A Tutorial on Filterless Optical Networks

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The recent acceleration in fiber-to-the-home deployment worldwide along with the emerging 5G communications are pressuring network operators to enhance their networks to serve these new deployments. Hence, operators are seeking new high-capacity optical-network architectures, while averting excessive capital and operational expenditures. Filterless Optical Networks (FONs), by replacing in switching nodes costly wavelength selective switches with passive optical power splitters/combiners, currently represent a prominent candidate for cost-effective optical-network deployment. In this tutorial, we provide an overview on the architecture and on the design issues of FONs when deployed in core and in metro networks. We also perform a techno-economic study to quantify economic benefits of FONs comparing their cost to that of state-of-the-art filtered optical networks, and we discuss on how several networking problems such as resource allocation, network slicing and protection, are tackled in the context of FONs. Finally, we present our vision on how research on FONs will evolve in next years.

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1. INTRODUCTION

The telecom industry has been experiencing challenging times recently to satisfy the growth in Internet traffic fueled by the emerging 5G communications and by the world-wide shift to tele-working and tele-education as a part of the global measures to limit the Covid-19 pandemic [1]. Network operators must meet increasing capacity requirements while averting excessive costs. As optical networks, in particular in the metro-aggregation segment, represent the main transport platform for 5G communications, network operators are always seeking architectures to scale up the capacity of their optical networks while averting excessive costs. *Filterless Optical Networks* (FON) are emerging as an eminent candidate to reduce network costs, and are in fact capturing the attention of the telecom industry. Over the past decade, extensive research work has been conducted covering various aspects of FON, however, to the best of our knowledge, there exists no survey or tutorial paper with comprehensive overview on FONs. A notable work in this sense is Ref. [5] (2016), which presents an overview of early works on FON. However, since then, substantial research and advances on FON have been performed

The concept of FON was first introduced in 2007 [2], while first deployments of FONs in Europe have appeared in 2012 [3] [4]. Over the past decade, extensive research work has been conducted covering various aspects of FON, however, to the best of our knowledge, there exists no survey or tutorial paper with comprehensive overview on FONs. A notable work in this sense is Ref. [5] (2016), which presents an overview on early works on FON. However, since then, substantial research and advances on FON have been performed. In this paper, we provide an introductory tutorial covering the main aspects of the architecture and design problems of FONs in core and in metro networks. In FONs, as the name suggests, switching nodes are not equipped with costly re-configurable filters (namely, the Wavelength Selective Switches, WSSs), which are instead replaced by splitters and combiners, building a broadcast-and-select node architecture (the filterless node architecture will be explained later in the tutorial), hence reducing the equipment cost in the Wavelength Division Multiplexing (WDM) layer. In addition to savings in equipment expenditures, FONs promise lower power consumption and footprint with respect to WSS-based optical networks (or Wavelength Selective Optical Networks, WSON as they will be referred in the rest of the paper). As a part of the tutorial, we perform a techno-economic analysis quantifying the economical benefits of deploying FONs in core and in metro networks.

The equipment cost savings in FONs come with a set of severe drawbacks, such as the spectrum waste and the signal-quality degradation caused by the elimination of filters. In this paper, we discuss in detail these drawbacks of the FON architecture and we discuss how the filterless architecture requires network operators to identify new and improved strategies to allocate resources and to guarantee protection of traffic demands. We discuss also the concept of semi-filterless optical networks, based on the idea that filters such as wavelength blockers can be deployed only at selected network nodes to mitigate drawbacks of FON while maintaining cost benefits.

The contribution of the paper as follows:

- we provide an overview on the architecture of filterless nodes and the design of FONs in core and in metro-aggregation networks highlighting their main advantages and disadvantages

- we perform a techno-economic analysis quantifying economic benefits of FONs
- we discuss, with the help of example, how to perform effective resource allocation (in the context of network slicing) and how to guarantee protection of lightpaths in FONs
- discuss strategies to reduce spectrum consumption employing the concept of semi-filterless optical networks
- we surveyed works involving FONs
- We identify gaps in existing literature and devise future research directions involving FONs

The tutorial is organized as follows. In Sec. 2 we introduce the FON node architecture, highlighting differences with respect to WSON nodes. Sec. 3 discusses in detail the design and resource allocation in FONs. Sec. 4 describes a practical FON deployment and presents the techno-economic study that quantifies the cost reductions of FONs. Sec. 5 focuses on network slicing and discusses the impact FON constraints have on network slicing. In Sec. 6 we discuss strategies to guarantee protection in FONs, while Sec. 7 introduces the concept of semi-filterless optical networks to reduce spectrum waste. In Sec. 8 we survey and discuss recent experimental evaluations involving FON. Finally, Sec. 9 discusses open areas of research and future directions, whereas Sec. 10 concludes the paper.

2. FILTERLESS NODE ARCHITECTURE

Fig. 1 shows the architecture of a WSON node (a) and a filterless node (b) for a simple degree-2 node. As shown in the figure, in filterless nodes passive splitters and combiners that operate on the entire frequency band substitute complex and costly active WSSs. Instead of filtering, signals are discriminated at the receiver using only coherent detection. In this example, also multiplexer/demultiplexer in the add-drop section of the filterless node is replaced by combiner/splitter, respectively, but other components such as transponders, optical amplifiers at the input- and output-ports are kept the same. Optical signals at the input ports of a filterless node are broadcasted to all its output ports. Hence, even if a signal reaches its destination, it is not dropped, but it in fact propagates further, and this can be the entire WDM comb of signals.

As an example of unintended signal propagation, in Fig. 2 we consider a more complex degree-3 filterless node, where the red signal entering through port 1 gets received, but it still propagates to ports 2 and 3. Same holds true for the green signal entering through port 3. Note, however, that blue signal, which originates at this node, gets propagated only to port 1, avoiding the broadcast.

By removing WSSs from nodes, FON can achieve savings both in capital expenditure (CapEx) and operational expenditure (OpEx). In terms of CapEx, cost of passive optical splitters and combiners is negligible compared to the cost of a WSS (see Section 4); it must be noted, though, that cost of a WSS does not exceed (10-30)% of the cost of a single transponder, so removing WSS is beneficial only if that does not increase the expenses on transponders. In terms of OpEx, passive switching leads to reduced energy consumption, lower cooling and space requirements. As splitters and combiners are drastically simpler than WSSs, maintenance and installation expenses decrease too.

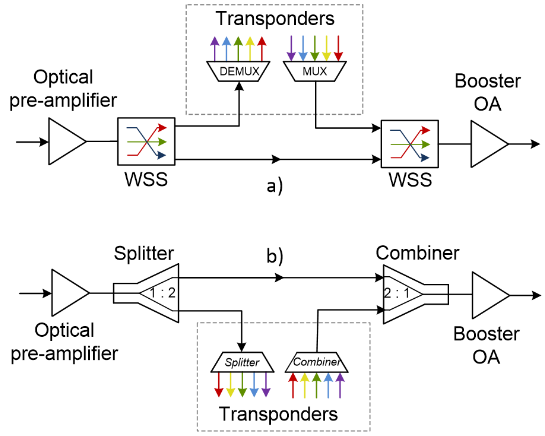

Fig. 1. Architecture of a) degree-2 WSON and b) FON nodes

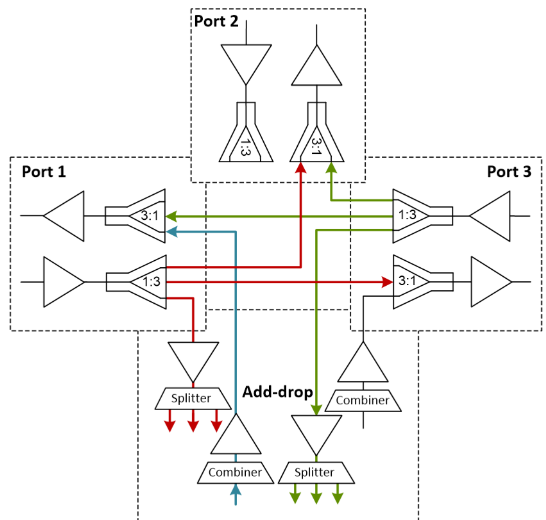

Fig. 2. Architecture of degree-3 FON node

Economical savings come at cost of reduced networking capabilities, as FON nodes cannot route and drop optical signals. Moreover, removal of filters affects optical signal quality [6]. In fact, even though in FONs optical signals do not experience additional attenuation and crosstalk from filtering, the unavoidable splitting in FON nodes makes node loss strongly dependent on the nodal degree, hence loss in a FON node can potentially exceed loss of a WSON node. Furthermore, in the absence of filtering, transmitters have to guarantee fine spectral shaping. Finally, as, without filtering, optical amplifier integrated in the transmitter contributes noise to all the channels in the band (discussed in details in Section 3), it becomes critical for this amplifier to be low-noise. These differences are summed up in Table 1.

3. DESIGN AND RESOURCE ALLOCATION IN FONS

This section focuses on the design and resource allocation. The design of FONs, as we will see in this section, differs significantly depending on which segment of the network FONs are deployed. Due to this reason, we divide the discussion into two sections. Sec. 3.A focuses on the design of FON in metro area networks while Sec. 3.B focuses on the design of FON in core networks.

Table 1. Differences of FON node with respect to WSON node

Aspect	Characteristic
Capabilities	Routing is no longer possible. All input signals are broadcasted to all output ports
CapEx	Passive splitters and combiners are few orders of magnitude cheaper than an active switch.
OpEx	Lower energy consumption and lower cooling requirements, less maintenance expenses, lower installation cost and lower space occupation
Signal degradation	No filtering loss. Potentially more crosstalk at the source node (as signal is not filtered at the output port). Inner OA at the transponder must be low-noise (it affects all the channels in the band)

A. FON in Metropolitan Area Networks

This section focuses on the design of filterless optical networks in metropolitan area networks. One of the widely-adopted architectures for FON in metropolitan area networks is the horseshoe filterless architecture [3], [4],[7],[8], although an alternative hierarchical architecture has been proposed in a recent work [9]. In this section, we first provide an illustrative example of interconnected horseshoe topologies and make emphasis on the broadcast nature of FON networks and its impact on the physical layer and lightpaths' signal quality. Then, we compare the horseshoe filterless architecture to the hierarchical architecture proposed in Ref. [9].

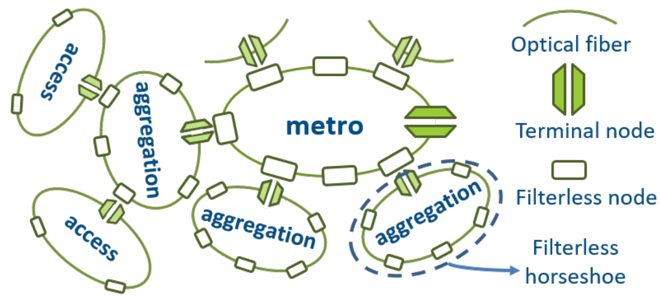

Fig. 3. Metro network composed of interconnected horseshoe topologies

A.1. Filterless Horseshoe Design

FON deployment has attracted particular interest for metro networks [10–14]. To minimize network cost, network operators are more prone to consider filterless horseshoe architectures, especially considering the high number of metro nodes.

Fig. 3 shows a practical deployment of a metro network composed by several interconnected filterless branches, where each branch is constituted by a horseshoe. Typically, a horseshoe FON contains two types of nodes: terminal nodes and filterless nodes. Terminal nodes serve to connect the horseshoe to the rest of the metro network and are equipped with WSSs to block signal propagation and thus avoid creating laser-loop effects due to the continuous propagation of optical signals [11]. Filterless nodes equipped only with splitters and combiners are placed along the optical line. Considering the broadcast nature of FONs, care must be taken to ensure that quality-of-transmission (QoT) of optical signals is satisfied for all traffic requests. Specifically, one must account that the absence of WSSs leads to propagation of Amplified Spontaneous Emission (ASE) noise generated by optical amplifiers beyond lightpath termination, and even to accumulation of ASE noise generated before a lightpath is initiated.

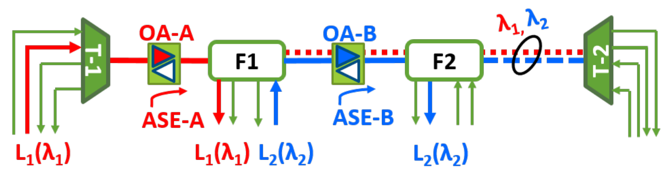

Fig. 4. Example of channel broadcast and ASE accumulation in a horseshoe filterless topology

Let us consider the example in Fig. 4 of signal propagation and ASE noise accumulation in a filterless horseshoe. Lightpath-1 (*LP-1*) is generated at *T1* on wavelength λ_1 (red colored) and destined to node *F1* and lightpath-2 (*LP-2*) is generated at node *F1* on wavelength λ_2 (blue colored) and terminated at node *F2*. Due to the broadcast feature of FON, λ_1 propagates beyond *F1* and λ_2 propagates beyond *F2*. As a result, ASE noise generated by *OA-A*, i.e., *ASE-A*, propagates beyond destination and accumulates with ASE noise generated by *OA-B*, i.e., *ASE-B*, and impact the QoT of *LP-2*. Given the additive nature of the ASE noise generated by optical amplifiers [15], the total linear Signal-to-Noise Ratio (SNR) due to ASE contribution for *LP-2*, i.e., SNR^{ASE}_{LP-2}, can be expressed as:

$$\frac{1}{SNR^{ASE}_{LP-2}} = \frac{1}{SNR^{ASE}_{A}} + \frac{1}{SNR^{ASE}_{B}} \quad \textbf{(1)}$$

where SNR^{ASE}_{A} is the accumulated SNR_{ASE} contribution due to optical amplifier *OA-A* and SNR^{ASE}_{B} is the SNR_{ASE} contribution due to optical amplifier *OA-B*. Note that, the same can be generalized for any lightpath i that traverses M optical amplifiers from source to destination and is impacted by the accumulated ASE noise of N optical amplifiers located before the source node:

$$\frac{1}{SNR^{ASE}_{LP-i}} = \sum_{n=1}^{N} \frac{1}{SNR^{ASE}_{n}} + \sum_{m=1}^{M} \frac{1}{SNR^{ASE}_{m}} \quad \textbf{(2)}$$

For further readings regarding the physical layer constraints and validation, we refer reader to [11, 14].

Recently, several works investigated the deployment of filterless architecture in horseshoe topologies [11, 13, 14]. Ref. [13] experimentally demonstrates how to upgrade disaggregated metro networks through *(C+L)* band and coherent receivers, Ref. [14] proposes and validates a bidirectional transmission over a single fiber by estimating the transmission impairments through closed-form expressions and Ref. [11] proposes a solution to reduce the cost of FON networks by optimizing the placement of amplifiers while preserving lightpaths' quality-of-transmission (QoT).

A.2. Routing and Spectrum Allocation

The routing and spectrum allocation in a horseshoe topology is limited by the linear nature of the topology, hence a traffic request can be routed only on two possible paths/directions. Let us consider the horseshoe topology highlighted with the dashed circle in the "*aggregation*" section in Fig. 3. A traffic request generated at terminal node and destined to filterless node placed in the middle of the horseshoe can be routed in either of two directions, left-hand side or right-hand side of terminal node. The allocated wavelength is propagated across the horseshoe due to broadcast feature of FONs. Hence, a wavelength allocated for a lightpath in a direction along the horse-shoe cannot be utilized by any other lightpath, an aspect which is also referred to as *no-reuse* (without wavelength reuse) [16].

The advantage of deploying FON in horseshoe is that terminal nodes will impede the signal to propagate beyond the horseshoe, therefore limiting the broadcast to other horseshoes in a scenario of several inter-connected FON horseshoes as shown in Fig. 3. Benefits in terms of spectrum allocation brought by employing elastic optical networks have also been investigated in the context of metro horseshoe topologies [17, 18].

We now compare the horseshoe-based FON topologies to the architecture proposed in Ref. [9] in terms of architecture, spectrum propagation and quality of transmission.

- Node types: Horseshoe-based FON is composed of FON nodes, and a terminal node equipped with filters to prevent signal propagation beyond horseshoe, and thus avoiding laser loops. Instead, in [9], the filterless solution is composed by three layers (comprised by a set of edge-disjoint fiber trees), considering the connection between different node types: 1) layer-1: interconnects collector nodes and core nodes; 2) layer-2: interconnects core nodes; and 3) layer-3: interconnects core nodes to gateway nodes. All nodes are assumed as filterless nodes and fiber trees are established to avoid laser loops.

- Spectrum propagation: In horseshoes, terminal nodes limit signal broadcast within the horseshoe. In the architecture proposed in Ref. [9], signal propagates along a fiber tree. We can expect a lower spectrum waste in the horse-shoe topology since the broadcast domain is limited.

- Quality-of-transmission: impairments due to signal propagation beyond destination can be expected to be lower in horseshoes due to the smaller broadcast domain. In case of fiber trees, as in Ref. [9], impairments are expected to be higher due to a larger broadcast domain and impairments generated in several links composing the fiber tree.

B. FON in Meshed Core Networks

When deployed in mesh networks such as, e.g., core networks, FONs require a preliminary design phase known as *fiber tree establishment* (or fiber tree design), which consists in subdividing the network topology into a set of filterless 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. As we will see later in this section, the fiber tree design defines the connectivity of the network, and, hence, the routing and wavelength assignment (RWA), or resource allocation in general, in FON strictly depends on the established fiber trees. In this subsection, we will first discuss the process of fiber tree design and then define the RWA problem in fiber tree-based FONs. Moreover, we will discuss recent work that tackled the RWA or the Routing and Spectrum Assignment (RSA) problem in FON.

B.1. Fiber Tree Design

The design of fiber trees has two main constraints:

- A fiber link (an edge) has to be assigned to exactly one fiber tree. In other words, fiber trees are link-disjoint.

- A fiber tree cannot contain a loop, otherwise broadcast and amplification of signals cannot be contained.

After dividing the mesh network in fiber trees, signal propagation is forced to occur within a fiber tree (signal cannot propagate from one fiber tree to another), hence limiting the continuous signal broadcast and preventing laser loops. However, fiber-tree design impacts network operation and constrains routing. As already commented in Section 3.A, one of the main impairments to lightpaths' QoT is the ASE noise generated by optical amplifiers. The presence of amplifiers will impact the QoT of all lightpaths belonging to the fiber tree as a result of ASE noise propagation beyond lightpath termination. In this context, in addition to the above mentioned constraints on tree establishment, a limit on maximum demand's length (in kms) can be taken into account due to physical layer constraints. Physical layer validation for FONs has been investigated in [24] in which a simple analytical model is proposed to estimate the ASE noise and the corresponding bit error rate (BER) for fiber trees. Equation 2 for calculating the SNR_{ASE} is valid for meshed FON as well, with the implication that the accumulated ASE noise contribution is generated by the amplifiers placed along all links belonging to the fiber tree, prior to lightpath generation.

Fig. 5(a) shows a 7-node network topology and Fig. 5(b) shows an example of a 7-node FON subdivided into two fiber trees, *Tree 1* and *Tree 2*, shown with solid and dotted lines, respectively. In the example, links (7,2), (2,3), (3,4), (4,5) and (5,6) belong to Tree 1, while the remaining links in the topology belong to Tree 2. As for the nodes, a node belongs to a fiber tree if it is an end-point of an edge belonging to that fiber tree. In our example, node 4 belongs to both trees, while node 5 belongs to only Tree 2. Note that two nodes cannot be connected transparently (i.e., via a direct lightpath that remains in the optical domain) if connecting path crosses different fiber trees, and in that case the connecting path requires OEO conversion. For instance, node 2 and node 5 cannot transparently connect through node 6, as input signal from node 2 at node 6 can be dropped and broadcasted towards nodes 3, 4 and 7 but not towards node 5. We show the internal architecture of node 6 in Fig. 5(c). Note that dynamically varying the fiber trees configuration is not practical as it requires modifying the fiber interconnections within the nodes. Moreover, we show in Fig. 5(d) an example of spectrum propagation considering two lightpaths from node 7 to node 6 routed on Tree 1, and from node 7 to node 5 on Tree 2, respectively. As it can be seen, spectrum broadcast (represented by dashed lines) occurs in the downward direction of a lightpath. In the example, 10 wavelengths are occupied for routing these two lightpaths over all links. Note that a wavelength allocated for a lightpath on a fiber tree is considered reserved and cannot be further utilized by another demand along that tree (no-reuse

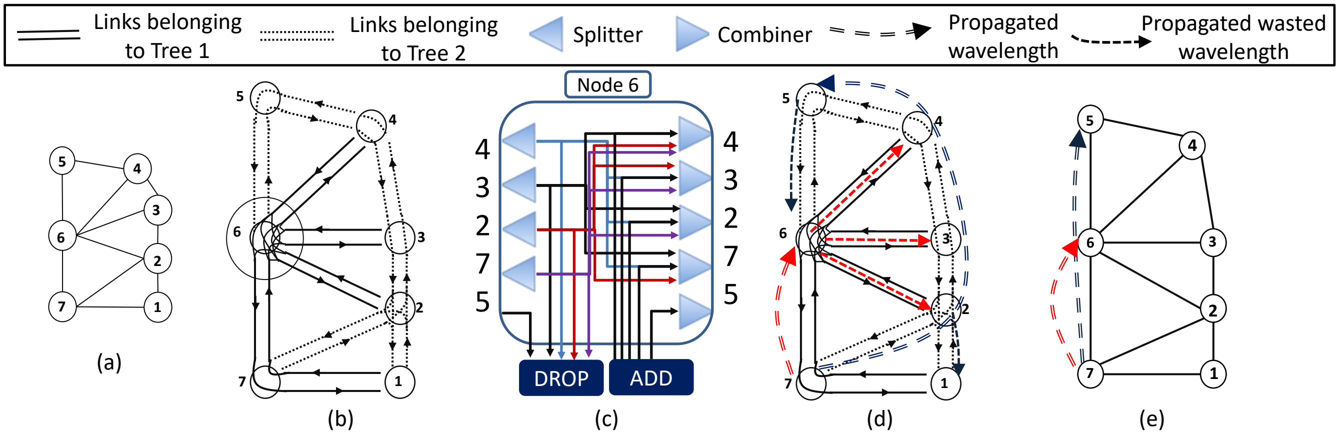

Fig. 5. An example fiber tree establishment (b) of the 7-node physical network topology (a). Internal architecture of filterless node 6 (c). (d) shows an example of the routing of two lightpaths over the FON of (b), and (e) over a traditional WSON.

Table 2. Related research work investigating resource allocation in core FON.

Ref.	Grid (Traffic)	Tree Establishment	Methodology	Objective(s)
[19]	Fixed (static)	Optimized	GA for TE	Guarantee network connectivity, reduce average demand's length
			Tabu Search for RWA	Minimize maximum wavelength index
[20]	Fixed (static)	Optimized	ILP for TE and RWA	Minimize the maximum wavelength index used
[21]	Fixed (dynamic)	Given	Heuristic for RWA	Minimize number of unfiltered channels
[22]	Fixed (static)	Optimized	ILP and heuristic algorithm	Minimize maximum wavelength index
[6]	Fixed (NA)	Optimized	Evolutionary algorithm for TE	Maximize protection ratio
[23]	Flexible (static)	Given	GA for TE [19]	Guarantee network connectivity
			Heuristic for MRSA	Minimize overall number of frequency slot units (FSUs) utilized
[5]	Flexible (static)	Given	ILP model and GA for MRSA	Minimize the maximum number of FSUs used on a fiber

feature), unless in very specific scenarios (discussed later in Sec. 5.A). For comparison reasons, we show in Fig 5(e) the routing of the two lightpaths in a WSON, which results in 3 wavelength channels occupied, less than third that of the FON.

B.2. Routing and Wavelength Assignment (RWA)

RWA in meshed FONs has been investigated in two cases: 1) when fiber trees are pre-established [5, 21, 23] (i.e., RWA is performed on a given FON) and 2) when the fiber trees are designed taking the traffic matrix into consideration [6, 19, 20] (i.e., when fiber tree design is jointly optimized with RWA). In the first case, the routing of traffic demands consists in selecting the tree on which to route a traffic demand however, in some cases, only one tree might be possible to route the demand. This means that once the fiber trees are established, there is not much room to optimize RWA, and hence to minimize the spectrum consumption. In the second case, when jointly optimizing the design of fiber trees with RWA, spectrum consumption in FON can be greatly minimized, because fiber trees can be designed taking into account the resulting RWA (hence spectrum consumption), of a possible fiber tree design, allowing to avoid designs leading to excessive spectrum consumption in the network. Note that, while designing the FON assuming the traffic matrix yields significant advantages, it is not always feasible, as the network operator may not always have complete knowledge of how traffic will evolve in time. The application of FON has been also investigated in flexible-grid networks [5, 23], where the RWA problem tackled in Refs. [6, 19–22] transforms into the more complex modulation format, routing and spectrum assignment (MRSA) problem.

In Tab. 2, we summarize the main aspects of the works that tackled the RWA and RSA problems in FON. On FON for fixed grid, Ref. [19] was the first work to tackle the RWA problem and the fiber tree establishment proposing a GA for tree establishment followed with a tabu search algorithm with the objective of minimizing wavelength consumption. Another work [21] considered the dynamic RWA problem, where a given set of fiber trees was assumed as an input of the problem. Ref. [21] proposed an evolutionary algorithm to optimize the fiber tree establishment in meshed FON. Moreover, Ref. [20] proposed an ILP model to jointly optimize the fiber tree establishment and the RWA problem, with the aim of minimizing the number of wavelengths used in the network, showing the importance of jointly optimizing the fiber tree establishment and RWA. A recent work [22] proposed scalable meta-heuristic approaches to jointly optimize the fiber tree establishment and the RWA in regional core networks. Focusing on FON in elastic optical networks, Ref. [23] first tackled the problem of MRSA in FON proposing a heuristic approach with the objective of minimizing the overall number of frequency slots utilized in the network. Ref. [5] further investigated the MRSA in FON proposing an ILP model and a GA with the aim of minimizing maximum frequency slot index used in the network. Finally, for multi-layer design of FON, we refer the reader to Ref. [25], which presents an open-source multi-layer design planning tool for spectrum management and cost planning in FONs.

4. TECHNO-ECONOMIC ANALYSIS

This section aims to investigate savings enabled by FON. First, in subsection A we discuss the economic advantages of FON and give an example of a practical FON deployment. In subsection B we discuss the different works investigating cost savings enabled by FON. In subsection C we present the cost model considered in our analysis and we then present our techno-economic analysis of FON in metro-aggregation (subsection D) and core (subsection E) networks.

A. Practical FON Deployment

Before going into the cost analysis, we discuss a real-world example of a FON deployment. We can consider the case of a major wholesale European network provider, which has chosen the FON architecture as a second supplier for its national Access and Regional networks, as an alternative to the traditional WSON-based systems. The major requirements which are satisfied by the FON architecture are the followings.

- Low Capex costs, in particular at initial deployment: The lower cost and the avoidance of WSS nodes allow the reduction of overall cost network. This is true in particular in the Access segment, where the channel bit rates requested are relatively low (10 Gbs) and therefore the WDM cost is comparable or lower than that of WSON one.
- low power consumption and footprint: in the access area, the available cabinets are often small and not expandable. A modular architecture based on pluggable filters and amplifiers and the lower power requirements due to the passive nature of couplers and splitters make possible a compact shelf configuration.
- Low initial system capacity (for access networks) or medium initial system capacity (for regional networks), with the ability and ease to grow it in the future: both at node level (by modular growth at add/drop section) and at ring level (by adding selected WSS nodes to overcome unfiltered ASE propagation impairment and eliminate 'Ghost', i.e.,unfiltered, channels to make wavelength reuse possible), it is possible to increase the system capacity driven by new traffic requirements.

As for the actual deployment, in the Access area, more than 50 chains comprising one hub and few remote nodes have been deployed with link lengths ranging from around 10 to over 200 km. In the Regional area, the deployment has comprised more than 15 horseshoe rings with lengths ranging from 100 to over 700 km, with intermediate in-line amplifiers used in the longest links to improve OSNR performance. In this section, we perform a techno-economic study simulating the deployment of this type of FON network architecture.

B. Previous Techno-Economic Analysis

Few studies have tackled this problem (Table 3). Ref. [19] is first work that analyzed the cost efficiency of FONs. The study focuses only on the capital expenditure of WDM layer equipment and optical amplifiers in core networks, showing cost savings of around 90%. Ref. [27] performed a similar study considering in addition the placement of switches at some network nodes, revealing cost savings of FON around 90%. Other works investigated the cost efficiency of FON in the metro-aggregation segment of the network. Ref. [26] presented an analysis also considering the cost of transponders. In this case, the study shows cost savings of only 5% due to the fact that savings of WDM layer equipment are elided by a small increase of the cost of transponders, which make up a huge percentage of overall network cost for both FON and WSON architectures. Moreover, Ref. [12] performed a techno-economic analysis considering the capital and operational cost of WDM equipment including transponders, showing cost savings up to 5%. While all these works investigated cost savings of FON, it is only recently that the degradation of physical-layer quality in FON (due, e.g., to ASE-noise propagation) has started being considered. One example is Ref. [28], which shows even lower cost savings of FON compared to WSON, of only 3%. We argue that taking these effects into consideration is crucial for the precise cost analysis.

C. Cost model

We model CapEx as equipment cost and consider three components of OpEx: electricity cost, installation cost as 30% of CAPEX and maintenance/repair costs as 75% of electricity cost, adopting the cost model from [28]. As equipment, we consider transponders, WSSs, splitters/combiners, (de-)multiplexers and amplifiers.

Optical amplifiers are placed at the input and output node ports and every 60 km along the fiber. We consider 2 types of transponders: type 1 only employs PM-QPSK, transmitting 100 Gbit/s, type 2 - modulation formats up to PM-64QAM, transmitting (100-300) Gbit/s. Equipment cost in Cost Units and energy consumption in Watt are listed in Table 4.

Price of electricity is estimated to be 0.001 CU/kWh. We also consider that price of any network component depreciates by 10% every year. Cost depreciation and OPEX make it advantageous to postpone the installation of new transponders.

We use a state-of-the-art Genetic Algorithm in [19] for fiber tree establishment. If a traffic demand can be assigned to more than one tree, we choose the one that guarantees the lowest propagation loss. Spectrum is assigned using First Fit allocation.

While comparing network costs, we investigate 2 possible scenarios: A) only type 1 transponders are available and B) type 1 and type 2 transponders are available.

To choose transponders we follow approach in [28]. At first, SNR of the lightpaths is estimated, and highest modulation format is chosen. Integer Linear Program then outputs how many transponders of each type are needed to satisfy the requested bitrate, which grows during N years, at minimal cost.

D. FON in Metro Networks

To investigate possible cost savings in metro networks we consider the 51-node (6a) and the 52-node metro-aggregation network topologies (6b). To mimic realistic deployment, the core segment of the network (shown in orange) always uses a WSON architecture, while the aggregation segment (shown in green) can use a FON architecture. In 51-node network, aggregation segment is by default separated into 6 bidirectional FON-horseshoes.

In the 52-node topology this is not the case, so to avoid loops when FON is used, we perform Tree Establishment (TE) in the aggregation segment with an objective of minimizing the longest route. Every tree must be connected to the core segment through at least one core node. Note that there might exist several designs with different number of bidirectional fiber trees that satisfy the

Table 3. Techno-economical studies in FON

Ref.	Year	Network segment	Cost model	Physical-layer aware	Savings
[19]	2010	Core	CapEx (switching equipment and OAs)	No	90%[a]
[26]	2017	Metro-aggregation	CapEx	No	5%
[27]	2020	Core	CapEx (switching equipment only)	No	90%[a]
[12]	2020	Metro-aggregation, core	CapEx, OpEx (electricity)	No	4% (metro), 5% (core)
[10]	2020	Metro-aggregation	CapEx, power consumption	No	-
[28]	2021	Metro-aggregation	CapEx, OpEx (electricity, installation, maintenance/repair)	Yes	3%

[a]Note that cost savings in this study are of higher order with respect to other studies as only switching equipment were considered.

Table 4. Cost and power consumption of components [29]

Network component	Cost, CU	Av. power, W
Splitter (combiner) 1x2; 1x4; 1x8	0.004; 0.01; 0.02	-
WSS 1x4; 1x9	1.1; 2.2	30; 40
Multiplexer/demultiplexer	0.08	-
Booster; preamplifier; inline OA	0.3; 0.3; 0.5	27
Transponder type 1; type 2	5; 12	120

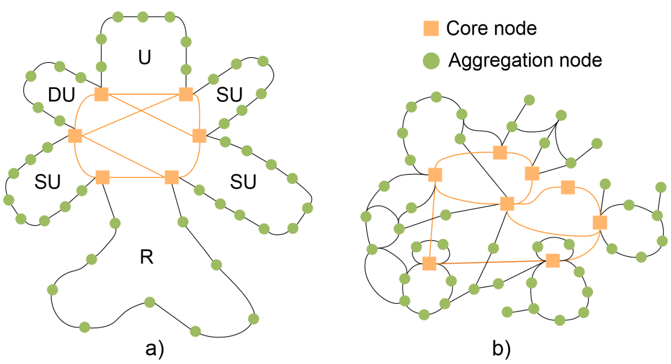

Fig. 6. a) 51-node and b) 52-node metro topologies

connectivity constraints. For our evaluations, we considered the design with the lowest number of fiber trees, which in this case was 10.

As for the traffic matrix, we consider bidirectional traffic between every metro-core node pair to be 300 Gb/s with 30% increase every year. In the aggregation segment we consider bidirectional traffic between each aggregation node and its closest core node, which is uniform and equal to 200 Gb/s at year 1 in 52-node metro network and is geotype-dependent in 51-node metro network: 250 Gb/s (dense urban, DU), 200 Gb/s (urban, U), 100 Gb/s (suburban, SU), 50 Gb/s (rural, R) at year 1. In both networks traffic in the aggregation segment grows by 20% per year.

Cost savings for 2 topologies are shown in Table 5 for scenarios A and B, at installation (only CapEx at year 1) and after 5 year traffic evolution. In scenario A, with 100G transponders, 7.6% and 6.2 % in total network cost (CapEx and OpEx combined) is saved in 51-node and 52-node networks, respectively, due to the removal of WSSs, at installation. It reduces to 3.7% and 3.1% after 5 years due to higher absolute expenses on transponders.

Table 5. Cost savings in metro-aggregation networks, at installation (at year 5)

Scenario	51-node metro	52-node metro
A	7.6 % (3.7 %)	6.2 % (3.1 %)
B	7.6 % (2.2 %)	6.2 % (3.2 %)

This holds for scenario B, when also (100-300)G transponders can carry traffic: 7.6 % and 6.2 % savings for the two metro topologies decrease to 2.2% and 3.2% in 5 years.

Even though lightpaths in the aggregation segment have slightly lower SNR due to ASE-noise propagation described above, losses in transponders are negligible, and FON is economically beneficial in this network scenario. In [28] we have shown that losses in transponders can be compensated, and further savings achieved, if placement of Optical Amplifiers can be optimized.

E. FON in Core Networks

To investigate possible cost savings from the use of FON in core optical networks we consider 17-node German (7a) and 21-node Italian (7b) network topologies.

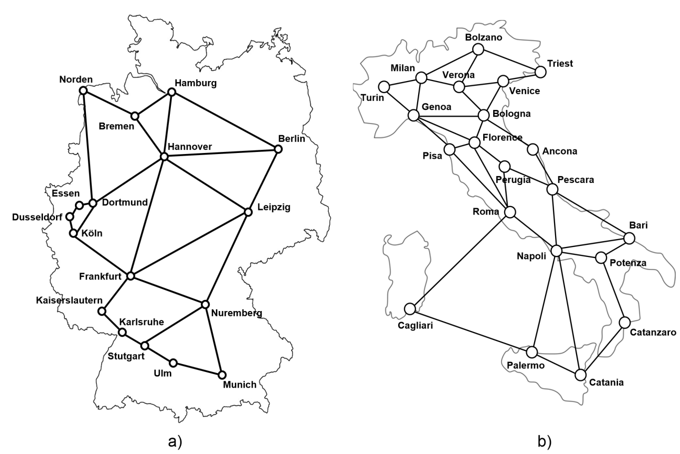

Fig. 7. a) 17-node German and b) 21-node Italian core topologies

Two bidirectional fiber trees are established in both cases. Traffic matrix is full mesh with the initial traffic of 400 Gb/s for each request and 30% increase every year.

Cost savings for 2 topologies are shown in Table 6 for scenarios A and B, at installation (only CapEx at year 1) and after 5-year traffic evolution. In scenario A with only 100G transponders, there are 1.18 % and 1.15 % savings in total network cost in the 17-node German and 21-node Italian networks respectively, due to removal of WSSs, at installation. This reduces to 0.54% and 0.57 % after 5 years. When (100-300)G transponders are also available, low SNR in FON still only allows the use of cheaper 100G transponders, so installation cost reduces by 5% and 13.9%. However, after 5 years, higher OpEx of a larger number of 100G transponders in FON leads to 12.5% and 13.5% losses in total network cost, and savings in WSSs are offset with losses in transponders. This finding shows that FON has stable cost savings when bit rate in the network is fixed (scenario A, 100G transponders), as the impact of the ASE propagation is low. On the contrary, when bit rate is not fixed, and hence, when high order modulation formats are used (scenario B, 100 to 300G), the penalty of FON on transponder cost elides the gain on WDM layer equipment.

Table 6. Cost savings in core networks, at installation (year 5)

Scenario	17-node German	21-node Italian
A	1.18 % (0.54 %)	1.15% (0.57 %)
B	5.1 % (-12.5 %)	13.9 % (-13.5 %)

The effect of ASE-noise propagation becomes crucial in core-networks, as there are many more EDFA-amplifiers in their long fiber-trees, reducing SNR of the lightpaths and requiring more transponders to be installed, which makes FON economically disadvantageous in this network scenario. To compensate for that, passive wavelength blockers can be placed at the input ports of the nodes to filter propagated ASE-noise in the empty channels. We assume their cost to be 0.8 CU, as in Ref. [30]. Table 7 demonstrates that small cost savings can be achieved at installation: 1.95% in the 21-node Italian network, and even when there are no savings, cost increases by at most 1.1%. Whether this can be compensated by an intelligent placement of optical amplifiers is open for research.

Table 7. Cost savings in core networks with wavelength blockers at every input port, at installation (year 5)

Scenario	17-node German	21-node Italian
B	-0.65 % (-1.1%)	+1.95 % (-0.84%)

5. NETWORK SLICING IN FONS

With the emergence of new 5G services, network operators are required to dynamically re-configure network resource allocation to agilely chain these services. In this context, FONs face serious challenges as they lack in terms of flexibility and reconfigurability. From this perspective, we see that it is important to shed light on the problem of network slicing and in particular, on the impact of FON constraints on network slicing. With slicing, network operators can offer to their customers slices of their physical (or "substrate") network resources, typically in the form of Virtual Networks (VNs) on a subset of the substrate resources to accommodate specific service requirements [31, 32]. From a resource allocation perspective, slicing can be achieved by Virtual Network Mapping (VNM), i.e., the by assigning physical resources to virtual links between pre-determined nodes (the placement of virtual nodes over physical nodes is considered to be given), or Virtual Network Embedding (VNE) [33], i.e., the placement of virtual nodes over physical nodes solved together with the assignment of physical resources to virtual links. We focus on the effect of FON's design on VNM and VNE in Sec. A. Another form of network slicing is a *service chain*, where a set of virtual network functions (VNFs) that can be run on commodity hardware are instantiated and connected in specific sequence to provide services to users [34, 35]. The main difference between Service Chaining (SC) and VNE is the fact that in SC multiple virtual nodes can be placed in the same physical node. We discuss the problem of dynamic SC in FON in Sec. B.

A. Virtual Network Mapping and Embedding in FON

VNM in FONs: In Fig. 8 we map a VN consisting of three virtual nodes (Fig. 8(a)) onto the FON shown in Fig. 8(c) also showing the propagation of unfiltered spectrum and, for comparison, we show the mapping of the same VN onto a WSON in Fig. 8(b). As can be seen, the mapping of the VN in the FON significantly differs than that in WSON as two out of three virtual links are mapped differently, due to constraints imposed on the routing between network nodes. The mapping of virtual links takes longer paths (average length of 3 hops) with respect to that of WSON (average length of 2 hops). In terms of spectrum consumption, if we assume each virtual link to request exactly one wavelength channel per direction, the wavelength consumption in FON amounts to 27 wavelength (9 unfiltered, not shown in figure for simplicity), 2.7x that of WSON (total of 10 wavelengths). The additional wavelength consumption in FON is not only due to longer paths with respect to WSON, but also to the broadcast-and-select architecture employed.

VNE in FONs: We now compare VNE in FONs and WSONs. In VNE, both the virtual nodes and the virtual links are embedded (mapped) onto the physical network. In Fig. 8(e) and (f) we embed the VN in Fig. 8(d), respecting candidate virtual node locations, with the aim of minimizing overall wavelength consumption. The overall wavelength consumption in FON amounts to 18 wavelengths while that in WSON is 8 wavelengths. Although FON still consumes significantly higher spectrum that WSON, that factor is reduced with respect to the case of VNM. This is because the embedding of virtual nodes provides more room to adapt to FON's design than in the case of VNM, taking into consideration the design of FON, hence minimizing spectrum consumption. We refer the reader to Ref. [36] for a detailed comparison of the spectrum consumption when performing VNM and when performing VNE. Furthermore, we note that, in addition to deciding which physical path to allocate for a virtual link, the wavelength assignment can also be optimized such as to waste the same propagated wavelength on unintended links, further reducing spectrum consumption. We highlight this aspect in Fig. 8(e) on link (6,3) with an oval shape combining two arrows indicating a wasted wavelength from two different virtual links, $l_{b,a}$ and $l_{c,a}$, as wavelength channels assigned to both virtual links do not overlap and their resulting unfiltered spectrum propagate on common links. We refer to this aspect as *harmless interference*. When performing VNE, harmless interference can be exploited more than in VNM, due to having the choice in placing virtual nodes at physical locations that allow such situations.

On the Interplay of VNE with TE in Meshed FON: Similar

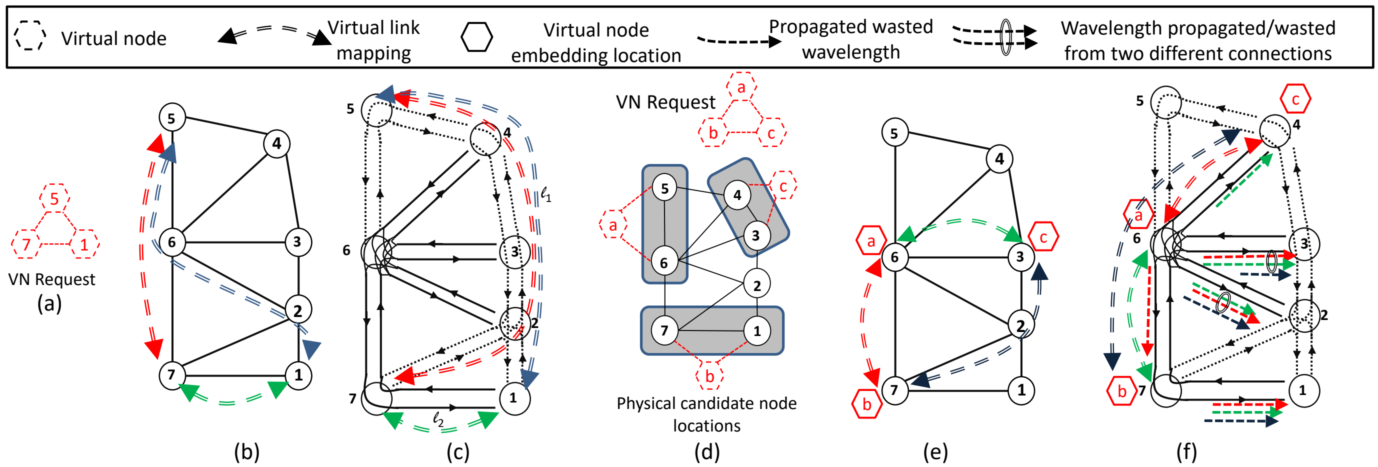

Fig. 8. (a) VN request, (b) VNM of the VN over a WSON, (c) VNM of the VN request over a FON (not showing the propagation of wavelengths due to broadcast-and-select architecture for simplicity), (d) VN request and a 7-node physical network highlighting candidate physical locations of the virtual nodes of the VN request, (e) VNE of the VN over WSON and (f) VNE of the VN over a FON showing the propagation of wavelengths.

to when jointly optimizing the fiber tree design and RWA, one can argue on the benefits of jointly optimizing designing fiber trees and mapping of VNs. Here, we note that, if VNs are very volatile (virtual links need to be reconfigured once new virtual nodes are set up), the problem of designing passive fiber trees in FON, which is a long-term, static problem, that is solved once, might not result very reasonable. On the contrary, if VNs are not very volatile, it is more reasonable to have a static version of the problem, i.e., to map, in a static scenario, multiple VNs, and establish fiber trees in a FON. In this case, the same entity should have control not only over the infrastructure to design fiber trees but also on the configuration of VNs. Yet, this does not rule out the relevance of the dynamic scenario, i.e., to dynamically map VNs, in FONs, which has not been tackled in literature. Ref. [37] evaluated the advantages in terms of wavelength consumption of jointly establishing fiber trees and performing VNM.

B. Service Chaining in FON

To provision SCs, the placement of VNFs on nodes equipped with computational capacity along with the SC routing and wavelength assignment should be decided. Due to the wavelength no-reuse constraint in FON, there might be a situation where some nodes capable of hosting NFVs still have computational capacity available but capacity of links connected to the nodes is exhausted. In this regard, it is preferred to consolidate VNFs of a SC on a single node to minimize the impact of wavelength no-reuse constraint, as the SC will utilize only one wavelength in this case. However, to have more flexibility in deciding the placement of VNFs, and hence, in where to terminate the SC, network operators may increase number of nodes equipped with computational resources. This requires a larger investment in computational resources, which may minimize the overall cost savings obtained in FON due to replacing WSS-based ROADMs by passive devices. The problem of dynamic SC in FON, and in particular, in metro-aggregation FON, has received attention recently. For instance, Ref. [38] proposed a heuristic approach for dynamic service chaining investigating the performance of FON while varying the number of nodes equipped with computational capacity while Ref. [39] presented a comparative analysis between FON and WSON architectures

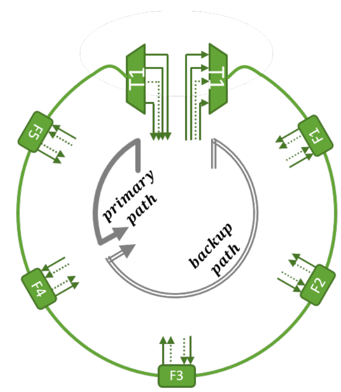

Fig. 9. Illustrative example of *DPP* protection in horseshoe FON for a traffic request between T1 and F4

varying traffic patterns of service chains in metro rings. Moreover, recent works such as Ref. [40] proposed a framework exploiting software defined networking-based control planes to achieve rapid and dynamic deployment of 5G services in a filterless-based architecture metro area network.

6. PROTECTION AND SURVIVABILITY IN FONS

In this section, we focus on protection in FONs. In particular, we consider dedicated path protection (*DPP*), a well-established protection strategy that consists in provisioning a working and a backup path for each lightpath request, under the constraints that working and backup paths are link disjoint. In the following sub-sections we show through illustrative examples how to ensure dedicated path protection in metro-aggregation FONs (Section 6.A) and in meshed FONs (Section 6.B).

A. Protection in Metro-Aggregation FON

In a horseshoe topology, a traffic request can be routed on two possible path: clockwise and counter-clockwise. Therefore, for any traffic request between a source-destination pair there is a working (*primary*) path and at most one *backup* path to ensure protection. In Fig. 9, we provide an illustrative example of *DPP* in a FON horseshoe topology. We consider a six node horseshoe topology, composed of five FON nodes (F1 to F5) and one terminal node (T1). We consider a traffic request established between terminal node (T1) and filterless node (F4). The primary (working) path is established in path *T1-F5-F4* while the backup (protection) path is established in path *T1-F1-F2-F3-F4*. Given that in horseshoe topologies there is no issue of fiber-tree establishment (there is one fiber-tree per direction), to ensure protection for any lightpath it is sufficient to ensure that a backup path is routed on the opposite direction with respect to the working path.

The main advantage of performing *DPP* in FON horseshoes is that it is relatively simple and intuitive, as there is only one backup path for each lightpath. The disadvantage is the additional cost to establish the backup lightpath, as more devices might be needed to be deployed, e.g., additional transponders for establishing the backup lightpath. Additionally, ensuring a backup path implies higher spectrum consumption as the allocated spectrum for the backup lightpath cannot be re-used due to the broadcast nature of FONs [41].

B. Protection in Meshed FON

To ensure DPP in meshed FONs, specific design issues emerge when solving the problem of routing and wavelength assignment, as a lightpath cannot optically traverse two fiber trees (see Sec. B). Since it is not always possible to guarantee that all node pairs are covered by two fiber trees, i.e., not all node pairs are optically connected on two different fiber trees, some node pairs cannot be served with a primary and a backup path. Therefore, to ensure protection of all traffic requests in FON, the deployment of additional network devices such as *Transceivers*, *Wavelength Blockers* or *Colored Passive Filters*, has been proposed [30, 37] to enable lightpaths to cross fiber trees. Before explaining how each of these devices can be utilized to enable lightpaths to cross fiber trees in the context of FON, we provide a brief description of each of them.

Transceivers are optical-electrical-optical (OEO) devices that enable to forward traffic from one fiber tree to another [37]. Transceivers are placed at nodes and allow to deploy edge-disjoint backup paths, and thus ensure protection in mesh FONs. They do so by allowing traffic to be dropped at "*Drop*" side of a node (e.g., on fiber tree F1 as in Fig. 10.c) and added at "*Add*" side of a node (e.g., on fiber tree F2 as in Fig. 10.c).

Wavelength Blockers (WBs) are photonic devices with singleinput/ouput that allow to block or let pass a specific set of wavelengths. The deployment of WBs in FONs has gained attention in conjunction with coherent transponder technology [42]. WBs ensure protection in FON by allowing one/multiple wavelengths to pass from one fiber tree to another, enabling an edge-disjoint backup path. Since they allow wavelengths to pass from one fiber tree to another, they are referred to as *Inter-Tree WBs*. Wavelengths which are let pass need to be blocked after reaching the destination, to prevent the creation of laser-loops. To serve this purpose, *Intra-tree WBs* can be deployed at any node and serve to block the wavelengths that are bridged by *inter-tree WBs* [30].

Colored Passive Filters (CPFs) are simple fixed filters which can block only one wavelength. CPFs are placed along the link and can ensure protection in FON when deployed along WBs, as illustrated in [30]. The main motivation to deploy CPFs is to prevent the creation of laser loops by wavelengths which are let pass by WBs.

Note that deploying WBs and CPFs implies going beyond the filterless solution leading to what is known as a *semi-filterless* architecture which is further discussed in the next section, while deploying transceivers the filterless architecture is preserved (but a significant additional cost is added, which might elide the cost savings of FON).

Fig. 10 shows an example of Transceivers, WBs and CPFs used to ensure protection in FONs. We consider a FON topology of five nodes composed of two fiber trees (F1: solid line and F2: dashed line), and a traffic request between node A and node C. Path *A-B-C* is the working path and traffic is routed along F1 fiber tree. A possible link-disjoint backup path is *A-E-D-C*, however the backup path needs to cross fiber tree F1 and F2, which is not possible in FON. Therefore, it is necessary to deploy transceivers or WBs and CPFs to ensure protection.

To ensure protection through *transceivers*, it is necessary to deploy a transceiver at node E and node D. Transceiver at node E will allow traffic to be dropped at *Drop* along fiber tree F1 and to be added at *Add* on fiber tree F2 (see Fig. 10.c). Analogously, transceiver at node D will allow traffic to be dropped along fiber tree F2 and added on fiber tree F1, this way ensuring an edge-disjoint backup path.

To ensure protection through *wavelength blockers*, it is necessary to deploy a WB at node E and at node D. Due to deploying a WB at node E, the wavelength carrying the backup traffic will propagate from F1 to F2 and all other wavelengths are blocked (see Fig. 10.d). Similarly, the WB deployed at node D will allow the wavelength carrying the traffic to pass from F2 to F1 and reach the destination node C. Note that, if the wavelength which is let pass by WBs at nodes E and D reaches the source node then a laser loop is created. Therefore in order to prevent laser loops, it is necessary to deploy an additional WB at node C in the pass-through path (see Fig. 10.e) or a CPF in link C-B. The WB at node C and CPF on link C-B have the same functionality and block one wavelength.

Each protection strategy is characterized by its advantages and disadvantages that may be quantified in terms of cost, wavelength consumption, availability and protection switching time. To date, only one work, Ref. [30], investigated guaranteeing protection of lightpaths in fiber tree-based FONs. Ref. [30] proposed a heuristic approach for the deployment of WBs and CPFs with the aim of minimizing the additional cost required for ensuring protection. Results show that an optimized deployment of WBs and CPFs allows ensuring protection while maintaining the cost of benefits of filterless architecture. The problem of survivability of virtual networks has been recently tackled in FON [43]. Ref. [43] proposed an ILP and heuristic approach to jointly optimize the fiber tree establishment and the survivability of virtual networks in FONs through the deployment of ITTs. Results show that when survivability is jointly optimized with fiber tree establishment, the investment in additional ITTs can be largely minimized, and even avoided in some cases. In contrast, with pre-established trees, the amount of additional network equipment needed to guarantee survivability is up to 60% with respect to WSON.

7. SEMI-FILTERLESS NETWORKS (SEMI-FON)

The concept of semi-FON was first introduced in Ref. [44]. Semi-FONs consist in the deployment of filters such as wavelength blockers or programmable optical switches at some network nodes [44–46]. The intuition behind Semi-FON is to mitigate some of the drawbacks of FON such as the spectrum waste, while maintaining cost benefits. We divide the discussion on Semi-FON in two parts. Sec. A discusses Semi-FON based

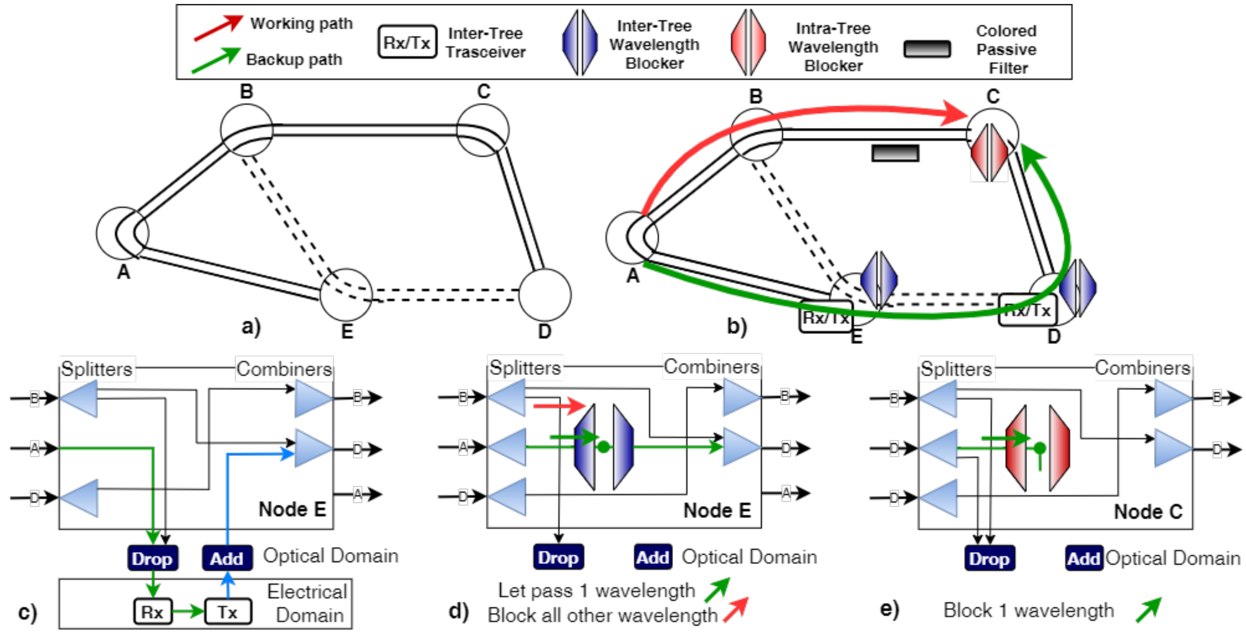

Fig. 10. Illustrative example of protection in FON: a) FON with two fiber trees (F1: solid line; F2: dashed line); b) Primary path (A-B-C) and backup path (A-E-D-C) for demand (A,C) when Inter-Tree Transceivers ITTs, WBs and CPFs are deployed; c) Node E architecture when an ITT is deployed; d) Node E architecture when an inter-tree WB is deployed and e) Node C architecture when an intra-tree WB is deployed

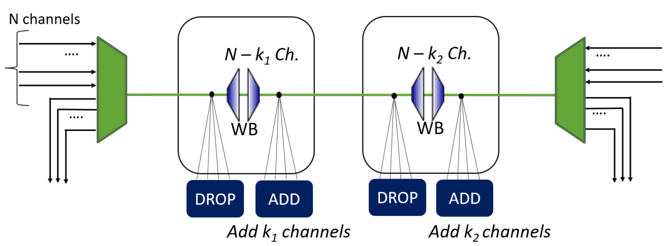

Fig. 11. Example of the placement of wavelength blockers in a filterless architecture-based node permitting wavelength re-use along a horseshoe.

on the deployment of filters at selected network nodes while Sec. B is dedicated to Semi-FON based on the use of low-cost programmable optical switches.

A. Semi-FON based on Filters Deployment in Selected Nodes

The placement of filters in selected nodes of filterless-based architectures aims to enable wavelength re-use by reducing the propagation of spectrum on unintended links. This solution is often considered in metro rings and is achieved through the use of WBs. Fig. 11 shows an example of such deployment with WBs deployed at filterless nodes. At every node, channels are first dropped (received at the node), the WB then blocks a pre-defined number of channels (k_1 at the first node) and then, at the add stage, up to k_1 channels can be added, therefore permitting the reuse of the same set of channels blocked by the WB. An experimental evaluation validating this architecture was performed in Ref. [42] showing that such implementation allows to boost the transmission capacity in the ring at a relatively lower cost compared to a WSS-based solution (wavelength blockers are relatively cheap compared to WSSs).

In meshed FON, the deployment of filters to enhance transmission capacity is more complex than in rings. This is because it involves the fiber tree establishment, routing, filter placement and wavelength assignment. In this respect, the joint optimization of the FON design, RWA and filter placement is necessary to maximize the benefits of the filters. Despite its importance, this problem is currently under investigation. Only Ref. [44] investigated filter placement in meshed FON showing that a limited number of filters (and therefore a limited additional investment) can significantly decrease the number of required wavelengths in the network.

B. Semi-FON based on Programmable Optical Switches

The concept of FON based on programmable optical switches has been proposed in [47] and is based on equipping network nodes with optical white boxes. In an optical white-box, optical devices deployed in FONs such as splitters and combiners can be interconnected through a re-configurable programmable optical switch. With the help of the programmable switch, each node can either connect input port to output port or interconnecting specific input ports to output ports through splitters and combiners. Note that switching is performed at fiber level, and hence, the fiber tree design is formed by the internal configuration of these white boxes.

To clarify how programmable optical switches can help reduce spectrum waste in FON, we show in Fig. 12 an example of the routing and wavelength assignment of 5 traffic demands, *D1-D5*, in a 6-node network topology divided into two fiber trees (Fig. 12(a)) and a SEMI-FON based on programmable optical switches (Fig. 12((b)), also showing the internal configurations of the nodes equipped. In the FON, 2 wavelengths are wasted on link (3,5), belonging to demands *D*1 and *D*2 respectively, due to splitting of input spectrum at node 3 from node 2. Similar waste of spectrum occurs on links (6,2) and (6,1) because of demands *D*3 and *D*4, respectively. We now show how a programmable optical switch can be helpful to reduce spectrum waste, and also highlight the case where they cannot be useful. For example, node 3 is configured to broadcast input spectrum from node

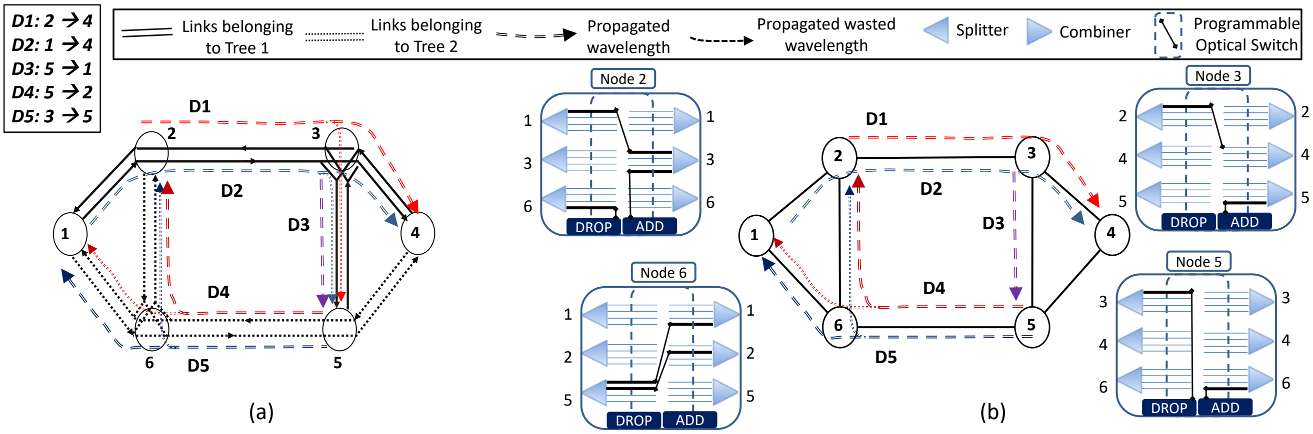

Fig. 12. Example of the routing and wavelength assignment of five demands over a FON (a) and over a semi-FON equipped with programmable optical switches at all nodes (b) showing the internal architecture of the nodes and the switches.

2 on output port 4 (see internal architecture of programmable switch of node 3) only, hence avoiding the propagation of wavelengths assigned to $D1$ and $D2$ towards node 5 and therefore eliminating spectrum waste on link (3,5). Note that, in this configuration, node 2 can only reach node 5 through node 6, and not through node 3 as in the FON in Fig. 12(a), which may be seen as a drawback of programmable FONs. We now highlight when programmable optical switches cannot be helpful to avoid spectrum waste. On node 6, a part of the spectrum arriving from node 5 is destined to node 2 while another part is destined to node 1. The fact that spectrum needs to be propagated to nodes 1 and 2 rules out the usefulness of the programmable switch. This is because a programmable optical switch is based on an optical circuit switching technology and can either connect or dis-connect an input port to an output port, and cannot operate on specific wavelengths, such as a WSS and which is, in fact, a main reason why programmable optical switches are relatively cheap compared to WSSs. To reduce spectrum waste in similar cases, the use of multi-core fibers based on spatial division multiplexing was introduced (Ref. [48]) however we do not cover aspect in this tutorial.

Furthermore, we note that in the example of Fig. 12(b), and for the sake of clarity, we kept the same as that in the FON routing however the routing can be further optimized along with the deployment of programmable switches. We refer the reader to Ref. [27] for more details on this aspect. We also highlight that the use of programmable optical switches has a major advantage over pure FON due to its flexibility, as it allows to re-configure fiber trees to adapt to varying traffic. Another advantage is the increased privacy and security due to limited propagation of spectrum to unintended nodes. The use of programmable switches can be also exploited to perform protection (rather than deploying additional network equipment as we have seen in Sec. 6). Several works have investigated the deployment of programmable FON comparing its performance in terms of spectrum consumption and equipment cost to FON and WSON architectures (Refs. [27, 47–49]). These studies conclude that, in comparison to WSON, programmable FON provides significant cost savings as expensive WSSs are eliminated from the architecture of the nodes and represents an attractive solution in meshed networks, as it reduces the drawbacks of the FON architecture.

8. EXPERIMENTAL EVALUATIONS

FON have already been deployed in Europe since 2015 [50] however recent experimental evaluations on FONs have tackled different angles with the aim of improving the performance of FONs. In this section, we focus on recent experiments involving FONs. The first experiment focuses on combining the concept of FON with Spatial Division Multiplexing (SDM) technologies for metro and inter-data center networks [51]. The experiment demonstrated a bidirectional filterless SDM optical network offering dynamic bandwidth allocation and eliminating drop-and-waste. Experimental deployments of filterless rings for metro-aggregation networks was undergone in Refs. [52] and [13]. Ref. [52] proposed and experimentally validated the deployment of C+L filterless network for metro-aggregation considering the performance the performance of a C+L band upgrade, showing that capacity can be doubled with respect to only C-band for a limited additional cost as well as without the use of additional optical amplifiers. Ref. [13] also proposed and evaluated a low-cost filterless unamplified L-band transmission line for short-reach low-latency connections. Experiment shows that when employing specific modulation formats, the reach is limited to relatively short single-hop connections (around 40 km), hence allowing channel reuse after receiving node. Moreover, Ref. [42] experimentally evaluated the performance in terms of QoT and wavelength usage of a semi-filterless horseshoe where nodes based on filterless architectures are equipped with wavelength blockers. Other experiments such as Ref. [53] focused on spectrum monitoring applying machine learning-based approaches. The work proposed a monitoring system that analyzes data of optical spectrum in the C-band to monitor lightpaths and detect laser drift failures before service disruption for filterless horseshoes in metro-aggregation networks.

9. FUTURE RESEARCH DIRECTIONS

In this section we discuss our vision on how research on FONs will progress in next years, focusing on some specific areas that we believe will require most attention.

Security in FONs: The broadcast-and-select node architecture in FONs can cause network operators concerns that go beyond spectrum consumption as traffic arrives at unintended network nodes. This allows eavesdroppers to tap communications and severely affect network's privacy and security if sensitive data was exposed such as, e.g., in quantum key distribution [54]. Therefore, it is essential to address possible security breaches, specifically in core FONs (in metro-aggregation networks the broadcast of spectrum is contained in a horseshoe ring). Despite its importance, it is only recently that the problem has been investigated. For example, Ref. [55] proposed a strategy based on the use of encryption cards to limit the security breaches due to broadcast-and-select such that a malicious part, if received data not addressed to it, cannot decrypt it. In this context, cost benefits of FONs need to be reevaluated to consider the cost of encryption cards.

FONs for Intra-Data Center Communications: Recent years have seen a shift in intra-data center communications due to cloud computing. While data center traffic was known to be outbound, it has now mostly become a rack-to-rack traffic [56] which introduced multi-cast traffic patterns, i.e., transmitting exact data from one-to-many nodes, to enhance resiliency of data center storage [57]. In this context, FONs can be exploited for intra-data center communications as they inherently feature a broadcast nature. As of today, no work has investigated the deployment of filterless architectures at data centers.

Machine Learning-based Methodologies for FONs: Machine Learning (ML) models have been widely applied for different applications in optical networks, such as failure management, QoT estimation and resource allocation. However, these models cannot be directly applied in FONs, because of FONs' distinct characteristics at both physical and networking layers. In this context, FON-tailored ML models need to be developed for the above-mentioned applications and how existing ML models change when specifically designed for FONs is to be explored.

Multi-band Transmission: Exploiting dual-band ((C+L)) transmission represents a novel approach to increase the number of supported channels in optical networks. In FONs, dual-band transmission has been recently investigated showing the possibility to increase network capacity without incurring additional costs [13]. On the same line, the extension to multi-band transmission exploiting the C, L and S bands represent a possible future direction and is yet to be investigated for FONs.

Further Cost Reductions: Although several works have focused on increasing the cost reductions of FONs, there is room for further increasing the economic benefits of FONs leveraging on higher-order modulation formats (hence reducing the number of transponders) and exploiting short links in metropolitan area networks to reduce number of optical amplifiers.

FON for Undersea Networks: FONs have also been proposed and investigated for undersea networks [58–60]. For instance, Ref. [59] evaluated a filterless network architecture for a trunk and branch undersea network topology while Ref. [60] evaluated cost savings due to adoption of filterless architecture for submarine networks. In spite of its importance, research work on FONs for undersea networks has been limited to the mentioned works.

10. CONCLUSION

Filterless Optical Network (FON) is a non-conventional optical network architecture that has been continuously attracting interest in the last two decades, due to FON's limited equipment cost and energy-efficiency. This technology has recently raised renewed attention as network operators seek to identify low-cost architectures to scale up network's capacity in the view of 5G and beyond communications and massive deployment of fiber access in many countries in the world. At the same time, FONs come with a number of challenges, which have been extensively investigated over the last years. In this tutorial, we provided an overview on the FON architecture and discussed its main differences with respect to traditional wavelength-switched optical networks. Moreover, we discussed various design and operational issues arising when dealing with FON, ranging from network resource allocation to protection/survivability in filterless networks, network slicing and field deployments, and highlighting how research has evolved over the years in each of the different cases. We also provided a techno-economic study to quantify cost reductions of FONs when deployed in metro and in core networks, and found that, in our considered case studies, (2-7)% of equipment cost can be saved in metro networks, and up to (0.5-2)% in some scenarios in core networks. In general, we remarked the importance of including physical-layer quality consideration in techno-economic studies for FON architecture due to large penalties on signal quality in large fiber trees. Finally, we identified gaps in existing literature and promising future research directions involving FONs

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