the multicast group size, while keeping the number of wavelength fixed. In this case, also, the number of wavelength conversions allowed by the application varied from 0 to 6. The results of the experiments are depicted in Figure 11.

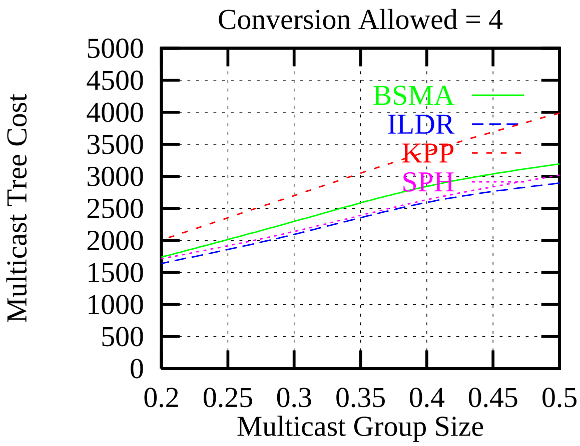
The results show that the computational cost of both, KPP and SPH, is not very sensitive the multicast group size. On the other hand, the computational cost of BSMA and ILDR increases as



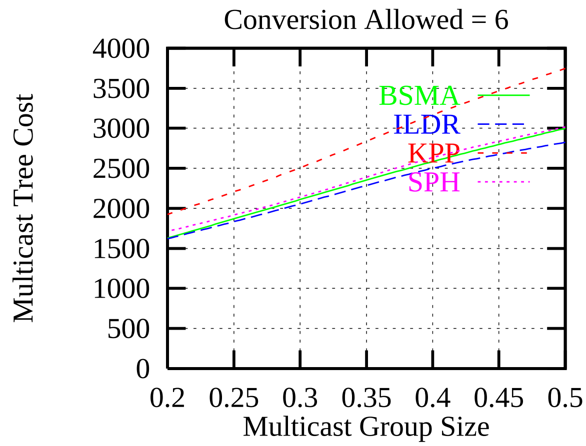
(a) $W = 6$; $\rho = 0.5$



(b) $W = 6$; $\rho = 0.5$



(c) $W = 6$; $\rho = 0.5$



(d) $W = 6$; $\rho = 0.5$

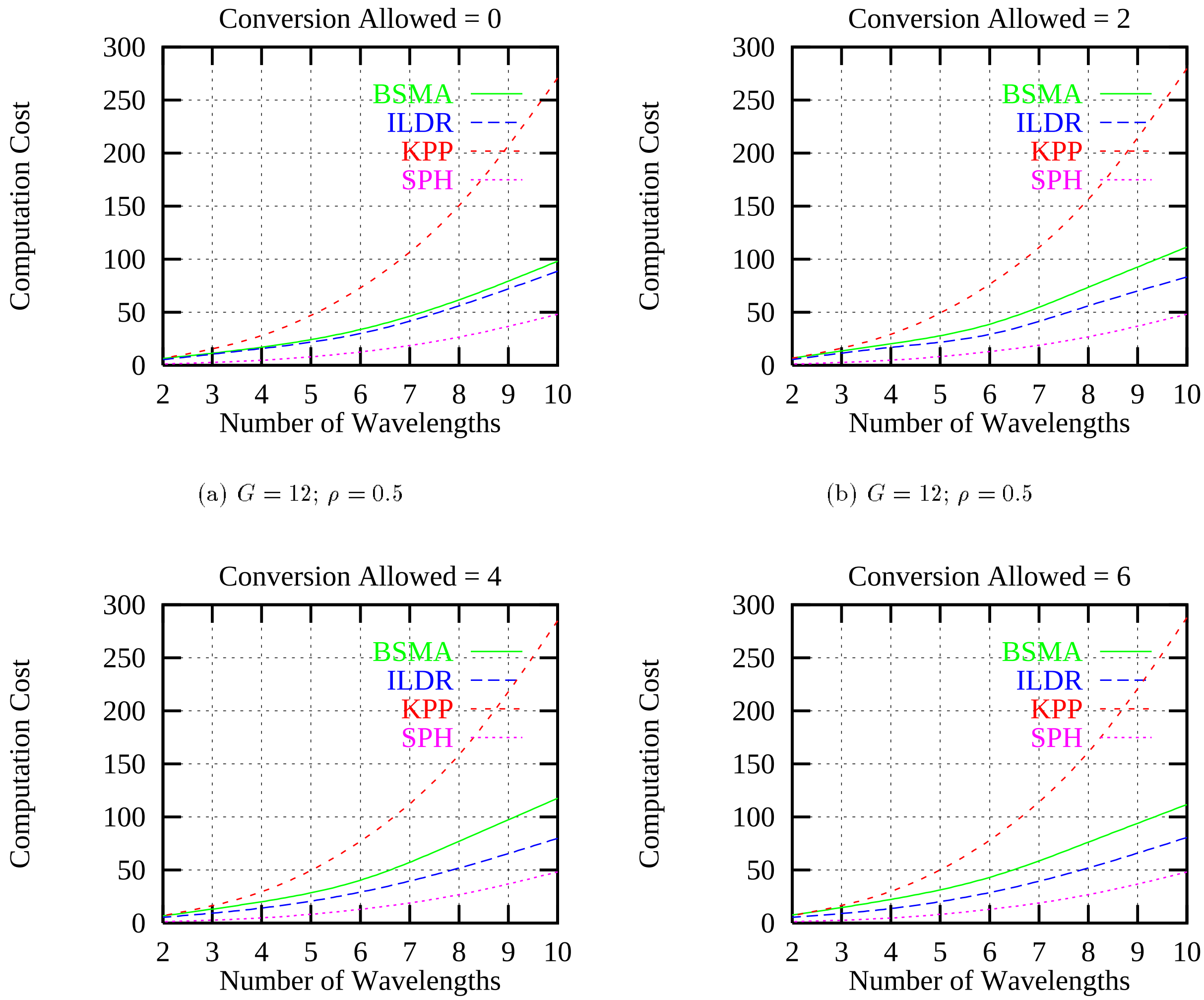
Fig. 9. Multicast Group Size Effect

the size of the multicast group increases. The results also show that ILDR outperforms BSMA in all settings. Furthermore, the difference in the computational cost between the two heuristics increases as the number of conversion allowed increases.

VII. Conclusion

In recent years, WDM networks have been the subject of research and development. Dense WDM technology, which uses minimum spacing between channels, can accommodate up to one hundred optical channels per fiber without coherent detection techniques. Furthermore, the ability to use tunable transmitters and receivers in WDM networks allows greater network flexibility as channels can be allocated dynamically according to traffic requirements. Both of these advantages make WDM an attractive technology to support the anticipated traffic of the next generation Internet. One specific aspect of future Internet services is multicasting.

High speed networking research efforts have concentrated on developing frameworks to support



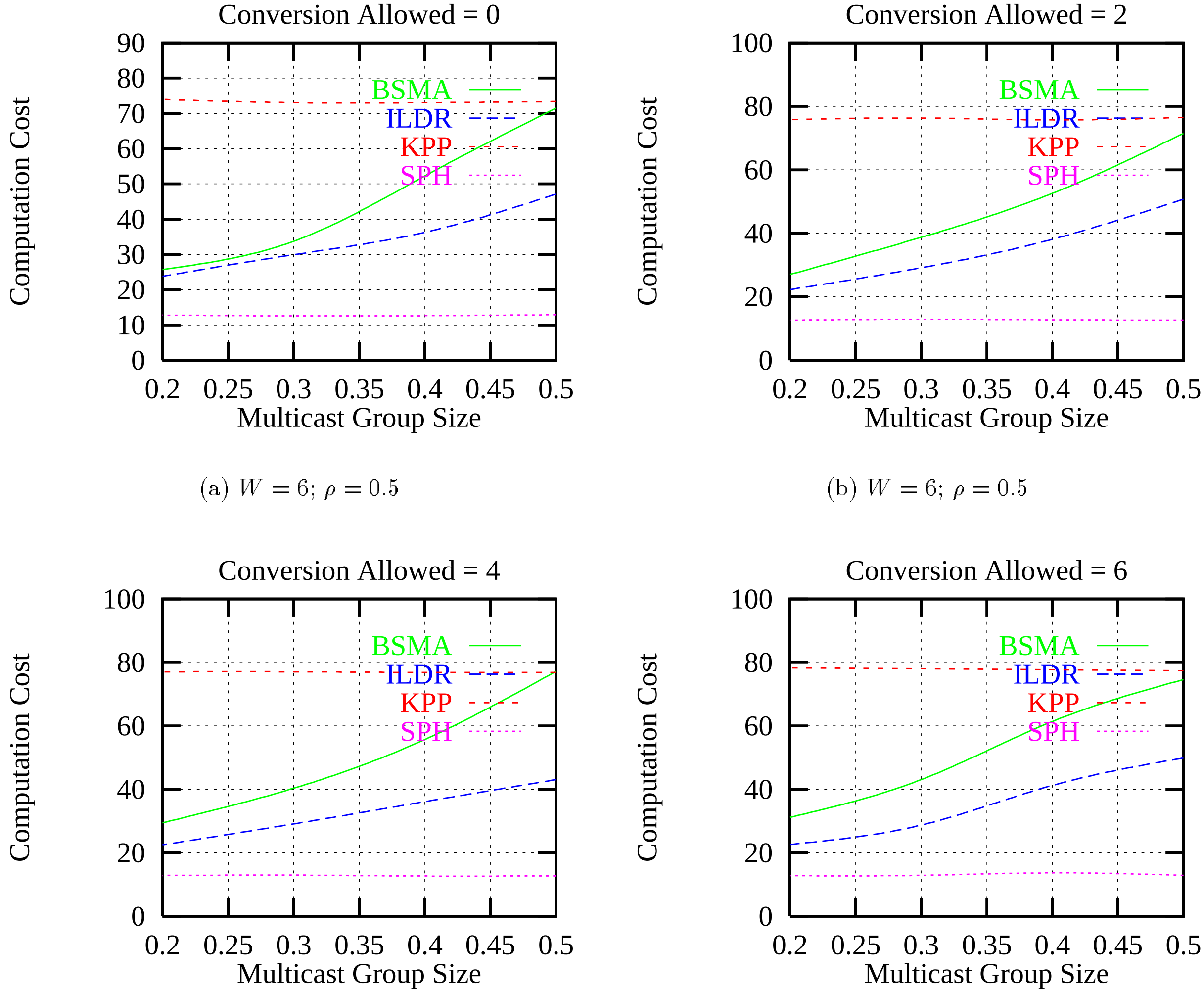
(a) $G = 12$; $\rho = 0.5$ (b) $G = 12$; $\rho = 0.5$

(c) $G = 12$; $\rho = 0.5$ (d) $G = 12$; $\rho = 0.5$

Fig. 10. Wavelength Conversion Effect

QoS guarantees. However, the success of these frameworks is strongly dependent on their ability to support routing and path establishment both for unicast and multicast communication. As the networks grow in size and user requirements increase in complexity the determination of the "best" route or multicast tree for the required level of QoS becomes a difficult task. Further, it is no longer sufficient to select routes with minimum cost; what is required is efficient mechanisms for building multicast trees that are not only of minimal cost but also support the application required level of QoS.

Given that WDM networks are fundamentally different from traditional networks when it comes to optimization objectives, it is imperative to explore the impact of the WDM networks' characteristics, in terms of wavelength availability, light-wave conversion cost and link delays, on the path selection process, both for unicast and multicast communication, and to understand the impact of the inaccuracy in the available network state information on the efficiency of the route establishment schemes. This paper addresses the first issue and proposes cost structure which takes into consideration both



(a) $W = 6$; $\rho = 0.5$

(b) $W = 6$; $\rho = 0.5$

(c) $W = 6$; $\rho = 0.5$

(d) $W = 6$; $\rho = 0.5$

Fig. 11. Multicast Group Size Effect

link cost and delay. Based on this cost structure, an optimization problem is formulated and three heuristics to this problem, which can be used to construct a low-cost, delay-bound multicast tree in WDM networks, are proposed.

The first heuristic, LDR, builds the least-cost tree using SPH, and then replaces the nodes whose delay were violated with the least-cost, delay-bounded path. If there is no delay violation, this heuristic gives the same approximation as SPH. The second heuristic, $ILDR$, builds the multicast tree in a way similar to SPH. However, it incorporates the delay bound checking within the construction process of the minimum cost tree. When there is a delay violation, it uses $LCCP$ to find the least-cost bounded path. The last proposed heuristic, LDF, is similar to $ILDR$. However, when it adds a node to the multicast trees, the heuristic selects the node whose least-cost path has the minimum delay. A performance analysis study showed that both ILDR and LDR perform efficiently in comparison to other multicast tree heuristics.

Future work in this field may focus on adaptive path establishment in WDM networks. A good

Heuristic	Time Complexity	Cost optimization approach
KPP	$O(max(\Delta_d) n^3)$	Dynamic programming optimization
LDH	$O(n^2)$	No cost optimization
LCH	$O(n^2)$	Union of all shortest cost paths from source to destination
DPH	$O(max(\Delta_d) * n^3)$	Similar to SPH
BSMA	$O(k n^3 \; log(n))$	Reducing cost by switching paths
LDR	$O(\|Z\| * n^2)$	Similar to SPH if no delay violation
LDF	$O(\|Z\| * n^2)$	Similar to SPH if no delay violation
ILDR	$O(\|Z\| * n^2)$	Similar to SPH if no delay violation

TABLE I

Time Complexity and bounds of the DBSMT heuristics

probabilistic model with up-to-date information about resource availability may select routes that can, with high probability, lead to the successful establishment of a multicast tree that satisfies the specified QoS requirements of the multicast nodes. However, when the rate of change in resource availability in the network is high, a distributed signaling protocol may fail to establish a connection with the specified QoS requirements along the selected route. Therefore, further research investigating multicast tree establishment protocols that can adapt to resource availability is required and different options for dynamically adapting to resource availability need to be developed. This includes allowing wavelength conversion when permitted by the QoS requirement, switching to overflow routes and selecting alternate routes dynamically.

Another aspect of multicasting that need to be addressed is on-line multicast and group management. The capability of on-line joining and leaving multicast groups is very important in today's multimedia systems. At the connection level, this requires the ability of individual nodes to set-up a connection to an already established point-to-multipoint connection. The choice of the path from the node to the tree should not only depend on the length of that path, but also on the availability of wavelengths and the number of wavelength conversions along that path. The problem is further complicated by the fact that, not only wavelength availability may dynamically change in the network, but also the multicast group membership may vary over time.

References

[1] T. Ballardie, P. Francis, and J. Crowcroft. Core-based trees (cgt) an architecture for scalable inter-domain multicast routing. *Computer Communcation Review*, 23(4):85–95, 1993.

[2] A. Barry and S. Subarmanian. The max_sum wavelength assignment algorithm for wdm ring networks. In Proceedings of OFC'97, February 1997.

[3] B. Beauquier, J.C. Gargano, S. Pereness, P. Hall, and U. Vaccaro. Graph problems arising from wave-length rounting in all. Proceedings of the 2nd Workshop on Optics and Computer Science (WOCS'97, 1997.

[4] I. Chlamtac, A. Faragó, and T. Zhang. Lightpath (wavelength) routing in large wdm networks. IEEE/ACM Journal on Selected Areas in Communications, 14:909–913, 1996.

[5] H. Choi, H.A. Choi, and M. Azizoglu. Efficient scheduling transmissions in optical broadcast networks. IEEE/ACM Transactions on Networking, December 1996.

[6] E. W. Dijkstra. A note on two problems in connection with graphs. *Numeriskche Mathematik*, 1:269–271, 1959.

[7] P. Dowd and K. Sivalingam. A multi-level wdm access protocol for an optically interconnectred parallel computer. Proceedings of IEEE INFOCOM'94, 1, June 1994.

[8] T. Erlebach and K. Janson. Scheduling of virtual connections in fast networks. Proc. of the 4th Workshop on Parallel Systems and Algorithms (PASA'96), pages 13–32, 1996.

[9] D. Estrin, D. Farinacci, A. Helmy, D. Thaler, S. Deering, M. Handley, V. Jacobson, C. Liu, P. Sharma, and L. Wei. Protocol independent multicast-sparse mode (PIM-SM): Protocol specification. *Internet RFC 2117*, http://ds.internic.net/rfc/rfc2117.txt, June 1997.

[10] M. Feldman, S Esener, C. Guest, and S. Lee. Comparison between optical and electrical interconnects based on power and speed considerations. Applied Optics, 29:1742–1751, 1990.

[11] G. Gravenstreter, R.G. Melhem, D.M. Chiarulli, S.P. Levitan, and J.P. Teza. The partitioned optical passive stars (POPS) topology. IEEE Proceedings of the Ninth International Parallel Processing Symposium, April 1995.

[12] V. Kompella, J. Pasquale, and G. Polyzos. Multicast routing for multimedia communication. *IEEE/ACM Transactions on Networking*, 1(3):286–292, June 1993.
[13] L. Kou, G. Markowsky, and L. Berman. A fast algorithm for steiner trees. *Acta Informatica*, 15:141–145, 1981.
[14] M. Kovaceivc and A. S. Acampora. Benefits of wavelength translation in all-optical clear channel networks. IEEE Journal on Selected Areas in Communication, 14(5):868–880, June 1996.
[15] P. Lalwaney, L. Zenou, A. Ganz, and I. Koren. Optical interconnects for multiprocessors: Cost performance analysis. Proceedings of the Symposium on Frontiers of Massively Parallel Computation, pages 278–285, 1992.
[16] W. Liang and H. Shen. Efficient multiple multicast in wdm networks. Proceedings of the 1998 Intern. Conf. on Parallel and Distributed Processing Techniques and Applications, 1998.
[17] W. Liang and H. Shen. Multicast broadcasting in large wdm networks. Proceedings of the 12th Intern. Conf. on Parallel Processing Symposium (IPPS/SPDP), 1998.
[18] J. Moy. Multicast routing extensions for OSPF. *Communications of the ACM*, 37(8):61–66, August 1994.
[19] B. Mukherjee. WDM-Based local lightwave networks, Part I: Single-hop systems. IEEE Networks, pages 12–27, May 1992.
[20] Y. Ofek and B. Yener. Reliable concurrent multicast from busrty sources. IEEE JSAC, 14(3), pages 1433–1441, April 1997.
[21] P. Prucnal, I. Glesk, and J. Sokoloff. Demonstration of all-optical self-clocked demultiplexing of tdm data at 250 gb/s. Proceedings of the Int. Workshop on Massively Parallel Processing Using Optical Interconnections, pages 106–117, 1994.
[22] T. Pusateri. Distance vector multicast routing protocol. *Internet Draft*, February 1997.
[23] B. Rajagopalan, D. Pendarakis, D. Saha, R.S. Ramamoorthy, and K. Bala. Ip over optical networks:architectural aspects. *IEEE Communication Magazine*, 38(9):94–103, September 2000.
[24] B. Ramamurthy and B. Mukherjee. Wavelength conversion in wdm networking. IEEE J. on Sellected Areas in Communications, 16(7), July 1998.
[25] S. Ramanathan. Multicast tree generation in networks with asymmetric links. *IEEE/ACM Transactions on Networking*, 4(4):558–568, November 1996.
[26] V.J. Rayward-Smith and A. Clare. On finding steiner vertices. *Networks*, 16:283–294, 1986.
[27] A. Somani and B. Ramamurthy. Issue on optical communication networks for the next-generation internet. *IEEE Network*, 14(6), November/December 2000.
[28] J. Strand, A.L. Chui, and R. Tkach. Issues for routing in the optical layer. *IEEE Communication Magazine*, 39(2):81–88, February 2001.
[29] Q. Sun and H. Langendoerfer. Efficient multicast routing for delay sensitive applications. *Proceedings of Second Workshop Protocols Multimedia Systems (PROMS'95)*, pages 452–458, April 1995.
[30] H. Takahashi and A. Matsuyama. An approximate solution for the steiner problem in graphs. *Mathematica Japonica*, 24:573–577, 1980.
[31] Bernard M. Waxman. Routing of multipoint connections. *IEEE Journal on Selected Areas in Communications*, 6(9):1611–1622, December 1988.