Reducing the CAPEX and OPEX Costs of Optical Backbone Networks

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Abstract—The focus of this paper is on the minimum cost resource provisioning and nodal equipment location (PROVLOC) problem for Wide Area Networks (OWANS), i.e., optical networks that cover broad areas. Minimizing the cost means minimizing the network capital and operational expenditures throughout the dimensioning of the nodal equipment, and the location of all-optical cross-connects, while granting all traffic requests. This is done thanks to large scale modeling and optimization tools relying on a scalable column generation method and an efficient rounding off heuristic. Experiments on various network and traffic instances show that a careful dimensioning and location of the nodal equipment can save up to 60% of the number of photonic cross-connects (PXC), and even more sometimes.

Index Terms—Multiservice Provisioning Platform; Photonic Cross-connect; Capital Expenditures; Operational Expenditures.

I. INTRODUCTION

A key objective of an OWAN design is its ability to keep the increase of Capital Expenditures (CAPEX) closely in line with the growth of network revenues. Indeed, the better is the network planning scheme, the better is the control of network Capital and Operational Expenditures (OPEX) growth. Thus, any new optical network design must minimize the initial CAPEX, as high CAPEX can make the provision of a new service unprofitable. Consequently, the challenge, when deploying a new optical network, is the ability to keep the growth of the network bandwidth in line with the increase of revenues. However, the literature contains few works that address those economical and trade-off issues.

In [1], Han studies an hybrid optical transport architecture in the context of ring Metro network design. He also presents a pertinent analysis of the economic impact of the integration of SONET and DWDM technologies on network CAPEX.

In [2], only a comparative qualitative description has been made on commonly accepted design scenarios, i.e., opaque, hybrid and all-optical. The authors look at the network design from the agility and scalability perspectives. Indeed, they investigate the effect of the used agility scenario and the predeployment network planning strategy on the capital and operational network expenditures. They do not address the network dimensioning aspect.

Similarly, in [3], a pertinent comparative study of hybrid and all-optical switching architectures is presented. The authors investigate the synergy between optical and electrical cross-connection and its effect on the network agility and scalability levels. In addition, they show that an hybrid switching architecture results in additional economical benefits, i.e., reduction of CAPEX and OPEX. However, the study only provides a qualitative evaluation of the aforementioned architecture.

In [4], the authors explore the merits of the coexistence of opaque and transparent architectures. They show that the higher complementarity of the two alternative technologies is, the higher is the control of network capital and operational expenditures. Indeed, the basic trade off between these switching technologies is cost versus flexibility.

In all the aforementioned references, the network designers adopt a uniform distribution of networking resources across network nodes and therefore, an homogeneous network architecture. The same nodal configuration is set in each network node. Such a design does not allow the optimization of the number of facilities and their strategical physical location and, accordingly, the minimization of the overall network capital and operational expenditures. Instead, it results in the deployment of much more networking resources than needed, meaning additional cost and complexity.

On the contrary, in our study, we investigate a joint optimization of the traffic provisioning, as well as the minimization of the CAPEX/OPEX expenditures. Demand provisioning is a classical problem which consists in the selection of a set of lightpaths to grant demand requests, and has been extensively studied in the case of homogeneous network architectures, i.e., each network node is equipped with a uniform structure, see [5] for surveys. Therefore, to the best of our knowledge, none of the existing studies has addressed the following questions: (i) Where are the optimal switching fabric locations among network nodes as well as their best dimensioning? (ii) How should all demands be provisioned in order to minimize the network CAPEX and OPEX expenditures.

The contribution of our paper lies on the forethought and
the examination of these issues. To do so, we establish a mathematical model which can be solved efficiently using large scale optimization tools based on column generation techniques, see, e.g., [6].

The paper is organized as follows. The next section describes the selected nodal architecture. Section III defines the explored network design issues. In Section IV, we elaborate the mathematical modeling. In Section V we propose an algorithm to solve the model of the previous section. In Section VI, we present the numerical results. Conclusions are drawn in the last section.

II. AN HYBRID SWITCHING ARCHITECTURE

We propose to investigate a translucent transport architecture based on two switching layers, one electrical and one photonic layer. The electrical layer is built with SONET equipment, i.e., Multi Service Provisioning Platform (MSPPs), for the edge traffic aggregation, shaping and grooming platforms (see, e.g., [1], [7]), while the photonic layer is based on a Photonic Cross-Connect fabric for the transport core component that enables a transparent optical mesh architecture. As illustrated in Figure 1(b), to multiplex and demultiplex WDM signals, we install as many MUX and DEMUX as the number of incoming/outgoing fibers in each node. The MSPP and the PXC (Photonic Cross Connects) are working on the same set of wavelengths.

![MSPP-PXC architecture of a node of degree 2](image)

III. PROVLOC DESIGN PROBLEM

In case if the selected nodal architecture, the CAPEX and OPEX expenditures include the cost of required add/drop client signals, i.e., SONET MSPP transport blades, switching components, i.e., PXC ports and PXC MEMS, and all other expenditures related to the network facilities, i.e., the commissioning and setting cost of network fabrics. As we note that: (i) The capital expenditures related to the initial installation cost of PXC fabrics used on high-speed network side to switch transport signals through backbone transport architecture are the main cost factor in network capital and operational expenditures, (ii) The MSPP transport blades, which are the interfaces between the optical and the electrical domains, are the main cost element on a MSPP fabric.

Accordingly, minimizing the number of required switching fabrics as well as the number of unused MSPP transport blades to grant all demand requests is then a good strategy for network CAPEX and OPEX costs minimization. Thus, the new objective of the addressed design problem is to find the minimum number of required switching fabrics and the minimum unused MSPP transport blades as well as their optimal node location and dimensioning, while granting all traffic demands by solving the provisioning problem, we call this design problem PROVLOC for Provisioning and Location.

IV. MATHEMATICAL MODELING

The optical mesh network is represented by a directed graph $G = (V, E)$ where $V$ denotes the set of nodes and $E$ the set of fiber directional links (we assume each physical link to be made of two directional fibers, one in each direction). Each directional fiber contains $W$ wavelengths. We denote by $\omega(v)$ the set of adjacent links of a node $v$, and, when necessary distinguish the set $\omega^+(v)$ of incoming links and the set $\omega^-(v)$ of outgoing links.

The traffic corresponds to a set $K$ of connection requests where $K = \bigcup_{(s,d) \in SD} K_{sd}$ and $SD = \{(s,d) \in V \times V : K_{sd} \neq \emptyset\}$ is the set of pairs of origin and destination of the requests. We denote by $k_{sd}$ the set of connection requests from source $s$ to destination $d$.

As aforementioned in Section I all the ILP formulations proposed in the literature for the static provisioning problem share the drawback to be highly symmetrical with respect to lightpaths permutation [8]. In order to circumvent this symmetry, which might be a significant drawback for solving the ILP problem exactly, we reformulate the provisioning problem in terms of Optical Independent Provisioning Configurations (OIPCs). We define an OIPC as a set of lightpaths using the same wavelength $\lambda$ and we denote by $R$ the set of all possible OIPC configurations.

Accordingly, the provisioning problem can be formulated with respect to the variables $w_r$, where $w_r$ is the number of times we use configuration $r$. Thus, the provisioning problem under the new formulation consists to choose a maximum of $W$ OIPCs to satisfy the client demands. The resulting formulation is called master problem in the context of a column generation approach [5].

1) Notations and variables: We assume that connection requests are served by a single-hop and/or two-hop and/or three-hop lightpaths. An OIPC configuration $r \in R$ is defined by the vector $(a_{sd}(r))_{(s,d) \in SD}$ as follows.

- If $a_{sd}(r) = 0$, no request is served from $s$ to $d$ on the wavelength associated with $r$. 

Fig. 1. MSPP-PXC architecture of a node of degree 2
• If \( a_{sd}^r = 1 \), there are two cases. If \( \beta_{svd}^r = 0 \) for all \( v \in V \) then, \( w_r(s,d) \) requests are granted with a single-hop lightpath. Else if \( \beta_{svd}^r = 1 \) then, \( w_r(s,d) \) requests are granted with two-hop or three-hop lightpaths depending on the number of times the current lightpath is switched through a MSPP.

where \( \beta_{svd}^r = 1 \) if there is an OEO switching through the MSPP of node \( v \in V \) between the source \( s \) and destination \( d \) and \( r \) otherwise. and we set an upper bound of two or three hops (\( \sum_v \beta_{svd}^r \leq 2; (s,d) \in SD, \) and \( r \in R \). ) on the selected provisioning paths as an indirect way to enforce the end-to-end delay, which is crucial for some real-time applications, i.e., VoIP, Video Conferencing, etc [8]. To count the number of PXC ports and MEMS used by the lightpath serving demand \((s,d)\) on configuration \( r \), we define the following variables: \( a_{sd}^r = 1 \) if there is an optical switching through the PXC of node \( v \in V \) between the source \( s \) and node \( d \) and \( r \) otherwise. We denote by cost \( c \), the cost of configuration \( r \). It corresponds to the costs of: (i) The MSPP ports used to add and drop connections on source and destination nodes respectively, (ii) the PXC input/output ports and the PXC 3D MEMS mirrors, used to switch connections through PXC’s of intermediate nodes, and (iii) the cost of MSPP ports used to switch electrically some connections through MSPPs of intermediate nodes. We define cost, as follows:

\[
\text{cost}_r = 2c_{\text{MSPP}} \sum_{(s,d) \in SD} a_{sd}^r + 2c_{\text{MSPP}} \sum_v \beta_{svd}^r + (2c_{\text{PXC}} + 2c_{\text{MEMS}}) \sum_{(s,d) \in SD} \sum_v \alpha_{svd}^r.
\]

To decide where we install a PXC in network nodes, we define the following variables. \( z_{v}^{\text{PXC}} = 1 \) if we install a PXC in node \( v \in V \) or 0 otherwise. To select the appropriate PXC size in node \( v \in V \), we define the following variables:

\[
z_{v}^{\text{PXC}} = \text{size of the PXC at node } v \text{ if we install one, 0 otherwise (no PXC at node } v)\]

To decide where we allow an OEO switching through the MSPP of network nodes, we define the following variables:

\[
y_{v}^{\text{MSPP}} = 1 \text{ if we allow an OEO switching through the MSPP in node } v \in V \text{ and 0 otherwise.}
\]

Thus the reduced cost of variable \( w_r \) can be written:

\[
\text{cost}_r = \text{cost}_r - \sum_{(s,d) \in SD} u_{sd} u_{sd}^T v + \sum_{v \in V} u_{v}^{\text{NBP}} \sum_{(s,d) \in SD} 2\alpha_{svd}^r + \sum_{v \in V} u_{v}^{\text{PXC}} \sum_{(s,d) \in SD} 2\beta_{svd}^r + u_0.
\]

2) Master problem: Let \( S_1 = \max_{v \in V} S_{v}^{\text{PXC}} \) and \( S_2 = \max_{v \in V} S_{v}^{\text{MSPP}} \) be an upper bound on the number of PXC ports and switching MSPP transport blade ports respectively. We denote by \( ILP(M) \) the master problem and we define it as follows.

**Objective:** \( \min \sum_r \text{cost}_r \)

**Constraints:**

1. \( \sum_r w_r \leq W \)
2. \( \sum_{r \in R} a_{sd}^r w_r \geq |h_{sd}| \quad (s,d) \in SD \)
3. \( \sum_{v \in V} y_v^{\text{PXC}} \leq N_{\text{PXC}}; \sum_{v \in V} y_v^{\text{MSPP}} \leq N_{\text{MSPP}} \)
4. \( z_{v}^{\text{PXC}} \leq z_{v}^{\text{PXC}}; z_{v}^{\text{MSPP}} \leq S_{v}^{\text{MSPP}} \quad v \in V \)
5. \( S_{1} y_{v}^{\text{PXC}} - z_{v}^{\text{PXC}} \geq 0 \quad v \in V \)
6. \( S_{2} y_{v}^{\text{MSPP}} - z_{v}^{\text{MSPP}} \geq 0 \quad v \in V \)
7. \( z_{v}^{\text{PXC}} - 2 \sum_{(s,d) \in SD} \sum_{r \in R} w_r \alpha_{r}^{s} \geq 0 \quad v \in V \)
8. \( z_{v}^{\text{MSPP}} - 2 \sum_{(s,d) \in SD} \sum_{r \in R} w_r \beta_{r}^{s} \geq 0 \quad v \in V \)
9. \( y_{v}^{\text{PXC}}, y_{v}^{\text{MSPP}} \in \{0,1\} ; \quad z_{v}^{\text{PXC}}, z_{v}^{\text{MSPP}} \in \mathbb{N} \quad v \in V \)
10. \( w_r \in \mathbb{N} \quad r \in R \)

Constraint (1) corresponds to the wavelength capacity, i.e., no more than \( W \) wavelengths are available on each fiber link. Constraints (2) ensure that all request demands are satisfied. Constraints (3) guarantee that there are no more than \( N_{\text{PXC}} \) and \( N_{\text{MSPP}} \) switching fabrics and transport blade ports available in minimum CAPEX and OPEX network budget respectively. Constraints (4) guarantee that the selected size of PXC fabric and the number of MSPP switching transport blade ports in a given network node, does not exceed the available sizes \( S_{v}^{\text{PXC}} \) and number \( S_{v}^{\text{MSPP}} \) respectively. Constraints (5) and (6) decide of the installation of a PXC and MSPP switching transport blades in a given network nodes respectively. Constraints (7) and (8) count the number of PXC ports and MSPP switching transport blades ports in a given network node respectively. Constraints (9) and (10) define the domain of the variables.

3) Pricing problem: We define the pricing problem as follows. Let \( u_0, u_{sd}^T, u_{v}^{\text{NBP-PXC}} \) and \( u_{v}^{\text{NBP-MSPP}} \) be the dual variables associated with the constraints (1), (2), (7) and (8) respectively. Thus the reduced cost of variable \( w_r \) can be written:

\[
\text{cost}_r = \text{cost}_r - \sum_{(s,d) \in SD} u_{sd} u_{sd}^T v + \sum_{v \in V} u_{v}^{\text{NBP-PXC}} \sum_{(s,d) \in SD} 2\alpha_{svd}^r + \sum_{v \in V} u_{v}^{\text{NBP-MSPP}} \sum_{(s,d) \in SD} 2\beta_{svd}^r + u_0.
\]

In order to linearize and express the reduced cost and the constraints of the pricing, let us define the following variables.
in functional graph \( G^F = (V^F, L^F) \) associated to \( G = (V, E) \): 
\[ x_{sd}^e = 1 \text{ if an } (s, d) \text{ connexion uses arc } e \in L^F \text{ and } 0 \text{ otherwise. Consequently, we derive for each } r \in R \text{ and } (s, d) \in SD \text{ the following relations:} \]
\[ a_{vd}^r = \sum_{e \in \omega^+(v)} x_{sd}^e \]

For each node \( v \in V \) where a bypass occurs at \( v \), we associate a PXC node with \( v \in V \) in graph \( G_F \). We then have:
\[ a_{vd}^r = \sum_{e \in \omega^+(v)} x_{sd}^e \]

For each node \( v \in V \) where a transport signal regeneration occurs at \( v \), we associate a MSPP node with \( v \in V \) in graph \( G_F \). We then have:
\[ a_{vd}^r = \sum_{e \in \omega^+(v)} x_{sd}^e \]

Using (11), (12), and (13), we can then deduce a linear expression of the reduced cost.

Let us now describe the constraints of the pricing problem.

**Hop limit constraints**
\[ \sum_{v \in V_{s, d}} \sum_{e \in \omega(v)} x_{sd}^e \leq H \quad (s, d) \in SD. \]

where \( H \leq 3 \) hops, depending on the selected provisioning scheme, i.e., we allow one or two passes through an MSPP, between any pair of source and destination nodes.

**Wavelength Clash constraints**
\[ \sum_{(s, d) \in SD} x_{sd}^e \leq 1 \quad e \in L^F. \]

**Flow conservation constraints**
\[ \sum_{e \in \omega^+(v)} x_{sd}^e - \sum_{e \in \omega^-(v)} x_{sd}^e = 0 \quad (s, d) \in SD, v \in V \setminus \{v_s, v_d\}. \]

**Provisioning path constraints**
\[ \sum_{e \in \omega^+(v)} x_{sd}^e \leq 1, \quad \sum_{e \in \omega^-(v)} x_{sd}^e \leq 1 \quad (s, d) \in SD. \]

V. SOLVING THE MATHEMATICAL MODELING
To solve the (ILP(M)) mathematical model of provisioning and equipment location problem, we propose the following algorithm.

**Network_Provisioning_Equipment_Location()**

Denote by \( LP(M) \) the continuous relaxations of \( ILP(M) \), obtained by exchanging the integrality constraints (10) by \( w_r \in \mathbb{R}^+ \) for any \( r \in R \). Initialize \( LP(M) \) by a subset of artificial configurations.

1. Relax the integrality of \( LP(M) \) variables as follows: 
\[ y_{uv}^{PXC}, y_{uv}^{MSPP} \in [0, 1], z_{uv}^{PXC}, z_{uv}^{MSPP} \in \mathbb{R}, v \in V \]
2. Call procedure \textbf{OIPC\_Generation()} to solve the resulting \( LP(M) \) to optimality.
3. Convert variables \( y_{uv}^{PXC} \) and \( y_{uv}^{MSPP} \) back to integer format, while keeping the variables \( w_r \) continuous. Use the MILP solver of (CPLEX) to solve the resulting MILP model.
4. Use the \textbf{OIPC\_Rounding()} procedure to derive an integer demand provisioning scheme so that variables \( w_r \) as well take integer values.
5. Assign a wavelength to each generated OIPC configurations.

**Procedure OIPC\_Generation()**

1. Solve exactly the \( LP(M) \) master problem using CPLEX algorithm and go to Step 2.
2. Solve the pricing problem (use the CPLEX solver) and go to Step 3.
3. Add the pricing problem to the \( LP(M) \), and re-iterate with Steps 1 and 2 until no column can be found with a negative reduced cost. In such a case the \( LP(M) \) is solved to optimality.

**Procedure OIPC\_Rounding()**

While (the current provisioning solution is not integer) do
Call the \textbf{Select\_OIPC} procedure,
Add the newly rounded off variable (column) to the list of selected variables.
End While.

**Procedure Select\_OIPC**

1. Select a subset \( R' \subseteq R \) of variables (columns) \( w_r \) with the highest fractional values.
2. Select, in \( R' \), the variable \( w_r \) with the highest fractional values and contributes the most to satisfying some demands. Then, go to Step 3.
3. Round off the value of the variable associated with the selected column \( w_r \) as follows. If \( w_r < 1 \) then we round it off to 1, else to \( \lfloor w_r \rfloor \).

VI. PERFORMANCE EVALUATION

A. Network and Traffic Instances

We consider two network instances NSFNET (14 nodes, 48 links) and EONET (20 nodes, 78 links) [5]. The network cost design structure is defined as the sum of the cost of the used MSPP transport blades, PXC ports and 3D PXC MEMS. Typical values are: \( c^{MSPP} = 20k\$, \( c^{PXC} = 1k\$ and \( c^{MEMS} = 5k\$ [8].

B. Experimental Results

In addition to deciding on where and how many optical switching fabrics we install in network nodes, we investigate the effects of the proposed translucent switching architecture on the demand provisioning scheme, and on a better network CAPEX and OPEX control.

Figure 2 shows the variation of the demand provisioning cost depending on the selected provisioning scheme, i.e, all-optical or translucent, and on the available PXC number.
in network nodes, for EONET and NSFNET networks respectively. We define five critical design threshold numbers: $C_0$, $C_1$, $C_2$, $C_3$ and $C_4$. $C_0$ defines the optimal demand provisioning cost when there is a PXC fabric in every network node, i.e., a typical or classical design in the literature. $C_1$ is equal to the minimum number of required PXC fabrics while keeping the $C_0$ provisioning cost. $C_2$ is equal to the minimum number of required PXC fabrics to grant all demands with single hop lightpaths. $C_3$ (resp. $C_4$) thresholds as the minimum PXC number to grant all the demand with up to two-hop (resp. three-hop) provisioning scheme.

![Fig. 2. Provisioning cost](image1.png)

We observe from the previous figures that, whenever there are at least $C_2$ available PXC fabrics in the network, the three provisioning schemes derive the same overall demand provisioning cost. This stems from the fact that all the demand is provisioned through single-hop lightpaths, which is implied in turn from the selected provisioning cost structure. Indeed, a request $k_1$ provisioned through the MSPP platform implies an OEO conversion with a cost of $2c_{MSPP}$. A request $k_2$ switched through the PXC fabric implies a cost of $(2c_{PXC} + 2c_{MEMS}) < 2c_{MSPP}$. As expected, beyond threshold $C_2$, $C_3$ and $C_4$, we observe a substantial decrease of the overall demand provisioning cost. It is a trivial consequence due to the reduction of the number of satisfied client requests. The distance between points $C_2$ and $C_3$ (resp. $C_4$) measures the maximum reduction of the number of PXC fabrics while handling the overall demand with two-hop (resp. three-hop) provisioning scheme. This reduction varies from 30% to 60% depending on the used provisioning scheme and the network topology. Consequently, a substantial decrease of network capital and operational expenditures related to the used PXC fabric number.

From the curves of Fig.3, the following observations can be made. First, it is clear that the demand blocking rate is quite related to the available PXC number in network nodes. Indeed, as the available PXC number decreases as the blocking rate increases. Secondly, beyond the $C_2$, $C_3$ and $C_4$ thresholds defined previously, we observe three distinct blocking rate curves depending on the selected provisioning schemes. Furthermore, in case of an all-optical provisioning scheme (single hop lightpaths), beyond threshold $C_2$ the overall demand blocking rate is increased dramatically up to 75% (resp. 80%) on EONET (resp. NSFNET) network. This trend is less important, in case of a translucent provisioning scheme (up to two-hop or up to three-hop lightpaths). Indeed, beyond threshold $C_3$ the overall demand blocking rate is less than 40% for EONET and NSFNET. Beyond threshold $C_4$ the blocking rate is decreased down to zero (resp. less than 5 %) for NSFNET (resp. EONET) network.

**VII. CONCLUSION**

We have investigated and discuss the effect of a translucent optical backbone network architecture (PXC and MSPP) on
the traffic provisioning and switching equipment location solution. We have presented a straightforward mathematical formulation based on column generation techniques that can be used to efficiently plan and select an optimal backbone network configuration. Experimental results show that a substantial network CAPEX/OPEX reduction related to the number of used PXC fabrics is achieved.

REFERENCES