Optimization of a Dedicated Path Protected TDM/WDM PetaWeb Architecture

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Abstract

This paper deals with the insertion of a dedicated path protection strategy in the design of a novel optical network structure, called PetaWeb, that can reach a total capacity of several Pb/s (10^{15} bit/s). Prior studies of the same authors have tackled the optimization of a PetaWeb network architecture with a regular composite-star topology and with a quasi-regular topology. In this paper, a protection strategy is added to the network model modifying the optimization algorithm. The results show that the optimized PetaWeb architecture is reliable and that every edge node is connected to at least two switching sites. We highlight the strength of the proposed network model for this composite-star architecture: a fast-switching backbone that eases signaling and switching operations at a competitive network cost. The network cost is evaluated on real physical costs and on a virtual cost due to lightpaths propagation delays.

1 Introduction

Given the high transport rate of modern telecommunication networks, a failure in optical networks can affect, above all, switching equipment and optical links. In optical networks, failures are very frequent in cable links because they are often placed near other transport utilities, as electricity or gas pipes. A failure on the transport media may cause a significant loss for the network operator. In the PetaWeb network architecture (see [5]), a prototype of wide high-capacity network structure capable of operating at a rate of the order of the petabits per second, a failure on a trunk line may cause the total isolation of an edge node if all the enabled core nodes are placed in the same site [1].

The first emulation of a PetaWeb composite-star topology has been conducted by Blouin et al. [6]. Other studies have compared the PetaWeb to typical optical mesh networks [7]; they concluded that, even if PetaWeb implementation demands for a more important quantity of optical fibers (roughly 17% more than in a multi-hop network), the simplifications in the engineering traffic procedures, and the simple linear extensibility, are very significant. After all, the authors observe that the decreasing cost of optical fibers encourages the installation of this type of network. Moreover, the adoption of a quasi-regular topology [1] demonstrated that the fibers cost can be kept between the 60% and the 73% of the total network cost.

In this paper we tackle the optimization of a PetaWeb network architecture with a Dedicated Path Protection (DPP) strategy; by doing so we want to avoid the design of PetaWeb physical topologies where restoration functions cannot allocate dynamically the protection paths because of the possible isolation of edge nodes. We briefly recall the PetaWeb architecture in Section 2. Section 3 contains a review on the network model and on the optimization procedure proposed in [1]. An ILP formulation for the resource allocation problem under dedicated path protection is presented in Section 4; Section 5 is devoted to the presentation and discussion of the results. Section 6 contains conclusions and suggestions for further work.

2 The PetaWeb architecture

The PetaWeb composite-star architecture has been presented in [5] and proposed as an optical core based network for next generation Internet infrastructures. This network architecture is composed of edge nodes connected through core nodes as showed in Figure 1. Every edge node is connected to every core node and the edge nodes are not connected directly to each other. Furthermore, core nodes are not at all connected to each other. This kind of configuration allows a one-hop optical path between two edge nodes through a core node.

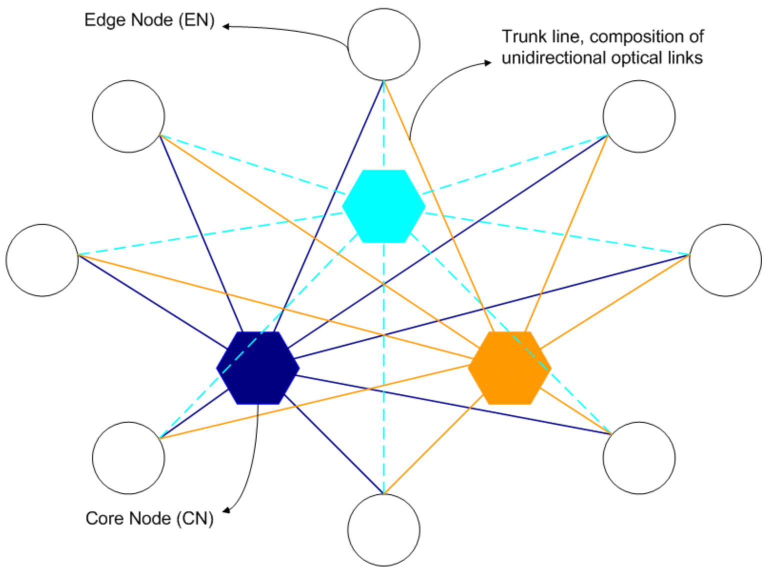


Figure 1: Composite-star PetaWeb structure.

An *edge node* (EN) is an electronic node that asks the transport network to supply media for its set of source-destination static connection requests with other edge nodes. 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 by one or more optical fibers. We suppose the use of unidirectional optical fibers, so that an

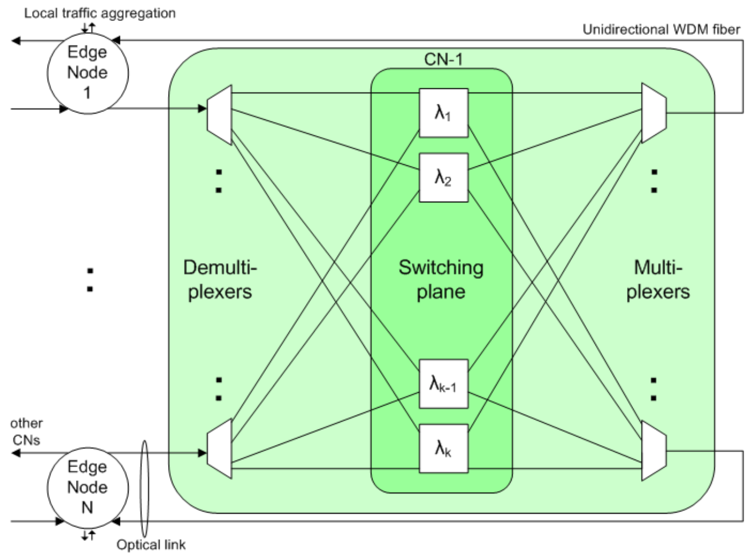


Figure 2: Parallel-planes optical core node in the PetaWeb.

edge node has one optical link incoming and one outgoing for every core node. We suppose that all the fibers of the network carry the same number of wavelenghts.

A *core node* (CN) is a set of arrays of parallel space switches, also called switching planes. We use three types of core nodes. The number of switching planes s_r identifies the type r of a CN (indicated with CN-r). It means that the optical link connecting an EN to a CN-r has s_r unidirectional optical fibers, one for every switching plane. In this paper, we will consider $s_1 = 1$, $s_2 = 2$ 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. These core switches do not require any wavelength converter, and no wavelength continuity constraint needs to be applied. Which renders the Petaweb an all-optical network. 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 CNs because a hypothetical failure in a switching plane would affect only the connections on that plane. In [7] Blouin supposed the use of TDM in the PetaWeb to realize sub-channels within a lambda-channel. To use the Time Division Multiplexing we need to extend the functionalities of switching cores nodes; we proposed in [1] the replacement of the described switching plane with the compatible all-optical TDM Wavelength Space Routers of Huang [9] which multiplexes in a time-slot basis remaining in the optical domain and, thus, without any buffering operation. In what follows, as suggested in [9], we call a time-slotted lightpath, a *ts-lightpath* (TLP).

The edge nodes locations define the set of network sites. A network site becomes a *switching site* if a CN is there installed. Many CNs can be installed in the same site. The physical connection between the site of an EN and a switching site can be composed by many optical links because more CNs can be installed in a network site. From now on we call this physical connection *optical trunk line.*

3 Network model

In [1] an optimization model was proposed to design the PetaWeb taking into account the TDM features of the proposed technology. In what follows, we first provide an overall view of the model presented in [1] before presenting the Dedicated Path Protection formulation.

A set of permanent connection requests with static traffic is served upon the PetaWeb physical topology through a set of ts-lightpaths (TLPs). We have three classes of TLPs: the first (TLP-1) uses the transport capacity of a time-slot, the second (TLP-2) the capacity of a whole wavelength while the third class (TLP-3) uses a whole optical fiber. Let us indicate Z_h the transport capacity of a ts-lightpath of class h, with C_{ch} being the capacity of a lambda-channel set to 10 Gbps and $W = 16$ being the number of wavelength per fiber. Then, we have $Z_2 = 10$ Gb/s, $Z_3 = 160$ Gb/s and $Z_1 = 0.625$ Gb/s [1]; using these bit-rate classes we obtain a correspondence with the bit-rates of SDH and OTN interfaces [4] as shown in Table 1. For example, a PetaWeb backbone may receive traffic from a concentration level based mainly on SDH rings; a TLP-1 may serve the traffic from and to an ADM of a STM-64 ring, or the aggregated traffic from and to ADMs of four STM-16 rings; similarly, TLP-2 and TLP-3 may accommodate higher bit-rate or may be rented to other operators.

Table 1: Mapping of SDH and OTN interfaces on TLP bit-rate classes.

CLASSES	BIT-RATE	SDH	OTN
TLP-1	$\frac{C_{ch}}{16} = 0.625Gb/s$	STM-4	OTU-1: 4 TLP-1s
TLP-2	$C_{ch} = 10Gb/s$	STM-64	OTU-2: 4 TLP-2s
TLP-3	$WC_{ch} = 160Gb/s$	STM-1024	4 OTU-3

The network design consists in the minimization of the total network cost that is composed of the core node cost, the fiber cost and the propagation delay cost. The *CN cost* is composed of a fixed cost f_r, depending on the type r of the CN and such that $f_r > f_{r-1} > ... > f_1$. Furthermore, 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 N_{en} the number of ENs and by γ the scale factor for P, the global cost of a CN-r is $K_r = f_r + 2N_{en}W s_r P\gamma^{(s_r-1)}$, such that $K_r < 2K_{r-1}$.

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

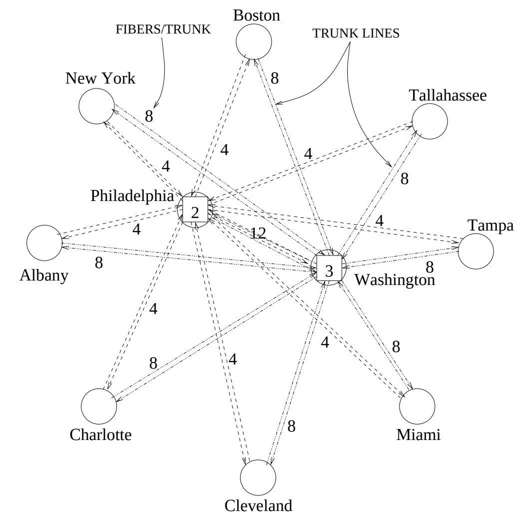
Every lightpath is transported through only two optical links; the *propagation delay cost*, indicated by β, is proportional to the distance traveled and to the lightpath bitrate. The reason for bitrate dependence is that we can assure a higher QoS to high bitrate lightpaths which may trasport traffic aggregate of added-value services requiring low propagation delay [1]. As of our knowledge, such kind of cost has never been considered in the dimensioning of optical networks; since an upcoming requirement for operators is the guarantee of end-to-end connections with low propagation delay in an always more congested Internet, we introduced this virtual cost because the propagation delay will become one of the most important pay-back factors in offering end-to-end circuits.

The PetaWeb design has to preserve the characteristics of network components and to simplify routing operations. Capacity constraints concern edge nodes and optical links; the capacities can be allocated and incremented 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 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.

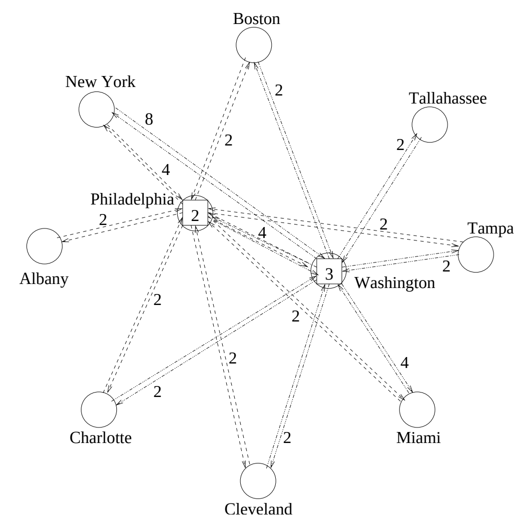
The optimization problem consists in finding the best composite-star physical topology for the given set of TLPs and to assign to the TLPs their communications medium (wavelengths and time-slots). Differently than the typical design problems for mesh networks, in the PetaWeb design problem the physical topology is not pre-assigned. The set of possible routes is not established a priori. The optimization consists even in dimensioning the physical topology, choosing the core nodes location and their size and thus allocating the resources for routes and fibers to transport the requested traffic volume. The design problem is divided in 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.

4 Dedicated Path Protection

Figure 3 reports optimized PetaWeb topologies obtained by using the optimization procedure proposed in [1]. The regular topology has all the optical links enabled, and the optical links connected to a CN-r are composed of s_r fibers. The quasi-regular topology, proposed in [1], contemplates the deactivation of those fibers that are unused in the optimized regular topology; in this way the network cost reduces more than the 55% and the network utilization more than duplicates. The quasi-regular topology is thus determined heuristically as reduction of an optimal regular PetaWeb topology, removing unused fibers and ports without any change in the lightpath routes and switching schemes. The drawback is that such a topology is not reliable. Why? The reader is



(a) Regular topology (10A)



(b) Quasi-regular topology (10A)

Figure 3: Optimized physical topologies without path protection

referred to the Tallahassee and Albany edge nodes in Figure 3b. They are connected to the transport network through only one trunk line. In case of failure of one of these trunk lines and if the network operator wants to adopt a restoration strategy, those edge nodes would remain totally isolated from the network and their outgoing and incoming traffic could not be restored at all. Moreover, consider even the case that all the core nodes are located in the same switching site (reasonably possible for little networks): all the edge nodes would be connected to the transport network through only one trunk line. It is thus necessary to introduce a protection strategy, which for every working lightpath furnishes a link-disjoint protection lightpath.

We want to design a reliable PetaWeb transport network offering restoration functions for its lightpaths directly in the physical layer. Restoration techniques already exist in the electronic layers (IP, TCP, ATM, SDH), but, even if effective, they require signaling procedures that slow down the restoration [10]. We need to limit the restoration time because the PetaWeb trunk lines may transport optical flows at a Tbit/s rate, belonging to various CRs.

Looking for a protection strategy to apply to our network model, we excluded link protection techniques because with the PetaWeb architecture the installation of backup trunk lines would require a replica of all the CNs in other switching sites with an enormous cost. For classical mesh architectures, in [11] the authors analyzed the availability of many protection schemes evaluating their availability degree. In [12] and [13] the authors worked on the optimization of WDM networks using the reliability as objective function. In [14] a dedicated path protection scheme is added to the RFWA problem for a multi-fiber WDM network with static traffic.

We want to choose a path protection strategy for our network model that does not alter its qualities in terms of simplicity and switching schemes and that protects the network in case of one trunk line failure. The protection functions are performed at the ENs and we want to avoid any signaling operations involving the CNs. Because of the high working rate of transmission and switching equipment, any ms of restoration elapsed time may imply Tbits of data loss. In the event of trunk line failure, a long signaling phase so as to establish protection paths for all the affected TLPs would be required; and it would involve not only the CNs and the EN connected by the faulty line, but even CNs of other switching sites candidate for the TLPs routing. Moreover, the EN affected by the failure should have knowledge of the actual lightpath topology and routing schemes in order to provide for physical reconfigurations of CNs and to compute in some way optimal protection path. Thus, this signaling phase would be reasonably long, and also hazardous because the CN reconfiguration may not be successful. For these reasons we chose a Dedicated Path Protection (DPP) strategy, in the modality 1+1: the protected signal is sent over two separate allocated paths, then the receiver selects one among them. Any signaling operation is required; if a failure falls on a trunk line, the destination EN notices it and starts considering the signal on the protected path. A shared path protection would for sure guarantee a less expensive network requiring fewer resources, but the signaling would be important and would involve CNs and ENs introducing a significant restoration delay.

For every working ts-lightpath (wTLP) of our network model we have to allocate a protection ts-lightpath (pTLP). In case of one trunk line failure all the wTLPs must be recovered from the allocated pTLPs. The DPP strategy requires the use of a *protection constraint*: every pTLP must be multiplexed on trunk lines different than 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.

The formulation we introduce is easily adaptable to a DPP 1:1 strategy (the protection signal is sent on the protection path only when the failure occurs), subtracting from the final result the propagation delay cost due to the protection TLPs.

4.1 RFA resolution

In mathematical terms, the RFA can be seen as a particular Location Problem since it has many similarities with the Plant Location Problem [2]: a set of clients is given and every client has a specific demand for a product; the goal is to optimally locate the plants, which send products to the clients, thus minimizing the global cost expressed by the fixed cost of plants and by the transport cost; the potential sites for plants are known and the demand of a client is satisfied by one plant. In the PetaWeb, core nodes are similar to plants and edge nodes are similar to customers. The propagation delay cost is a transport cost. Nevertheless, while in the PLP the product is transported from a plant to a client, in the RFA the product use the plant as transit; moreover, because of the capacity constraints on optical links, ENs and CNs, it also presents some similarities to the Capacitated Facility Location Problem [3].

Let us introduce the not already explicated notations in Table 2. We add further notations to those used in [1] to insert the concept of protection TLP. Through the use of the parameter δ we want to scale the propagation delay cost of pTLPs in order to assign the best paths to the wTLPs; choosing a value $\delta < 1$ the optimization procedure is forced to route on the optimal path a wTLP and on a longer path its pTLP. As δ tends to 0, the pTLP will be routed on longer routes.

The optimization consists in the minimization of the following objective function:

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

$$s.t \quad \sum_{r \in V} \sum_{e=1}^{E_r} x_{phl}^{ire} + \sum_{r \in V} \sum_{e=1}^{E_r} x_{phl_p}^{ire} \leq 1 \tag{2}$$

$\forall i \in M$, $\forall (p,h,l) \in \Omega_w, l_p = l + L_h$

$$\sum_{(i,r,e)} x_{phl}^{ire} = 1 \qquad \forall (p,h,l) \in \Omega \tag{3}$$

$$\sum_{(i,r,e)} C_{ch}\, W\, s_r\, y_{ire} \leq C_j \qquad \forall j \in M \tag{4}$$

Table 2: Notations

M	set of sites
T	set of pairs of sites ($M \times M$), $p \in T$ represents a CR
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 is switched by the CN (i,r,e)
$(p,h,l+L_h)$	triple identifying uniquely the pTLP of the wTLP (p,h,l)
δ	weigh to give to the propagation delay cost of pTLPs, $0 \leq \delta \leq 1$
Ω_w	set of all wTLPs, $p \in T$, $h \in H$ and $0 < l \leq L_h$
Ω_p	set of all pTLPs, $L_h < l \leq 2L_h$
Ω	set of all TLPs, $0 < l \leq 2L_h$

$$\sum_{(p \in O_j, h, l) \in \Omega} Z_h\, x_{phl}^{ire} \leq C_{ch}\, W\, s_r\, y_{ire} \qquad \forall j \in M, \forall (i,r,e) \tag{5}$$

$$\sum_{(p \in D_k, h, l) \in \Omega} Z_h\, x_{phl}^{ire} \leq C_{ch}\, W\, s_r\, y_{ire} \qquad \forall k \in M, \forall (i,r,e) \tag{6}$$

$$x_{phl}^{ire} \in \{0,1\} \tag{7}$$

$$y_{ire} \in \{0,1\} \tag{8}$$

In the objective function (1) the second and the third term are the cost of the propagation delays for, respectively, the wTLPs and the pTLPs.
(2) imposes the DPP constraint: a pTLP can not be routed on the

trunk lines where the corresponded wTLP is routed, i.e. the pTLP must be switched in a different site than its wTLP. Given a switching site and a wTLP, the sum of the CNs enabled switching that wTLP in that site, and of the CNs enabled switching the correspondent pTLP in the same site, must be minor or equal to 1;
(3) imposes that the traffic transported through a TLP, from an origin EN to a destination EN, must be entirely switched in the same CN and, thus, transported in the same optical links;
(4) imposes the respect of the capacity constraint for every EN;
(5), (6) impose the respect of the capacity constraint for the optical links between every origin EN and every CN, and between every destination EN and every CN;
(7) and (8) impose the binarity of the variables.

4.2 WTA resolution

The WTA algorithm, as described in [1], is transparent to the adoption of a DPP protection strategy; in the assignment a pTLP is considered as a wTLP because correct routes have already been assigned by the RFA resolution. Indeed, working and protection ts-lightpaths have been already assigned to disjoint optical links by the RFA optimization. The WTA resolution algorithm must now assign to the TLPs wavelengths and the time-slots, and the complexity of this resources assignment phase is negligible. For completeness we report the WTA algorithm flow diagram in Figure 4.

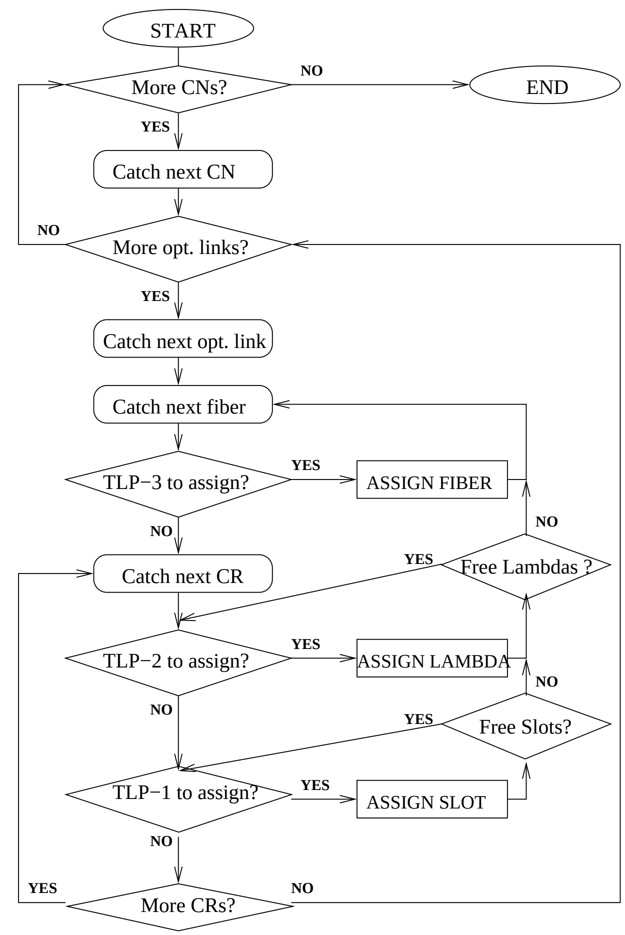


Figure 4: Flow chart for WTA resolution algorithm [1]

5 Results

In this section we show the results obtained implementing the resolution algorithms for the PetaWeb design problem. The algorithms have been implemented in C++, and we used the callable library of CPLEX 9.0.1 to solve the ILP formulation of the RFA problem. The simulations run on a CPU AMD Opteron 64bit 2.4Ghz, 1MB cache, 16GB RAM.

We will consider topologies with 10 and 34 edge nodes and with two types of traffic matrixes: **A** matrixes contain industrial traffic data, with many zero values; **B** matrixes are dense and are obtained from a gravity model estimating the traffic between two cities as being directly proportional to the product of the populations and inversely proportional to the square of the distance between the sites. An element of a traffic matrix is a connection request of an origin-destination pair, which is accommodated in the physical topology using one or more TLPs.

Underlining that the final network cost is normalized to F, the parameters values (some furnished by an industrial partner) not yet explicited are: $E_1 = 1$, $E_2 = 1$, $E_3 = 4$, $\gamma = 0.95$, $P/F = 150$, $\beta/F = 0.1$ $[Km\,Gb/s]^{-1}$, $f_1/F = 20$, $f_2/F = 50$, $f_3/F = 100$, for 10A and 10B $C_j = 2000$ Gb/s, for 34A $C_j = 4200$ Gb/s, for 34B $C_j = 4800$ Gb/s, $L_1 = L_2 = 12$, $L_3 = 20$, $\delta = 0.9$. We employed $\phi(W) = W$ considering, thus, that the cost of a fiber is proportional to the number of wavelengths.

Because of the larger amount of traffic requested by the working and the protection ligthpaths, we increased E_3 and the ENs capacity constraints C_j with respect to the old values in [1].

5.1 RFA results

In Table 3 and Table 4 one can find the results, obtained solving the resource allocation problem through (1)-(8), for the 10A, 10B, 34A and 34B models, with, respectively, the regular and the quasi-regular topology. The objectives are normalized to F. With μ_R we indicate the network utilization, that is the ratio between the transport capacity allocated for the TLPs and the global allocated capacity. Figures 5 and 6 illustrates the optimized regular and quasi-regular topologies for the 10-node architectures. Figure 7 displays the CNs geographical distribution for the optimized 34-node networks.

Observing these results and comparing them to those in [1] one can notice that: the CNs number is approximately doubled and the CNs disposition is very similar to that of the case without DPP (the CNs of the case without DPP have been re-enabled in a dual site to switch the pTLPs/wTLPs of their TLPs); the network cost has not doubled, because doubling the traffic volume does not mean doubling the switching capacity; the network utilization has increased, the links are thus better exploited than before. Furthermore, we can see that there is a better distribution of the costs; only the delays cost weigh has decreased a little because the cost due to delays of pTLP is scaled by δ, while the one due to wTLP is not.

Table 3: RFA DPP solution

Model	10A	10B	34A	34B
Objective	4260644	4340130	61419238	77837599
Execution time	2768s	2330s	59.59h	62.1h
Fibers cost	77.58%	82.25%	82.28%	80.95%
CNs cost	11.11%	11.80%	5.35%	5.24%
Delays cost	11.31%	5.95%	12.37%	13.81%
μ_R	23.19%	19.19%	17.38%	13.67%

Table 4: RFA DPP solution changes using a quasi-regular topology

Model	10A	10B	34A	34B
Cost	2196002	1829473	27086832	36407731
Fibers cost	65.85%	71.68%	67.13%	66.33%
CNs cost	12.21%	14.28%	4.82%	4.15%
Delays cost	21.95%	14.04%	28.05%	29.52%
μ_R	46.39%	43.18%	46.94%	39.35%

Nevertheless, the execution time has increased, but it is still reasonable. Adding the protection constraint to the heuristic tool described in [8], opportunely modified to adapt it to our network model, we could set up good cut-off values for CPLEX.

Looking at Figure 5 one can notice that, differently than in Figure 3, the optimized network with the quasi-regular topology is now reliable: every EN is connected to at least two switching sites; every wTLP has its trunk-disjoint pTLP where the signal is split. In case of failure of one of the two trunk lines where a wTLP passes, the destination EN can recover the traffic of the wTLP from the pTLP. The case that all the core nodes are installed in the same site is now impossible because the constraint (2) imposes that every pair working-protection lightpath must be trunk-disjoint.

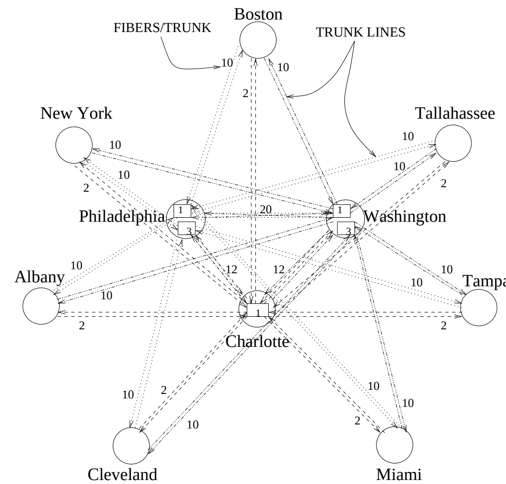
Once again the EN in New York keeps enabled and fully uses the CNs because it has high traffic CRs. The quasi-regular topology of 10A presents the trunk lines Charlotte-Boston, Charlotte-Albany and Philadelphia-Tallahassee disabled, but in this case the network remains survivable. And the quasi-regular topology for 10B is, equally than in the case without DPP, fully meshed with a big number of disabled fibers.

5.2 WTA results

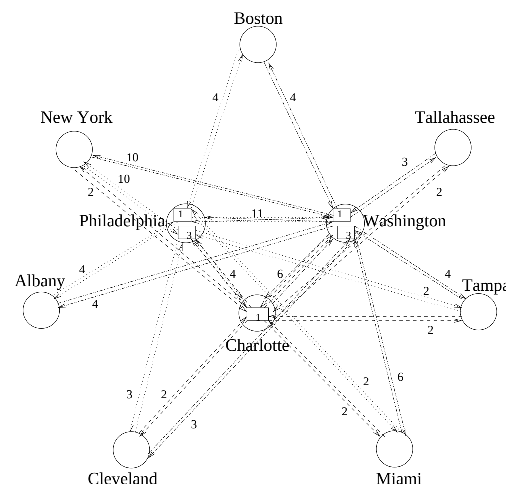
In this section we report the wavelength and time-slot assignment in a case study in order to verify how the pTLPs have been assigned. We analyze, for simplicity, only the optical links exiting the EN in Tallahassee for the 10A quasi-regular solution. As it can be noticed in Figure 5, using the quasi-regular topology the trunk line Tallahassee-Washington went from 5 fibers per direction to 1 fiber from Tallahassee to the CN-1 in Washington and 2 fibers from Washington to Tallahassee. Thus the 4-fibers optical link between the EN in Tallahassee and the CN-3 in Washington has been disabled in the quasi-regular topology. Then, Tallahassee is connected to the CN-1 in Charlotte through one fiber per direction.

The EN in Tallahassee has only two outgoing CRs, one of 1.64 Gb/s with Tampa ($CR_{9,8}$), and one of 0.2 Gb/s with Washington ($CR_{9,10}$): the first is accommodated using three TLP-1s and the correspondent pTLPs; the second is served by one TLP-1 and its pTLP. The RFA results indicates that on the fiber going from Tallahassee to Washington one must transport the wTLP of $CR_{9,10}$ and the pTLPs of $CR_{9,8}$, and that on the fiber going from Tallahassee to Charlotte one must transport the wTLPs of $CR_{9,8}$ and the pTLP of $CR_{9,10}$. What are the optimal paths for these wTLPs and their correspondent pTLPs? Figure 8 shows the assignment and the routing of the TLPs (only on the outgoing fibers of Tallahassee). And what is the effect of choosing $\delta < 1$? The path chosen for the 9-8 wTLPs is the shortest one, a total of 858+1132 = 1999 Km, while the path for the pTLPs is 1574+1799 = 3663 Km.

On both the fibers quitting the edge node in Tallahassee we have yet 15 wavelengths and 12 time-slots available. This is possible because the EN in Tallahassee requests resources for only two CRs with low traffic demand.

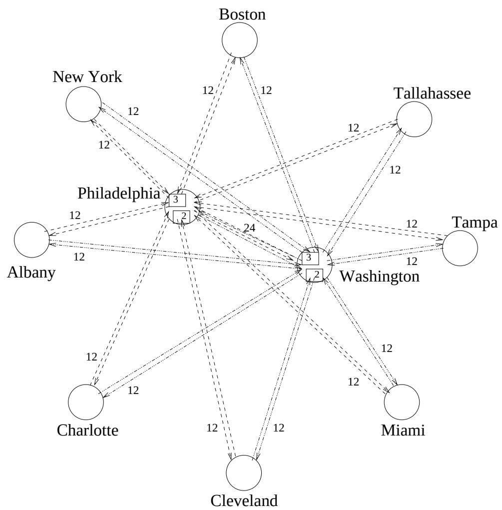


(a) 10A regular

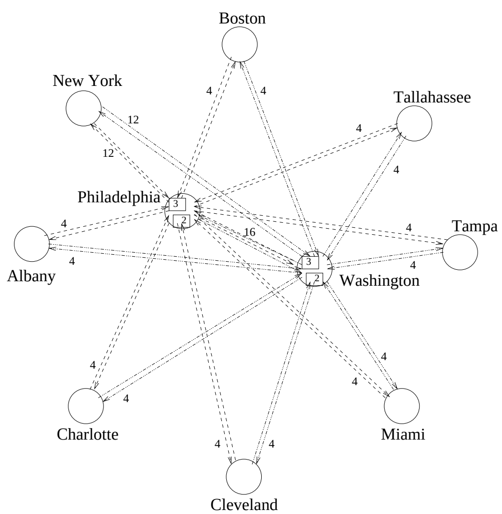


(b) 10A quasi-regular

Figure 5: RFA solution for 10A model with dedicated path protection

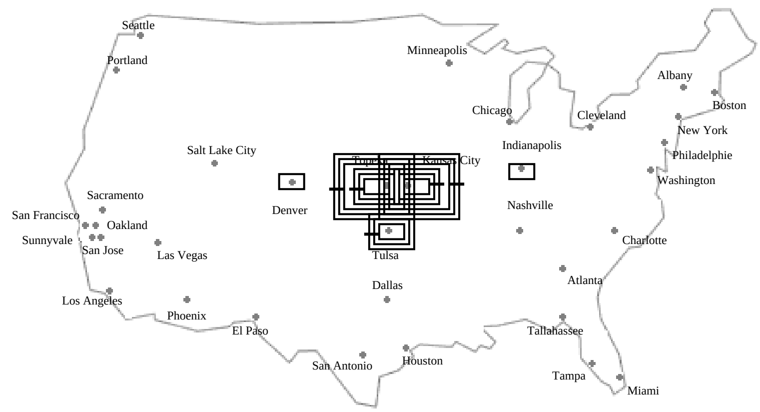


(a) 10B regular

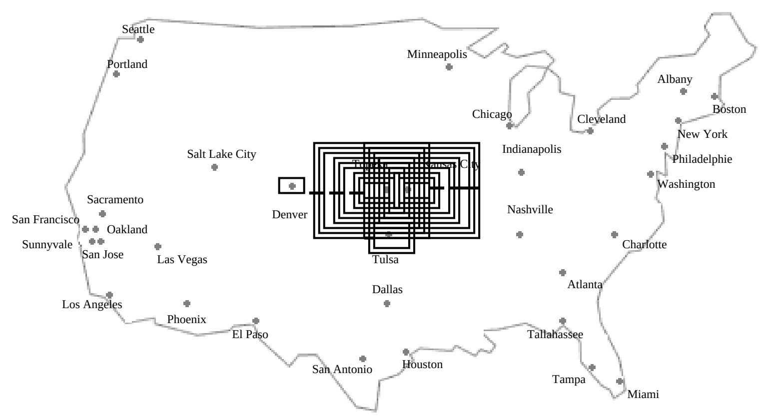


(b) 10B quasi-regular

Figure 6: RFA solution for 10B model with dedicated path protection



(a) 34A



(b) 34B

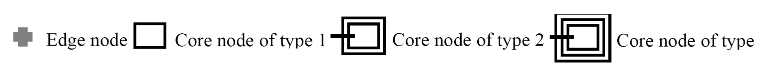


Figure 7: Core nodes geographical distribution for 34-nodes networks

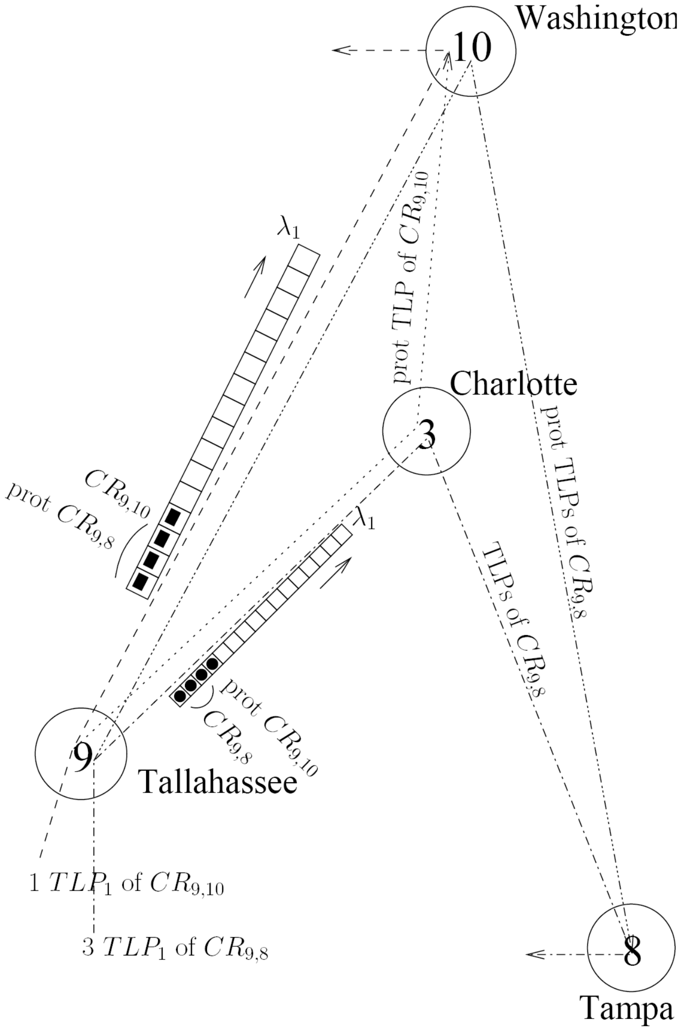


Figure 8: Routing and assignment in a study case of 10A solution

6 Conclusions

In this paper we have introduced a model and a methodology to design a robust Petaweb architecture based on the Dedicated Path Protection method. The results show how a reliable Petaweb network architecture can be optimized. The network has still a large amount of idle transport capacity that can be used for further upgrades, dynamic bandwidth provisioning and on-demand services. The DPP strategy is easily modifiable and a further possible work may consider a connection request as an aggregate of traffic divided in different classes: to some lightpaths one could give no protection, to others one-link failure protection and to the most important class a multiple-link failure protection, and so on.

We are currently working on an upgrade procedure for a Petaweb network with regular or quasi-regular topology. Moreover, we are studying how to plan a quasi-regular physical topology directly and not heuristically (extracted from an optimal regular topology); an optimally designed quasi-regular Petaweb infrastructure would be surely more convenient and may directly compete with mesh architectures.

In our works about Petaweb design we introduced in the cost model a concept quite new and disregarded in optical networks design: the propagation delay cost. Usually the objective is the minimization of real physical costs or the minimization of the number of hops; the first objective is realistic if the lightpath length is carefree, the second does not imply a short path. Actually, Telco operators are looking towards fast-switching broadband networks besides minimum cost networks: virtual private networks for banks, circuits for worldwide short-delay transactions, aggregated broadband circuit dedicated to added-value services need short delays both for basic requirement and for customers satisfaction. And the operators are asked to decide big amounts of infrastructure investments. Because of these new customer requirements the research in optimal network design is going in the direction of planning fast-switching architectures. We invite thus the research community to receive these new requirements and to conceive novel optical transport networks infrastructures for their satisfaction.

In our network model we integrated real physical costs with a virtual cost due to propagation delays; the strength of the Petaweb architecture and of our network model is the capability of thinking a new backbone infrastructure that eases signaling and switching operations and that offers fast routing, at a quite expensive physical layer cost that is, however, drastically reduced with a quasi-regular topology.

Acknowledgments

The authors would like to express their gratitude to A. Pattavina for having allowed the collaboration that produced this work, to M. Beshai and F. Blouin of Nortel Networks for proposing the initial design problem. This work was supported by NSERC strategic grant nb. STPG 246/59.

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