Provisioning of Survivable Multicast Sessions in Wavelength-Routed Optical Networks With Scheduled Traffic

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***Abstract*—Provisioning survivable multicast sessions in wavelength-routed optical networks has already been studied under static or dynamic traffic. However, in many practical cases, customers tend to require a large bandwidth at a specified time interval. Scheduled traffic model, in which the setup and teardown times are known in advance or vary in a specified larger time window, is more appropriate to characterize this kind of traffic. In this paper, two scheduled traffic models are formulated and investigated for multicast protection in wavelength-routed optical networks, namely, Fixed Scheduled Traffic Model (FSTM) and Sliding Scheduled Traffic Model (SSTM). With the guaranteed 100% restorability against any single link failure, the FSTM formulation can achieve a global minimum cost for establishing all multicast sessions. A two-step optimization approach is further proposed to deal with the survivable multicast provisioning problem under SSTM. By optimizing the network resources jointly in space and time, survivable multicast sessions can be provisioned at much lower costs.**

***Index Terms*—Multicast, protection, scheduled traffic model, WDM optical networks.**

I. Introduction

NOWADAYS, provisioning of multicast sessions over a wavelength-routed (WDM) optical network is an efficient means to deliver many popular applications, such as video-on-demand, interactive distance learning, etc., which require point-to-multipoint connections. The concept of light-path has been extended to light-tree in [1]. To support multicasting, the branching nodes must be multicast-capable and have the ability to duplicate an input signal to several output signals. This capability of duplication can be realized in either optical domain or electronic domain, where optical power splitters or electronic replicators are needed, respectively. To assure the service availability, it is imperative to protect the optical multicast sessions, since a single failure may disrupt several downstream destinations and lead to huge data loss. Singhal [2] studied protecting a single link failure using directed-link-disjoint backup trees. Unlike link-disjoint backup tree protection, the idea of directed-link-disjoint allowed the primary and the backup trees to share links but only in opposite directions. It has been shown in [2] that a directed-link-disjoint backup tree could be successfully utilized to protect the multicast sessions against a single link failure and was more bandwidth-efficient than a link-disjoint backup tree. In [3], link, segment and path protection were proposed to provide survivability to multicast sessions. Extensions of link, segment or path protection were further derived in [4]–[6]. P-cycle based link protection of multicast sessions was proposed in [7]. Generally speaking, segment and path protection can be more resource efficient than tree protection because path and segment protection can share bandwidth among primary tree and backup resources. However, dedicated tree protection can provide 100% guaranteed restoration and shorter restoration time, as it uses $1+1$ dedicated protection which needs no reconfiguration at intermediate nodes once a link failure happens.

Most of the previous studies on multicast protection considered either a static or dynamic traffic model, which might not well-characterize the applications that require bandwidths at specified time intervals. Network resources may be reserved by users in advance. For instance, a soccer game is usually broadcasted to audiences according to a predetermined timetable. Therefore, scheduled traffic model [8], in which the setup and tear-down times of the traffic demands are known in advance or vary in a specified larger time window, is a more proper traffic model for these kinds of applications. With the scheduled time information, network resources can be further optimized both in space and time. The routing and wavelength assignment problem (RWA) for survivable unicast scheduled traffic demands have been studied in [9], [10]. In [11], multicast tree protection under fixed scheduled traffic was studied and the results have shown that the cost for provisioning the survivable multicast sessions could be much lowered. Further investigations are discussed in this paper.

In this work, we consider a set of multicast sessions with scheduled traffic. Single link failure is assumed because of its predominance in optical networks. Two kinds of scheduled traffic model are considered, namely, Fixed Scheduled Traffic Model (FSTM) and Sliding Scheduled Traffic Model (SSTM). Under FSTM, a multicast session $\boldsymbol{S_i}$ is represented by $\{s_i, (d_{i1}, d_{i2}, \ldots, d_{ij}, \ldots), (t_{is}, t_{ie})\}$, where s_i is the source node and d_{ij} is the jth destination of the session $\boldsymbol{S_i}$. t_{is} and t_{ie} are the exact setup and teardown times of $\boldsymbol{S_i}$, respectively. On the other hand, under SSTM, a multicast session $\boldsymbol{S_i}$ is represented by $\{s_i, (d_{i1}, d_{i2}, \ldots, d_{ij}, \ldots), (t_{is}, t_{ie}), \tau_i\}$, where $t_{is} - t_{ie} \geq \tau_i \geq 0$. s_i and d_{ij} have the same definitions as in

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FSTM. (t_{is}, t_{ie}) is a larger time window during which $\boldsymbol{S_i}$ must be provisioned and τ_i is the holding time of $\boldsymbol{S_i}$. The multicast demand can slide within the larger time window (t_{is}, t_{ie}), which gives the service providers more flexibility to allocate the limited network resources to multiple traffic demands.

Based on the FSTM traffic model, an integer linear programming (ILP) formulation, namely *Multicast Tree Protection with Scheduled Traffic* (MTP-ST), is performed to solve the routing and wavelength assignment (RWA) of survivable multicast sessions in a WDM optical network. Both wavelength-convertible and wavelength- continuity constrained cases are investigated. With the guaranteed 100% restorability against any single link failure, the formulation can achieve a global minimum cost for establishing all multicast sessions. Numerical experiments have indicated that the proposed MTP-ST formulation can achieve significant reduction in the cost for establishing all multicast sessions, compared to the previously proposed schemes which were unaware of the traffic time information. Hence, better network resource optimization is realized. In addition, in order to tackle the survivable multicast provisioning problem under SSTM traffic model, a two-step optimization approach similar to that in [10] is further adopted. First, each multicast request is optimally scheduled within its specified time window, such that the problem is reduced to FSTM, which is then solved using our proposed MTP-ST formulation, in the second step. In general our proposed approach can increase the resource efficiency of directed-link-disjoint backup tree protection by optimizing the network resources jointly in space and time, while keeping the advantage of short restoration time.

This paper is organized as follows. In Section II, the ILP formulation for MTP-ST under Fixed Scheduled Traffic Model (FSTM) is presented. In Section III, two numerical examples are studied and the results are discussed. In Section IV, a two-step optimization approach is proposed for MTP-ST under Sliding Scheduled Traffic Model (SSTM). Section V summarizes the paper.

II. MTP-ST Problem Formulation Under FSTM

The inputs of the problem are listed as follows:

- The network topology $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$ is given as a weighted undirected graph. $\boldsymbol{V}$ is the set of N multicast-capable network nodes. $\boldsymbol{E}$ is the set of weighted links.
- $\omega_{m,n} = \omega_{n,m}$ is the cost of using one wavelength on the link between nodes m and n. The costs can be considered as the costs of the transceivers and amplifiers and the costs of reconfiguration of each wavelength link.
- $\boldsymbol{D}_p(m)$ is the degree of node m and equals the number of fiber links connecting to node m.
- $\boldsymbol{W}$ is the maximum number of wavelengths in each direction of a fiber link.
- A set of k primary multicast sessions (trees). $\boldsymbol{P_i} = 1$ or 0 indicating whether session $\boldsymbol{S_i}$ requires protection against single link failure or not, respectively. If the primary tree $\boldsymbol{S_i}$ requires protection, the backup tree for $\boldsymbol{S_i}$ is denoted as $\boldsymbol{S_{i+k}}$. Thus, there are totally $2k$ trees at most. $\boldsymbol{L_i}$ is the number of destinations in the tree $\boldsymbol{S_i}$. $\boldsymbol{T_{i,j}} = \boldsymbol{T_{j,i}}$ is a Boolean, indicating whether tree $\boldsymbol{S_i}$ and tree $\boldsymbol{S_j}$ overlap in time (=1) or not (=0). For example, if the two time intervals (t_{is}, t_{ie}) and (t_{js}, t_{je}) overlap, $\boldsymbol{T_{i,j}} = 1$. We also assume that each multicast session requires a full wavelength bandwidth.

The variables for the ILP are defined as follows:

- Boolean variable $X^c_{m,n}$ indicates whether one or more multicast trees traverse the link from node m to n using wavelength $c(=1)$ or not (=0).
- Boolean variable $M^{i,c}_{m,n}$ indicates whether wavelength c on the link from node m to n is occupied by tree $i(=1)$ or not $(=0)$.
- Boolean variable V^i_p indicates whether node p belongs to tree $i(=1)$ or not $(=0)$.
- Integer commodity-flow variable $F^i_{m,n}$ is the number of commodity flow units of tree i going through the link from node m to n. Each destination requires 1 unit of commodity.
- If there is no wavelength converter, Boolean variable C^i_c is needed which indicates whether tree i uses wavelength $c(=1)$ or not $(=0)$.

The objective of the ILP is:

$$\text{Minimize} \sum_{c=1}^{c=W} \sum_{m,n} \omega_{m,n} \cdot X^c_{m,n} \tag{1}$$

Subject to:

Tree creation constraints:

$$\forall i, \forall n \neq s_i : \sum_{m,c} M^{i,c}_{m,n} = V^i_n \tag{2}$$

$$\forall i : \sum_{m,c} M^{i,c}_{m,s_i} = 0 \tag{3}$$

$$\forall i, \forall j \in S_i : V^i_j = 1 \tag{4}$$

$$\forall i, \forall m \neq d_{ij}, j \geq 1 : \sum_{n,c} M^{i,c}_{m,n} \geq V^i_m \tag{5}$$

$$\forall i, m : \sum_{n,c} M^{i,c}_{m,n} \leq D_p(m) \cdot V^i_m \tag{6}$$

Commodity flow constraints:

$$\forall i, \forall m \notin S_i : \sum_n F^i_{m,n} = \sum_n F^i_{n,m} \tag{7}$$

$$\forall i, \forall m = s_i : \sum_n F^i_{s_i,n} = L_i \tag{8}$$

$$\forall i, \forall m = s_i : \sum_n F^i_{n,s_i} = 0 \tag{9}$$

$$\forall i, \forall m = d_{ij}, j \geq 1 : \sum_n F^i_{n,m} = \sum_n F^i_{m,n} + 1 \tag{10}$$

$$\forall i, m, n : \sum_c M^{i,c}_{m,n} \leq F^i_{m,n} \tag{11}$$

$$\forall i, m, n : F^i_{m,n} \leq N \cdot \sum_c M^{i,c}_{m,n} \tag{12}$$

Directed link disjointness constraint:

$$\forall i = 1 \cdots k, \forall m, n : \sum_c M^{i,c}_{m,n} + \sum_c M^{i+k,c}_{m,n} \leq 1 \tag{13}$$

Wavelength usage constraints:

$$\forall m,n,c : X^c_{m,n} \le \sum_i M^{i,c}_{m,n} \tag{14}$$

$$\forall m,n,c : k \cdot X^c_{m,n} \ge \sum_i M^{i,c}_{m,n} \tag{15}$$

Time joint constraint:

$$\forall m,n,p,q(T_{p,q}=1) : M^{p,c}_{m,n} + M^{q,c}_{m,n} \le 1 \tag{16}$$

Wavelength-continuity constraints
(when there is no wavelength converter)

$$\forall i : \sum_c C^i_c = 1 \tag{17}$$

$$\forall i,c,m,n(n>m) : M^{i,c}_{m,n} + M^{i,c}_{n,m} \le C^i_c \tag{18}$$

Our formulation allows wavelength sharing by different trees which do not overlap in time, which is a special feature of the scheduled traffic model. The objective function (1) minimizes the total costs of establishing all multicast trees. Equation (2) ensures that every node which belongs to a multicast session (except the source node) has one and only one incoming wavelength. Equation (3) ensures that the source node of each tree has no incoming wavelength. Equation (4) ensures that every source node and destination node of each multicast tree belong to the tree. Equation (5) ensures that every node (except the destination nodes) has at least one outgoing wavelength. Equation (6) ensures that the number of outgoing wavelengths of a node is limited by the degree of the node and every node with at least one outgoing wavelength belongs to the tree.

Equations (7)–(12) are flow-conservation equations. Equation (7) ensures that the incoming flow is the same as the outgoing flow for every node which is neither a source nor a destination. Equations (8) and (9) ensure that the outgoing flow and incoming flow of the source node are the number of the destinations in the tree and zero, respectively. Equation (10) ensures that the outgoing flow is just one unit less than the incoming flow for destination nodes. Equation (11) ensures that the flow on each direction of a link is positive if one of the wavelengths on that direction of the link is occupied by the tree. Equation (12) ensures that there is no flow on each direction of a link if it is not occupied by the tree. Equation (13) ensures that a primary tree and its protection tree cannot share a link in the same direction. Equation (14) ensures that a wavelength on each direction of a link is occupied if one or more trees choose to use it. Equation (15) ensures that a wavelength on each direction of a link can be shared by k trees at most. This is because a primary tree and its backup cannot share a wavelength in the same direction of each link. Equation (16) ensures that two trees cannot share a wavelength in the same direction of a link if they overlap in time. Equations (17) and (18) are active only when wavelength-continuity constraints are applied. Equation (17) ensures that only one wavelength is chosen for a multicast tree. Equation (18) ensures that all links occupied by a tree are on the same wavelength and one tree can not occupy both directions of a link (avoiding the loop).

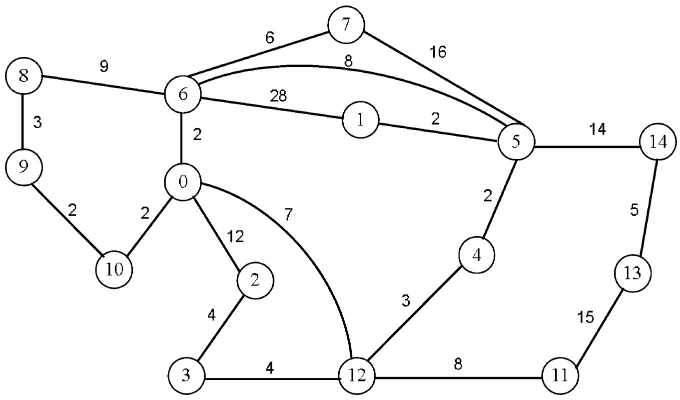

Fig. 1. 15-node Pacific Bell network with bidirectional links, for Example 1.

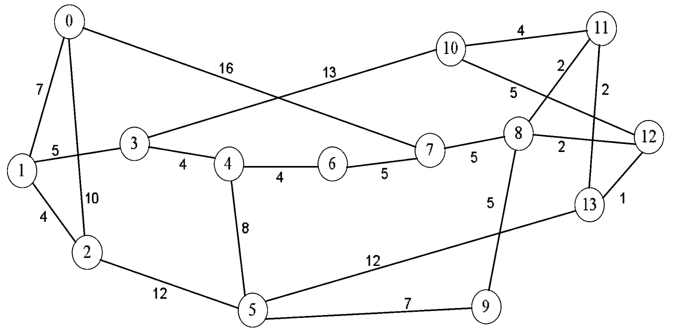

Fig. 2. 14-node NSFNET with bidirectional links for Example 2.

III. Illustrative Examples of MTP-ST Under FSTM

We have studied our proposed MTP-ST under FSTM on two network topologies, namely 15-node Pacific Bell network (shown in Fig. 1) and 14-node NSFNET (shown in Fig. 2). Each link carries four wavelengths in both directions.

For the case of 15-node Pacific Bell network, denoted as Example 1, there are five primary multicast sessions ($k=5$). $\boldsymbol{S_1} = \{0,(1,2,4,5,10,11,12,13,14),(t_{1s},t_{1e})\}$, $\boldsymbol{S_2} = \{9,(1,2,3,4,5,6,10,11),(t_{2s},t_{2e})\}$, $\boldsymbol{S_3} = \{12,(0,5,8,9,10,14),(t_{3s},t_{3e})\}$, $\boldsymbol{S_4} = \{14,(1,2,3,4),(t_{4s},t_{4e})\}$, $\boldsymbol{S_5} = \{7,(0,6),(t_{5s},t_{5e})\}$. t_{is} and t_{ie} are used as parameters to control the time overlap in our formulation. Only sessions $\boldsymbol{S_1}, \boldsymbol{S_4}$ and $\boldsymbol{S_5}$ require single-link protection ($\boldsymbol{P_1} = \boldsymbol{P_4} = \boldsymbol{P_5} = 1$). Each of them requires a backup tree $\boldsymbol{S_6}, \boldsymbol{S_9}$ and $\boldsymbol{S_{10}}$, respectively. These backup trees have the same setup and tear-down time as their corresponding primary trees. Time correlation parameter refers to the relative degree of time-overlap among the trees. In Example 1, time correlation parameter "High" means $\boldsymbol{T_{1(6),2}} = \boldsymbol{T_{1(6),3}} = \boldsymbol{T_{2,3}} = \boldsymbol{T_{3,4(9)}} = \boldsymbol{T_{3,5(10)}} = \boldsymbol{T_{4(9),5(10)}} = 1$; "Medium" means $\boldsymbol{T_{2,3}} = \boldsymbol{T_{3,4(9)}} = \boldsymbol{T_{3,5(10)}} = \boldsymbol{T_{4(9),5(10)}} = 1$; and "Low" means $\boldsymbol{T_{3,4(9)}} = \boldsymbol{T_{3,5(10)}} = 1$. The indexes in the subscript brackets refer to the respective backup trees.

For the case of 14-node NSFNET, denoted as Example 2, we also adopt five primary sessions ($k=5$). $\boldsymbol{S_1} = \{0,(2,3,4,6,10,11,12,13),(t_{1s},t_{1e})\}$, $\boldsymbol{S_2} = \{5,(0,1,2,7,8),(t_{2s},t_{2e})\}$, $\boldsymbol{S_3} = \{7,(3,4,5,6),(t_{3s},t_{3e})\}$, $\boldsymbol{S_4} = \{11,(1,2,10,13),(t_{4s},t_{4e})\}$, $\boldsymbol{S_5} = \{12,(8,9,10),(t_{5s},t_{5e})\}$. We assume that all of the five primary sessions require single-link protection

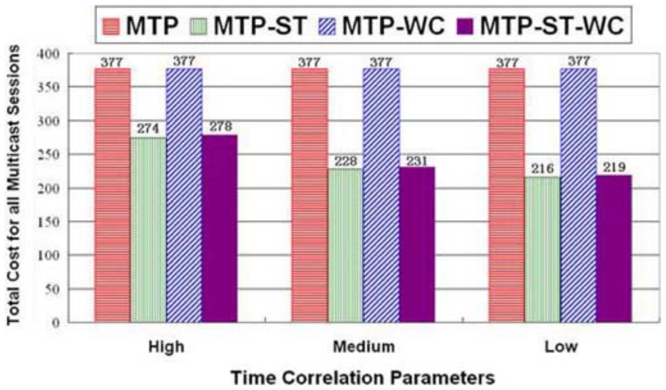

Fig. 3. Costs of establishing all multicast trees under different schemes and different time correlation parameters, in Example 1.

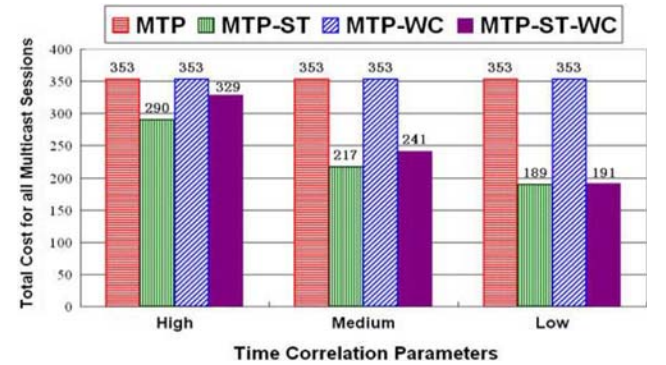

Fig. 4. Costs of establishing all multicast trees under different schemes and different time correlation parameters, in Example 2.

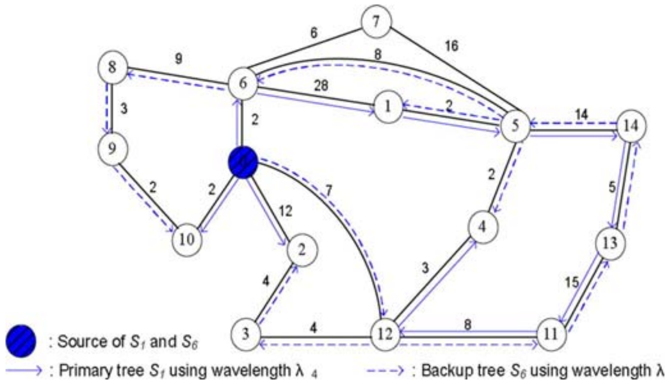

Fig. 5. Example 1: the established multicast primary tree S_1 (blue (online version) solid arrowed lines) and its respective backup tree S_6 (blue (online version) dashed arrowed lines).

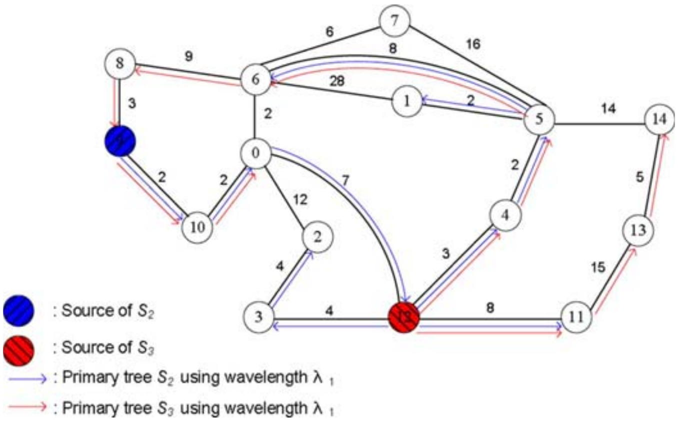

Fig. 6. Example 1: the established multicast primary tree S_2 (blue (online version) solid arrowed lines) and primary tree S_3 (red (online version) solid arrowed lines).

$(P_1 = P_2 = P_3$ and $P_4 = P_5 = 1)$. So the corresponding backup tree for them are S_6, S_7, S_8, S_9 and S_{10}, respectively. These backup trees have the same setup and tear-down time as their corresponding primary trees. In Example 2, time correlation parameter "High" means $T_{1(6),2(7)} = T_{1(6),3(8)} = T_{2(7),3(8)} = T_{3(8),4(9)} = T_{3(8),5(10)} = T_{4(9),5(10)} = 1$; "Medium" means $T_{2(7),3(8)} = T_{3(8),4(9)} = T_{3(8),5(10)} = T_{4(9),5(10)} = 1$; and "Low" means $T_{3(8),4(9)} = T_{3(8),5(10)} = 1$.

The traffic patterns (number of requests, source and destinations of each request, time correlations) in the above examples are chosen randomly for illustration purpose. Similar results can be derived if other traffic patterns are adopted. The ILPs are solved by CPLEX.

Figs. 3 and 4 show the costs of establishing all trees by different schemes for Example 1 and Example 2, respectively. MTP and MTP-WC refer to the previously proposed Multicast Tree Protection [2] considering no time information without and with wavelength continuity constraints, respectively. MTP-ST and MTP-ST-WC refer to our proposed Multicast Tree Protection with Scheduled Traffic formulations without and with wavelength continuity constraints, respectively. From both Figs. 3 and 4, it is observed that the lower the time correlation, the more improvement in our proposed MTP-ST and MTP-ST-WC formulations. In Example 1, both the performance improvements of MTP-ST and MTP-ST-WC over their respective counterparts (MTP and MTP-WC) are about 27%, 39% and 42% under "High", "Medium" and "Low" time correlations, respectively. In Example 2, the performance improvements of MTP-ST over STP are about 18%, 39% and 46% under "High", "Medium" and "Low" time correlations, respectively; the performance improvements of MTP-ST-WC over MTP-WC are about 7%, 32% and 46% under "High", "Medium" and "Low" time correlations, respectively. In both examples, the costs of MTP and MTP-WC are independent of the time correlation parameters, since no time information is considered by MTP and MTP-WC. With the additional wavelength continuity constraints, the costs of MTP-WC and MTP-ST-WC are not smaller than the costs of MTP and MTP-ST, respectively, if the same time correlation is applied. It is worthy to note that, in Example 2, some suboptimal solutions are recorded if the optimal solution cannot be obtained within certain time limits.

In Example 1, Figs. 5–7 show the optimal RWA for all eight trees (one or two primary multicast sessions in each figure) by MTP-ST-WC under "Low" time correlation. We observe that only two wavelengths (λ_1 and λ_4) are needed to establish all the multicast trees. From Fig. 5, we can see that the primary tree S_1 and its backup tree S_6 can share a link only in opposite directions (for example, the link between node 1 and node 5). This is because we adopt directed-link-disjoint backup tree protection in this work. In addition, we can see that different trees which do not overlap in time can share a wavelength in the same direction of a link. The cost for that wavelength is only counted once. To illustrate, in Fig. 6, both trees S_2 and S_3 use the same

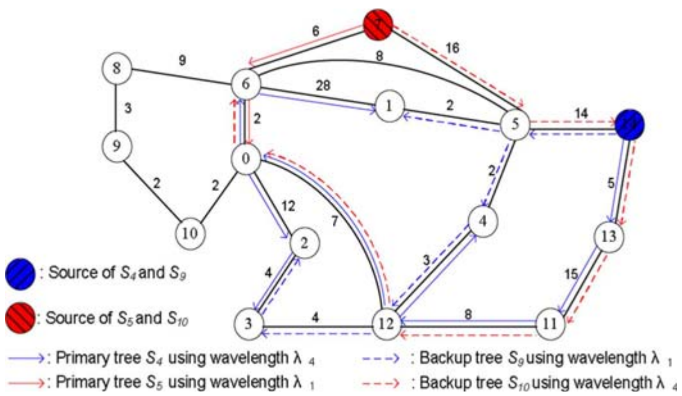

Fig. 7. Example 1: the established multicast primary tree S_4 (blue (online version) solid arrowed lines) and its respective backup tree S_9 (blue (online version) dashed arrowed lines), primary tree S_5 (red (online version) solid arrowed lines) and its respective backup tree S_{10} (red (online version) dashed arrowed lines).

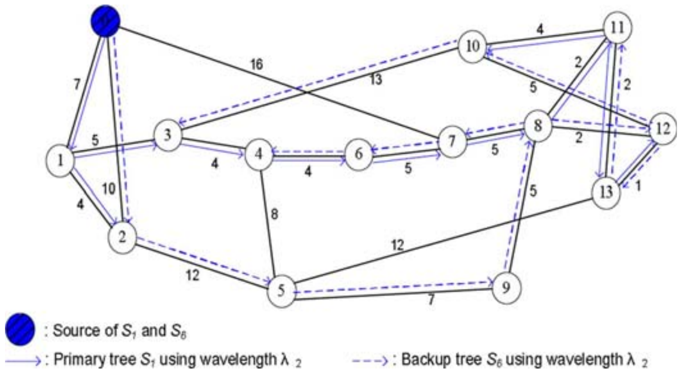

Fig. 8. Example 2: the established multicast primary tree S_1 (blue (online version) solid arrowed lines) and its respective backup tree S_6 (blue (online version) dashed arrowed lines).

wavelength λ_1 on the link from node 5 to node 6, link from node 9 to node 10, etc., because the two trees do not overlap in time ($T_{2,3} = 0$ under "low" time correlation). On the contrary, if two trees overlap in time, they can not share a wavelength in the same direction of a link. For example, by jointly observing Figs. 6 and 7, even if trees S_3 and S_5 use the same wavelength λ_1, they do not share the wavelength in the same direction of a link. This is because S_3 and S_5 overlap in time ($T_{3,5} = 1$ under "low" time correlation).

In Example 2, similar results as Example 1 can be obtained. Figs. 8–10 show the suboptimal RWA for all ten trees (one or two primary multicast sessions in each figure) by MTP-ST-WC under "Low" time correlation. We can observe that all ten multicast trees (including the backup trees) use the same wavelength λ_2 (any other wavelength can also be chosen without changing the total costs). In Fig. 8, we can see that the primary tree S_1 and its backup tree S_6 can share a link only in opposite directions (for example, the link between node 6 and node 7). This is because directed-link-disjoint backup tree protection is adopted in this work. In Fig. 9, both trees S_2 and S_3 use the same wavelength λ_2 on the link from node 3 to node 4, and the link from node 4 to node 6, etc., because the two trees do not overlap in time ($T_{2,3} = 0$ under "low" time correlation). By jointly observing Figs. 9 and 10, tree S_3 (or S_8) do not share any wavelength in the same direction of a link with tree S_4 (or S_9) and tree S_5 (or S_{10}). This is because "low" time correlation is applied where $T_{3(8),4(9)} = T_{3(8),5(10)} = 1$.

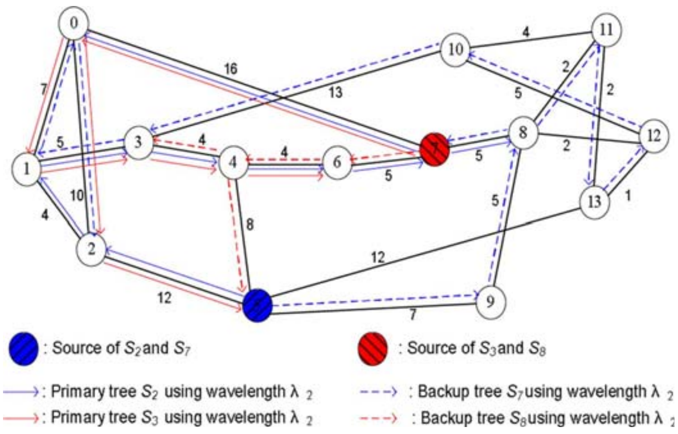

Fig. 9. Example 2: the established multicast primary tree S_2 (blue (online version) solid arrowed lines) and its respective backup tree S_7 (blue (online version) dashed arrowed lines), primary tree S_3 (red (online version) solid red arrowed lines) and its respective backup tree S_8 (red (online version) dashed arrowed lines).

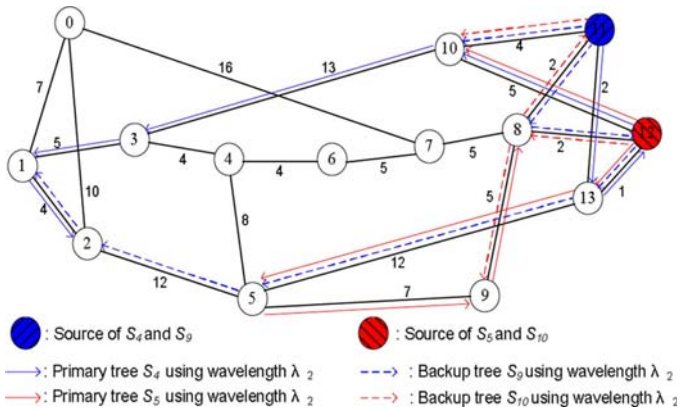

Fig. 10. Example 2: the established multicast primary tree S_4 (blue (online version) solid arrowed lines) and its respective backup tree S_9 (dashed arrowed lines), primary tree S_5 (red (online version) solid red arrowed lines) and its respective backup tree S_{10} (red (online version) dashed arrowed lines).

IV. Two-Step Optimization for MTP-ST Under SSTM

To deal with the RWA of multicast sessions under SSTM, a two-step optimization approach similar to that in [10] is adopted. In the first step, each multicast session is optimally scheduled within its specified larger time window in order to minimize the time-overlap degree. In the second step, the problem is reduced to the FSTM problem and can be solved by our proposed ILPs in Section II.

In the following, a Mixed Integer Linear Programming (MILP) is formulated to optimally slide each multicast session within is specified larger time window in the first step.

The inputs of the MILP formulation are listed as follows:

- A set of k primary multicast sessions (trees). L_i and P_i have the same meanings as in Sections II and III.
- (t_{is}, t_{ie}) is a larger time window during which S_i must be provisioned and τ_i is the holding time of S_i.

- $\boldsymbol{M}$ is the time duration from earliest window start time and the latest window end time of the k windows.

The variables for the MILP are defined as follows:

- Boolean variable $\boldsymbol{T_{i,j}}$ indicates whether tree $\boldsymbol{S_i}$ and tree $\boldsymbol{S_j}$ overlap in time $(=1)$ or not $(=0)$. In MILP formulation, $\boldsymbol{T_{i,j}}$ is variable. After being solved in MILP, it is used as inputs to the ILP in the second step.
- $\boldsymbol{ST_i}$ is the actual start time of multicast session $\boldsymbol{S_i}$.
- Boolean variable $\boldsymbol{Y_{i,j}}$ indicates that whether $\boldsymbol{S_i}$ ends after $\boldsymbol{S_j}$ starts, i.e., $\boldsymbol{ST_i}+\tau_i-\boldsymbol{ST_j}>0$. Note that $\boldsymbol{Y_{i,j}}$ and $\boldsymbol{Y_{j,i}}$ are *not* symmetrical.

The objective of the MILP is:

$$\text{Minimize} \sum_{1\le i<j\le k} [L_i(P_i+1)L_j(P_j+1)]T_{i,j} \tag{19}$$

Subject to:

$$\forall 1 \le i \le k, ST_i \ge t_{is} \tag{20}$$

$$\forall 1 \le i \le k, ST_i + \tau_i \le t_{ie} \tag{21}$$

$$\forall 1 \le i \le k, 1 \le j \le k, i \ne j, ST_i + \tau_i - ST_j \le MY_{i,j} \tag{22}$$

$$\forall 1 \le i < j \le k, Y_{i,j} + Y_{j,i} - T_{i,j} \le 1 \tag{23}$$

$$\forall 1 \le i < j \le k, Y_{i,j} - T_{i,j} \ge 0 \tag{24}$$

$$\forall 1 \le i < j \le k, Y_{j,i} - T_{i,j} \ge 0 \tag{25}$$

Explanation of MILP: The objective (19) is to minimize the total time-overlap degree of multicast sessions. The weight of each pair of time overlap is proportional to the product of the expected bandwidth consumption. Equation (20) and (21) ensures that each multicast session is scheduled within its specified larger time window. Equation (22) defines the meaning of $\boldsymbol{Y_{i,j}}$. Equation (23) ensures that if both $\boldsymbol{Y_{i,j}}$ and $\boldsymbol{Y_{j,i}}$ are equal to 1, session $\boldsymbol{S_i}$ and $\boldsymbol{S_j}$ must overlap with each other in time. Equation (24) and (25) ensure that if session $\boldsymbol{S_i}$ and $\boldsymbol{S_j}$ overlap in time, each of them ends after the other starts.

For example, we assume there are five primary multicast sessions which are the same as those in Example 1 in the previous section. The larger time windows for the five multicast sessions are (00:00, 03:00), (02:00, 04:30), (05:00, 06:00), (08:00, 10:00), (08:00, 10:00), respectively. The holding time for the five multicast sessions are $\tau_1=2.5$ (h), $\tau_2=1.2$ (h), $\tau_3=1$ (h), $\tau_4=1$ (h), $\tau_5=1$ (h), respectively. We use CPLEX to solve the formulated MILP. The solutions of this example are $\boldsymbol{T_{i,j}}=0(1\le i<j\le 5)$. And the actual start times of the five multicast sessions are $\boldsymbol{ST_1}=00:00, \boldsymbol{ST_2}=03:00, \boldsymbol{ST_3}=05:00, \boldsymbol{ST_4}=08:00, \boldsymbol{ST_5}=09:00$, respectively. After the MILP has been solved in the first step, the solutions $(\boldsymbol{T_{i,j}})$ can be inputted into the ILP formulated in Section II, as the second step. So after the two-step optimization, the RWA problem of survivable multicast sessions under SSTM has been solved.

V. Summary

Multicast tree protection with scheduled traffic has been formulated and numerically investigated under different traffic models. First, an ILP formulation has been presented to minimize the total costs of establishing all multicast sessions under FSTM. The results have shown that the network resources can be jointly optimized both in space and time to provision survivable multicast sessions at much lower costs, compared to the previous schemes which are unaware of the traffic time information. Second, a two-step optimization approach has been adopted to deal with the survivable multicast provisioning problem under SSTM. Thus, the survivable multicast sessions can be provisioned at much lower costs.

References

[1] L. H. Sahasrabuddhe and B. Mukherjee, “Light-trees: Optical multicasting for improved performance in wavelength-routed networks,” *IEEE Commun. Mag.*, vol. 37, pp. 67–73, 1999.

[2] N. Singhal and B. Mukherjee, “Protecting multicast sessions in WDM optical mesh networks,” *J. Lightw. Technol.*, vol. 21, no. 4, pp. 884–892, Apr. 2003.

[3] N. K. Singhal, L. H. Sahasrabuddhe, and B. Mukherjee, “Provisioning of survivable multicast sessions against single link failures in optical WDM mesh networks,” *J. Lightw. Technol.*, vol. 21, no. 11, pp. 2587–2594, Nov. 2003.

[4] A. Khalil, A. Hadjiantonis, G. Ellinas, and M. Ali, “Dynamic provisioning of survivable heterogeneous multicast and unicast traffic in WDM networks,” in *Proc. IEEE ICC*, Jun. 2006, vol. 6, pp. 2465–2470.

[5] H. Luo, L. Li, and H. Yu, “Algorithm for protecting light-trees in survivable mesh wavelength-division-multiplexing networks,” *J. Opt. Networking*, vol. 5, no. 10, pp. 1084–1092, Oct. 2006.

[6] H. Luo, L. Li, H. Yu, and S. Wang, “Achieving shared protection for dynamic multicast sessions in survivable mesh WDM networks,” *IEEE J. Sel. Areas Commun.*, vol. 25, no. 9, pp. 83–95, Dec. 2007.

[7] T. Feng, L. Ruan, and W. Zhang, “Intelligent p-cycle protection for multicast sessions in WDM networks,” in *Proc. IEEE ICC*, May 2008, pp. 5165–5169.

[8] J. Kuri, N. Puech, M. Gagnaire, E. Dotaro, and R. Douville, “Routing and wavelength assignment of scheduled lightpath demands,” *IEEE J. Sel. Areas Commun.*, vol. 21, no. 8, pp. 1231–1240, Oct. 2003.

[9] B. Wang, T. Li, C. Xin, and X. Zhang, “On survivable service provisioning in WDM networks under a scheduled traffic model,” in *Proc. GLOBECOM*, Nov.–Dec. 2005, pp. 1900–1904.

[10] A. Jackel, “Lightpath scheduling and allocation under a flexible scheduled traffic model,” in *Proc. IEEE Globecom*, Nov. 2006, paper OPN09–02.

[11] S. Q. Zhang and C. K. Chan, “Multicast protection in WDM optical networks with scheduled traffic,” in *Proc. ECOC*, Sep. 2009, paper P5.06.

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