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Optimal and Reliable Routing for Multicast Sessions in WDM Networks

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***Abstract*—This paper studies the problem of optimal and reliable routing for multicast sessions in wavelength-division-multiplexing (WDM) networks. The objective is to minimize the cost and the blocking probability when establishing several multicast sessions while guaranteeing protection against any single link failure. In the presence of static traffic, two different Integer Linear Programming (ILP) formulations, Joint ILP 1 and Joint ILP 2, find the working trees and the link-disjoint backup paths for the sessions simultaneously, with Joint ILP 2 choosing a specific number of links to route the working trees. The proposed ILPs reduce the cost by 25 - 30 % while coping with a larger number of demands per session compared to state-of-the-art solutions. This work also addresses the problem in a dynamic environment, with sequential multicast sessions of random demands, by proposing an ILP for the optimal solution and a heuristic called Demand-Aware Tree-Forming Optimal Path Pairs (DA-TF-OPP). Dealing with one multicast session at a time, DA-TF-OPP takes into account the sequence in which the demands should be routed and provides a working tree to prevent traffic loops, along with the backup paths. Compared to the state-of-the-art, DA-TF-OPP provides up to 5 % lower average cost and up to 3 % lower average blocking probability.**

***Index Terms*—multicast sessions, WDM networks, survivability, reliability**

I. Introduction

Wavelength Division Multiplexing (WDM) networks have transformed data transmission by utilizing optical signals at different wavelengths to concurrently carry multiple data streams across optical fibers. Multicasting is a data transmission method where information is sent from one source to multiple destinations simultaneously. In order to facilitate multicasting within optical WDM networks, network nodes need to be equipped with either multicast-capable wavelength-routing switches (MWRSs) or optical cross-connects (MC-OXC). The former ones duplicate a bit stream originating from the source node to multiple destination nodes and employ opaque cross-connects to execute optical–electronic–optical (O/E/O) conversion, eliminating the need for converters and regenerators. Network operators aim to establish multicast sessions by optimizing the spectrum utilization and, hence, reduce the required wavelengths, achieve minimum routing costs, and provide the best quality of service [1], [2].

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A multicast session is defined by the source src and several destination nodes $d_1, d_2, .., d_M$. Each pair $(src,\, d_i)$ is referred to as a demand of that multicast session. In the world of data transmission, multicast sessions play a vital role since they are used in many contemporary applications such as optical IPTV and video distribution, multicasting in data centers [3], broadcast services (e.g., live events, such as concerts or sports), optical content delivery networks for delivery of large files, software updates, or streaming media to geographically dispersed users. However, beyond merely transmitting data efficiently, providing reliability and survivability for multicast sessions is crucial [4], [5], [6]. Reliability ensures that data reaches its destinations consistently, without disruption or loss, which is especially critical for real-time applications. Survivability mechanisms are essential to maintain communication even in the face of network failures, ensuring uninterrupted multicast sessions in scenarios of link or node failures, natural disasters, or deliberate attacks [7], [8], [9].

Multicast sessions face challenges in routing and protecting both static [10], [11] and dynamic traffic [3], [4], [12] patterns within WDM networks. Static traffic, characterized by predefined, constant multicast sessions, poses challenges in efficiently allocating wavelengths and optimizing the cost of resources. In contrast, dynamic traffic - where the sources and the destinations of the multicast sessions are not fixed and may vary frequently - exhibits varying bandwidth demands, unpredictable fluctuations, and/or sudden bursts of data. This unpredictability introduces wavelength contention, leading to potential congestion and degraded performance. Satisfying the demands in both scenarios while optimizing the cost and utilization of network resources is a critical challenge.

This work proposes routing strategies that aim to establish multicast sessions optimally with the need for protection against single-link failures while minimizing costs and blocking probability. Firstly, the problem is addressed in the static traffic scenario; two Integer Linear Programming (ILP) formulations are proposed, which minimize the routing costs and the utilized resources for both working and protection (backup) paths. The first ILP, *Joint ILP 1*, finds a working tree for each multicast session while allocating resources for a link-disjoint backup path for every demand of each session. The second ILP, *Joint ILP 2*, adds to Joint ILP 1 the extra requirement that the working trees of all sessions must also form a single tree structure in the network. Joint ILP 2 aims to maximize the sharing of the backup resources among different sessions and enhance the reliability of the working paths of the demands. Regarding the case of dynamic traffic, this work presents an ILP, referred to as *Tree-Forming Optimal Path Pairs ILP (TF-OPP-ILP)*, to provide the optimal solution for one session at a time. Since the computation time of the ILP may be prohibitive for the dynamicity of the traffic, a respective heuristic is proposed. Namely, the *Demand-Aware Tree-Forming Optimal Path Pairs (DA-TF-OPP)* algorithm finds a pair of link-disjoint paths for every demand of the session, guaranteeing that the working paths will be on a tree and examining the sequence in which the demands should be routed towards the minimum cost and blocking probability.

II. Related work

Routing multicast sessions optimally in WDM networks while providing survivability has been studied extensively in the related literature. This section focuses on an overview of the most related works and a comparison with the presented approaches.

The work in [11] proposed the idea of *arc-disjoint trees* for protecting several multicast sessions in a static environment, considering two kinds of multicast-capable switch architectures: the opaque and the transparent approach. The objective was to optimize the cost of provisioning two arc-disjoint trees for every session, one for the working path (WP) routing and a directed-link-disjoint one for the backup path (BP) routing. This strategy can lead to a high blocking probability of the protected sessions since it is not always possible to find two arc-disjoint trees in the network topology for every set of a source and several destinations.

The same team of authors extended their work with *self-sharing trees* in [4], where the working and the backup tree of a session can share the same directed link. This approach achieves better resource utilization but still presents a high blocking probability. They also propose a *path-protection-based* algorithm, which discovers an optimal path pair for every demand of the session. Namely, *OPP-SDP* is considered to be the state-of-the-art for setting protected multicast sessions in a dynamic environment, as it is the most efficient one in terms of cost and blocking probability.

Towards a higher level of sharing backup resources, in [10], *cross-sharing trees* were proposed to offer protection for several multicast sessions against any single link failure by maximizing sharing among backup edges. This work focuses on the case of static traffic and first finds the minimum-cost working trees of all the sessions. It then proposes an ILP to minimize the cost of protection, allowing the same wavelength of a link to be used among different sessions.

In [13], the idea of *segment-based* protection tree was proposed, where given a multicast session and the primary working tree of the session, each *segment* on the tree is protected by a tree instead of a path, using fewer resources. This approach is evaluated only according to routing cost and the number of reconfigurations for a single session.

The most recent work in [7] developed three heuristics that protect multicast sessions against any single link failure. The authors aimed to reduce the amount of the utilized network resources by reducing the number of branches in the multicast tree. However, their objective is only related to blocking probability in the presence of dynamic traffic and not the total routing costs of the protected sessions.

This paper investigates optimal routing strategies for static and dynamic traffic in the network. Regarding the former, this work proposes two ILPs that minimize the cost of utilized wavelengths for the routing of several protected multicast sessions. In sharp contrast to [10], the routing optimization is performed jointly, both for the WPs and the BPs of all the sessions. For a dynamic environment, this paper formulates an ILP with the same objective as in the static traffic case but adjusted to route one session at a time. It also proposes a heuristic called DA-TF-OPP. Compared to the state-of-the-art OPP-SDP [4], DA-TF-OPP checks into which sequence the demands of a session should be routed since this sequence is entirely random for OPP-SDP. Moreover, DA-TF-OPP ensures that the WPs of the session are routed on a multicast tree; this is not required for OPP-SDP, and it can result in unneeded traffic loops in the network.

III. Problem Definition

The problem of the optimal routing of protected multicast sessions in WDM networks is defined by the following:

1) A network topology $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, which is represented by a weighted directed graph, where $\mathcal{N}$ is the set of nodes and $\mathcal{L}$ is the set of directed links, representing the fibers of the network. The set of the undirected edges of the topology is denoted as $\mathcal{E}$, where $(i,j) \in \mathcal{E}$ iff $(i,j) \in \mathcal{L}$ and $(j,i) \in \mathcal{L}$.
2) Each fiber has a number of available wavelengths, with a maximum of W wavelengths. This can be represented by a $3D$ *wavelength matrix*, **WLs**, where $wls_{w,ij}$ is equal to $w = \{1, ..., W\}$ for each directed link $(i,j) \in \mathcal{L}$. For example $wls_{1,ij}$ is a $2D$ matrix that stores 1 in the cell $[i,j]$, $\forall\, (i,j) \in \mathcal{L}$.
3) Each directed link is assigned a weight representing the cost of moving traffic from one node to another. This can be represented by a $3D$ *cost matrix*, $\mathbf{C}$, where $c_{w,ij}$ is a $2D$ matrix that stores the cost that is assigned to link $(i,j) \in \mathcal{L}$ when w wavelengths are used on (i,j). For example, $c_{2,ij}$ is a $2D$ matrix that stores the cost that is assigned to each link $(i,j) \in \mathcal{L}$ when 2 wavelengths are used on (i,j).
4) A set of K multicast sessions, $S = \{s_1, ..., s_K\}$ to be established in the network. Each session, s_i, is defined by a source, src, and a set of $\mathcal{D} = \{d_1, ..., d_M\}$ destinations, as $s_i = \{src, d_1, ..., d_M\}$, with $i = \{1, ..., K\}$. Thus, each session consists of $|\mathcal{D}|$ (or M) demands.

5) It is considered that a link failure disrupts the traffic in both directions of the link.
6) All nodes in the network are equipped with multicast-capable opaque cross-connects, which convert the signal from optical to electrical to optical (OEO) domain, allowing full wavelength conversion.

Given this input, the objective of this work is to minimize the cost of the utilized wavelengths and the blocking probability of establishing all the required sessions in the network, considering 1+1 protection for every demand. Thus, the output should consist of K multicast working trees (one for each session) and $K \cdot M$ link-disjoint BPs (one for each demand of each session) with respect to the WPs of the demands.

IV. Static scenario: Joint ILP 1 and 2 formulations

In the presence of static traffic in the network, multicast sessions, also called *multicast requests*, have infinite holding time, meaning they never leave the network. Having a priori knowledge of all the sessions that must be established allows the formulation of an ILP problem, which will minimize costs and wavelength usage over all sessions, both for the WPs and the BPs routing, *jointly*. The idea is that the WPs of the demands of each session have to be routed on a tree starting from the src of the session, reaching out to each destination. Also, a link-disjoint BP has to be found for every WP in every session so that protection is guaranteed.

Two different ILPs are proposed to tackle the problem of this work for the static scenario:

1) The *Joint ILP* 1, which finds one working tree per session to route all the WPs of the session, along with a link-disjoint BP for every demand of each session.
2) The *Joint ILP* 2, which does the same as the Joint ILP 1, with the extra constraint that the working trees of all the sessions should be formulated based on a single undirected tree. More particularly, if the network has $|\mathcal{N}|$ nodes, the required single tree should have at most $2 \cdot (|\mathcal{N}| - 1)$ directed links, with both directions of each edge included in the tree. All the working trees of the sessions should be formulated based on this single tree.

Two examples based on the two ILPs are presented in Fig. 1, where two sessions should be established, $S_1 = \{2 \rightarrow 3, 4, 5\}$ and $S_2 = \{5 \rightarrow 2, 4, 6\}$, marked with blue and green, respectively. In Fig. 1a, the working trees include among others the edges $(3,5), (5,4), (3,4)$, which form the undirected cycle $3-4-5-3$. On the other hand, in Fig. 1b, the working trees are routed in both directions of the edges $(1,2), (1,6), (6,5), (5,3), (5,4)$, forming an undirected tree.

The formulation of Joint ILP 1 is presented below.

Input: Specified in Section III.

Variables:

- $w_{ij}^{st,ses}$: is 1 if the link $(i,j) \in \mathcal{L}$ belongs to the WP of demand (s,t) of session ses, 0 otherwise.
- yw_{ij}^{ses}: is 1 if the link $(i,j) \in \mathcal{L}$ is used for the WPs of session ses, 0 otherwise.
- $b_{ij}^{st,ses}$: is 1 if link $(i,j) \in \mathcal{L}$ belongs to the BP of the demand (s,t) of session ses, 0 otherwise.

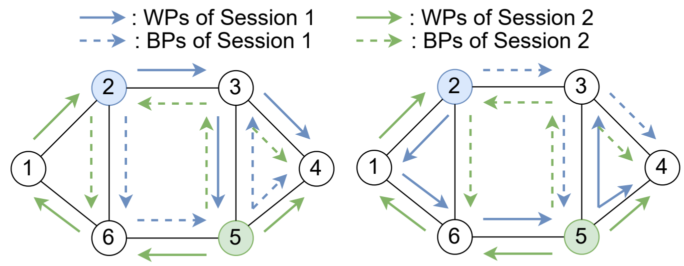

Fig. 1. Routing of the two sessions $S_1 = \{2 \rightarrow 3, 4, 5\}$ and $S_2 = \{5 \rightarrow 2, 4, 6\}$ with $1+1$ protection: (a) with Joint ILP 1, (b) with Joint ILP 2.

- yb_{ij}^{ses}: is 1 if the link $(i,j) \in \mathcal{L}$ is used for the BPs of session ses, 0 otherwise.
- y_{ij}^{ses}: is 1 if the link $(i,j) \in \mathcal{L}$ is used of session ses, 0 otherwise, regardless if it is by a WP or a BP.
- $x_{ij,w}$: is 1 if the link $(i,j) \in \mathcal{L}$ is used with a number w of wavelengths, 0 otherwise.

Objective:

$$\min \sum_{(i,j)\in\mathcal{L}} \sum_{w=1}^{W} (c_{w,ij} \cdot x_{w,ij}) \tag{1}$$

The objective function minimizes the cost of the utilized wavelengths of links that will be used for the routing and the protection of the multicast sessions.

Constraints:

$$\sum_{(k,j)\in\mathcal{L}} w_{kj}^{st,ses} - \sum_{(i,k)\in\mathcal{L}} w_{ik}^{st,ses} = \begin{cases} 1, & k = s \\ -1, & k = t \\ 0, & \text{otherwise} \end{cases} \quad \forall k \in \mathcal{N}, \forall (s,t) \in \mathcal{D}, \forall ses \in S \tag{2}$$

$$w_{ij}^{st,ses} + w_{ji}^{st,ses} \leq 1 \quad \forall (i,j) \in \mathcal{L},\, i<j,\, \forall (s,t) \in \mathcal{D}, \forall ses \in S \tag{3}$$

$$\sum_{(k,j)\in\mathcal{L}} w_{kj}^{st,ses} + \sum_{(i,k)\in\mathcal{L}} w_{ik}^{st,ses} \leq 2 \quad \forall k \in \mathcal{N}, \forall (s,t) \in \mathcal{D}, \forall ses \in S \tag{4}$$

$$yw_{ij}^{ses} \leq \sum_{(s,t)\in\mathcal{D}} w_{ij}^{st,ses} \quad \forall (i,j) \in \mathcal{L}, \forall ses \in S \tag{5}$$

$$yw_{ij}^{ses} \geq \frac{\sum_{(s,t)\in\mathcal{D}} w_{ij}^{st,ses}}{|\mathcal{D}|} \quad \forall (i,j) \in \mathcal{L}, \forall ses \in S \tag{6}$$

$$\sum_{(i,j)\in\mathcal{L}} yw_{ij}^{ses} \leq |\mathcal{N}| - 1 \quad \forall ses \in S \tag{7}$$

$$\sum_{(i,j)\in\mathcal{L}, i,j\in\mathcal{S}} yw_{ij}^{ses} \leq |\mathcal{S}| - 1 \quad \forall \mathcal{S} \subseteq \mathcal{N}, \mathcal{S} \neq \mathcal{N}, \mathcal{S} \neq \emptyset, \forall ses \in S \tag{8}$$

$$\sum_{(k,j)\in\mathcal{L}} b_{kj}^{st,ses} - \sum_{(i,k)\in\mathcal{L}} b_{ik}^{st,ses} = \begin{cases} 1, & k=s \\ -1, & k=t \\ 0, & \text{otherwise} \end{cases} \tag{9}$$
$$\forall k \in \mathcal{N}, \forall (s,t) \in D, \forall ses \in S$$

$$b_{ij}^{st,ses} + b_{ji}^{st,ses} \leq 1$$
$$\forall (i,j) \in \mathcal{L}, i<j, \forall (s,t) \in \mathcal{D}, \forall ses \in S \tag{10}$$

$$\sum_{(k,j)\in\mathcal{L}} b_{kj}^{st,ses} + \sum_{(i,k)\in\mathcal{L}} b_{ik}^{st,ses} \leq 2$$
$$\forall k \in \mathcal{N}, \forall (s,t) \in \mathcal{D}, \forall ses \in S \tag{11}$$

$$yb_{ij}^{ses} \leq \sum_{(s,t)\in\mathcal{D}} b_{ij}^{st,ses} \quad \forall (i,j) \in \mathcal{L}, \forall ses \in S \tag{12}$$

$$yb_{ij}^{ses} \geq \frac{\sum_{(s,t)\in\mathcal{D}} b_{ij}^{st,ses}}{|\mathcal{D}|} \quad \forall (i,j) \in \mathcal{L}, \forall ses \in S \tag{13}$$

$$w_{ij}^{st,ses} + b_{ij}^{st,ses} \leq 1 \quad \forall (i,j) \in \mathcal{L}, \forall (s,t) \in \mathcal{D}, \forall ses \in S \tag{14}$$

$$w_{ij}^{st,ses} + b_{ji}^{st,ses} \leq 1 \quad \forall (i,j) \in \mathcal{L}, \forall (s,t) \in \mathcal{D}, \forall ses \in S \tag{15}$$

$$y_{ij}^{ses} = yw_{ij}^{ses} \wedge yb_{ij}^{ses} \quad \forall (i,j) \in \mathcal{L} \ \forall ses \in S \tag{16}$$

$$\sum_{ses\in S} y_{ij}^{ses} \leq \sum_{w=1}^{W} (wls_{w,ij} \cdot x_{w,ij}) \quad \forall (i,j) \in \mathcal{L} \tag{17}$$

$$\sum_{w=1}^{W} x_{w,ij} \leq 1 \quad \forall (i,j) \in \mathcal{L} \tag{18}$$

Constraints (2), (3) and (4) are responsible for the flow conservation and the loop-free routing of the WPs of all the demands among all sessions. Constraints (5) and (6) define which links are used for the WPs of a specific session ses. Constraints (7) and (8) guarantee the routing of the WPs on a tree topology for each session ses. More specifically, constraint (7) expresses that a directed graph with $|\mathcal{N}|$ nodes can have at most $|\mathcal{N}| - 1$ directed links. Constraint (8) guarantees for every subset of nodes $\mathcal{S}$ of the graph that the number of directed links connecting its nodes is at most $|\mathcal{S}| - 1$, which practically means that there will be no cycles in the required tree. Constraints (9), (10) and (11) perform the routing of the BPs of every demand of each session in the exact same manner as (2), (3) and (4) for the WPs, respectively. Constraints (12) and (13) define which links are used for the BPs of a specific session ses, symmetrically with constraints (7) and (8), respectively. Constraints (14) and (15) make sure that the WP and the BP of a particular demand in each session are going to be link-disjoint in both directions of the link. Constraint (16) defines which links are used in each session, regardless of whether they are for a WP or a BP. Constraints (17) and (18) are responsible for the wavelength usage; each link $(i,j) \in \mathcal{L}$ should not use more than W wavelengths.

For Joint ILP 2, the formulation changes as follows: Constraints (7) and (8) will be replaced by the following constraints, where $yw2_{ij}$ is a binary variable that is 1 if the link $(i,j) \in \mathcal{L}$ is used for any WP of any session ses:

$$yw2_{ij} \leq \sum_{ses\in S} yw_{ij}^{ses} \quad \forall (i,j) \in \mathcal{L} \tag{19}$$

$$yw2_{ij} \geq \frac{\sum_{ses\in S} yw_{ij}^{ses}}{|S|} \quad \forall (i,j) \in \mathcal{L} \tag{20}$$

$$yw2_{ij} = yw2_{ji} \quad \forall (i,j) \in \mathcal{L} \tag{21}$$

$$\sum_{(i,j)\in\mathcal{L}} yw2_{ij} \leq 2 \cdot (|\mathcal{N}| - 1) \tag{22}$$

$$\sum_{(i,j)\in\mathcal{L}, i,j\in\mathcal{S}} yw2_{ij} \leq 2 \cdot (|\mathcal{S}| - 1) \quad \forall \mathcal{S} \subseteq \mathcal{N}, \mathcal{S} \neq \mathcal{N}, \mathcal{S} \neq \emptyset \tag{23}$$

Constraints (19) and (20) will define which links will be used for the routing of WPs among all sessions. The last three constraints will form the tree based on these links. More particularly, constraint (21) ensures that both directions of a used link will be added to the undirected tree. This should be done in order for all possible multicast sessions to be established, no matter the choice of the source and the destination nodes. Basically, the traffic flow should not be restricted to a single direction because this would block too many sessions. Finally, the last two constraints are responsible for the tree formation. Here, the main difference from the Joint ILP 1 is that since we consider that whenever a link (i,j) is used, both link directions are included in the solution, the tree should be formed based on both directions. This is the reason why the right side of the constraints is multiplied by 2.

The joint approach for the routing of multicast sessions presents the drawback that one wavelength per link per session has to be reserved if this link is chosen as part of the routing by the ILP. For the sequential routing optimization presented in [10], the same wavelength of a link could be chosen among different sessions so that the total cost for protecting all the sessions is minimized. Based on this idea of the cross-sharing trees, we can check the possibility of cross-sharing after the configuration of the WPs and the BPs is given by the two ILPs and further reduce the cost and the utilized wavelengths. This procedure is described in the flowchart of Fig. 2, where *idle BP links* are the links only used as backup resources.

The idea behind the Joint ILP 2 is to increase the possibility of *cross-sharing* of the backup resources among all sessions and to enhance the reliability of the working trees. By restricting the WPs to be routed using $2 \cdot (|\mathcal{N}| - 1)$ links, the idle BP

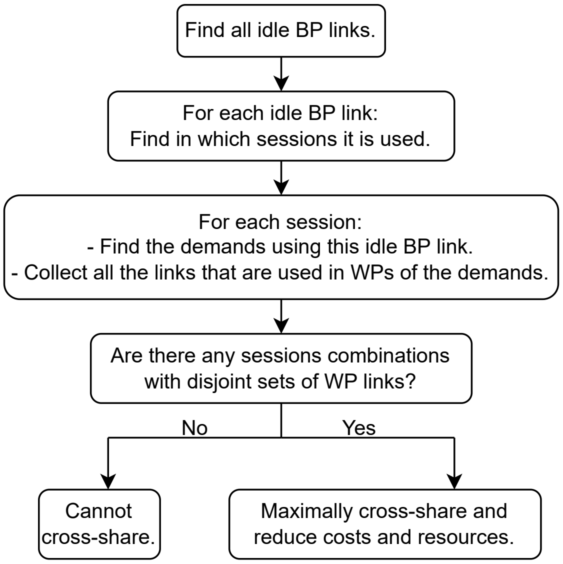

Fig. 2. Cross-sharing after the routing of the joint ILPs.

links for the protection part of the problem are increased. This also means that the possibility of cross-sharing increases, and the chances for further cost and resource utilization reduction arise. Moreover, using only $2 \cdot (|\mathcal{N}| - 1)$ links means that only $|\mathcal{N}| - 1$ out of the $|\mathcal{E}|$ edges in the network are used for the working trees. Thus, the probability of a single edge failure in the network is reduced, compared to the case where the WPs can be routed using all possible $|\mathcal{E}|$ edges (Joint ILP 1). For example, in Fig. 1, Joint ILP 1 uses 7 out of the 8 edges to route the WPs, while Joint ILP 2 uses only 5. The downside of this approach is that it is more restrictive regarding resource utilization, which can potentially lead to a higher blocking probability with respect to Joint ILP 1.

V. Dynamic Scenario: TF-OPP-ILP and DA-TF-OPP Heuristic

In the presence of dynamic traffic, multicast sessions arrive in the network, stay for a finite amount of time, and are either satisfied or blocked if there are not enough available resources.

An ILP provides the optimal solution in this case with the same objective and constraints as the Joint ILP 1 of Section IV. The only difference is that the number of sessions is set to 1. For the dynamic scenario, this ILP approach is denoted as *Tree-Forming Optimal Path Pair ILP* (TF-OPP-ILP), and its main difference from the ILP of [4] (denoted as OPP-ILP) is that it requires the WPs of a session to be on a tree so that unnecessary loops of traffic are prevented.

Dealing with dynamic multicast sessions in a WDM network, where changes occur frequently, and real-time decisions are needed, the ILP can be prohibitive due to its complexity and unscalable behavior. In this dynamic environment, heuristics might offer more practical solutions due to their speed and adaptability. Given a session and the available resources in the network at a specific point in time, this work offers a heuristic that takes into account the sequence of the demand routing (which for OPP-SDP [4] is completely random) and the fact that the WPs of the demands should form a tree. Namely, the *Demand-Aware Tree-Forming Optimal Path Pairs* (DA-TF-OPP) is presented in Algorithm 1.

Algorithm 1 Demand-Aware Tree-Forming Optimal Path Pairs (DA-TF-OPP)

Input: Specified in Section III.
Output: Routing of the WPs and BPs for the current session.

1: Run Depth-First-Search (DFS) from the source of the session.
2: Sort the destinations w.r.t. the source based on path length: from the closest to the furthest and the opposite.
3: Run OPP-SDP [4] for both sortings.
4: Select the sorting that gives the lowest total cost.
5: Choose as the WP subgraph the one with the lowest average path length.
6: Run DFS on the WP subgraph from the source of the session.
7: From the DFS tree of step 6, find the links removed from the initial WP subgraph of step 5.
8: **procedure** Rerouting of the affected demands
9:     Reroute the WPs based on the DFS tree from step 6.
10:     Reroute the BPs based on the entire subgraph from step 4 and add links if needed.

Clearly, DA-TF-OPP is characterized by a higher complexity than OPP-SDP. More specifically, the complexity of DA-TF-OPP can be calculated as $2\,O(DFS) + O(Sort) + 2\,O(OPP-SDP) + O(DFS) + O(Procedure)$. OPP-SDP uses the Suurballe algorithm $|\mathcal{D}|$ times, so its complexity is of order $O(|\mathcal{D}|(|\mathcal{E}| + |\mathcal{N}|log(|\mathcal{N}|))$. The complexity of DFS is equal to $O(|\mathcal{E}| + |\mathcal{N}|)$, and the one for sorting a list equal to $O(|\mathcal{N}|)$. The complexity of the procedure described in Algorithm 1 is at the worst case equal to $O(|\mathcal{E}|+|\mathcal{N}|log(|\mathcal{N}|))$. Overall, this complexity is still polynomial, and since cutting-edge network controllers have enough processing power to apply algorithms of relatively high - but still polynomial - complexity, DA-TF-OPP can be readily applied, resulting in increased network performance.

VI. Numerical Results

A. Simulation Setup

The proposed strategies for the static and dynamic environment were evaluated using the NSF, Poland, and the Dfnbwin topologies from [14]. Due to space limitations, results are presented only for the NSF topology of Fig. 3; numerical results and comparisons regarding all metrics were similar and consistent for all tested topologies. It is considered that the network operator reserves a limited number of wavelengths for the multicast services; thus, each fiber in the network holds $W = 16$ wavelengths in the scope of this work. The cost associated with each fiber is the link length in kilometers (km), which increases linearly according to the number of wavelengths used on this link. For example, if 2 wavelengths

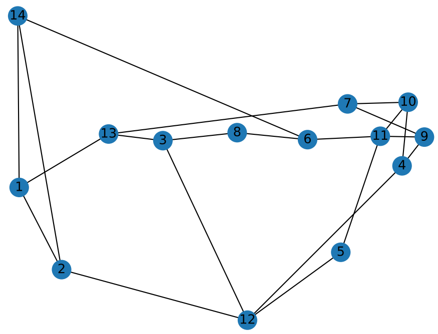

Fig. 3. The NSF topology.

are used on link (i, j), its cost is $2l_{ij}$, where l_{ij} is the link length. For the static scenario, $K = 18$ sessions have to be established in the network for different numbers of destinations $M = \{3, 5, 7, 9, 11, 13\}$. For the proposed Joint ILPs, results regarding routing costs, wavelength utilization, and average WP and BP lengths are offered. In the dynamic environment, TF-OPP-ILP and DA-TF-OPP are evaluated in terms of cost and blocking probability. One multicast session is set each time for 5000 independent experiments, and the average cost is presented. For the evaluation of blocking probability, sessions arrive in the network according to a Poisson process with arrival rate $\lambda = \{30, 60\}$, and have a unit holding time. If the resources are not enough, the session is blocked. The results are averaged over 50000 multicast sessions. In both environments, the source and the destinations of a session are chosen randomly among the network nodes.

B. Results for the static scenario

In this section, the performance of the two proposed Joint ILP 1 and 2 is discussed based on routing costs, wavelength utilization, and average WP and BP lengths. They are compared to the sequential optimization approach presented in [10], which is referred to as *Sequential ILP* in this paper.

In Fig. 4, all three approaches are evaluated according to the routing cost. The proposed Joint ILPs present a $25 - 30\,\%$ lower cost than the Sequential ILP. Joint ILP 1 and 2 demonstrate similar costs among each other, with Joint ILP 1 usually being slightly less expensive than Joint ILP 2 since the latter is more restrictive overall. However, since Joint ILP 2 offers a higher chance for cross-sharing of the backup resources, it can happen that with further cost reduction, Joint ILP 2 can achieve a lower cost than Joint ILP 1, which can be seen for the 9 destinations in Fig. 4. Another important aspect is that for 11 destinations, the Sequential ILP cannot cope with the protection of all the sessions, while the Joint ILPs can both provide a solution. This is expected with the increasing number of destinations; the resource utilization for configuring the WPs in the first step of the Sequential ILP makes the optimization for the protection infeasible. Finally, for the broadcasting case, i.e., for 13 destinations, the resources in the network are not enough for all three presented solutions.

Fig. 5 offers results regarding the utilization of wavelengths over all links and among all sessions for different numbers of destinations. The three methods present quite similar distribution of the wavelength utilization, having almost the same mean value for every number of destinations. The most interesting observation here is for Joint ILP 2, which always presents the highest maximum number of utilized wavelengths per link, the maximum value for the third quartile, and usually the lowest one for the first quartile. This is due to the restrictive nature of Joint ILP 2 to route all the WPs on $2 \cdot (|\mathcal{N}| - 1)$ links. Given that 18 sessions have to be established over 16-wavelength links, most of these $2 \cdot (|\mathcal{N}| - 1)$ are going to be heavy to fully utilized for the WP configuration, leaving all the rest of the links entirely free for the protection of the session.

Figs. 6 and 7 demonstrate the distribution of the average lengths of the WPs and BPs, respectively, among all sessions. This analysis investigated possible delay penalties that the Joint ILPs may induce. As expected, the Sequential ILP presents the lowest average WP lengths, while the mean value proves to be very similar among the three methods. The most extreme difference is observed for the case of 3 destinations, where the maximum value difference reaches 500 km with respect to Joint ILP 1 but only 150 km with respect to Joint ILP 2. Clearly, for the case of BPs, in Fig. 7, the Joint ILPs always perform better than the Sequential one. Regarding the two proposed ILPs specifically, the length differences are not stable or constant. In most cases, Joint ILP 1 leads to a higher average WP length than Joint ILP 2, but for the BPs, the differences are even smaller.

Let us evaluate the scalability of the ILP solutions in terms of execution time. All experiments have been executed using Python and the Gurobi optimizer on a PC with a CPU model Intel Core i7-4790. Considering the worst-case scenario of the maximum number of destinations per session, the Sequential and Joint ILP 1 did not exceed the running time of 1 hour for all topology instances. Joint ILP 2, the most demanding ILP out of the three, required approximately 3 hours. The ILPs are expected to require more time to run as the number of sessions, wavelengths, and the size of the network increase. The number of nodes and the number of links are the most critical parameters for the scalability of the ILPs since they affect the execution time in an exponential way.

C. Results for the dynamic scenario

In this section, TF-OPP-ILP and DA-TF-OPP for the dynamic environment are compared to state-of-the-art OPP-ILP and OPP-SDP of [4], respectively.

Fig. 8 presents the average costs for all the aforementioned schemes. Regarding the ILPs, it is proven that TF-OPP-ILP provides the exact same optimal cost as OPP-ILP [4]. This means that the constraints for the WPs to form a tree for every session do not add any cost penalty to the total routing and protection cost of the multicast session. TF-OPP-ILP avoids the unneccesary loops of traffic regarding the WPs of the session. OPP-ILP does not take that into account, offering several minima to the problem, which leads to numerous traffic

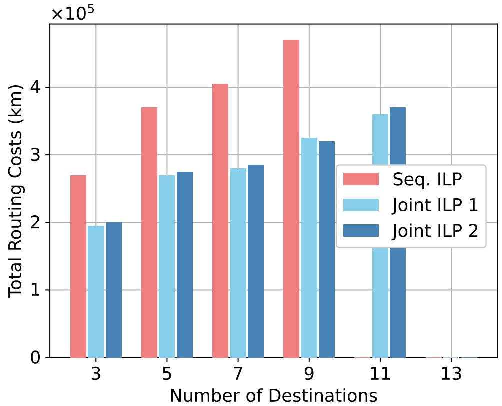

Fig. 4. Routing costs over different numbers of destinations.

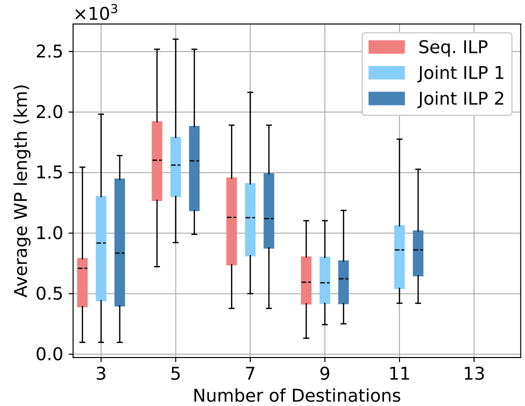

Fig. 6. Distribution of the average lengths of the WPs over all sessions.

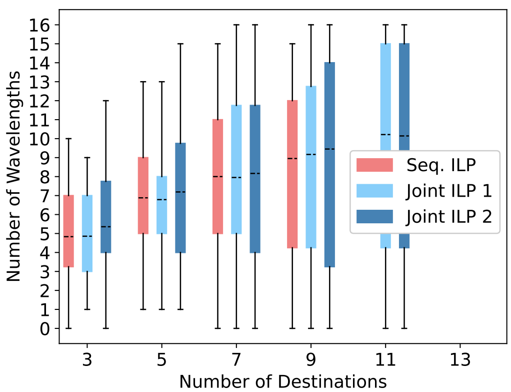

Fig. 5. Wavelength utilization distribution over all links and among all sessions.

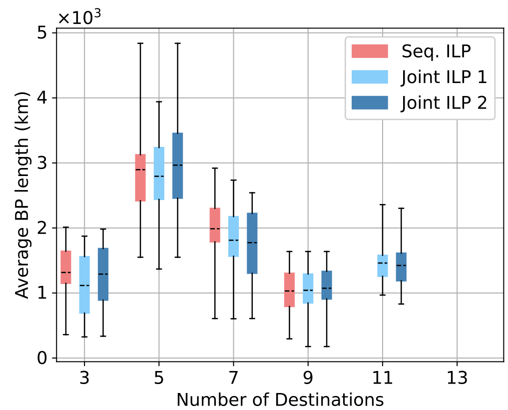

Fig. 7. Distribution of the average lengths of the BPs over all sessions.

loops. The proposed optimal solution of this work manages to overcome this problem with the exact same cost, which initially was not expected, as TF-OPP-ILP is more restrictive than OPP-ILP [4]. Regarding the heuristics, it is shown that DA-TF-OPP provides up to $5\,\%$ lower cost than OPP-SDP, even though it is more restrictive as well. This means that DA-TF-OPP achieves a solution $\sim 33\,\%$ closer to the optimal one by TF-OPP-ILP, thanks to the demand-aware sequence of establishing each demand of a session. Apart from the average costs, Fig. 9 presents the distribution of the cost differences between DA-TF-OPP and OPP-SDP [4] over the 5000 independent experiments. This figure shows that DA-TF-OPP will provide up to 8000 km lower cost than OPP-SDP with a probability of $\sim 75\,\%$. On the other hand, the cost penalty added by DA-TF-OPP with respect to OPP-SDP is $50\,\%$ lower and only with a chance of $25\,\%$.

In Figs. 10 and 11 the blocking probability of DA-TF-OPP is investigated with two different session arrival rates, given that multicast sessions arrive in the network according to a Poisson process. Both figures show that DA-TF-OPP achieves up to $3\,\%$ lower blocking probability than OPP-SDP. The difference is more intense for the arrival rate $\lambda = 30$, while the performance of the two algorithms is much closer for $\lambda = 60$. The important advantage of DA-TF-OPP is that it manages to provide a lower blocking probability, even though it does not have as many degrees of routing freedom as OPP-SDP; DA-TF-OPP manages to route the WPs of each session on a tree, which is an aspect that OPP-SDP does not address. Regarding running times, it should be noted that TF-OPP-ILP can take up to 5 minutes to be executed, while DA-TF-OPP provides the solution within a few milliseconds.

VII. Conclusions

This work aims to minimize the routing cost and the blocking probability of establishing multiple protected multicast sessions in a WDM network, investigating both a static and a dynamic environment. For the former case, two different ILPs optimize the routing and the protection of the sessions simultaneously, with the second ILP restricting the routing of the working paths on a specific number of links in the network. Results showed that the proposed ILP schemes achieve $25-30\,\%$ lower cost and can cope with more destinations per session compared to the state-of-the-art without inducing further overloading or delays. In the presence of dynamic

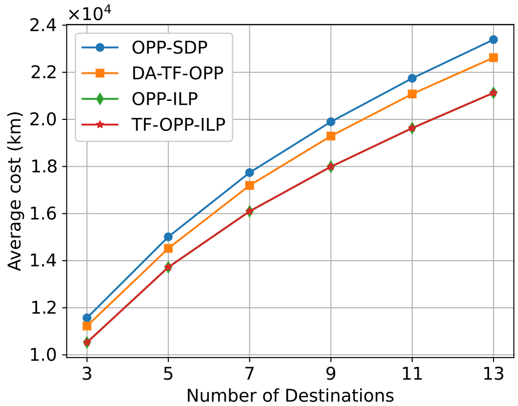

Fig. 8. Avegare cost comparison of DA-TF-OPP and TF-OPP-ILP.

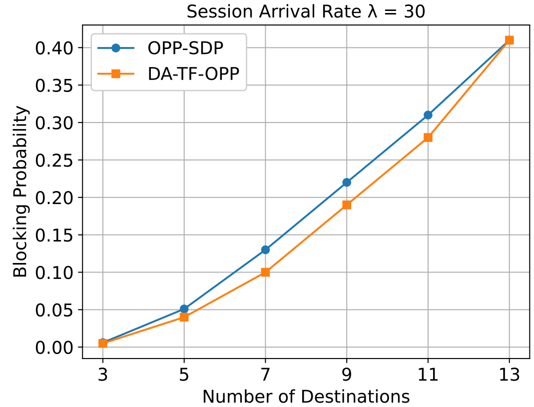

Fig. 10. Average blocking probability for $\lambda = 30$.

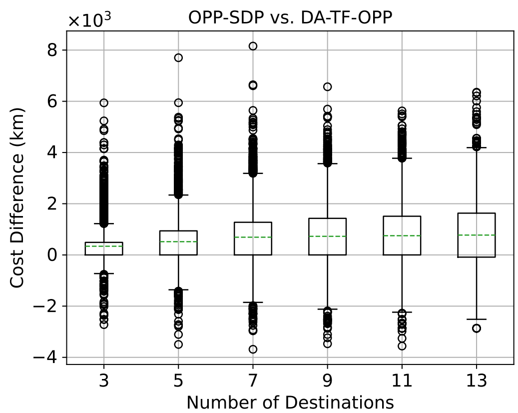

Fig. 9. Cost difference distribution between OPP-SDP and DA-TF-OPP.

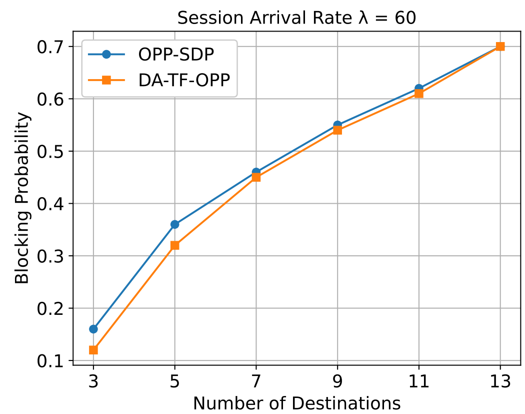

Fig. 11. Average blocking probability for $\lambda = 60$.

traffic in the network, TF-OPP-ILP provides the optimal solution for one session at a time by providing the working tree and backup paths for every demand. A heuristic called DA-TF-OPP was also offered; compared to the state-of-the-art, it provides a solution $\sim 33\,\%$ closer to the optimal cost and it further reduces the blocking probability up to $3\,\%$, while preventing traffic loops.

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