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**Abstract**

In this manuscript we tackle the optimal upgrade of an innovative optical transport network architecture called the Petaweb, which has a particular composite-star infrastructure that allows two-hop communications between edge nodes. Prior studies of the same authors have tackled the design and dimensioning problem for the Petaweb assuming TDM/WDM equipment and adopting a dedicated path protection strategy. A quasi-regular topology, more efficient than the regular, has also been proposed to minimize the quantity of fiber to install while preserving the regularity of the architecture. Exploiting the same network model, we propose an upgrade procedure for the extension of an existing optimized network, having one of the two possible topologies, under traffic increase and edge node addition.

**Résumé**

Dans ce cahier nous traitons la mise à jour optimale d'une architecture innovante de réseau de transport optique appelé le Petaweb caractérisée par une infrastructure à superposition d'étoiles permettant une communication à deux sauts entre nœuds d'accès. Des études précédentes des même auteurs ont traité le problème de design et de dimensionnement pour le Petaweb en considérant des équipements TDM/WDM et en adoptant une stratégie de protection dédiée du chemin. De plus, une topologie quasi-régulière, plus performante que la régulière, a été proposée pour minimiser la quantité de fibre à installer en préservant la régularité de l'architecture. En exploitant le même modèle, nous proposons une procédure de mise à jour pour l'extension d'un réseau optimisé existant, ayant une des deux topologies et soumis à augmentation du trafic et à l'ajout de nœuds.

**Riassunto**

In questo manoscritto affrontiamo l'aggiornamento ottimo di un'innovante architettura di rete di trasporto ottica chiamata Petaweb, la quale ha una particolare infrastruttura a sovrapposizione di stelle che permette una comunicazione a due hops fra nodi di accesso. Degli studi precedenti degli stessi autori hanno affrontato il problema di design e dimensionamento per una rete di tipo Petaweb considerando degli apparati TDM/WDM e adottando una strategia di protezione dedicata del percorso. Inoltre, una topologia quasi-regolare, più performante che la regolare, è stata proposta per minimizzare la quantità di fibra da installare preservando la regolarità dell'architettura. Sfruttando lo stesso modello, proponiamo una procedura di aggiornamento per l'estensione di una rete ottimizzata esistente, avente una delle due topologie e sottoposta ad aumento di traffico e ad aggiunta di nodi.

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# 1 Introduction

With new and enhanced IP services that consume large amounts of bandwidth, the demand for optical transport services increases day by day. There is an important need for a smooth and cost-effective way to upgrade WDM networks. Such an upgrade is not an easy task given the network structure. For instance, in WDM mesh networks the use of the idle capacity by multi-hop lightpaths is complicated by the need of re-dimensioning core nodes, resizing transport links and reconfiguring a large number of optical switches.

In [1] a novel optical architecture called the Petaweb was proposed for the next generation transport infrastructure. This network is formed by edge nodes connected through core nodes as showed in Figure 1. Every edge node is connected to every core node. Note that the core nodes are not connected to each other, forming a backbone network where all the nodes are disconnected. Given its topology, the Petaweb allows for two-hop optical lightpaths between two edge nodes through a single core node.

In this architecture the classical pitfalls of the WDM network upgrades where existing network capacity may not be available because of structural bottlenecks can now be avoided. In fact, the Petaweb offers few easily-manageable and independently-configured core nodes and all its components are modular and can be extended without reconfiguring the existing equipment [2]. Moreover, given the regularity of the structure, an upgrade will not jeopardize the management of an optimized network as idle capacity can be easily allocated without compromising network management.

In previous work, we have dealt with the design and dimensioning of the Petaweb structure. In [3] the design problem was defined and an efficient resolution approach was presented. In [4] the TDM/WDM features of the Petaweb were investigated and a new design optimization was proposed. In that paper, a quasi-regular topology for the Petaweb was also introduced. Although the quasi-regular topology has a lower cost when compared to the regular one, it has the disadvantage that in the event of failures, some minor edge nodes could get disconnected. Then, the reliability issues were dealt with in [5].

Now, once the Petaweb network is designed, the question remains on how to upgrade the structure taking into account the architectural constraints. The object of this paper is precisely to tackle this issue and to present an effective formulation and resolution approach. The paper is divided as follows. In Section 2 the Petaweb architecture is briefly discussed. For the sake of completeness, the network model and the design problem illustrated in [4] and [5] are also presented. In Section 3 other network expansion problems tackled in the literature are briefly reviewed. The problem of upgrading a Petaweb architecture is presented in Section 4 where an Integer Linear Programming (ILP) formulation is proposed. Section 5 shows the results for two cases: the case for which there is only a traffic increase, and the case for which there is traffic increase and edge node addition. Section 6 is devoted to conclusions and suggestions for further work.

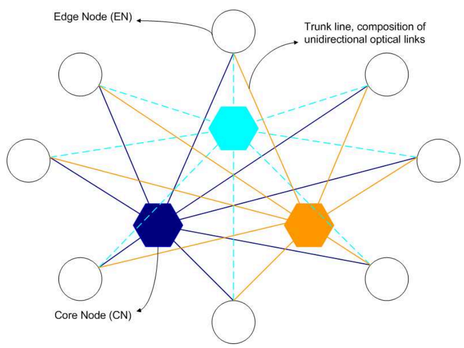



Figure 1: The Petaweb composite-star architecture

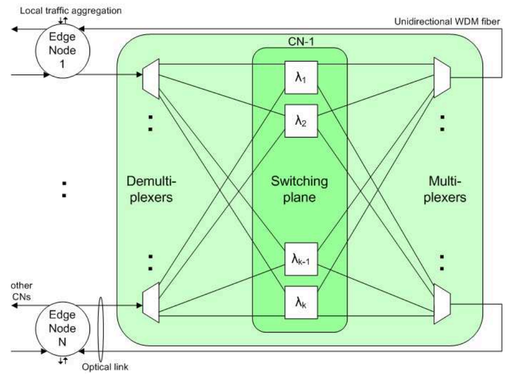



Figure 2: Parallel-planes optical core node in the Petaweb.

## 2 The Petaweb network model

In the Petaweb, an *edge node* (EN) is an electronic node that requests bandwidth to the transport network. The connection between $N$ edge nodes and a core node is showed in Figure 2.

Every edge node is connected to a core node through one *optical link*, composed of one or more optical fibers. We suppose unidirectional optical fibers so that an edge node has one optical link incoming from, and one optical link outgoing to, every core node. Every fiber has several optical channels and we assume that all fibers of the network carry the same number of channels.

A *core node* (CN) is a set of arrays of parallel space switches, also called switching planes. The number of switching planes $s_r$ identifies the type $r$ of a CN (indicated by CN-$r$). Note that the optical link connecting an EN to a CN-$r$ has $s_r$ unidirectional optical fibers, one for every switching plane. In this work, we assume three types of core nodes, with one, two and four switching planes, that is, $s_1 = 1$, $s_2 = 2$ and $s_3 = 4$. All the incoming WDM fibers are demultiplexed into their different lambda-channels, each of which is connected to the associated space switch of the respective array. Each space switch handles channels of the same wavelength; those referred to the same EN are then multiplexed into the optical link going back to that EN. Such parallel-planes structure increases the reliability of the core nodes because a hypothetical failure in a switching plane would affect only the connections on that plane. In [2] Blouin proposed the use of TDM in the Petaweb to produce sub-channels within a wavelength channel. To integrate Time Division Multiplexing into the Petaweb, the switching cores functionalities must be specified. In [4] we proposed the replacement of the described switching plane with the compatible all-optical TDM Wavelength Space Routers of Huang [6], which multiplexes in a time-slot basis remaining in the optical domain and without any buffering operation; the behavior of such node architecture has been recently evaluated in [7]. The edge node locations define the set of potential *switching sites*. Note that several core nodes can be installed in the same site. Therefore, the physical connection between an edge node and a switching site can be composed of several links, given that there may be several core nodes present at the site. From now on we call this physical connection an *optical trunk line*.

In [4] and [5], two possible topologies were studied. The regular and the quasi-regular topology. In the regular topology every switching plane is connected with every edge node. The quasi-regular topology is built removing from the regular architecture the equipment that will remain unused in the dimensioned network.

We will refer in the following to a time-slotted lightpath with the term *ts-lightpath* (as suggested in [6]) or with the acronym TLP; it is the data channel of a time-slot in a wavelength. Let us now indicate by $Z_h$ the transport capacity of a TLP of class $h$ and let $C_{ch}$ be the capacity of a lambda-channel set to 10 Gbps. We also assume that there are $W = 16$ wavelengths per fiber. Then, we have $Z_2 = 10$ Gb/s, $Z_3 = 160$ Gb/s and $Z_1 = 0.625$ Gb/s [4]. Note that these bit-rate classes were chosen so that a perfect correspondence with the bit-rates of SDH and OTN interfaces is obtained [8].

To optimize the Petaweb design, a total network cost must be minimized. In our model such cost is composed of three elements: the cost of the core node, the cost of the fiber and an additional cost to take into account the propagation delay. The *cost of the core nodes* is composed of a fixed cost $f_r$ that depends on the type $r$ of core and that is defined so that $f_r > f_{r-1} > ... > f_1$. The number of switching planes is such that $s_r = 2s_{r-1}$. An active port has a cost $P$ scaled for higher types. Let us indicate by $M$ the set of edge node sites; $|M|$ is thus the number of edge nodes of the network. Let $\gamma$ be the scale factor for $P$, then the global cost of a core node of type $r$ is $K_r = f_r + 2|M|W s_r P \gamma^{(s_r - 1)}$, with $K_r < 2K_{r-1}$.

The *fiber cost* is indicated as $F$ and is in unit of length. It is the cost of a reference fiber type, which is then scaled by a discrete function $\phi(W)$ that depends on the number of wavelengths. Let us indicate by $\Delta_{ij}$ the distance between the sites $i$ and $j$; the installation of a CN-$r$ on site $i$ requires the installation of $s_r$ fibers per direction for every edge node, which yields a global cost of $F_{i,r} = 2\,\phi(W)\,F\,s_r \sum_j \Delta_{ij}$.

Since in [1] the authors highlighted that a drawback of the Petaweb network may be a larger propagation delay for some connections, we decided to account it as a virtual cost of the network cost to minimize. Indeed, with proper design the traffic weighted propagation delay may be smaller than that of conventional networks. The *propagation delay cost*, indicated by $\beta$, is proportional to the distance traveled and to the lightpath bit-rate. This is an interesting addition to the classical equipment cost functions to guarantee that the solution is such that the connections between edge nodes that have the largest exchange of traffic experience as low a propagation time as possible.

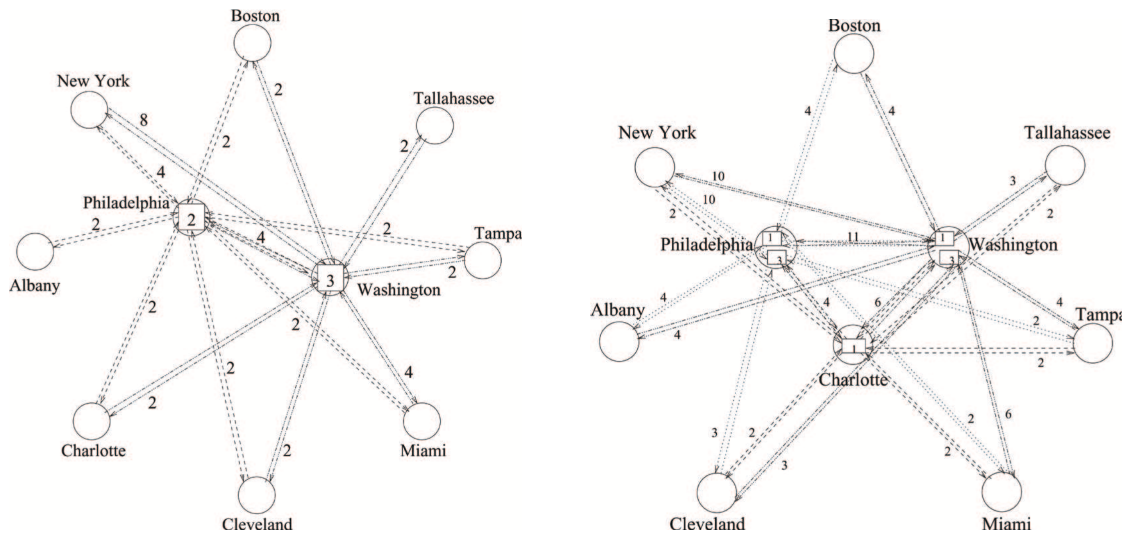
The Petaweb design must respect the physical characteristics of network components. Capacity constraints concern edge nodes and optical links. The capacities can be allocated and increased only through discrete quantities: the link capacity can be increased by a multiple of the capacity of $W$ lambda-channels at a time; the capacity of an EN depends on the number of optical fibers connected to it. Furthermore, to control the delay in buffering operations, all the TLPs of a Connection Request (CR) must be transported on the same optical trunk line, all the time-slots associated to a TLP must be transported on the same optical link, and all the TLPs of a CR must be transported contiguously in the time and in the frequency domains.

The design problem consists in finding the best composite-star physical topology for the given set of TLPs and in assigning to the TLPs their communications medium (wavelengths and time-slots). Hence it is jointly an optimal dimensioning and a resource assignment problem. It is divided into two sub-problems: Route and Fiber Allocation (RFA) problem, which treats the allocation of the resources guaranteeing an efficient routing, and the Wavelength and Time-slot Assignment (WTA) problem, which concerns the assignment of the allocated resources.

The RFA problem gives rise to an ILP formulation that is solved with CPLEX, or with a specialized heuristic [3]. For the WTA problem a straightforward algorithm was devised in [4] and [5]. It assigns time-slots, wavelengths and fibers to TLPs starting form the solution of the resource allocation: each TLP-1 has one time-slot assigned, each TLP-2 one wavelength and each TLP-3 one fiber. The TLPs related to the same connection request have assigned contiguous time-slots and wavelengths, when possible. An example of the WTA solution is given in Section 5.4. A variant of the Petaweb design was recently presented in [5] where a Dedicated Path Protection (DPP) strategy was added to the network model proposed in [4] to tackle reliability issues. The idea is that for every working TLP (wTLP) a protection link-disjoint TLP (p-TLP) is allocated [9]. Thus, in case of one trunk line failure all the wTLPs are recovered from the allocated pTLPs without an excessive signaling interruptions. In the 1+1 DPP case there would not be a signaling phase. In case of 1:1 DPP it makes sense to enable a shorter path for w-LPs, and a longer path to p-TLPs to be used in case of failure along the working one. For this reason the optimization problem should give priority to w-TLPs in the contention for short paths. The DPP strategy requires an additional constraint to allow the protection mechanism: every pTLP must be multiplexed on trunk lines different from those of the corresponding wTLP; in the Petaweb architecture this means that a pTLP must be switched in a different network site than that of its wTLP. Note that such constraint guarantees even the node protection since if a core node or part of it fails, all the affected paths can be restored by the receivers.

In this paper it is assumed that the Petaweb networks to be upgraded were first optimized using the DPP policy. To illustrate the differences in the architecture, we refer the reader to the following figures. Figure 3a shows a 10-node quasi-regular topology optimized without path protection [4] and Figure 3b[1] shows the case with DPP [5]: one can notice that in the first case many edge nodes are connected to the network through only one

[1]The trunk lines connecting two switching sites are not link between core nodes, but links between edge node and core nodes, and vice-versa




(a) Without path protection (b) With dedicated path protection

Figure 3: Optimized 10-node Petaweb. The numbers on the links represent the number of fibers per line

trunk line whereas this does not happen in the second case when, instead, there is a larger quantity of fibers to install. Therefore, the path protection method produced a survivable quasi-regular Petaweb architecture.

## 3 Reviewing update and upgrade problems

An increase in traffic volume imposes changes in the network configuration; there are two ways to face such an increase: by updating or by upgrading the network.

*Updating* a transport network means configuring new circuits to further exploit the available equipment and resources; in that case, a reconfiguration of the network virtual topology may be useful to free more resources via re-optimization and hence postponing network upgrades [10]. For example, in [11] the authors tackled the problem of accommodating an expansion of the original traffic matrix for a pre-optimized WDM mesh network with the restriction that no more physical equipment should be added to the existing infrastructure, and that only the existing idle capacity could be exploited without touching active lightpaths.

*Upgrading* a network means resizing its infrastructure and, optionally, reconfiguring its routes. An upgrade may require removal and/or addition of new equipment to satisfy a set of new end-to-end requests. In [12] the upgrade design problem for WDM mesh networks is solved through a methodology that exploits the idle capacity of an optimized network adding more resources if the idle ones are not enough. They do not consider reconfiguring the original connections.

In this article, we focus on the upgrade of the Petaweb architecture without reconfiguration; in an edge-controlled transport network, such as the Petaweb, the reconfiguration of the lightpaths routing would imply high data flows interruption for a significant gap of time. Moreover, the re-optimization of active lightpaths becomes no more an essential operation for this composite-star architecture because all the idle capacity is directly exploitable, differently than with meshed WDM networks. Another feature not explicitly taken into account in our model is the equipment removal. Even though that might be considered in some networks ( [13]), it is not a real option in nationwide optical transport networks. In any case, this is a feature that can be easily incorporated into the model that we present in the next section.

# 4 Petaweb upgrade

The proposed upgrade model for the Petaweb not only considers the addition of new core node and fiber equipment, but also the exploitation of the idle capacity that is present in the initial architecture. In fact, in [5] we found that optimized survivable Petaweb networks still present a significant amount of idle capacity, which remains then available to accommodate subsequent bandwidth requests.

When the traffic volumes or the number of the connection requests between the existing edge nodes increase, they need new TLPs for which a route through a core node has to be decided. Thus, some switching sites that had few or low bit-rate Connection Requests, may now be updated with more core nodes, optical fibers and links. New switching sites may also be opened. In this work, we also consider that new edge nodes can be added to the network, which could imply that the opening of new switching sites is even more likely.

As previously stated, equipment removal is not considered in our update model. Therefore, the *upgrade cost* only includes the cost of the *new equipments* (i.e. fibers, core nodes and ports) and a propagation delay cost of the *new TLPs*. This latest term is added to make sure that the new TLPs are not routed on paths that will produce too long propagation delays.

The philosophy of the update model is to keep the initial Petaweb topology, whether it is regular or quasi-regular. Moreover, it is assumed that the existing optimized network was designed with a survivable strategy (DPP model) that is kept after the upgrade.

Since we assume that existing core nodes and fibers cannot be removed, and that the number of new TLPs are likely to be fewer than the existing ones, the complexity of the upgrade problem is reasonably lower than that of the initial planning problem [4].

The philosophy of the upgrade model is to use the same type of objectives and constraints of [5] but forcing the design to keep the existing equipment, and altering the capacity available on each single link so that the transport media already in use is not considered for the routing of new traffic.

The existing network is identified by all the enabled core nodes, the set of TLPs they commute, and by the number of fibers per optical link. From these, the used and the available transport capacity can be extracted and considered in the capacity constraints. Regarding the objective, it is worth noting that the optimization will be carried aiming at the minimization of the current total equipment costs. Thus, to assess the cost of the update, the cost of the equipment already installed will be subtracted.

The set of new TLPs $(p, h, l)$ identifies the additional traffic volume, and the set $M$ comprehends the pre-existing ENs sites and the new ones, if any. Thus, the solution is an optimized network with a regular or a quasi-regular topology, it indicates where the new TLPs must be routed and the equipment that have to be installed to satisfy the additional traffic.

We now present the mathematical formulation of the problem. The reference notations – the ones not already introduced – are displayed in Table 1.

$$\begin{aligned}\min G(\overline{y},\overline{x}) = &\sum_{(i,r,e)} (K_r + F_{i,r})\; y_{ire} \\ &+ \sum_{(i,r,e)} \sum_{(p,h,l)\in\Omega_w} \beta\, d_{ip}\, Z_h\, x^{ire}_{phl} \\ &+ \sum_{(i,r,e)} \sum_{(p,h,l)\in\Omega_p} \delta\,\beta\, d_{ip}\, Z_h\, x^{ire}_{phl} \qquad (1)\end{aligned}$$

$$s.t. \quad y_{ire} = 1 \qquad \forall (i,r,e) \in \chi \qquad (2)$$

$$\sum_{r\in V}\sum_{e=1}^{E_r} x^{ire}_{phl} + \sum_{r\in V}\sum_{e=1}^{E_r} x^{ire}_{phl_p} \le 1 \qquad \forall i \in M,\, \forall (p,h,l) \in \Omega_w, l_p = l + L_h \quad (3)$$

$$\sum_{(i,r,e)} x^{ire}_{phl} = 1 \qquad \forall (p,h,l) \in \Omega \qquad (4)$$

$$\sum_{(i,r,e)} C_{ch}\, W\, s_r\, y_{ire} \le C_j \qquad \forall j \in M \qquad (5)$$

$$\sum_{(p\in O_j,h,l)\in\Omega} Z_h x^{ire}_{phl} \le \left(C_{ch} W s_r - Q^{ire}_j\right) y_{ire} \qquad \forall j \in M, \forall (i,r,e) \qquad (6)$$

$$\sum_{(p\in D_k,h,l)\in\Omega} Z_h x^{ire}_{phl} \le \left(C_{ch} W s_r - Q^{k}_{ire}\right) y_{ire} \qquad \forall k \in M, \forall (i,r,e) \qquad (7)$$

$$x^{ire}_{phl} \in \{0,1\}, \quad y_{ire} \in \{0,1\} \qquad (8)$$

Table 1: Notations

| | |
|---|---|
| $M$ | set of sites |
| $T$ | set of pairs of sites $(M \times M)$, $p \in T$ is a Connection Request |
| $O_j$ | a subset of $T$ with a fixed origin site $j$ |
| $D_k$ | a subset of $T$ with a fixed destination site $k$ |
| $V$ | set of types of core nodes |
| $E_r$ | number of CN-$r$ specimens that can be enabled in a site |
| $(i,r,e)$ | triple representing a CN specimen, $i \in M, r \in V, 1 \leq e \leq E_r$ |
| $C_j$ | capacity, in Gb/s, of the edge node in site $j, j \in M$ |
| $H$ | set of TLPs classes |
| $L_h$ | maximal number of TLP-$h$ specimens for a CR, $h \in H$ |
| $(p,h,l)$ | triple representing a TLP specimen, $p \in T, h \in H, 1 \leq l \leq L_h$ |
| $d_{ip}$ | distance traveled going from the origin $j$ to the destination $k$ of the CR $p$ passing by the site $i$: $d_{ip} = \Delta_{ij} + \Delta_{ik}$ |
| $y_{ire}$ | indicates if the $e^{th}$ CN-$r$ specimen is enabled in the site $i$ |
| $x_{phl}^{ire}$ | indicates if $l^{th}$ TLP-$h$ specimen of CR$p$ exists and isswitched by the CN$(i,r,e)$ |
| $(p,h,l+L_h)$ | triple identifying uniquely the pTLP of the wTLP $(p,h,l)$ |
| $\delta$ | weigh to give to the propagation delay cost of pTLPs,$0 \leq \delta \leq 1$ |
| $\Omega_w$ | set of all wTLPs, $p \in T$, $h \in H$ and $0 < l \leq L_h$ |
| $\Omega_p$ | set of all pTLPs, $L_h < l \leq 2L_h$ |
| $\Omega$ | set of all TLPs, $0 < l \leq 2L_h$ |
| $\chi$ | set of core nodes of the existing optimized network |
| $Q_j^{ire}$ | pre-used capacity from site $j$ to the existing CN $(i,r,e)$if $(i,r,e) \in \chi$ |
| $Q_{ire}^k$ | pre-used capacity from the existing CN $(i,r,e)$ to site $k$if $(i,r,e) \in \chi$ |

The objective (1) includes the cost of switches and fiber plus two cost terms to account for propagation delay: one for the pTLPs and one for the wTLPs. Note that the two terms are ponderated differently to avoid that the pTLP and its corresponding wTLP contend for the same shortest path. (2) imposes the enabling of the existing core nodes; (3) is the protection constraint; (4) insures that a TLP must be switched only by one CN; (5) enforces EN capacity constraint; (6) and (7) impose the capacity constraints on the idle capacity for the optical links going from every core node and every edge node, and vice versa, subtracting the already occupied transport capacity; (8) defines the binary domain of the variables.

As it was already mentioned, the upgrade cost is obtained subtracting from the final objective value the equivalent cost of the pre-existing network. Also mentioned was the fact that the upgrade aims at a regular topology. Then if the initial topology was quasi-regular and the planner intends the update to keep a quasi-regular structure, the quasi-regular topology can be extracted from the regular one.

To extract the quasi-regular topology one proceeds taking into account every optical link in the optimized regular network, looking for how much of its fibers would be used by the TLPs routed there, and disabling those fibers that would not be used at all. So, a whole optical link may be disabled in the quasi-regular topology, and, also, a whole trunk line may be disabled [4] (e.g. see Figure 3). Moreover, even the ports associated to the disabled fibers are not considered in the quasi-regular architecture. Hence the cost reduction concerns the cost of unused fibers and ports. Note that the TLPs remain associated to the same core node than in the regular topology and that the routes are not affected by the disabling of fibers and ports.

# 5 Upgrade results

The initial network status is defined by the 10-node networks dimensioned in [5]. We consider two scenarios: simple traffic increase and traffic increase with edge node additions. Moreover, we consider two types of traffic matrixes: **A** matrixes contain industrial traffic data, with many zero values; **B** matrixes are dense and are obtained from the well known gravity model, used for example in [14]. An element of a traffic matrix is a CR of an origin-destination pair, which is accommodated in the physical topology using one or more TLPs.

The choice of parameters is: $E_1 = 1$, $E_2 = 1$, $E_3 = 4$, $\gamma = 0.95$, $P/F = 150$, $\beta/F = 0.1$ $[Km\, Gb/s]^{-1}$, $f_1/F = 20$, $f_2/F = 50$, $f_3/F = 100$, $C_j = 2000$ Gb/s, $L_1 = L_2 = 12$, $L_3 = 20$, $\delta = 0.9$. The CPLEX MIPGAP was set to 0.1%. We employed $\phi(W) = W$ considering that the cost of a fiber is proportional to the number of wavelengths. Other functions can also be considered. The simulations ran on a CPU AMD Opteron 64bit 2.4Ghz, 1MB cache, 16GB RAM.

## 5.1 Traffic increase

In this study case the traffic of every existing Connection Request is increased by 200%. The left side of Table 2 reports the upgrade results obtained solving the formulation (1)–(8) for the 10A and the 10B pre-planned network with regular and quasi-regular topologies.

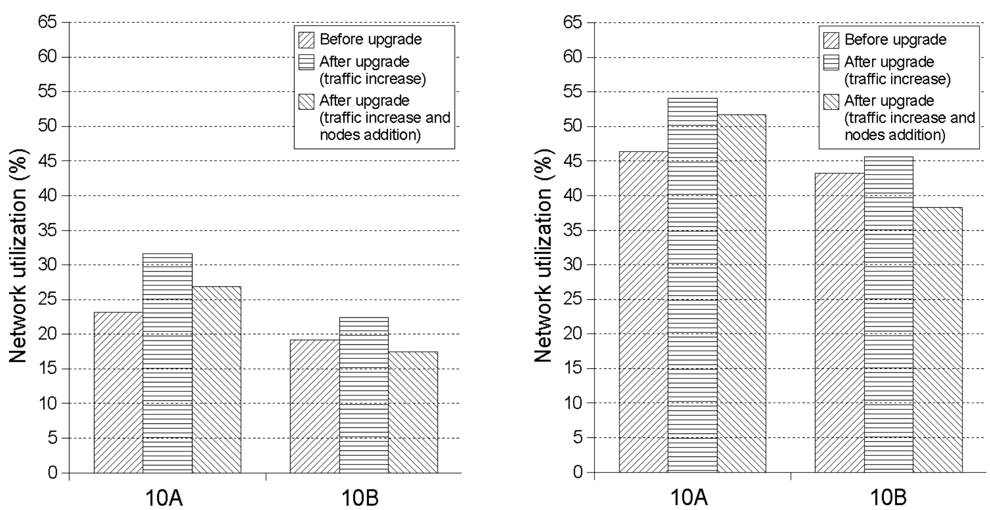
The results show that the network utilization $\mu_R$, defined as the ratio between the used and the available capacities, increases for both topologies as illustrated in Figure 4 (data extracted from [5]). Such an increase is more important for the regular topology. This is due to the equipment already installed that allow the new TLPs to be routed more efficiently than with the quasi-regular topology. This behavior seems to be confirmed by the average path length (weighted on the traffic unit), indicated by $\nu$ in Table 2; it is slightly bigger with quasi-regular topologies. This seems to indicate that, if a network

Table 2: Upgrade solutions

| | traffic increase | | | | traffic increase and nodes addition | | | |
|---|---|---|---|---|---|---|---|---|
| | regular topology | | quasi-reg. top. | | regular topology | | quasi-reg. top. | |
| Model | 10$A$ | 10$B$ | 10$A$ | 10$B$ | 10$A$ | 10$B$ | 10$A$ | 10$B$ |
| cost | 856983 | 975431 | 1304076 | 717565 | 4817336 | 3471536 | 2984283 | 1670231 |
| upgrade cost distribution | | | | | | | | |
| fiber | 35.7% | 74.9% | 52.3% | 69.6% | 73.1% | 32.2% | 60.2% | 75.0% |
| CN | 5.7% | 10.7% | 6.3% | 11.2% | 8.8% | 2.7% | 8.9% | 9.7% |
| delay | 58.6% | 14.4% | 41.4% | 19.2% | 18.1% | 65.1% | 30.9% | 15.3% |
| global cost distribution | | | | | | | | |
| fiber | 70.9% | 80.9% | 60.8% | 71.1% | 75.4% | 82.7% | 62.6% | 73.3% |
| CN | 10.2% | 11.6% | 10.0% | 13.4% | 9.9% | 10.7% | 10.3% | 12.1% |
| delay | 18.9% | 7.4% | 29.2% | 15.5% | 14.7% | 6.5% | 27.0% | 14.6% |
| $\mu_R$ | 31.6% | 22.4% | 54.1% | 45.6% | 26.9% | 17.5% | 51.7% | 38.3% |
| $\nu$ | 2924 | 894 | 2953 | 911 | 1719 | 1151 | 1717 | 1138 |
| time (s) | 1.3 | 23.9 | 1.2 | 36.2 | 1269 | 128 | 1178 | 86 |

operator foresees to make regular upgrades of its network and want to route its TLPs in the most effective way, the cost to pay is the initial regularity.

For example, for the 10A model, the added traffic amount exploits mainly the idle capacity without enabling lots of new switching planes; indeed, the network utilization ($\mu_R$) went from 23.19% and 46.39% (data extracted from the solutions in [5]) to 31.6% and 54.1%, and the weight of the fiber cost felt by 5-7 percentage points (as depicted in




(a) regular topology (b) quasi-regular topology

Figure 4: Network utilization before and after the 10A upgrade.

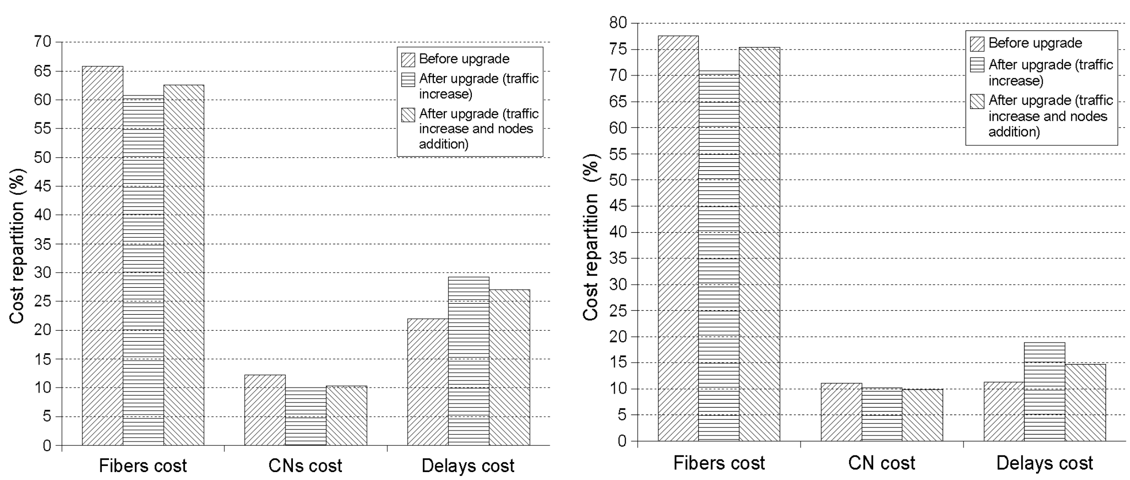
Figure 5). In this case one can notice how the upgrade cost is bigger for a quasi-regular topology than for a regular topology; in the first case one has to install fibers that, instead, with a correspondent regular topology may have already been installed.

In Table 2 the cost distribution concerning only upgrade costs and the one concerning the whole network equipments (those installed before the upgrade together with those installed after) are portrayed. For comparison purposes the global cost distribution before [5] and after the upgrade for the 10A case are illustrated in Figure 5. We can see that the most remarkable effect of the new TLPs and subsequent network upgrade is an increase of the weight of the cost due to propagation delays and, thus, a decrease of the fibers cost and of the core node cost weights.

The upgrade cost fraction due to new fibers and core nodes is minor if compared to the one related to the whole network; on the contrary, the upgrade fraction due to the delay of the new TLPs is significantly bigger than the one related to the whole network. This confirms that the upgrade tends to exploit the existing resources rather than requiring new ones. And the difference is more evident for the upgrade of a quasi-regular topology, because the existing fibers are better exploited, and, even if new fibers are placed, the overall fibers cost weight still decreases.

## 5.2 Traffic increase and edge nodes addition

In this study case we increased by 200% the existing Connection Requests, and we added 4 ENs to the existing ones (the Connection Requests of the added ENs are extracted from the 34A and 34B matrixes used in [5]). The right side of Table 2 displays the upgrade results obtained for 10A and 10B with, respectively, regular and quasi-regular topologies.




(a) regular topology (b) quasi-regular topology

Figure 5: Cost distribution before and after the 10A upgrade

The resulting networks are composed of 14 ENs. As expected, the addition of new ENs causes a large upgrade cost because of the new trunk lines that are needed to connect the new ENs to at least two CNs (because of the DPP constraint). Figure 5 shows how the equipment cost weights are still smaller than the correspondent value for the pre-existing network, but, in the case of the fiber cost, slightly higher than the value for the case with only traffic increase. Figure 4 reflects that under EN addition the overall network utilization may decrease, as it happens for the 10B case; indeed, the new installed trunk lines are under-used with respect to the old ones that were better exploited.

Observing the upgrade cost in the two cases we notice that it is lower for an existing quasi-regular topology. When new edge nodes are added to the network, they can be integrated installing new equipment, mainly new optical links. And with quasi-regular topologies these new optical links are composed only by the essential number of fibers, and nothing more. We can conclude that the upgrade with ENs addition is more convenient if one adopts a quasi-regular topology; the cost gain is significant and the network operator may prefer to start with a quasi-regular topology and to upgrade it only in case of new ENs addition. Until new ENs have to be added, it may be possible to accommodate increases of traffic only exploiting the present idle capacity, without additional physical equipments, i.e. through updates (see Section 3); this update method may be a subject for further work (similar to the method used in [11] for mesh networks).

### 5.3 Comparison with a greedy upgrade

In this section we comment on the results obtained applying an upgrade method based on a straightforward greedy strategy when compared with the results obtained with the method proposed in this paper. The greedy upgrade can be described as follows: when a new TLP is created, it is switched in the closest switching site with core nodes already installed. Then the two trunk lines supposed to route the TLP may be opportunely resized and new core nodes may be installed at that site. Note that the edge node capacity constraint (5) may not be respected for regular topologies. In such a case, the edge node should be replaced.

We analyze the results for the two study cases 5.1 and 5.2. The behavior of the greedy method is the same for an existing regular or quasi-regular architecture. In either case, the resulting network is suboptimal as can be seen in Table 3 where the gaps with respect to the optimal solution given by the upgrade are depicted. It can be seen that the greedy update may yield a solution costing twice as much as a solution produced by the optimized procedure. Interestingly, the worst differences are produced with the 10A matrices.

In the 10B cases the upgrade cost is not too large compared with the previous values; only one new switching plane was required. But, along with the 10A cases, we can see the worst values of fiber cost and network utilization: the route for TLPs was not carefully chosen. In terms of average path length, the greedy method gives better values than the optimal method, this can be seen by the gaps with respect to the optimal solutions

Table 3: Greedy upgrade solutions

| | traffic increase | | | | traffic increase and nodes addition | | | |
|---|---|---|---|---|---|---|---|---|
| | regular topology | | quasi-reg. top. | | regular topology | | quasi-reg. top. | |
| Model | 10$A$ | 10$B$ | 10$A$ | 10$B$ | 10$A$ | 10$B$ | 10$A$ | 10$B$ |
| Cost | 1874996 | 999035 | 1369553 | 1029584 | 6894998 | 3551366 | 3278257 | 1791541 |
| gap | +118% | +2% | +5% | +43% | +43% | +2% | +9% | +7% |
| upgrade cost distribution | | | | | | | | |
| fiber | 69.2% | 75.6% | 43.2% | 66.7% | 76.5% | 83.9% | 60.8% | 69.8% |
| CN | 10.1% | 11.3% | 5.8% | 12.7% | 9.6% | 9.4% | 8.7% | 10.7% |
| delay | 20.7% | 13.1% | 51.0% | 20.6% | 13.9% | 6.7% | 30.5% | 19.5% |
| global cost distribution | | | | | | | | |
| fiber | 75.3% | 81.0% | 63.7% | 69.9% | 77.1% | 83.0% | 62.8% | 70.9% |
| CN | 10.8% | 11.7% | 10.9% | 13.7% | 10.2% | 10.7% | 10.1% | 12.5% |
| delay | 13.8% | 7.3% | 25.4% | 16.5% | 12.7% | 6.3% | 27.1% | 16.6% |
| $\mu_R$ | 24% | 21.5% | 49.1% | 47% | 20.5% | 16.7% | 50.4% | 42.6% |
| $\nu$ | 2375 | 871 | 2375 | 871 | 1798 | 1074 | 1798 | 1074 |
| gap | -23% | -2.6% | -24% | -4.5% | +4.6% | -7% | +4.7% | -5.9% |

that are negative in almost all the instances. Clearly, plugging the new connections to the closer core nodes produces an improvement in overall path length, but this is often a more expensive choice with respect to the cost model. The upgrade cost distribution has a behavior very close to that of the global cost distribution: the greedy method can not profit efficiently of the available resources.

### 5.4 WTA results

The dimensioning phase presented in the previous sections provides the equipment to be installed and the switching node assigned to each TLP. The next phase to complete the design is to apply the WTA algorithm [4] that allocates transport units (time-slots, wavelengths and fibers) to every new TLP. In this section the allocation of resources for the study case in 5.2 are illustrated, considering, for sake of simplicity, only the outgoing fibers of the EN in Tallahassee (the one connected by two trunk lines in Figure 3b).

Let us concentrate on node 9. Before the update, the node had three TLP-1 for $CR_{9,8}$ and one TLP-1 for $CR_{9,10}$ opportunely protected as reported in Figure 6a from [5]. After the upgrade, the volume of the pre-existing CRs of node 9 increased and the additional traffic has to be served by nine more TLP-1, six for $CR_{9,8}$ and three for $CR_{9,10}$. Moreover, a new EN is added in the Chicago site (site 13) and the new $CR_{9,13}$ has to be served by two TLP-1.

Figure 6 illustrates the routing and the assignment of the new TLPs. As it can be noticed, the TLPs of the $CR_{9,8}$ and $CR_{9,10}$, as well as the pTLPs of the $CR_{9,13}$, occupy the free time-slots on the already installed fibers. The wTLPs of $CR_{9,13}$ are switched in a CN in site 4 and transported on the first two time-slots of the first wavelength on the

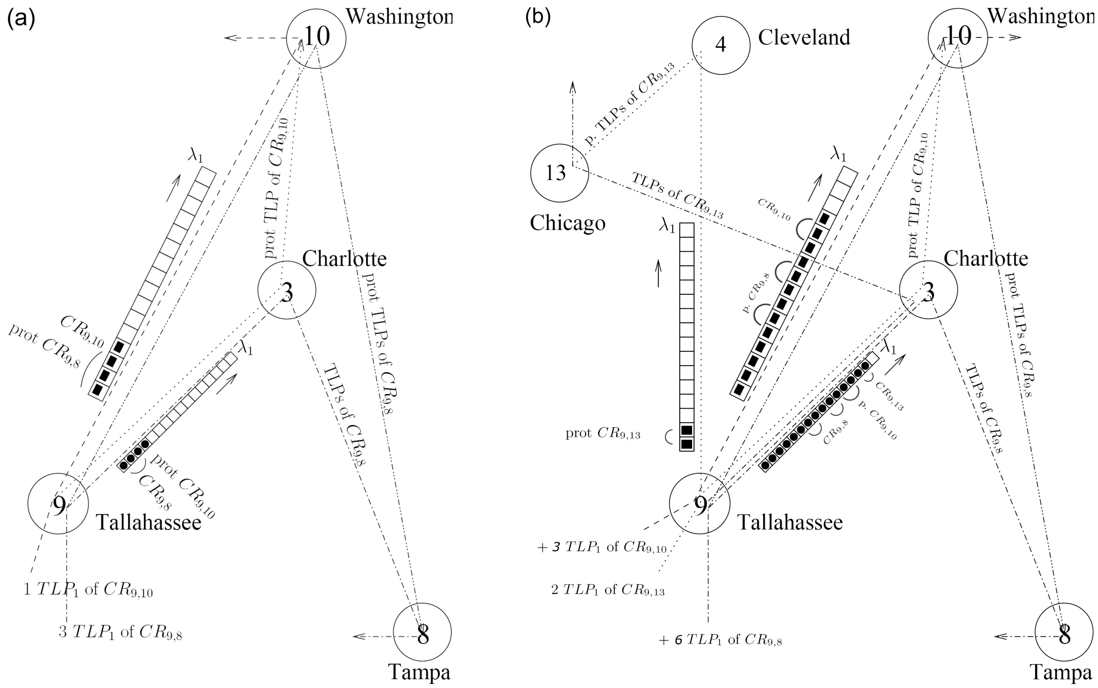



Figure 6: WTA results before (a) and after (b) the upgrade. 5.2 case (10A)

only fiber connecting the EN-9 to the switching site 4. Consequently, the utilization of the pre-existing fibers increases, while the utilization of the new fiber between 9 and 4 remains reasonably low.

## 6 Conclusions

In this paper, a formulation and a resolution approach for the Petaweb upgrade problem were presented for the first time. The analysis shows the scalability qualities of the Petaweb architecture. On the basis of the shown results, it can be concluded that a regular topology is advisable if the network operator has a good initial budget and if frequent upgrades are foreseen; a quasi-regular topology is the best choice in case of low budget and rare upgrades, especially when the upgrade contemplates edge nodes addition.

The proposed method underlined the importance of conducting a cost-effective upgrade when compared with the common practical paradigm “plug where it is closer”, often used in the industry. Such greedy upgrade provisioning method applied to the Petaweb architecture can bring a lower network utilization at significantly higher cost.

Further work is needed on the advantages and drawbacks of a Petaweb backbone architecture. We are currently working on the comparison between Petaweb and mesh backbones in terms of cost and quality of service factors.

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