RRPD strategies for a T-OBS network architecture

Oscar Pedrola*, Davide Careglio*, Miroslaw Klinkowski[†], and Josep Solé-Pareta*

* CCABA, Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, e-mail: opedrola@ac.upc.edu
[†] National Institute of Telecommunications (NIT), Warsaw, Poland, e-mail: mklinkow@itl.waw.pl

Abstract—**In this paper, we deal with the physical layer impairments (PLIs) in optical burst switching (OBS). In particular we present a formulation of the routing and regenerator placement and dimensioning (RRPD) problem for a feasible translucent OBS (T-OBS) network architecture. Since addressing the joint RRPD problem results in an extremely complex undertaking, we decouple the problem, and hence, we eventually provide formal models to solve routing and RPD separately in the so-called R+RPD problem. Thus, making use of mixed integer linear programming (MILP) formulations, we first address the routing problem with the aim of minimizing congestion in bottleneck network links, and second, we tackle the issue of performing a sparse placement of electrical regenerators in the network. Since the RPD formulation requires high computational effort for large problem instances, we also propose two alternative heuristic strategies that provide good near-optimal solutions within reasonable time limits. To be precise, we evaluate the trade-off between optimality and complexity provided by these methods. Finally, we conduct a series of simulation experiments on the T-OBS network that prove that the R+RPD strategies effectively deal with burst losses caused by the impact of PLIs, and therefore, ensure that the overall T-OBS network performance remains unaffected.**

I. Introduction

Research effort on optical burst switching (OBS) has been mainly geared towards evaluating two particular optical network architectures, namely the opaque (i.e, using electrical 3R regeneration at each node) and the transparent (i.e., optical 3R regeneration). In an opaque or a transparent network scenario, the existence, and therefore, the impact of physical layer impairments (PLIs) can be neglected. Indeed, as long as realistic core node parameters (e.g., node degree and the link and wavelength capacity) are considered, the optical signal degradation between two neighbouring core nodes is not an issue [1]. Unfortunately, however, the high cost of optical-electrical-optical (O/E/O) devices on the one hand, and the lack of mature optical technology able to perform fully optical 3R regeneration on the other, prevent the deployment of these architectures. Therefore, there is no way to neglect the severe impact that PLIs have on the performance of optical transport networks (OTNs)[2].

For this very reason, the consideration of translucent architectures [3] as a feasible intermediate step in the migration towards fully transparent OTNs, has gained huge momentum. Indeed, the fact that in translucent networks O/E/O regenerators are only available at selected nodes makes of this architecture the ideal yet feasible candidate for bridging the gap between the transparent and opaque solutions. Among the optical switching paradigms, OBS has emerged as a competitive choice for the transmission of highly dynamic data

traffic in the near future. Accordingly, in [4], we presented a novel translucent OBS (T-OBS) network architecture in which core nodes switch incoming data bursts to their output ports either in an all-optical fashion or through O/E/O regenerators when signal regeneration is required. Indeed, O/E/O regenerators are sparsely deployed across the network according to the decision of routing and regenerator placement and dimensioning (RRPD) heuristics which take into account the optical signal to noise ratio (OSNR) at the receiving end as the signal quality performance indicator.

In this paper, we present a formal model for the RRPD problem which is based on a mixed integer linear programming (MILP) formulation. We begin by stressing the novelty of our solution which incorporates the dimensioning phase that clearly distinguishes it from the RRP problem applied in wavelength switched optical networks (WSONs)[5]. Afterwards, the quality of the MILP method developed is compared against that of two different heuristic algorithms. To be precise, we analyze the trade-off between optimality and complexity provided by these methods. Finally, we prove the effectiveness of these methods when applied to the T-OBS network.

The rest of this paper is organized as follows. In Section II, we briefly survey some relevant works on PLI-aware OTNs. Moreover, we explain the T-OBS network architecture and the model we use to capture the impact of PLIs. In Section III, first we define the RRPD problem, and then, we present a MILP model to solve it. An heuristic algorithm to solve the RRPD problem is proposed in Section IV. All strategies presented are compared and evaluated in Section V. Finally, the conclusions of this study are given in Section VI.

II. Related work and contributions

Owing to the natural evolution of OTNs towards transparent architectures, the consideration of PLIs has become unavoidable. Indeed, due to the cumulative impact that PLIs have on the optical signal transmission, the deployment of a fully transparent long-haul network is not a viable option, at least in the short-medium term [2]. Translucent WSON architectures have been the first to receive the attention from the research community due to the maturity of the technology they require. Protocol extensions and requirements to take into account the presence of PLIs in WSONs are currently under development within IETF [5], and in [6], a translucent-oriented routing strategy for a WSON is experimentally validated. Moreover, in [7]-[9], different RRP strategies are proposed to cope with the requirements of PLI-aware WSONs. However, the off-line/static RRP problem has a substantial difference when

applied to OBS networks. Note that due to the switching granularity of WSONs, such a problem does not require a dimensioning of the regenerator pools since there exists a one-to-one correspondence between optical path/connection and electrical regenerator. In OBS, by contrast, the access to regenerators is, like any other resource, subject to statistical multiplexing and so the introduction of an additional dimensioning phase which eventually extends the problem to RRPD.

In [4], we presented a novel T-OBS network which consists of all-optical core switching nodes built according to the well-known tune-and-select (TAS) [1] architecture. These nodes may also be equipped with electrical regenerators according to the decision of the RRPD strategies considered. In order to capture the impact of the main PLIs, we provided an OSNR model which takes into account the contributions that both nodes and links in an optical path have on the OSNR figure. Furthermore, we illustrated a method to compute a power budget and to perform a noise analysis taking into consideration network components which are already commercially available or that are, at most, lab trial devices (see. e.g., [10]). Finally, we presented two distinct RRPD heuristics, that is, the link congestion reduction (LCR) and the regenerator grouping (RG) algorithms, and evaluated their performance when applied to the T-OBS network. Among them, the LCR algorithm stood out as the best method since it relies on optimal MILP routing formulations.

The study here presented is aimed at providing the best possible network performance whilst at the same time minimizing the cost and power consumption of the T-OBS network. Note that both issues are related to the number of electrical regenerators deployed. For this purpose, we introduce a formal definition of the RRPD problem. Since the joint problem of RRPD is computationally impractical, we decouple it into the routing and the regenerator placement and dimensioning (RPD) subproblems, and hence, we eventually provide a formal model to solve the R+RPD problem. However, the RPD problem also becomes difficult if large problem instances are considered. Thus, we consider two different heuristics to solve the RPD problem and evaluate them by considering the trade-off between optimality and computational complexity they provide. These strategies are based on either MILP or heuristic algorithms. Finally, we analyze the performance of the proposed T-OBS network under the considered RRPD methods by means of network simulation.

III. MILP FORMULATION OF THE R+RPD PROBLEM

A. RRPD Problem definition

We address the RRPD problem by uncoupling the routing formulation from that of the RPD issue, and therefore, we provide a model to tackle the problem of R+RPD. Two main reasons support this modeling decision. First, treating both problems together and at once would definitely make of the problem an extremely complex undertaking, particularly in terms of computation times or even of solving feasibility. Second, and most compelling, is the fact that in OBS networks, routing must be carefully engineered since the main source of

performance degradation are the contentions between bursts that arise due to both the lack of optical buffering and the generally considered one-way resource reservation scheme.

Hence, given a set of traffic demands, we first find a proper routing that minimizes burst losses due to congestion in bottleneck network links. Then, this routing solution is used as input information to solve the RPD problem. Since in the T-OBS network the access to the regenerator pools is based on statistical multiplexing, the RPD method must deal with both the selection of regeneration nodes and the dimensioning of regenerator pools so that a given target burst loss rate due to OSNR non-compliant bursts is satisfied. The aim of the RPD formulation here proposed is hence the minimization of the number of O/E/O regenerators deployed in the network.

B. Global notation

We use $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ to denote the graph of an OBS network; the set of nodes is denoted as $\mathcal{V}$, and the set of unidirectional links is denoted as $\mathcal{E}$. Let $\mathcal{P}$ denote the set of predefined candidate paths between source s and termination t nodes, where $s, t \in \mathcal{V}$, and $s \neq t$. Let s_p and t_p denote the source and termination nodes of path $p \in \mathcal{P}$. Let $\mathcal{D}$ denote the set of demands, where each demand corresponds to a pair of source-termination nodes. For each demand $d \in \mathcal{D}$, let $h_d \in \mathbb{R}_+$ denote the average offered burst traffic rate; let $\mathcal{P}_d \subseteq \mathcal{P}$ denote the set of candidate paths supporting demand d; $\mathcal{P} = \bigcup_{d \in D} \mathcal{P}_d$. Each subset $\mathcal{P}_d$ comprises a (small) number of paths, for example, k shortest paths. Let $\mathcal{N}_p$ be the set of all nodes constituting path p. Finally, let $\mathcal{V}_p$ denote the set of intermediate nodes on path p such that $\mathcal{V}_p = \mathcal{N}_p \setminus \{s_p, t_p\}$.

C. Routing problem

The routing model that we consider is based on a Linear Programming (LP) algorithm presented in [11]. To be precise, the authors consider a multi-path routing (MPR) approach (i.e., splittable routing) to solve the routing problem. The objective of this method is to select, for each pair of nodes, paths that lead to the minimization of the congestion in bottleneck network links. For this purpose, the network is assumed to apply source based routing, and hence, the source node is able to determine the path that a burst entering the network must follow. In the study here presented, by contrast, we consider unsplittable (non-bifurcated) routing by forcing routing variables to be binary, and hence, we eventually solve the resulting MILP problem. However, due to space limitations, we do not include the formulation of the routing algorithm and refer the reader to Section 4.2 in [11] for more details.

Once the routing problem is solved, the path p that will be in charge of carrying the traffic for each demand d is determined. Hence, only one path $p_d \in \mathcal{P}_d$ is selected as the valid path to be followed by all bursts belonging to demand d. Thus, we can now denote $\mathcal{Q}$ as the set of valid paths, $\mathcal{Q} = \{p_d : d \in \mathcal{D}\}$, to be used as input information to solve the RPD problem.

D. RPD problem

1) Model assumptions: Let $\mathcal{P}^o \subseteq \mathcal{Q}$ denote the subset of paths for which the OSNR level at receiver t is non-
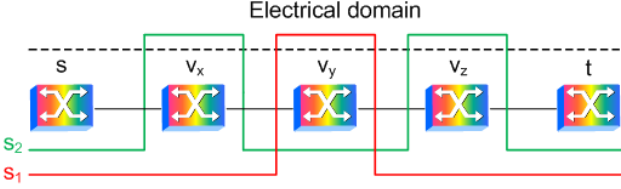
Fig. 1. Two different valid options to perform the regeneration for a particular source-termination pair.

compliant with the quality of signal requirements, and thus, paths $p \in \mathcal{Q}$ requiring regeneration at some node $v \in \mathcal{V}_p$. For each $p \in \mathcal{P}^o$ there may exist many different options on how to build an end-to-end OSNR compliant path, composed by its transparent segments, since the node or group of nodes where the regeneration has to be performed might not be a unique solution. Thus, let $\mathcal{S}_p = \{s_1, \ldots, s_{|\mathcal{S}_p|}\}$ denote the set of different options to establish an OSNR compliant path for each path $p \in \mathcal{P}^o$, where $s_i \subseteq \mathcal{V}$, $i = 1 \ldots |\mathcal{S}_p|$ and size $|\mathcal{S}_p|$ depends on the length of the transparent segments in path p. Figure 1 illustrates this concept by means of an optical path between a source-termination pair $(s - t)$ with two different options to establish an OSNR compliant path. To be precise, if s_1 is selected, the optical signal only undergoes 3R electrical regeneration at node v_y, whereas if s_2 is the choice, it is converted to the electrical domain two times (i.e., at nodes v_x and v_z). Hence, $s_1 = \{v_y\}$ and $s_2 = \{v_x, v_z\}$. In this particular case, the transparent segments that make it possible to use both regeneration solutions are segments $[s-v_y]$-$[v_y-t]$ and $[s - v_x]$-$[v_x - v_z]$-$[v_z - t]$. Notice that we could also consider other cases like $s_3 = \{v_x, v_y, v_z\}$, however, we have not depicted all of the options for the sake of clarity. Here it is worth pointing out that we obtain $\mathcal{S}_p$, $p \in \mathcal{P}^o$ by means of a precomputation phase where all possible regeneration options are obtained using the OSNR model presented in [4].

We assume that for each path $p \in \mathcal{P}^o$, the selection of the regeneration option s from set $\mathcal{S}_p$ is performed according to a decision variable z_{ps}, which later is referred to as regenerator placement variable, such that the following constraints are fulfilled:

$$\sum_{s \in S_p} z_{ps} = 1, \quad \forall p \in \mathcal{P}^o, \tag{1a}$$

$$z_{ps} \in \{0, 1\}, \quad \forall s \in \mathcal{S}_p, \forall p \in \mathcal{P}^o. \tag{1b}$$

Let ρ_v^o denote the offered traffic load requiring regeneration at node v. To estimate ρ_v^o (approximately) we add up the traffic load ρ_p offered to each path $p \in \mathcal{P}^o$ that both crosses and undergoes regeneration at node v:

$$\rho_v^o = \sum_{p \in \mathcal{P}^o : \mathcal{V}_p \ni v} \sum_{s \in \mathcal{S}_p : s \ni v} z_{ps} \rho_p. \tag{2}$$

Similarly, $\rho_v = \sum_{p \in \mathcal{P}^o : \mathcal{V}_p \ni v} \rho_p$, denotes an estimation of the maximal traffic load that is subject to regeneration at node $v \in \mathcal{V}$. Eventually, we define a regenerator pool dimensioning function $F_v(\cdot)$, which for a given traffic load ρ_v^o, determines

the minimum number of regenerators to be allocated in node v. This number must ensure that a given target burst blocking probability (B^{osnr}) for bursts competing for regeneration resources is met. Assuming Poisson arrivals and fairness in the access to regenerator pools among bursts (see subsection IV-B) such a function is given by the following discontinuous, step-increasing function,

$$F_v(\rho_v^o) = \left\lceil B^{-1}(\rho_v^o, B^{osnr}) \right\rceil, \tag{3}$$

where B corresponds to the Erlang B-loss formula which for a given number of regenerators $r \in \mathbb{N}$ available at node v can be calculated as,

$$B(\rho_v^o, r) = \frac{(\rho_v^o)^r / r!}{\sum_{k=0}^{r} (\rho_v^o)^k / k!}, \tag{4}$$

and where $B^{-1}(\rho_v^o, B^{osnr})$ is the inverse function of (4) extended to the real domain [12], and $\lceil \cdot \rceil$ is the ceiling function. It is worth noticing that the Poisson arrivals which lead to an Erlang formula for the dimensioning of regenerator pools can be replaced with another distribution for which the blocking probability is attainable. Because B^{osnr} is a predetermined parameter, for simplicity of presentation we skipped it from the list of arguments of function $F_v(\cdot)$. Note that $B^{-1}(\cdot)$ is a real-valued concave function.

For the purpose of problem formulation, it is convenient to define a_r as the maximal load supported by r regenerators given a B^{osnr}, i.e., $a_r = B^{-1}(r, B^{osnr})$. Note that the inverse function $B^{-1}(r, B^{osnr})$ is expressed with respect to r and B^{osnr}, which is not the same as in function (3).

Although there is no close formula to compute the inverse of (4), we can make use of a line search method (see e.g., [13]) to find the root ρ^* of the function $f(\rho) = B^{osnr} - B(\rho, r)$ so that the value of a_r is approximated by $a_r = \rho^*$ for any index r. Finally, let R denote the number of regenerators required in the most loaded node, that is, $R = \max\{F_v(\rho_v) : v \in \mathcal{V}\}$.

Vector $\mathbf{a} = (a_1, ..., a_R)$ will also be used in subsection IV-B to determine $F_v(\rho_v^o)$ according to Procedure 1. Note that Procedure 1 is a polynomial time algorithm of complexity $O(R)$.

Procedure 1 Regenerator Pool Dimensioning

1: $r \leftarrow 0$
2: **while** $\rho_v^o > a_r$ **do**
3:     $r \leftarrow r + 1$
4: **end while**
5: $F_v \leftarrow r$

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2) Problem formulation: The RPD problem can be formulated as a non-convex optimization problem:

$$\underset{\mathbf{z}}{minimize} \quad F = \sum_v F_v(\rho_v^o(\mathbf{z})) \tag{NLP1}$$

$$subject\ to \quad \text{(1a) and (1b)} \tag{5a}$$

where $F_v(\cdot)$ is the step-increasing regenerator pool dimensioning function defined by (3) and $\rho_v^o(\mathbf{z})$ is the function

representing the traffic load offered to a regenerator node defined by (2). The optimization objective of NLP1 is to minimize the sum of regenerators installed in network nodes. Constraints (5a) represent the selection of an OSNR compliant path from the provided options for each path requiring regeneration. Eventually, the RP decision vector $\mathbf{z}$ is defined as $\mathbf{z} = (z_{11} \ldots z_{1|\mathcal{S}_p|}, \ldots, z_{|\mathcal{P}^o|1} \ldots z_{|\mathcal{P}^o||\mathcal{S}_{|\mathcal{P}^o|}|})$.

The difficulty of formulation NLP1 lays in the fact that there is no close formula to express $F_v(\cdot)$ since no such formula exists for the inverse of the Erlang function $B^{-1}(\cdot)$. A way to solve the problem is to substitute function $F_v(\cdot)$, $v \in \mathcal{V}$ with its piecewise linear approximation and reformulate NLP1 as a MILP problem.

For a single node $v \in \mathcal{V}$, the piecewise linear approximation of $F_v(\cdot)$ can be expressed as $F_v(\rho_v^o) = \min\{r : a_r > \rho_v^o\}$, or by means of a 0-1 integer programming (IP) formulation:

$$\underset{\mathbf{u}}{minimize} \quad F_v = \sum_r u_v^r r \tag{IP1}$$

$$subject\ to \quad u_v^r(a_r - \rho_v^o) \geq 0, \ \forall r \in [1, R], \tag{6a}$$

$$\sum_r u_v^r = 1, \tag{6b}$$

$$u_v^r \in \{0, 1\}, \ \forall r \in [1, R]. \tag{6c}$$

In IP1, decision variables u_v^r have been introduced in order to represent the number of regenerators required in node v. Due to constraint (6b), in each node only one variable u_v^r is active (i.e., equal to 1), and the one with minimum r satisfying $a_r \geq \rho_v^o$ is found when solving the problem. Notice that formulation IP1, when solved, gives the same solution as Procedure 1. The shortcoming of IP1 is that since ρ_v^o is dependent on vector $\mathbf{z}$ (i.e., ρ_v^o is a function of $\mathbf{z}$), constraints (6a) have quadratic form. To overcome this difficulty, we can reformulate IP1 simply by adding up constraints (6a) over r and simplify $\rho_v^o \sum_r u_v^r$ in ρ_v^o using (6b).

Eventually, taking into account all network nodes and introducing the regenerator placement decision variables, problem NLP1 can be reformulated as a MILP problem:

$$\underset{\mathbf{u}, \boldsymbol{\rho}^o, \mathbf{z}}{minimize} \quad F = \sum_v \sum_r u_v^r r \tag{MILP1}$$

$$subject\ to$$

$$\sum_r u_v^r a_r - \rho_v^o \geq 0, \ \ \forall v \in \mathcal{V}, \tag{7a}$$

$$\sum_r u_v^r = 1, \ \ \forall v \in \mathcal{V}, \tag{7b}$$

$$\sum_{s \in S_p} z_{ps} = 1, \ \ \forall p \in \mathcal{P}^o, \tag{7c}$$

$$\sum_{p \in \mathcal{P}^o : \mathcal{V}_p \ni v} \sum_{s \in \mathcal{S}_p : s \ni v} z_{ps} \rho_p - \rho_v^o = 0, \ \forall v \in \mathcal{V}, \tag{7d}$$

$$u_v^r \in \{0, 1\}, \ \ \forall r \in [1, R], \forall v \in \mathcal{V}, \tag{7e}$$

$$z_{ps} \in \{0, 1\}, \ \ \forall p \in \mathcal{P}^o, \forall s \in \mathcal{S}_p, \tag{7f}$$

$$\rho_v^o \in \mathbb{R}^+, \ \ \forall v \in \mathcal{V}. \tag{7g}$$

where we consider ρ_v^o to be an auxiliary variable representing the traffic load requiring regeneration offered to node $v \in \mathcal{V}$.

The objective of the optimization problem MILP1 is to minimize the total number of regenerators that have to be placed in the network. Constraints (7a) and (7b) result from

the 0-1 representation of the dimensioning function and from the reformulation of IP1 as mentioned before. In particular, the number of regenerators in node $v \in \mathcal{V}$ should be such that the maximum traffic load (given a B^{osnr}) is greater or equal to offered traffic load ρ_v^o. Constraints (7c) are the OSNR compliant path selection constraints. Constraints (7d) are the traffic load offered to a regenerator node calculation constraints. Eventually, (7e), (7f), and (7g) are the variable range constraints.

MILP1 is a well-known Discrete Cost Multicommodity Flow (DCMCF) problem [14]. DCMCF was shown to be an extremely difficult combinatorial problem for which only fairly small instances (in our case, situations where $\mathcal{P}^o$ has a rather small size) can be solved exactly with currently available techniques. In the next Section, we propose a less complex heuristic method to solve the RPD problem.

IV. RPD HEURISTIC RESOLUTION METHODS

To overcome the difficulty imposed by the resolution of MILP1, in this Section, we split the RPD formulation so that the problem becomes RP+D. To address the RP problem, we propose a new MILP-based algorithm that is detailed in the next subsection. Then, in subsection IV-B, we describe the dimensioning method employed.

A. Load-based MILP formulation

The MILP formulation here proposed is focused on the distribution of the traffic load requiring regeneration (i.e., ρ_v^o, $\forall v \in \mathcal{V}$). Hence, this load must be aggregated in such a way that the number of regenerators to be deployed is minimized. After a ρ_v^o solution is obtained for each node $v \in \mathcal{V}$, we take advantage of the regenerator pool dimensioning function detailed in Section IV-B to obtain the number of regenerators required.

Owing to the concave character of the dimensioning function (3), it must be noted that it is of our interest to aggregate the traffic requiring regeneration in as few nodes as possible rather than spreading out such load in little amounts over a large number of nodes. Hence, we propose to solve the problem by making use of two MILP models, namely MILP2 and MILP3. These models can be sequentially solved to obtain a sub-optimal solution of MILP1.

First, MILP2 aims at minimizing the number of nodes where the regenerators must be installed (i.e., nodes such that $\rho_v^o > 0$), and thus, groups as much as possible the load that requires regeneration. Let $\mathbf{y} = (y_1, ..., y_{|\mathcal{V}|})$ denote a vector of binary decision variables. Each value corresponds to one node and determines if this node is used as regeneration point by some path $p \in \mathcal{P}^o$ ($y_v = 1$) or not ($y_v = 0$).

Then, we solve the following problem:

$$\underset{\boldsymbol{\rho}^o, \mathbf{z}, \mathbf{y}}{minimize} \quad \sum_v y_v \tag{MILP2}$$

$$subject\ to \quad \rho_v y_v \geq \rho_v^o, \ \ \forall v \in \mathcal{V}, \tag{8a}$$

$$y_v \in \{0, 1\}, \ \forall v \in \mathcal{V}. \tag{8b}$$

and subject to constraints (1a), (1b), (7d) and (7g).

Although MILP2 minimizes the number of nodes where the regenerations are performed, multiple solutions to this problem may exist and some of them may exploit more regenerations than required, increasing unnecessarily ρ_v^o at some nodes. Therefore, a second MILP model, that is, MILP3, needs to be formulated with the objective to minimize the total network load requiring regeneration.

To this end, let k^* denote an optimal solution of MILP2. Second, we solve the following problem:

$$\underset{\rho^o, \mathbf{z}, \mathbf{y}}{minimize} \quad \sum_v \rho_v^o \qquad \text{(MILP3)}$$

$$subject\ to \quad \sum_v y_v \leq k^*, \qquad \text{(9a)}$$

and subject to constraints (1a), (1b), (7d), (7g), (8a) and (8b).

Due to the simplicity of both formulations, both models are expected to be promptly solved even for large-sized problem instances.

It is also important to notice that the sequential resolution of both MILP2 and MILP3, which will hereinafter be cited within the text as MILP2/3, provides an optimal solution in terms of the distribution of the traffic and not with respect to the number of regenerators (which is precisely the case of MILP1). This being said, the last step in this method is the dimensioning of regenerator pools as detailed in Section IV-B.

B. Regenerator dimensioning phase

The load of burst traffic requiring regeneration at node $v \in \mathcal{V}$ is given by ρ_v^o after solving the RP problem (see Section IV-A). In order to determine the number of regenerators required in node v, we define a dimensioning function $f(\rho_v^o, B^{osnr}) : (R^+, R^+) \mapsto \mathbb{Z}^+$. Under the assumption that any burst may access any regenerator in a node (as shown in [4], the architecture proposed allows a fair access to the regenerator pool), we make use of the inverse of the Erlang B-loss function as the dimensioning function f. An straightforward way to implement this dimensioning function is to make use of vector $\mathbf{a}$ and Procedure 1, which have been both detailed in Section III-D.

V. RESULTS AND DISCUSSION

In this Section, we first compare the performance of the MILP1 and MILP2/3 problems with that of the LCR algorithm which we proposed in [4]. Then, we study the performance of the T-OBS network under the different RRPD strategies to prove their effectiveness at keeping OSNR losses under control.

A. Simulation scenario

Four network topologies are considered: (a) three Pan-European networks known as: Large, Basic and Core [4] with 37, 28 and 16 nodes and 57, 41 and 23 links respectively; (b) the NSFNET (a US network) [11] with 14 nodes and 21 links. Traffic is uniformly distributed and each link has 32 channels of $10Gbps$ each. In our context, an erlang corresponds to the amount of traffic that occupies an entire channel (e.g., 20 erlangs mean each edge node generates $200Gbps$). Burst

Parameter	NSFNET	Core	Basic	Large
$|\mathcal{P}^o|$	35	18	349	746
$T_{osnr}[dB]$	18	20	20	20

TABLE I
NUMBER OF PATHS THAT REQUIRE REGENERATION AND OSNR
THRESHOLD VALUES

Method	NSFNET	Core	Basic	Large
MILP1	112	55	499 (> 6% gap)	971 (> 17% gap)
MILP2/3	113	56	500	866
LCR	112	55	607	1021
OPAQUE	1344	1472	2624	3648

TABLE II
RP RESULTS COMPARISON

arrivals follow a Poisson distribution, their mean duration is $100\mu s$, and 99% confidence intervals have been considered. Besides, B^{osnr} is set to 10^{-3}. All MILP problems have been solved using IBM ILOG CPLEX v.12.1 and simulations have been conducted on the JAVOBS network simulator [15].

B. Resolution methods comparison

For this experiment and hereinafter in this paper, we consider the smallest $K = 20$ regeneration options (with respect to the size of set $|s_i|$) to fill set $\mathcal{S}_p, p \in \mathcal{P}^o$, and the T_{osnr} values provided in Table I. Note that for the NSFNET network topology, due to larger link distance values, we had to consider a lower T_{osnr}. In particular, the highest T_{osnr} that guarantees that any link of the network is feasible (in terms of the OSNR signal quality) was selected. For the Pan-European networks we consider a value that is in accordance with recent studies (see e.g., [6]). T_{osnr} also determines the number of paths that require regeneration (i.e., see in Table I sizes of $\mathcal{P}^o$ sets), and hence, the level of complexity that is given to the problem.

The results obtained are presented in Table II (number of regenerators) and Table III (computation times). Table II also provides the number of regenerators required when an opaque network architecture is considered. In this study, each node injects 20.8 erlangs into the network. One can note that MILP1 is solved very effectively when small instances are considered (i.e., NSFNET and Core). This is not, however, the case with both the Basic and the Large networks, where MILP1 struggles several hours to reach poor solutions. Among the two heuristic algorithms proposed, the MILP2/3 method provides the most satisfactory trade-off between complexity and optimality. However, if computation resources are the top priority, the LCR heuristic clearly outperforms the other strategies.

C. Impact on the OBS network performance

To evaluate the effectiveness of both the MILP2/3 and the LCR methods in the T-OBS network, we consider the overall burst loss probability (BLP) as the metric of interest. Figure

Method	NSFNET	Core	Basic	Large
MILP1	0.5	0.61	> 7 hours	> 11 hours
MILP2/3	0.1836	0.254	3.97	15.71
LCR	0.086	0.116	0.37	0.55

TABLE III

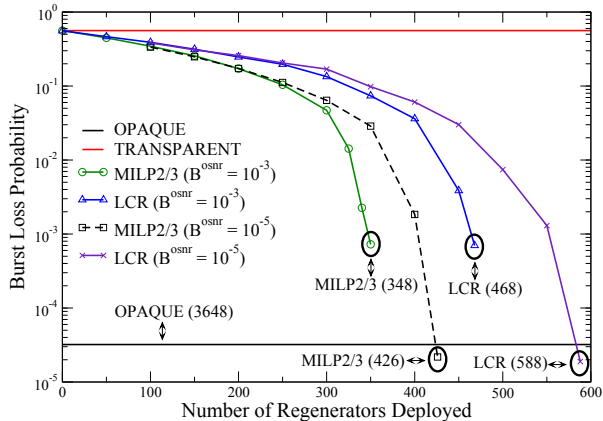RP EXECUTION TIMES (SECONDS) COMPARISON

Fig. 2.   MILP2/3 vs. LCR performance comparison in the Large topology.

2 presents the results obtained under both the MILP2/3 and LCR methods in the Large topology when the number of erlangs offered per node is equal to 6.4. In this experiment, two different B^{osnr} targets are considered, namely 10^{-3} and 10^{-5}. In addition, the opaque (i.e., O/E/O et every node) and transparent (i.e., no regeneration) scenarios are plot and used as benchmarking indicators. It is easy to observe that the progressive and even placement of regenerators (i.e., the amount of regenerators to be placed is fairly distributed among all selected nodes) reduces the overall BLP until both B^{osnr} targets are reached (i.e., the required number of regenerators has been deployed). As it was to be expected, MILP2/3 reaches both B^{osnr} targets well before than LCR. In the $B^{osnr} = 10^{-3}$ case the BLP is dominated by OSNR losses, and consequently, when all the regenerators have been deployed $BLP \approx B^{osnr}$. On the other hand, if B^{osnr} is set to 10^{-5}, contention losses become predominant, and therefore, $BLP \approx BLP_{OPAQUE}$. Here it is worth pointing out the fact that the BLP found slightly improves that of the opaque case. This is due to the differences in node architectures between the opaque and translucent networks: note that whilst the opaque network relies on in-line regenerators as in [1], our translucent architecture operates in the feed-back mode as proposed in [4].

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we have addressed the RRPD problem in a T-OBS network. Since joint RRPD is a complex problem, we have separately formulated the routing, which aims at reducing congestion in bottleneck links, and RPD problems. Our RPD strategy relies on the piecewise linear approximation of the inverse of the Erlang-B dimensioning function. Since such

formulation corresponds to the complex DCMCF problem, we have eventually provided a heuristic method to solve the RPD problem. We have evaluated and compared these methods by considering the trade-off between optimality and complexity they provide. Among them, the MILP2/3 strategy stood out as the best quality trade-off, and the LCR heuristic as the fastest method. Finally, we proved the effectiveness of these methods when applied to the T-OBS network. From the results obtained, we can conclude that the T-OBS network performance, under the RRPD strategies proposed in this paper, remains unaffected since losses due to signal degradation are kept satisfactorily under control. In our future work, we plan to extend our model to consider the case of an on-line/dynamic scenario.

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