Offline Impairment-Aware RWA and Regenerator Placement in Translucent Optical Networks

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***Abstract*—In translucent optical networks, the physical layer impairments degrading the optical signal are considered in the network planning. In this paper, we investigate the offline problem of routing and wavelength assignment (RWA) and regenerator placement (RP) in translucent networks, minimizing the lightpath blocking and regenerator equipment cost. We address two variants of the problem, which correspond to two different types of quality of transmission (QoT) estimators, called linear and nonlinear. In a nonlinear QoT, nonlinear impairments like crosstalk or cross-phase modulation, which account for the interferences from neighboring lightpaths in the network are explicitly computed. Then, the QoT estimated for a lightpath depends on the routes of other lightpaths in the network. In the linear QoT, the effects of the nonlinear impairments are overestimated and accumulated to the rest of the impairments in the QoT calculation. As a result, the QoT estimation of a lightpath solely depends on its route.**

For the linear case, we formulate an optimal integer linear programming model of the problem, to the best of the authors' knowledge, for the first time in the literature. Its simplicity allows us to test it for small- and medium-size networks. Also, we propose two heuristic methods, namely, lightpath segmentation and three-step, and a tight lower bound for the regenerator equipment cost. For the nonlinear QoT case, we propose a new heuristic called iterative RP (IRP). Both the IRP and three-step algorithms are designed to guarantee that no lightpath blocking is produced by signal degradation. This is a relevant difference with respect to earlier proposals. The performance and the scalability of our proposals are then investigated by carrying out extensive tests. Results reveal that the solutions obtained by the heuristic algorithms are optimal or close to optimal, and outperform the earlier proposals in the literature.

***Index Terms*—Impairment-aware (IA) network planning, regenerator placement (RP), translucent optical networks.**

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I. Introduction

The popularization of bandwidth-hungry applications and services is enforcing the deployment of optical wavelength division multiplexing (WDM) networks with a clear trend toward increasing the capacity and lowering the network cost (both CAPEX and OPEX). On the one hand, this trend can be translated to higher, i.e., 40/100 Gb/s, line rates and denser WDM transmission systems with 80 to 160 wavelengths per fiber. On the other hand, aiming at reducing the cost, recent advances in optical technologies are fostering an evolution from traditional opaque-to-transparent optical network architectures [1].

In an opaque network, each node is equipped with optical-electrical-optical (OEO) interfaces meaning that the optical-signal-carrying traffic terminates at each node to undergo an OEO conversion and an electronic processing. This approach simplifies the network design and control, since there is a full independence between the network and the physical layer. On the contrary, it requires a large amount of OEO devices greatly increasing the network cost and the energy consumption.

In transparent optical networks, the optical signal originated at the source nodes reaches its destination bypassing optically the intermediate nodes. This approach reduces considerably the cost, since neither OEO conversions nor electronic processing is required at each node along a lightpath. However, it implies that the physical layer must support end-to-end communication. Unluckily, the transmission reach of optical signals is limited due to the accumulation of physical layer impairments, which cause transmitted data to not be received correctly, e.g., the bit error rate (BER) is higher than an acceptable threshold.

For that very reason, translucent (or semitransparent) optical networks are emerging as a promising solution for bridging the gap between opaque and transparent networks. Indeed, translucent networks combine features of both opaque and transparent networks strategically placing electrical regeneration (i.e., by means of OEO conversion) only at selected points in the network [2]. This approach eliminates much of the required electronic processing and allows a signal to remain in the optical domain for much of its path. Moreover, an electrical regenerator enables the possibility of wavelength conversion, which may help to decrease the number of rejected lightpaths compared to the transparent case [3].

In both transparent and translucent optical networks, the network and the physical layer cannot be decoupled (as in opaque networks) and a cross-layer design is necessary. The traditional problem of routing and wavelength assignment (RWA) must take into account the signal impairments in the lightpath computation process in the so-called impairment-aware RWA (IA-RWA). Two cases can be faced. During the planning phase, the traffic demand is already known at least partially; therefore, the decisions can be taken offline using static IA-RWA algorithms. The other case, whereby traffic demands are assumed to arrive in a dynamic fashion, is referred to as the online or dynamic IA-RWA problem. A comprehensive literature review of proposed static and dynamic IA-RWA algorithms can be found in [4].

Besides, in the translucent optical networks, there are additional problems of regenerator placement (RP) and allocation. In the planning phase, the RP consists of selecting, which nodes of the network have regeneration capabilities and how many signals can be regenerated at these nodes. In contrast, in the operation phase, the regenerator allocation tries to determine how the already placed regenerators are used in a dynamic scenario.

In all these issues, a quality of transmission (QoT) estimator accounting for the accumulation of the physical layer impairments along the path, and thus, determining the signal QoT is needed. These impairments include chromatic- and polarization-mode dispersion, optical fiber nonlinearities, noise accumulated due to amplified spontaneous emission (ASE), crosstalk, etc. In literature, there are three main QoT estimators [5] based on the numerical calculation of the optical SNR (OSNR) [6], applying analytical formulas [7] or interpolating numerical and laboratory measurements [8], [9] to compute the Q factor value. Note that the Q factor of a lightpath is in direct relation to its signal BER performance [10]. For example, to evaluate the feasibility of a lightpath, its QoT in terms of OSNR must be higher than (typically) 19 dB for a 10-G system; it must be lower than 10^{-9} in the case of BER, or it must be higher than 15.5 dB in case of Q factor.

In this paper, we focus on translucent optical networks and we address the offline problem of network planning, where, given a network topology and an estimation of the traffic demands, both the static IA-RWA and the RP problems are solved jointly. We denote this problem as IA-RWA-RP. As a QoT estimator, we use two different models, which we denote as linear and nonlinear QoT. In both cases, a lightpath is accepted, if its QoT is higher than a given threshold. The two models are representative of two different strategies of accounting for the so-called nonlinear impairments. In this context, nonlinear impairments refer to signal degradations in a lightpath caused by neighboring lightpaths [e.g., crosstalk or cross-phase modulation (XPM)]. In its turn, linear impairments refer to those, which depend only on the lightpath route and wavelength (e.g., ASE). In a nonlinear QoT estimator, nonlinear impairments are explicitly computed. Then, the QoT obtained for a lightpath is dependent on the routes of other lightpaths in the network. In the linear QoT, the effects of the nonlinear impairments are overestimated and accumulated to the linear ones. As a result, the QoT estimation of a lightpath solely depends on its route. In this paper, we use the extended Q-Personick model defined in [9] as a representative of linear QoT estimator. For the nonlinear QoT case, we implement a Q factor based on analytical models [11]–[16]. We denote it as Q-NL factor.

The two QoT models trigger different algorithmic approaches to the planning problem. For this reason, we denote the associated problem variants as linear IA-RWA-RP and nonlinear IA-RWA-RP, respectively. In both cases, our target is to find the network planning that minimizes both 1) the lightpath blocking caused by the optical signal degradation and wavelength conversion requirements and 2) the cost of the regeneration equipment. We denote the lightpath blocking directly caused by the signal degradation and wavelength conversion requirements as *signal regeneration blocking*. Note that in the offline planning of translucent networks, there is other source of lightpath blocking: the one caused by the limited number of wavelengths of the links. We name this second type of blocking as *network capacity blocking*. The network capacity blocking cannot be solved by using more regenerator equipment: if no routes with available channels exist between two nodes, neither wavelength conversion nor regenerator equipment will allow the provisioning of a lightpath between those nodes and consequently the request will be blocked.

The use of a linear QoT estimator allows us to model the linear IA-RWA-RP problem as an integer linear programming (ILP) combining a node-link formulation with the concept of transparent semilightpath (in the reminder, referred to as semilightpath). A semilightpath is an optical signal traversing a sequence of fiber links without going through any signal regeneration and any wavelength conversion. Note that this definition slightly differs from the definition used in [17], where the semilightpath corresponds to a lightpath with the wavelength continuity constraint relaxed. Then, a lightpath is implemented as a chain of semilightpaths, requiring one regenerator, where each semilightpath ends (but the last). We emphasize as a merit of this model its simplicity, which makes possible to obtain optimal solutions for the linear IA-RWA-RP problem in medium-size networks with 16 wavelengths per fiber. The IA-RWA-RP problem is clearly nondeterministic polynomial-time hard (NP-hard), since it contains the RWA NP-hard problem [18] as a special case. For planning larger networks, we present two effective heuristic algorithms: the lightpath segmentation (LS) and the three-step heuristics, being the latter specially designed to guarantee zero-signal regeneration blocking. We also provide a lower bound to the regenerator equipment cost, which is measured in total number of regenerators placed in the network. Note that our aim is to reduce the overall number of devices and not the regenerator sites, which may contain more than one device. However, it is possible to constraint the problem setting as an input parameter the set of nodes, which are able to host regenerator equipment.

On the contrary, an ILP approach for the nonlinear IA-RWA-RP problem that adopts a nonlinear QoT is impracticable. For this reason, we propose an efficient heuristic called iterative RP (IRP). The heuristic is based on the three-step heuristic, and includes an iterative regeneration placement phase. In each iteration, a new regenerator is added, and the method reoptimizes the wavelength assignment, with the aim of minimizing the interferences between lightpaths. The result is a fast and effective search in the solution space.

An extensive battery of tests is included in this paper. The tests have been carefully selected so that they correspond to networks, which allow solutions with zero network capacity blocking in the linear case. Then, we are able to fairly assess both the signal regeneration blocking and the regenerator cost of the provided solutions. As a contribution of this paper, we also investigate how the regeneration equipment cost increases for different network sizes. For this, we define a normalized network size factor, which captures the relative length of the network links with respect to the longest signal propagation without regeneration.

The rest of the paper is organized as follows. In Section II, we review the related work. Section III presents our investigations in the linear IA-RWA-RP problem, while Section IV focuses on the nonlinear IA-RWA-RP variant. Section V presents the obtained results. Finally, Section VI concludes the paper.

II. Related Work

The first studies on the IA-RWA problem for translucent optical networks propose to divide the optical core network into several islands of transparency or optically transparent domains [19], [20]. An island consists of a part of the physical topology in which any lightpath can be established without intermediate signal regeneration. If a connection traverses several islands, the island boundary nodes carry out the signal regeneration. The same idea has been employed in some recent studies such as [21]. The problem of this approach is its low scalability. Only the nodes on the islands' borders can host a regenerator and, in order to minimize the number of regenerators, these islands must be defined ensuring a minimum overlapping. Any change in the network (a failure, an upgrade, etc.) may require a reorganization of the islands and a re-placement of the majority of the regenerators.

An alternative approach called sparse RP is being studied in [22]–[39]. In this case, any node can host, in principle, a regenerator (not only the nodes on the islands' border) and an RP algorithm defines the subset of nodes that actually need a regenerator: in the end, they are deployed sparsely in the network. This is also the approach considered in this paper.

The majority of the proposals for RP in translucent networks deal with the IA-RWA and the RPs problems separately, as if they were two different phases of the network planning. Commonly, the RP is solved first, producing a network for which the IA-RWA problem is then addressed. This strategy has been followed in [25]–[29] for static traffic, and in [22]–[24] and [30]–[33] considering dynamic traffic. Other studies have been presented, which focus on minimizing the number of nodes with signal regeneration capability in the network, guaranteeing a certain degree of connectivity [30], [34], [35].

Ramamurthy *et al.*[23], [24], [32] studied the RP and the regenerator allocation problem. The former plans the number of regenerators to be placed in each node assuming a nondeterministic traffic demand. The latter allocates the idle regenerators to the dynamic arrivals of new connection requests. Four offline algorithms for the sparse RP and two dynamic schemes for the regenerator allocation are proposed. The RPs are based on static network states and merely empirical considerations: either placing the regenerators considering the maximum transmission reach of a transparent path, in the most central nodes, in the nodes with the higher number of links, or in those with the higher loads. The regenerator allocations called *fragmentation* and *trace back* reorganize how the regenerator equipment in each node is assigned taking into account the current network state. The placement allocation process is investigated also in [31] and [33]. A heuristic algorithm is first applied for the RP in [31]; the nodes crossed by the majority of the shortest paths host the regenerators. Then, the IA-RWA and the regenerator allocation problems assuming dynamic traffic are solved using a 2-D Dijkstra algorithm. Marín-Tordera *et al.*[33] investigated the impact of the physical-layer information inaccuracy on the efficiency of a regenerator allocation technique.

A mixed ILP (MILP) formulation and a sequential heuristic algorithm based on the K-least-wavelength-weight-path routing are proposed in [26] to solve the IA-RWA problem. The objective of both the schemes is the maximization of the number of established connections, which means that a connection blocking can occur. In principle, any node can host a regenerator, but the total number of regenerators is an input value and it is not minimized.

Savasini *et al.* [34] studied the problem of minimizing the number of nodes equipped with signal regeneration giving the guarantee that at least k end-to-end connections are always accepted. To this end, they suggest a two-step algorithm that is compared to a k-coverage algorithm for mobile and ad hoc wireless networks. Pachnicke *et al.* [30], [35] proposed an RP based on the greedy algorithm from [36] to get full connectivity and two simple RWA algorithms based on shortest path and first-fit wavelength assignment. One model considers the worst case physical transmission penalties, while the other model takes into account the current network status in order to obtain the physical impairments.

In contrast to earlier studies, in this paper we study how to solve the RP and the IA-RWA problems jointly, which have been earlier studied only in [25], [29], [38], and [39].

A sequential algorithm called lightpath establishment with RP (LERP) is proposed in [25]. This algorithm minimizes simultaneously the number of rejected traffic demands and the number of required regenerators. Zahr *et al.* [27], [28] continued their study. They investigated the impact of deploying in-line gain equalizers in terms of the number of required regenerators. Moreover, they propose two new wavelength assignment strategies to employ in the LERP algorithm. These proposals use a linear QoT model.

The nonlinear variant of the IA-RWA-RP problem is addressed in [29]. The algorithms proposed divide the problem into three consecutive phases. Given a set of lightpaths demands (i.e., the traffic matrix), the first phase finds those lightpaths that cannot be served transparently by any of the k-shortest available paths. An ILP model and four different heuristic algorithms are proposed to decide how to split all these nontransparent lightpaths into a sequence of transparent lightpaths and place the regenerators accordingly. The result of this phase is a transformed traffic matrix. In the second phase, an IA-RWA algorithm is applied to route the transformed traffic matrix using an ILP formulation. If some connections cannot be served, a third phase tries to reroute them using the remaining network resources. However, at the end of all these phases, some connections can be still blocked due to unacceptable QoT performance or the lack of free resources.

A heuristic algorithm for the linear IA-RWA-RP problem is proposed in [38] . The algorithm aims at minimizing both the number of required regenerators and the number of regeneration sites in the network. The RP problem is based on *a priori* choice of potential regeneration sites considering the most restrictive lightpaths whose quality level is checked without considering the impairments provoked by the neighboring lightpaths.

The problem of IA-RWA-RP with the traffic grooming is studied in [39]. Patel *et al.* proposed a heuristic algorithm that decouples the placement of regenerators and the dimensioning of the electronic grooming equipment. The RP subroutine is based on shortest path routing and first-fit wavelength selection, both performed within an auxiliary reachability graph that addresses the impairment constraint just as a limit of physical hops.

In this paper, we deal both with the linear and nonlinear versions of the IA-RWA-RP problems. For the linear case, we propose a novel ILP formulation, yielding optimal solutions to the problem and being the first one to achieve this objective as far as the authors know. The simplicity of the model allows optimal solution for small-/medium-scale nontrivial problems. For larger networks, we also present a regenerator cost lower bound, and two novel heuristics. These heuristics have shown very good scalability properties, and accurate results, outperforming earlier proposals. In addition, a heuristic algorithm is proposed for the nonlinear case, also outperforming the earlier proposals.

III. Linear IA-RWA-RP Problem

A. Linear QoT Estimator

In this section, we make use of a linear QoT estimator. We recall that a linear QoT computes the Q factor of a lightpath overestimating the effects of the nonlinear impairments and accumulating them to the linear ones. The fact that the linear QoT of a lightpath does not take into consideration the effects of the other lightpaths simplifies considerably the problem formulation. In the following, we provide a formal ILP model for the linear IA-RWA-RP problem and two heuristics. Although such methods are based on a generic linear QoT, in the performance evaluation we use the Q-Personick factor [40]. The Q-Personick factor takes into account both linear and nonlinear effects. The measure of linear effects in the Q factor computation is the OSNR. The semilightpath OSNR can be calculated considering the OSNR across each of the elementary optical system components (such as the fiber spans and the nodes) along the semilightpath and by combining the partial results. The nonlinear effects are incorporated into the model by means of signal degradation factors determined by experimental analysis, which account for all amplifiers (both boosters and in-line amplifiers) along the semilightpath. For more details on the Q factor calculation, we refer to [9].

B. Problem Formulation

In this section, we present an exact ILP formulation (named as OptILP in the reminder) that solves optimally the linear IA-RWA-RP problem. The input parameters are the physical topology, the lightpath demands and the physical impairments. Let N be the set of nodes in the network, E the set of unidirectional fiber links, and W the set of wavelengths in each link. We assume that all fibers in the network have the same number of wavelengths. We denote as $a(e)$ and $b(e)$ the initial and ending nodes of fiber $e \in E$. We also denote $\delta^+(n)$ and $\delta^-(n)$ the set of fibers initiated and ending at node $n \in N$, respectively. T denotes the set of lightpath demands, being T_{sd}, the number of lightpaths to be established from node s to $d, s, d \in N$.

Our formulation is based on the concept of semilightpath. As a preprocessing step, the set of valid semilightpaths P_Q is calculated in the network. They consist of the set of all the paths, which are valid considering the physical impairments. Note that the set of semilightpaths forms a reachability graph [37], [39]. The model presented in this paper uses the semilightpaths as the links in a node-link formulation of the problem. We assume that regenerators are capable of wavelength conversion. The decision variables of the problem are

1) $x_{pwsd} = \{0, 1\}, p \in P_Q, w \in W, s, d \in N$. x_{pwsd} takes the value 1, if the path p in P_Q uses the wavelength w for carrying one lightpath of the demand from s to d.
2) $t_{sd} = \{0, 1, 2, \ldots\}, s, d \in N$. Number of lightpaths carried from node s to node d.

The problem formulation is given by the following equations:

$$\min \left(\sum_{p \in P_Q, w \in W, s, d \in N} x_{pwsd} - \sum_{s,d \in N} t_{sd} \right) + M \left(\sum_{s,d \in N} (T_{sd} - t_{sd}) \right) \quad (1a)$$

subject to

$$\sum_{\substack{p \in \delta^+(n) \\ w \in W}} x_{pwsd} - \sum_{\substack{p \in \delta^-(n) \\ w \in W}} x_{pwsd} = \begin{cases} t_{sd}, & \text{if } n = s \\ -t_{sd}, & \text{if } n = d \\ 0, & \text{otherwise} \end{cases} \quad \forall n, s, d \in N \quad (1b)$$

$$\sum_{p \in Q_e, s, d \in N} x_{pwsd} \leq 1 \qquad \forall e \in E, w \in W \quad (1c)$$

$$t_{sd} \leq T_{sd}, \qquad s, d \in N. \quad (1d)$$

The objective function (1a) consists of two elements. The first component aims to minimize the number of regenerators to be placed. The number of optical regenerators required by a lightpath is given by its number of semilightpaths minus 1. Then, the total number of regenerators is given by the total number of active semilightpaths minus the number of carried lightpaths. The second part of the objective function deals with the minimization of the number of blocked lightpath requests. By using a constant M high enough, it is possible to set the blocking minimization as the dominating criteria in the optimization (e.g., $M = |W||N|$). Then, a solution that carries more traffic would be always preferred whatever amount of extra signal regenerators requires. Constraints (1b) are the flow conservation constraints for the link-flow formulation. Constraints (1c) avoid the wavelength clashing, i.e., a wavelength in a fiber can be used only once. We denote as Q_e to the set of semilightpaths that traverse the fiber e. Finally, constraints (1d) state that carried traffic is limited by the offered traffic.

Note that this model can be easily modified adding a *placement constraint*; in such a case, only a subset N_r of the nodes is allowed to be equipped with regenerator/converter devices. The constraint (1e) introduces this into the model as follows:

$$x_{pwsd} = 0 \qquad \forall p \in P_Q, \quad b(p) \neq d, \quad w \in W, \quad s \in N, \quad d \notin N_r. \tag{1e}$$

In (1e), the semilightpaths ending in a node without regenerator equipment capability can only be active, if they are the last semilightpath of the lightpath. That is, for a semilightpath p, its ending node, which we denote as $b(p)$, does not need to belong to the subset N_r when $b(p)$ is the ending node of the lightpath.

C. LS Algorithm

An LS algorithm is an ILP-based algorithm that applies the concept of semilightpaths introduced in Section I. On the contrary to the ILP formulation (OptILP) presented in Section III-B, which makes use of precomputed semilightpaths that are composed into lightpaths, the idea behind LS is to start with predefined end-to-end paths, which are then decomposed onto transparent semilightpaths. Besides, we must highlight that OptILP considers the set of all the existing valid semilightpaths obtaining an optimal solution, while LS calculates a reduced set of candidate paths to limit the complexity of the formulation and, thus, a heuristic solution is found. To formulate the problem, we use a similar notation as in Section III-B.

We assume that each lightpath that is established in the network follows an explicit routing path. Accordingly, as a preprocessing step, a set of candidate paths L_{sd} (e.g., k shortest paths) is calculated for each pair of nodes $s, d \in N, s \neq d$. Let L denote the set of all paths.

Let L^{reg} and L^{noreg} denote, respectively, a subset of paths requiring regeneration at some intermediate node(s) and a subset of paths with no regeneration required; $L = L^{\text{reg}} \cup L^{\text{noreg}}$. For paths $p \in L^{\text{reg}}$, which are not valid considering the physical impairments, a segmentation procedure is performed in the preprocessing step to decompose them on valid semilightpaths. We perform such a procedure iteratively by segmenting a path on a number of sub-paths and by checking the physical impairment validity of each subpath. Since path p may be segmented in a number of ways, we obtain a set of candidate segmentations R_p. Each segmentation corresponds to a sequence of valid semilightpaths composing path p. In order to limit the size of R_p, in our implementation of the segmentation procedure, we begin the search with the lowest number of subpaths (i.e., two) that divides a given path and increment their number until a valid segmentation is found.

From combinatorial analysis, at the worst case, the number of segmentations per path is $R = \binom{\delta - 1}{\lceil(\delta-1)/2\rceil}$, where δ is the length (in hops) of the longest path in L^{reg}. Concurrently, the worst case complexity of the segmentation preprocessing step is bounded by $O(S|L|)$, where $S = \sum_{k=1}^{\delta} k\binom{\delta-1}{k-1} = (1+\delta)2^{\delta-2}$ corresponds to the number of QoT validations (one per each semilightpath).

Having calculated L and R_p, where $p \in L^{\text{reg}}$, in the pre-processing step, the LS problem concerns the selection of path p from the set of candidate paths L for each lightpath request and, if $p \in L^{\text{reg}}$, the selection of a segmentation of this lightpath from the set of candidate segmentations R_p. Concurrently, the RWA constraints, such as wavelength continuity, flow conservation, wavelength capacity, etc., have to be satisfied for all established lightpaths in the network. We continue formulating the optimization problem. First, the set of problem coefficients and constants coming from the preprocessing steps are as follows.

1) $l_{pr}, p \in L, r \in R_p$. Number of transparent segments (semilightpaths) on path p in L under segmentation r in R_p.
2) $\delta_{ep}, e \in E, p \in L$. Coefficient which is equal to 1, if link e belongs to path p, and equal to 0, otherwise.
3) $\eta_{elpr}, e \in E, l \in \{1, \ldots, l_{pr}\}, p \in L^{\text{reg}}, r \in R_p$. Coefficient which is equal to 1, if link e belongs to segment l of path p under segmentation r, and equal to 0, otherwise.
4) M. Big constant number used as a weighting coefficient to give a priority to the blocking objective over the regenerator usage objective; to achieve it, it is enough to have $M = |L^{\text{reg}}| \cdot |W| \cdot (\max\{s_{pr} : p \in L^{\text{reg}}, r \in R_p\} - 1) + 1$.

The problem decision variables are the following.

1) $x_{sd} \in Z_+, s, d \in N$. Number of not accepted lightpath requests from node s to node d.
2) $x_p \in Z_+, p \in L$. Number of accepted lightpath requests that follow path p.
3) $x_{pw} \in \{0, 1\}, p \in L, w \in W$. x_{pw} is equal to 1, if wavelength w on path p is assigned to a lightpath (in case if $p \in L^{\text{noreg}}$) or to the first semilightpath (if $p \in L^{\text{reg}}$), and equal to 0, otherwise.
4) $x_{\text{pwrl}} \in \{0, 1\}$, $p \in L^{\text{reg}}, r \in R_p, w \in W, l \in \{1, \ldots, l_{pr}\}$. x_{pwrl} is equal to 1, if semilightpath l on path p under candidate segmentation r has assigned wavelength w, and equal to 0, otherwise.

The formulation is described in the following equations:

$$\text{minimize} \sum_{p \in L^{\text{reg}}} \sum_{w \in W} \sum_{r \in R_p} (l_{pr} - 1) x_{\text{pwr1}} + M \sum_{s,d \in N} x_{sd} \tag{2a}$$

subject to

$$\sum_{p \in L_{sd}} x_p + x_{sd} = T_{sd} \qquad \forall s, d \in N \tag{2b}$$

$$\sum_{w \in W} x_{pw} = x_p \qquad \forall p \in L \tag{2c}$$

$$\sum_{r \in R_p} x_{pwr1} = x_{pw} \qquad \forall p \in L^{\text{reg}}, w \in W \tag{2d}$$

$$\sum_{w \in W} x_{pwr(l-1)} = \sum_{w \in W} x_{\text{pwrl}} \qquad \forall p \in L^{\text{reg}}, \quad r \in R_p, \quad l = 2, \ldots, l_{pr} \tag{2e}$$

$$\sum_{p \in L^{\text{noreg}}} \delta_{ep} x_{pw} + \sum_{p \in L^{\text{reg}}} \sum_{r \in R_p} \sum_{l=1,\ldots,l_{pr}} \eta_{elpr} x_{\text{pwrl}} \leq 1 \qquad \forall e \in E, w \in W. \tag{2f}$$

The objective function (2a) consists of two components. The first one counts the number of regenerators, which depends on the number of semilightpaths that compose the lightpaths requiring signal regeneration. The second component represents the number of blocked lightpath requests. The constant M is assumed to be big enough so that the blocking objective dominates the optimization. Constraints (2b) are the traffic constraints, which mean that either the offered connection requests are distributed over candidate paths or they are lost. Constraints (2c) and (2d) are the wavelength assignment constraints both for the lightpaths that do not require the signal regeneration and for the lightpaths that are composed of semilightpaths. In particular, in (2d), the wavelength of the first semilightpath together with a convenient segmentation of the corresponding lightpath is determined. Concurrently, constraints (2e) are the flow conservation constraints, which assign wavelengths to consecutive semilightpaths under the assumption that the regenerative nodes are capable of the wavelength conversion. Eventually, constraints (2f) represent the wavelength capacity constraints.

The number of variables and constraints of formulation (2) is upper bounded, respectively, by $|N|^2 + |L| + |L||W| + R\delta|L^{\text{reg}}||W|$ and $|N|^2 + |L| + |L^{\text{reg}}||W| + R\delta|L^{\text{reg}}| + |E||W|$. Since optimization problem (2) is a variant of the RWA problem (to see it, consider $L^{\text{reg}} = \oslash$), the problem is NP-hard. Nevertheless, under the condition that the sets of candidate paths and candidate segmentations are not large, the algorithm performance is satisfying, even for larger network instances, as shown in Section V.

D. Three-Step Heuristic

The second heuristic algorithm proposed consists of three consecutive steps.

1) (*Routing*): An instance of the integral multicommodity flow problem [41] is optimally solved for the network. In the Integral Multicommodity Flow formulation, each link represents a fiber in the original network, with a capacity given by $|W|$. The flows to allocate are the lightpaths. Each carried lightpath occupies a capacity of one in each traversed fiber. The purpose of this formulation is to find a route for every lightpath demand without considering either the wavelength assignment or the physical impairments. The objective function is set to a) minimize the lightpaths blocked and b) among the solutions with the minimum blocking, search for the one minimizing the average number of physical hops of the carried lightpaths.
2) (*Wavelength assignment and converter placement*): The carried lightpaths from the earlier stage are sequentially processed. For each lightpath, a first fit wavelength assignment is carried out. When wavelength continuity is not possible, regenerators are used as wavelength converters. We use the first wavelength that allows carrying the lightpath using one regenerator. If that is not possible, the same is applied for 2), 3), etc. regenerators till a solution is found.
3) (*Regenerator placement*): The set of lightpaths produced from earlier iterations are sequentially processed. The Q factor of each lightpath is evaluated. If its Q factor value is below the QoT threshold set, it is trivially split into the minimum number semilightpaths needed, placing the regenerators in the appropriate nodes.

Step 1 of the algorithm produces the set of lightpaths to be carried, minimizing the network capacity blocking. After that, steps 2 and 3 of the algorithm heuristically search for the minimum number of regenerators, which solve the wavelength clashing and signal degradation issues. However, note that no blocking exists in both last steps. Therefore, the three-step Heuristic optimally minimizes the network capacity blocking, and guarantees a zero-signal regenerator blocking.

Finally, while the integral version of the multicommodity flow problem used in step 1 is known to be NP-hard, its complexity has shown to be acceptable for the network sizes of interest, as shown in Section V.

IV. Nonlinear IA-RWA-RP Problem

A. Nonlinear QoT Estimator

For the nonlinear IA-RWA-RP problem, we make use of a nonlinear QoT estimator called Q-NL. Q-NL factor explicitly considers linear and nonlinear effects. The main impairments included in this Q factor, and modeled according to the references, are: ASE [11], intrachannel crosstalk (XT) [11], XPM, self-phase modulation (SPM) [12], [13], four-wave mixing (FWM) [13]–[15], and polarization-mode dispersion (PMD) [16]. Chromatic dispersion (CD) is considered completely compensated by the transmission system.

B. Iterative RP Heuristic

In the nonlinear IA-RWA-RP problem, the interferences between lightpaths are included explicitly in the QoT estimation. In this context, the Q factor of a semilightpath depends on the existence of other semilightpaths with common links and common nodes. To address this problem, we propose the IRP algorithm. It consists of the following steps.

1) (*Routing*): The routing of each lightpath is conducted as in the step 1 of the three-step algorithm.
2) (*Converter placement*): Wavelength converters are placed as in the step 2 of the three-step algorithm.
3) (*Iterative wavelength reassignment and RP*): The input parameters to this step are the semilightpaths defined by the already placed converters/regenerators. Note that the wavelength assignment obtained in step 2 is not used as an input parameter.
    1) *Wavelength assignment*: The formulation (3) is executed to assign a wavelength to each semilightpath, minimizing an estimation of the noise variance caused by nonlinear impairments.
    2) *Validity check*: If all the semilightpaths have a Q factor within the valid range, the algorithm ends.
    3) *Regenerator placement*: The semilightpath with the worst Q factor estimator is split into two semilightpaths by placing one regenerator. Let n be the initial node of the original semilightpath. The regenerator is placed at node $n'f$ so that i) the semilightpath from n to n' is Q-valid and 2) but if the regenerator was placed at node n ", one link further from n, the

resulting semilightpath from n to n' would not be Q-valid.

Step 1 of the algorithm routes the lightpath demand. If lightpath blocking occurs at this stage, that would be network capacity blocking, which is not solvable by placing regenerators. Further steps place regenerators till all the semilightpaths are QoT-valid.

The wavelength assignment step is obtained by solving the following ILP:

$$\min \sum_{p \in P_a} S_p \tag{3a}$$

subject to

$$\sum_{w \in W} x_{pw} = 1 \qquad \forall p \in P_a \tag{3b}$$

$$\sum_{p \in P_a \cap Q_e} x_{pw} \leq 1 \qquad \forall e \in E, w \in W \tag{3c}$$

$$\sum_{e \in p} \begin{pmatrix} s^2_{\mathrm{XT},b(e)} \sum_{p'|b(e) \in p'} x_{p'w} \\ +s^2_{\mathrm{XPM}-1,e} \sum_{p \in P_a \cap Q_e} (x_{p'w-1} + x_{p'w+1}) \\ +s^2_{\mathrm{XPM}-2,e} \sum_{p \in P_a \cap Q_e} (x_{p'w-2} + x_{p'w+2}) \\ +c_{\mathrm{FWM}} - S_p \end{pmatrix} \leq \sigma^2_{\mathrm{pw,\ MAX}} + B(1 - x_{pw}) \quad p \in P_a, w \in W. \tag{3d}$$

The formulation assigns one wavelength to each one of the semilightpaths already defined at this step of the algorithm, represented by set P_a. Constraints (3b) set that one wavelength is assigned per semilightpath. The wavelength clashing constraints are defined in (3c). Constraints (3d) include the effects of the nonlinear impairments. Left-hand side of (3d) is an estimation of the noise variance suffered by semilightpath p, if assigned wavelength w, caused by: 1) XT from other semilightpaths with common nodes; 2) XPM; and 3) FWM caused by other semilightpaths with common links. In its turn, $\sigma^2_{\mathrm{pw,\ MAX}}$ represents the maximum noise variance related to nonlinear impairments that semilightpath (p, w) could accept while maintaining the required QoT. Worst case variances s^2 and c_{FWM}, and maximum acceptable variance $\sigma^2_{\mathrm{pw,\ MAX}}$ are calculated according to [11]–[15]. The variables $S_p \geq 0$ are slack variables to permit that some semilightpaths exceed the accepted noise variance. The sum of these slack variables is the figure of merit to optimize (3a).

V. Results

This section collects and analyzes extensive results obtained for validating the algorithms proposed, under different testing scenarios. As a comparison, we also provide the lightpath blocking and regenerator cost performances calculated by the LERP algorithm proposed in [25] for the linear IA-RWA-RP case, and the PH-ILPmax algorithm proposed in [29] for the nonlinear IA-RWA-RP case. The latter algorithm provides the best performance among the family of algorithms proposed in [29]. All the algorithms have been implemented in MATLAB code, integrated and tested in the MatPlanWDM tool [42], which interfaces with the TOMLAB/CPLEX solver [43].

TABLE I
Information on the Topologies Tested

	Internet2	NSFNET	NOBEL-EU
Reference	[44]	[45]	[46]
Nodes	9	14	28
Unidirectional links	26	42	82
Average in degree (link)	1.44	1.50	1.46
Average link length β=β^{MIN} (km) (Q-Personick)	531.3	432.4	292.2
Average link length β=β^{MAX} (km) (Q-Personick)	1806.4	1081	1043
Ratio maximum/average link length (>1) (Q-Personick)	1.6	2.6	2.5
Average link length β=β^{MIN} (km) (Q-NL)	425.0	324.3	-
Average link length β=β^{MAX} (km) (Q-NL)	2019.0	1189.0	-
Ratio maximum/average link length (>1) (Q-NL)	1.6	2.6	-

A. Testing Scenarios

Three reference network topologies, together with their corresponding reference traffic matrices, are used in our study: Internet2 [44], NSFNET [45], and NOBEL-EU [46]. Table I summarizes some major data from these topologies. All the nodes are allowed to host regenerators. The number of wavelengths per fiber tested is $W \in \{8, 16\}$ for medium-sized networks Internet2 and NSFNET, and $W \in \{80\}$ for the NOBEL-EU test.

As commented earlier, in this paper, we employ the Q-Personick factor [40] implemented as in [9], as a representative of the linear QoT estimators and the Q-NL estimator based on analytical models for the nonlinear QoT case. We recall that a Q factor estimates the quality of optical signal along a transparent semilightpath, i.e., the segment of a lightpath comprised between two regenerators.

The optical transmission system parameters considered for the Q-Personick are the same as in [9], and they are shown in Table II. We assume spans of standard single-mode fiber (SSMF). The threshold on the acceptable Q factor value is equal to 17 dB. As a result, the maximum link length, which is valid according to the Q threshold is 2688 km.

The Q-NL assumes the link and node architectures proposed in [47] and [11], respectively, with spans of SSMF undercompensated with dispersion compensation fibers to a value of 30 ps/nm·km to diminish the nonlinear effects. An appropriate postcompensation module in the end of the link compensates the accumulated dispersion. The transmission parameters used are depicted in Table II. The same threshold (17 dB) on the acceptable Q factor is used to validate the QoT of a semilightpath. The resulting maximum link length considering worst case nonlinear impairments (links totally populated with lightpaths) is in the order 3000 km, with slight variations between different topologies and number of wavelengths per fiber.

In our tests, three traffic loads are considered: low, medium, and high $(\rho \in \{0.4, 0.7, 1\})$. Given a network topology, a reference traffic matrix for that topology T^{BASE} (measured in any arbitrary traffic units), a number of wavelengths per fiber W and a

TABLE II
TRANSMISSION SYSTEM PARAMETERS

Parameter	Q-Personick	Q-NL
Transmitter Bit Rate	10 Gbps	10 Gbps
Modulation Type	-	NRZ-OOK
Grid Spacing	-	50 Ghz
Maximum Span Length	85 km	85 km
Input Power to SSMFs	3 dBm	3 dBm
Input Power to DMFs	-	-4 dBm
SSMF Attenuation Parameter	0.23 dB/km	0.23 dB/km
DCF Attenuation Parameter	-	0.5 dB/km
SSMF CD Parameter	-	17 ps/nm·km
DCF CD Parameter	-	-80 ps/nm·km
Noise Figure of in-line and pre-amplifiers	5 dB	5 dB
Noise Figure of boosters	6 dB	6 dB
PMD Parameter	-	0.1 ps/$\sqrt{km}$
Switching Power Attenuation	13 dB	as in [11]
Switch Crosstalk Ratio	-	32 dB

traffic load factor ρ, the lightpath demand matrix is calculated as follows. First, we calculate the maximum lightpath demand matrix T^{MAX}. This is done by finding the maximum value α^{MAX} for which the lightpath demand matrix in (4) admits a feasible routing solution for an instance of the integral multicommodity flow problem (built as in the step 1 of the three-step algorithm). This guarantees that the lightpaths in T^{MAX} can be fully carried by the network with a 0% of lightpath blocking, if a sufficient number of regenerators are used

$$T^{\mathrm{MAX}} = \mathrm{round}\ (\alpha^{\mathrm{MAX}} \cdot T^{\mathrm{BASE}}). \quad (4)$$

The maximum lightpath demand matrix, T^{MAX} is associated to load $\rho = 1$. Let us denote S_T the total number of lightpaths in $T^{\mathrm{MAX}}, S_T = \sum_{s,d \in N} T_{sd}^{\mathrm{MAX}}$. Then, the lightpath demand matrices T^{ρ} at other network loads ρ are calculated by finding the factor $\alpha < \alpha^{\mathrm{MAX}}$ for which its associated lightpath demand matrix has a volume equal to ρS_T (or its closest integer value)

$$T^{\rho} = \left\{ \begin{array}{ll} \mathrm{round}\ (\alpha \cdot T^{\mathrm{BASE}}) & \text{so that } \alpha \leq \alpha^{\mathrm{MAX}} \\ \sum_{s,d \in N} T^{\rho} = \mathrm{round}\ (\rho S_T) & \end{array} \right\}. \quad (5)$$

The traffic normalization designed in our tests implies that all the planning instances admit a solution with a 0% of network capacity blocking.

We are also interested in studying the effects of the network link lengths on the regenerator equipment cost planned. For each network topology, we follow this sequence of steps

1) We calculate the maximum factor β^{MAX} so that after multiplying the length of all the links of the network by β^{MAX}, the longest link has a Q factor value just equal to the acceptable detection threshold (17 dB). Note that values $\beta > \beta^{\mathrm{MAX}}$ are not considered, since they could require an optical signal to be regenerated in the middle of a fiber link.
2) We calculate the minimum factor β^{MIN} so that after multiplying the length of all the links of the network by β^{MIN}, the shortest path between every pair of nodes with the worse (lowest) Q factor still has a Q factor $Q = 17$ dB.
3) We repeat the tests for four distance factors in the network: $\{\beta^1, \beta^2, \beta^3, \beta^4\}$, where $\beta^1 = \beta^{\mathrm{MIN}}, \beta^4 = \beta^{\mathrm{MAX}}$, and we obtain β^2 and β^3 as intermediate points between the values of β^1 and β^4.

Note that β multipliers define a sort of normalized network size. They depend on the relation between the link lengths and the QoT degradation. This latter effect is affected by technological aspects like the transceivers bit rate and modulation, or the amplification and compensation equipment installed in the network. In other words, higher β multipliers could be associated either to continental long-haul networks, or to smaller networks with, e.g., shorter reach transmission technologies.

B. Results: Linear IA-RWA-RP Case

Tables III and IV collect the testing results for the networks Internet2 and NSFNET. In both cases, the tests has been conducted for $W \in \{8, 16\}$ wavelengths, three load levels $\rho \in \{0.4, 0.7, 1\}$ and four distance factors $\beta \in \{\beta^1, \beta^2, \beta^3, \beta^4\}$. In the linear case, five RP methods are compared: 1) OptILP, the exact formulation presented in Section III-A; 2) three-step heuristic in Section III-C; 3) LS heuristic in Section III-B; and 4) the LERP algorithm proposed in [25]. The LERP algorithm has been executed ranging different values of a set of specific parameters that tune how the solution space is heuristically explored. The results shown in this paper correspond to those parameters, which provided the best performances. We reproduce their values to allow the results in this paper to be repeatable: 1) the number of shortest paths computed associated to each demand is set to 4; 2) the LERP black list size is set to 100; and 3) the number of permutations performed in the demand set is 10000. The reader should refer to [25] for more details on the operation of the LERP algorithm. For the LS algorithm, the set of candidate paths is calculated as k shortest paths between every pair of nodes according to the physical distance. When the value of k is selected, we must take into account that using more candidate paths avoids the problem of network capacity blocking, but it increases the algorithm complexity. Therefore, we execute several experiments for each topology scenario and find the lowest number of candidate paths that allows to reach the zero-blocking objective, in particular, $k = 3, k = 5$, and $k = 2$, respectively, for Internet2, NSFNET, and NOBEL-EU.

In Tables III and IV, we provide the information related to the regenerator equipment cost and the execution time of the algorithms. The regenerator cost is given as the average number of regenerators that a carried lightpath needs (in %). That is, the total number of regenerators planned divided by the carried demand volume. The lightpath-blocking information is not provided for the OptILP, three-step, and LS algorithms, since it is zero for all of them. Note that this was guaranteed for both the OptILP and three-step methods. Results have shown that although LS heuristic does not necessarily guarantee a 0% of signal regeneration lightpath blocking, it provides this benefit in practice thanks to the appropriate choice of the set size of predefined paths. In contrast, the LERP algorithm exhibits lightpath blocking in numerous cases. The column LB provides a lower bound to the regenerator cost. It corresponds to the number of regenerators needed, if each of the lightpaths was carried alone in the network using the path with the lowest possible number

TABLE III
INTERNET2 AND NSFNET: PERCENTAGE OF REGENERATORS (AND BLOCKING)

			Internet2							**NSFNET**						
			Linear					**Non-Linear**		**Linear**					**Non-Linear**	
w	**β**	**ρ**	**ILP**	**3-Step**	**LS**	**LERP (%Block.)**	**LB**	**IRP**	**[29]**	**ILP**	**3-Step**	**LS**	**LERP (%Block.)**	**LB**	**IRP**	**[29]**
8		0.4	0.0	0.0	0.0	(0.0) 0.0	0.0	0.0	(0.0) 0.0	0.0	0.0	0.0	(0.00) 0.0	0.0	0.0	(0.0) 0.0
	1	0.7	0.0	0.0	0.0	(0.0) 0.0	0.0	0.0	(0.0) 4.3	0.0	0.0	0.0	(0.00) 0.0	0.0	0.0	(0.0) 0.0
		1	0.0	0.0	0.0	(0.0) 0.0	0.0	0.0	(0.0) 14.7	0.0	0.0	0.0	(0.05) 0.0	0.0	0.8	(2.6) 0.0
		0.4	7.6	7.6	7.6	(3.8) 4.0	7.6	11.5	(4.0) 24.0	0.0	0.0	0.0	(0.00) 0.0	0.0	0.0	(4.3) 13.0
	2	0.7	4.3	4.3	4.3	(2.1) 2.2	4.3	10.8	(17.9) 46.1	0.0	1.1	0.0	(0.01) 1.2	0.0	1.1	(3.7) 22.2
		1	5.8	10.2	5.8	(0.0) 8.8	5.8	25.0	(11.4) 72.1	2.5	3.3	2.5	(0.06) 0.8	0.0	13.3	(23.7) 0.0
		0.4	7.6	7.6	7.6	(3.8) 4.0	7.6	19.2	(8.3) 8.3	0.0	0.0	0.0	(0.00) 0.0	0.0	0.0	(0.0) 8.3
	3	0.7	8.7	8.7	8.7	(4.3) 4.5	8.7	19.5	(12.1) 56.0	3.5	4.7	3.6	(0.07) 0.0	3.5	19.0	(3.7) 40.7
		1	26.4	26.4	26.4	(1.4) 35.8	26.4	57.3	(54.4) 36.3	13.3	13.3	13.3	(0.08) 6.3	6.6	41.6	-
		0.4	23.0	23.0	23.0	(7.6) 12.5	23.0	23.0	(0.0) 23.0	2.0	2.0	2.1	(0.02) 0.0	2.0	8.3	(4.3) 43.5
	4	0.7	34.7	34.7	34.7	(4.3) 31.8	34.7	36.9	(0.0) 39.1	16.6	17.8	17.9	(0.14) 6.9	11.9	33.3	-
		1	61.7	61.7	61.7	(1.4) 71.6	61.7	69.1	-	30.0	31.6	30.0	(0.18) 19.1	17.5	55.8	-
16		0.4	0.0	0.0	0.0	(0.0) 0.0	0.0	0.0	(0.0) 3.5	0.0	0.0	0.0	(0.00) 0.0	0.0	0.0	-
	1	0.7	0.0	0.0	0.0	(0.0) 0.0	0.0	0.0	(1.0) 18.5	0.0	0.0	0.0	(0.00) 0.0	0.0	0.0	-
		1	0.0	0.0	0.0	(0.0) 0.0	0.0	0.0	(13.8) 0.0	0.0	0.0	0.0	(0.05) 0.0	0.0	0.4	-
		0.4	3.5	3.5	3.5	(1.7) 1.8	3.5	5.3	(16.6) 0.0	0.0	0.0	0.0	(0.00) 0.0	0.0	1.0	(3.2) 23.4
	2	0.7	12.2	12.2	12.2	(0.0) 15.3	12.2	26.5	(18.8) 86.7	0.0	0.0	0.0	(0.00) 0.5	0.0	8.8	-
		1	8.5	11.4	8.5	(0.0) 13.5	8.5	25.0	(55.5) 2.2	1.2	2.8	1.2	(0.06) 1.3	0.0	22.2	-
		0.4	14.2	14.2	14.2	(1.7) 14.5	14.2	16.0	(1.8) 52.7	5.1	5.1	5.2	(0.03) 2.1	5.1	14.4	(7.8) 45.6
	3	0.7	28.5	28.5	28.5	(0.0) 42.8	28.5	64.2	(48.4) 39.3	10.5	11.7	10.6	(0.06) 11.8	10.5	40.0	(11.8) 86.8
		1	24.2	27.1	25.7	(0.0) 43.5	24.2	60.7	(72.8) 37.0	16.4	18.1	16.9	(0.06) 17.4	8.6	50.6	-
		0.4	39.2	39.2	39.2	(1.7) 40.0	39.2	35.7	(3.7) 48.1	13.4	14.4	13.4	(0.08) 6.7	13.4	38.1	(5.4) 54.4
	4	0.7	63.2	65.3	63.2	(0.0) 73.4	63.2	75.5	(8.8) 138.8	23.5	28.8	24.7	(0.06) 29.5	20.5	51.1	-
		1	55.7	57.1	55.7	(0.7) 74.1	55.7	67.1	-	33.7	36.2	33.7	(0.07) 38.7	18.5	68.3	-

of semilightpaths traversed. The interest on plotting the LB information in Table III is evaluating its accuracy by comparing its value to that of the optimal cost in OptILP column. The accuracy of the LB has shown to be perfect in the Internet2 topology. For the NSFNET network, a null or small gap between the LB and the optimal cost is observed in all the low- and medium-load occasions. A more significant gap between the LB and the optimal cost is found in high network loads and high normalized network sizes (with a maximum of $\sim$15% in the worst case). This is logical, since the lower bound assumes a shortest path routing, which is in general not possible at high-load conditions.

By comparing the regenerator cost performance in OptILP with those from the heuristic algorithms, we can assess their quality for the small to medium size topologies tested. Results in Table III show that the number of regenerators required by the three-step and LS algorithms are equal to the results obtained by OptILP in almost all the cases. On the contrary, the LERP algorithm obtains accurate results only for the distance factor β^1. For the rest of scenarios, it needs a higher number of regenerators and/or incurs in lightpath blocking. Note that in some occasions, the regenerator cost of the LERP solution is lower than the optimum. This is because LERP has significant lightpath blocking and, therefore, requires a smaller number of regenerators. In summary, the three-step and LS algorithms outperform the LERP algorithm for the scenarios considered obtaining a close to optimal regenerator cost, without incurring in lightpath blocking.

Table V collects the results of the heuristic algorithms for the case of NOBEL-EU network, and $W = 80$ wavelengths per fiber. Given the larger number of nodes and wavelengths, it has not been possible to obtain results with OptILP. However, it is very interesting to see that in this case, both the three-step and LS heuristics achieve the optimum solution that minimizes the regenerator equipment cost with a zero percent of lightpath blocking. Optimality is guaranteed, since its cost equals the cost of the lower bound. The results of three-step and LS algorithms outperform the ones of LERP, which incurred in lightpath blocking in the instances with normalized network sizes β^3 and β^4. In some of these situations, the LERP algorithm required a lower amount of regenerators than the lower bound. Again, this is due to the higher number of blocked lightpaths in the LERP solution, causing an overall decrease of the regeneration requirements.

Summarizing the comparison of the heuristics, the LS and three-step algorithms provide very similar solutions in all the occasions, very close to the optimal solutions. In Internet2 and NSFNET cases, they were more frequent the cases in which the LS algorithm provided better solutions. Finally, some interesting remarks can be made by observing the regenerators placed by three-step algorithm in its second and third step. It has been observed that in practically all of the cases, no regenerators were placed in step 2 of the algorithm. That means that regenerators were seldom needed for wavelength conversion purposes. Only in some problem instances at higher loads, some lightpaths (below 0.5%) changed their wavelength along the path. The uncommonness of the wavelength conversion in offline planned optical networks is supported by earlier studies like [48].

By observing the values in the OptILP column and the results from the LS and three-step heuristics in Table III, it is possible to capture some trends in the regenerator equipment

TABLE IV
INTERNET2 AND NSFNET: EXECUTION TIMES (S)

			Internet2						Nsfnet					
			Linear				Non-Linear		Linear				Non-Linear	
w	β	ρ	ILP	3-Step	LS	LERP	IRP	[29]	ILP	3-Step	LS	LERP	IRP	[29]
8	1	0.4	9	< 1	< 1	< 1	8	34	503	< 1	< 1	< 1	15	38
		0.7	7	< 1	< 1	< 1	10	74	3830	< 1	< 1	< 1	20	51
		1	26	< 1	< 1	< 1	14	92	65989	< 1	2	< 1	68	117
	2	0.4	1	< 1	< 1	< 1	19	21	120	< 1	< 1	< 1	17	83
		0.7	1	< 1	< 1	< 1	41	25	188	< 1	1	< 1	43	91
		1	2	< 1	< 1	1	251	34	2925	< 1	4	2	532	117
	3	0.4	< 1	< 1	< 1	< 1	28	6	51	< 1	< 1	< 1	23	53
		0.7	< 1	< 1	< 1	< 1	65	15	101	< 1	1	< 1	304	62
		1	< 1	< 1	< 1	1	539	17	2368	< 1	3	1	1615	-
	4	0.4	< 1	< 1	< 1	< 1	34	5	27	< 1	< 1	< 1	54	41
		0.7	< 1	< 1	< 1	< 1	114	15	43	< 1	1	< 1	501	-
		1	< 1	< 1	< 1	< 1	658	-	123	< 1	5	1	2205	-
16	1	0.4	17	< 1	< 1	< 1	47	306	1540	< 1	< 1	< 1	81	-
		0.7	22	< 1	< 1	< 1	73	352	180594	< 1	36	< 1	118	-
		1	109	< 1	< 1	6	102	372	>300000	< 1	55	8	518	-
	2	0.4	3	< 1	< 1	< 1	114	93	169	< 1	1	< 1	154	311
		0.7	5	< 1	< 1	< 1	2313	126	343	< 1	16	< 1	2315	-
		1	11	< 1	< 1	13	5261	123	202857	< 1	100	7	14164	-
	3	0.4	1	< 1	< 1	< 1	226	57	97	< 1	1	< 1	866	260
		0.7	1	< 1	< 1	< 1	4828	65	12796	< 1	8	1	9121	307
		1	5	< 1	< 1	12	11235	53	11884	< 1	83	1	16879	-
	4	0.4	< 1	< 1	< 1	< 1	442	49	60	< 1	2	< 1	1292	184
		0.7	< 1	< 1	< 1	< 1	5611	88	284	< 1	8	< 1	6714	-
		1	< 1	< 1	< 1	78	12447	-	18879	< 1	28	9	22656	-

TABLE V
NOBEL-EU: PERCENTAGE OF REGENERATORS (AND BLOCKING) AND EXECUTION TIMES (S)

		No. Regenerators (%)				Time (s)		
β	ρ	3-Step	LS	LERP (%Block.)	LB	3-Step	LS	LERP
1	0.4	0.0	0.0	(0.0) 0.0	0.0	< 1	3	23
	0.7	0.0	0.0	(0.0) 0.0	0.0	< 1	4	43
	1	0.0	0.0	(0.0) 0.0	0.0	< 1	7	61
2	0.4	0.0	0.0	(0.0) 0.0	0.0	< 1	4	23
	0.7	0.0	0.0	(0.0) 0.0	0.0	< 1	5	43
	1	0.0	0.0	(0.0) 0.0	0.0	< 1	8	61
3	0.4	5.6	5.6	(3.5) 2.2	5.6	< 1	11	23
	0.7	8.5	8.5	(2.4) 7.4	8.5	< 1	15	43
	1	7.0	7.0	(1.8) 6.1	7.0	< 1	18	60
4	0.4	18.4	18.4	(8.8) 10.5	18.4	< 1	12	23
	0.7	29.1	29.1	(7.6) 31.1	29.1	< 1	27	43
	1	24.7	24.7	(6.3) 26.3	24.7	< 1	60	61

cost. It seems clear that irrespective of the network load, networks with a small normalized size ($\beta = \beta^{\text{MIN}}$) do not require regeneration equipment. After that, larger network sizes are associated to higher regeneration needs. The same happens with the network load conditions, if we measure the regenerator equipment in absolute values. However, in some occasions higher load values implied lower *per-lightpath* regenerator cost. We observed that this behavior is explained by how the traffic matrices are synthesized. The *round* operation in (5) adds a sort of uncontrolled effect, depending on whether the coordinates of the lightpath demand matrix corresponding to distant nodes are more frequently rounded up or rounded down at a given network load. Finally, the regeneration equipment cost showed to be significantly topology dependent. For the maximum network factor β^{MAX}, the number of regeneration units per carried lightpath was in the order of 60% for Internet2 network, and 30% for the NSFNET and NOBEL-EU topologies. The reason for that difference can be found in the ratio between the maximum and average link lengths in the network. In Internet2 topology, the maximum link length is only 1.6 times the size of the average link length, while in NSFNET and NOBEL-EU topologies, there is a higher disparity in link lengths. Then, the average link length measured when we normalize the network at $\beta = \beta^{\text{MAX}}$ is significantly higher in the Internet2 topology ($\sim$1800 km in Internet2, and $\sim$1000 km in NSFNET and NOBEL-EU). Consequently, the percentage of the paths that need signal regeneration at $\beta = \beta^{\text{MAX}}$ is also higher in the Internet2 topology.

Tables III and IV display the execution time observed in each of the tests performed for all the algorithms. The most reduced execution times are obtained by the three-step algorithm whose times were *below of* 1 *second* in all the tests.

Naturally, the highest execution times correspond to the exact problem solving, in OptILP column. For Internet2, the execution times were reasonable, below two minutes in all the occasions. In the NSFNET network, execution times ranged from minutes to several hours. The longest time observed was about 80 h. Running times are higher for a higher number of nodes in the network and a higher number of wavelengths. This is caused by the increase in the number of decision variables of the problem. The effects of the network load and the normalized network size factors are more random, since they affect the performance of the branch-and-bound pruning step. As general trend, longer running times were observed for low-to-medium normalized network size factors.

The execution of the LS algorithm has shown to be around 1 s in all the Internet2 tests, and for NSFNET $W = 8$. The rest of the execution times are in the order of tens of seconds, always below 2 min. Longer execution times seem to be associated with larger networks with normalized size factors β^3 and β^4. However, this trend is not deterministic, since it is again affected by the performance of the branch-and-bound algorithm solving the LS formulation. Finally, the response time of the LERP algorithm is in general longer than the three-step and LS execution times.

C. Results Considering Nonlinear Impairments

Columns IRP and [29] of Table III show the planning results of the IRP algorithm and PH-ILPmax algorithm [29], respectively. Results show that IRP outperforms PH-ILPmaxby eliminating the lightpath blocking in all circumstances. In the occasions in which the PH-ILPmax algorithm produces solutions with zero blocking, the regeneration cost of IRP is always equal or lower. Note that the lightpath blocking is in general quite high in the solutions found by PH-ILPmax. Moreover, in the cases tagged with "-," the PH-ILPmax algorithm is not able to find a feasible solution in its phase 2, which stops the algorithm (see [29] for details).

The trends in the regenerator cost in the nonlinear IA-RWA-RP problem are similar to that of the linear case. This is logical, since the same principles apply in the relations among traffic, link length, and signal impairments. However, the absolute numbers of regenerators do not coincide. In general, the regenerator costs associated with the solutions of the nonlinear case are significantly higher. This happens more intensely for higher network loads and higher distance factors. It is explained by the different assumptions about the physical layer, node and link models, and by how the tests are designed. In the tests, the maximum distance factor (β^{MAX}) in the network is calculated as the maximum distance of a link to be able to accommodate a one hop semilightpath. For this situation, the Q-Personick factor produces more pessimistic Q values. Because of the link distance normalization performed, this produces smaller networks for distance factors β^3 and β^4 than in the Q-NL case (see the average link lengths $\beta = \beta^{\text{MAX}}$ for Q-Personick and Q-NL in Table I). The opposite situation happens for $\beta = \beta^{\text{MIN}}$. In this case, the distance factor β^{MIN} depends on the Q factor of a lightpath following the longest shortest path in the network, and now Q-NL provides more pessimistic estimations. The reason for these effects is that the Q-NL factor overestimates (with respect to the Q-Personick factor) the impairments, which depend on the number of nodes traversed (like crosstalk). Then, the Q factor of those routes requiring more hops will be penalized in the nonlinear case. This happens more often with high network loads (since the lightpaths may have to find routes with more hops), and with higher distance factors (since more routes are long enough to require regenerators and the links are longer in the Q-NL factor normalization). We would like to stress that the QoT estimators were chosen as representatives suitable to validate the quality of the planning algorithms. However, the results in this paper cannot be used to directly compare the Q factor estimators between them, since they do not relay on exactly the same network model.

Finally, columns IRP and [29] in Table IV show the execution time results for both algorithms. IRP is faster than PH-ILPmax for lower load and β values, but can be substantially slower in the rest of the cases. We have performed a code profiling study to observe the causes of this effect. Interestingly, the study shows that about 90% of the time is used in the Q factor computations, which are required in each algorithm iteration. Recall that the number of iterations is roughly given by the number of regenerators in the final solution, which increases with network load and network size. In particular, the ILP formulation (3) required less than 1 s to execute in the majority of the cases and 10 s in the worst case. Therefore, the scalability of the algorithm can be greatly improved by using other QoT estimators with lower computation requirements. In its turn, the PH-ILPmax algorithm makes a much lower use of the Q factor computation function, and thus, is not so intensely affected by this issue.

VI. Conclusion

This paper investigates the offline network planning and RP in translucent optical networks, minimizing the RP cost. We separately define and address the linear and nonlinear variants of these problems. As far as the authors know, we provide the first ILP model to optimally solve the linear IA-RWA-RP problem. Thanks to its simplicity, it is able to solve problem instances in small-to-medium scale networks. For larger network topologies, we present two heuristic algorithms named LS and three-step. In the nonlinear case, the IRP heuristic is proposed.

An extensive battery of tests is conducted. The traffic load in the tests is normalized to fairly assess the ability of the algorithms for minimizing the regeneration cost, without producing any signal regeneration related to lightpath blocking. The results show that the LS and three-step algorithms provide optimal or close-to-optimal solutions in all these tests. They outperform an earlier heuristic algorithm presented [25], both in the quality of the solution found and the algorithm execution time. In addition, the three-step algorithm guarantees that no signal regeneration lightpath blocking is produced. Consequently, both algorithms can be used to efficiently solve the linear IA-RWA-RP problem (e.g., selecting the best solution provided by both schemes). For solving the nonlinear IA-RWA-RP problem, we present the IRP heuristic. This heuristic is able to provide a zero-signal regenerator blocking. It outperforms in both lightpath blocking and regenerator equipment cost, the earlier proposals in the literature tested.

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