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A cost comparison of survivable subwavelength switching optical metro networks

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***Abstract*—In this paper, we compare the cost of the survivable optical transport solutions with subwavelength switching granularity. The focus is on Time-Domain Wavelength Interleaved Network (TWIN) and Packet Optical Add/Drop Multiplexer (POADM) network. Both technologies exploit optical slot switching: TWIN on a physical mesh topology, and POADM on a physical ring. The cost model accounts for the node components, the transponder cost and the cost of wavelength use per km of fiber. For the first time, a single network dimensioning model supporting protection is proposed for these metro technologies. The network planning solution is based on linear programming, and addresses the routing and wavelength assignment problem (RWA) and the optimal scheduler calculation. We consider dedicated protection, which consist in doubling the capacity of each operational connection in the network and shared protection, in which the protection capacity is potentially shared between multiple backup flows. By running the linear programming optimization we study the impact of different protection models on the cost of networks in different configurations and identify the scenarios for which each of the technologies is best suited.**

***Index Terms*—Optical slot switching, network dimensioning, protection, metro network, mesh, ring.**

I. INTRODUCTION

Optical transport solutions with subwavelength-granularity switching have been proposed for the metro networks (see [1] for an overview), to improve the dynamics and the bandwidth utilization. In this paper, we focus on two such subwavelength-granularity switching technologies, Time-Domain Wavelength Interleaved Network (TWIN) [2], adapted to physically meshed networks, and Packet Optical Add/Drop Multiplexer (POADM) [3], which applies to physical rings only. In addition to efficient bandwidth utilization thanks to the subwavelength switching granularity, TWIN and POADM are designed to minimize electronic switching and power consumption by resorting to the optical transparency for transit traffic [4]. In TWIN and POADM, nodes can communicate directly, without the need for a centralized traffic hub that electronically processes all data transmitted in the network.

An appealing property of TWIN is its entirely passive core infrastructure: the electronic processing of the traffic is performed only when inserting or extracting the optical bursts. This allows to have a core part of the network composed of inexpensive, and passive optical elements, such as couplers, splitters and wavelength blockers which consume no or little energy. Although its intermediate nodes are not entirely passive, POADM is more energy efficient than traditional ROADM and Ethernet over WDM (wavelength division multiplexing) solutions [4].

From the bandwidth efficiency point of view, in [5] and [6], the achievable throughputs of TWIN and POADM are studied, respectively, and it is shown that the network in both cases can achieve the capacity use efficiency of more than 90%. Both networks have a synchronous, slotted operation; the scheduling problem consists in efficiently allocating the time slots to different source-destination pairs. In contrast to POADM, where both opportunistic and non-opportunistic slot access can be used for scheduling slots, TWIN needs to use some kind of slot reservation or grant mechanism [7]. In both cases, the slot allocation is non-separable from the network planning, and the network configuration has a strong impact on the network performances such as latency [5], [6].

Another example of a difference between POADM and TWIN is the way they use the WDM spectrum. In the original version of TWIN, different destinations must use different subsets of wavelengths, while in POADM the wavelengths can be shared by different destinations. This is an important advantage of POADM, which differentiates it from other metro technologies [8], [9].

Because of theirs differences, TWIN and POADM may have different CAPEX/OPEX cost and quality of service performances. In this paper, for the first time we propose a cost and dimensioning model for the two technologies which allows us to get initial conclusions on their CAPEX price. In particular, we include the protection model in our solution. Indeed, when planning the network, the resource needs for the protection shall be taken into account and can significantly increase the final network cost [10].

The protection in TWIN is first considered in [2], where the possibility of using multiple trees to provide $1:1$ protection is studied. In that paper, the process of allocating the slots is based on an approximative algorithm, while the TWIN-tree calculation problem has been resolved separately from the slot allocation. The cost of $1+1$ protection was not considered. In [11], the authors discuss the possible protection methods for a variant of TWIN using the coherent technology, but they do not present the numerical results on protection. In

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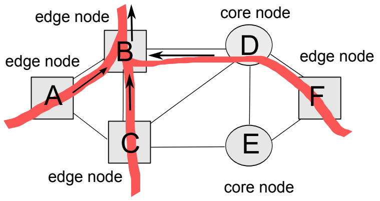

Fig. 1. TWIN network.

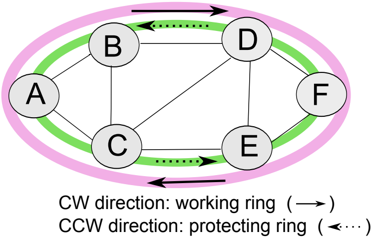

Fig. 2. POADM version 1.

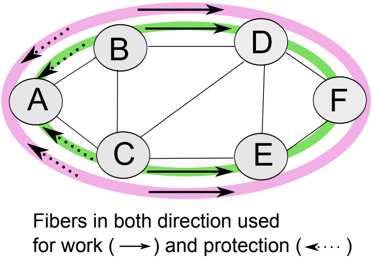

Fig. 3. POADM version 2.

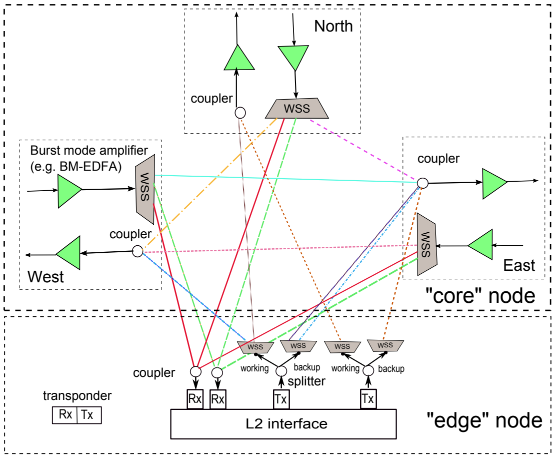

Fig. 4. TWIN core and edge node architecture.

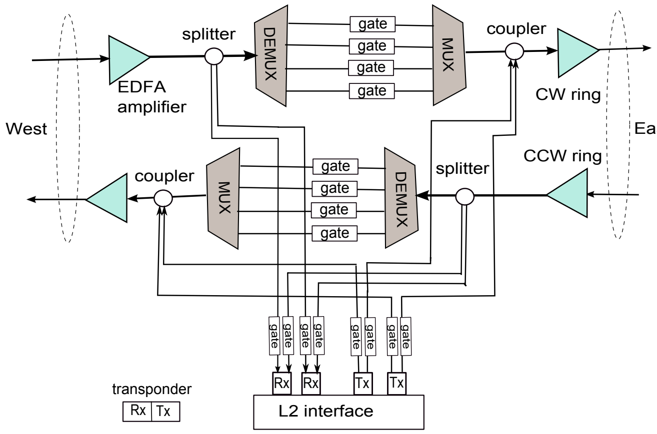

Fig. 5. POADM node architecture.

our previous paper [12], we studied the cost of protection in TWIN, by using an optimal algorithm that resolves the routing and wavelength assignment (RWA) and the scheduling problem, in the protection settings. Protection in bidirectional POADM rings is addressed in [13].

In this paper, the comparison solution is based on the use of a linear program (LP), and supports, for the first time, network planning for both TWIN and POADM, taking POADM as a special case of TWIN dimensioning where the underlying topology is a ring. The LP solves the scheduling problem while minimizing the total number of transponders to be deployed and the price of wavelength per km. For POADM, the cost of fast wavelength blockers utilization is also accounted. Note that the cost function is approximate, as it approximates the real cost of the main components present in TWIN and POADM. However, the model allows to estimate the efficiency of two solutions when using the basic network resources (transponders and wavelengths). In fact, all the cost components that depend on dimensioning are accounted for in the model. All the other costs are per-node costs, which do not depend on dimensioning, since nodes are known as an input. Furthermore, the cost model is strengthened by the fact that we consider wide ranges for each cost component, that are estimated based on available data. In the result section, the cost models for the two networks are compared in different simulation scenarios, for different protection methods and the performances are discussed.

The remainder of the paper is organized as follows. In Section II the characteristics of POADM and TWIN are detailed. In Section III we review the protection methods for metro networks and present our cost model. Section IV is devoted to the joint, linear programming dimensioning method, for TWIN and POADM. The numerical results are presented in Section V. Finally, we conclude the paper in the last section.

II. STUDIED NETWORK ARCHITECTURES

A. *Time-Domain Wavelength Interleaved Network (TWIN)*

Time-Domain Wavelength Interleaved Network or TWIN [2], is a subwavelength switching technique that transmits bursts or slots of data on WDM channels without resorting to electronic processing in transit nodes, the electronic processing functions being pushed to its edge source and destination nodes (Fig. 1). TWIN consists of simple core nodes based on passive devices and of intelligent edge nodes that are equipped with transponders (TRX). Routing inside this passive network is performed thanks to preconfigured static wavelength trees whose roots are destination nodes. The destinations use separate sets of wavelengths for the reception. By tuning its emitter to the appropriate wavelength, a source can send a burst to any destination. The switching in intermediate nodes is only based on the burst wavelength and is thus purely passive. Thus, the logical topology of TWIN can be viewed as set of optical multipoint-to-point trees overlaid on top of a mesh network, one for each of the destinations. Fig. 1 illustrates one tree, with node B being a destination that receives traffic from nodes A, C, and F, by using a dedicated wavelength. In this configuration, node D is a “core” passive node, connecting two “edge” nodes (F and B).

In TWIN, each TRX is equipped with a fast wavelength-tunable transmitter and a burst-mode (e.g., access-grade) wavelength-colored receiver. Relatively inexpensive non-coherent (e.g., 10 Gb/s) technology can be leveraged to implement those edge nodes, but coherent solution can be also envisaged. TWIN is expected to be realized over Reconfigurable Optical Add/Drop Multiplexer (ROADM) architecture. For illustration, in Fig. 4 we plotted a possible realization of TWIN by using the ROADMs exploiting wavelength selective switches (WSS). The degree of the plotted TWIN node is three. The most significant cost in TWIN have the transponders, which are composed of a transmitting (TX) and a receiving part (RX). The core node architecture in TWIN differs from the edge node in absence of any add/drop ports, i.e. the interface to the second layer of ISO/OSI network layer model (“L2 interface”) and the transponders are absent (Fig. 4).

In this paper we assume that optical bursts in TWIN are of fixed duration: the channels are slotted and synchronous i.e. slots propagating on different wavelengths are time-aligned. For simplicity we assume that all links have a length corresponding to an integer number of slots. The scheduling problem consists in allocating the finite number of slots to all source-destination pairs by avoiding the burst collisions in the entire network. The number of slots to allocate is called “scheduler size”, K, and it is an input parameter in our study. The slot allocation repeats after these K slots, during network operation. In our previous paper [5] we proposed a dimensioning solution for TWIN which resolves the scheduling problem together with the routing and wavelength assignment problem. In the protection configuration, the slot allocation is needed simultaneously for both working and backup paths.

B. Packet Optical Add/Drop Multiplexer (POADM)

In Packet Optical Add/Drop Multiplexer (POADM), the physical topology of the network is a bidirectional ring (Figs. 2-3), where each network node can use any fiber and any wavelength for the insertion or the extraction of traffic [3]. The wavelengths for the insertion/extraction process might be shared by different network destinations. The only condition is that the destinations must have the transponders able to receive on these wavelengths. The simplified node architecture of POADM is illustrated in Fig. 5. Wavelength blocking is achieved with fast optical gates that can selectively erase any slot. These gates can be based on semiconductor optical amplifiers (SOAs). The transponders share the same architecture as in TWIN, and the channels are slotted and synchronous at the slot level.

The most expensive component in POADM, apart from the transponders, is the slot blocker. The number of gates in POADM is equal to the number of wavelengths used in the network (per ring direction).

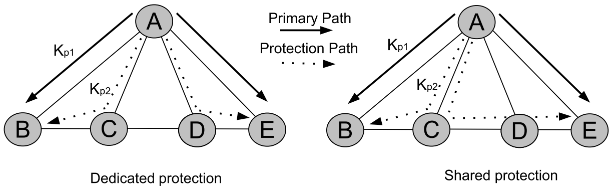

Fig. 6. Basic protection methods for mesh network.

For protection purpose, we consider two POADM configurations (illustrated in Figs. 2-3, where the POADM ring is formed on the links AB, BD, DF, FE, EC and CA). The first one is named POADM version 1 (Fig. 2), where one fiber ring is dedicated to the working traffic and the opposite fiber is used exclusively for carrying the backup traffic. The second one, is POADM version 2 (Fig. 3), where both working and backup traffic can be carried in any directions. The advantage of POADM v.1 is a simple restoration mechanism, while the advantage of POADM v.2 is in its more efficient capacity use.

III. COMPARISON SCENARIOS

In this part of paper, we first define shared and dedicated protection. Then, we introduce a cost model, which is based on TWIN and POADM node architectures.

A. Classic Protection Methods in Metro Networks

We consider the problem of protecting the traffic flowing through a network against a single link failure. The basic type of protection consist in doubling the used channel capacity and is called **“dedicated”** protection.[1] Traffic between two nodes is simultaneously sent over two link-disjoint routes. For instance, if K_{p1} is the rate of a flow between nodes A and B (Fig. 6), on the shortest path, then, for protection, a flow of the same rate $K_{p2} = K_{p1}$ will be sent from A to B on another path. Such protection is the most expensive in terms of capacity utilization, but it is the most effective, because the irregularities due to delays and packet loss in case of failure of any part of the network are minimized.

The second type is the protection when in the case of failure the traffic is switched and sent on a predetermined backup path. If the same capacity is shared simultaneously by more than one backup path (e.g. link AC is shared for protection of paths A-B and A-E in Fig. 6), we are speaking about “**shared**” protection. Such protection is used for example in SONET/SDH [14]. The advantage of this form of protection is the lower price, because the capacities designed to preserve the connections in case of different link failures are not used at the same time, since they can be shared by several (source, destination) node pairs. The disadvantages of this kind of protection are the higher delay needed to restore a route going through a failed link and hence higher data losses upon protection switching.

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[1] More specifically, here we consider the so-called “path” protection, meaning that we use completely disjoint paths for the backup. “Link” protection also exists, but is out of scope of this paper.

Note that in TWIN and POADM v.2 we can consider both shared and dedicated protection. In POADM v.1, the focus in on simplifying the restoration procedure by switching all traffic between one direction and the opposite direction in case of failure. Both directions are dimensioned to carry the whole traffic matrix, which implies that the notion of shared protection does not apply.

B. Cost model

The objective function that we use is composed of three main costs: the transponder cost C_t, the cost of wavelength use per km of fiber C_{lw}, and the cost of gate C_s (for POADM).

When estimating the cost of a transponder (TRX) for TWIN and POADM, we consider that it shall be similar to a cost of an Ethernet port. The price of 10G XFP (Ethernet) TRX is around \$ 1000 [15]. However, since Ethernet is well standardized but the POADM/TWIN encapsulation layers are not, the real price for a WDM POADM/TWIN TRX may be significantly larger. Having in mind this, and Moore's law impact on the equipment price, we can estimate that the final cost for the TRX is between \$ 1000-2000 .

The cost of wavelength use per km of fiber length (hereafter denoted simply by "wavelength cost") is primarily the cost of wavelength leasing, when the same fibers are shared by several operators. This cost varies from $C_{lw}(LB)$ (lower bound) to $C_{lw}(UB)$ (upper bound), with values expressed in km^{-1}. The lower bound on C_{lw} we set to $\frac{C_t}{\sum_\ell L_\ell \cdot W}$, where $\sum_\ell L_\ell$ is the total fiber length in the network (obtained as the sum of individual link lengths L_ℓ, over all links ℓ) and W is the total number of wavelengths. Such lower bound guarantees that the wavelength cost is negligible w.r.t. the TRX cost. The upper bound is taken to be $C_{lw}(UB) = 0.1 \cdot C_t$, which is derived from [1], where the ratio between the wavelength cost per ring and the receiver cost is estimated on a ring circumference of 100 km.

Finally, we account for the gate cost when POADM rings are used. This cost is considered to be in the range from \$ 50-100 , when gates are implemented with reflective SOAs. Here, we consider the cost of a discrete device, without taking into account the integration of the components (which could lower the price), nor the cost of the electronic drivers (which could increase the price).

IV. ILP FORMULATION FOR TWIN AND POADM DIMENSIONING, WITH PROTECTION SUPPORT

The dimensioning problem usually consists in allocating the wavelengths and the equipment (i.e., transmitters, receivers) in order to support the given traffic demands, with the objective of minimizing the CAPEX cost. As defined by the cost model in the previous section, the CAPEX cost of the network is composed of wavelength cost, (C_{lw}), cost of transponder, TRX, (C_t), and cost of gates, (C_s). Since the wavelength cost is defined per link, we are able to encompass the impact that the physical topology has on the final network cost, as the traffic routes over greater distances have higher price. The formulation can easily be adapted to include fiber installation cost rather than wavelength leasing.

TABLE I
GIVEN PARAMETERS

Name	Definition
$G(V,E)$	a non-directed graph describing the mesh topology, where V is the set of nodes, E is the set of links;
T_d	normalized number of slots to be allocated for demand d;
$\mathcal{R}_d$	set of routing paths $\{R_{d,1}, R_{d,2}, \dots, R_{d,\lvert\mathcal{R}_d\rvert}\}$, where $R_{d,r}$ can be used to carry demand d, see below;
$R_{d,r}$	set of links used to route a demand d;
start($R_{d,r}$)	the (set of) link(s) of $R_{d,r}$ that are attached to source nodes of demand d;
end($R_{d,r}$)	the (set of) link(s) of $R_{d,r}$ that are attached to destination nodes of demand d;
$L(d,r)$	the number of links of route r of demand d;
W	maximum number of wavelengths per fiber;
C_{lw}	wavelength leasing cost per km of the used fiber (link);
C_t,C_s	transponder and gate costs, respectively;
L_ℓ	length of link ℓ in km;
$D_{d,\ell,r}$	delay (in slots) experienced by a slot emitted by the source of demand d to reach link ℓ, by using the route r;
K	number of slots to allocate (the "schedule length");
A	number of traffic demands d;
B	the maximum number of alternate routes in $\mathcal{R}_d$ (i.e. $\max_d \mathcal{R}_d$).

TABLE II
OUTPUT VARIABLES

Name	Definition
$x_{\ell,w}^{k,d,r}$	equal to 1 if slot k is used to carry demand d on wavelength w, by using link ℓ and route r from $\mathcal{R}_d$;
$z_{\ell,w}^{k,d,r,b}$	equal to 1 if slot k on wavelength w, link ℓ and backup route b is used for protecting demand d on route r ($r, b \in \mathcal{R}_d$);
y_w	equal to 1 if the wavelength w is used in the network;
$u_{i,w}$	equal to 1 if a TRX with fast tunable laser and a receiver for fixed wavelength w is deployed at node i;
$e_{\ell,w}$	equal to 1 if link l on wavelength w is used;
$a_{d,r}$	equal to 1 when route r is used to carry the primary traffic for demand d;
$c_{d,b}$	equal to 1 when route b is used to carry the backup traffic for demand d.

The 0-1 Integer Linear Programming (0-1 ILP) [2] solution presented next, assesses the RWA and the problem of optimal slot allocation simultaneously. We use the traffic matrix expressed in Gb/s, and we allocate the minimum needed number of slots to each traffic demand. Both, the size of the scheduler K and the input traffic matrix are the input parameters in the formulation. Three different variations of the formulation are given, enabling us to study the dedicated protection, the shared protection and the case without any protection.

An important aspect of the solution is to satisfy the constraints that will prevent the collisions of the optical slots at destinations, sources, and everywhere in the network. As in [5], we suppose that the slots that are the object of allocation are enumerated by numbers $0, 1, ..., K-1$ and that at a given moment in time, all the sources send the slots enumerated with the same number.

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[2] It can be shown that the problem described by the proposed 0-1 ILP belongs to the complexity class of NP-complete problems, but the formal proof of this property is out of the scope of the present paper.

A. 0-1 ILP Formulation

The input parameters to the formulation are listed in Tab. I. The list of output binary variables that are used is given in Tab. II. The full list of 0-1 ILP constraints is given next.

Objective function, minimizing the number of used channels on the links, number of transponders and number of SOAs, is:

$$\min \left(C_{lw} \sum_{\ell}^{E} \sum_{w=1}^{W} L_\ell \cdot e_{\ell,w} + C_t \sum_{i=1}^{|V|} \sum_{w=1}^{W} u_{i,w} + C_s |V| \sum_{w=1}^{W} y_w \right) \tag{1}$$

Capacity constraint, ensuring the allocation of sufficient number of slots:

$$\sum_{r=1}^{|\mathcal{R}_d|} \sum_{\substack{\exists \ell \in E \\ \ell \in r}}^{E} \sum_{w=1}^{W} \sum_{k=1}^{K} x_{\ell,w}^{k,d,r} = T_d, \qquad \forall d \leq A; \tag{2}$$

Constraint ensuring that there is enough backup capacity for each working path:

$$\sum_{w=1}^{W} \sum_{l}^{E} \sum_{k=1}^{K} x_{l,w}^{k,d,r} / L(d,r) = \sum_{w=1}^{W} \sum_{l}^{E} \sum_{k=1}^{K} \sum_{b=1}^{|\mathcal{R}_d|} z_{l,w}^{k,d,r,b} / L(d,b),$$
$$\forall d \leq A, \forall r \leq |\mathcal{R}_d|; \tag{3}$$

Slot-wavelength continuity constraint (i.e., ensuring that an allocated slot is on the same wavelength, at the same slot location, all the way from a source node to any destination node):

$$x_{\ell,w}^{k,d,r} = x_{\ell',w}^{k,d,r}, \qquad \forall w \leq W, \forall d \leq A, \forall r \leq |\mathcal{R}_d|,$$
$$(\forall \ell, \ell' \in R_{d,r})(\ell \neq \ell'), \forall k \in K, \tag{4}$$

$$z_{\ell,w}^{k,d,r,b} = z_{\ell',w}^{k,d,r,b}, \qquad \forall w, \forall d \leq A, r \leq |\mathcal{R}_d|, b \leq |\mathcal{R}_d|,$$
$$(\forall \ell, \ell' \in R_{d,b})(\ell \neq \ell'), \forall k \in K, \tag{5}$$

Next, constraint ensuring that slots are allocated only if traffic demand is non-zero:

$$\sum_{\ell}^{E} \sum_{\substack{r=1, \\ \ell \in r}}^{|\mathcal{R}_d|} \sum_{k=1}^{K} \sum_{w=1}^{W} x_{\ell,w}^{k,d,r} + \sum_{\ell}^{E} \sum_{\substack{r=1, \\ \ell \in r}}^{|\mathcal{R}_d|} \sum_{k=1}^{K} \sum_{w=1}^{W} \sum_{\substack{b=1, \\ \ell \notin b}}^{|\mathcal{R}_d|} z_{l,w}^{k,d,r,b}$$
$$\leq 2 \cdot B \cdot K \cdot W \cdot |E| \cdot T_d, \qquad \forall d \leq A; \tag{6}$$

Wavelength variable constraint (used to compute the number of wavelengths):

$$\sum_{d=1}^{A} \sum_{\substack{r=1, \\ \ell \in r}}^{|\mathcal{R}_d|} \sum_{\ell}^{E} \sum_{k=1}^{K} x_{\ell,w}^{k,d,r} + \sum_{d=1}^{A} \sum_{\substack{r=1, \\ \ell \notin r}}^{|\mathcal{R}_d|} \sum_{\substack{b=1, \\ \ell \in r}}^{|\mathcal{R}_d|} \sum_{\ell}^{E} \sum_{k=1}^{K} z_{l,w}^{k,d,r,b}$$
$$\leq 2 \cdot K \cdot A \cdot |E| \cdot B \cdot y_w, \qquad \forall w \leq W; \tag{7}$$

Link utilization variable constraint (used to determine which wavelength is used on which links):

$$\sum_{d=1}^{A} \sum_{r=1}^{|\mathcal{R}_d|} \sum_{k=1}^{K} x_{\ell,w}^{k,d,r} + \sum_{d=1}^{A} \sum_{\substack{r=1, \\ \ell \notin r}}^{|\mathcal{R}_d|} \sum_{k=1}^{K} \sum_{\substack{b=1, \\ \ell \in b}}^{|\mathcal{R}_d|} z_{l,w}^{k,d,r,b} \leq 2ABKe_{\ell,w}, \forall \ell; \tag{8}$$

Constraint ensuring that two nodes do not share the same color, which is a native TWIN property (only for TWIN):

$$\sum_{i=1}^{|V|} u_{i,w} \leq 1, \qquad \forall w \leq W; \tag{9}$$

Constraints ensuring that each traffic demand d is carried over a single working path and protected with a single backup path (the absence of multiple paths prevents the reordering of bursts at the reception):

$$\sum_{k=1}^{K} \sum_{\ell \in r}^{E} \sum_{w=1}^{W} x_{\ell,w}^{k,d,r} \leq W \cdot K \cdot |E| \cdot a_{d,r}, \;\; \forall d, \forall r \leq |\mathcal{R}_d|; \tag{10}$$

$$\sum_{k=1}^{K} \sum_{\ell \in b}^{E} \sum_{\substack{r=1, \\ \ell \notin r}}^{|\mathcal{R}_d|} \sum_{w=1}^{W} z_{\ell,w}^{k,d,r,b} \leq B \cdot W \cdot K \cdot |E| \cdot c_{d,b}, \forall d, \forall b; \tag{11}$$

$$\sum_{r=1}^{|\mathcal{R}_d|} a_{d,r} \leq 1, \sum_{b=1}^{|\mathcal{R}_d|} c_{d,b} \leq 1, \qquad \forall d \leq A; \tag{12}$$

1) Dedicated path protection: Fast wavelength-tunable TX capacity constraint (allocates the TXs at each node based on sent slots):

$$\sum_{\substack{d=1, \\ i \in d}}^{A} \sum_{\ell}^{E} \sum_{\substack{r=1, \\ \ell = |\text{start}(R_{d,r})|}}^{|\mathcal{R}_d|} \sum_{w=1}^{W} x_{\ell,w}^{k,d,r} + \sum_{\substack{d=1, \\ i \in d}}^{A} \sum_{\ell}^{E} \sum_{\substack{r=1, \\ \ell \notin r}}^{|\mathcal{R}_d|} \sum_{\substack{b=1, \\ \ell = |\text{start}(R_{d,b})|}}^{|\mathcal{R}_d|}$$

$$\sum_{w=1}^{W} z_{l,w}^{k,d,r,b} \leq \sum_{w=1}^{W} u_{i,w}, \;\; \forall k \leq K, i \leq |V|, i = \text{start}(\ell); \tag{13}$$

Colored RX capacity constraint (allocates the RXs at each node based on received slots):

$$\sum_{\substack{d=1, \\ i \in d}}^{A} \sum_{\ell}^{E} \sum_{\substack{r=1, \\ \ell = |\text{end}(R_{d,r})|}}^{|\mathcal{R}_d|} x_{\ell,w}^{k',d,r} + \sum_{\substack{d=1, \\ i \in d}}^{A} \sum_{\ell}^{E} \sum_{\substack{r=1, \\ \ell \notin r}}^{|\mathcal{R}_d|} \sum_{\substack{b=1, \\ \ell = |\text{end}(R_{d,b})|}}^{|\mathcal{R}_d|} z_{l,w}^{k'',d,r,b}$$
$$\leq u_{i,w}, \;\; \forall w \leq W, \forall k \leq K, i \leq |V|, i = \text{end}(\ell); \tag{14}$$

where $k' \equiv k - D_{d,\ell,r} (mod\, K)$ and $k'' \equiv k - D_{d,\ell,b} (mod\, K)$.

The slot indexes k' and k'' are calculated to account for different propagation delays of traffic flows taking different propagation paths between a source and a destination.

Constraint which avoids link collision by preventing several demands from using the same link on the same wavelength and the same slot:

$$\sum_{d=1}^{A} \sum_{\substack{r=1, \\ \ell \in r}}^{|\mathcal{R}_d|} \sum_{k'=1}^{K} x_{\ell,w}^{k',d,r} + \sum_{d=1}^{A} \sum_{\substack{r=1, \\ \ell \notin r}}^{|\mathcal{R}_d|} \sum_{\substack{b=1, \\ \ell \in b}}^{|\mathcal{R}_d|} \sum_{k''=1}^{K} z_{\ell,w}^{k'',d,r,b} \leq 1,$$
$$\forall \ell \in E, \forall w \leq W, \forall k \leq K; \tag{15}$$

where $k' \equiv k - D_{d,\ell,r} (mod\, K)$ and $k'' \equiv k - D_{d,\ell,b} (mod\, K)$.

2) Shared path protection: Fast wavelength-tunable TX capacity constraint (allocates the TXs at each node based on sent slots):

$$\sum_{\substack{d=1,\\ i\in d}}^{A}\sum_{\ell}^{E}\sum_{\substack{r=1,\\ \ell=\\ |\text{start}(R_{d,r})|}}^{|\mathcal{R}_d|}\sum_{w=1}^{W} x_{\ell,w}^{k,d,r}+\sum_{\substack{d=1,\\ i\in d}}^{A}\sum_{\ell}^{E}\sum_{\substack{r=1,\\ \ell\notin r,\\ e\in r}}^{|\mathcal{R}_d|}\sum_{\substack{b=1,\\ \ell=\\ |\text{start}(R_{d,b})|}}^{|\mathcal{R}_d|}\sum_{w=1}^{W} z_{\ell,w}^{k,d,r,b}$$

$$\leq \sum_{w=1}^{W} u_{i,w},\quad \forall k, e\in E\ (e\neq \ell), i\leq |V|, i=\text{start}(\ell); \tag{16}$$

$$\sum_{\substack{d=1,\\ i\in d}}^{A}\sum_{\ell}^{E}\sum_{\substack{r=1,\\ \ell=|\text{start}(R_{d,r})|}}^{|\mathcal{R}_d|}\sum_{w=1}^{W} x_{\ell,w}^{k,d,r}+\sum_{\substack{d=1,\\ i\in d}}^{A}\sum_{\ell}^{E}\sum_{\substack{r=1,\\ \ell\notin r}}^{|\mathcal{R}_d|}\sum_{\substack{b=1,\\ \ell=|\text{start}(R_{d,b})|}}^{|\mathcal{R}_d|}$$

$$\sum_{w=1}^{W} z_{\ell,w}^{k,d,r,b}\leq A\cdot\sum_{w=1}^{W} u_{i,w},\quad \forall k, i\leq |V|, i=\text{start}(\ell); \tag{17}$$

Colored RX capacity constraint (allocates the RXs at each node based on received slots):

$$\sum_{\substack{d=1,\\ i\in d}}^{A}\sum_{\ell}^{E}\sum_{\substack{r=1,\\ \ell=|\text{end}(R_{d,r})|}}^{|\mathcal{R}_d|} x_{\ell,w}^{k',d,r}+\sum_{\substack{d=1,\\ i\in d}}^{A}\sum_{\ell}^{E}\sum_{\substack{r=1,\\ \ell\notin r,\\ e\in r}}^{|\mathcal{R}_d|}\sum_{\substack{b=1,\\ \ell=|\text{end}(R_{d,b})|}}^{|\mathcal{R}_d|} z_{\ell,w}^{k'',d,r,b}$$

$$\leq u_{i,w}, \forall w, \forall k, \forall e\in E\ (e\neq \ell), i\leq |V|, i=\text{end}(\ell); \tag{18}$$

where $k'\equiv k-D_{d,\ell,r}(mod\,K)$ and $k''\equiv k-D_{d,\ell,b}(mod\,K)$.

$$\sum_{\substack{d=1,\\ i\in d}}^{A}\sum_{\ell}^{E}\sum_{\substack{r=1,\\ \ell=|\text{end}(R_{d,r})|}}^{|\mathcal{R}_d|} x_{\ell,w}^{k',d,r}+\sum_{\substack{d=1,\\ i\in d}}^{A}\sum_{\ell}^{E}\sum_{\substack{r=1,\\ \ell\notin r}}^{|\mathcal{R}_d|}\sum_{\substack{b=1,\\ \ell=|\text{end}(R_{d,b})|}}^{|\mathcal{R}_d|} z_{\ell,w}^{k'',d,r,b}$$

$$\leq A\cdot u_{i,w},\quad \forall w\leq W, \forall k\leq K, i\leq |V|, i=\text{end}(\ell); \tag{19}$$

where $k'\equiv k-D_{d,\ell,r}(mod\,K)$ and $k''\equiv k-D_{d,\ell,b}(mod\,K)$.

Constraint which avoids link collision by preventing several demands from using the same link on the same wavelength and the same slot:

$$\sum_{d=1}^{A}\sum_{\substack{r=1,\\ \ell\in r}}^{|\mathcal{R}_d|}\sum_{k'=1}^{K} x_{\ell,w}^{k',d,r}+\sum_{d=1}^{A}\sum_{\substack{r=1,\\ \ell\notin r,\\ e\in r}}^{|\mathcal{R}_d|}\sum_{\substack{b=1,\\ \ell\in b}}^{|\mathcal{R}_d|}\sum_{k''=1}^{K} z_{\ell,w}^{k'',d,r,b}\leq 1,$$

$$\forall \ell, e\in E\ (\ell\neq e), \forall w\leq W, \forall k\leq K; \tag{20}$$

where $k'\equiv k-D_{d,\ell,r}(mod\,K)$ and $k''\equiv k-D_{d,\ell,b}(mod\,K)$.

$$\sum_{d=1}^{A}\sum_{\substack{r=1,\\ \ell\in r}}^{|\mathcal{R}_d|}\sum_{k'=1}^{K} x_{\ell,w}^{k',d',r}+\sum_{d=1}^{A}\sum_{\substack{r=1,\\ \ell\notin r}}^{|\mathcal{R}_d|}\sum_{\substack{b=1,\\ \ell\in b}}^{|\mathcal{R}_d|}\sum_{k''=1}^{K} z_{\ell,w}^{k'',d,r,b}\leq A,$$

$$\forall \ell\in E, \forall w\leq W, \forall k\leq K; \tag{21}$$

where $k'\equiv k-D_{d,\ell,r}(mod\,K)$ and $k''\equiv k-D_{d,\ell,b}(mod\,K)$.

3) No protection case: This case is obtained from "dedicated path protection" case, by removing the variables $z_{\ell,w}^{k,d,r,b}$ from all the constraints.

B. Applicability of the 0-1 ILP model to TWIN and POADM

Note that all the equations of the 0-1 ILP model are the same for TWIN and POADM, except the eq. (9), which applies only for TWIN to account for the separation of the wavelength sets used at different destinations.

The output of the model gives the optimal slot allocation (scheduling) for both TWIN and POADM. In the present paper, scheduling in POADM is thus supposed to exploit the static slot reservation, like in TWIN, although POADM performance might be improved by resorting to an opportunistic slot access. On the other hand, opportunistic slot access presents a specific stability problem, as shown in [6]. As the scope of the present paper is to compare TWIN with POADM, we chose to use a unified dimensioning method.

V. ANALYSIS AND DISCUSSION

We consider the 6-node logical topology, with 9 links, depicted in Figs. 1-3. The traffic matrix is symmetric and non-centralized. It is supposed that nodes A and B (Figs. 1-3) exchange traffic with same amplitude α (normalized to the TRX capacity) with nodes E and F in both directions (e.g. there are 8 traffic flows in the network). This section reports the results from a commercially available LP solver, in which the 0-1 ILP formulation has been implemented. All the results are given within an optimality gap of 10%. Other assumptions are: TRX (and channel) capacity of 10 Gb/s, the link lengths of 10 slots[3] (corresponding to a link distance of 10km for a slot duration of 5 μs), and the schedule length $K = 5$. The number of alternative paths between each pair of nodes is $B = 5$, and the available number of WDM channels is $W = 80$.

The goal of our study is evaluate the cost of different technologies and protection methods, for different traffic intensities, and to separately study the impact of different cost components on the final solution.

In the first set of simulations, we set the TRX cost to $C_t = 1$ (arbitrary units, a.u.), as a normalized value corresponding to \$ 1000 in reality. For such C_t, the wavelength cost is taken at its upper bound, and is fixed to $C_{lw} = 0.1$ (a.u.) km^{-1} . Finally, gate cost is fixed to $C_s = 0.05$ (a.u.), corresponding to \$ 50.

A. Scenario 1: Impact of traffic intensity on the cost efficiency of TWIN and POADM

We first study the cost of the protection in TWIN and POADM for the increasing values of traffic amplitude α (Scenario 1). For readability of the results, we separately plot the results for the shared and the dedicated protection. Note that the only protection mode considered for POADM v.1 is dedicated protection

The design cost in this scenario is plotted in Figs. 7 and 8. In the considered settings, TWIN is less cost efficient, than both versions of POADM: in the case of shared protection (Fig. 7) TWIN is more expensive than POADM v.1 by 10%

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[3] Note that the length of a link can be interchangeably expressed in terms of km or integer number of slots. It is also possible to account for non-integer number of slots, but it is outside the scope of the paper.

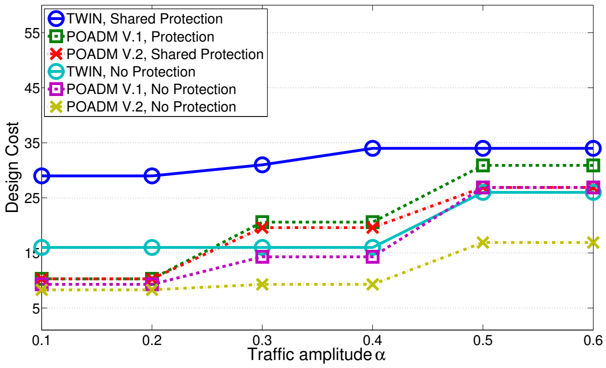

Fig. 7. Design cost in Scenario 1, shared protection.

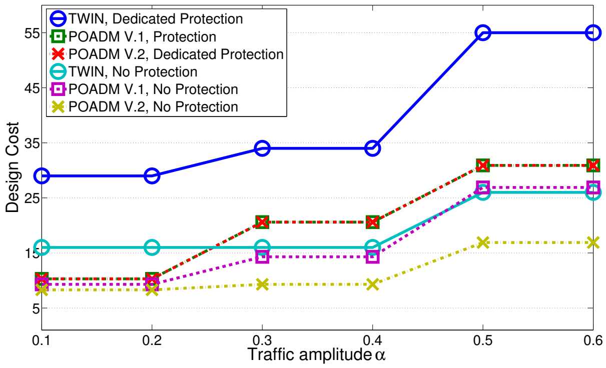

Fig. 8. Design cost in Scenario 1, dedicated protection.

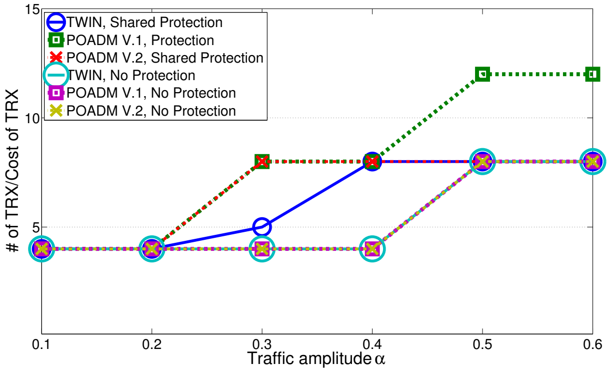

Fig. 9. Transponder cost in Scenario 1, shared protection.

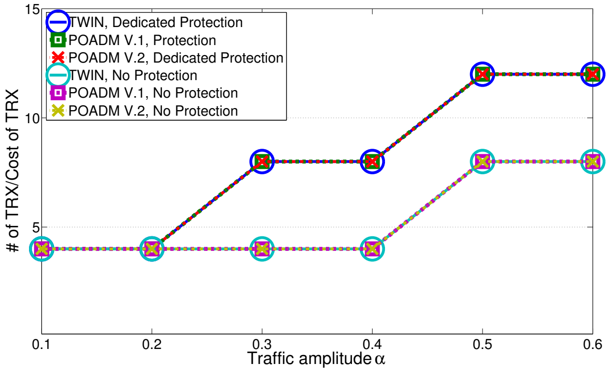

Fig. 10. Transponder cost in Scenario 1, dedicated protection.

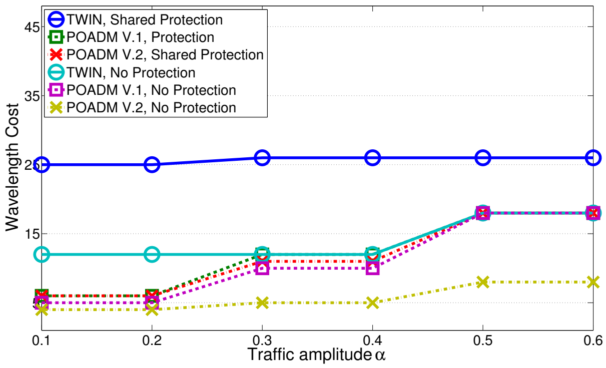

Fig. 11. Wavelength cost in Scenario 1, shared protection.

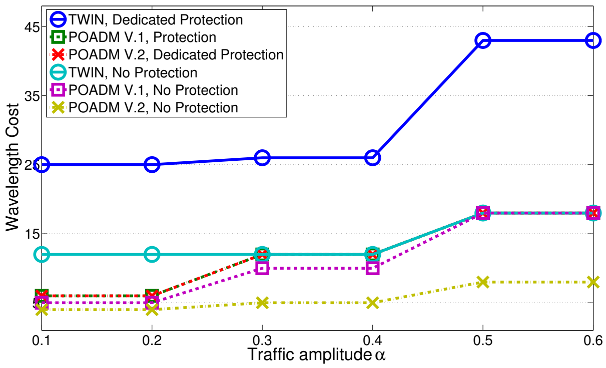

Fig. 12. Wavelength cost in Scenario 1, dedicated protection.

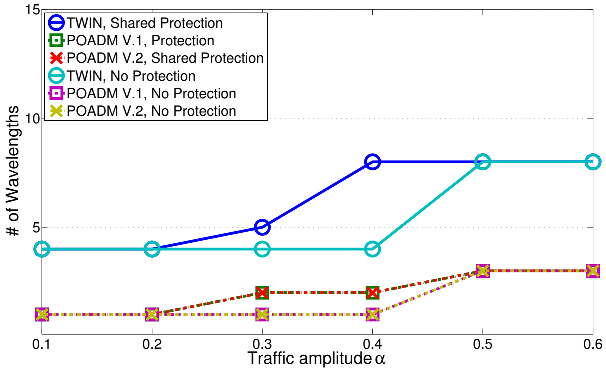

Fig. 13. Number of wavelengths in Scenario 1, shared protection.

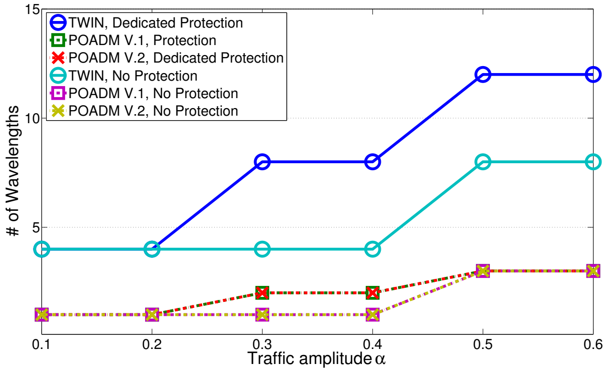

Fig. 14. Number of wavelengths in Scenario 1, dedicated protection.

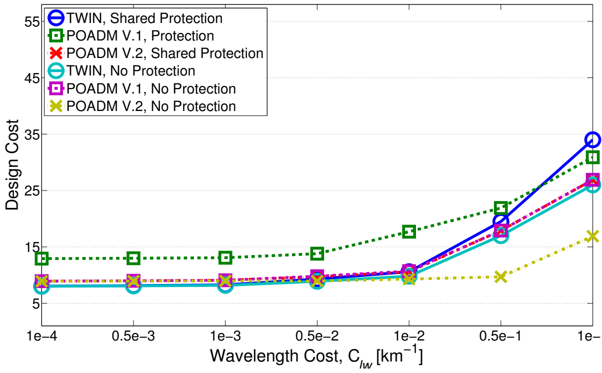

Fig. 15. Scenario 2: design cost for different values of C_{lw}, shared protection.

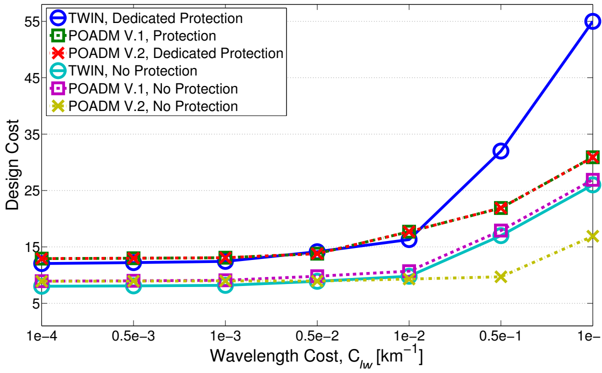

Fig. 16. Scenario 2: design cost for different values of C_{lw}, dedicated protection.

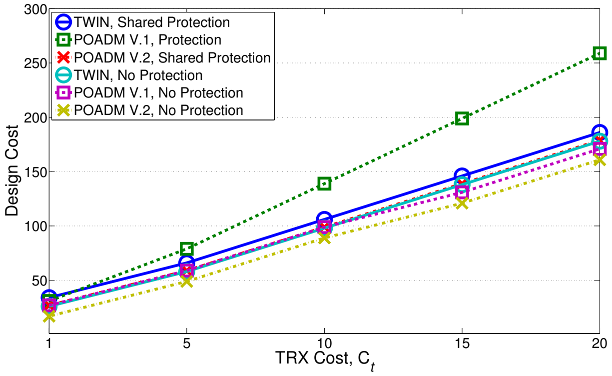

Fig. 17. Scenario 3: design cost for different values of C_t, shared protection.

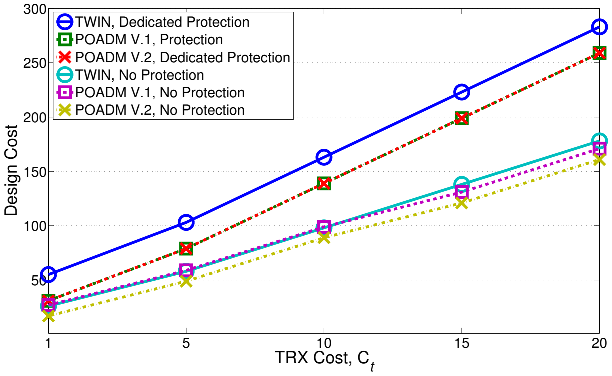

Fig. 18. Scenario 3: design cost for different values of C_t, dedicated protection.

in terms of design cost, and more expensive than POADM v.2 by more than 20%. POADM is more efficient since it can reuse the wavelengths towards any destination. In the case of dedicated protection (Fig. 8), TWIN is even more expensive: POADM v.1 and 2 are less expensive by more than 45%.

As expected, POADM v.1 protection is more expensive than POADM v.2 shared (more than 10%), and is as expensive as POADM v.2 dedicated. For all technologies, the dedicated protection method is more expensive than shared (35% more for TWIN, and 20% more for POADM v.2). A very important remark is that the cost of TWIN's dedicated protection increases much faster that of POADM. We observe that TWIN is less efficient for the increased traffic loads.

To understand better the reasons for the previous results, for the same experiment we plotted the transponder cost in Figs. 9 and 10. The results on these diagrams show that POADM v.2 requires the highest number of TRXs in shared protection case. However, TWIN and POADM are equally efficient in terms of the allocated number of TRXs, for dedicated protection. Thus, the number of transponders is not the actual reason for the better POADM performance.

The second cost element, the wavelength cost, is plotted in Figs. 11 and 12. POADM has better performance as result of a more efficient wavelength use. The wavelength use in TWIN is poor, because of different wavelength allocation: in TWIN each destination employs a separate subset of wavelengths. This assumption is used to simplify the network core, but increases the network cost if the wavelength cost is not negligible. Let us note that TWIN's wavelength cost increases more and more rapidly at higher loads. The wavelength cost is more favorable for POADM, although the number of links in POADM is typically larger w.r.t. TWIN's mesh network (a result not shown here due to the space limitations).

The previous reasoning is confirmed with the number of wavelengths plots, given in Figs. 13 and 14. The number of wavelengths in TWIN is doubled (for shared protection) or tripled (for dedicated protection) compared with POADM. Although the cost of gates is included in the cost model only for POADM, the total design cost is much lower for POADM (Figs. 7 and 8).

In the following, we compare TWIN and POADM for wide range of particular costs. We are particularly interested to see how the wavelength cost C_{lw} impacts the TWIN performance.

B. The impact of the particular cost components on the protection efficiency in TWIN and POADM

Here, the traffic amplitude α has the fixed value of 0.6, in the same traffic model as previously. We define two scenarios in order to study separately the impact of different cost components (we focus on C_{lw} and C_t).

1) Scenario 2: Impact of wavelength cost: It is supposed that $C_t = 1$, and $C_s = 0.05$, while C_{lw} changes in the range, between 1e-4 (a.u.) km^{-1} and 0.1 (a.u.) km^{-1}, defined by the cost model.

Figs. 15 and 16 present the design cost for shared and dedicated protection, respectively. For shared protection, POADM v.1 is the most expensive for C_{lw} up to 0.07. For dedicated protection, however, there is no difference between different technologies for C_{lw} up to 0.01. In many real network situations, where the fibers are already installed, and there is no need for leasing of wavelengths, the values of C_{lw} can be set to very low values and in this case TWIN's wavelength inefficiency will not be penalized.

2) Scenario 3: Impact of TRX cost: Here, we suppose that C_t changes in the range [1,20] (cost model range normalized to \$ 1000), while the other cost components are fixed to $C_s = 0.05$ and $C_{lw} = 0.1$. The resulting design cost is shown in Figs. 17 and 18. According to the simulation results on Fig. 17, POADM v.1 is more expensive than other protection methods in shared scenario, while POADM v.2 and TWIN have the same cost. The cost increases linearly for all technologies. The linearity is the sign that the transponder cost do not affect the final optimization configuration, which remains unchanged. For dedicated protection, TWIN remains more expensive than POADM (Fig. 18), however, the relative difference between them decreases from 45% (for $C_t = 1$) to 10% (for $C_t = 20$).

Note that the impact of the gate cost, C_s, is not separately studied here, due to the lack of space. However, our results have shown that the increase of this cost (in the range defined by the cost model) has a much lower impact on the total cost increase, w.r.t. to the impact that have the costs of transponders and wavelengths in the same scenario. The total cost increase, due to the C_s increase, remains limited to few percent.

VI. CONCLUSION

A new joint method for network dimensioning is proposed for two metro technologies, TWIN and POADM, allowing to allocate the needed resources for dedicated and shared path protection. For the comparison, we propose for a first time a CAPEX cost model for the two networks, which takes into account the cost of the transponders, the cost of the wavelength use per km of fiber, and the cost of optical gates for POADM. All the cost components that depend on dimensioning are accounted for in the model. All other costs are per-node costs, which do not depend on dimensioning, since nodes are known as an input. According to our results, the number of allocated transponders is similar in TWIN and POADM. The transponder cost increase does not change the network configuration, but decreases the relative difference between the two technologies. TWIN network is more sensitive to the wavelength cost, since it allocates more wavelengths than POADM, and is thus less cost efficient than POADM, generally. Gate cost (accounted for POADM) has a very limited impact on the final solution.

In the future steps, the study should be extended to further improve the cost model, and QoS performance comparison should be carried out.

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