A Novel Shared Segment Protection Algorithm for Multicast Sessions in Mesh WDM Networks

Cai Lu, Hongbin Luo, Sheng Wang, and Lemin Li

This paper investigates the problem of protecting multicast sessions in mesh wavelength-division multiplexing (WDM) networks against single link failures, for example, a fiber cut in optical networks. First, we study the two characteristics of multicast sessions in mesh WDM networks with sparse light splitter configuration. Traditionally, a multicast tree does not contain any circles, and the first characteristic is that a multicast tree has better performance if it contains some circles. Note that a multicast tree has several branches. If a path is added between the leave nodes on different branches, the segment between them on the multicast tree is protected. Based the two characteristics, the survivable multicast sessions routing problem is formulated into an Integer Linear Programming (ILP). Then, a heuristic algorithm, named the adaptive shared segment protection (ASSP) algorithm, is proposed for multicast sessions. The ASSP algorithm need not previously identify the segments for a multicast tree. The segments are determined during the algorithm process. Comparisons are made between the ASSP and two other reported schemes, link disjoint trees (LDT) and shared disjoint paths (SDP), in terms of blocking probability and resource cost on CERNET and USNET topologies. Simulations show that the ASSP algorithm has better performance than other existing schemes.

Keywords: Multicasting, adaptive shared segment protection, single link failures, wavelength-division multiplexing (WDM).

I. Introduction

Survivability is one of the most important issues in the design of high-speed optical wavelength-division multiplexing (WDM) networks. Additionally, multicast-based service applications are becoming widely popular. Since single fiber failure is the dominating failure scenario, this paper investigates a multicast session survivable problem against single link failure in optical WDM mesh networks.

To support multicast sessions in optical WDM networks, we need multicast-capable optical cross-connects (MC-OXCs) [1], which replicate a bit stream from one input port to multiple output ports. With MC-OXC, the concept of a light tree is defined in [2]. In view of cost, networks always are configured with a sparse number of light splitters. If all nodes are MC-OXCs, the problem of an optimal multicast tree is the famous Steiner Tree Problem (STP) [3]. It is apparent that the problem of a sparse-light-splitter configuration is more difficult than the STP. Xijun Zhang and others [4] proposed four algorithms of multicast routing with sparse light splitting and concluded that member-only (MO) is the most efficient algorithm.

Simultaneously, survival routing of a unicast has been studied during the past several years. Many schemes such as link protection-based, path-protection-based and segment-protection-based schemes have been proposed. Comparatively, the approach of shared segment protection (SSP) has more flexibility on routing and resource efficiency, scalability, and limited restoration time [5]-[10]. With SSP, a lightpath in a unicast is protected by one or multiple self-healing loops, each of which behaves as a self-healing unit performing local restoration once the corresponding working lightpath segment is subject to any unexpected interruption. This scheme is more efficient compared with light-path-based protecting and link-

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based protecting in a unicast. But these schemes do not work well for protecting a multicast session.

A straightforward scheme to protect a multicast session is to establish two link-disjoint multicast trees. Such link-disjoint trees (LDT) can be used to provide 1+1 dedicated protection [11], where both working tree and protecting tree can carry identical bit streams to all the destination nodes. When a fiber is cut, the multicast session reconfigures the switches to receive a bit stream from the protecting tree. Though the LDT scheme is perspicuous, it is an excessive use of resources and has an inability to discover link-disjoint trees in a mesh network, which may lead to the blocking of a large a number of multicast sessions.

The scheme of a shared segment-protecting multicast session is proposed in [12] and is named a shared disjoint-segment (SDS). Given a multicast tree, the first step of SDS is to identify the segments on the working multicast tree. The most critical problem is how to identify the segments for a multicast tree. The scheme of the segments seriously affects the performance of the algorithm.

Actually, if we can establish two link-disjoint light paths between every destination node and source node, we ensure the multicast session routing can be restored when a single link fails. The shared disjoint path (SDP) scheme [12] tries to find a pair of smart paths between the source and every destination. Based on simulations, the SDP scheme is more efficient than LDT and SSP [12]. Besides these protecting schemes, a ring-based protection technique is used to ensure the source and all the destinations belonging to a ring [13]. The authors in [13] give a line program and do not propose heuristic algorithms.

In this paper, we inspect the two special characteristics of multicast trees. A multicast tree is shown in Fig. 1. The multicast session (s, d_1, d_2, d_3) is carried by the multicast tree. S, d_1, d_2, d_3 are the leaves of the multicast tree. If we find a light path between d_3 and d_2, we can protect the segment of $d_3 \rightarrow 2 \rightarrow 1 \rightarrow 3 \rightarrow d_2$. What is more, if the network is sparse-light-splitter configured, a novel multicast tree does not adhere to the traditional concept of the graph theory. It may contain some circles. To the best of our knowledge, this characteristic has not been mentioned previously. Based on the two characteristics, we propose a scheme named adaptive shared segment protection (ASSP) for a multicast tree. In particular, the ASSP algorithm does not previously identify the segment. The segment scheme is determined according to the multicast tree and current sparse network resource during the process of the algorithm.

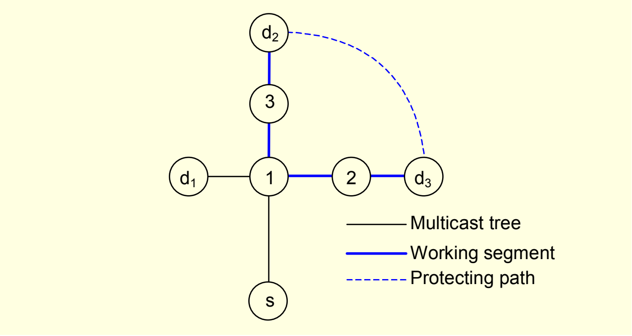

Fig. 1. Multicast tree and segment protection.

This paper is organized as follows. In section II, we narrate several aspects of multicast session protection. Section III develops Integer Linear Program (ILP) formulations for the survival multicast routing. Section IV presents the ASSP algorithm in two phases: the first phase is to establish a novel multicast tree for a multicast session; and the second is to construct the protection path for the multicast tree. Section V carries on several simulations and analyzes their results. Section VI concludes this work with a discussion of its main contributions.

II. Problem Statement

In this paper, we investigate the problem of surviving multicast routing on full-range wavelength conversion mesh networks. Here we discuss several aspects of this problem.

1. Extension Multicast Tree Concept with Sparse MC-OXC Configuration

Traditionally, we have always taken all the multicast paths as a multicast tree or multicast forest (several multicast trees rooted at the source node) when we study the problem of multicast routing. In the graph theory, a tree does not contain any simple circles. Actually, the concept of a multicast tree cannot describe the problem in mesh WDM networks with partial MC-OXC precisely, for a multicast tree may contain some circles. An example is shown in Fig. 2, where the multicast session is {s, d_1, d_2}, node 1 is an MC-OXC, and node 3 is a multicast-incapable OXC (MI-OXC). Then, we can construct the multicast tree as in Fig. 2. The bit stream is replicated into two streams by node 1. Since node 3 is MI, the branch of d_1 is $1 \rightarrow 3 \rightarrow d_1$; and the branch of d_2 is $1 \rightarrow 2 \rightarrow 3 \rightarrow d_2$ since there is no idle wavelength from node 1 to 3. Nodes 1, 2 and 3 consist of a circle. To the best of our knowledge, this characteristic has not been mentioned in the literature. This session will be blocked since the routing algorithm cannot establish a multicast tree without any circles. In the ASSP algorithm, we improve the multicast routing algorithm performance by allowing a multicast containing some circles. For ease of description, we also use multicast tree to denote the multicast routes with some circles, though the concept is not that of the graph theory.

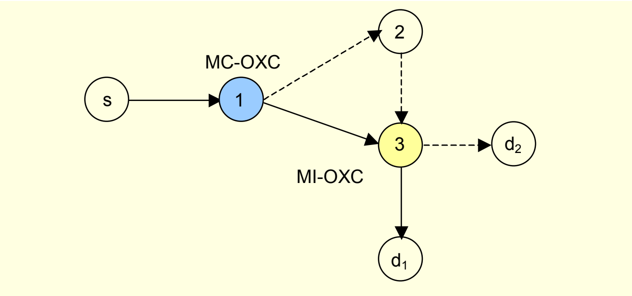

Fig. 2. Multicast tree containing a circle-with-sparse MC-OXC configuration.

2. Overview of SSP

Comparatively, the SSP scheme is flexible and efficient. The first step of the SSP is to identify the segments, and then to protect each of them. An example is shown in Fig. 3. Node v segments the multicast tree as two parts: s→v and d_1→v→d_2. Node v is called a switching node. As mentioned in section Ⅰ, the most critical problem is how to determine the switching nodes given a multicast tree. It is obvious that it is an NP-hard to optimal segment scheme. The literature [14] does not mention how to identify the segments on the multicast tree.

When we inspect a multicast tree, we can find some leaf nodes that have only one connection degree. Here, we give the definition of a leaf node.

Definition. The node is an ending node (EN) whose connection degree is 1.

Based on the definition, we give a claim about ENs.

Claim. A multicast tree contains at least two ENs.

Proof: if the multicast tree does not contain any circles, it is a traditional tree. It is obvious that a tree has at least two vertices of degree 1. We inspect the multicast tree containing some circles. Let $(d_1,d_2,\ldots,d_l)$ be one of the circles in the multicast tree. We can find at least two nodes, d_i and d_j, whose degrees are at least 3 (one is an MC-OXC and the other is an MI-OXC) and the nodes between d_i and d_j on the circle have a 2 degree connection. If we delete the part between d_i and d_j we do not add any additional ENs. Repeating the process until there are no circles on the tree, we can convert the multicast tree with some circles to a common one without circles. Because a tree has at least two ENs, we can claim that a multicast tree contains at least two ENs. □

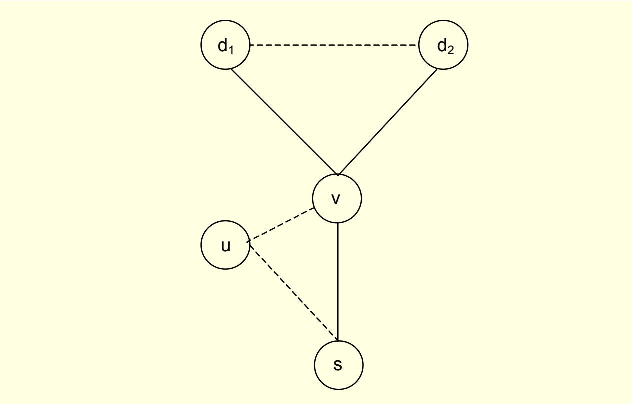

Fig. 3. Segment protection of multicast tree.

Corollary. If we protect any section of a circle, we can protect all the links on the circle.

An example is shown in Fig. 4. A multicast session is (s, d_1, d_2, d_3). The solid line is the multicast tree. It contains a circle u→v→j→k→i→u. We use path d_1→m→d_2 to protect the section d_1→i→k→j→d_2. We can find that the multicast session can be restored from any link failure on the circle. For example, if link u→i is cut, we can use paths u→v→j→d_2→m→d_1→i→k→j→d_3 to restore the multicast session.

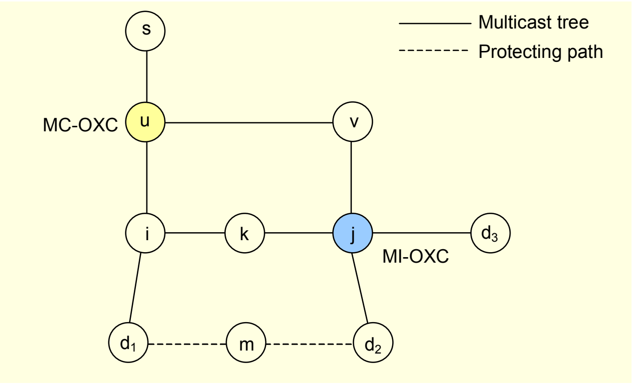

Fig. 4. Protection circle on a multicast tree.

3. Protection Efficiency (PE)

For achieving an efficient segment scheme, we define the parameter protection efficiency (PE) as the following:

$$PE = \frac{C_w}{C_p} = \frac{\sum_{i\in S_w} c_i}{\sum_{j\in S_p} c_j}, \tag{1}$$

where C_w is the cost of the working segment on a multicast tree, C_p is the cost of the protecting path for C_w, and c_j is the cost of link j.

As shown in Fig. 4, the cost sum of segment d_1→i→k→j→d_2 is C_w and the cost sum of d_1→m→d_2 is C_p. If we use path d_1→m→d_2 to protect segment d_1→i→k→j→d_2, we can calculate the PE of protection path d_1→m→d_2.

III. Problem Formulation

In this paper, we suppose all of the nodes are wavelength convertible. If two link-disjointed light paths can be established from a source node to each destination, the multicast route will survive against single link failures. In this section, the problem of multicast routing against single link failures is formatted as an ILP.

1. Problem Description

Consider the following input problem.

1) There is a network topology G= (V, E) consisting of a weighted undirected graph, where V is a set of network nodes, and E is the set of links connecting the nodes. Each link is assigned a weight to represent the cost of moving traffic from one node to the other.
2) The destination number is k, where k≥1 and k ≤ |V| –1. If k=1, the session is a unicast; if k=|V| –1, the session is a broadcast. If a routing algorithm discovers sufficient resources in the network, the multicast session is established; otherwise, it is blocked.
3) Every link has W = 1 wavelength channels.

2. Mathematical Formulation

For survival multicast routing against any single link failures, we must ensure that we can find two link-disjoint paths from a source node to any destination node on the network resource (including MC-OXC resource and wavelength channel resource). Therefore, the problem transfers to allocate the minimal resources and ensures there are two link-disjoint paths between source node and any destination node.

Given

- An undirected graph G (V, E), N=|V|.
- Every physical link between nodes m and n is associated with a weight and cost c_{mn}. If there is not a physical link between nodes m and n, $c_{mn}=\infty$.
- A multicast session S = {s, $d_1, \cdots, d_L$}, where s is the source node, d_j ($j=1, 2, \cdots, L$) is the destination node, and L is the number of distribution nodes.

Variables

- Boolean variable L^{dw}_{mn}, which is equal to one if the link between nodes m and n is occupied by the working paths of destination d;
- Boolean variable L^{dp}_{mn}, which is equal to one if the link between nodes m and n is occupied by the protecting path of destination d;
- Boolean variable L_{mn}, which is equal to one if link between nodes m and n is occupied by either the working or the protecting paths of any destination node;

Optimize:

$$Mininize : \sum_{m,n} c_{nm} \times L_{mn} \,. \tag{2}$$

Constraints

- Working path constraints for every destination

$$\forall d : \sum_{n} L^{dw}_{ns} = 0 \,, \tag{3}$$

$$\forall d : \sum_{n} L^{dw}_{sn} = 1 \,, \tag{4}$$

$$\forall d : \sum_{n} L^{dw}_{nd} = 1 \,, \tag{5}$$

$$\forall d : \sum_{n} L^{dw}_{dn} = 0 \,, \tag{6}$$

$$\forall m \notin S, d : \sum_{n} L^{dw}_{nm} = \sum_{n} L^{dw}_{mn}. \tag{7}$$

- Protecting path constraints for every destination

$$\forall d : \sum_{n} L^{dp}_{ns} = 0 \,, \tag{8}$$

$$\forall d : \sum_{n} L^{dp}_{sn} = 1 \,, \tag{9}$$

$$\forall d : \sum_{n} L^{dp}_{nd} = 1 \,, \tag{10}$$

$$\forall d : \sum_{n} L^{dp}_{dn} = 0 \,, \tag{11}$$

$$\forall m \notin S, d : \sum_{n} L^{dp}_{nm} = \sum_{n} L^{dp}_{mn} \,. \tag{12}$$

- Working path and protecting path for every destination are link disjointed

$$\forall m, n : L^{dw}_{nm} + L^{dw}_{mn} + L^{dp}_{nm} + L^{dp}_{mn} \leq 1 \,. \tag{13}$$

- Constraints of cost

$$\forall m, n, d : L^{dp}_{mn} + L^{dw}_{mn} + L^{dp}_{nm} + L^{dw}_{nm} \leq L_{nm} \,, \tag{14}$$

$$\forall m, n : L_{mn} \leq \sum_{d} (L^{dp}_{mn} + L^{dw}_{mn} + L^{dp}_{nm} + L^{dw}_{nm}) \,. \tag{15}$$

Explanation of Equations

Equation (2) is the optimal object: minimize the cost of the provision for survival multicast routing against single link failures. Equations (3) through (7) and (8) through (12) constrain the working path and protecting path from source node s to destination node d, respectively. Equation (13) ensures the protecting path and working path are link disjointed for any destination node. Equations (14) and (15) ensure that the link cost is calculated only once if the link is occupied by either multiple working paths or protecting paths, respectively.

The problem of an optimal multicast tree is an NP problem [3]. It is obvious that the problem of a survival multicast tree is more complex than an optimal multicast tree. Thus, the problem of a survival multicast tree is NP-hard.

IV. Adaptive Share Segment Protection for Multicast Session

In this section, we introduce our scheme of ASSP for a multicast session. The scheme has two phases: the first step is to establish a multicast tree; and the second step is to construct the protecting paths against single link failures for the multicast tree.

1. Establish Multicast Tree with Sparse MC-OXC Configuration

Here, we give the algorithm for constructing a multicast tree with sparse MC-OXC configuration. Let T(s, D) be a record of the multicast tree, where s is the source node and D is the set of destinations. Let V_T be the set of nodes that are on the current multicast tree, which are either MC-OXCs or leaf destination nodes.

Step 1. T(s, D) =Φ, V_T=s.
Step 2. Try to find the shortest path p(v, u), where $v \in V_T$ and $u \in D$.
Step 3. If we cannot find that path, multicast session is blocked and stops.
Step 4. Add every link $e \in p(v, u)$ to T and remove it from G.
Step 5. For any node y on p(v, u), $y \neq v$ and $y \neq u$. If y is MC, add it to V_T.
Step 6. If v is MI and $v \neq s$, remove it from V_T.
Step 7. Remove u from D and add it to V_T.
Step 8. If D=Φ, algorithm stops; otherwise go back to step 2.

The multicast tree constructed by the algorithm may contain some circles. It is more efficient than the member-only (MO) algorithm [4].

2. Adaptive Shared Segment Protection for a Multicast Tree

Given a multicast session {s, D}, where s is the source and D is the group of destinations, we establish the multicast tree using our multicast tree algorithm. Let T be the multicast tree, V_E be the set of ENs on T, S_{vu} be the segment between two ENs on the multicast tree, P_T be the set protecting paths, and δ_i be the connection degree node i on T. We give an example to illuminate the steps of ASSP.

Given a multicast session (s, d_1, d_2, d_3), we construct the multicast tree shown in Fig. 4. We calculate the connection degree for every node on the tree: $\delta_s=\delta_{d1}=\delta_{d2}=\delta_{d3}=1$, $\delta_u=\delta_i=3$, $\delta_v=\delta_k=2$, $\delta_j=4$. V_E={s, d_1, d_2, d_3}. Then we calculate the shortest paths between any pair nodes in V_E on the multicast tree: $S_{s,d1}$, $S_{s,d2}$, $S_{s,d3}$, $S_{d1,d2}$, $S_{d1,d3}$, $S_{d2,d3}$. We then try to establish the protecting paths for these segments: $P_{s,d1}$, $P_{s,d2}$, $P_{s,d3}$, $P_{d1,d2}$, $P_{d1,d3}$, $P_{d2,d3}$. Each protecting path is link-disjointed to the corresponding segment. For example $P_{s,d1}$ is link disjointed to $S_{s,d1}$. Then, we can calculate the PE for every segment. Let $P_{d1,d2}$: $d_1 \rightarrow m \rightarrow d_2$ and its segment $S_{d1,d2}$: $d_1 \rightarrow i \rightarrow k \rightarrow j \rightarrow d_2$ be the most efficient among the other protecting paths. We add the path $d_1 \rightarrow m \rightarrow d_2$ to P_T and update the cost of each link on $S_{d1,d2}$ and $P_{d1,d2}$ to 0 for resource sharing. Then, update $\delta_{d1}=0$, $\delta_i=1$, $\delta_k=0$, $\delta_2=2$, $\delta_{d2}=0$. So we get the new V_E={s, i, d3} and repeat the process until V_E=Φ.

The following are the steps of the ASSP.

Step 1. Construct the multicast working tree T.
Step 2. Initialize V_E and δ_i, i=0,1,… .
Step 3. For every segment S_{vu} of T, where v, u $\in V_E$, calculate the protecting path P_{vu} link disjointed with S_{vu}. Try to find S_{vu} and P_{vu} with the minimized PE;
Step 4. If such S_{vu} and P_{vu} are not found, session is blocked and stops.
Step 5. If the cost of S_{vu} = 0, $\delta_v=\delta_v-1$, $\delta_u=\delta_u-1$, remove v and u from VE, and go back to step 3.
Step 6. Add every link of P_{vu} to P_T.
Step 7. For any link L_{nm} on S_{vu}, if the cost of $L_{nm}>0$, $\delta_n=\delta_n-1$ and $\delta_m=\delta_m-1$;
Step 8. Update V_E and the weight of every link on P_{vu} and S_{vu} to zero in G(V, E).
Step 9. If V_E = Φ, stop; otherwise, go back to step 3.

3. Algorithm Complexity

The ASSP algorithm has two phases, the first step is to establish the multicast tree; the second step is to construct protecting paths for the tree.

The computation of the shortest path takes $O(V^2)$ time. If the multicast session is broadcast, we have to calculate the shortest path $O(V^3)$ times. Thus, the complexity of establishing the multicast tree is $O(V^5)$. Given a multicast session, the multicast tree has V–1 leaf nodes at most. We calculate the shortest path $O(V^2)$ times for each repeat. Therefore, the complexity of calculating the protecting path is $O(V^5)$. Hence, the computational complexity of the ASSP is $O(V^5)$.

V. Simulation Study and Results

In this section, we simulated the performance of the ASSP scheme. According to the conclusion of paper [12], the scheme of the optimal path-pair-based SDP (shared disjoint paths) is the most efficient one. Of course the algorithm of the Link-Disjoint Tree (LDT) is a basic scheme, though it is not very efficient in view of the resource utility ratio.

1. Static Simulation

In this session, we consider the average cost of survival multicast routing against single link failures. In view of the complexity, we build the simulation on a small network CERNET with 10 nodes. The network topology is shown in Fig. 5. The link weight (cost) represents fiber lengths between node pairs or the cost of moving traffic from one node to another.

We generate a random multicast connection of size k and compare the results of the ASSP with LDT, SDP schemes, and the optimal routing of ILP. The source node and destination nodes of a connection are uniformly distributed across the network. If a scheme finds sufficient resources, the connection is established; otherwise, it is blocked. We repeat the experiment for 20 thousands different connections of the same group size.

Figure 6 shows that the blocking probability of the LDT algorithm is very high. But none of the multicast sessions were blocked for SDP and ASSP. Figure 7 shows the average cost of LDT, SDP, ASSP, and the optimal solution of ILP.

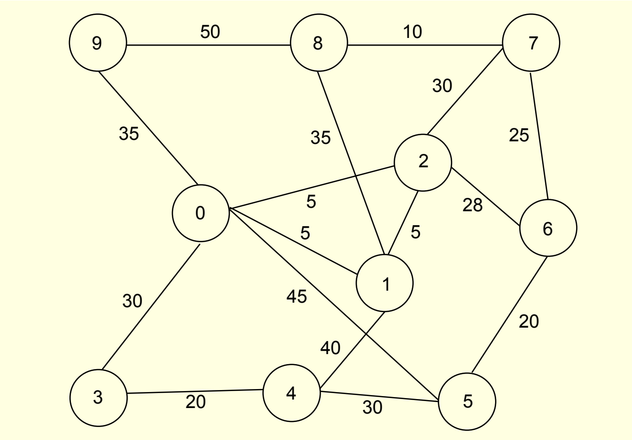

Fig. 5. CERNET network topology.

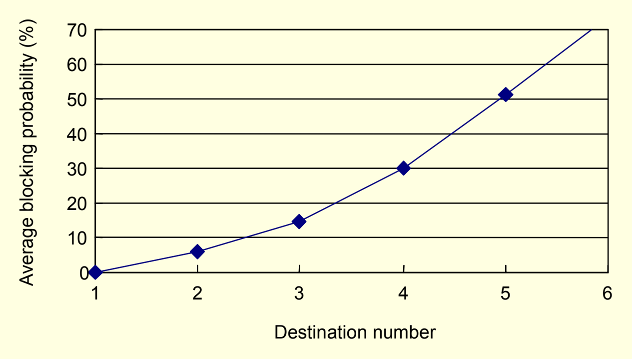

Fig. 6. The blocking probability of different sized multicast sessions with LDT scheme.

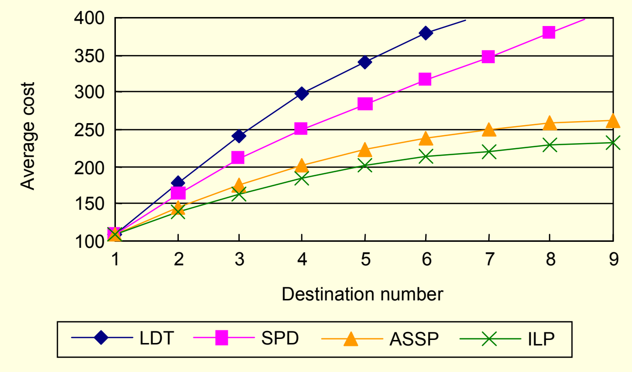

Fig. 7. The average cost of different size multicast sessions of LDT, SDP, and ASSP.

2. Dynamic Provisioning of Survival Multicast Session

In this section, we establish simulations on dynamic provisioning of survival multicast sessions in an optical WDM mesh network. The number of wavelength channels carried by the link is W. The multicast session arrives according to a Poisson process, and the duration of each session is exponentially distributed. A multicast session is accommodated if we can allocate enough resource according to different schemes. The session is successful; otherwise, it is blocked. Figure 8 shows the topology of USNET with 24 nodes. Figure 9 shows the blocking probability of every scheme.

3. The Influence of MC-OXC Number

This simulation intends to inspect the influence of blocking probability with different MC-OXC numbers. The wavelength number of each link is 64, and the offered load is 100 Erlangs. Let M be the MC-OXC number. The MC-OXCs are randomly distributed for each multicast session. Figure 10 shows the simulation results.

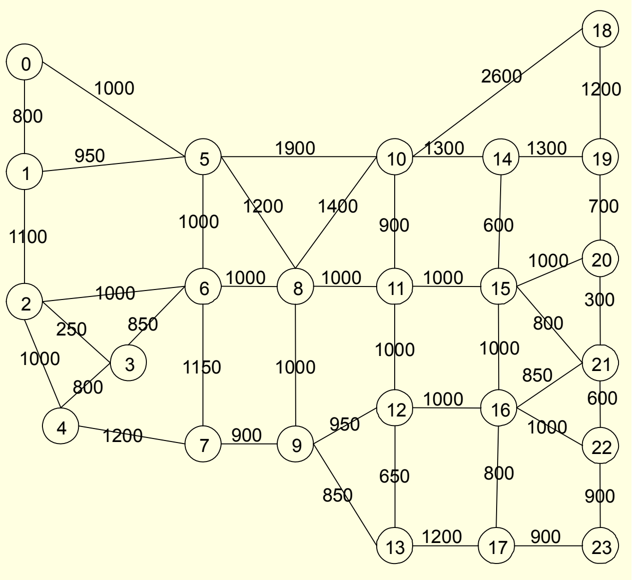

Fig. 8. USNET network topology.

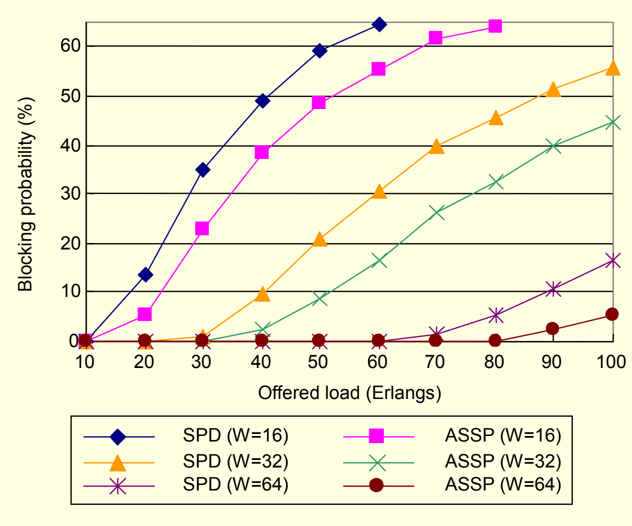

Fig. 9. Comparison of an efficient scheme for the dynamic provisioning of a multicast session on WDM mesh networks.

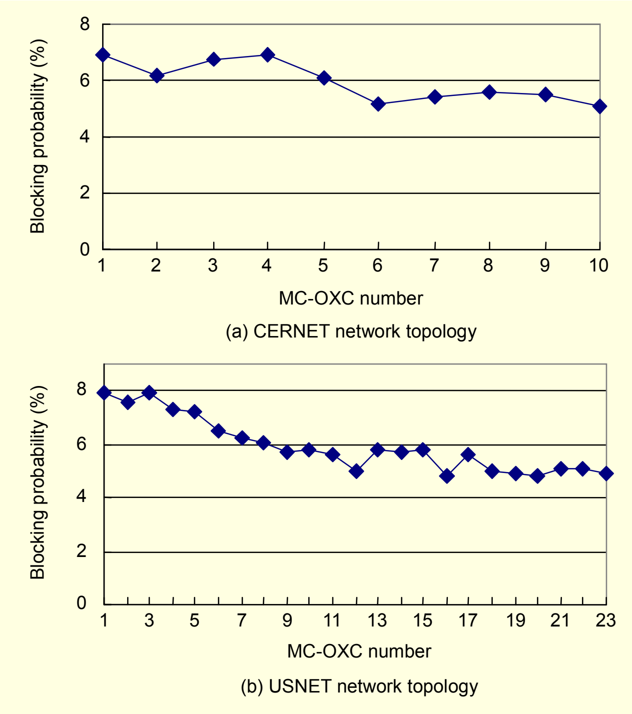

Fig. 10. Blocking probability with different number of MC-OXCs.

4. Analysis of Simulation Results

Figure 7 shows that the LDT scheme has very high blocking probabilities and an excessive use of resources, though it is simple and intuitionistic. Figure 8 shows the average cost of setting up a multicast session exclusive of the blocked sessions for LDT, SDP, and SPPMT. We can find that given a network, the ASSP scheme can find the cheapest survival routing for a multicast session. Figure 9 shows the blocking probabilities with different configuration and network load. From the results, we can conclude that the ASSP scheme has the lowest blocking probability. Figure 10 shows the blocking probabilities with different number of MC-OXCs. We can find that the blocking probability decrease with more MC-OXCs. Of course the placement policy of MC-OXC impacts the blocking probability severely. Ali, M [14] discusses the problem of how to place the splitting node. In our simulation, the MC-OXC is distributed uniformly. This is the reason that the blocking rate does not decrease monotonically.

VI. Conclusions

In this paper, we investigated the problem of setting up a multicast session in a mesh network against any single link failures. We formulated the problem mathematically as ILP to obtain the optimal solution. According to the two characteristics of a multicast tree—one, that the novel multicast tree has some circles with sparse MC-OXC configuration; and the other, that a multicast tree has some branches, (and if we build a light path between two leaf nodes on different branches, we can protect the segment of these two branches)—we give the algorithm to establish a multicast tree that may contain some circles. Then, we design an adaptive shared segment protecting multicast tree (ASSP) algorithm to construct survival multicast routing. Through the simulations, we can conclude that the ASSP algorithm has better performance than other existing multicast survival routing schemes.

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