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Abstract

In this paper, we present a scalable and agile design for next generation optical backbone networks. We assume each node to be equipped with a MultiService Provisioning Platform (MSPP) and a Photonic Switch (PXC). The objective is to come up with a minimum cost dimensioning of those nodal equipment together with a network provisioning under dynamic traffic. We propose two greedy provisioning approaches within the framework of small-batch provisioning under asymmetric traffic. Consequently, in a multi-time period/interval context, at the outset of each time period/interval, the provisioning of the batch of new incoming requests is conducted in such a way that each new demand request is routed on a single hop or a two-hop ligthpath and assigned to an Optical Independent Routing Configuration (OIRC).

We present two node dimensioning strategies, i.e., a myopic one and an anticipative one in view of an efficient resource pre-deployment and a cost-effective network lifetime planning scheme. Performance evaluation and comparisons are conducted on different network and traffic instances. Experiments show that, not only the proposed heuristics are highly scalable, but the resulting network design architectures are very close to the optimal ones. Experiments also allow the investigation of the conditions under which, and of how much, an anticipative strategy is beneficial over a myopic one.

Résumé

Nous présentons, dans cet article, un modèle de conception de réseau pour les réseaux de cœur optiques, qui est à la fois versatile et fonctionnel à grande échelle. Nous supposons que chaque nœud est équipé d'une plate-forme d'allocation de ressources multi-services (MSPP–MultiService Provisioning Platform) et d'un commutateur optique (PXC–MultiService Provisioning Platform). L'objectif est de fournir un outil de dimensionnement à coût minimum de ces équipements de nœuds de réseaux, en même temps qu'une allocation de ressources en présence de trafic dynamique. Nous proposons deux approches gloutonnes d'allocation de ressources dans le contexte d'un trafic asymétrique par lots. En conséquence, dans un contexte d'horizon temporel réparti sur plusieurs périodes (intervalles) de temps, au début de chaque période (intervalle) de temps, l'allocation de ressources est effectuée, pour des lots de plusieurs requêtes, de telle sorte que chaque nouvelle requête est routée sur un chemin optique avec un ou deux sauts optiques logiques et affectée à une configuration optique indépendante de routage.

Nous présentons deux stratégies de dimensionnement d'un nœud dans un réseau, c'est-à-dire une myope et une anticipative en vue d'un déploiement efficace des ressources et d'un schéma de planification à long terme d'un réseau. Les évaluations de performance et les comparaisons sont effectuées sur différents jeux de données, aussi bien en termes de réseaux que de trafic. Les expériences montrent que, non seulement les heuristiques sont efficaces à grande échelle, mais que les architectures de réseaux obtenues sont très proches des architectures optimales. Les expériences permettent aussi l'exploration des conditions sous lesquelles, et de combien, une stratégie anticipative est bénéfique par rapport à une stratégie myope.

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1 Introduction

The projections of the earlier stages of optical network evolution have now become a reality. The demand for bandwidth is unequivocal. Even conservative assessment of Internet traffic growth predicts an ongoing 100% increase [1,2,3] for the forthcoming years. In order to face the traffic trends, network operators have adopted DWDM (Dense Wavelength Division Multiplexing) point-to-point infrastructures. With such a multiplexing technology, bandwidth is divided into a set of wavelengths where each sub-band is capable of carrying the equivalent speed of a single fiber in TDM (Time Division Multiplexing) mode.

With the maturity of DWDM multiplexing technology and the emergence of new application classes, e.g., video conferencing, Internet telephony and e-commerce, optical network architectures have evolved from a typical static topology based on SADM (SONET Add/Drop Multiplexer), OADM (Optical Add/Drop Multiplexer) and DXC (Digital Cross-Connect) equipment to more intelligent network designs with multi-platform transponders and transparent switching fabrics such as MultiService Provisioning Platform (MSPP) and Photonic Switch (PXC) equipment. The new network design trend is then to capitalize on reconfigurable equipment which are able to provide new transparent optical services such as bandwidth on demand, automated end-to-end connection provisioning and remote connection redirection around failing resources.

In such an environment, the add/drop operations are performed, at each access node, through an Electrical-Optical/Optical-Electrical equipment in parallel with an all-optical switch. Such an architecture eliminates all useless OEO (Optical/Electrical/Optical) conversions of the transport signal, offers very fast transport signal provisioning and provides flexible reconfiguration when traffic changes.

In the context of dynamic traffic patterns, granting a new incoming connection is a question of finding a path and a wavelength in the network without, a priori, disturbing already established connections. Under heavy provisioning and traffic scenarios, it may be impossible to grant a new incoming connection. However, if we allow the disturbance of a few already established connections, by taking advantage of the most tolerant classes of services, then the current provisioning problem may have a solution. To circumvent unnecessary request denials, flexible network dimensioning strategies should be developed in order to allow a better resource usage. It is also necessary to make a judicious provisioning path and wavelength assignment choice for each new incoming connection.

In this paper, we propose to answer the following node dimensioning and network provisioning questions. In the context of dynamic traffic, *(i)* What is the best nodal design architecture? *(ii)* What is the most suitable node dimensioning strategy and provisioning scheme in order to minimize the overall network design cost?

The paper is organized as follows. Previous work are reviewed in Section 2.1, followed by the motivations of the paper in Section 2.2. In Section 3, we discuss the distinctions to be made when dealing with dynamic provisioning. In Section 4, we analyze two scalable and agile nodal equipment architectures, and select the best one for the sequel of the study. Under that selection, we then investigate, in Section 5, the joint solution of the dimensioning of the nodal equipment and of the network small-batch provisioning under dynamic traffic. We propose two dimensioning strategies for the nodal equipment and two associated provisioning algorithms that can be efficiently implemented thanks to highly scalable and efficient greedy provisioning heuristic. In the context of network planning, we next deduce a scheme that covers the whole network lifetime cycle. Experiments are carried out on several network and traffic instances in order to assess the lifetime planning (or the core network management according to the studied dynamic traffic context) heuristics with respect to the two nodal equipment dimensioning strategies and their associated network provisioning algorithm. Performance evaluation is made possible using an exact provisioning algorithm previously developed by the authors [4]. Future work is discussed in the last section.

2 Literature Review and Motivations

Several network architectures have been proposed in the literature for the nodal equipment and network design issues in DWDM core optical networks. We now review them in Paragraph 2 and pursue with the resulting motivations of the current study in Paragraph 2.2.

2.1 Literature Review

Parnis et al. [5] investigate the scalability level of photonic/electrical overlay cross-connection architectures. They conclude that an hybrid switching architecture introduces additional flexibility and reduces the complexity of the photonic layer in the context of an uncertain growing traffic. Ho et al. [6] present a scalable design for next generation optical cross-connects (OXCs) as well as a long term planning scheme, i.e., how to dimension the optical switching capabilities in order to cope with a growing traffic demand. However, the proposed design does not include details about the dimensioning scheme of the required interface components between access and backbone network nodes. Moreover, the experimental results show that the multi-granularity switching architecture may require much more input/output ports than the one using pure lambda-switching, i.e., PXCs.

Tzanakaki et al. [7] investigate a variety of network nodal design architectures. They compare two particular architectures for ring and linear networks, i.e., the Wavelength Selective (WS) and the Broadcast and Select (B&S) solutions. They also provide a generic classification of optical cross-connect (OXCs) architectures into opaque and transparent solutions in mesh network topologies.

Mokthar et al. [8] propose a generic two-layer optical network architecture based on an electrical layer over a reconfigurable photonic layer. Then, they investigate its benefits in the reduction of the overall network cost in the context of bandwidth-on-demand traffic.

Gerstel and Raza [9] makes a comparative qualitative description on commonly accepted design scenarios, i.e., opaque, hybrid and all-optical. They look at the network design from the agility and scalability perspectives. Indeed, they investigate the effect of an agility scenario and a predeployment network planning strategy with respect to the capital and operational network expenses. They do not address the network dimensioning aspect.

Melian et al. [10] propose a very simplistic nodal architecture. The network design is defined as a set of OXCs interconnected with WDM fiber links in a mesh topology. The authors present an interesting study of the expansion capacity of WDM networks, i.e., location and sizing of fiber links and switching equipment. However, as aforementioned, the proposed architecture does not include add/drop, aggregation and signal regeneration interfaces. The modeling network cost is reduced to the switching cost.

Oki et al. [11] propose a generic switching architecture based on packet/photonic router for IP/Optical generalized MPLS networks. Indeed, the cross-connection is done through the cascading of packet and photonic fabrics. No details are given on the network access interfaces. The authors do not propose a network dimensioning scheme and the performance evaluation of the proposed network design is only performed through simulation tools.

In Straub et al. [12], the proposed nodal design configuration is based on a two-stage waveband demultiplexing architecture in which the neighboring WDM channels are grouped into bands to limit the cross-connection fabric size and the crosstalk effect (interference between transport signals in space switching). The switching architecture is based on fully reconfigurable switching components, where there is the capability to select the channel to be added/dropped and there is a fully connectivity matrix between add/drop and pass-through ports, providing the basis for a flexible wavelength assignment function. However, the demultiplexing at wavelength-band granularity level reduces the switching capacity. Accordingly, the proposed architecture provides a poor scalability and low agility level, a key drawback in the context of backbone networks where the traffic variation in time is slow and continuous. Indeed, the reconfiguration of demultiplexers, multiplexers and switches are prone to disruption of some already established connections to accommodate the new ones. Once again, as aforementioned, the proposed nodal architecture does not include an efficient access platform as required for traffic aggregation in order to circumvent the discrepancy between client and WDM transport signal granularities.

In Hsu [13], the same design architecture as in Ho et al. [6] was adopted. It does not take into account the equipment needed for GMPLS and add/drop interfaces.

2.2 Motivations

In this paper, in order to address the previously eluded design aspects (multi-signal access interfaces, transport signal regeneration, scalability, reconfigurability), we propose a transparent transport architecture where each node is equipped with a MultiService Provisioning Platform (MSPP) enabling the management (adding or dropping connections, converting or regenerating signals) of a large number of transport signals and a Photonic Cross-Connect (PXC) with a 3D MEMS (Micro Electro Mechanical System) switching matrix, for enabling any combination of ports when performing optical cross connections.

Our goal is to provide an optimization tool for finding the minimum cost of such an agile network design. We investigate two network dimensioning strategies, taking into account all network resources needed across the demand provisioning paths: A myopic strategy where network resources are selected as needed and an anticipative one where resources are pre-installed according to a given forecast traffic pattern.

For the provisioning problem, an extensive literature already exists in the static traffic case, several compact ILP formulations have been proposed, see for example [14, 15, 16, 17, 18, 19, 20], but none of them include the nodal equipment dimensioning. In addition, they all share the drawback to be highly symmetrical with respect to lightpath permutations [21], and suffer from very high computation time because of their exponential number of variables and constraints. Even large scale optimization tools, such as column generation techniques and branch-and-price methods, see [21], have not been highly successful in terms of scalability.

To reduce the computational complexity time induced by the previously proposed ILP formulations [4] and take into account the dynamic aspect of traffic, we propose a novel greedy heuristic approach, where the whole optimization process is divided in two stages that are sequentially performed. At the outset of each time period/interval, the provisioning of a batch of new incoming demand requests is conducted in such a way that each new request is routed on a single optical hop[1] or a two optical hop ligthpath and assigned to an Optical Independent Routing Configurations (OIRC), where an OIRC is a set of routes that can be assigned the same wavelength.

We limit the number of optical hops to two between the source and destination nodes as an indirect way to enforce the end-to-end delay constraints in a backbone network, (see 4.3 for further details), where whenever an OEO conversion is performed, it costs a 10 ms delay with an overall end-to-end delay that cannot exceed 150 ms (critical propagation time for voice traffic, [23]) including the delays encountered in the access and metropolitan networks.

3 Dynamic Provisioning

Dynamic provisioning can have a different meaning depending on the connection management and control network context. Clearly, in any large network, connections do not remain static and the lower the network layer, the less frequent are the changes. An accurate traffic modeling is needed in to order to ensure an efficient network provisioning and its ability to survive unpredicted traffic changes. However, depending whether we deal with traffic engineering, or network engineering or network planning (see Mukherjee [24] for definitions), dynamic traffic has a different interpretation. We next attempt to clarify the various dynamic traffic contexts that have been distinguished in the literature studies and consequently, make sure of the understanding of the small batch dynamic interpretation of our study.

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[1] An optical hop, also called logical hop, is an internodal fiber link made of a sequence of fiber links such that OEO conversions occur only at the two endpoints of the internodal fiber link, see, e.g., [22]

3.1 Single Request Dynamic Provisioning

In the context of single request provisioning, new incoming requests are dealt with, one at a time. A single lightpath has to be established, one at a time, and independently of the other request paths. Delay has usually to be kept at minimum between the connection request and the request provisioning. We are in the context of traffic engineering ("put the traffic where the bandwidth is" according to the definition given in [24]) where decisions must be made within a few millisecond time frame. In such a context, we must be able to react to short-lived events such as breaking news, flash crowd events, or server farms [25]. The typical performance metric is the blocking probability.

3.2 Small Batch Dynamic Provisioning

In the context of a longer time frame made of seconds, weeks up to a few years, the objective evolves from a minimum blocking rate to a minimum cost network design or management. Indeed, we are in an efficient network management or network planning context, so the objective is often to plan granting all connection requests at minimum network cost (CAPEX and OPEX). In such a context, the traffic model can be described with a set of traffic matrices, one for each time interval/period, where a large fraction of the traffic matrix remains unchanged from one period to the next. We distinguish two classes of small batch provisioning scheme according to the time frame.

3.2.1 Short Time Scale

In the context of a backbone network, even if a wide range of applications may be envisioned to require on-demand connection provisioning, it seems reasonable, that a delay in the range of few seconds up to few minutes, depending on the applications, can be reasonably tolerated between connection request and setup. In the particular context of a backbone network, we are dealing with the establishment of lightpaths that can convey up to 10 Gbs or even 40 Gbs, and cost thousands of dollars to use. We can therefore think of routers making the request for an additional lightpath on the basis of observed trends, slightly before the added capacity is fully needed, see [26, 27].

The traffic changes are not periodic, however the overall traffic is often constant (there is often an implicit assumption of a global steady state) or at least quite stable. A traffic change can therefore be measured with a small turnover rate, e.g., a 20% of incoming requests and a 20% of leaving requests. The traffic may be shifted from one area to another area of the network. For instance, in a 24 hour time frame, the traffic may be concentrated in downtown during the day time, in the residential areas at night.

3.2.2 Long Time Scale

We are here within the context of network engineering (week or month time periods) or network planning (year time frame). The traffic pattern changes from one period to another: it faces traffic addition and dropping in the network engineering context, and essentially only increases over the time (e.g., overall increase of the Internet traffic) in the network planning context.

While the algorithms we propose apply for the two above classes, we will use the terminology of the second class of traffic in our experiments.

4 Nodal Agile Architectures

Agility in optical networks is often associated with dynamic provisioning, but agile networks should include much more than the ability to remotely provision an end-to-end transport signal. In order to achieve the promise of reducing operational expenses of dispatching operators to remote sites for manual connection setting, agile networks should incorporate scalable nodal components and automated network monitoring and upgrading tools. Through the use of tunable devices (e.g., PXCs, MSPPs, ROADMs - Reconfigurable

Add/Drop Multiplexers, filters) and reliable network planning tools, the deployment and the management of the optical network architecture is greatly simplified. The labor cost of manual operations and cabling required to provision new lightpaths or new services is reduced. Moreover, an agile network upgrade plan can help to significantly reduce the number of human errors.

We believe that the main ingredient of agility comes from the selected nodal configuration. Therefore, we next analyze below, two agile nodal network designs which make use of some combination of MSPP platforms, ROADMs, PXCs, and MUX/DEMUX (optical multiplexer/demultiplexer).

4.1 MSPP-ROADM architecture

In a MSPP-ROADM configuration, as shown in Figue 1, we define a nodal configuration with one MSPP in parallel with some ROADMs. We allow a priori as many ROADMs as the number of input fiber links in each node. Each ROADM has one input and one output fiber port and some wavelength and/or waveband ports. At each node, the wavelengths and waveband ports are used to communicate with the other ROADMs and the MSPP. It is assumed that each ROADM uses a photonic filter to extract a wavelength subset from the WDM composite transport signal to be redirected through the MSPP for the add/drop operations of the client connections. Wavelengths, which are not solicited by the MSPP, are switched through the ROADM filter matrix to reach the selected output routing port (i.e., wavelength, waveband and fiber).

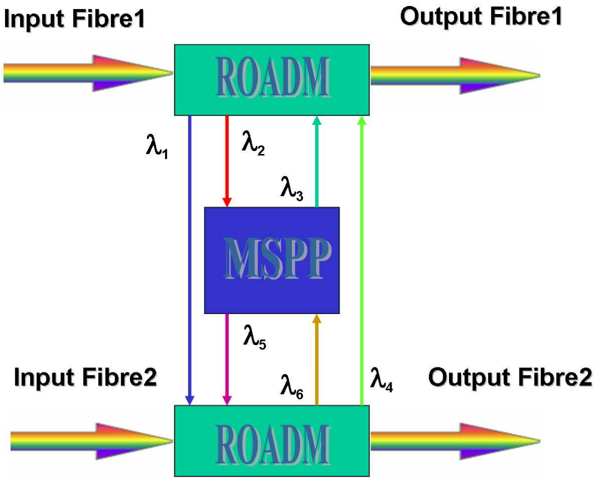


Figure 1: MSPP-ROADM Architecture

Thanks to a GMPLS control plan and flexible MSPP and ROADM technologies, ROADMs can remotely handle add/drop operations of wavelengths without any OEO conversions of the whole optical pass-through. Thus, it offers a high reconfigurability level at the optical layer similar to what is provided by a SADM at the sub-wavelength level. Indeed, a ROADM supports any input-to-output wavelength port connectivity without any re-engineering. Accordingly, a ROADM reduces operational expenses and increases the ability of the network operators to get services up on demand. Scalability and flexibility are also offered by the MultiService Provisioning Platform (MSPP) in replacement of the traditional ADM (Add/Drop Multiplexer) metro area equipment. A MSPP platform includes a client interface module handling a large range of physical interfaces, e.g., telephony interfaces (e.g., DS-1, DS-3), optical interfaces (e.g, OC-3, OC-12), Ethernet interfaces (e.g., 10/100Base-T, 100 Base-T). A MSPP platform also reduces the number of network control modules, and decreases resources needed to provision and maintain the network scalability.

A MSPP-ROADM configuration is better adapted for access and metropolitan networks than for backbone mesh networks for the following scalability issues:

- A large mesh network requires a complex ROADM cascading process in nodes with a lot of switching needs. This implies an important increase of capital expenses.
- Cascading a great number of ROADMs implies a degradation of the SNR (Signal to Noise Ratio) of DWDM composite transport signals.
- A ROADM cascading process implies an increase of the operational expenses due to significant manual settings.

4.2 MSPP-PXC architecture

In a MSPP-PXC nodal architecture, as shown in Figure 2, node configuration is such that one MSPP is installed in parallel with one modular all-optical PXC. DWDM composite signal is demultiplexed and multiplexed respectively through DEMUX and MUX modules. The MSPP is used for the optical add/drop operations. Wavelength conversion and transport signal regeneration are made through the MSPP transport blades and the DXC component. To overcome the scalability limits of a MSPP-ROADM configuration, we replace the ROADM pool by one scalable switching equipment, a photonic switching fabric. A PXC is able to support a large number of input and output fiber ports. Moreover, a PXC is able to redirect traffic from any input port to any output port through the corresponding switching block. PXC scalability is guaranteed through its modular switching blocks, each block being reserved for a given wavelength. Indeed, the switching capacity can be increased by the addition of new switching blocks as needed.

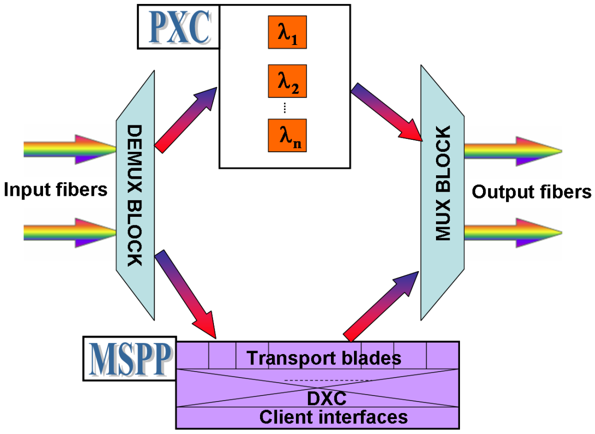


Figure 2: MSPP-PXC Architecture

A MSPP-PXC architecture can be highly beneficial in long-haul networks and at the interface with metropolitan networks. Indeed, since each wavelength switching block has a reconfigurable design thanks to a MEMS matrix, it is very easy to remotely adapt and set up the switching components to a new traffic pattern. The advantage of the MSPP-PXC architecture compared to a MSPP-ROADM architecture is that the former one offers the opportunity to switch all wavelengths in the optical domain. The latter one can switch only a subset of wavelengths in the optical domain. Thus, to overcome the lack of scalability in a MSPP-ROADM network architecture design, and to meet the expected network operator agility level, we choose a MSPP-PXC node architecture for the sequel of the paper.

4.3 E2E Delay

As shown in Figure 3, any lightpath that joins a source v_s to a destination v_d goes twice through an access network, twice through a metro network, and cuts across a long-haul core network, often refereed as an OWAN (Optical Wide Area Network). The end-to-end delay $E2E\_\text{DELAY}$ from v_s to v_d can be approximately calculated by the following formula:

$$E2E\_\text{DELAY} = 2T_{\text{ACCESS}} + 2T_{\text{METRO}} + T_{\text{CORE}}$$

where T_{CORE} measures the end-to-end delay through the core network. Depending on the selected nodal architecture, signal switching may occur in the optical domain (using the PXC) or in the electrical domain (using the MSPP). In the first case, wavelength conversion is not possible and optical switching is used to make sure the signals exit the node in the proper output fiber. In the second case, the transport signal can be regenerated and transferring a given signal from one wavelength to another one is possible. Accordingly, T_{CORE} can be approximately calculated as follows:

$$T_{\text{CORE}} \leq 2T_{\text{MSPP}} + 2hT_{\text{MSPP}} + (L+1)d + LT_{\text{PXC}} \tag{1}$$

where

- T_{ACCESS}: End-to-end delay associated with the traversal of an access network.
- T_{METRO}: End-to-end delay associated with the traversal of a metro network.
- T_{MSPP}: Transport signal regeneration delay encountered by the traversal of a MSPP.
- T_{PXC}: Cross-connection delay encountered by the traversal of a PXC.
- h: Maximum number of optical hops in an end-to-end core network lightpath, where an optical hop is a logical hop associated with a lightpath that is only switched through some PXCs, without going through any MSPP, except at its two end-nodes.
- d: Average propagation delay on a fiber link.
- L: Number of fiber links in the core network.

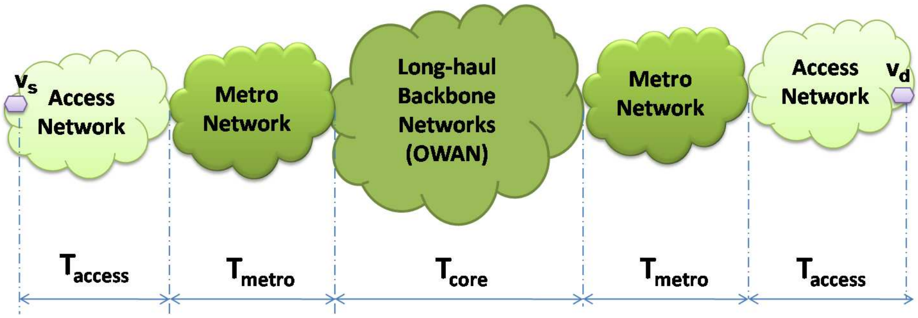


Figure 3: Core Network (OWAN) (from [25])

Note that the values for some of these terms may vary depending on the optical components that are used. Typical values, as given in [28], are:

- $d = 400$ microseconds for a fiber link length of 80 km.
- T_{PXC} is negligible taking into account that the light takes about 400 μs for 80 km of fiber (while the switching time, if a mirror reconfiguration is required, is $\approx$ 10 ms, assuming the use of MEMS).
- $T_{\text{MSPP}} \approx 10$ ms.

When conveying interactive multimedia signals (e.g., videoconferencing, IP telephony, etc.), the end-to-end delay must be kept below some threshold. As an example, standard ITU-T G.114b [23] specifies that the average one-way delay should remain below 150 ms, where the 150 ms delay is the sum of every encountered delay along the transmission path: access network delay, metropolitan network delay and backbone network delay, see (1).

As in this paper, we only deal with the end-to-end delay contribution of the backbone network component, we now present an analysis in order to estimate the T_{CORE} delay. First note that T_{CORE} depends on two critical parameters: L, the number of fiber links and h the number of optical hops encountered along the lightpath. The first parameter depends largely on the length of the selected routing path which in turn depends on several other parameters such as the current traffic pattern, the network link states, the provisioning strategy, etc. Thus, it is quite hard to select the appropriate critical value for L.

Accordingly, as the electrical switching through MSPP transport blades is the dominant delay value in (1), we believe that bounding the number of optical hops can guarantee an acceptable core end-to-end delay. Indeed, switching through a MSPP requires an OEO conversion that may be quite detrimental with respect to the end-to-end delay in a core network. Thus, using (1), we derive the following upper bound on T_{CORE}:

$$T_{\text{CORE}} \leq 150 - (2T_{\text{ACCESS}} + 2T_{\text{METRO}}).$$

As, in this paper, we only deal with the backbone part of the lightpaths, we must make sure that we do not forget about the delay budget for the access and the metro networks. Consequently, we allow at most one OEO conversion between a source and a destination node pair. In the worst scenario, the OEO conversion delay is within the order of 2 × 10 ms, [28]. If we also consider another 10 ms delay for the EO and OE conversions at the source and the destination nodes, we end up using about 40 ms (out of the 150 ms limit) for the core network traversal, once we have subtracted the delays in the metro and access networks.

5 Multi-Period Node Dimensioning and Provisioning Scheme

For a given MSPP-PXC network nodal architecture, we now investigate how to size it in a dynamic small-batch traffic context. We first state formally the dynamic network provisioning and node dimensioning problem within a multi-period (or multi-interval) network planning scheme (Section 5.1). We next introduce, in Section 5.2, the concept of Optical Independent Routing Configurations (OIRCs) to be used in the network provisioning, where each OIRC is associated with a given wavelength. In Section 5.3, we present two nodal dimensioning strategies, a myopic one and a pre-deployment/anticipative one. Strategies are implemented thanks to two greedy heuristics that are described in Section 5.4.

5.1 Mutli-Period Network Provisioning

In this study, as in [26], we propose to examine dynamic provisioning with the framework of small-batch provisioning under asymmetric traffic. In the context of a dynamic traffic, variations of the client demand correspond to the addition or the termination of some requests. Each ending request releases some resources which can be reused to grant some new requests.

Let T be the set of network planning periods, indexed by $t \geq 1$ and let K^0 be the initial set of requests, indexed by k. At the beginning of period t, the set of requests is defined by:

$$K^t \leftarrow K^{t-1} + K^t_{\text{ADD}} - K^t_{\text{DROP}},$$

where K^t is the set of granted requests at the beginning of period t, K^t_{ADD} (resp. K^t_{DROP}) is the set of new incoming (resp. ending) requests at the outset of period t. At period t, given the provisioning scheme at period $t-1$ and the sets of new incoming and ending requests, we want to find a cost effective network provisioning scheme to satisfy the new incoming request set K^t_{ADD} with respect to the minimum deployment cost, and without any disturbance of the set K^{t-1} of previously granted requests. Nodal equipment setting is modified if needed.

From one period to the next, we assume that a significant fraction of the traffic demand remains the same, representing, e.g., the global steady state traffic or the long term service contract agreements between the service provider and its customers. However, part of the traffic demand varies from one period to the other as a fraction of traffic requests begins or ends at the outset of each period. In our experiments, traffic requests that are either initiated or ending from one period to the other are randomly selected. The percentage of varying traffic requests belongs to the set {5%, 10%, 15%, 20%, 25%, 30%}, giving us a range of cases from slowly fluctuating dynamic traffic instances (5%) to fast changing dynamic traffic instances (30%).

The provisioning cost is defined as the sum of:

- The cost of required MSPP transport blades for add/drop connections at source and destination nodes (or at intermediate nodes when signal regeneration occurs),

- The cost of input/output PXC ports and PXC MEMS mirrors, used to switch connections through the PXCs at the intermediate nodes (where optical bypasses take place). CAPEX (Capital expenses) corresponds to the cost of predeployed provisioning equipment.

We denote by c^{MSPP} the unit cost of a MSPP transport blade port, c^{PXC} the unit cost of a PXC port and c^{MEMS} the unit cost of a 3D PXC MEMS mirror.

5.2 Optical Independent Routing Configurations OIRCs

We can represent an optical mesh network by a directed graph $G = (V, L)$, where V denotes the set of network nodes and L the set of directional fiber links (we assume each physical link to be made of two directional fibers, one in each direction). The transport capacity of each fiber link ℓ is set to W wavelengths belonging to the wavelength set $\Lambda = \{\lambda_1, \lambda_2, \dots, \lambda_W\}$. The number of available wavelengths (transport capacity) is derived from the DWDM system capacity, and the minimum number of required wavelengths (W) in order to grant all requests will be determined in the proposed network provisioning scheme. At any given period, the traffic requests correspond to the set

$$K = \bigcup_{(v_s,v_d)\in\mathcal{SD}} K_{sd},$$

where K_{sd} is the set of requests from v_s to v_d and $\mathcal{SD} = \{(v_s, v_d) \in V \times V : K_{sd} \neq \emptyset\}$ (we omit the t index when there is no ambiguity in order to alleviate the notations).

We define an Optical Independent Routing Configuration (OIRC), denoted by R, as a set of link disjoint single hop lightpaths, indexed by r, that can be all assigned the same wavelength, see Figure 4 and Figure 5(a). A lightpath r is defined by a sequence of fiber links ($\ell \in L$) that join a given source v_s^r to a given destination v_d^r. In addition, for a given request, a single hop lightpath is a lightpath that is only switched through some PXCs, without going through any MSPP, except at the source and destination nodes of the request. Note that an OIRC R is defined by two sets, i.e., the optical link set $L^R = \{\ell \in L :$ there exists a route in R that uses the fiber link $\ell\}$, and the set $V^R = \{v \in V : v$ is the source or the destination of a fiber link $\ell \in L^R\}$ of optical nodes encountered by the lightpaths. We divide the set of lightpaths belonging to a given OIRC as follows. Let $r \in R$ be a lightpath of OIRC R originating at $v_s^r \in V^r$ and ending at $v_d^r \in V^r$. Let k be an arbitrary request of K, originated at node v_s and ending at node v_d.

- If $(v_s^r = v_s)$ and $(v_d^r = v_d)$, then r is a 1H-OIRC lightpath (single hop OIRC lightpath) without any OEO conversion in intermediate nodes between source v_s and destination v_d, as shown in Figure 5(b).
- If $(v_d^r = v_d)$ and $(v_s^r \neq v_s)$, then r is an Hd-OIRC lightpath (OIRC lightpath ending at a request destination node) with an OEO conversion at node v_s^r, as shown in Figure 5(c).
- If $(v_d^r = v_s)$ and $(v_d^r \neq v_d)$, then r is an Hs-OIRC lightpath (OIRC lightpath originating at a request source node) with an OEO conversion at node v_d^r, as shown in Figure 5(d).

We assume that requests are either served by a single hop lightpath, or by a two-hop lightpath. Then, any given request $k \in K$ can be supported by a maximum of two OIRCs.

5.3 Node Dimensioning Strategies

We propose two node dimensioning strategies, i.e., a myopic strategy and an anticipative one. Let $S^{\text{PXC}} \subseteq S$ and $S^{\text{MSPP}} \subseteq S$ be the sets of PXC and MSPP available manufacturing sizes respectively, where $S = \{8, 16, 32, 48, 64, \dots\}$.

5.3.1 Myopic strategy

In the myopic strategy, the nodal dimensioning is done per period of time, i.e., the nodal equipment sizes are updated as needed at each new period t.

We calculate an initial nodal dimensioning (period t_0) using the initial provisioning solution. For each network node $v \in V$, we proceed as follows.

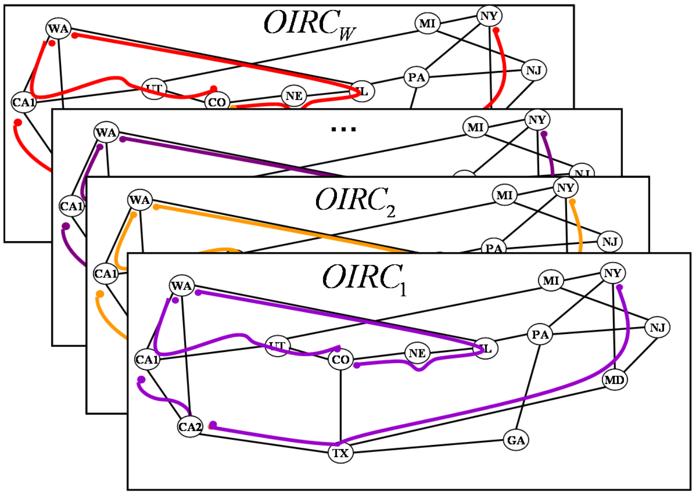
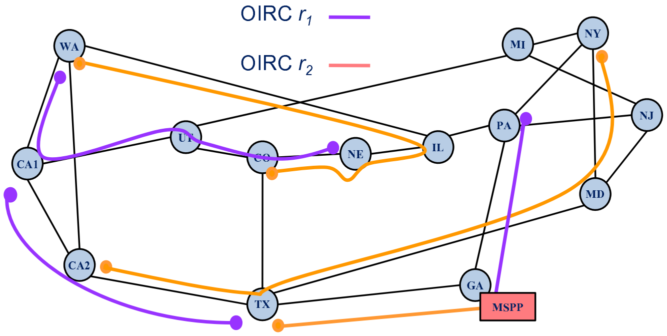
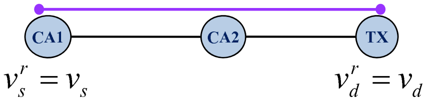


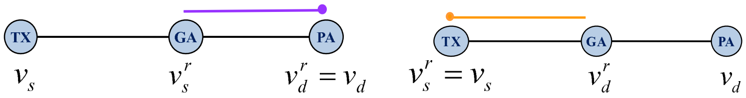
Figure 4: Combining several OIRCs in order to build a network provisioning solution



(a) A set of two OIRCs



(b) 1H-OIRC



(c) Hd-OIRC (d) Hs-OIRC

Figure 5: OIRC, 1H-OIRC, Hd-OIRC, and Hs-OIRC examples

- We look at the node bypasses and we compute the number of needed PXC MEMS mirrors and PXC ports for optical switching. We adjust the resulting numbers to the values of S^{PXC}.
- We look at the add/drop operations of client signals and compute the number of needed MSPP transport blades. Then, we adjust the resulting numbers to the values of S^{MSPP}. The differences between the selected MSPP sizes and the available manufactured sizes will be used later for adding flexibility with a nodal OEO conversion capacity.

At each period t, we first define the network provisioning (see Section 5.4). Next, if the blocking rate is not null, we proceed as follows:

- We increase the number W of available wavelengths as needed at each iteration until we cannot decrease anymore the blocking rate.
- To serve all blocked requests, we increase the number of PXC ports, PXC MEMS and MSPP transport blades as needed, with respect to the available manufactured sizes.

5.3.2 Predeployment strategy

In the anticipative strategy, the network node dimensioning is planned ahead of time, assuming an accurate forecast of the traffic demand is available. To predeploy network resources (i.e., PXC ports and PXC MEMS, MSPP transport blades, and wavelengths) in preparation for traffic demand in a period $t \in T$, we proceed as follows. We calculate the α-shortest paths (see [29]) between all pairs of (source, destination) of set $\mathcal{SD}$, where α is estimated as follows:

$$\alpha = \max \left\{ \alpha^{\max}, \max_{(v_s, v_d) \in \mathcal{SD}} |K_{sd}| \right\}, \tag{2}$$

where $\alpha^{\max}$ is a given bound on the number of paths from v_s to v_d to be considered (beyond a threshold number, they might be too long). Next, we count the number of paths routed through each node. We use the resulting numbers to derive the nodal PXC sizes $N_v^{\text{PXC}}, v \in V$. We next adjust the selected PXC dimensions to the values of S^{PXC}. The nodal MSPP size N_v^{MSPP} is derived as follows:

$$N_v^{\text{MSPP}} = \lceil N_v^{AD} + \frac{N_v^{AD} + N_v^{\text{PXC}}}{1 + N_v^{AD}/N_v^{\text{PXC}}} \rceil^{\text{MSPP}} \qquad v \in V \tag{3}$$

where N_v^{AD} is the number of add/drop in v and $\lceil x \rceil^{\text{MSPP}}$ is the smallest upper value of x belonging to S^{MSPP}.

Formula (3) is driven by the ratio $\frac{N_v^{AD}}{N_v^{\text{PXC}}}$. We can distinguish the following three cases. When the number of bypasses in node v is very small compared to the number of add/drop, then the ratio $\frac{N_v^{AD}}{N_v^{\text{PXC}}}$ negligible and the required N_v^{MSPP} in node v can be estimated through the number of add/drop. When the number of bypasses in node v is close to the number of add/drop, then the ratio $\frac{N_v^{AD}}{N_v^{\text{PXC}}}$ is close to 1 and the required N_v^{MSPP} in node v can be estimated through the sum of the number of add/drop plus the number of bypasses (indeed, we can predict that there are some potential OEO conversion in node v, and in the worst case the number of OEO conversion is equal to N_v^{PXC}). Last, when the number of bypasses in node v is very large compared to the number of add/drop, then the ratio $\frac{N_v^{AD}}{N_v^{\text{PXC}}}$ is dominant in the denominator. It follows that the required N_v^{MSPP} in node v is estimated through the sum of the number of bypasses in node v (we predict that there is a potential need for OEOconversion in node v, and in the worst case the number of OEO conversion is equal to N_v^{PXC}).

5.4 Dynamic Greedy Provisioning Algorithms

We study the case of dynamic provisioning without disturbing the provisioning of any previously granted request. At the beginning of a new period t, we call one of the greedy OIRC algorithms described below, depending on the selected node dimensioning strategy, i.e., myopic or anticipative, in order to provision the new incoming requests of the K^t_{ADD} set.

For both provisioning greedy algorithms, the objective is to establish a provisioning $\mathcal{R}(K^t)$ defined by a set of W Optical Independent Routing Configurations. Let R^{Hs_OIRC}, R^{Hd_OIRC} and R^{1H_OIRC} be the sets of denied Hs-OIRCs, Hd-OIRCs and 1H-OIRCs respectively.

Myopic Dimensioning and Greedy Network Provisioning (MD_GNPRO) Algorithm

Input.
K^t_{ADD}: Set of new incoming connection requests,
$\mathcal{R}(K^{t-1} \setminus K^t_{\text{DROP}})$: Legacy provisioning on the on-going connection requests of the previous time period.

Initialization.
Release the resources allocated to the terminating requests of K_{DROP}, i.e., release their MSPP transport blade ports, PXC ports and PXC MEMS and wavelengths.

Initialize the routing solution of the current t time period as follows: All previously granted requests that are still going on are associated to the same OIRCs than during period $t-1$ as we do not allow any disturbance. Initialize the set of OIRCs with those of the previous time period and the lightpaths which are still active.

Set the list R^{1H}_{sd} of routes for the 1H-OIRC lightpaths to the set of the $|K_{sd}|$ available shortest paths, for all node pairs (v_s, v_d). Let $R^{1H} = \bigcup_{(v_s,v_d)\in\mathcal{SD}} R^{1H}_{sd}$.

Step 2. For every $r \in R^{1H}$, calculate its cost:

$$\text{COST}(r) = 2c^{\text{MSPP}} + N_{sd}(r)(2c^{\text{PXC}} + 2c^{\text{MEMS}})$$

where $N_{sd}(r)$ is the number of traversed nodes between the source v_s and the destination v_d, $2c^{\text{MSPP}}$ is the cost of the MSPP input and output ports used respectively to add and drop the r lightpath signal, $2c^{\text{PXC}} + 2c^{\text{MEMS}}$ is the cost of the PXC input/output ports and MEMS mirrors used to switch the r lightpath through a PXC at an intermediate node.

Step 3. Sort the routes of R^{1H} in their increasing cost order.

Step 4.
```
If ($R^{1H} \neq \emptyset$) then
  Select the first 1H-OIRC $r$ in the list.
  Check the number of available PXC ports $N_v^{\text{PXC}}$ at each
    intermediate node $v \in r$ for $v \notin \{v_s, v_d\}$.
  If ($N_v^{\text{PXC}} > 0$) for all $v \in r$, then go to Step 5.
  Else
    If ($N_v^{\text{PXC}} = 0$) for exactly one node $v \in r$, then
      Increase the number $N_v^{\text{MSPP}}$ of available MSPP transport
        blades as needed in the regeneration node $v$
        (i.e., by 2 MSPP ports),
      Set $r_{sv}$ to the H$s$-OIRC lightpath and $r_{vd}$ to the
        H$d$-OIRC lightpath derived from the splitting of $r$
        following the addition of an OEO conversion at node $v$,
      Add $r_{sv}$ to $R^{\text{Hs\_OIRC}}$ and $r_{vd}$ to $R^{\text{Hd\_OIRC}}$,
      Go to the beginning of Step 4.
    Else
      Add $r$ to the list $R^{1H\_\text{OIRC}}$ of denied 1H-OIRC lightpath
      Go to the beginning of Step 4.
Else Go to Step 6.
```

Step 5. If there exists a configuration R in the current set of OIRCs such that $L^R \cap \{r\} = \emptyset$, then add the fiber links of r to L^R. Otherwise, augment the current set of OIRCs with a new one configuration defined by route r. Go to Step 4.

Step 6. For each $r_{sv} \in R^{\text{Hs\_OIRC}}$, find if there exists a configuration R in the current set of OIRCs that is available in order to route the first optical hop (Hs-OIRC). If yes, find if there is a second configuration OIRC r' that can support the complementary optical hop (Hd-OIRC) $r_{vd} \in R^{\text{Hd\_OIRC}}$. If such configurations do not exist for one or two of the optical hops, then we add a new OIRC to the current set of OIRCs for routing the optical hops r_{sv} or r_{vd} which remain unmatched with a physical route.

Step 7. If $R^{1H\_\text{OIRC}} \neq \emptyset$, then sort the routes of R^{1H_OIRC} in their increasing cost order, and go to Step 8. Otherwise, all demands are satisfied, go to Step 9.

Step 8. For each blocked 1H-OIRC lightpath $r \in R^{1H\_\text{OIRC}}$, we increase the number of available PXC ports N_v^{PXC} at each intermediate node $v \in r$ (i.e., by 2 PXC ports and 2 MEMS). Then add R^{1H_OIRC} to R^{1H} and return to Step 4.

Step 9. Assign wavelengths to the OIRC configurations as follows:

```
If the OIRC configuration has been generated in the previous
    periods and has on-going request connections, then
    it is assigned the same wavelength as in the
    previous time period
Else the OIRC configuration is assigned an available
    unused wavelength.
```

Predeployment Dimensioning and Greedy Network Provisioning (PD_GNPRO) Algorithm

The PD_GNPRO algorithm has the same input parameters and the same steps as the GD_GNPRO algorithm, except for Steps 4 to 9 which are replaced by the following Steps 4 to 7.

Step 4.

```
If ($R_{1H} \neq \emptyset$) then
  select the first 1H-OIRC $r$ in the list.
  check the number of available PXC ports $N_v^{\text{PXC}}$ at each
    intermediate node $v \in r$ for $v \notin \{v_s, v_d\}$.
  If ($N_v^{\text{PXC}} > 0$) for all $v \in r$, then go to Step 5.
  Else
    If ($N_v^{\text{PXC}} = 0$) for exactly one node $v \in r$, then
      Set $r_{sv}$ to the H$s$-OIRC lightpath and $r_{vd}$ to the
      H$d$-OIRC lightpath derived from the splitting of $r$
      following the addition of an OEO conversion at node $v$.
      Add $r_{sv}$ to $R_{\text{Hs\_OIRC}}$, and $r_{vd}$ to $R_{\text{Hd\_OIRC}}$,
      go to the beginning of Step 4.
Else go to Step 6.
```

Step 5. Choose a configuration R in the current set of OIRCs, such that $L^R \cap r = \emptyset$ then add r to L^R and go to Step 4.

Step 6. For each $r_{sv} \in R^{\text{Hs\_OIRC}}$, find a configuration R from W OIRCs to route the first optical hop (Hs-OIRC). Then, find a second configuration OIRC r' to support the complementary optical hop (Hd-OIRC) $r_{vd} \in R^{\text{Hd\_OIRC}}$.

Step 7. Identical to Step 9 in the GD_GNPRO algorithm.

5.5 Lifetime Network Planning Scheme

In a dynamic traffic context, optical networks are usually upgraded over the whole lifetime network cycle to be adapted to a new demand pattern. As these manual settings imply additional costs, appropriate choice of the node dimensioning and provisioning strategy must be dealt with at the beginning and during the whole network planning process. We present in Figure 6 our proposed planning scheme, where the meaning of the acronyms is as follows:

- PROV(K^t): Provisioning of the set K of traffic requests at time period t.
- NEC(K^t): Required nodal equipment dimensioning in order to satisfy the set K of requests at time period t.
- CG: Column Generation (CG) Provisioning algorithm previously proposed by the authors [4].

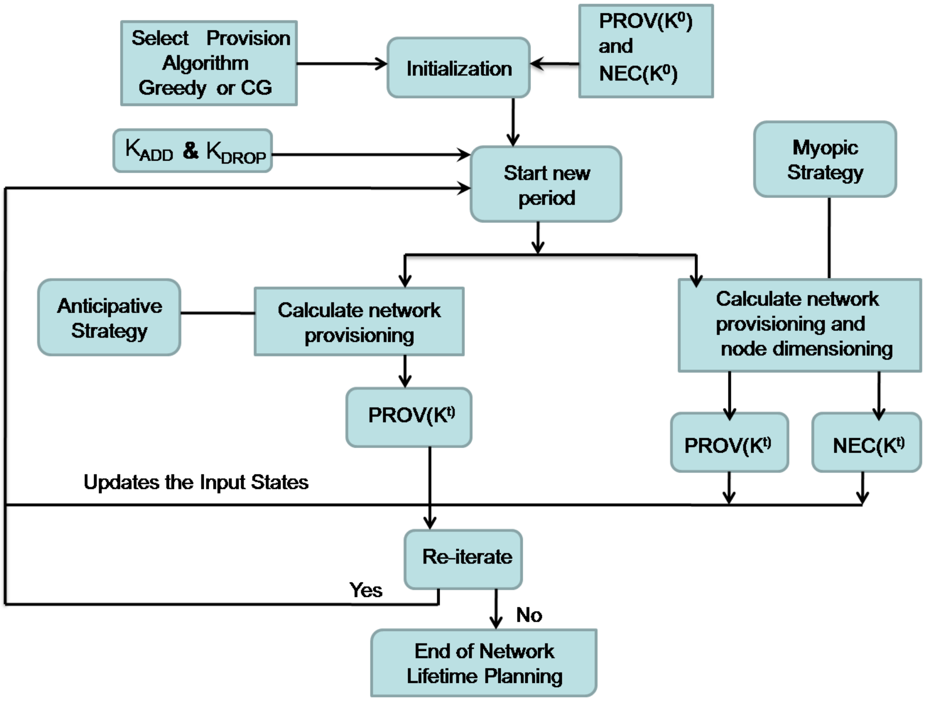


Figure 6: Network lifetime planning

6 Computational Results

We implemented the myopic and anticipative strategies proposed in Sections 5.3.1 and 5.3.2. We compared their resulting solutions against the optimal one obtained using the column generation algorithm [4]. We describe in Section 6.1 the network and traffic instances. We define in Section 6.2 some metrics in order to facilitate the interpretation of the experimental results. Numerical results are presented in Section 6.3.

6.1 Network and Traffic Instances

We consider two network instances NSFNET (14 nodes, 48 links) and EONET (20 nodes, 78 links). To study the effects of the selected dimensioning strategy and provisioning approach, we consider a set T of periods for each traffic instance. At period $t \in T$, we have ADD new requests and DROP dropped requests, where ADD, DROP $\leq 30\%$ of current traffic requests, see Section 5.1. For each network, we consider an initial instance of traffic randomly and uniformly distributed among all network nodes. The network cost design structure as described in Section 5.1 uses the following typical values: $c^{\text{MSPP}} = 20k\$$, $c^{\text{PXC}} = 1k\$$ and $c^{\text{MEMS}} = 5k\$$, see [30], p. 42. Performance evaluation of provisioning and dimensioning algorithms are run on DELL machines with Intel PIV 3.1 GHZ and 3 GB of RAM memory, we use ILOG CPLEX Optimizer 9.1.3 for the column generation network provisioning algorithm [4].

6.2 Metrics

To facilitate the interpretation of the numerical results, we use the following metrics.

- Network load:

$$\text{LOAD} = \frac{\sum\limits_{\lambda \in \Lambda} \sum\limits_{e \in E} \sum\limits_{k \in K} x_{ke}^{\lambda}}{W \times |E|} \tag{4}$$

  where $x_{sde}^{\lambda} \in \{0,1\}$ is associated with a triplet composed of a connection $k \in K$, an arc $e \in E$ and a wavelength $\lambda \in \Lambda$, and it is defined as follows: $x_{ke}^{\lambda} = 1$ if connection k uses wavelength λ on fiber link e and 0 otherwise.

- Overall MSPP transport blade usage:

$$R_{\text{MSPP}} = \frac{\sum\limits_{v \in V} U_v^{\text{MSPP}}}{\sum\limits_{v \in V} N_v^{\text{MSPP}}} \tag{5}$$

  where U_v^{MSPP} and N_v^{MSPP} are respectively the number of used and available MSPP transport blades in node $v \in V$.

- Overall PXC MEMS and port usage:

$$R_{\text{PXC}} = \frac{\sum\limits_{v \in V} U_v^{\text{PXC}}}{\sum\limits_{v \in V} N_v^{\text{PXC}}} \tag{6}$$

  where U_v^{PXC} and N_v^{PXC} are respectively the number of used and available PXC MEMS in node $v \in V$.

6.3 Numerical Results

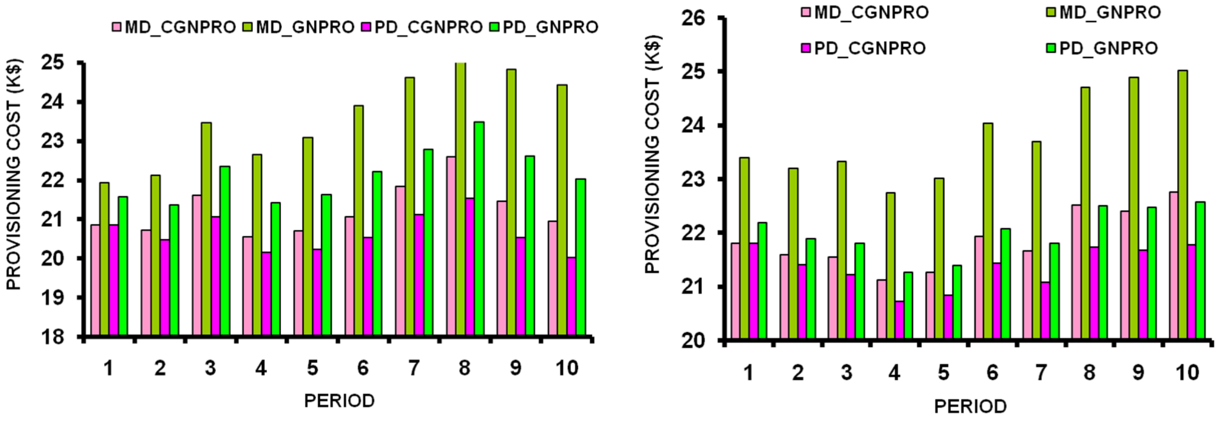
Performance evaluation was performed on two network topologies with respect to: Demand provisioning cost, computing time, network load, nodal equipment usage, and network CAPEX. Comparisons were made using the four provisioning and dimensioning algorithms described in Section 5.5. They will be cited as follows:

- MD_CGNPRO: Myopic dimensioning with the column generation network provisioning algorithm [4].
- PD_CGNPRO: Predeployment dimensioning with the column generation network provisioning algorithm [4].
- MD_GNPRO: Myopic dimensioning and greedy network provisioning algorithm (see Section 5.4).
- PD_GNPRO: Predeployment dimensioning and greedy network provisioning algorithm (see Section 5.4).

Note that, MD_CGNPRO and PD_CGNPRO are two integer linear programming (ILP) algorithms providing optimal solutions, thanks to large scale optimization tools (i.e., column generation techniques).

6.3.1 Provisioning Cost Comparison

In Figure 7(a) (resp. Figure 7(b)), we compare the provisioning cost for the four algorithms on the NSFNET (resp. EONET) topology. The gap between CG (Column Generation) and the greedy provisioning cost solution is on average less than 10% for the two different network instancesand for both network dimensioning strategies. We observe that wa are able to derive a near optimal provisioning and dimensioning solution with the greedy algorithms, even for a large network and an important traffic demand. Indeed, the provisioning cost gap depends largely on the network topology and on the dimensioning strategy. In the case of less connected networks, i.e., NSFNET, the mean network provisioning cost gap is in the order of 10% for the MD (Myopic Dimensioning) and 7% for the PD (Predeployment Dimensioning). This gap becomes less important as the network becomes more connected, see the results for EONET where the nodal degree is never less than 3: Therein, the network provisioning cost gap is in the order of 8% and 4% for the MD and PD strategies, respectively.



(a) NSF Network (b) EONET Network

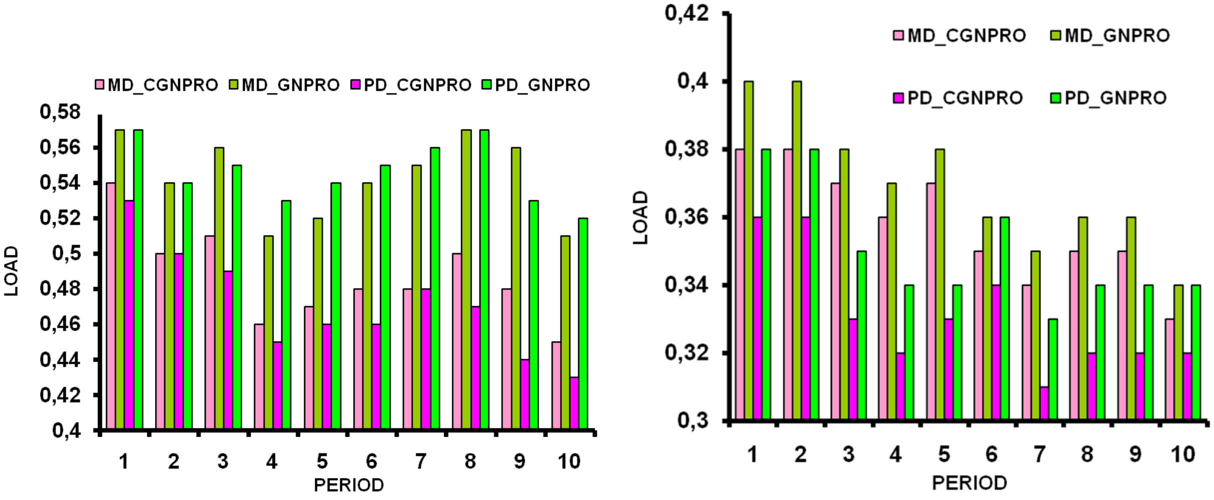
Figure 7: Provisioning Cost

6.3.2 Computing Times

We investigate the effects of network topology and the dimensioning strategy on the ratio between greedy and CG computing time. On average, this ratio varies from $\frac{1}{5000}$ to $\frac{1}{40000}$ for NSFNET network and from $\frac{1}{400}$ to $\frac{1}{45000}$ for EONET network. Thus, this ratio becomes less important as the network becomes more connected. Moreover, we observe that the computing time ratio is proportional to the quantity of resources available on the network nodes. In predeployment dimensioning scheme, network resources were predeployed over-time assuming a future forecast of traffic pattern is known. Thus, the provisioning process becomes less constrained to network resource availability, and the convergence to optimal or near optimal provisioning solutions is faster.

6.3.3 Network Load

Figure 8(a) (resp. Figure 8(b)) plots the network load for the NSFNET (resp. EONET) network. We observe a better bandwidth usage in the case of the predeployment dimensioning strategy, for both provisioning algorithms, i.e., the greedy one and the CG exact one. As expected, the network load is inversely proportional to the network resource availability. Indeed, the selected provisioning path length (i.e., number of network links) depends largely on the availability of PXC MEMS and PXC ports, and MSPP transport blades in the network nodes.



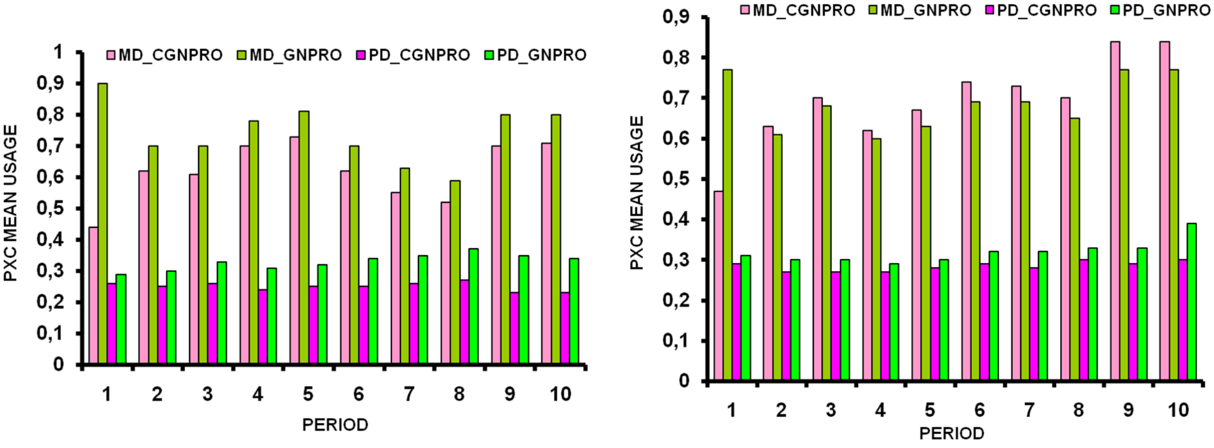
(a) NSF Network

(b) EONET Network

Figure 8: Network Load

6.3.4 Nodal Equipment Usage

In Figures 9(a) and 9(b), we investigate the performance network parameter R_{PXC} for NSFNET and EONET networks, respectively . From these histograms, it is clear that the predeployment dimensioning strategy achieves a better use of PXC ports and MEMS. The PXC mean usage gap between myopic and predeployment strategies is proportional to network mean nodal degree, i.e., it increases with the network nodal degree.

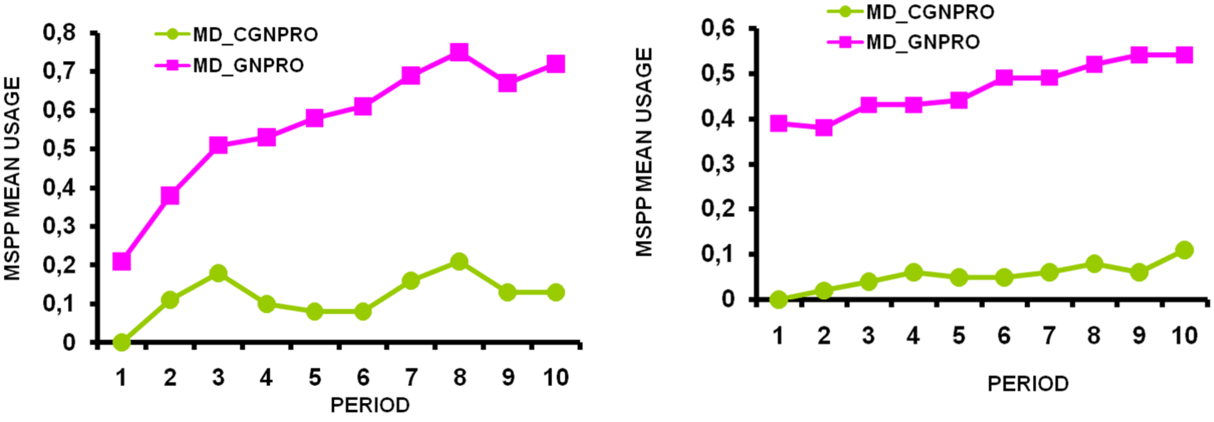


(a) NSF Network

(b) EONET Network

Figure 9: PXC Mean Usage

As expected, with the predeployment dimensioning strategy, we observe that all requests are switched through the PXC fabrics. This is due to the cost provisioning structure. Indeed, a request k_1 routed through the MSPP platform implies an OEO conversion with a cost of $2c^{\text{MSPP}}$. A request k_2 switched through the PXC fabric implies a cost of $(2c^{\text{PXC}} + 2c^{\text{MEMS}}) < 2c^{\text{MSPP}}$. For that reason, we study, in Figures 10(a) and 10(b), the R_{MSPP} performance parameter only for the myopic dimensioning strategy, where we observe that some requests are switched through the MSPP platforms. In these graphs, we explore the effects of the selected provisioning demand algorithm on the MSPP mean usage. We observe that the greedy provisioning scheme uses more MSPP transport blades than the CG provisioning scenario. The MSPP mean usage is proportional to the PXC mean usage with the myopic strategy. Indeed, client requests are routed through the MSPP when there is no more available optical switching ports and MEMS in the PXC fabric. In other words, the PXC mean usage gets closer to the full switching capacity as more demands are routed through the MSPP transport blades. As a result, the MSPP mean usage increases.



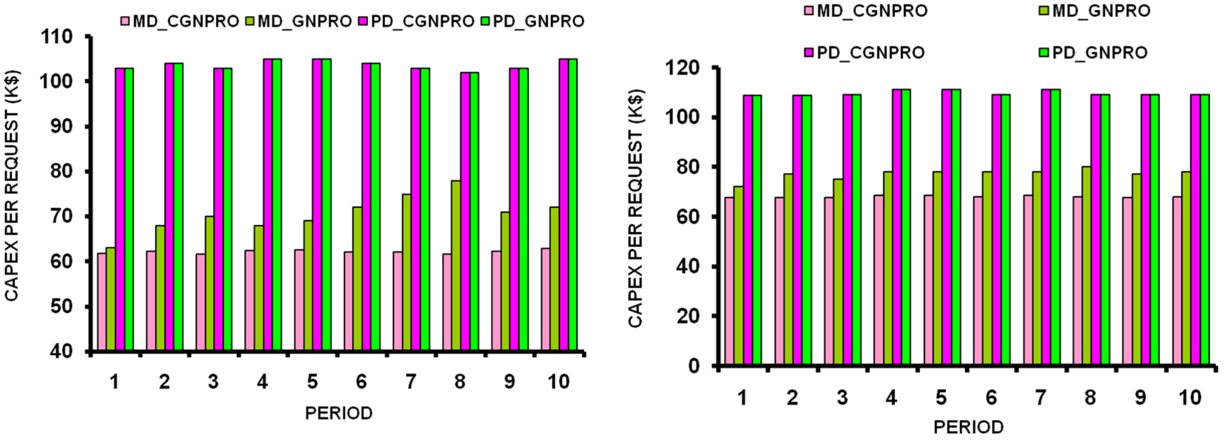
(a) NSF Network (b) EONET Network

Figure 10: MSPP Mean Usage

Myopic dimensioning strategy takes into account separately the demand for each planning period. Thus network resources are extended and resized as needed. This gives us surely the cheapest resources usage per period. However, such a cheap resource usage comes at the expense of the optimality over the full network lifetime planning process. In the predeployment network dimensioning strategy, resources are planned ahead of time assuming a forecast of the traffic matrix is available. Thus, this dimensioning approach guarantees an optimal resource usage over the planning network lifetime. Then, the following question arises: Why do we need to investigate the myopic dimensioning strategy? We next discuss the CAPEX in order to answer this question.

6.3.5 Network CAPEX

Figures 11(a) and 11(b) present a CAPEX analysis, which gives us the first part of the answer. Indeed, it is clear from these histograms that, the predeployment dimensioning strategy has a greater CAPEX per demand mean value than the myopic one. This is also true for the CG and the greedy approaches. The second part of the answer is provided by the demand deviation factor, see [12] for its definition. The client traffic forecast is an estimate and can change over time. Thus, if the real network traffic diverges from the predicted pattern, then predeployment strategy no longer guarantees network resource optimality use over the whole lifetime planning process. Myopic approach is not impaired as the network planning is done per period and does not rely on future client behaviors. In addition, technology evolution factor, see [12] for its definition, can affect the cost of network resources. This in turn would affect the predeployment resources plan, e.g., case where optical switching through PXC fabric becomes more expensive than an OEO provisioning through the MSPP. In such a case, myopic strategy is not impaired since the planning process can react per period. If we take into account the above highlighted factors then predeployment dimensioning strategy cannot guarantee an efficient network extension over time.



(a) NSF Network

(b) EONET Network

Figure 11: CAPEX per Demand

7 Conclusion and Future Work

We present an agile and scalable network design based on Multi-Service Provisioning Platform and Photonic Cross-Connect. We compare two network dimensioning strategies, i.e., myopic vs. predeployment. We propose a new dynamic network provisioning greedy approach to avoid the high computation time observed in case of column generation rounding algorithm, proposed previously by the authors. From experiment results, we conclude that the greedy heuristic can achieve a very good approximation of optimal network dimensioning and demand provisioning solution. We explore also the impact of the selected dimensioning strategy on the provisioning scheme and on the network CAPEX. The numerical results show that the lowest provisioning cost is obtained with the predeployment strategy, however it yields an initial high CAPEX cost. The myopic strategy derives the cheapest network dimensioning expenses per period over the lifetime planning plan, however it derives a greater provisioning cost than the predeployment one. Thus, predeployment strategy is preferable if demand forecast pattern is reliable.

In the present work, each node was equipped with an MSPP and a PXC that had enough ports to ensure every traffic request is properly serviced. Although useful for the development of our greedy algorithms, cost issues in real life situations might not permit that every node is fully equipped with a PXC. Our future work will consider the dimensioning of the PXC switching fabrics and the impact of the PXC location on the demand network provisioning cost. Using our greedy algorithms, we will reduce the number of PXCs in the network while keeping the size of their switching fabric at a minimum. Influence of the few PXCs location will be investigated. We suspect the best PXC location is within high connectivity nodes. It will also be interesting to verify if nodes with PXCs will naturally act as "traffic demand attractors". It is effectively possible that the few nodes equipped with PXCs, due to their additional wavelength switching capability, will have a tendency, in average, to be crossed by more traffic requests than non-PXC nodes. This remains to be verified.

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