Survivable Virtual Network Mapping in Filterless Optical Networks

Omran Ayoub*, Andrea Bovio, Francesco Musumeci, Massimo Tornatore
Politecnico di Milano, Milan, Italy. *Corresponding author: omran.ayoub@polimi.it

***Abstract*—Today's optical networks must meet the unprecedented capacity requirements of 5G communications and provide such capacity under strict cost constraints. Filterless Optical Networks (FONs) (i.e., optical networks where optical nodes are solely based on passive splitters and combiners) are emerging as an outstanding solution to reduce network cost while supporting capacity growth. Due to FONs' specific design criteria (the network topology must be divided into edge-disjoint filterless fiber trees), traditional network problems, such as, e.g., routing and wavelength assignment and virtual network mapping, shall be tackled adopting distinct approaches with respect to state-of-the-art filtered optical networks networks. In this paper, we investigate the problem of survivable virtual network mapping (SVNM) in FONs. We propose an Integer Linear Programming model to establish fiber trees and provide survivable mapping of virtual networks, while minimizing cost of additional equipment and spectrum. We show that joint optimization of filterless trees and survivable mapping significantly decreases transceivers and spectrum cost compared to a disjoint solution where the tree establishment does not consider SVNM constraints.**

I. Introduction

Filterless Optical Networks (FONs) are emerging as an outstanding technological solution to reduce capital and operational expenditures in optical networks. FONs have been investigated around a decade ago [1], and they have been recently revived by the need of building cost-effective optical metro networks for the incoming deployment of 5G communications [2]. In FONs, common optical switching architectures, consisting of Reconfigurable Optical Add-Drop Multiplexers (ROADMs) and based on costly Wavelength Selective Switches (WSS), are replaced by simpler and more cost-effective architectures, constituted by passive splitters and combiners that operate on the entire set of lightpaths using a *broadcast-and-select* switching approach [3].

Due to this broadcast-switching nature, FONs incur higher spectrum wastage in comparison to wavelength-switched optical networks (WSON) and, more importantly, they require the establishment of *fiber trees*, i.e., a loop-free fiber coverage interconnecting add/drop traffic nodes, to prevent undesired laser-loop effects due to continuous signal broadcasting and amplification [1], [4]. Consequently, ensuring survivability becomes more challenging in FONs, as the trees establishment constrains the routing possibilities between nodes, and hence, additional equipment (e.g., transceivers) might be required to guarantee multiple disjoint routes between nodes. In this study, we focus on the problem of Survivable Virtual Network Mapping (SVNM) in the context of FONs. SVNM consists of assigning physical network resources to a given set of lightpaths requests between node pairs, represented by *logical links* in a virtual network (i.e., the *logical topology*), such that the logical topology is survivable to failures in the physical topology [5], i.e., the logical topology does not break into isolated networks in case of link failure. Fig. 1(b) shows an example of a *non-survivable mapping* of the logical topology depicted in 1(a) as a failure of fiber (5,6) interrupts both logical links l_1 (5,6) and l_4 (5,3). On the contrary, the mapping in Fig. 1(c) is *survivable* as any link failure does not disconnect the logical topology.

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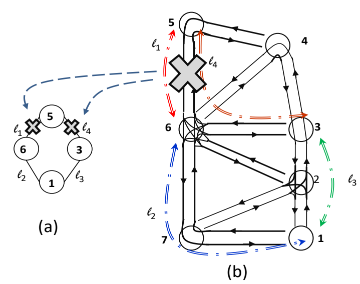

Fig. 1. (a) Logical topology, (b) Non-survivable and (c) survivable virtual network mapping of the logical topology onto a 7-node physical network topology.

When applied in FONs, the SVNM encompasses a number of problems that, to the best of our knowledge, have not been investigated so far. More specifically: *1) How to ensure survivability in FONs? 2) What is its cost, e.g., in terms of additional equipment and network capacity? 3) Is this higher than WSON? 4) How does a proper tree establishment affect the SVNM and its cost?*

Two examples of SVNM in FON. To highlight the importance of proper trees establishment in FONs, consider the example in Fig. 2. We map the virtual network in Fig. 1(b) (i.e., we allocate a physical optical path to each virtual link), on the physical topology shown in Fig. 2(a), considering two different FON tree establishments, shown in Figs. 2(c) and (d), respectively. In both cases, two edge-disjoint fiber trees are considered and are shown with solid and dotted lines, respectively. Note that nodes not belonging to the same fiber tree cannot transparently reach one another (i.e., through a lightpath that remains in the optical domain). For this reason, the only viable solution to inter-connect nodes that do not belong to the same fiber tree is equipping specific nodes with additional inter-tree transceivers that serve as a bridge to allow

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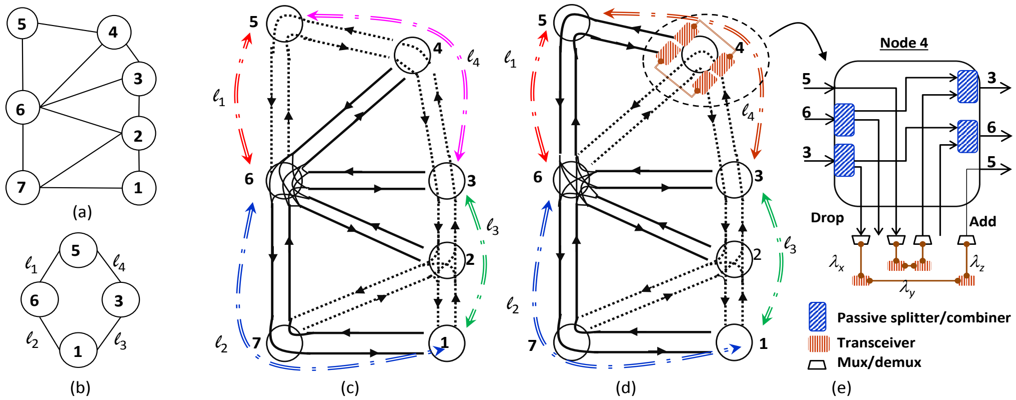


Fig. 2. (a) 7-node German network, (b) virtual network, (c) and (d) show two fiber tree establishments (highlighted by solid and dotted lines in each of the figures) and SVNM of the logical topology (in (c) a SVNM is possible without the use of inter-tree transceivers while in (d) the deployment of inter-tree transceivers is necessary to guarantee a SVNM), and (e) architecture of node 4 showing position of inter-tree transceivers deployed

OEO signal traversing from one fiber tree to another even if this means incurring in additional transceiver cost. The impact of the fiber tree establishment on SVNM is shown in Figs. 2(c) and (d). Each of the figures shows a mapping for each of the links of the virtual network ($l_1 - l_4$) guaranteeing survivability, i.e., guaranteeing that any failure in the physical network does not interrupt the virtual network. Only the fiber tree establishment in Fig. 2(c) enables a feasible SVNM without use of inter-tree transceivers as each of the 4 virtual links ($l_1 - l_4$) is mapped on a physical path belonging to a single fiber tree (note that in a fiber tree, a wavelength used to map a virtual link exclusively reserves that wavelength over the entire fiber tree). On the contrary, to achieve SVNM of the virtual network over the fiber tree establishment in Fig. 2(d), logical link l_4 is mapped on a physical path belonging to two trees (crossing fiber trees at node 4) and therefore it requires the placement of 4 transceivers at node 4. The internal architecture of node 4 is shown in Fig. 2(e). Note that a pair of transceivers is necessary to allow traversing exactly one lightpath (i.e., one logical link in the virtual network) from one fiber tree to another, and so, the wavelength used by the virtual link traversing two fiber trees will be reserved on both fiber trees. This suggests that, when performing SVNM in FONs, an accurate trees establishment is crucial to avoid deploying unnecessary transceivers to traverse lightpahts between trees. In this study, we model the SVNM problem in FONs as an integer linear program (ILP) and conduct a numerical analysis to evaluate the additional cost required to guarantee SVNM in a FON. The ILP model establishes filterless fiber trees, maps virtual topology onto the physical filterless network and places transceivers, when required, to guarantee a survivable virtual network mapping with the objective of minimizing cost in terms of transceivers and spectrum.

A. Related Work

In recent literature, the interest in FONs has been increasing. Several works studied the design of filterless optical networks without taking survivability into account. In [1], a design tool is provided to establish fiber trees and perform routing and wavelength assignment. In [6] and [7], the authors proposed an ILP formulation for resource allocation to minimize spectrum consumption in elastic and fixed filterless optical networks, respectively. Some works have also investigated the concept of semi-filterless optical networks to mitigate excessive spectrum consumption [8] [9]. Protection in FONs has been studied in [10], where the authors propose a heuristic approach to establish fiber trees and guarantee 1+1 optical-layer protection of traffic demands. Results show that a 1+1 optical-layer protection requires going beyond purely filterless solutions, and wavelength blockers must be placed at selected network nodes. Ref. [11] investigated the amount of wavelengths required to provide protection in filterless networks focusing on horse-shoe topologies. In our work, we perform the fiber tree establishment, routing and wavelength assignment considering the survivable mapping of virtual networks, which requires distinct approaches than those presented in previous works. With respect to protection, which ensures end-nodes of lightpaths to stay connected in case of failure, SVNM assumes different properties as it requires to ensure connectivity of a virtual network for any cut-set in the network [5]. To the best of our knowledge, no existing work has investigated the problem of establishing fiber trees and performing a survivable virtual network mapping in FONs.

B. Paper Contribution

The main contributions of this paper are as follows: (1) we define the problem of SVNM in FON highlighting the differences with respect to SVNM in WSON; (2) we propose an ILP formulation to jointly establish fiber trees and perform survivable virtual network mapping, while minimizing network cost in terms of additional inter-tree transceivers and wavelength consumption; (3) we analyze the benefit of joint optimization of fiber tree establishment and SVNM against the case when fiber trees are pre-established; (4) we analyze the cost of survivability in FONs comparing it against two benchmark scenario where (i) SVNM is applied to WSON and (ii) virtual network mapping is performed in FON without considering survivability.

The rest of the paper is organized as follows. Section II introduces the problem of SVNM in FON and presents the proposed ILP model to solve it. Section III discusses illustrative numerical results, and Section IV draws the conclusion.

II. Survivable Virtual Network Mapping in Filterless Optical Networks

A. Problem Statement

We model the SVNM problem in FON as an ILP optimization model, referred to as ***SVNM in FONs (Surv-FON)***. The problem is stated as follows: **Given** a physical network topology consisting of filterless nodes and bidirectional links with one fiber per direction and a capacity of L wavelengths, and a virtual network, constituted by a set of virtual links representing bidirectional lightpaths requests (for simplicity, we assume that each virtual link requests exactly one wavelength), we **decide** $i)$ the fiber tree establishment, $ii)$ the placement of inter-tree transceivers (if any), and $iii)$ the SVNM into the physical trees (i.e., the routing and wavelength assignment of virtual links), with the **objective** of minimizing, in order of priority, *1) the number of inter-tree transceivers placed* and *2) wavelength occupation in the network*, **constrained by:** *i) SVNM constraint*, i.e., any failure in the physical topology shall not disconnect the logical topology (i.e., the virtual network) [5], *ii) fiber tree establishment constraints*, i.e., each fiber link belongs to exactly one fiber tree and a fiber tree cannot contain closed loops [1], *iii) wavelength continuity and contiguity*, and *iv) maximum link capacity*. Note that compared to classical SVNM in WSON, we had to redefine the constraints of survivable mapping of virtual networks to adapt to the fiber tree constraints and we added new constraints to model the placement of inter-tree transceivers in FONs, which adds up to the complexity of the problem.

B. Integer Linear Programming Formulation

Sets and parameters

- $G = (N, A)$ graph modeling the physical topology, where N is the set of physical nodes and A is the set of bidirectional physical links
- $G_L = (N_L, A_L)$ graph modeling logical (virtual) topology, where N_L is the set of logical nodes and A_L the set of bidirectional logical links
- L is the set of wavelengths. |L| represents the maximum number of wavelengths on a unidirectional fiber
- F is the set of possible fiber trees
- Cutsets $CS(S, N_L - S)$ are the sets of logical links that belong to a cut of the logical topology. $S \subset N_L$ represents a subset of logical nodes N_L
- $N_{sub} \subset N$ are the possible sets of physical nodes
- M: large number $>$ max. wavelength consumption

Decision Variables:

- x_{ij}^f: binary, equal to 1 if physical link (i, j) belongs to fiber tree f, 0 otherwise
- q_{ij}^{st}: binary, equal to 1 if logical link (s, t) is mapped onto physical link (i, j), 0 otherwise
- z_{ij}^{stf}: binary, equal to 1 if logical link (s, t) is mapped on physical link (i, j) belonging to fiber tree f, 0 otherwise
- w_{ij}^{stlf}: binary, equal to 1 if logical link (s, t) mapped on link (i, j) belonging to fiber tree f uses wavelength l, 0 otherwise
- p_{ij}^{lf}: binary, equal to 1 if wavelength l is utilized on link (i, j) belonging to fiber tree f, 0 otherwise
- v_{st}^{lf}: binary, equal to 1 if logical link (s, t) uses wavelength l on fiber tree f, 0 otherwise
- d_{ijjo}^{stfr}: binary, equal to 1 if logical link (s, t) is mapped on physical links (i, j) and (j, o) which belong to fiber trees f and r respectively, 0 otherwise
- e_{ijjo}^{stlf}: binary, equal to 1 if logical link (s, t) is mapped on physical links (i, j) and (j, o) belonging to fiber tree f is assigned wavelength l, 0 otherwise
- m_{ijjo}^{stlrf}: binary, equal to 1 if logical link (s, t) is mapped on physical links (i, j) and (j, o) belonging to fiber trees r and f, respectively, and is assigned wavelength l, 0 otherwise
- y_{st}^f: binary, equal to 1 if logical link (s,t) fiber tree is assigned any physical link belonging to fiber tree f, 0 otherwise
- d_f: binary, equal to 1 if fiber tree f is used, 0 otherwise
- g_i^f: binary, equal to 1 if node i is an end point of a link belonging to fiber tree f, 0 otherwise
- h_{ij}^{lf}: binary, equal to 1 if wavelength l on link (i, j) on fiber tree f is wasted (broadcasted), 0 otherwise

Objective function

$$\begin{aligned} \mathit{Minimize} \sum_{(i,j)\in A} \sum_{(j,o)\in A} \sum_{(s,t)\in A_L} \sum_{r,f\in F} M \cdot d_{ijjo}^{strf} \\ + \sum_{(i,j)\in A} \sum_{f\in F} \sum_{l\in L} (\sum_{(s,t)\in A_L} w_{ij}^{stlf} + h_{ij}^{lf}) \end{aligned} \quad (1)$$

Minimize number of inter-tree transceivers placed (given highest priority), and number of overall wavelengths utilized (sum of all wavelengths pccupied on all links).

C. Subject to:

$$\sum_{j:(i,j)\in A} q_{ij}^{st} - \sum_{j:(j,i)\in A} q_{ji}^{st} = \begin{cases} 1 & if \quad s = i \\ -1 & if \quad t = i \forall i \in N, \ (s,t) \in A_L \\ 0 & otherwise \end{cases} \quad (2)$$

$$\sum_{(s,t)\in CS(S,N_L-S)} q_{ij}^{st} < |CS(S, N_L - S)| \ \ \forall (i,j) \in A, S \subset N_L \quad (3)$$

Constraint 2 is the flow constraint and it ensures that every logical link (s,t) of the virtual network is mapped onto one physical path of the physical topology, while Constr. 3 guarantees that the mapping of all logical links is survivable. Specifically, Constr. 3 states that all the logical links which belong to a cutset of the logical topology cannot have a mapping on the same physical link.

$$\sum_{f\in F} x_{ij}^f = 1 \qquad \forall (i,j) \in A \quad (4)$$

$$x_{ij}^f - x_{ji}^f = 0 \qquad \forall (i,j) \in A, f \in F \quad (5)$$

$$\sum_{(i,j)\in A(N_{sub})} x_{ij}^f \ \leq \ |N_{sub}| - 1 \qquad \forall f \in F, N_{sub} \subset N : |N_{sub}| > 2 \quad (6)$$

$$\sum_{(i,j)\in A} x_{ij}^f/M \le d_f \le \sum_{(i,j)\in A} x_{ij}^f \qquad \forall f \in F \quad (7)$$

$$\sum_{i:(i,j)\in A} x_{ij}^f/M \le g_j^f \le \sum_{i:(i,j)\in A} x_{ij}^f \qquad \forall j \in N, f \in F \quad (8)$$

$$\sum_{(i,j)\in A} x_{ij}^f = 2\cdot(-d_f + \sum_{i\in N} g_i^f) \qquad \forall f \in F \quad (9)$$

$$z_{ij}^{stf} \le x_{ij}^f \qquad \forall (i,j)\in A, (s,t)\in A_L, f\in F \quad (10)$$

$$z_{ij}^{stf} \le q_{ij}^{st} \qquad \forall (i,j)\in A, (s,t)\in A_L, f\in F \quad (11)$$

$$z_{ij}^{stf} \ge q_{ij}^{st} + x_{ij}^f - 1 \quad \forall (i,j)\in A, (s,t)\in A_L, f\in F \quad (12)$$

$$z_{ij}^{stf} \le y_{st}^f \qquad \forall (i,j)\in A, (s,t)\in A_L, f\in F \quad (13)$$

Constraints 4-9 establish edge-disjoint fiber trees and guarantee all fiber tree establishment constraints. Constr. 4 assigns each physical link (i,j) to exactly one fiber tree f while constr. 5 enforces bidirectionality of fiber tree establishment (i.e., if link (i,j) is assigned to fiber tree f, link (j,i) is also assigned to fiber tree f). Constr. 6 enforces that fiber trees are loops-free, by ensuring that the sum of links belonging to a fiber tree that connect each subset of nodes of the physical topology is less than cardinality of the subset of nodes, i.e., the number of nodes inside the subset. For instance, if N_{sub} contains three nodes then at most 2 links that connect those nodes can belong to the same fiber tree. Constraints 7-9 guarantee that all the links of a fiber tree are connected. Constraints 10-13 ensure consistency between mapping and fiber tree establishment assignment.

$$\sum_{l\in L}\sum_{f\in F} v_{st}^{lf} \ge 1 \qquad \forall (s,t)\in A_L \quad (14)$$

$$\sum_{l\in L} v_{st}^{lf} = y_{st}^f \qquad \forall (s,t)\in A_L, f\in F \quad (15)$$

$$w_{ij}^{stlf} \le v_{st}^{lf} \qquad \forall (i,j)\in A, (s,t)\in A_L, f\in F, l\in L \quad (16)$$

$$w_{ij}^{stlf} \le z_{ij}^{stf} \qquad \forall (i,j)\in A, (s,t)\in A_L, f\in F, l\in L \quad (17)$$

$$w_{ij}^{stlf} \ge z_{ij}^{stf} + v_{st}^{lf} - 1 \quad \forall (i,j)\in A, f\in F, l\in L, (s,t)\in A_L \quad (18)$$

$$w_{ij}^{stlf} + w_{ij}^{urlf} \le 1 \quad \forall f\in F, l\in L, (i,j)\in A, (s,t),(u,r)\in A_L : (s,t)\neq(u,r) \quad (19)$$

$$w_{ij}^{stlf} + h_{ij}^{lf} \le 1 \quad \forall (i,j)\in A, (s,t)\in A_L, l\in L, f\in F \quad (20)$$

Constraints 14 ensures that each virtual link (s,t) is assigned exactly one (and the same) wavelength l on a physical path it is mapped on along fiber tree f. Note that in case a logical link is assigned physical links belonging to more than one tree, wavelength conversion is possible. Constr. 15 ensures that a logical link uses exactly one wavelength on the fiber tree (and therefore the physical path) it is mapped on. Constr. 16-18 guarantee consistency between wavelength assignment, link mapping and fiber tree establishment constraints. Constr. 19 and 20 ensure that logical links cannot use same wavelength on the same physical path.

$$0 \le w_{ij}^{stlf} + w_{jo}^{stlf} - 2\cdot e_{ijjo}^{stlf} \le 1 \quad \forall f\in F, l\in L, (s,t)\in A_L, (i,j),(j,o)\in A : i\neq o, j\neq s, j\neq t \quad (21)$$

$$p_{ju}^{lf} \ge \sum_{(s,t)\in A_L} e_{ijjo}^{stlf}/M \quad \forall j\in N, f\in F, l\in L, (i,j),(j,o),(j,u)\in A : i\neq u, u\neq o, o\neq i \quad (22)$$

$$0 \le w_{ij}^{stlf} + w_{jo}^{stlr} - 2\cdot m_{ijjo}^{stlfr} \le 1 \quad \forall f,r\in F, (s,t)\in A_L, (i,j),(j,o)\in A, l\in L : f\neq r, i\neq o, j\neq s, j\neq t \quad (23)$$

$$0 \le z_{ij}^{stf} + z_{jo}^{str} - 2\cdot d_{ijjo}^{stfr} \le 1 \quad \forall f\in F, r\in F, (s,t)\in A_L, (i,j),(j,o)\in A : i\neq o, f\neq r \quad (24)$$

Constraints 21 and 22 identify the nodes along a physical path of a fiber tree of which a logical link is mapped, and ensure that arriving signals (wavelengths) are broadcasted over the outgoing ports of these nodes onto links of the same filterless fiber tree.

Moreover, Constr. 23 identifies the nodes in which a lightpath of a physical path mapping a logical link crosses two fiber trees. Constr. 24 places inter-tree transceivers at such nodes. In particular, if (i,j) and (j,o) are links that belongs to a virtual link (s,t) and are on different fiber tree f and r then variable (d_{ijjo}^{stfr}) = 1.

$$p_{ju}^{lf} \ge \sum_{(s,t)\in A_L} m_{ijjo}^{stlfr}/M \quad \forall f,r\in F, j\in N, l\in L, (i,j),(j,o),(j,u)\in A : f\neq r, i\neq u, u\neq o, o\neq i \quad (25)$$

$$p_{ju}^{lf} \ge \sum_{(s,t)\in A_L : t=j} w_{ij}^{stlf}/M \quad \forall j\in N, (i,j),(j,u)\in A, l\in L : i\neq u, f\in F \quad (26)$$

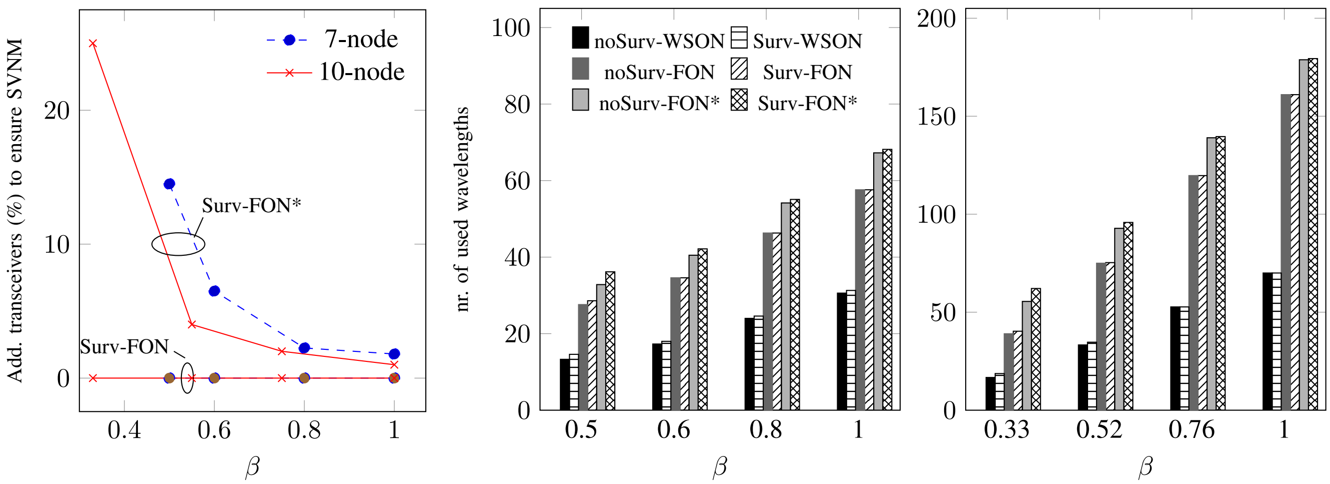
$$p_{ju}^{lf} \ge h_{ij}^{lf} \quad \forall j\in N, (i,j),(j,u)\in A, f\in F, l\in L : i\neq u \quad (27)$$

$$0 \le p_{ij}^{lf} + x_{ij}^f - 2\cdot h_{ij}^{lf} \le 1 \quad \forall f\in F, (i,j)\in A, l\in L \quad (28)$$

$$\sum_{(s,t)\in A_l}\sum_{l\in L} w_{ij}^{stlf} + \sum_{l\in L} p_{ij}^{lf} \le |L| \quad \forall (i,j)\in A, f\in F \quad (29)$$

Constraints 25-28 make sure nodes broadcast spectrum received along the links of fiber tree they are connected to. Constraint 29 is the fiber capacity constraint.

We also evaluate a scenario, referred to as ***Surv-FON****, in which the fiber tree establishment is given as an input to the problem rather than being jointly optimized with SVNM as it was done in the case of *Surv-FON*. Specifically, for this scenario, x_{ij}^f and g_i^f are considered as parameters and are no longer decision variable. Consequently, constraints regarding fiber tree establishment (Constr. 4-9) are discarded. Comparing *Surv-FON* to *Surv-FON** allows us to assess the benefits, i.e., the savings in terms of number inter-tree transceivers and wavelength consumption, of jointly optimizing the fiber trees and the SVNM.



(a) Additional nr. transceivers (%) (b) Wavelengths used (7-nodes topology) (c) Wavelengths used (10-nodes topology)

Fig. 3. Numerical results for the six network scenarios as a function of β for two different topologies

TABLE I
NETWORK SCENARIOS CONSIDERED IN THE EVALUATION.

Network Scenarios	Network Architecture	Fiber Tree Establishment	Survivability
Surv-FON	Filterless	ILP	✓
NoSurv-FON	Filterless	ILP	X
Surv-FON*	Filterless	Given	✓
NoSurv-FON*	Filterless	Given	X
Surv-WSON	Wavelength-Switched	NA	✓
NoSurv-WSON	Wavelength-Switched	NA	X

III. ILLUSTRATIVE NUMERICAL RESULTS AND EVALUATION

In addition to Surv-FON and Surv-FON*, we consider these other four baseline network scenarios:

- i) ***noSurv-FON***: Virtual Network Mapping (VNM) in FON without survivability
- ii) ***noSurv-FON****: VNM in FON without survivability and without optimizing tree establishment
- iii) ***Surv-WSON***: SVNM in WSON
- iv) ***noSurv-WSON***: VNM in WSON without survivability

Table. I summarizes the characteristics of the different scenarios considered.

We use CPLEX 12.10 to solve all the six versions of the optimization problem over a 7-node German network (shown in Fig. 2(a)) and a 10-node Italian network (shown in Fig. 4), considering various virtual networks with increasing connectivity degree β, defined as the ratio between the number of links in the considered logical topology and that in the full-mesh logical topology. For the 7-node German network, we consider a 5-node logical topology with β ranging from 0.5 to 1, whereas for the 10-node Italian network we consider a 7-node logical topology with β ranging from 0.33 to 1 (note that β values are different in the two cases as we consider virtual networks with different number of nodes) considering L = 40. To increase generality of our numerical results, we average them over three different node mappings for each value of β, and, for the scenarios with given fiber tree establishments, we perform, for every node mapping and value of β, 5 different evaluations assuming 5 different fiber tree establishments optimized to guarantee highest network connectivity degree.

A. Inter-Tree Transceivers

For increasing values of β and for the two topologies, we show in Fig. 3(a) the percentage of additional inter-tree transceivers deployed in the *Surv-FON* and *Surv-FON** cases with respect to number of transceivers needed in *Surv-WSON* (in short, the additional cost of survivability in a FON vs. WSON). For *Surv-FON*, a SVNM is always found without deploying additional inter-tree transceivers while for *Surv-FON** the percentage of additional inter-tree transceivers (with respect to the total number of transceivers in the network) ranges between 3% and 24%. *This shows that jointly optimizing the fiber tree establishment and the SVNM is decisive to avoid additional inter-tree transceivers*. Moreover, results show that the percentage of additional inter-tree transceivers for *Surv-FON** is higher for lower values of β, while, for increasing β (i.e., as the logical topology becomes more connected) it decreases to around 2% and 3% for the 7-node and 10-node networks, respectively, when $\beta = 1$. This is because when the connectivity degree of the logical topology β is relatively low, mappings of logical links are restricted to specific paths to guarantee network survivability, which require deployment of inter-tree transceivers. Conversely, for higher β, the nodal degree of the virtual network is higher as more logical paths must be mapped, hence more physical paths mapping logical links while guaranteeing survivability become available, thus avoiding the deployment of additional inter-tree transceivers. Fig. 4 illustrates this case by showing the SVNM of two logical topologies (i.e., with β = 0.29 and β = 0.43) over the same fiber tree establishment. In the first virtual network case (β = 0.29), logical link (4,9) can only be mapped over physical path (4,8,10,9), which requires inter-tree transceivers at node 10, to guarantee survivability. Note that physical path (4,2,7,9) which belongs to same fiber tree does not provide a SVNM of the virtual network. This is because node 4 would be connected to its 2 adjacent nodes in the logical topology via the same unique physical link (4,2) and hence, the logical topology will be interrupted if link (4,2) fails. In the second case, i.e., for β = 0.43, when 4 additional virtual links are present in the virtual network, a SVNM is found without the need for inter-tree transceivers as logical link (4,9) can be mapped over physical path (4,2,7,9) without violating survivability constraints, thanks to the higher number of paths available in the virtual network.

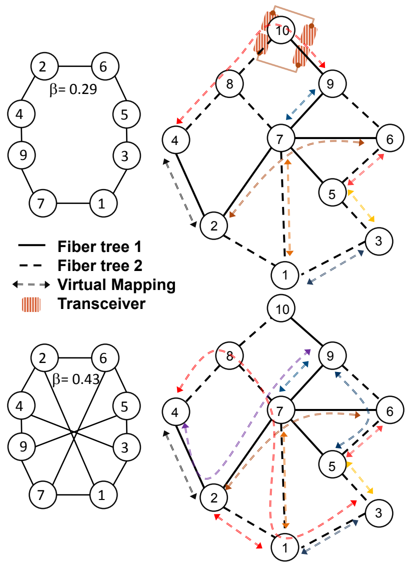


Fig. 4. Two SVNMs for *Surv-FON**

B. Wavelength Consumption

Figures 3(b)-(c) show the overall number of wavelength channels used for all six scenarios in the case of 7-node and 10-node topology, respectively. As expected, FON requires a significantly larger number of wavelength channels (ranging between 60% and 100%) compared to the WSON. However, when jointly optimizing the fiber tree establishment and the SVNM, i.e., for *noSurv-FON* and *Surv-FON*, significant savings (up to 25%) are achieved in comparison to the corresponding cases when fiber tree establishment is not optimized, i.e., the *noSurv-FON** and *Surv-FON** cases, respectively. This shows that, when considering SVNM in FONs, joint optimization of tree establishment and SVNM is decisive to reduce both wavelengths usage and number of inter-tree transceivers deployed. Comparing *noSurv-FON* and *Surv-FON*, we further observe that, for both topologies, when β is low, *Surv-FON* uses slightly more wavelengths than *noSurv-FON*, whereas for increasing values of β, wavelengths usage in the two cases converges to the same value. *This shows that, in a FON scenario, survivability can be guaranteed with negligible (or even with no need for) additional capacity, especially when the logical topology is highly connected, provided that fiber tree establishment and SVNM are jointly optimized.* Conversely, when fiber trees are already established (i.e., comparing *Surv-FON** and *noSurv-FON** cases) survivability is guaranteed only via a significant amount (up to 30%) of additional wavelengths for all values of β. It is interesting to note that the placement of inter-tree transceivers to guarantee SVNM contributes further to spectrum waste. This shows even more the importance of jointly optimizing the fiber tree establishment and the SVNM.

IV. Conclusion

We investigated the survivable virtual network mapping in filterless optical networks with the objective of minimizing additional network cost, expressed as the number of additional inter-tree transceivers deployed and overall wavelength consumption. To this aim, we developed an ILP model to jointly optimize the fiber tree establishment and the survivable mapping of virtual networks in FONs. Numerical results show that jointly optimizing tree establishment and survivable virtual networks mapping is decisive to minimize additional transceivers and limit spectrum waste. Conversely, when fiber tree establishment is a given to out problem, we find that up to 25% additional inter-tree transceivers are required to guarantee survivable mapping. Results also show that our proposed model guarantees survivability with negligible (i.e., less than 5%) additional wavelength usage. As a future work, we plan to propose heuristic approaches to consider mapping of multiple virtual networks on larger filterless network instances .

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