Cost of Protection in Time-Domain Wavelength Interleaved Networks

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Abstract—In this paper, we study the cost of protection in Time-Domain Wavelength Interleaved Network (TWIN), an optical burst switching technology for transport networks with active edge nodes, passive core nodes, and time slotted operation. For the first time, an optimal network dimensioning with protection is proposed for TWIN, allowing to allocate the needed resources for dedicated and shared path protection. The dimensioning model is in the form of a 0-1 Integer Linear Program (0-1 ILP), and addresses both the routing and wavelength assignment problem, and the scheduler calculation. The cost of protection is studied for centralized and distributed traffic models, and it is shown that the shared path protection in TWIN is the most cost efficient.

Index Terms—Optical burst switching, network dimensioning, protection, transport network.

I. INTRODUCTION

Time-Domain Wavelength Interleaved Network or TWIN [1], [2], is an energy efficient optical burst switching technology, for the transport networks. The energy efficiency in the network is achieved by pushing the electronic processing functions from the network center to its edge. TWIN (Fig. 1) consists of simple core nodes based on passive devices and of an intelligent edge nodes that are equipped with transponders (TRX). Usually, a particular wavelength is attributed to each egress (edge) node to receive its data, thus, the number of required wavelengths is equal to the number of edge nodes. Each edge node is equipped with a fast wavelength-tunable transmitter [3] and a burst-mode (e.g., access-grade) receiver. Relatively inexpensive non-coherent (e.g. 10 Gb/s) technology can be leveraged to implement those active nodes while the passive (core) nodes are implemented with optical couplers and wavelength blockers. By tuning its emitter to the appropriate wavelength, a source can send a burst to any destination. The routing in intermediate nodes is only based on the burst wavelength and thus purely passive. Thus, the logical topology of TWIN can be viewed as overlaid optical multipoint-to-point trees, one for each of the destinations.

A node knows when to send and receive slots thanks to a schedule that is computed in a centralized fashion; the schedule additionally defines what link and wavelength (in addition to which slot) is used for a source to send data to a destination. Hence, the classical problem of routing and wavelength allocation (RWA) is a sub-problem of schedule computation in TWIN. The schedule can be periodically sent to each node via a control channel that is processed at every node. The control channel can be implemented with low data-rate equipment (e.g. 1 Gb/s) to mitigate its cost.

The scheduling issues due to propagation delays is the central topic in TWIN, and has been studied for instance in [4]–[6]. When scheduling the slots in TWIN, conflicts between different sources and destinations may result in slot collisions and hence must be avoided in the entire network. In the general case, slot collision could occur on any network link in TWIN. If the network is equipped with protection mechanism to circumvent equipment failure (e.g., a fiber cut), the propagation delay should be considered in the protection mechanisms as well, i.e. the slot collisions should be avoided at both working and backup paths.

Since enabling protection in TWIN is a very important task, it needs to be taken into account when planning a network. In a case of a failure such as a link cut, part of the traffic shall be rerouted on other precomputed paths, which yields for a need of additional bandwidth reservation. This bandwidth shall be available at every moment, but its quantity will depend on the protection scheme — shared (the same resource can be used for the protection of several paths, or, in the context of TWIN, trees) or dedicated (the separate backup resources are allocated to each working connection) — that is used.

This paper proposes a scheduling method for TWIN that also includes planned shared or dedicated protection; in addition the proposed method allocates TRX where needed, according to the traffic matrix and type of protection, in order to minimize the network cost.
The remainder of the paper is organized as follows. In Section II we review existing work and we position this paper with respect to other papers, emphasizing on its novelty. In Section III we review classical protection methods in mesh networks. Section IV is devoted to the linear programming dimensioning method for TWIN protection. The numerical results are presented in Section V. We give brief conclusions in Section VI.

II. LITERATURE REVIEW AND PAPER POSITIONING

There are numerous studies on the transport network protection mechanisms. For instance, Resilient Packet Ring (RPR) offers two protection mechanisms against a link failure event, “wrapping” and “steering” which differ in the protection triggering speed and in the efficiency of the bandwidth use [7]. MPLS-TP is expected to have an improved set of resilience features in comparison to MPLS, mainly by introducing novel OAM (Operation, Administration and Management) mechanisms for protection triggering and by addressing ring topology protection with wrapping and steering methods [8]. In paper [9], the authors presented an extensive study of different protection methods for circuit switching networks.

The protection in TWIN has been only partially addressed so far. In [1], the possibility of using multiple trees to provide dedicated protection is considered. In that paper, the process of allocating the slots is based on a heuristic algorithm, while the TWIN-tree calculation problem has been resolved separately from the slot allocation. The cost of shared protection was not considered, and the cost of allocating the backup resources is considered in terms of the scheduler size increase, and not in terms of the CAPEX (capital expenditure) cost. In [10], the authors discuss the possible protection methods for a variation of TWIN that uses coherent technology, but protection is not numerically assessed. In our previous paper [11], we showed how the ring covering algorithm could be used for TWIN to simplify the control plane functionalities related to protection. Virtual rings were used for joining all sources and destinations in order to support both an out-of-band control channel and all protection paths, however the type of the protection and the required backup capacity was out the scope of the study.

The current paper is a continuation of our work [12], where we have proposed a dimensioning strategy including QoS (latency) constraints, for a TWIN network without protection. It is very important to simultaneously address the RWA and the slot allocation problem in TWIN, since the scheduler depends on the propagation delays in the network. Indeed, in TWIN, the scheduling should be calculated to avoid any slot collisions between the concurrent sources and destinations. The configuration of the overlapping slots depends on the propagation distances between source-destination pairs in the network, which are the output of the RWA problem. In the present paper, for the first time, a combined dimensioning formulation for TWIN is proposed, which is able to simultaneously address the routing and wavelength assignment problem, and to calculate the optimal schedule and the backup paths for dedicated and shared protection. Our cost function is representative of the CAPEX of such a network, and can include both transponder and cost capacity utilization/deployment cost (wavelength leasing or fiber deployment) costs. Such solution can be of use to network planners, whether the network fibers are already installed, or in the case of so-called "green field" investments, when the network paths should be optimized as well. The dimensioning method that we propose is optimal, as it is based on a linear programme (LP).

III. CLASSICAL PROTECTION METHODS IN MESH NETWORKS

We consider here the problem of protecting the traffic flowing through a network against a single link failure. The basic type of protection consist in doubling the capacity and is called “dedicated” protection.1 Traffic between two stations is simultaneously sent over two link-disjoint routes. For instance, if $K_{p1}$ is the rate of a flow between stations A and B (Fig. 2), on the shortest path, then, for protection, a flow of the same rate $K_{p2} = K_{p1}$ will be sent simultaneously 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 rerouted and sent on the predetermined 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. 2), we are speaking about "shared" protection. Such protection is used for example in SONET/SDH [13]. 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 ("reroute") going through a failed link and hence higher data losses (in addition to possible reordering) upon rerouting.

IV. ILP FORMULATION FOR TWIN DIMENSIONING, WITH PROTECTION SUPPORT

The dimensioning problem usually consists in allocating the wavelengths and the equipment (i.e., transmitters, receivers, transponders) in order to support the given traffic demands, with the objective of minimizing the CAPEX cost. In our

1More 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.
case, the CAPEX cost of the network is composed of two main costs: wavelength leasing cost per km of the used fiber (link), \( C_{lw} \), and cost of transponder, TRX (\( C_t \)). 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. When allocating the transponders, TRXs, we suppose that each of them is composed of a transmitting part (TX), with a fast wavelength-tunable laser, being able to quickly change the transmitting wavelength after each emitted optical burst, and a receiving part (RX), with a fixed wavelength receiver.

The 0-1 Integer Linear Programming (0-1 ILP) 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 TWIN’s scheduler \( K \), and the input traffic matrix are the input parameters in the formulation. Three different variants of the formulation are given enabling us to study the dedicated protection, the shared protection and the case without any protection.

The proposed 0-1 ILP is NP-complete, for the reason that it addresses the problem of RWA and thus contains multicommodity flow problem, as its subproblem, and it is well known that the latter problem is NP complete.

An important aspect of the solution is to satisfy the constraints that will prevent the collisions of the optical bursts at destinations, sources, and everywhere in the network. As in [12], we suppose that the slots that are the object of allocation are enumerated by numbers \( 0, 1, \ldots, K - 1 \), i.e. mod \( K \), and that the scheduling that is the result of the optimization is periodically repeated. Finally, since the edge nodes in TWIN are supposed to have a synchronized operation, we consider that at a given moment in time, all the sources send the slots enumerated with the same number.

**Given Parameters**
- \( G(V, E) \): a non-directed graph describing the physical 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 \( d \);
- \( R_d = \{ R_{d,1}, R_{d,2}, \ldots, R_{d,|\mathcal{R}_d|} \} \): set of routing paths \( R_{d,r} \) which can be used to carry demand \( d \), see below;
- \( R_{d,r} \): set of links used to route a demand \( d \);
- \( L(d, r) \): the number of links of route \( r \) of demand \( d \);
- \( \text{start}(R_{d,r}) \) is the link of \( R_{d,r} \) that is attached to the source node of demand \( d \); (depending on the node structure, \( \text{start}(R_{d,r}) \) may actually contain several links if there is a splitter right after a TX);
- \( \text{end}(R_{d,r}) \) is the (set of) link(s) of \( R_{d,r} \) that are attached to destination nodes of demand \( d \);
- \( W \): maximum number of wavelengths per fiber;
- \( C_{lw} \): wavelength leasing cost per km of the used fiber (link); \( C_t \): transponder cost;
- \( L_\ell \): length of link \( \ell \) in km;
- \( D_{d,\ell, r} \): delay (number of slots) experienced by a slot emitted by the source of demand \( d \) to reach link \( \ell \), by using the route \( r \);
- \( K \): number of slots used for the allocation, i.e. the “schedule length” (a number at least as large as the number of edge nodes, i.e. sources and destinations);
- \( A \): number of demands;
- \( B = \max_{d} |\mathcal{R}_d| \): maximum number of alternate routes in a structure \( \mathcal{R}_d \);

**Output Variables**
- binary \( x_{d,\ell, w}^{k, d, r} \) equal to 1 if slot \( k \) is used for communication for demand \( d \) on wavelength \( w \) and link \( \ell \) and route indexed by \( r \) in \( \mathcal{R}_d \);
- binary \( \ell_{d, w}^{k, d, r, b} \) equal to 1 if slot \( k \) is used for protection of the communication for demand \( d \) on wavelength \( w \) and link \( \ell \) and route indexed by \( r \), by using the backup route \( b \) in \( \mathcal{R}_d \);
- binary \( u_{i, \ell, w} \) equal to 1 if a TRX with fast tunable laser and a receiver for fixed wavelength \( w \) is deployed on node \( i \) and link \( \ell \), for all traffic type);
- binary \( u_{i, \ell, w} \) equal to 1 if a TRX with fast tunable laser and a receiver for fixed wavelength \( w \) is deployed on node \( i \), for all traffic type;
- binary \( e_{\ell, w} \) equal to 1 if link \( l \) on wavelength \( w \) is used;

**0-1 ILP Formulation**

Objective function, minimizing the network costs:

\[
\min \left( C_{lw} \sum_{w=1}^{W} \sum_{\ell} E \cdot L_{\ell} \cdot e_{\ell, w} + C_t \sum_{i=1}^{V} \sum_{w=1}^{W} \sum_{\ell} u_{i, \ell, w} \right)
\]

(1)

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

\[
\sum_{r=1}^{|\mathcal{R}_d|} \sum_{\ell \in E} \sum_{w=1}^{W} x_{d,\ell, w}^{k, d, r} = T_d, \quad \forall d \leq A;
\]

(2)

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

\[
\sum_{w=1}^{W} \sum_{\ell} \sum_{k=1}^{K} x_{d,\ell, w}^{k, d, r} / L(d, r) = \sum_{w=1}^{W} \sum_{\ell} \sum_{k=1}^{K} \sum_{b=1}^{L(d, b)} \ell_{d, w}^{k, d, r, b} / L(d, b), \quad \forall d \leq A, \forall r \leq |\mathcal{R}_d|;
\]

(3)

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

\[
x_{d,\ell, w}^{k, d, r} = x_{d,\ell', w}^{k, d, r}, \quad \forall w \leq W, \forall d \leq A, \forall r \leq |\mathcal{R}_d|, \quad \forall k \leq K;
\]

(4)

\[
z_{\ell, w}^{k, d, r, b} = z_{\ell', w}^{k, d, r, b}, \quad \forall w \leq W, \forall d \leq A, \forall r \leq |\mathcal{R}_d|, b \leq |\mathcal{R}_d|, \quad \forall k \leq K;
\]

(5)
Constraint ensuring that slots are allocated only if traffic demand is non-zero:

\[
E \sum_{k=1}^K \sum_{w=1}^W x_{k,d,r} \leq 2 \cdot B \cdot K \cdot W \cdot |E| \cdot T_d, \quad \forall d \leq A; \quad (6)
\]

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

\[
\sum_{d=1}^D \sum_{r=1}^R \sum_{k=1}^K x_{k,d,r} + \sum_{d=1}^D \sum_{r=1}^R \sum_{k=1}^K z_{k,d,r,b} \leq 2ABK e_{t,w}, \forall l;
\]

\[
\sum_{r=1}^R \sum_{k=1}^K \sum_{w=1}^W x_{k,d,r} \leq (|V| - 1) \cdot u_{t,w} + \forall w \leq W, \forall i \leq |V|; \quad (8)
\]

\[
\sum_{i=1}^I u_{i,t,w} \leq 1, \quad \forall w \leq W;
\]

\[
A. \text{ Dedicated path protection}
\]

Fast wavelength-tunable TX capacity constraint: allocate the TX at each node based on sent slots:

\[
\sum_{d=1}^D \sum_{r=1}^R \sum_{k=1}^K x_{k,d,r} + \sum_{d=1}^D \sum_{r=1}^R \sum_{k=1}^K z_{k,d,r,b} \leq 2ABK e_{t,w}, \forall l;
\]

\[
\sum_{u=1}^U u_{i,t,w} \leq K, \forall k \leq K, \forall \ell \in E, i \leq |V|, i = \text{start}(l); \quad (10)
\]

\[
\forall w \leq W, \forall k \leq K, \forall \ell \in E, i \leq |V|, i = \text{end}(l);
\]

\[
\text{where } k' \equiv k - D_{d,t,r}(\text{mod } K) \quad \text{and} \quad k'' \equiv k - D_{d,t,b}(\text{mod } K).
\]

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

\[
\text{Constraint which avoids link collision: Prevent several demands from using the same link on the same wavelength and the same slot:}
\]

\[
\sum_{j=1}^J \sum_{u=1}^U u_{j,t,w} \leq 2ABK e_{t,w}, \forall l;
\]

\[
\forall w \leq W, \forall k \leq K, \forall \ell \in E, i \leq |V|, i = \text{end}(l);
\]

\[
\text{where } k' \equiv k - D_{d,t,r}(\text{mod } K) \quad \text{and} \quad k'' \equiv k - D_{d,t,b}(\text{mod } K).
\]

\[
\text{This case is obtained from “dedicated path protection” case, by removing the variables } z_{k,d,r,b} \text{ from all the constraints.}
\]

\[
B. \text{ Shared protection}
\]

Fast wavelength-tunable TX capacity constraint: allocate the TX at each node based on sent slots:

\[
\sum_{d=1}^D \sum_{r=1}^R \sum_{k=1}^K x_{k,d,r} + \sum_{d=1}^D \sum_{r=1}^R \sum_{k=1}^K z_{k,d,r,b} \leq 2ABK e_{t,w}, \forall l;
\]

\[
\sum_{u=1}^U u_{i,t,w} \leq K, \forall k \leq K, \forall \ell \in E, i \leq |V|, i = \text{start}(l); \quad (13)
\]

\[
\forall w \leq W, \forall k \leq K, \forall \ell \in E, i \leq |V|, i = \text{end}(l); \quad (14)
\]

\[
\text{Colored RX capacity constraint: allocate the RX at each node based on received slots:}
\]

\[
\sum_{d=1}^D \sum_{r=1}^R \sum_{k=1}^K x_{k,d,r} + \sum_{d=1}^D \sum_{r=1}^R \sum_{k=1}^K z_{k,d,r,b} \leq 2ABK e_{t,w}, \forall l;
\]

\[
\forall w \leq W, \forall k \leq K, \forall \ell \in E, i \leq |V|, i = \text{end}(l);
\]

\[
\text{where } k' \equiv k - D_{d,t,r}(\text{mod } K) \quad \text{and} \quad k'' \equiv k - D_{d,t,b}(\text{mod } K).
\]

\[
\text{Constraint which avoids link collision: Prevent several demands from using the same link on the same wavelength and the same slot:}
\]

\[
\sum_{j=1}^J \sum_{u=1}^U u_{j,t,w} \leq 2ABK e_{t,w}, \forall l;
\]

\[
\forall w \leq W, \forall k \leq K, \forall \ell \in E, i \leq |V|, i = \text{end}(l);
\]

\[
\text{where } k' \equiv k - D_{d,t,r}(\text{mod } K) \quad \text{and} \quad k'' \equiv k - D_{d,t,b}(\text{mod } K).
\]

\[
\text{This case is obtained from “dedicated path protection” case, by removing the variables } z_{k,d,r,b} \text{ from all the constraints.}
\]
A. Distributed traffic

In the first studied case, the traffic matrix is symmetric and non-centralized. It is supposed that nodes 6 and 7 (Fig. 3) exchange traffic with the same amplitude $\alpha_1$ (normalized to TRX capacity) with nodes 10 and 11 in both directions (e.g. there are 8 traffic flows in the network). The design cost in this scenario, for increasing values of amplitude $\alpha_1$, is plotted in Fig. 4, for different wavelength costs.

From Fig. 4(a), we observe that for $C_{lw} = 0.1$ km$^{-1}$, dedicated protection costs up to 100% more than the unprotected network, while shared protection costs only around 20% more than the case with no protection. For negligible wavelength cost (Fig. 4(b)), the design cost increase for both dedicated and shared protection is lower, peaking around 30% for dedicated protection and being negligible for shared protection.

To understand why protection comes at little extra cost for the lower wavelength cost, let us observe Figs. 5 and 6 that depict each of the CAPEX cost components, i.e. the wavelength (Fig. 5) and the TRX cost (Fig. 6). For non-negligible $C_{lw}$ (Fig. 5(a)), the wavelength cost is the same for dedicated and shared protection at lower and moderate rates, with shared protection being more efficient at higher data rates only. As expected, the wavelength cost is negligible for the lowest value of $C_{lw}$ (Fig. 5(b)) and the increase of design cost comes only from the increase in TRX cost, in such case.

From Fig. 6 reveals that the shared protection is much more efficient than the dedicated one, in terms of the number of used TRXs. It is since in shared protection, the transponders of the same active node can be reused for several backup paths, whose primary paths do not fail simultaneously. Let us also note that for lower traffic loads, the TRX number is the same for shared, dedicated and case without any protection.

Finally, Fig. 7 shows the number of needed lightpaths, i.e. wavelengths, calculated by dimensioning solution, for different protection types, when the traffic load is increasing. (Note that the number of wavelengths is different that the "wavelength cost", shown in Fig. 5, which is a name for the cost of the "wavelength per km of fiber used"). From Fig. 7 we can see that the dedicated protection requires more wavelengths w.r.t. the shared protection, which results in the increase of the wavelength cost, especially for higher loads (the similar effect is observed in Fig. 5). Moreover, we observe that the number of required wavelengths does not depend on $C_{lw}$.

B. Centralized traffic

Centralized traffic is a case where one of the nodes in the network plays the role of a gateway to the backbone network. The traffic model that we adopted follows the concentration-distribution scheme, where the gateway sends much more traffic to the other nodes, than it receives from them, in that way mimicking the client-server service model, which is very usual in today’s metro networks. In our example, the gateway is located at node 6, and it is supposed that this node sends a traffic of amplitude $\alpha_2$ to nodes 9, 10 and 11, and receives back from them the traffic of much lower amplitude, $\alpha_2/10$. 

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Fig. 3. Metro network with 6 active/edge nodes and 6 passive/core nodes.

V. NUMERICAL RESULTS

We consider the 12-node topology depicted in Fig. 3, which consists of 6 active (edge) nodes and 6 passive (core) nodes. In this example, the core and edge nodes are co-located in order to simulate a network where the operator owns a set of premises (such as central offices) and needs to ensure full logical connectivity between those offices. As mentioned earlier, in the general case, there could be more core nodes than edge nodes.

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, $b = 10$ slots$^2$, $a = 0$ slot and schedule length $K = 5$. The number of alternative paths between each pair of nodes is 5.

We set the TRX cost to $C_t = 1$ (arbitrary unit), while the cost of wavelength use per km of fiber length (hereafter denoted simply by "wavelength cost") varies from $C_{lw} = 10^{-4}$ (arbitrary unit)-km$^{-1}$ (lower bound) to $C_{lw} = 0.1$ (arbitrary unit)-km$^{-1}$ (upper bound). The lower bound on $C_{lw}$ is below the value $\frac{\sum_t L_t \cdot W}{C_t}$, representing a scenario where the network price is dominated by the transponder cost, such that transponder cost is minimized first, and wavelength utilization is minimized as a secondary goal. The value obtained with the lower bound for $C_{lw}$ guarantees that in the final solution no TRX will be exchanged for a wavelength. The assumption for the upper bound on $C_{lw}$ is derived from [14], where the ratio between the wavelength cost per ring and the receiver cost is estimated on a ring circumference of 100 km.

In the study, since core nodes and edge nodes are co-located, we assume that only the links between the core nodes can be a subject of failure, and shall be protected. We study distributed and centralized traffic matrices.

$^2$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.
The design cost comparison is presented in Fig. 8. The shared and dedicated protection perform much more equally, than in the previous scenario. It is since, for more centralized traffic patterns, the number of links carrying traffic is lower, and the links are more charged. As a consequence, the savings in resources achieved by shared protection are much lower, w.r.t. the distributed traffic case. To summarize, compared with the "no protection" case, the design cost increase for \( C_{lw} = 0.1 \text{ km}^{-1} \), calculated over all points for distributed and centralized traffic patterns, is approx. 95% and 80% for dedicated and shared protection, respectively. For \( C_{lw} = 10^{-4} \text{ km}^{-1} \), the design cost increase is 50% and 25%, for dedicated and shared protection, respectively. In both cases, shared protection is much more efficient.

C. The impact of the wavelength cost on the final network price

The previous simulations have showed the advantages of the shared path protection in TWIN, for increasing traffic loads. In order to get a more complete understanding of the behaviour of different protection methods, in the following experiment we study the impact of the wavelength cost \( C_{lw} \) on protection, for an instance of a distributed traffic profile, with fixed amplitude \( \alpha_1 \).

We consider different values for the traffic amplitude, in order to see the impact of the network saturation. The results are plotted in Fig. 9(a) and Fig. 9(b), for \( \alpha_1 = 0.1 \) and \( \alpha_1 = 0.6 \), respectively. According to the results, for \( \alpha_1 = 0.1 \), which is a small value of traffic amplitude, both protection methods have similar cost. In addition, for high value of \( C_{lw} \), protected network is much more expensive than the network without any protection.

However, for higher traffic loads (\( \alpha_1 = 0.6 \)), shared protection has the same cost as the case without protection, for \( C_{lw} \) going up to 0.005. For higher wavelength costs, although the cost of shared protection increases, it always remains better than for the cost of dedicated protection. The shared protection
owns its efficiency to its better wavelength use, as shown in all the previous results. The present experiment shows that the efficiency of shared protection increases with the increase of wavelength cost.

The cost of protection is particularly high for high $C_{lw}$ values. For such values, the wavelength cost becomes a very important factor in the overall CAPEX cost.

VI. CONCLUSION

We presented a new method for optimal planning of a survivable TWIN network, based on linear programming, and considering in the same time the slot allocation and the routing and wavelength assignment problem.

We considered “dedicated” protection, which consists in doubling the capacity of each operational connection in the network, and “shared” protection, when the protection capacity is shared between multiple connections. We studied the cost of the protection, by taking into account both the equipment (transponder) cost and the wavelength leasing cost per km of fiber.

By using detailed simulations, we studied the cost efficiency of different protection options. The results suggest that the dedicated protection significantly increases the network CAPEX cost, up to 50 – 95% (depending on the wavelength cost), while for the shared protection this increase is much lower, and is from 25 – 80%. Finally, it is shown that the efficiency of the shared protection is due to its better wavelength use.

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