Survivable Virtual Network Mapping with Fiber Tree Establishment in Filterless Optical Networks

Omran Ayoub, Andrea Bovio, Francesco Musumeci and Massimo Tornatore

Abstract*—Filterless Optical Networks (FONs) (i.e., optical networks where switching nodes are solely based on passive splitters and combiners) enjoy features that are highly appreciated by network operators, such as their low cost and their energy efficiency, posing them as an alternative solution to filtered Wavelength-Switched Optical Networks (WSON) based on active switching nodes. Due to FONs' specific design criteria (the network topology must be divided into link-disjoint filterless fiber trees to avoid laser loops), traditional network problems, such as survivable virtual network mapping, shall be revisited and tackled adopting novel solutions with respect to state-of-the-art filtered WSONs. In this paper, we investigate the problem of survivable virtual network mapping (SVNM) in FONs with the aim of evaluating the cost of survivability when adopting FON technology. We first model the problem as an Integer Linear Program to establish fiber trees and provide survivable mapping of virtual networks, while minimizing cost of additional network equipment and spectrum with respect to WSON. We then propose multiple heuristic and meta-heuristic approaches to tackle large problem instances. In our numerical evaluations, we consider three scenarios: FON, WSON, and FON with pre-established fiber trees. Results show that in FON, where SVNM is jointly optimized with fiber tree establishment, the investment in additional network equipment can be largely minimized, and even avoided in some cases. In contrast, in FON with pre-established trees, amount of additional network equipment needed to guarantee survivability is significant (up to 60% with respect to WSON).

***Index Terms*—Survivability, Filterless Optical Networks, Survivable Virtual Network Mapping.**

I. INTRODUCTION

Several operators worldwide are currently struggling to identify low cost architectures for the next generation of optical metro-aggregation networks that will provide the transport technology for 5G communications and capillary deployment of Fiber-to-the-Home. As operators seek for network architectures that can support capacity growth while averting excessive costs, Filterless Optical Network (FON) is currently raising renewed attention thanks to its limited equipment expenditure and energy consumption [1], [2]. In a FON, nodes are mainly constituted by passive splitters and combiners, that replace costly Wavelength Selective Switches (WSS), hence reducing the cost of the components at the Wavelength Division Multiplexing (WDM) layer. However, the elimination of WSSs results in a *broadcast-and-select* switching approach, where switching nodes operate indistinctly on all wavelengths transported by optical fibers [3].

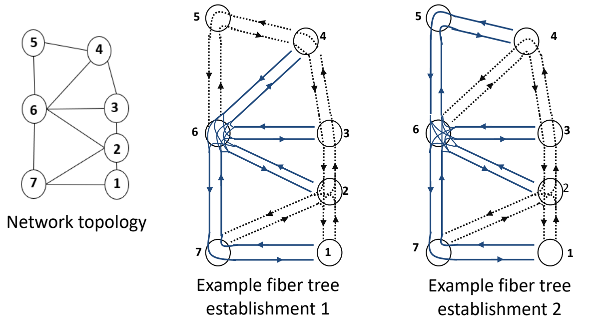
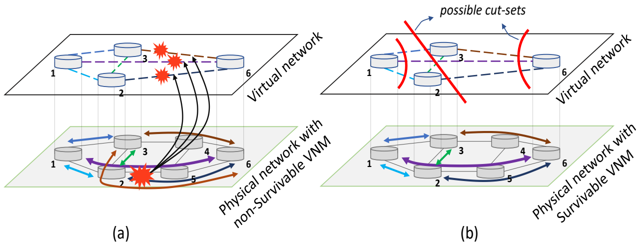


Fig. 1: Two examples of fiber tree establishment each of two fiber trees (distinguished by solid blue and dashed black lines) for a sample 7-nodes network topology.

Due to this broadcast nature, FONs suffer from spectrum waste and result in higher wavelength utilization in comparison to wavelength-switched optical networks (WSON). Moreover, when deployed in meshed networks such as, e.g., core networks, FONs require a preliminary design phase to subdivide the network topology into a set of fiber trees, i.e., a loop-free fiber coverage interconnecting add/drop nodes to prevent possible laser-loop effects due to continuous signal broadcasting and amplification [3] [4]. This process, known as *fiber tree establishment* (or fiber tree design), constrains the routing possibilities between nodes, consequently making traditional network problems more challenging. Fig. 1 shows two examples of fiber tree establishment of a sample 7-node network topology. In both examples, two link-disjoint fiber trees are considered and are shown with solid and dotted lines, respectively. Note that nodes belonging to different fiber trees cannot be connected transparently (i.e., via a direct lightpath that remains in the optical domain). For instance, in fiber tree establishment 1, node 7 cannot transparently reach node 5 passing through node 6, as input signal from node 7 at node 6 can be dropped and broadcasted towards nodes 2, 3 or 4 but not towards node 5. In this study, we focus on the



(a) (b)

Fig. 2: (a) Non-survivable VNM and (b) SVNM of a 4-node VN of 6 virtual links onto a 6-node sample physical network topology.

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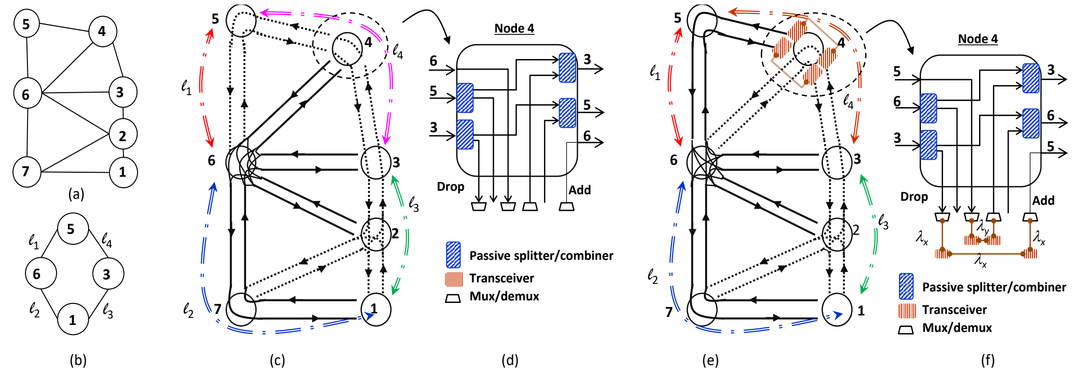

Fig. 3: (a) 7-node physical network, (b) 4-node VN, (c) and (d) show a fiber tree establishment of two fiber trees (highlighted by solid and dotted lines) and SVNM of the VN and the internal architecture of node 4, respectively, while (e) and (f) show a fiber tree establishment where the deployment of *(ITTs)* is necessary to guarantee a SVNM and the internal architecture of node 4 showing position of ITTs deployed, respectively.

problem of Survivable Virtual Network Mapping (SVNM) in the context of FONs. SVNM consists of assigning physical network resources (a route and a wavelength) to a given set of lightpath requests between node pairs, represented by *virtual links* in a *logical topology*, i.e., the *Virtual Network* (VN), such that the VN is survivable to failures in the physical topology [5], i.e., the VN does not break into isolated networks in case of link failure. Fig. 2(a) shows an example of a *non-survivable mapping* of a VN as a failure of fiber (5,2) interrupts three virtual links, (6,2), (6,3) and (6,1) and disconnects the network (node 6 becomes isolated from rest of VN). On the contrary, the mapping in Fig. 2(b) is *survivable* as no link failure can disconnect the VN. In other words, all virtual links that belong to a *cut-set* of the VN (a cut set is a set of links whose removal disconnects the VN), cannot be mapped on the same physical link. Fig. 2(b) highlights possible logical cut-sets (in red) that disconnect the VN.

In FONs, the SVNM problem is aggravated as SVNM interplays with the fiber tree establishment, presenting two main challenges:

- First, routing of transparent paths between nodes is constrained by fiber trees. As not all paths can be used, deployment of additional equipment (e.g., transceivers) might be required in FONs to guarantee SVNM.
- Second, SVNM in FON needs to take the FON broadcast nature into consideration such as to minimize the number of broadcasted wavelengths.

In this work, we address the following questions: *1) How to ensure survivability in FONs? 2) What is its cost, e.g., in terms of additional equipment and network capacity? 3) How does a proper tree establishment affect the SVNM and its cost?*

Two examples of SVNM in FON: To highlight the importance of the fiber tree establishment to optimize SVNM in FONs, consider the example in Fig. 3. We map the VN (i.e., we allocate a physical optical path to each virtual link) in Fig. 3(b) on the physical topology shown in Fig. 3(a), considering two different fiber tree establishments, shown in Figs. 3(c) and (e), respectively. In both cases, two fiber trees are considered and are shown with solid and dotted lines, respectively. As nodes belonging to different fiber tree cannot be connected transparently, the only viable solution to inter-connect nodes that do not belong to the same fiber tree is to equip specific nodes with additional *Inter-Tree Transceivers* (ITT) that serve as a Optical-electrical-Optical (OEO) bridge to allow the lightpath to traverse from one fiber tree to another, even if this means incurring in additional transceiver cost. In Fig. 3(d), we show the internal architecture of node 4 based on the fiber tree establishment of Fig. 3(c). With the considered fiber tree design, node 3, for instance, cannot transparently reach node 6 passing through node 4, as input signal from node 3 can only be dropped and broadcasted towards node 5. The impact of the fiber tree establishment on SVNM is shown in Figs. 3(c) and (e). Both figures show a survivable mapping of the virtual links ($l_1 - l_4$), i.e., a mapping that guarantees that no failure in the physical network disconnect the VN. The fiber tree establishment in Fig. 3(c) enables a feasible SVNM without using ITTs as each of the 4 virtual links ($l_1 - l_4$) is mapped on a physical path belonging to a single fiber tree (In a fiber tree, a wavelength used to map a virtual link is exclusively reserved over the entire fiber tree). On the contrary, to achieve SVNM over the fiber tree establishment in Fig. 3(d), virtual link l_4 must be mapped on a physical path belonging to two trees (crossing fiber trees at node 4) and, therefore, it requires the placement of four ITTs at node 4 (two transceivers are necessary to allow traversing one lightpath from one fiber tree to another). The internal architecture of node 4 is shown in Fig. 3(e). Here, the wavelength used by a virtual link traversing two fiber trees will be reserved on both fiber trees. This suggests that an optimized fiber tree establishment is crucial to avoid unnecessary ITTs. Yet, it might not be always possible to avoid deployment of ITTs due to the constraints imposed by the fiber tree establishment.

In our previous work [6], we modeled the SVNM problem in FONs as an integer linear program (ILP) and conducted a numerical analysis to compare network cost of SVNM to VNM in FON. Results show that while VNM does not require the deployment of additional network equipment, SVNM requires the deployment of inter-tree transceivers to guarantee logical survivability. In this work, we propose novel heuristic and meta-heuristic approaches to tackle large problem instances (with large physical network topologies and multiple VNs), and perform comprehensive quantitative evaluation of the cost (expressed in terms of transceivers and spectrum) necessary to guarantee SVNM in a FON, both when fiber trees are pre-established, and when fiber trees are to be established. When fiber trees are pre-established represents the scenario in which the infrastructure and the VNs are controlled by different entities while when fiber trees are to be established represents the case in which one entity controls both. Our numerical evaluations show that, when jointly optimizing fiber tree design and SVNM, placement of additional ITTs in the network can be avoided, and, even when unavoidable, the number of additional ITTs placed in the network is very limited. On the contrary, with pre-established fiber trees, placement of additional ITTs in the network cannot be avoided, which affects the cost efficiency of FONs.

The rest of the paper is organized as follows. Sec. II discusses related work. Sec. III formally states the problem of SVNM in FONs and includes the ILP model proposed to solve it. Sec. IV presents the proposed heuristic approaches. Sec. V discusses numerical results. Sec. VI concludes the paper.

II. RELATED WORK

In this section, we first discuss existing works that address the generic SVNM problem (i.e., not in FONs). Then, we briefly discuss works on design and resource allocation in FONs. Finally, we focus on the studies that investigated protection in FONs.

Survivable Virtual Network Mapping (SVNM): The SVNM problem in wavelength-switched optical networks has been modeled and solved in several previous works, under different assumptions [5], [7]–[10]. Refs. [5], [7], [8] proposed ILP models and heuristic approaches to perform SVNM in IP-over-WDM networks. Ref. [9] proposed evolutionary-based heuristic approaches for SVNM while Ref. [10] proposed SVNM approaches based on creating backup logical topologies to survive single link failure while minimizing network resource consumption. More general to the SVNM problem, other works such as Refs. [11]–[13] focused on the Survivable Virtual Network Embedding (SVNE) problem where the locations of the virtual nodes are an output of the problem (i.e., also embedding of logical nodes, not only of physical links, in physical network must be decided, unlike in SVNM). Refs. [11], [12], [14], [15] formulated ILP models and proposed heuristic approaches to solve the SVNE problem while Ref. [13] further studied the SVNE problem with dedicated 1+1 protection. In contrast, the SVNM in FON problem has significant differences as the design of FON (establishment of fiber trees) imposes constraints on the routing among the physical nodes which is not present in traditional networks, forcing the placement of ITTs at specific network nodes, as aspect not previously dealt with in the problem of SVNM. Moreover, in our work, we jointly perform SVNM and establish filterless fiber trees, i.e., incorporating the design of physical network, another aspect which is not previously dealt with in the scope of SVNM.

Design and Resource Allocation in FON: Several works studied the design of FONs without survivability. Refs. [3] and [16] proposed ILP models and genetic algorithms to establish fiber trees and perform routing and wavelength assignment, respectively. Ref. [17] investigated elastic FONs and proposed an ILP model for spectrum allocation with minimum spectrum consumption. Ref. [18] proposed ILP models for both the embedding and the mapping of VNs in FON however with pre-established fiber trees. Our approach is significantly different with respect to these works, that do not consider survivable mapping of VNs. **Protection in FON:** Protection in FONs has been investigated in Ref. [19], where authors establish fiber trees with the aim of maximizing demands' protection ratio proposing a multi-goal evolutionary Pareto optimization algorithm. Results show that, due to the constraints that fiber trees impose on routing, 100% protection ratio is not achievable. In fact, Ref. [20] proposes a heuristic approach to guarantee 1+1 optical-layer protection of traffic demands showing that 100% protection ratio of traffic demands is only feasible with the use of wavelength blockers. Ref. [21] investigated the amount of wavelengths required to provide protection in FON focusing on horse-shoe topologies. While protection techniques in Ref. [20], [21] use backup physical lightpaths to ensure connectivity in case of failure, the SVNM investigated in our study assumes a different approach to survivability. In SVNM, the survivability of a VN is achieved by ensuring that the VN remains connected in presence of a physical link failure, assuming IP (or, generically, logical level protocols) will re-route traffic in the remaining connected VN capacity [5]. To the best of our knowledge, no existing work has investigated the problem of establishing fiber trees and jointly performing SVNM in FONs.

III. SURVIVABLE VIRTUAL NETWORK MAPPING IN FON

A. Problem Modeling

The SVNM problem in FON can be stated as follows. **Given** a physical network topology modeled by a graph $G = (N, E)$ consisting of filterless nodes N and bidirectional links E with one fiber per direction and capacity of |W| wavelengths per fiber (W is the set of wavelengths), and a set of VNs Θ each represented by graph $G_L^\theta = (N_L^\theta, E_L^\theta)$, where N_L^θ is the set of virtual (logical) nodes and E_L^θ is the set of virtual (logical) links representing bidirectional lightpaths requests (for simplicity, we assume that each virtual link requests exactly one wavelength) of VN $\theta \in \Theta$. All $G_L^\theta = (N_L^\theta, E_L^\theta)$ constitute graph $G_L = (N_L, E_L)$ where N_L is the set of all virtual nodes and E_L is the set of all virtual links in all VNs. **Decide** i) the number of fiber trees in the network among |E| fiber trees[1], ii) the fiber tree establishment creating set of fiber trees F, iii) the placement of ITTs (if any), and iv) 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 ITTs 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 any VN in Θ [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 [3], *iii) wavelength continuity and contiguity*, and *iv)*

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[1] |E| represents the maximum number of fiber trees in the network where each link is a fiber tree by its own however such a fiber tree establishment would require performing an OEO conversion at every node.

Tab. I: Description of the variables of the ILP model.

Variable	Description
$x^{f}_{(i,j)}$	Binary, equals to 1 if physical link $(i,j) \in E$ belongs to fiber tree $f \in F$
$q^{(s,t,\theta)}_{(i,j)}$	Binary, equals to 1 if virtual link $(s,t) \in E_L$ of VN θ (also called virtual connection (s,t,θ)) is mapped on physical link $(i,j) \in E$
$z^{(s,t,\theta),f}_{(i,j)}$	Binary, equals to 1 if virtual connection $(s,t,\theta) \in E^{\theta}_{L}$ is mapped on physical link $(i,j) \in E$ belonging to fiber tree $f \in F$
$w^{(s,t,\theta),l,f}_{(i,j)}$	Binary, equals to 1 if virtual connection $(s,t,\theta) \in E^{\theta}_{L}$ is mapped on physical link $(i,j) \in E$ belonging to fiber tree $f \in F$ and uses wavelength $l \in W$
$p^{l,f}_{(i,j)}$	Binary, equals to 1 if wavelength $l \in W$ is used on link $(i,j) \in E$ belonging to fiber tree $f \in F$
$v^{l,f}_{(s,t,\theta)}$	Binary, equals to 1 if virtual connection $(s,t,\theta) \in E^{\theta}_{L}$ uses wavelength $l \in W$ on fiber tree $f \in F$
$d^{(s,t,\theta),f,r}_{(i,j),(j,o)}$	Binary, equals to 1 if virtual connection $(s,t,\theta) \in E^{\theta}_{L}$ is mapped on physical links $(i,j) \in E$ and $(j,o) \in E$ which belong to fiber trees $f \in F$ and $r \in F$, respectively
$e^{(s,t,\theta),l,f}_{(i,j),(j,o)}$	Binary, equals to 1 if virtual connection $(s,t,\theta) \in E^{\theta}_{L}$ is mapped on physical links $(i,j) \in E$ and $(j,o) \in E$ belonging to fiber tree $f \in F$ is assigned wavelength $l \in W$
$m^{(s,t,\theta),l,r,f}_{(i,j),(j,o)}$	Binary, equals to 1 if virtual connection $(s,t,\theta) \in E^{\theta}_{L}$ is mapped on physical links (i,j) and $(j,o) \in E$ belonging to fiber trees $f \in F$ and $r \in F$, respectively, using wavelength $l \in W$
$y^{f}_{(s,t,\theta)}$	Binary, equals to 1 if virtual connection $(s,t,\theta) \in E^{\theta}_{L}$ is mapped on any physical link belonging to fiber tree $f \in F$
d_f	Binary, equals to 1 if fiber tree $f \in F$ is used
g^{f}_{i}	Binary, equals to 1 if node i is an end point of a physical link belonging to fiber tree $f \in F$
$h^{l,f}_{(i,j)}$	Binary, equals to 1 if wavelength $l \in W$ on physical link $(i,j) \in E$ on fiber tree $f \in F$ is wasted (broadcasted)

maximum link capacity. As for the trade-off between the two terms of the objective function, we note that ITTs are very expensive, and we expect them to be the first priority of minimization. In fact, if an operator was primarily concerned by wavelength utilization, it would not use FON in first place, as FON has high spectrum waste. Moreover, there is not a promising trade-off between number of ITTs deployed and overall number of wavelengths occupied. In fact, the use of ITTs to cross fiber trees aggravates the overall number of wavelengths occupied as wavelengths will propagate hence be broadcasted on two fiber trees instead of one. In conclusion, we maintain our primary objective as the minimization of the number of ITTs. Compared to classical SVNM in WSON, we had to redefine the model to incorporate i) fiber tree establishment constraints, ii) placement of ITTs in FONs and iii) propagation of spectrum along fiber trees. This adds up to the complexity of the problem. We refer to the ILP model of the problem as SVNM with Tree Establishment in FON (**SVNM-TE-FON**).

In addition to *SVNM-TE-FON*, we also model a scenario, referred to as ***SVNM-FON***, in which the fiber tree design is given as an input to the problem, instead of being jointly optimized with SVNM as in the case of ***SVNM-TE-FON***. Comparing *SVNM-TE-FON* to *SVNM-FON* allows us to assess the benefits, e.g., the savings in terms of number ITTs and wavelength consumption, of jointly optimizing the fiber trees and the SVNM.

B. Integer Linear Programming Formulation

The decision variables are listed and described in Tab. I.

Objectives:

$$minimize \sum_{(i,j)\in E} \sum_{(j,o)\in E} \sum_{(s,t,\theta)\in G^{\theta}_{L}} \sum_{r\in F} \sum_{f\in F} d^{(s,t,\theta),r,f}_{(i,j),(j,o)} \quad (1)$$

$$minimize \sum_{(i,j)\in E} \sum_{f\in F} \sum_{l\in W} \Big(\sum_{(s,t,\theta)\in G^{\theta}_{L}} w^{(s,t,\theta),l,f}_{(i,j)} + h^{lf}_{(i,j)} \Big) \quad (2)$$

Objective (1) is the minimization of the number of ITTs placed and Obj. (2) is the minimization of the sum of the number of wavelengths utilized (occupied) on all links. Note that the objective function minimizes the number of inter-tree transceivers only and does not include the number of transceivers deployed at source and destination nodes of a lightpath. This is because the number of transceivers (excluding inter-tree transceivers) required at source and destination nodes depends solely on the number of virtual links forming the VN and is in fact independent of whether SVNM is performed.

Subject to:

Mapping and Survivability Constraints: Constr. 3 is the virtual link mapping and flow constraint and it ensures that every virtual connection (s,t,θ) of a VN θ is mapped onto one physical path of the physical topology. Constr. 4 is the survivability constraint and it guarantees that the mapping of all virtual links of a VN is survivable, enforcing that all virtual links which belong to a cut-set of the VN cannot have a mapping on the same physical link, where $CS(S^{\theta}, N^{\theta}_{L} - S^{\theta})$ represents the set of virtual links that belong to a cut of VN $G^{\theta}_{L} = (N^{\theta}_{L}, E^{\theta}_{L})$ where $S^{\theta} \subset N^{\theta}_{L}$ represents a subset of logical nodes N^{θ}_{L}[2].

$$\sum_{j:(i,j)\in E} q^{(s,t,\theta)}_{(i,j)} - \sum_{j:(j,i)\in E} q^{(s,t,\theta)}_{(j,i)} = \begin{cases} 1 & if \;\; s = i \\ -1 & if \;\; t = i \\ 0 & otherwise \end{cases} \quad (3)$$

$$\forall i \in N, (s,t,\theta) \in G^{\theta}_{L}$$

$$\sum_{(s,t)\in CS(S^{\theta}, N^{\theta}_{L} - S^{\theta})} q^{(s,t,\theta)}_{(i,j)} < |CS(S^{\theta}, N^{\theta}_{L} - S^{\theta})| \quad (4)$$

$$\forall (i,j) \in E, S^{\theta} \subset N^{\theta}_{L}$$

Fiber Tree Establishment Constraints: Constr. 5-10 establish fiber trees and guarantee all fiber tree establishment

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[2] See Ref. [5] for more details on how the cut-set is found.

constraints. Constr. 5 assigns each physical link (i, j) to exactly one fiber tree f, while Constr. 6 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. 7 enforces that fiber trees are loops-free, by ensuring that the sum of links belonging to a fiber tree that connect a subset (N_{sub} of nodes of the physical topology ($N_{sub} \subset N$, where N represents all the possible sets of physical nodes) is less than cardinality (N_{sub} of the subset of nodes, i.e., the number of nodes inside N_{sub}. For instance, if $\mathrm{N}_{\mathrm{sub}}$ contains three nodes then at most 2 links that connect those nodes can belong to the same fiber tree. Constr. 8-10 guarantee that links assigned to same fiber tree f are connected by ensuring that the sum of links belonging to f ($\sum_{(i,j)\in E} x^f_{(i,j)}$) that connect each of the nodes belonging to[3] f (if link (i, j) belongs to f then g^f_i = 1 and g^f_j = 1) is exactly equal to 2 $\cdot$ (*number of nodes belonging to fiber tree f - 1*). Constr. 11-14 ensure consistency between mapping and fiber tree establishment assignment.

$$\sum_{f\in F} x^f_{(i,j)} = 1 \qquad \forall (i,j) \in E \tag{5}$$

$$x^f_{(i,j)} - x^f_{(j,i)} = 0 \qquad \forall (i,j) \in E, f \in F \tag{6}$$

$$\begin{gathered}\sum_{(i,j)\in E(N_{sub})} x^f_{(i,j)} \ \le\ 2 \cdot |N_{sub}| - 1 \\ \forall f \in F, N_{sub} \subset N : |N_{sub}| > 2\end{gathered} \tag{7}$$

$$\sum_{(i,j)\in E} x^f_{(i,j)}/M \le d_f \le \sum_{(i,j)\in E} x^f_{(i,j)} \qquad \forall f \in F \tag{8}$$

$$\sum_{i:(i,j)\in E} x^f_{(i,j)}/M \ \le\ g^f_j \le \sum_{i:(i,j)\in E} x^f_{(i,j)} \qquad \forall j \in N, f \in F \tag{9}$$

$$\sum_{(i,j)\in E} x^f_{(i,j)} \ = 2 \cdot (-d_f \ + \sum_{i\in N} g^f_i) \qquad \forall f \in F \tag{10}$$

$$z^{(s,t,\theta),f}_{(i,j)} \le x^f_{(i,j)} \qquad \forall (i,j) \in E, (s,t,\theta) \in G^\theta_L, f \in F \tag{11}$$

$$z^{(s,t,\theta),f}_{(i,j)} \le q^{(s,t,\theta)}_{(i,j)} \qquad \forall (i,j) \in E, (s,t,\theta) \in G^\theta_L, f \in F \tag{12}$$

$$\begin{gathered}z^{(s,t,\theta),f}_{(i,j)} \ge q^{(s,t,\theta)}_{(i,j)} \ + \ x^f_{(i,j)} - 1 \\ \forall (i,j) \in E, (s,t,\theta) \in G^\theta_L, f \in F\end{gathered} \tag{13}$$

$$z^{(s,t,\theta),f}_{(i,j)} \le y^f_{(s,t,\theta)} \qquad \forall (i,j) \in E, (s,t,\theta) \in G^\theta_L, f \in F \tag{14}$$

Wavelength Assignment Constraints: Constr. 15 and 16 are the wavelength continuity and contiguity constraints and they ensure that each virtual connection is assigned exactly one (and the same) wavelength on the fiber tree it is mapped on[4]. Constr. 17-19 guarantee consistency between wavelength assignment, link mapping and fiber tree design constraints. Constr. 20 and 21 ensure that virtual connections cannot use same wavelength on the same physical path and that a wavelength cannot be occupied by more than one virtual connection.

$$\sum_{l\in W}\sum_{f\in F} v^{l,f}_{(s,t,\theta)} \ge 1 \qquad \forall (s,t,\theta) \in G^\theta_L \tag{15}$$

$$\sum_{l\in W} v^{l,f}_{(s,t,\theta)} = y^f_{(s,t,\theta)} \qquad \forall (s,t,\theta) \in G^\theta_L, f \in F \tag{16}$$

$$w^{(s,t,\theta),l,f}_{(i,j)} \le v^{l,f}_{(s,t,\theta)} \forall (i,j) \in E, (s,t,\theta) \in G^\theta_L, f \in F, l \in W \tag{17}$$

$$\begin{gathered}w^{(s,t,\theta),l,f}_{(i,j)} \le z^{(s,t,\theta),f}_{(i,j)} \\ \forall (i,j) \in E, (s,t,\theta) \in G^\theta_L, f \in F, l \in W\end{gathered} \tag{18}$$

$$\begin{gathered}w^{(s,t,\theta),l,f}_{(i,j)} \ge z^{(s,t,\theta),f}_{(i,j)} \ + \ v^{l,f}_{(s,t,\theta)} - 1 \\ \forall (i,j) \in E, f \in F, l \in W, (s,t,\theta) \in G^\theta_L\end{gathered} \tag{19}$$

$$\begin{gathered}w^{(s,t,\theta),l,f}_{(i,j)} + w^{(u,v,\theta),l,f}_{(i,j)} \le 1 \qquad \forall f \in F, l \in W, (i,j) \in E, \\ (s,t,\theta), (u,v,\theta) \in G^\theta_L : (s,t,\theta) \neq (u,v,\theta)\end{gathered} \tag{20}$$

$$\begin{gathered}w^{(s,t,\theta),l,f}_{(i,j)} \ + h^{l,f}_{(i,j)} \le 1 \\ \forall (i,j) \in E, (s,t,\theta) \in G^\theta_L, l \in W, f \in F\end{gathered} \tag{21}$$

Transceiver Placement Constraints: Constr. 22 and 23 identify the nodes in which a physical path mapping a virtual connection crosses two fiber trees and ensure ITTs are placed at such nodes (($d^{(s,t,\theta),f,r}_{(i,j),(j,o)}$) = 1 if a virtual connection (s, t, θ) is mapped on physical links (i, j) and (j, o) belonging to fiber trees f and r, respectively).

$$\begin{aligned}&0 \le w^{(s,t,\theta),l,f}_{(i,j)} + w^{(s,t,\theta),l,r}_{(j,o)} - 2 \cdot m^{(s,t,\theta),l,f,r}_{(i,j),(j,o)} \le 1 \\ &\forall f, r \in F, (s,t,\theta) \in G^\theta_L, (i,j), (j,o) \in E, \\ &l \in W : f \neq r, i \neq o, j \neq s, j \neq t\end{aligned} \tag{22}$$

$$\begin{gathered}0 \le z^{(s,t,\theta),f}_{(i,j)} + z^{(s,t,\theta),r}_{(j,o)} - 2 \cdot d^{(s,t,\theta),f,r}_{(i,j),(j,o)} \le 1 \quad \forall f \in F, r \in F, \\ (s,t,\theta) \in G^\theta_L, (i,j), (j,o) \in E : i \neq o, f \neq r\end{gathered} \tag{23}$$

Wavelength Broadcast Constraints: Constr. 24 identifies the nodes of a fiber tree along which a virtual connection is mapped. Constr. 25 and 26 ensure that signals incoming to nodes are broadcasted over outgoing links if the links belong to the same fiber tree. Constr. 27-29 are consistency constraints ensuring that broadcasted wavelengths are reserved and cannot be used by any virtual connection. Constr. 30 is the fiber capacity constraint.

$$\begin{gathered}0 \le w^{(s,t,\theta),l,f}_{(i,j)} + w^{(s,t,\theta),l,f}_{(j,o)} - 2 \cdot e^{(s,t,\theta),l,f}_{(i,j),(j,o)} \le 1 \quad \forall f \in F, l \in W, \\ (s,t,\theta) \in G^\theta_L, (i,j), (j,o) \in E : i \neq o, j \neq s, j \neq t\end{gathered} \tag{24}$$

$$\begin{gathered}p^{l,f}_{(j,u)} \ge \sum_{(s,t,\theta)\in G^\theta_L} e^{(s,t,\theta),l,f}_{(i,j)(j,o)}/M \quad \forall j \in N, f \in F, l \in W, \\ (i,j), (j,o), (j,u) \in E : i \neq u, u \neq o, o \neq i\end{gathered} \tag{25}$$

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[3] A nodes is considered to belong to a fiber tree if any of the links connected to it belongs to the fiber tree.

[4] In case a virtual connection is mapped on physical links belonging to different fiber trees, wavelength conversion is possible.

$$p^{l,f}_{(j,u)} \geq \sum_{(s,t,\theta)\in G^{\theta}_{L}} m^{(s,t),\theta,l,f,r}_{(i,j),(j,o)}/M \quad \forall f,r \in F, j \in N, \tag{26}$$
$$l \in W, (i,j),(j,o),(j,u) \in E : f \neq r, i \neq u, u \neq o, o \neq i$$

$$p^{l,f}_{(j,u)} \geq \sum_{(s,t,\theta)\in G^{\theta}_{L}:t=j} w^{(s,t,\theta),l,f}_{(i,j)}/M \tag{27}$$
$$\forall j \in N, (i,j),(j,u) \in E, l \in W : i \neq u, f \in F$$

$$p^{l,f}_{(j,u)} \geq h^{l,f}_{(i,j)} \quad \forall j \in N, (i,j),(j,u) \in E, f \in F, l \in W : i \neq u \tag{28}$$

$$0 \leq p^{l,f}_{(i,j)} + x^{f}_{(i,j)} - 2\cdot h^{l,f}_{(i,j)} \leq 1 \quad \forall f \in F, (i,j) \in E, l \in W \tag{29}$$

$$\sum_{l\in W} h^{l,f}_{(i,j)} \leq |W| \qquad \forall (i,j) \in E, f \in F \tag{30}$$

The ***SVNM-TE-FON*** problem is solved by first optimizing the number of ITTs ($|ITT|$) through Obj. (1) and then by optimizing Obj. (2). To optimize Obj. (2), we add Const. 31 which constrains the number of ITTs to be equal to that found by Obj. (1):

$$\sum_{(i,j)\in E} \sum_{(j,o)\in E} \sum_{(s,t,\theta)\in G^{\theta}_{L}} \sum_{r\in F} \sum_{f\in F} d^{(s,t,\theta),r,f}_{(i,j),(j,o)} = |ITT| \tag{31}$$

For ***SVNM-FON***, the network scenario in which the fiber tree design is given as an input the problem, x^{f}_{ij} and g^{f}_{i} are input parameters and are no longer decision variable. Consequently, constraints regarding fiber tree establishment (Constr. 5-10) are discarded.

C. *NP-hardness of* SVNM-TE-FON *and* SVNM-FON

Ref. [22] proves that the Virtual Network Embedding (VNE) problem, i.e., the allocation of physical links and physical nodes in a given substrate network to VNs is NP-hard, as it relates to the multi-way separator problem. Even with a given virtual node mapping in the VNE problem, the problem of optimally mapping virtual links on a given substrate network, which is also known as the *VNM problem*, reduces to the unsplittable flow problem, which is a known NP-hard problem [22] [23]. In this context, *SVNM-FON*, the problem of SVNM in FON with placement of ITTs to allow mapping a virtual link over physical links pertaining to two different fiber trees to guarantee survivability is proved to be NP-hard. Moreover, with respect to *SVNM-FON*, *SVNM-TE-FON* further encompasses the fiber tree establishment problem, and hence can be proven to be NP-hard.

IV. HEURISTIC APPROACHES

In this section, we present the heuristic approaches developed to solve the SVNM problem in FON in the two cases considered, i.e., when the fiber trees are pre-established (i.e., given) and when the fiber trees are to be established. For the case with pre-established fiber trees, we develop a meta-heuristic approach, referred to as *SMART-FON*, which is a modified FON-adapted version of SMART (Survivable Mapping Algorithm by Ring Trimming) algorithm, a heuristic approach proposed in Ref. [24] for the SVNM problem. In *SMART-FON*, we develop and make use of a simple ILP model and a local search algorithm to adapt *SMART* to the SVNM problem in FON. For the case where the fiber trees need to be established, we propose a heuristic approach referred to as *SMART-TE-FON*. *SMART-TE-FON* is a two-step approach which, as a first step, generates fiber tree establishment solutions by a genetic algorithm and, as a second step, applies *SMART-FON* to perform SVNM in FON for all fiber tree designs found by the first step with the aim of (1) minimizing number of inter-tree transceivers and (2) minimizing overall wavelengths occupied. As a comparison term for WSON, we used the *SMART* algorithm previously proposed in [24] [8]. The choice of adopting *SMART* to solve the SVNM problem in WSON is based on findings in Ref. [24], where *SMART* is proven to be more scalable and rapidly convergent with respect to other heuristics based on Tabu Search [7] [25] and Simulated Annealing [26] designed to solve the same problem. Tab. II lists the heuristic approaches considered in each network scenario.

Tab. II: Heuristic approaches considered for each network scenario.

Network Scenario	**Heuristic Approach**
WSON	SMART [24]
FON: Fiber Trees Given	SMART-FON (see Sec. IV-B)
FON: Fiber Trees to be established	SMART-TE-FON (see Sec. IV-C)

A. *Background on SMART Algorithm*

Before explaining our new proposed heuristics, we briefly introduce *SMART*, as this algorithm is an important building block of both *FON-SMART* and *TE-FON-SMART*. *SMART* consists in breaking the problem of cut-disjoint mapping of the virtual links of a VN into smaller problems, which are easier to solve, making it a scalable approach. First, let us define *G = (N,E)* as an undirected graph that represents the physical topology, $\mathrm{G_L} = (\mathrm{N_L},\mathrm{E_L})$ as an undirected graph which represents the VN, and $C \subset E_{\mathrm{L}}$ a cycle (loop) contained in the VN. We also define two main concepts: **Contraction** of an edge (or a set of edges) is the elimination of the edge from the topology merging in a new node the extreme nodes of the edge. All the remaining edges that were connected to one of the merged nodes become connected to this new node. The resulting contracted topology will be called $\mathrm{G_C}$. **Disjoint Mapping** represents the mapping of a subset of VN edges over the physical topology $S \subset E_{\mathrm{L}}$ such that no physical link can carry more than a virtual link.

SMART is initialized giving in input the physical topology G, the VN $\mathrm{G_L}$ and the contracted topology $\mathrm{G_C} = \mathrm{G_L}$. It proceeds as follows:

Step 1: Select a cycle from the contracted topology ($C \subset G_{\mathrm{C}}$) giving priority to smaller cycles.

Step 2: Map the selected cycle in a disjoint way. If not possible, *SMART* returns to *step 1* to select another cycle from the ones not selected previously. In this step, shortest path routing is used for virtual link mapping over the physical topology.

Step 3: Contract the mapped loop in the topology $\mathrm{G_C}$.

Step 4: If the contracted VN $\mathrm{G_C}$ is composed by only one node, then map the remaining self-loops (here each virtual link represents a loop). Otherwise, return to *step 1.*

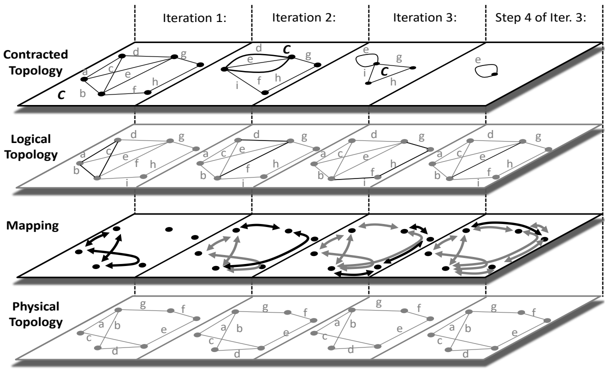

Fig. 4: Example of the iterations of SMART [8].

Combining all the mappings of each iteration, we obtain a SVNM. Fig. 4 shows a schematic representation of the iterations of *SMART*. We refer to using *SMART* in WSON as *SMART-WSON*.

B. Fiber Trees Given: FON-Adaptive SMART for SVNM in FON (SMART-FON)

SMART-FON is a FON-adapted modified version of *SMART*. Specifically, in *step 2* of *SMART*, virtual link mapping is performed through shortest path routing for each virtual link over the physical topology. Applying the same procedure in FON may result in the need of ITTs due to the possible crossing of fiber trees. To mitigate this drawback, we modify *step 2* by developing a simple ILP model to perform the mapping, observing the disjoint survivable mapping constraint, with the aim of minimizing the number of ITTs deployed. Note that applying an ILP model at this step, as we will see later, does not heavily impact the computational time of *SMART-FON* as the ILP has to deal with a relatively small instance of the problem at every iteration.

The following is the ILP formulation[5]. **Objective Function:** Obj. 32 is the objective function which aims to minimize the number of ITTs deployed.

$$min \sum_{(i,j)\in E} \sum_{(r,k)\in E} \sum_{(s,t)\in E_L} d^{(s,t)}_{(i,j),r,k} \tag{32}$$

Subject to: Constr. 33 and 34 ensure the mapping of each virtual link (s,t) while guaranteeing that virtual links are not mapped on same physical link. Since we have only one loop per iteration, the cut-set constraint (Constr. 4 in Sec. III) collapses to the requirement of not having more than a virtual link mapped over the same physical link. Constr. 35 identifies whether a virtual link crosses fiber trees. The formulation also includes wavelength assignment constraints however we omit showing them in this section.

$$\sum_{j:(i,j)\in E} q^{(s,t)}_{(i,j)} - \sum_{j:(j,i)\in E} q^{(s,t)}_{(j,i)} = \begin{cases} 1 & if \;\; s=i \\ -1 & if \;\; t=i \\ 0 & otherwise \end{cases}$$
$$\forall i \in N, \; (s,t) \in E_L \tag{33}$$

$$\sum_{(s,t)\in E_L} q^{(s,t)}_{(i,j)} \le 1 \qquad \forall (i,j) \in E \tag{34}$$

$$0 \le q^{(s,t)}_{(i,j)} + q^{(s,t)}_{(j,o)} - 2 \cdot d^{(s,t)}_{(i,j),(j,o)} \le 1$$
$$\forall (s,t) \in E_L, (i,j) \in E(f), (j,o) \in E(r) : i \ne o, f \ne r \tag{35}$$

After performing the mapping in each iteration through the ILP model, *SMART-FON* continues until a SVNM solution is found, i.e., until the VN is composed of only one node (steps 3 and 4 of *SMART-FON*).

Finally, since the outcome of *SMART-FON* might not be optimal as the ILP model performs local optimum choices at each iteration, we perform an additional step adopting a *Local Search* algorithm. The *Local Search* algorithm finds the set of virtual links that cross fiber trees, i.e., that require ITTs, and tries mapping them on different physical paths without violating the survivability constraint[6]. The steps taken are as follows:

1) Find the set of virtual links mapped over two fiber trees and a set of possible alternative mappings for each of them.
2) Select a virtual link and iterate over the set of alternative mappings to find a solution which requires lower number of ITTs or same number of ITTs but lower number of wavelengths occupied with respect to the solution previously found.
3) If an alternative mapping is found, check if it violates the cut-disjointness condition[7].
4) If no alternative mapping is available or if the cut-disjointness condition is violated, return to point 2 considering next virtual link in list.

For the case of multiple VNs, the VNs are sorted and the algorithm is run separately for each VN, iterating over all VNs. Note that, when given the fiber trees, the SVNM of each VN can be separately optimized as far as no link capacity is exceeded. In case a link's capacity is exceeded, the sorting of the VNs is changed and the algorithm is run again. Finally, the SVNM of all VNs providing best solution is selected.

C. Fiber Trees to be Established: Genetic-Based TE Algorithm + FON-adapt SMART (SMART-TE-FON)

SMART-TE-FON consists in creating, given a physical network topology, a set of different fiber tree establishments through a Genetic Algorithm (GA)[8] and then in applying, given a set of VNs, *SMART-FON* on each fiber tree establishment obtained. Then, the fiber tree establishment and SVNM solution providing the best results in terms of number of ITTs and wavelength utilization is considered as the solution of *SMART-TE-FON*.

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[5] We omit the index of the VN as here we consider one VN as once.

[6] We select, among the virtual links that cross fiber trees, only those that have their end-nodes (source and destination) over one fiber tree

[7] At this step, we do not need to check all possible cut-sets but we simply check if the VN remains connected simulating failures over the physical links used by the new physical path.

[8] Genetic-based algorithms have proved to be an efficient approach to establish fiber trees in FON (see Ref. [3]).

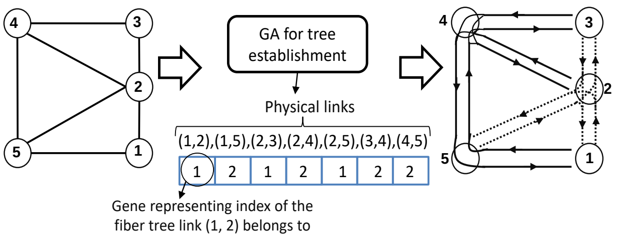

Fig. 5: GA chromosome structure and an example of a tree establishment.

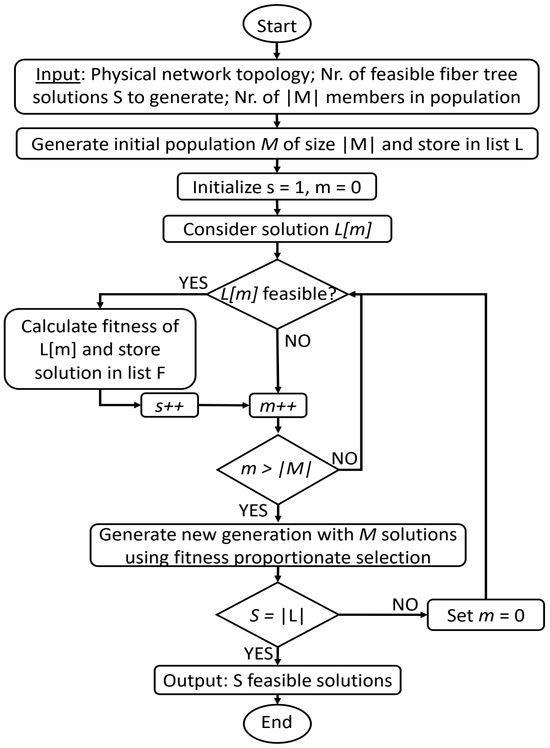

Fig. 6: Flowchart of the GA for fiber tree establishment.

The objective of the GA is to establish fiber trees that meet the fiber tree establishment constraints (i.e., a fiber tree must not contain loops, and both directions of a physical link must belong to same fiber tree). We refer to a fiber tree establishment that meets the constraints as a feasible solution. Each individual (chromosome) of the population GA represents a solution of the problem and consists of a number of elements (genes), where a gene is an integer value representing the index of the fiber tree a bidirectional physical link belongs to. Fig. 5 shows the chromosome structure and an example of fiber tree establishment. The fitness value of a solution, which we aim to minimize, is the number of fiber trees (can range from 2 to |E|, where |E| is the number of bidirectional links in the network) while the stopping condition is a predefined number of feasible solutions found.

Figure 6 shows the flowchart of the GA. First, the initial population is randomly generated. Then, iterating over all the population, a feasibility check is performed and feasible individuals (i.e., solutions meeting the fiber tree establishment constraints) are stored along with their fitness value. Then, using *fitness proportionate selection*, parent chromosomes are selected and operations of crossover and mutation are performed in order to create off-springs. In the crossover operation, we randomly select a subset of genes of the first parent and then fill the remainder of the chromosome with the genes of the second parent. In the mutation, each gene representing to which fiber tree a link belongs can change value and therefore change fiber tree it belongs to. Since we need to find different fiber trees establishments, we use high mutation probability index (10%) in order to span diverse solutions. The GA continues until the pre-defined number of feasible solutions is found.

After terminating the GA, *SMART-FON* is applied on each feasible solution of fiber tree design and the solution providing best results is considered.

For the case of multiple VNs, we perform SVNM for each VN iterating over all VNs for each fiber tree design found by the GA. Finally, the fiber tree design and SVNM providing best solution is selected.

D. Complexity of the Heuristic Algorithms

SMART: Ref. [8] proves that i) the complexity of one iteration of *SMART* is dominated by the disjoint mapping performed in *step 2*, which uses O(1) times the Dijkstra shortest path algorithm, and therefore has the complexity of Dijkstra algorithm $O(Dijkstra)$, and ii) the number of iterations needed to map N virtual links and converge to a successful solution is in the order of $O(N)$ edges and therefore, since the worst case complexity of Dijkstra $O(N^2)$, the worst case complexity of SMART algorithm for a one VN is $O(Dijkstra) \cdot O(N) = O(N^3)$. **SMART-FON** consists of a modified version of *SMART* which utilizes an ILP at step 2 to perform disjoint mapping of virtual links, one at a time, instead of the Dijkstra algorithm originally applied in *SMART*, and 2) of a local search algorithm that searches for alternative mapping of each virtual link. To map N virtual links, the complexity of the first part is $O(N^2)$ and that of the worst case of the local search is $O(N) \cdot O(N^2) = O(N^3)$. Therefore, the worst case complexity of *SMART-FON* is in the order of $O(N^3)$. **SMART-TE-FON** performs fiber tree establishment through a GA and then utilizes *SMART-FON*, whose complexity is proved in the order of $O(N^3)$. The complexity of the GA depends on the number of times the fitness function is evaluated and the genetic operations performed. For number of generations G, size of population P and size of chromosome M, the complexity of the GA is in the order of $O(G \cdot P \cdot M)$.

V. ILLUSTRATIVE NUMERICAL RESULTS

This section presents numerical results. We first compare the ILP and the heuristic approaches considering relatively small instances of the problem. Then, we present results of larger instances with one VN to provide a sensitivity analysis and to investigate the impact of the VN connectivity degree β on cost of survivability in FONs. Finally, we present results on the more generic case of multiple co-existing VNs to investigate the impact of number of VNs on cost of survivability in FONs.

A. Evaluation Settings

Table III lists the ILP models and heuristic approaches of each network scenario. We implemented the ILP using

Tab. III: ILP models and heuristic approaches of each network scenario.

Network Scenario	ILP Model	Heuristic Approach
WSON	SVNM-WSON	SMART-WSON
FON: Fiber Trees Given	SVNM-FON	SMART-FON
FON: Fiber Trees to be established	SVNM-TE-FON	SMART-TE-FON

AMPL and we used CPLEX 12.10 to solve all the three ILP versions of the optimization problem. All evaluations for ILP and heuristic approaches are performed on a workstation with Intel(R)Core(TM) i5-8400 CPU (6 cores @ 2.80GHz) processor and 32768 MB of memory. We compare the performance of the network scenarios in terms of i) *percentage of ITTs deployed with respect to the WSON case* (*%ITT*) and ii) *total wavelength consumption* (*Nr. Wavelengths*). For more clarity, we give an example of calculation of *%ITT*. To map a VN formed by 5 virtual bi-directional links in WSON, 10 transceivers are required (2 transceivers per directional virtual link). While 10 transceivers is the minimum number of transceivers required to map the VN, additional ITTs may be required to allow mapping a virtual link over two different fiber trees to guarantee survivability. In case four additional ITTs are required, *%ITT* will be equal to 40%. In short, *%ITT* represents the additional cost of survivability in a FON vs. WSON.

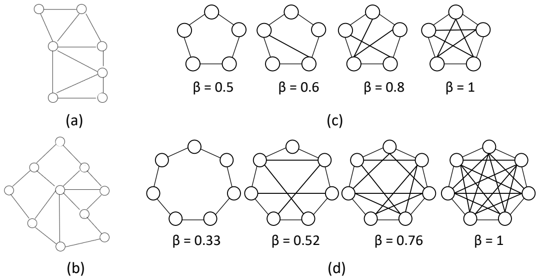

Fig. 7: The (a) 7-node and (b) 10-node physical networks, and the set of VNs ((c) and (d)) considered in the evaluations.

B. Comparison between ILP and Heuristic Approaches

We first benchmark the performance of the heuristic against ILP. As physical networks, we consider a 7-node German network with 11 bi-directional links (shown in Fig. 7(a)) and a 10-node Italian network with 15 bi-directional links (shown in Fig. 7(b)) with link capacity L equal to 40 wavelengths. We consider various VNs with increasing connectivity degree, β, defined as the ratio between the number of links in the considered VN and that in the full-mesh VN. We form VNs by randomly selecting the set of nodes constituting them, and then by randomly connecting the nodes through virtual links until the desired number of virtual links is reached. The only constraint we impose is that each virtual node is connected to two other virtual nodes, as otherwise an SVNM cannot be guaranteed. For the 7-node German network, we consider a 5-node VN with β ranging from 0.5 to 1 (shown in Fig. 7(c)), whereas for the 10-node Italian network we consider a 7-node VN with β ranging from 0.33 to 1 (shown in Fig. 7(d)). Note that β values are different in the two cases as we consider VNs with different number of nodes.

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 designs, we perform, for every node mapping and value of β, 5 different evaluations considering 5 different fiber tree designs optimized to guarantee highest network connectivity degree[9].

Table IV reports the results comparing the ILP and the heuristic approaches for the two FON scenarios, fiber trees given and fiber trees to be established, for the 7-node German network and the 10-node Italian network, respectively. Focusing initially on the scenario of fiber trees given, ILP and heuristic (*SMART-FON* in this case) return same performance in terms of *%ITT* (i.e., the main optimization objective). In terms of *Nr. Wavelengths* (second objective of the optimization), *SMART-FON* has an optimality gap ranging up to 8.5% when β is 0.8 in the 7-node German topology and up to 6.4% when β is 0.52 in the 10-node Italian topology, respectively.

Considering the case of fiber trees to be established, (*SMART-TE-FON* shows same performance as the ILP in terms of *%ITT* with no additional ITTs deployed. In terms of *Nr. Wavelengths*, *SMART-TE-FON* has an optimality gap ranging up to 6% and 7.6% in the 7-node German and 10-node Italian, respectively. In conclusion, the performance of the heuristic approach does not show any optimality gaps with respect to the first objective of the optimization problem (*%ITT*) and an acceptable optimality gap in regards to the second objective (*Nr. Wavelengths*).

Regarding the execution time, for the case with pre-established fiber trees, *SMART-FON* has a significantly lower execution time than the ILP model, especially for β equal to 1 for the 10-node topology, as it requires 0.39 seconds while the ILP 79.3 seconds. In the case fiber trees are jointly optimized with SVNM, *SMART-TE-FON* has an execution time in the same order of that of the ILP for low values of β while it has a significantly lower execution time for high values of β. In conclusion, the proposed heuristic approaches outperform their counterpart ILP models in terms of scalability paying off only a small optimality gap.

C. Evaluations on Large Problem Instances with Single VN: Impact of β

We now perform a sensitivity analysis with a single VN to investigate the impact of the VN connectivity degree β on cost of survivability in FONs. We consider, as physical networks, a 17-node (26 bidirectional links) topology and a 23-node (41 bi directional links) topology (shown in Fig. 9(a) and Fig. 9(b) respectively) with link capacity L = 40 wavelengths. For the 17-node topology, we consider an 8-node VN with β ranging from 0.29 to 1 (shown in Fig. 9(c)) while for the 30-node topology we consider a 10-node VN with β ranging between 0.22 and 1 (shown in Fig. 9(d)).

1) Discussion on Inter-Tree Transceivers: Figure 8(a) shows the *percentage of additional ITTs* (*%ITT*) required to guarantee SVNM in FON (with respect to WSON) in the 17-nodes and the 23-nodes topologies as a function of β. For

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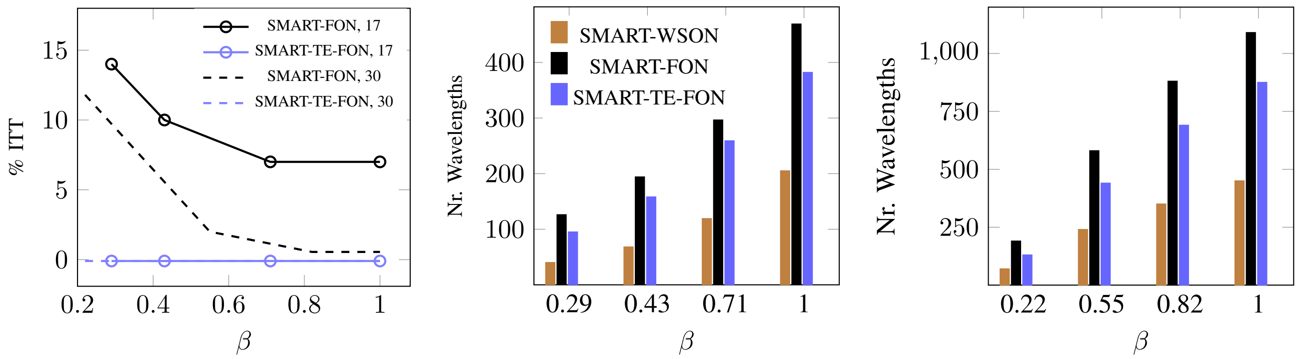
[9] The highest network connectivity degree of fiber tree establishment is measured by the number of possible routes between filterless network nodes.

Tab. IV: Comparison of the ILP models and the heuristic approaches in terms of percentage of additional ITTs, wavelength consumption, optimality gap and execution time in the two FON scenarios for the 7-node and the 10-node networks.

7-Node Network		**% transceivers (% gap vs. ILP)**				**Nr. wavelengths (% gap vs. ILP)**				**Execution time (sec.)**			
Network scenario	**Approach**	β = 0.5	0.6	0.8	1.0	0.5	0.6	0.8	1.0	0.5	0.6	0.8	1.0
Fiber Trees Given	ILP: SVNM-FON	14.5	6.5	2.2	1.8	32.8	40.5	54.1	67.2	1.7	5.1	18.8	21.2
	SMART-FON	14.5 (0)	6.5 (0)	2.25 (0)	1.8 (0)	33.7 (2.8)	43 (6.1)	58.5 (8.5)	70.9 (5.4)	0.13	0.18	0.28	0.39
Fiber Trees to be Established	ILP: SVNM-TE-FON	0	0	0	0	28.6	34.6	46.3	57.6	11.7	70.6	319.2	768.8
	SMART-TE-FON	0	0	0	0	29 (1.3)	34.6 (0)	48 (3.6)	60.3 (4.6)	65.6	68	73	78.3
10-Node Network		**% transceivers (% gap vs. ILP)**				**Nr. wavelengths (% gap vs. ILP)**				**Execution time (sec.)**			
Network scenario	**Approach**	β = 0.33	0.52	0.76	1.0	0.33	0.52	0.76	1.0	0.33	0.52	0.76	1.0
Fiber Trees Given	ILP: SVNM-FON	25	4	2	1	62.1	95.8	139.6	179.4	5.3	25.5	50.7	79.3
	SMART-FON	25 (0)	4 (0)	2 (0)	1 (0)	64.6 (4)	102 (6.4)	148.5 (6.3)	188.8 (5.2)	0.13	0.18	0.28	0.39
Fiber Trees to be Established	ILP: SVNM-TE-FON	0	0	0	0	40.3	75.3	119.7	161	80.8	28042.8	88064.3	176449.5
	SMART-TE-FON	0	0	0	0	42.6 (5.7)	79 (4.9)	128.6 (7.4)	173.3 (7.6)	81	95.1	115.1	133.5



(a) % ITT (b) Wavelengths used (17-nodes topology) (c) Wavelengths used (30-nodes topology)

Fig. 8: *%ITT* and *Nr. Wavelengths* for the different network scenarios as a function of β for two the 17-nodes (referred to as 17 in legend of (a)) and the 30-nodes (30 in legend of (a)) physical topologies.

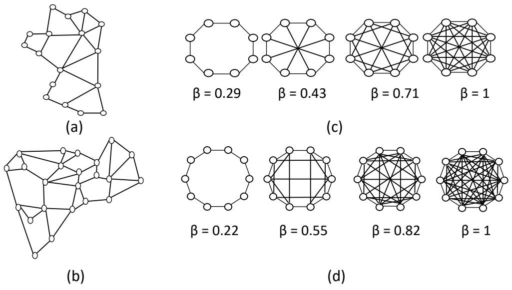


Fig. 9: The (a) 17-node and (b) 23-node physical networks, and the set of VNs ((c) and (d)) considered in the evaluations.

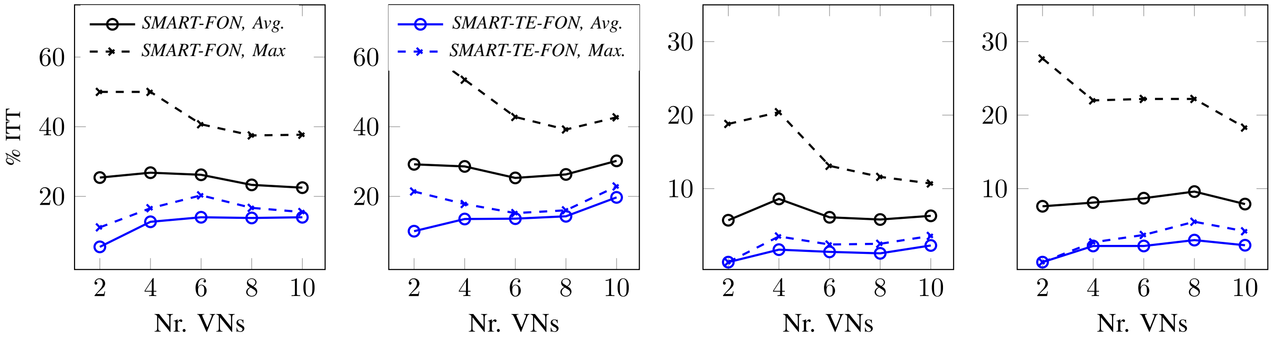
the case in which fiber trees are given, we apply *SMART-FON* algorithm and for the case in which fiber trees are to be established, i.e., optimized jointly with SVNM, we apply *SMART-TE-FON* (see Tab. II).

For the case in which fiber trees are given, *SMART-FON* requires up to 14% and up to 11.8% of *%ITT* for the 17- and the 23-nodes networks, respectively. When fiber trees are established jointly with SVNM, *SMART-TE-FON* devises a solution without deploying additional ITTs in both 17- and 23-nodes networks, *showing that jointly optimizing the fiber tree design and the SVNM is decisive to avoid additional ITTs*.

Furthermore, we comment on the behavior of *%ITT* with respect to β. Results show that *%ITT* required to guarantee survivability decreases as β increases. This is because when the connectivity degree of the VN β is relatively low, mappings of virtual links are restricted to specific paths to guarantee network survivability, which require deployment of ITTs. Conversely, for higher β, the nodal degree of the VN is higher as more logical paths must be mapped, hence more physical paths mapping virtual links while guaranteeing survivability become available, thus reducing the need of additional ITTs (please refer to Ref. [6] for more detail). Here, another option to guarantee survivability without deploying ITT would be to re-adapt the VN by purposely adding one or more virtual links. However, we argue that to eliminate the need for four additional ITT to map a virtual link over two fiber trees, at least one virtual link needs to be added to the VN, which ends up utilizing the same amount of additional transceivers. In other words, adding virtual links to the VN might help reducing number of ITT deployed but does not help reducing the cost. Beside, adding virtual links does not necessarily guarantee a SVNM. Results of Tab. IV and Fig. 8 show that even for VN with β = 1, additional ITT remain needed to guarantee survivability.

2) Discussion on Wavelength Consumption: Figures 8(b)-(c) show the overall number of wavelength channels used for the three network scenarios (Tab. II) in the 17-node and the 23-node topologies, respectively. As expected, FON requires a significantly larger number of wavelength channels compared to the WSON which is much higher with pre-established fiber trees, i.e., for *SMART-FON*, than when jointly optimizing the fiber tree establishment and the SVNM, i.e., for *SMART-TE-FON*. In other words, when jointly optimizing the design of fiber trees and the SVNM, significant savings (up to 45%) are achieved in comparison to the corresponding cases when the design of fiber trees is not optimized. Note that the placement of ITTs to guarantee SVNM contributes further to spectrum waste. This confirms the importance of jointly optimizing the fiber tree establishment and the SVNM.

3) Summary on Cost of Survivability: When the fiber trees are already deployed, i.e., for *SMART-FON*, cost of survivability strictly depends on the connectivity degree of the VN. For



(a) β = 0.6 (6 virtual nodes) (b) β = 0.7 (5 virtual nodes) (c) β = 0.5 (8 virtual nodes) (d) β = 0.6 (6 virtual nodes)

Fig. 10: %ITT with respect to number of VNs with (a) β = 0.6 and (b) β = 0.7 for the 17-node physical network, and (c) β = 0.5 and (d) β = 0.6 for the 23-node physical network.

low connectivity degree, the cost is mostly in terms of ITTs as waste of spectrum is not alarming due to limited number of virtual links. Oppositely, deployment of ITTs can be averted for high VN connectivity degree however network's capacity is drained due to high number of virtual links to be mapped. For the case when fiber trees are jointly optimized with SVNM of a single VN, results show that deployment of ITTs can be averted and the overall wavelength consumption is lower with respect to when the fiber trees are already deployed.

D. *Evaluations on Large Problem Instances with Multiple VNs*

We now compare the network scenarios considering multiple co-existing VNs to investigate their impact on the cost of survivability in FONs. As physical network, we consider the 17-node and the 23-node network topologies. As VNs, we consider VNs with moderate connectivity degrees (i.e., neither low or high); For the 17-node physical network, we consider VNs with β = 0.7 (5 virtual nodes) and β = 0.6 (6 virtual nodes) while for the 30-node physical network, we consider VNs with β = 0.6 (6 virtual nodes) and β = 0.5 (8 virtual nodes)[10]. In each case, we vary the number of VNs in the network from 2 to 10. To increase generality of our results, we perform, for each physical network and number of VNs to map, 10 different evaluations varying the virtual nodes and virtual links forming the VNs, and, for the scenario with given fiber trees, we consider 70 different fiber tree establishments, and report averaged results of *%ITT* and *Nr. Wavelength*. We also report the maximum *%ITT*, i.e., the highest percentage of additional ITT found among all evaluations in each case, which represents the worst case found in each scenario.

1) Discussion on Inter-Tree Transceivers: Figure 10 shows average and maximum *%ITT* (*%ITT avg* and *%ITT max*) for *SMART-TE-FON* and *SMART-FON* with respect to number of VNs to map in the 4 different case studies. In all cases, and irrespective of number of VNs to map in the network, *%ITT avg* of *SMART-TE-FON* is lower than that of *SMART-FON*. Moreover, *%ITT avg* of *SMART-FON* fluctuates, not showing a clear increase or decrease, as the number of VNs increase, while that of *SMART-TE-FON* increases gradually with the increase in number of VNs. This is because, with the increase of VNs, it becomes difficult to find a fiber tree design that satisfies the survivable mapping of all VNs without the need of deploying ITT, implying that the benefits of establishing fiber trees decreases with the increase in number of VNs. Comparing performances in terms of *%ITT max*, *%ITT max* of *SMART-FON* is significantly high (up to 60% as shown for the case of 2 VNs in Fig. 10(b)). On the contrary, for *SMART-TE-FON*, when the fiber trees are jointly optimized with the SVNM, high *%ITT max* values similar to the case of *SMART-FON* are always averted. This shows that jointly optimizing the fiber tree establishment and SVNM remains vital to avert excessive network costs, even though the benefits of this joint optimization decrease for larger number of VNs.

2) Discussion on Wavelength Consumption: Fig. 11 shows *Nr. Wavelength* for the three network scenarios with respect to number of VNs. As expected, FON requires a significantly larger number of wavelength channels than WSON, which varies depending on size and number of VNs. In all cases, the two FON scenarios show a comparable performance, with a slight advantage for *SMART-TE-FON* over *SMART-FON* in some of the cases.

3) Summary on Cost of Survivability: In the case of multiple VNs, results show that the benefits of joint optimization of fiber tree design and SVNM decreases as the number of VNs increases. This is because it becomes harder to design fiber trees that satisfy SVNM for all VNs without the need for ITTs. However, it should be noted that the placement of additional ITTs in the network remains very limited, unless a large number of heterogeneous VNs (i.e., VNs with diverse node mapping) must be mapped in the physical topology. Moreover, in metro aggregation networks, this scenario is unlikely to emerge, as traffic patterns are typically "hub-and-spoke" (from edge nodes to collector nodes) and not overly meshed, suggesting the low-cost solution for SVNM in filterless metro aggregation network can be found in most cases. Moreover, we note that our study focuses on the cost of survivability and not on the overall network cost. FON is known in fact to provide significant cost savings as it removes expensive WSS from the switching nodes. To accurately determine if the proposed scheme in FON is cost-efficient, a cost analysis considering cost of all network equipment shall be performed, which goes beyond the scope of our study.

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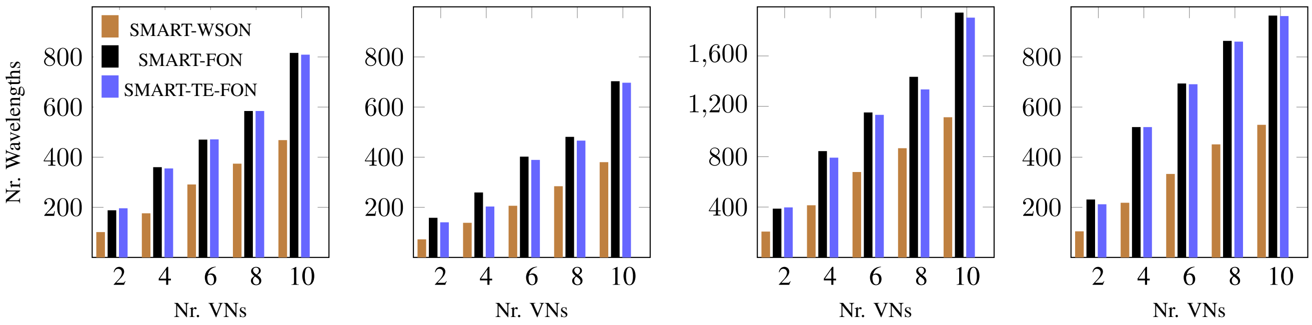
[10] We consider multiple VNs with same size and connectivity degree in each case to investigate if they have an impact on cost of survivability.



(a) β = 0.6 (6 virtual nodes) (b) β = 0.7 (5 virtual nodes) (c) β = 0.5 (8 virtual nodes) (d) β = 0.6 (6 virtual nodes)

Fig. 11: *Nr. Wavelength* with respect to number of VNs with (a) β = 0.6 and (b) β = 0.7 for the 17-node physical network, and (c) β = 0.5 and (d) β = 0.6 for the 23-node physical network.

VI. CONCLUSION

FONs are attracting the attention of network operators due to their simple design and cost savings with respect to WSON. In this paper, we investigated the SVNM in FONs with the objective of minimizing additional network cost, expressed as the number of additional ITTs and overall wavelength consumption. To this end, we developed an ILP model and heuristic and meta-heuristic approaches to jointly optimize the fiber tree establishment and the SVNM in FONs. Numerical results show that jointly optimizing tree establishment and SVNM is decisive to reduce number of additional inter-tree transceivers (no additional inter-tree transceivers in some cases) and limit spectrum waste in FONs. Conversely, when the fiber tree design is a given to the problem, up to 60% more inter-tree transceivers are required than the case of WSON and up to 100% than when jointly optimizing tree establishment and survivable virtual networks mapping. Also for the case of multiple co-existing VNs, results show that, even if it becomes harder to establish fiber trees that satisfy the SVNM of all VNs without the need for ITT, yet, jointly optimizing the fiber tree establishment and SVNM remains vital to avoid unnecessary network costs. Nevertheless, FONs can be considered a low cost solution for SVNM in metro aggregation networks, where traffic is are typically bounded between edge nodes and collector nodes.

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