Strategies for Dedicated Path Protection in Filterless Optical Networks

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***Abstract*—Enabling Dedicated Path Protection (DPP) in Filterless Optical Networks (FONs) poses specific design challenges, as FONs require dividing the network topology in non-overlapping fiber trees, and lightpaths cannot cross from one tree to another unless additional devices are installed. In this study, we consider the possibility to deploy three type of devices, namely *Inter-Tree Transceivers (ITTs)*, *Wavelength Blockers (WBs)* and *Colored Passive Filters (CPFs)* to achieve DPP in FON, and we compare the three resulting DPP strategies, called *P-ITT, P-WB and P-WBC*. More specifically, we formulate three Integer Linear Programming (ILP) models for DPP in FON with the objective to minimize additional device cost and minimize total wavelength consumption. Numerical results over two realistic topologies show that *P-WBC* achieves cost savings up to 33% in comparison to P-WB and up to 97% in comparison to *P-ITT*. However, even if it is the costliest approach, *P-ITT* ensures up to 7% savings in wavelength consumption and up to 23% savings in resource overbuild compared to *P-WB* and *P-WBC*, making it a possible candidate in spectrum-scarce deployments.**

***Index Terms*—Filterless Optical Networks, Protection, Transceivers, Wavelength Blockers, Colored Passive Filters**

I. Introduction

Filterless Optical Networks (FONs) represent a cost-effective solution for the design of optical networks, and they are currently attracting renewed industrial interest both for mesh-core [1]–[3] and ring-metro networks [4]–[6]. In FONs, inexpensive passive splitters and combiners are used in place of costly wavelength selective switches (WSSs) in optical switching nodes. FON nodes are hence cheaper than WSS-based nodes, but they enforce a broadcast-and-select switching architecture that leads to high spectrum waste and possible laser-loops effects. To avoid laser loops and limit spectrum waste, mesh FONs are deployed using edge-disjoint *fiber trees* that separate the network into several loop-free network segments [3].

Protection against failures is a primary design concern in optical networks, because even a single link failure can interrupt signals' transmission over several optical channels, leading to a huge data loss and unacceptable service outages. In this work, we consider *Dedicated Path Protection* (DPP) in FON, 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. To apply DPP in FONs, specific design issues emerge when solving the problem of routing and wavelength assignment, especially when dealing with mesh topologies, as a lightpath cannot flow from one fiber tree to another. Figure 1.a shows an example of DPP in a FON with two fiber-trees (FT1: solid line and FT2: dashed line). Let us consider a traffic request (*A,C*): if *primary* (working) path is path *A-B-C* on *FT1*, a possible link-disjoint backup path could be *A-E-D-C*. However, the *backup* path needs to cross from fiber-tree FT1 to FT2, which is not allowed in FON (a ligthpath cannot cross from one fiber tree to another). Note that, in some cases, a link disjoint path pair can be found in FONs, namely when source and destination node both belong to two different fiber trees (consider, e.g., primary path B-C-D, protected by backup path B-E-D). However, since it is not always possible to guarantee that all source-destination node pairs are covered by two edge-disjoint trees, some node pairs cannot be served with a primary and a backup path. In these cases a *protection ratio*, i.e., percentage of demands protected out of the total number of demands, is defined, which is usually less than 100%. To achieve 100% protection ratio, DPP requires the installation of additional network equipment, namely *Inter-Tree Transceivers (ITTs)*, *Wavelength Blockers (WBs)* and *Colored Passive Filters (CPFs)*, to enable fiber tree crossing by the backup path.

Depending by which additional equipment is considered, three strategies to guarantee DPP in FON can be identified: *1)* DPP by deploying ITTs *(P-ITT)*, *2)* DPP by deploying WBs *(P-WB)* and *3)* DPP by deploying WBs and CPFs *(P-WBC)*. In Section III, we will provide a detailed description of ITTs, WBs and CPFs and an illustrative example of how to ensure protection in FON. In this study, we model these protection strategies using three Integer Linear Programming (ILP) formulations with the objective of minimizing the cost of additional equipment deployed to guarantee 100% protection ratio (primary objective) and minimizing overall wavelength consumption (secondary objective). These ILP formulations allow us to compare the three protection strategies in terms of protection ratio and resource consumption. The rest of the paper is organized as follows. Section II overviews related work in this area. Section III discusses examples of deploying ITTs, WBs and CPFs to ensure protection. Section IV formally states the DPP problem in FON and presents the proposed ILP models to solve it. Section V discusses numerical results. Section VI draws the conclusion.

II. Related work

Research and industrial interest for FON design has recently revamped as FONs are emerging as a low-cost optical network

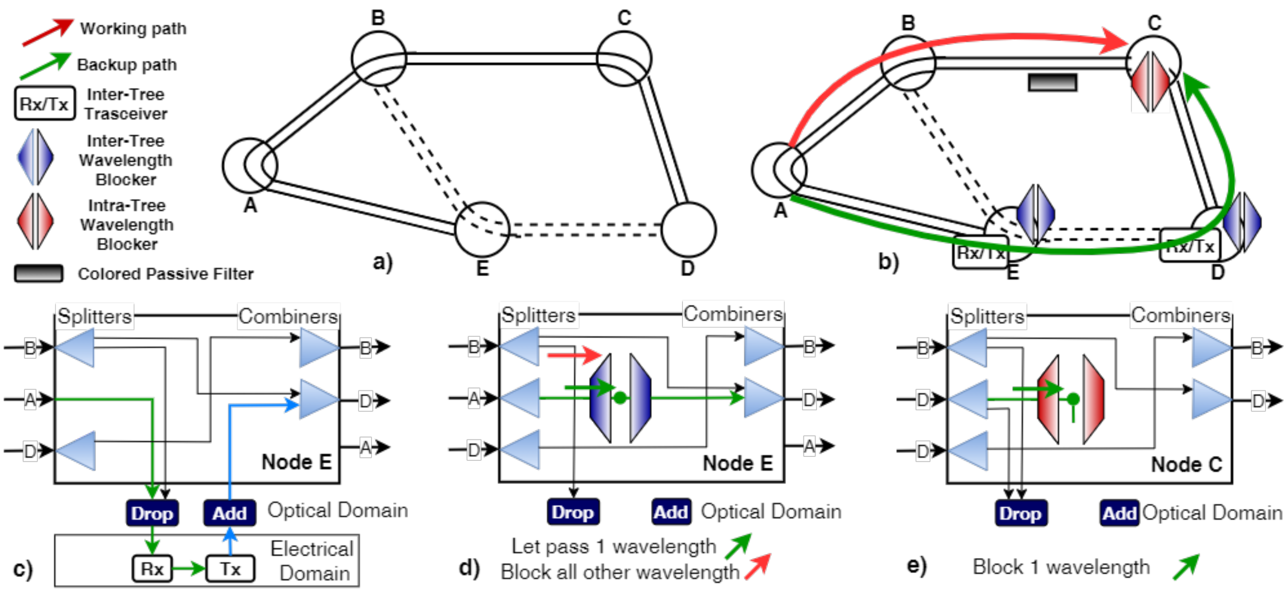

Fig. 1: Illustrative example of protection in FON: a) FON with two fiber trees (FT1: solid line; FT2: dashed line); b) Primary path (A-B-C) and backup path (A-E-D-C) for demand (A,C) when ITTs, WBs and CPFs are deployed; c) Node E architecture when an ITT is deployed; d) Node E architecture when an inter-tree WB is deployed and e) Node C architecture when an intra-tree WB is deployed

architecture, especially for the metro-aggregation segment, where FONs can jointly achieve cost savings and satisfactory quality-of-transmission [5]. An ILP approach for solving the offline routing and spectrum assignment (RSA) problem in elastic FONs was described in [10], while authors in [11] proposed a joint optimization approach that performs fiber tree establishment and routing and wavelength assignment (RWA) to optimize the overall spectrum consumption. Given the broadcast nature of FONs, spectrum allocation becomes even more precious. Some recent works, such as [12], proposed to limit spectrum waste by using programmable optical switches.

Only a few works addressed the problem of protection in FONs. Ref. [7] and [14] investigated ILP approaches to perform different types of survivable virtual network mapping/embedding in FONs, considering the deployment of ITTs. Ref. [13] proposed a multi-objective evolutionary Pareto optimization approach that maximizes the protection ratio of traffic demands. The most relevant work to our approach is [9], providing a heuristic approach that ensures 100% protection ratio by introducing a limited number of WBs at selected intermediate nodes. With respect to [9], we investigate a larger set of DPP options in FON (including, e.g., ITTs) and formally model the problem using three ILP approaches to evaluate the cost and wavelength utilization of the three strategies.

III. Protection in Filterless Optical Networks

This section provides a detailed description of ITTs, WBs and CPFs and their utilization for DPP in FON. We introduce them using examples on how to ensure DPP in FON by deploying ITTs (i.e., *P-ITT*), *inter-tree* and *intra-tree* WBs (i.e., *P-WB*), and *inter-tree* WBs and CPFs (i.e., *P-WBC*).

- *Inter-Tree Transceivers (ITTs).* ITTs are deployed at nodes connected to at least two fiber trees to enable optical-electrical-optical (*OEO*) conversion and forward traffic from one fiber tree to another [7]. ITTs allow to find multiple paths between source-destination node pairs that are covered by two edge-disjoint trees.
- *Wavelength blockers (WBs).* WBs are photonic devices with single input/output that allow specific wavelengths to pass through or get blocked [8]. They can be deployed as *inter-tree WBs* or *intra-tree WBs*. *Inter-tree* WBs are deployed at nodes connecting different trees and are used to bridge one or more wavelengths between fiber trees and/or selectively block some or all other wavelengths. They ensure protection by allowing wavelengths to pass from one fiber tree to another, without OEO conversion as *ITTs*. *Intra-tree* WBs can be deployed at any node and serve to block the wavelengths that are bridged by *inter-tree* WBs, to prevent laser loops.
- *Colored Passive Filters (CPFs).* CPFs are simple fixed filters placed along the link that can block only one wavelength [9] and may be only deployed together with *inter-tree* WBs. CPFs serve to block the wavelength which is let pass by an *inter-tree* WBs, to prevent laser loops. CPFs can be deployed instead of *intra-tree* WBs to decrease total wavelength consumption.

Let us observe the example in Fig. 1.a and consider traffic request *(A,C)*: path A-B-C is the primary path and path A-E-D-C is the backup path that passes through FT1 and FT2.

P-ITT: to provision the *backup* path A-E-D-C, an ITT can be deployed at node E and at node D to allow wavelength conversion from FT1 to FT2 and from FT2 to FT1, respectively (see Fig. 1.b). The internal structure of node E is shown in Fig. 1.c when an ITT is deployed. Traffic carried on a wavelength λ_x (FT1) is dropped (*Drop*) and passed to electrical domain and then passed back to the optical domain

TABLE I: Objective function for P-ITT, P-WB and P-WBC

P-ITT: minimize number of inter-tree transceivers (first term) and wavelength consumption (second term)

$$min\ M \cdot \left(\sum_{(i,j)\in E} \sum_{(j,k)\in E} \sum_{(s,t)\in D} \sum_{n\in P} d^{s,t,n}_{i,j,j,k} * c_d \right) + \sum_{(i,j)\in E} \sum_{\lambda\in W} \sum_{(s,t)\in D} \sum_{n\in P} (w^{s,t,n}_{i,j,\lambda} + p^{s,t,n}_{i,j,\lambda})$$

P-WB: minimize number of *inter-tree* and *intra-tree* wavelength blockers (first term) and wavelength consumption (second term):

$$min\ M \cdot \left(\sum_{(i,j)\in E} \sum_{(j,k)\in E} c_{i,j,j,k} * c_c + x_{i,j,j,k} * c_x \right) + \sum_{(i,j)\in E} \sum_{\lambda\in W} \sum_{(s,t)\in D} \sum_{n\in P} (w^{s,t,n}_{i,j,\lambda} + p^{s,t,n}_{i,j,\lambda})$$

P-WBC: minimize number of *inter-tree* wavelength blockers and colored passive filters (first term) and wavelength consumption (second term):

$$min\ M \cdot \left(\sum_{(i,j)\in E} \sum_{(j,k)\in E} c_{i,j,j,k} * c_c + \sum_{(i,j)\in E} \sum_{\lambda\in W} v_{i,j,\lambda} * c_v \right) + \sum_{(i,j)\in E} \sum_{\lambda\in W} \sum_{(s,t)\in D} \sum_{n\in P} (w^{s,t,n}_{i,j,\lambda} + p^{s,t,n}_{i,j,\lambda})$$

(*Add*) on a wavelength λ_y (FT2). The same procedure is followed at node D, where traffic is passed from FT2 to FT1 using an ITT. Generally speaking, ITTs ensure protection in FON by performing wavelength conversion and allowing traffic to go from one fiber tree to another. However, demand *(A,C)* can be protected also by deploying WBs and CPFs.

P-WB: to support *backup* path A-E-D-C, an *inter-tree* WB can be deployed at node E and at node D. An *inter-tree* WB at node E allows wavelength λ_x to pass from FT1 to FT2 and blocks all the other wavelengths. The structure of node E when an *inter-tree* WB is deployed is shown in Fig. 1.d. Similarly, the *inter-tree* WB at node D will let wavelength λ_x pass to FT2. WBs at nodes E and D are referred to as *inter-tree* WBs, as they allow wavelengths to pass from one fiber-tree to another. A drawback of deploying *inter-tree* WBs is that their deployment may lead to a creating laser loops. Consequently, additional devices must be deployed to prevent laser-loops, e.g., *intra-tree* WBs or CPFs. In Fig. 1.a, to prevent the laser loop, i.e., to prevent λ_x creating a loop by passing source node A, an *intra-tree* WB is placed either at node C, node B or node A. The *intra-tree* WB placed at either of the nodes, e.g., at node C as in Fig. 1.e, will block λ_x to propagate further and prevent the creation of a laser loop. Deploying an *intra-tree* WB at either node has the same functionality, however, to reduce wasted spectrum, it is preferable to place it at node C.

P-WBC: an alternative to deploying an *intra-tree* WB at node C, is to deploy a CPF along the link. Note that CPFs may be deployed only with *inter-tree* WBs as they serve to block a wavelength that is let pass by an *inter-tree* WB. In our example, a CPF is placed either on link (C-B) or link (B-A) to block λ_x and prevents the creation of a laser loop.

IV. ILP APPROACH FOR PROTECTION IN FON

A. Problem statement

The problem of routing and wavelength assignment (RWA) with DPP in FONs can be stated as follows: **Given** a FON topology with given fiber trees and a set of traffic demands, **decide** where and how many optical devices (ITT, WB and CPFs) need to be deployed and the RWA for each traffic demand, **constrained to** ensure dedicated path protection for each lightpath, wavelength continuity and limited network capacity, with the **objective** of minimizing the cost of additional optical devices deployed[1] and overall wavelength consumption.

[1]We only focus on the cost of additional equipment, as the baseline FON devices (i.e., splitters and combiners) have the same cost in all three strategies.

TABLE II: Sets and parameters

N	set of nodes in the physical topology
E	set of physical bidirectional edges
D	set of source-destination (s,t) pairs, or demands
T	set of fiber-trees in FON
W	capacity of a link in number of wavelengths
F	set of bidirectional links belonging to a fiber tree
P	set of paths per demand
M	$= 10^4$ is a parameter used to favor the minimization of one term over another in the objective function
c_d	cost of device *d*, deployed to ensure protection where d $\in (ITT, WB, CPF)$

B. ILP approaches for protection

We have developed four versions of the ILP formulation: *P-FON*, *P-ITT*, *P-WB*, *P-WBC*. Note that, *P-FON* maximizes the protection ratio, given that no additional equipment is deployed, and is considered as a baseline approach.

We report the objective function for ***P-ITT***, ***P-WB*** and ***P-WBC*** in Table I, sets and parameters in Table II and binary decision variables in Table III. In the following, we report constraints for each strategy:

1) *P-ITT:*

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

$\forall i \in N, (s,t) \in D, n \in P$

$$q^{s,t,n}_{i,j} + q^{s,t,k}_{i,j} \leq 1, \forall (s,t) \in D, (i,j) \in E, n, k \in P : n \neq k \quad (2)$$

Constraint (1) is the *flow* and *protection* constraint. It ensures that for each demand, there are two paths. Constraint (2) ensures *link-disjointness* between the *working* and *backup* path for *(s,t)*.

$$g^{f,n}_{s,t} \leq \sum_{(i,j)\in F_f} q^{s,t,n}_{i,j} \leq M \cdot g^{f,n}_{s,t}, \forall (s,t) \in D, f \in T, n \in P \quad (3)$$

Constraint (3) maps each path over a fiber tree and it is used in (4) to denote on which fiber tree to use a wavelength.

$$\sum_{\lambda\in W} y^{s,t,n}_{f,\lambda} \geq g^{s,t}_{f,n} \forall f \in T, (s,t) \in D, n \in P \quad (4)$$

$$y^{s,t,n}_{f,\lambda} + y^{s,t,n}_{r,\lambda} \leq 1, \forall f, r \in T (s,t) \in D, n \in P, \lambda \in W : f \neq r \quad (5)$$

$$w^{s,t,n}_{i,j,\lambda} \leq q^{s,t,n}_{i,j}, \forall f \in T, (s,t) \in D, (i,j) \in F_f, \lambda \in W, n \in P \quad (6)$$

$$w^{s,t,n}_{i,j,\lambda} \leq y^{s,t,n}_{\lambda,f}, \forall f \in T, (i,j) \in F_f, (s,t) \in D, \lambda \in W, n \in P \quad (7)$$

$$0 \leq y^{s,t,n}_{f,\lambda} + q^{s,t,n}_{i,j} - \sum_{\gamma\in W} w^{s,t,n}_{i,j,\gamma} \leq 1$$

$$\forall f \in T, (i,j) \in F_f, (s,t) \in D, \lambda \in W \quad (8)$$

TABLE III: Binary decision variables

$q_{i,j}^{s,t,n}$	1 iff n^{th} path of (s,t) is routed on link (i,j)
$w_{i,j,\lambda}^{s,t,n}$	1 iff n^{th} path of (s,t) is mapped on link (i,j) as *working* or *backup* link using wavelength λ
$d_{i,j,j,k}^{s,t,n}$	1 iff n^{th} path of (s,t) is mapped on links (i,j) and (j,k), which belong to two different fiber trees
$g_f^{s,t,n}$	1 iff n^{th} path of (s,t) is mapped on fiber tree f
$y_{\lambda,f}^{s,t,n}$	1 iff n^{th} path of (s,t) is mapped on fiber tree f using wavelength λ
$a_{i,j,j,k,\lambda}^{s,t,n}$	1 iff (i,j) and (j,k) links belong to different fiber trees and relate to n^{th} path of (s,t), using λ
$p_{i,j,\lambda}^{s,t,n}$	1 iff wavelength λ is broadcasted (wasted) on link (i,j) on behalf of n^{th} path of (s,t)
$e_{i,j,j,k,\lambda}^{s,t,n}$	1 iff n^{th} path of (s,t) is mapped on links (i,j) and (j,k) belonging to same fiber tree, using λ
$c_{i,j,j,k}$	1 iff an inter-tree WB is placed in node j to connect (i,j) and (j,k) links belonging to different fiber trees
$x_{i,j,j,k}$	1 iff an intra-tree WB is placed in node j to block a set of wavelengths going from i to k through node j
$h_{i,j,j,k,\lambda}$	1 iff an *intra-tree* WB is placed in j to prevent λ pass from i to k, where (i,j) & (j,k) are on same fiber tree
$v_{i,j,\lambda}$	1 iff wavelength λ is blocked on link (i,j) that is, if a CPF is placed on link (i,j)
$y_{\lambda}^{s,t,n}$	1 iff n^{th} path of (s,t) uses wavelength λ

$$0 \leq q_{i,j}^{s,t,n} + q_{j,k}^{s,t,n} - 2 \cdot \sum_{\lambda \in W} e_{i,j,j,k,\lambda}^{s,t,n} \leq 1, \forall f \in T, (i,j),(j,k) \in F_f, (s,t) \in D, n \in P : j \neq s,t \wedge i \neq k \quad (9)$$

$$\sum_{n \in P} (w_{i,j,\lambda}^{s,t,n} + w_{i,j,\lambda}^{u,r,n}) \leq 1 \quad \forall (i,j) \in E, (s,t),(u,r) \in D, \lambda \in W : (s,t) \neq (u,r) \quad (10)$$

Constraints (4)-(9) ensure wavelength continuity: a wavelength cannot pass from one fiber tree to another. Constraint (8) assigns a wavelength to *working* and *backup* flow, (9) ensures that only one wavelength can pass through a transit node for a single path of each demand and (10) imposes that two demands cannot share the same wavelength in link (i,j).

$$0 \leq w_{i,j,\lambda}^{s,t,n} + w_{j,k,\lambda}^{s,t,n} - 2 \cdot e_{i,j,j,k,\lambda}^{s,t,n} \leq 1, \forall f \in T, (i,j),(j,k) \in F_f, \lambda \in W, (s,t) \in D, n \in P : k \neq i \wedge j \neq s,t \quad (11)$$

$$0 \leq w_{i,j,\lambda}^{s,t,n} + d_{i,j,j,k}^{s,t,n} - 2 \cdot a_{i,j,j,k,\lambda}^{s,t,n} \leq 1, \forall f,r \in T, (i,j) \in F_f, (j,k) \in F_r, (s,t) \in D, n \in P, \lambda \in W : j \neq s,t \wedge i \neq k \quad (12)$$

Constraint (11) enforces wavelength continuity and identifies transit nodes, useful to model the broadcast propagation jointly with constraint (12), in case of fiber tree crossing.

$$0 \leq q_{i,j}^{s,t,n} + q_{j,k}^{s,t,n} - 2 \cdot d_{i,j,j,k}^{s,t,n} \leq 1, \forall (s,t) \in D, n \in P, f,r \in T, (i,j) \in F_f, (j,k) \in F_r : r \neq f \wedge j \neq s,t \wedge i \neq k \quad (13)$$

Constraint (13) imposes the use of an ITT whenever a working/backup flow has to pass from one fiber tree to another.

$$p_{j,u,\lambda}^{s,t,n} \geq e_{i,j,j,k,\lambda}^{s,t,n} \forall f \in T, \lambda \in W, (s,t) \in D, n \in P, (i,j),(j,k),(j,u) \in F_f : u \neq i,n \wedge n \neq i \wedge j \neq s,t \quad (14)$$

$$p_{j,u,\lambda}^{s,t,n} \geq a_{i,j,j,k,\lambda}^{s,t,n} \forall f,r \in T, \lambda \in W, (s,t) \in D, n \in P, (i,j),(j,u) \in F_f, (j,k) \in F_r : r \neq f \wedge u \neq i,k \wedge k \neq i \wedge j \neq s,t \quad (15)$$

$$p_{j,u,\lambda}^{s,t,n} \geq w_{i,j,\lambda}^{s,t,n}, \forall f \in T, \lambda \in W, (s,t) \in D, n \in P, (i,j), (j,u) \in F_f : u \neq i \wedge j = t \quad (16)$$

$$p_{j,u,\lambda}^{s,t,n} \geq p_{i,j,\lambda}^{s,t,n}, \forall f \in T, \lambda \in W, (i,j),(j,u) \in F_f, (s,t) \in D, n \in P, u \neq i \quad (17)$$

Constraints (14)-(17) model the broadcast of wasted wavelengths: from transit nodes and destination nodes.

$$\sum_{n \in P} (w_{i,j,\lambda}^{s,t,n} + p_{i,j,\lambda}^{s,t,n}) \leq 1 \qquad \forall (i,j) \in E, (s,t) \in D, \lambda \in W \quad (18)$$

$$\sum_{\lambda \in W} \sum_{(s,t) \in D} \sum_{n \in P} (w_{i,j,\lambda}^{s,t,n} + p_{i,j,\lambda}^{s,t,n}) \leq |W| \qquad \forall (i,j) \in E \quad (19)$$

Constraint (18) imposes no wavelength overlapping between useful and wasted flows on the same link and (19) is the capacity constraint.

*2) **P-WB and P-WBC**:* use the same constrains regarding wavelength assignment as *P-ITT* with some slight modifications (not shown due to page limitations): we can remove index f in case of WB placement, since there is no *OEO* conversion, and no wavelength conversion. The following constraints correspond to WBs and CPFs placement: constraints (20)-(21) apply to both *P-WB* and *P-WBC*, while constraints (22)-(24) apply only to *P-WB* and (25)-(28) only to *P-WBC*.

$$c_{i,j,j,k} \leq \sum_{(s,t) \in D} \sum_{n \in P} d_{i,j,j,k}^{s,t,n} \leq M \cdot c_{i,j,j,k}, \quad \forall (i,j),(j,k) \in E \quad (20)$$

$$x_{i,j,j,k} \leq \sum_{\lambda \in W} h_{i,j,j,k,\lambda} \leq M \cdot x_{i,j,j,k}, \forall (i,j),(j,k) \in E \quad (21)$$

Constraint (20) represents grouping of fiber tree crossing instances: each $d_{i,j,j,k}^{s,t,n}$ represents a connection passing through an *inter-tree* WB ($c_{i,j,j,k}$). Similarly, constraint (21): x denotes an *intra-tree* WBs, and h the wavelength (λ) that has to be blocked by the *intra-tree* WB.

$$p_{j,u,\lambda}^{s,t,n} \geq w_{i,j,\lambda}^{s,t,n} - h_{i,j,j,u,\lambda}, \forall f \in T, \lambda \in W, (s,t) \in D, n \in P, (i,j),(j,u) \in F_f : u \neq i \wedge j = t \quad (22)$$

$$p_{j,u,\lambda}^{s,t,n} \geq p_{i,j,\lambda}^{s,t,n} - h_{i,j,j,u,\lambda} \quad \forall f \in T, \lambda \in W, (i,j),(j,u) \in F_f, (s,t) \in D, n \in P, u \neq i \quad (23)$$

$$e_{i,j,j,u,\lambda}^{s,t,n} + h_{i,j,j,u,\lambda} \leq 1 \quad \forall f \in T, (i,j),(j,u) \in F_f, (s,t) \in D, n \in P, \lambda \in W \quad (24)$$

Constraints (22)-(24) describe *intra-tree* WB placement. WB can be placed at destination node, in a transit node or directly in the source node. A wavelength cannot be used on a path on which an *intra-tree* WB is present (24).

$$p_{j,u,\lambda}^{s,t,n} \geq w_{i,j,\lambda}^{s,t,n} - v_{j,u,\lambda}, \forall f \in T, \lambda \in W, (s,t) \in D, n \in P, (i,j),(j,u) \in F_f : u \neq i \wedge j = t \quad (25)$$

$$p_{j,u,\lambda}^{s,t,n} \geq p_{i,j,\lambda}^{s,t,n} - v_{i,j,\lambda}, \forall f \in T, \lambda \in W, (i,j),(j,u) \in F_f, (s,t) \in D, n \in P, u \neq i \quad (26)$$

$$\sum_{\lambda \in W} v_{i,j,\lambda} \leq 1 \qquad \forall (i,j) \in E \quad (27)$$

$$w_{i,j,\lambda}^{s,t,n} + v_{i,j,\lambda} \leq 1, \forall (i,j) \in E, (s,t) \in D, n \in P, \lambda \in W \quad (28)$$

Constraints (25)-(28) model the placement of CPFs along the links. In particular, CPFs can be deployed after the destination node or between destination node and source node, blocking *up to* one wavelength. In addition, a working/backup flow cannot use a wavelength that is blocked along the path.

V. ILLUSTRATIVE NUMERICAL RESULTS

A. Evaluation settings

To solve our optimization instances, we use CPLEX 20.1.0 over a workstation with Inel(R) Core(TM) i5-8400 CPU (6 cores @2.80 GHz) processor and 32 GB of memory. We consider two sample network topologies: a 7-node network (G7) and a 10-node network (IT10), see Fig. 2. To gain generality of our results, for each topology, we consider four different fiber tree establishments (each consisting of two fiber trees) and a full-mesh traffic matrix (same for all fiber trees), and report averaged results.

We compare the performance of *P-ITT*, *P-WB*, *P-WBC* and *P-FON* (the last one is used as baseline reference) in terms of: *i)* protection ratio (*PR*), *ii)* total cost of additional devices deployed, expressed in cost units (*cu*) and normalized to the cost of one *CPF*, *iii)* total wavelength consumption, given in terms of wavelength links used by *primary* and *backup* paths ($w^{s,t,n}_{i,j,\lambda}$) and broadcast of wasted wavelengths ($p^{s,t,n}_{i,j,\lambda}$), and *iv)* resource overbuild (*RO*) which is the ratio between the amount of wavelength links used by *backup* paths (*BP*) and *primary* paths (*PP*): $RO = \frac{BP}{PP}$ (note that wasted wavelengths are not accounted in RO calculation). For each equipment type we consider the following cost in cost unit (*cu*), normalized to the cost of a *CPF*: CPF cost = 1.0 *cu* [9]; WB cost = 225 *cu* [9] and ITT cost = 1400 *cu* [15].

B. Numerical results and discussion

Protection ratio: Fig. 3.a shows the protection ratio (*PR*) for the four strategies for G7 and IT10 network topologies. *P-FON* has a *PR* of 71% and 47% for G7 and IT10, respectively. *P-FON* cannot reach a 100% *PR* because it is not possible to find a disjoint backup path for all traffic requests. However, as expected, deploying additional equipment using *P-ITT*, *P-WB* and *P-WBC* ensures a 100% *PR*.

Total cost of additional equipment: Fig. 3.b shows the total cost of additional equipment in 10^3 *cu* for *P-ITT*, *P-WB* and *P-WBC* for G7 and IT10 topologies. *P-ITT* has a cost up to 97% higher compared to *P-WB* and *P-WBC*. This is also expected, considering the much higher cost of an ITT compared to a WB. Comparing *P-WB* and *P-WBC*, we observe that for G7 they have the same cost as the same number of *inter-tree* WBs is deployed in both strategies, while no CPFs are necessary in *P-WBC* in this case. In case of IT10, *P-WBC* has a 33% lower cost of additional devices than *P-WB*. The savings in *P-WBC* arise from the opportunity of deploying CPFs instead of *intra-tree* WB to avoid *laser-loops*.

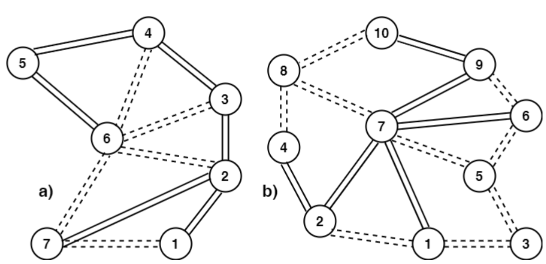

Fig. 2: Example of a fiber tree for a) G7 and b) IT10

The cost may vary with network topology, even for the same protection strategy, e.g., a higher cost of 78%, 40% and 11% in case of IT10 compared to G7 for *P-ITT*, *P-WB* and *P-WBC*.

Wavelength consumption: Fig. 3.c shows that *P-ITT* achieves savings up to 2% in case of G7 and up to 7% in case of IT10 compared to *P-WB* and *P-WBC*. *P-ITT* enables such savings as it performs wavelength conversion for a traffic request passing from one fiber tree to another. Wavelength consumption for *P-FON* is the lowest because it does not guarantee a 100% PR.

Resource overbuild: Fig. 3.d shows that *P-ITT* has a lower RO of 11% for G7 and 23% for IT10 than *P-WB* and *P-WBC*. RO is the same for *P-WB* and *P-WBC* since placement of *inter-tree* WBs is the same in both strategies.

In conclusion, the higher cost of *P-ITT* leads in turn to a lower wavelength consumption and RO compared to *P-WB* and *P-WBC*, hence *P-ITT* might represent a justifiable choice in situation of spectrum scarcity. ILP solving time varies with topology and protection strategy. For G7, it ranges between 14 *sec* for *P-FON* and 20 *mins* for *P-ITT*, while for IT10, it varies between 2 *mins* for *P-FON* and 4 *hrs* for *P-WBC*.

C. Sensitivity analysis: Traffic variation

In the following, we provide a sensitivity analysis for *P-ITT*, *P-WB* and *P-WBC* for IT10 topology and evaluate the variation of total cost of additional equipment, total wavelength consumption and RO by varying the traffic volume. We consider six cases: 15, 30, 45, 60, 75 and 90 traffic requests.

Total cost of additional equipment: Fig. 4.a shows the total cost of additional equipment in 10^3 *cu* for *P-ITT*, *P-WB* and *P-WBC* for varying traffic volume.

P-ITT: the cost increases linearly with traffic from 11.2 *cu* to 75.6 *cu*. This linear increase is expected, as for each demand that requires to pass from one fiber tree to another, an ITT is necessary to be deployed. Therefore, a higher number of demands implies a higher number of deployed ITTs.

P-WB: the cost increases from 0.9 *cu* and 1.8 *cu* (hence we observe a 50% increase in cost for a 83% traffic increase). This sublinear increase is due to the shareability of WBs, i.e., one WBs can be used to let pass or block several lightpaths from one fiber tree to another. This is beneficial since the increase in traffic does not necessarily mean that the number of deployed WBs is increased as it happens when ITTs are deployed in *P-ITT*. Hence *P-WB* cost savings with respect to *P-ITT* increase from 92% and 97% for increasing traffic volume.

P-WBC: the cost varies between 0.676 *cu* and 1.131 *cu* (an increase of 40% in cost for a 83% traffic increase). Compared to *P-WB*, the number of *inter-tree* WBs is the same, however the total cost changes for each traffic matrix since a different number of CPFs is deployed in each case. Such behaviour is expected given that CPFs can only block one wavelength, so a higher number of demands implies a higher number of CPFs deployed. *P-WBC* cost savings vary from 94% to 97% compared to *P-ITT*, and from 25% to 33% compared to *P-WB*.

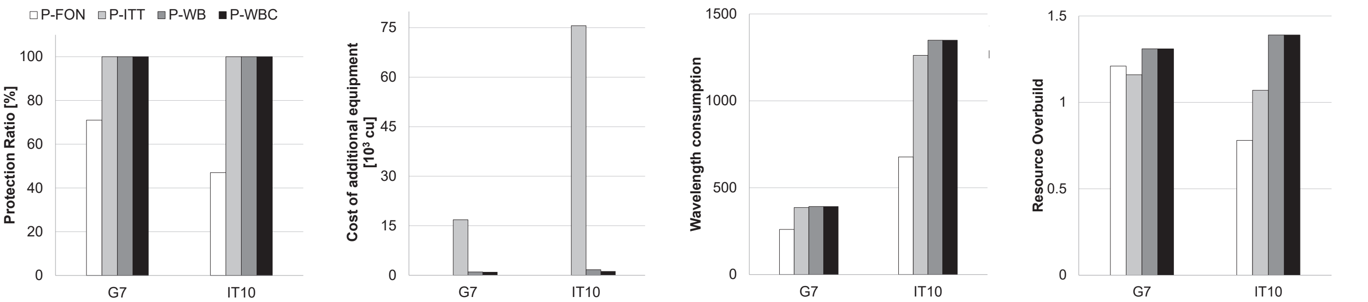

Fig. 3: a) Protection ratio, b) Total cost of additional equipment, c) Total wavelength consumption and d) Resource Overbuild for P-FON, P-ITT, P-WB and P-WBC in G7 and IT10 network topologies

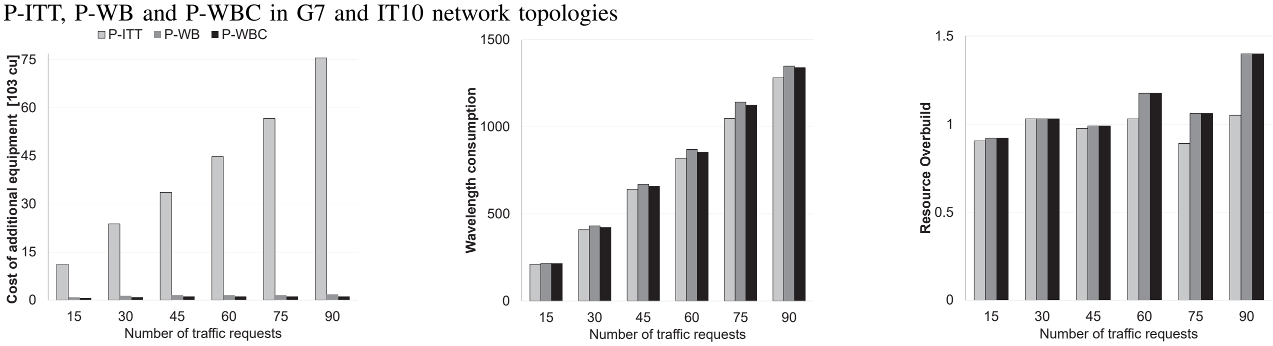

Fig. 4: a) Total cost of additional equipment, b) Total wavelength consumption and c) Resource Overbuild for P-ITT, P-WB and P-WBC in IT10 topology for varying number of traffic requests

Wavelength consumption: We observe a linear increase of wavelength consumption with increasing number of traffic requests for all three strategies. *P-ITT* maintains the lowest wavelength consumption for each traffic matrix compared to *P-WB* and *P-WBC* (Fig. 3.b). In particular, *P-ITT* has a lower wavelength consumption varying from 3% to 8% compared to *P-WB* and from 2% to 7% compared to *P-WBC*.

Resource overbuild: Fig. 4.c shows that RO may vary in each protection strategy depending on traffic volume. RO varies between 0.90 and 1.05 in case of *P-ITT* and between 0.92 and 1.39 in case of *P-WB* and *P-WBC*. *P-ITT* is characterized with a lower RO that varies between 2% and 24% compared to *P-WB* and *P-WBC*. The case of 30 demands is an exception in which all strategies have the same RO.

VI. Conclusion and Future Work

We modeled three protection strategies for DPP in FON, named, *P-ITT, P-WB and P-WBC*, with the goal of minimizing the cost of additional devices and minimizing wavelength consumption. In terms of cost of additional devices, *P-WBC* is the most cost-efficient approach compared to *P-ITT* and *P-WB*. *P-WBC* achieves cost-savings up to 97% compared to *P-ITT* and up to 33% compared to *P-WB*. While *P-ITT* is the most expensive approach due to the high cost of ITTs, it ensures a lower wavelength consumption (up to 7%) and a lower RO (up to 23%) compared to *P-WB* and *P-WBC*, which makes it still a valid choice in case of spectrum scarcity. All three proposed strategies reflect the need to deploy additional equipment to ensure 100% protection ratio in FON. As a future work, we plan to develop a heuristic approach to generalize results running simulations on larger networks.

VII. Acknowledgement

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