Comparison of Quasi-Regular Composite-Star and Multi-Hop Structures for Core Networks

Stefano Secci[1,2], Jean-Louis Rougier[1], Achille Pattavina[2]
[1]TELECOM ParisTech (ENST), 37/39, rue Dareau, 75014 Paris, France
[2]Politecnico di Milano, P.za Leonardo da Vinci, 32, 20133 Milano, Italy
E-mails: secci@telecom-paristech.fr, rougier@telecom-paristech.fr, pattavina@elet.polimi.it

***Abstract*— A novel composite-star architecture, nicknamed the Petaweb, has been recently proposed for high capacity optical core networks. Its topologic structure is such that electronic edge nodes are always connected to each other through a single core switch, and that the core switches are disconnected. The aim is to simplify the traffic engineering and the upgradeability of core networks. In its regular form, this architecture suffers from high fiber cost and low utilization. A recent work tackles the problem of directly designing a quasi-regular composite-star structure, showing that the network cost can get more than halved and that the resources utilization can be significantly improved. In this paper, we compare the quasi-regular composite-star structure to classical irregular multi-hop structures. We show that increasing the weight of a propagation delay virtual cost in the design dimensioning objective function, multi-hop core networks tend to assume a quasi-regular composite-star like topologic structure, with a few core fibers. This suggests that such an architecture is the natural solution whether length-dependent additive costs are considered as part of the design dimensioning objective [1] .**

I. Introduction

Recent works on optical transport networks architectures have investigated a novel high capacity physical architecture with a composite-star topology structure. Such an architecture was originally proposed in [1] and nicknamed "the Petaweb" since it might serve a global traffic volume in the order of the petabit per second (10^{15} bit/s). Its structure provides fully meshed connectivity with direct optical paths between electronic edge nodes (e.g. IP routers, ATM switches, Ethernet bearers). It is composed of several OXCs (Optical Cross-Connectors), also called core nodes, that commute the traffic exchanged by the edge nodes without wavelength conversion. A particular feature is that each core node is connected to all edge nodes. Another peculiar feature is that the core nodes are not connected among themselves, making it a complete architectural breakthrough. This architecture might require a higher fiber distance value; however, the cost savings in operational engineering can be significant.

The design dimensioning problem of the Petaweb architecture has been tackled for the first time in [2]. The authors demonstrated that it is NP-hard, by reduction to a facility location problem, and proposed optimal and suboptimal resolution methods. The physical performance of this architecture has been analyzed in [3]; the authors underlined that a very low resource utilization may characterize this architecture in the case of traffic matrices with a few peaks and a lot of low-rate connections. They showed that by removing unused equipments (fibers, ports) from the optimal regular architecture, the utilization can pass from 20% to 50%, roughly. As a consequence, the network cost gets almost halved. The resulting "quasi-regular composite-star" structure can still guarantee to reach a regular structure by simple addition of elements, at the expense of some wavelength conversions at the core nodes. However, the quasi-regular composite-star architecture appeared to be not reliable for small networks because some edge nodes may become isolated. To overcome these aspects possible protection strategies were analyzed in [4], concluding that for such a two-hop structure the best strategy seems to be the dedication path protection. In a further work in [5] the authors compare regular and quasi-regular structures in terms of upgradability, concluding experimentally that the quasi-regular one is to be preferred especially whether upgrades require nodes addition (otherwise the idle capacity can be exploited for fast provisioning). Motivated by these results, in [6] the authors propose a method to directly optimize a quasi-regular composite-star architecture, instead of determining it by downgrading an optimal regular one. The results show that the network utilization can reach 70% and the network cost can be further reduced by 30%.

In Fig.1 different Petaweb topological structures are illustrated for 10-node networks. The same traffic matrix and edge node topology of [2] and [6] were used (10A type). Fig.1a illustrates the optimal regular Petaweb, where the number of fibers per trunk is indicated over each link, and a square is a core node (and the number inside a square indicates the core node size). Fig.1b illustrates the corresponding quasi-regular structure obtained by removal of fibers and ports from the optimal regular one. It appears clearly that edge nodes can become isolated when they are connected through a single trunk line to the backbone, as it happens for the edge node in Tallahassee. Fig.1c illustrates the network in the case of dedicated path protection: edge nodes dispose now of a larger path diversity. Fig.1d illustrates the network obtained by directly optimizing the quasi-regular structure as explained in [6]. It can be noticed that we get a fairer geographical distribution of core nodes and hence a larger path diversity.

Despite all this work, an extensive comparison between the quasi-regular Petaweb and classical multi-hop irregular mesh architectures has not been performed, yet. Previous studies of Blouin et al. [7] compared the regular Petaweb with multi-hop architectures, in the case of changing demands. They concluded that roughly 17% more fiber-km is needed for

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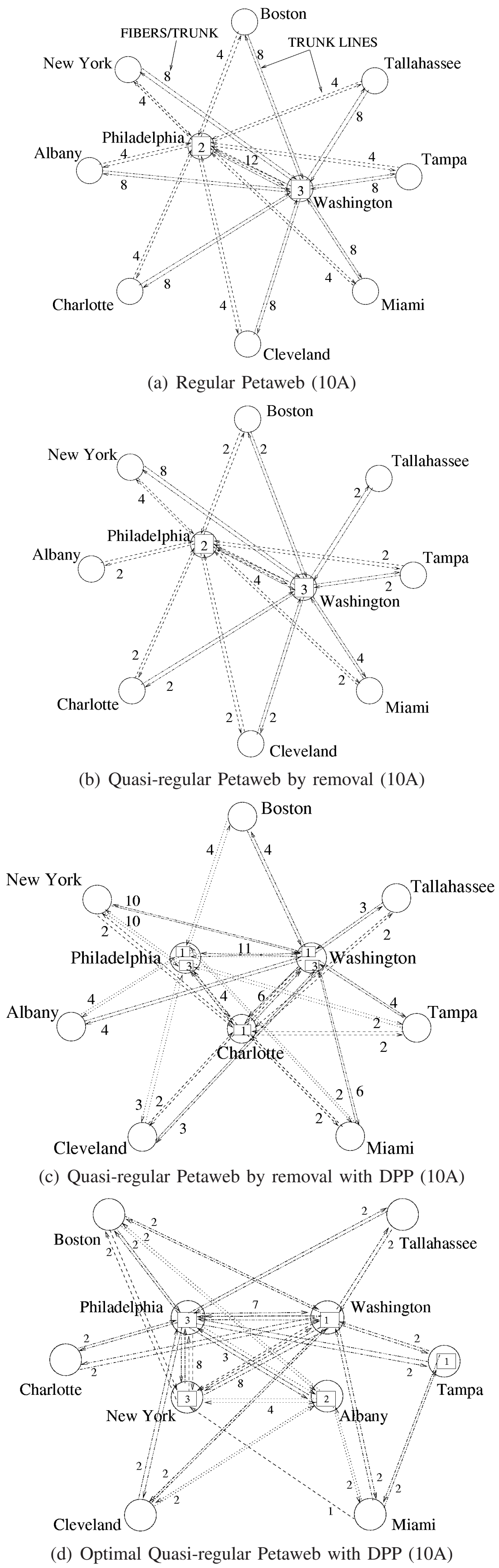


(a) Regular Petaweb (10A)

(b) Quasi-regular Petaweb by removal (10A)

(c) Quasi-regular Petaweb by removal with DPP (10A)

(d) Optimal Quasi-regular Petaweb with DPP (10A)

Fig. 1. 10-node Petaweb structures

the regular Petaweb, while requiring roughly 66% less ports. However, the meaning of that comparison is limited by the fact that the authors forced a five-stage structure for the multi-hop network core, limiting thus the degrees of freedom. The object of this paper is, instead, to compare, for the first time, the *quasi-regular* Petaweb to multi-hop irregular mesh structures, in terms of network cost, network utilization and fiber length. We leave all the degrees of freedom to the design dimensioning for the multi-hop case.

The paper is organized as follows. In Sect.II we detail the switching systems for both the architectures. In Sect.III we present the network model, the cost model, and the two design problems. In Sect.IV we compare the performance and in Sect.V we draw some conclusions.

II. Switching Systems

In order to fairly compare the quasi-regular Petaweb to irregular mesh structures we need to use comparable switching systems, described in the following. It is worth mentioning that in the previous studies a hierarchy of switching core nodes, with a cost decreasing with the size, was considered in the modeling. To perform a fair comparison we do not adopt this hierarchy. For the same reason, we assume that the fibers have the same number of wavelengths, W, and thus that each fiber requires W ports to be connected to a switching plane.

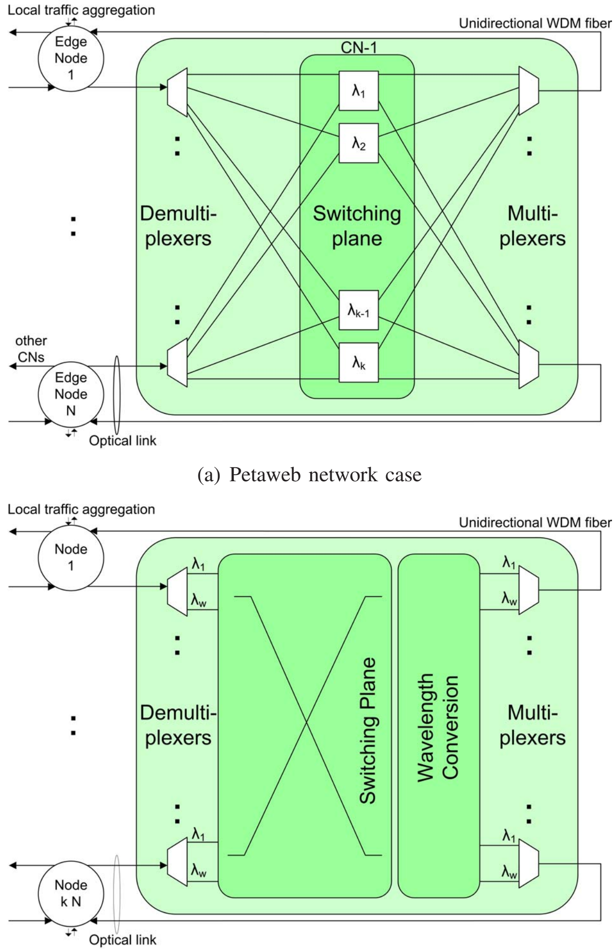
A. Petaweb's Core Node

For the regular Petaweb architecture, each edge node is connected to each core node with one fiber per direction. A core node is composed of a single switching plane. A switching plane interconnects one fiber per edge node and per direction. A switching site can house many core nodes, and edge and core nodes may be co-located and locally interconnected. As illustrated in Fig.2a, the core node is an OXC with parallel switching sub-planes, one per wavelength. Since core nodes are not connected to each other, there is no need for wavelength conversion in the regular structure.

In the quasi-regular structure, it is possible to relax the constraint imposing each edge node to be connected to each core node with a single fiber. Unused fibers and corresponding ports can be removed to reduce the physical cost without modifying the switching scheme. In this case, wavelength conversion is still not necessary. However, whether at a given switching site there are many core nodes, with a quasi-regular structure we may further disable fibers by multiplexing/demultiplexing wavelength-channels switched by different core nodes, by allowing thus wavelength conversion. Indeed, the relaxation of the wavelength continuity constraint allows wavelength-channels coming from different edge nodes, but with the same destination, to be multiplexed into the same fiber (idem for the ingress stages). Hence the interest in directly optimizing the quasi-regular structure instead of heuristically determining it by downgrading an optimal regular structure [6].

B. Multi-Hop Network's Core Node

In this case a core node can have different sizes and a site can have a single core node. As illustrated in Fig.2b, the switching plane has a number of incoming and outgoing fibers multiple of the number of edge nodes, and offers full wavelength conversion. For example, in a 10-node network a switching plane of size k can house $10 \cdot k$ ingress/egress fibers,



(a) Petaweb network case

(b) Multi-hop network case

Fig. 2. Core Node Structures. N: number of edge nodes

independently of the origin/destination node, which can be an edge node or another core node. Fiber links and ports can be disabled if unused. Fiber links can be *access fiber links* connecting core nodes to edge nodes (and vice-versa), and *core fiber links* interconnecting two core nodes. Certainly, the number of core links can be bigger than the number of edge links since this might facilitates path finding. Also for this reason, we let the design procedure dimension the number of edge and core links at each core node.

III. Network Design Dimensioning Problem

The design dimensioning problem consists in optimally locating the core nodes' site, in determining their number or size, and in dimensioning the number of fibers per trunk line. The candidate switching sites are the sites of the edge nodes: edge and core nodes can be co-located. The input static traffic matrix defines the candidate sites for core nodes, and the connection requests between edge nodes (one single, or any, connection request per pair of edge nodes).

For the Petaweb a trunk line connects an edge node to a core node, or vice-versa. The quasi-regular Petaweb design dimensioning problem was tackled for the first time in [6], where the authors present an optimal mathematical approach, and a heuristic able to reach good solutions for large networks. In particular, the authors assume three switching granularities: the time-slot, the wavelength and the fiber. In this work, we relax many modeling choices that would bias the comparison with the multi-hop structure. In particular, we assume that each connection request between two edge nodes is expressed in unit of wavelength-channels and that these channels are routed over the same path. For the Petaweb structure, this means that wavelength-channels of the same connection requests have to be switched in the same site.

For the multi-hop network we have access fiber links and core fiber links. The first type requires one single ingress (egress) interconnection stage at the core node; the multiplexing (demultiplexing) stages at the edge nodes are not considered as part of the core network. The latter type requires two interconnection stages (an egress one and an ingress one at two core nodes), and thus a double number of ports with respect to access fiber links. At the source (destination) edge node it could be more convenient to plug to a local core node, instead of installing a new access fiber, if the cost of the local plugging (i.e. the cost of ingress ports at the local core node) is minor than a new inter-site fiber link.

The design dimensioning problem consists thus in:

- optimally locate core node location and number or size
- optimally assign lightpath routes to connection requests

minimizing the overall network cost, given the traffic matrix, the switching system's constraints, and the elements' cost.

A. Cost Model

As in the previous works, the core network cost is considered as composed of a core node cost, a fiber cost and a propagation delay virtual cost.

The core node cost is composed of a fixed part and a variable part. The variable part is determined by the number of enabled ports (one port per ingress or egress wavelength).

The fiber cost is considered per unit of length. It is the unitary cost of a reference fiber type that can be discretely scaled as function of the number of wavelengths per fiber.

The propagation delay cost is a virtual cost proportional to the distance traveled and to the lightpath bitrate. Such a cost differs from the nature of other costs in that it is not a CAPEX cost. We introduce it and tune it in the simulations in order to evaluate the effects of considering such a cost in the design dimensioning of core networks. We add such a cost to account for the common thought that the propagation delay will become one of the most important pay-back factor in offering end-to-end circuits, especially in a multi-provider scope [8]. Moreover, the reason for the bitrate dependence of the delay unitary cost is that we want to assure shorter end-to-end delay to high bitrate lightpaths, which are supposed to transport aggregates requiring low propagation delay.

B. Multihop Network Dimensioning ILP Formulation

We here present the mathematical formulation used to model the multi-hop network dimensioning problem. The following notations are used: M, set of sites; Q, set of connection requests; $w(q)$, number of wavelengths for $q \in Q$; $s(q)/d(q)$, source/destination of q; W, number of wavelengths per fiber; F, cost of the reference fiber in unit of length; $\phi(W)$, scaling factor for F as function of W; β, delay cost in unit of wavelength and of distance; P, cost of a single port; C, fixed cost of a core node switching unit; (i,j), link between $i \in M$ and $j \in M$; Δ_{ij}, length of (i,j).

We introduce the following variables, helped by Fig.3:

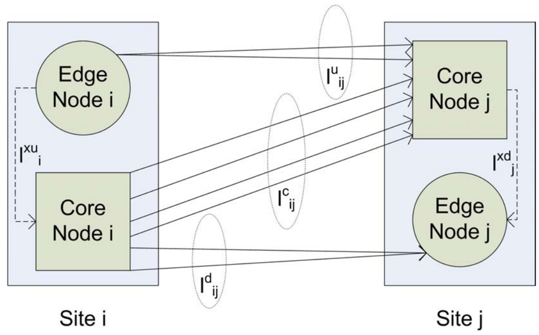


Fig. 3. Counting locally added and dropped wavelength channels, and edge-to-edge, edge-to-core and core-to-core fiber links with l variables.

- l^c_{ij}: number of fibers connecting the core node in site $i \in M$ to the core node in site $j \in M$;
- l^u_{ij} (resp. l^d_{ij}): number of fibers connecting the edge node in site i to the core node in site j (resp. viceversa);
- l^{xu}_i (resp. l^{xd}_i): number of fibers needed for local edge-to-core (resp. core-to-edge) interconnections;
- a^q_{ij}: binary variable indicating if the lightpath of the connection request $q \in Q$ is switched over the link (i,j);
- x^u_q (resp. x^d_q): number of wavelength-channels for q added from the source edge node to the local core node, if any, bypassing a direct edge-to-core fiber (respectively, locally dropped for the core node, if any, to the destination edge node, bypassing a direct core-to-edge fiber);

The design dimensioning objective is thus:

$$\begin{aligned}\min G(y,l,a) \quad = \quad & \sum_{i\in M}\sum_{j\in M} \phi(W)\, F\, \Delta_{ij}\, (l^c_{ij}+l^u_{ij}+l^d_{ij}) \\ + \quad & \sum_{i\in M}\sum_{j\in M} WP(2l^c_{ij}+l^u_{ij}+l^d_{ij}) \\ + \quad & \sum_{i\in M} WP(l^{xd}_i + l^{xu}_i) + \sum_{i\in M} C\, y_i \\ + \quad & \sum_{q\in Q}\sum_{i\in M}\sum_{j\in M} \beta w(q)\Delta_{ij} a^q_{ij} \qquad (1)\end{aligned}$$

$$s.t. \sum_{j\in M} a^q_{ij} - \sum_{j\in M} a^q_{ji} = \begin{cases} 1 & \text{if } i = s(q) \quad \forall i \in M \\ -1 & \text{if } i = d(q) \quad \forall q \in Q \\ 0 & \text{otherwise} \end{cases} \qquad (2)$$

$$\sum_{q\in Q}^{s(q)\neq i, d(q)\neq j} w(q)a^q_{ij} + w(q)\left[x^u_{q|s(q)=i} + x^d_{q|d(q)=j}\right] \le W\, l^c_{ij} \quad \forall (i,j) \in M\times M \qquad (3)$$

$$\sum_{q\in Q}^{s(q)=i} w(q)a^q_{ij} - w(q)x^u_{q|s(q)=i} \le W\, l^u_{ij} \quad \forall (i,j) \in M\times M \qquad (4)$$

$$\sum_{q\in Q}^{d(q)=j} w(q)a^q_{ij} - w(q)x^d_{q|d(q)=j} \le W\, l^d_{ij} \quad \forall (i,j) \in M\times M \qquad (5)$$

$$\sum_{q\in Q}^{d(q)=i} w(q)x^d_q \le W l^{xd}_i \;\forall i \in M \qquad (6)$$

$$\sum_{q\in Q}^{s(q)=i} w(q)x^u_q \le W l^{xu}_i \;\forall i \in M \qquad (7)$$

$$l^{xu}_j + \sum_{i\in M}(l^c_{ij}+l^u_{ij}) \le |M| y_j \;\forall j \in M \qquad (8)$$

$$l^{xd}_i + \sum_{j\in M}(l^c_{ij}+l^d_{ij}) \le |M| y_i \;\forall i \in M \qquad (9)$$

$$a^q_{ij}, x^d_q, x^u_q \in \{0,1\};\; y_i, l^c_{ij}, l^d_{ij}, l^u_{ij}, l^{xu}_i, l^{xd}_i \in Z_+ \qquad (10)$$

(1) expresses the minimization of the total network cost due to propagation delays, fibers and switching ports. The port cost for core-to-core fibers is double than that for edge-to-core and core-to-edge fibers: a core-to-core fiber link would be preferred to a new edge-to-core or core-to-edge link to route a demand if it disposes of enough capacity and if the cost of W additional ports is minor than the cost of a edge-to-core or core-to-edge fiber. Moreover, we add the port cost for local interconnection. (2) is the traffic conservation constraint, imposing that the flow leaving node i is balanced by the entering flow, except for the source (destination) node; (3) dimension the core-to-core fiber links; (4) and (5) dimension the edge-to-core and the core-to-edge fibers; (6) and (7) dimension the local edge-to-core and core-to-edge fiber interconnections; (8) and (9) enforce the maximum size of the core nodes; (10) imposes the binary constraint for a and x variables, and the integer constraint for l and y variables.

IV. Numerical Results

In our case study we consider the 10-node network topology previously used in the related works [2]-[6]. We use three types of traffic profiles, all characterized by a few peaks of traffic: the **A** type comes from an industrial matrix, which presents many zero values [2]; the **B** type follows a gravitational profile which assign the connection request volume as directly proportional to the product of the population of two cities and inversely proportional to the square distance between the sites [2]; the **C** type does not consider the inversely proportional dependence on the square distance, still considering the population product proportionality. **B** and **C** matrices are opportunely scaled for having a global traffic volume comparable to that of the A matrix, i.e. roughly 0.8 Tbit/s. We denote with 10A, 10B, 10C the three case studies. Each connection request then consists in a discrete number of wavelength-channels. In Fig.4 we display the profiles of the three traffic matrices. Given that the considered instances are of 10 nodes, the switching plane unit is composed of 10 ingress/egress fibers (see Sect.II).

The cost parameters' values are expressed in unit of fiber cost. Such a choice seems reasonable in that the fiber cost is the one more likely to oscillate. We use the values used for the related works: a single port costs 150 times the unitary per km fiber cost, and a switching plane 25 times. The delay

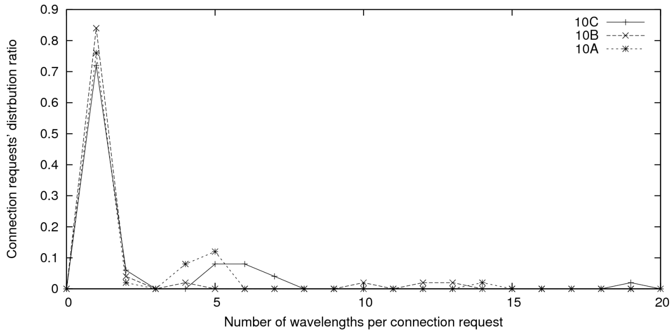


Fig. 4. Profiles of the traffic matrices

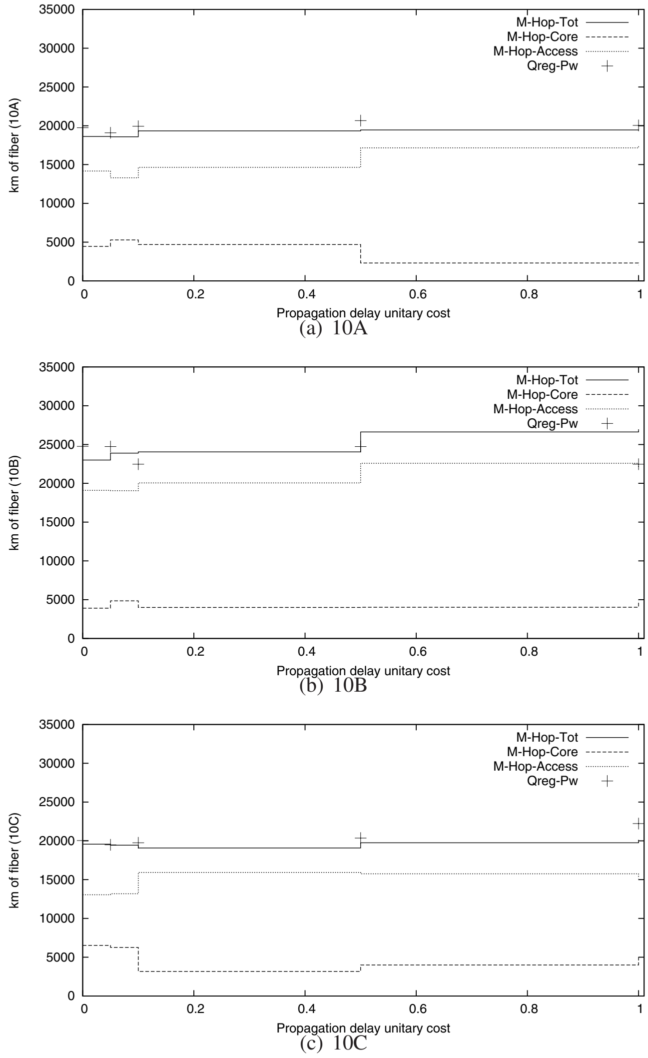
unitary cost is tuned on four different values: 0, 0.05, 0.1, 0.5 and 1 times the unitary per km fiber cost.

A. Cost allocation

In Table I we display the cost allocation solutions, for both the architectures, as function of the delay unitary cost (indicated by β/F). As expected the quasi-regular Petaweb requires more fiber link resources than the multi-hop structure, at most 7% more. This is detected by a higher cost allocation for core nodes in the multi-hop architecture, and by a higher delay cost for the quasi-regular Petaweb. Also expected is the fact that the composite-star architecture has a higher network cost. Indeed, it may be considered as a not optimal special case of the multi-hop structure with strong constraints on the switching system to keep the regularity as a target. These constraints force one switching plane per ingress fiber from a given edge node even if it is the single one connected, while in the multi-hop switching system an equal-in-size switching plane can house more than one fiber per edge node. However, the difference in cost is not exceedingly high: the quasi-regular Petaweb costs at most 20% more than the multi-hop structure, and in some cases the two solutions are very close. This suggests that multi-hop architectures may tend toward a quasi-regular composite-star structure when one lets all the degrees of freedom to the design dimensioning procedure.

B. Fiber Length

In order to assess the relevance of the propagation delay cost in the design dimensioning, we analyze how it affects the amount of fiber, in km, needed for both the architectures. In Fig.5 we indicate with a "+" point the quasi-regular Petaweb case, with a continuous step the multi-hop case, and with dotted steps the core part and the access part for the multi-hop case. The high fiber cost allocation for the quasi-regular Petaweb indicated in Table I is reflected by a larger amount of fiber, indeed. The multi-hop architecture allows an efficient fiber distribution and the overall amount slightly increases when the propagation delay unitary cost is increased. Moreover, as the propagation delay is increased much more fiber is allocated to the access than to the core: the km of core fiber decreases, making the multi-hop network similar to the quasi-regular composite-star network, which has no core fibers indeed. If we look at this behavior for the three traffic profiles (10A, 10B, 10C), we can notice that the amount of core fibers is comparable for the three cases, while the amount of access fibers differs. In particular, the 10B profile has a very relevant impact on the access fibers' amount, since its matrix is dense and has a lot of single-wavelength connections (Fig.4).



(a) 10A

(b) 10B

(c) 10C

Fig. 5. Fiber length comparison in km.

C. Fiber Link Utilization

Fig.6 display, for all the considered cases, the fiber resources utilization as of the classical definition given in [9]. We can affirm that for multi-hop networks:

- the access fibers tend to be under-used.
- the resources utilization is worsened by higher weights of the propagation delay cost.

V. Conclusion

In this paper we compared, for the first time, a quasi-regular composite-star optical core architecture to the classical multi-hop irregular structure. Such an architecture is interesting in that it allows drastically reducing traffic engineering issues it grants fully utilization of the available capacity thanks to its two-hop physical connectivity.

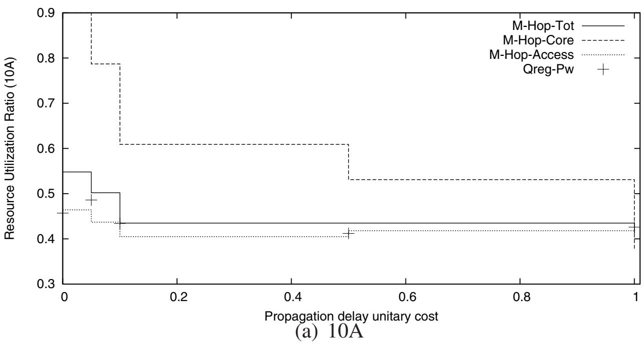
By simulations on different instances, we showed that the amount of core fibers in multi-hop core networks decreases whether a larger impact is given to a propagation delay virtual

TABLE I

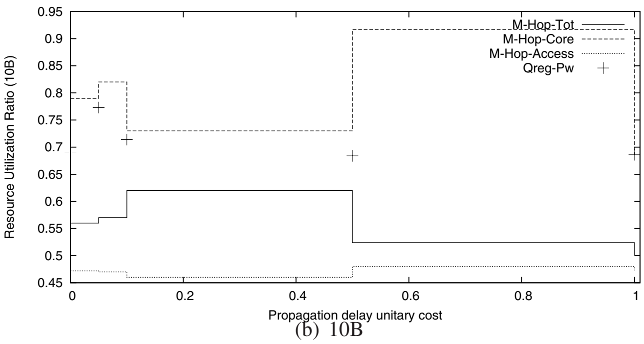
COST ALLOCATIONS AS FUNCTION OF THE PROPAGATION DELAY UNITARY COST AND OF THE TRAFFIC PROFILE. THE OBJECTIVES ARE IN THOUSANDS; CN = CORE NODE.

Quasi-Regular Composite Star Architecture															
	$\beta/F = 0$			$\beta/F = 0.05$			$\beta/F = 0.1$			$\beta/F = 0.5$			$\beta/F = 1$		
Case	10A	10B	10C	10A	10B	10C	10A	10B	10C	10A	10B	10C	10A	10B	10C
Objective	376	538	454	392	587	399	399	691	465	458	753	578	630	1019	645
Fiber cost	86.2%	77.4%	86.4%	84.7%	76.7%	84.1%	82.6%	73.0%	82.4%	72.3%	63.7%	70.2%	61.9%	53.9%	60.9%
CN cost	13.8%	22.6%	13.6%	13.3%	21.0%	13.6%	13.7%	22.5%	13.2%	12.1%	18.6%	11.9%	10.7%	16.2%	9.4%
Delay cost	0.0%	0.0%	0.0%	2.0%	2.3%	2.3%	3.7%	4.5%	4.4%	25.7%	17.7%	17.9%	27.4%	30.0%	29.7%

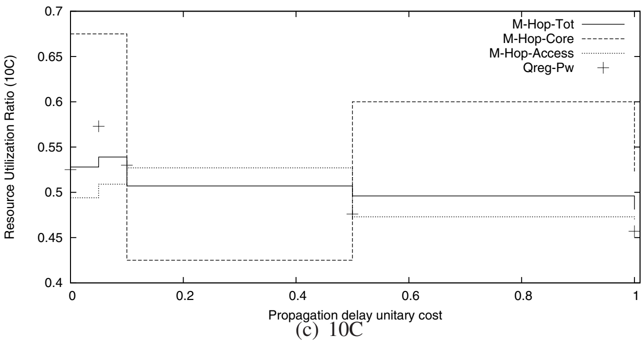
Multi-Hop Irregular Mesh Architecture															
	$\beta/F = 0$			$\beta/F = 0.05$			$\beta/F = 0.1$			$\beta/F = 0.5$			$\beta/F = 1$		
Case	10A	10B	10C	10A	10B	10C	10A	10B	10C	10A	10B	10C	10A	10B	10C
Objective	372	530	390	382	571	397	398	605	397	457	690	480	523	801	572
Fiber cost	80.0%	73.2%	80.3%	77.7%	72.3%	78.4%	77.6%	69.4%	76.9%	68.1%	61.7%	65.9%	59.2%	53.8%	56.2%
CN cost	20.0%	26.8%	19.7%	20.1%	24.8%	19.4%	18.7%	27.6%	18.8%	15.8%	23.0%	16.5%	13.8%	20.7%	14.7%
Delay cost	0.0%	0.0%	0.0%	2.1%	2.9%	2.3%	3.7%	3.0%	4.3%	16.1%	15.3%	17.6%	27.0%	25.5%	29.1%



(a) 10A



(b) 10B



(c) 10C

Fig. 6. Resource utilization ratio comparison.

cost in the design dimensioning objective. This suggests that as the propagation delay cost increases, the multi-hop structure tends to assume a composite-star configuration, which has no core fibers indeed. Moreover, the quasi-regular composite-star architecture assumed at most 20% higher network cost because of its more stringent switching constraints. The simplification in traffic engineering operations that the composite-star core architecture offers may convince the decision maker that such a small difference in network cost is not an issue.

Given a wide area carrier which has to build its core network from scratch, if the decision maker has to meet stringent requirements on the end-to-end delay and should hence decide to dimension the core network with respect to these constraints, he should evaluate the possibility of building a quasi-regular composite-star structure. Indeed, it is a common feeling that the end-to-end delay will be the payback factor in the next generation Internet, driven especially by the requirements of critical applications as storage area networks (typically those of bank customers) or of added-value interactive communication platforms.

REFERENCES

[1] R. Vickers, M. Beshai, "Petaweb Architecture", in *Proc. of* 9^{th} *Int. Telecomm. Network Planning Symposium*, Toronto, Canada (2000).

[2] A. Reinert, B. Sansò, S. Secci, "Design Optimization of the Petaweb Architecture", *IEEE/ACM Transactions on Networking*, accepted for publication, February 2009.

[3] S. Secci, B. Sansò, "Design and dimensioning of a novel composite-star WDM network with TDM channel partitioning", in *Proc. of IEEE BROADNETS'06*, Oct. 1-5 2006, San José, USA.

[4] S. Secci, B. Sansò, "Optimization of a dedicated path protected TDM/WDM Petaweb architecture", in *Proc. of NAEC 2006*, Oct. 19-22 2006, Riva Del Garda, Italy.

[5] S. Secci, B. Sansò, "Upgrade of a Composite-Star Optical Network", in *Proc. of NTMS 2007*, 7-9 May 2007, Paris, France.

[6] S. Secci, A. Ceselli, F. Malucelli, A. Pattavina, B. Sansò, "Direct Optimal Design of a Quasi-Regular Composite-Star Core Network", in *Proc. of DRCN 2007*, Oct. 7-10 2007, La Rochelle, France.

[7] F.J. Blouin, A.W. Lee, A. J.M. Lee, M. Beshai, "A comparison of two Optical-Core Networks", *J. of Optical Networking*, Vol. 1, No. 1 (2001).

[8] R. Douville, J.-L. Le Roux, J.-L. Rougier, S. Secci, "A Service Plane over the PCE Architecture for Automatic Multi-Domain Connection-Oriented Services", *Communications Magazine*, submitted.

[9] F. Yegenoglu, E. Sherk, "Network characterization using constraint-based definitions of capacity, utilization, and efficiency", *Communications Magazine*, Vol. 43, No. 9 (2005).