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Translucent network design from a CapEx/OpEx perspective

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Abstract Translucent WDM network design has been widely investigated during the last 10 years. Translucent networks stand halfway between opaque and transparent networks improving the signal budget while reducing the network cost. On one hand, opaque networks provide satisfying quality from source to destination by the use of electrical 3R regeneration (Re-amplifying, Re-shaping, and Re-timing) at each network node. In addition to their high cost inherent to numerous 3R regenerations, opaque networks are also constrained by the bit-rate dependence of electrical components. Transparent networks, on the other hand, do not include any electrical regeneration; therefore, the signal quality is degraded due to the accumulation of linear and non-linear effects along the signal's route. Translucent networks include electrical regeneration at some network nodes. Among the different possible strategies for translucent network design, sparse regeneration inserts regenerators whenever needed to help establish connection requests. In this context, the objective of translucent network design is to judiciously choose the regeneration sites in order to guarantee a certain quality of transmission while minimizing the network cost. In this paper, we propose to solve the translucent network design problem by introducing a heuristic for routing, wavelength assignment, and regenerator placement. This heuristic, called COR2P (Cross-Optimization for RWA and Regenerator Placement) aims not only to minimize the number of required regenerators, but also to minimize the number of regeneration sites. In this perspective, we introduce an original cost function that contributes to the optimization of CapEx/OpEx expenditures in translucent network design. In fact, the CapEx-to-OpEx ratio strongly depends on the pricing and management strategy of the carrier. In this respect, COR2P is designed in a way that its parameters can be adjusted according to carriers' strategies. In order to discuss its different features, we compare COR2P's performance with two other algorithms proposed in the literature for translucent network design.

Keywords Translucent WDM network · Quality of transmission · Routing and wavelength assignment · Regenerator placement · CapEx · OpEx

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1 Introduction

With the emergence of optical amplification and optical switching, the impact of physical layer impairments on the quality of transmission (QoT) must be considered within the dimensioning phase of WDM transport networks. The flexibility and high capacity provided by *transparent* WDM networks are faced with physical degradations due to transmission over fiber, namely dispersion, attenuation, and non-linear effects. Optical transmission systems currently used in WDM networks extend the optical reach by partially compensating for some of the physical layer impairments such as chromatic dispersion or attenuation. Meanwhile, considering linear impairments does not guarantee the effective bit error rate (BER) at the destination [1,2]. Recent research in the field of optical network planning takes into account the different limitations of the physical layer in the routing and wavelength assignment (RWA) operation. The Impairment-Aware RWA (IA- RWA) approaches define rules and strategies for lightpath establishment in a transparent network in order to minimize the number of rejected requests due to either capacity or QoT limitations. Besides combating transmission impairments in all-optical networks, some related studies focused on regenerator placement using 3R regeneration[1] (Re-amplifying, Re-shaping, and Re-timing) to extend the reach of the transported signal. Different possible implementations of optical-electrical-optical (O- E- O) regeneration for *translucent* networks are considered in the literature [3,4]. In this paper, we define a translucent network as a transparent network for which finite pools of regenerators are installed at a certain number of nodes in order to guarantee an admissible QoT at the destination for each connection. *Opaque* networks provide a-priori an admissible QoT at the price of costly electrical switches enabling systematic electrical regeneration and traffic aggregation at each node of the network. Simulations in [5,6] show that translucent networks can achieve connection rejection ratios close to those obtained in fully opaque networks while significantly reducing network's cost by decreasing the number of regenerators. In addition, all-optical cross-connects based on wavelength selective switches (WSS) and currently used in carrier networks are less energy consuming than electrical cross-connects. Moreover, simulations in [7] show that translucent networks (referred to as all-optical express networks where wavelength conversion is only possible at regeneration points) achieve the same network efficiency as can be achieved with full wavelength conversion at all nodes. In [8], Al Zahr et al. proposed an algorithm called lightpath establishment and regenerator placement (LERP) for translucent network design aiming at minimizing the number of rejected requests as well as the number of required regenerators. In [9,10], Pachnicke et al. deal with the problem of translucent network design assuming a fixed number of regeneration sites. In [11], we proposed an improved version of Pachnicke's algorithm to further minimize the number of regenerators. We refer to this ameliorated algorithm as regenerator placement and constraint-based routing (RP-CBR+).

It has been shown experimentally that 3R regeneration not only costs in terms of deployment (CapEx) but also in terms of operation and management (OAM) referring to OpEx costs. In this paper, we present a translucent network design strategy considering both linear and non-linear impairments. Only permanent traffic is considered. Our strategy called cross-optimization for RWA and regenerator placement (COR2P) also considers QoT to define an order for request processing. The OpEx costs inherent to the maintenance of electrical regenerators are considered in general as confidential information by the carriers. For this reason, we propose a model that takes into account the ratio of the CapEx and OpEx costs so that it may be exploited by carriers according to their own perception of this ratio.

The remainder of this paper is organized as follows. In Sect. 2, we provide a review of related work. In Sect. 3, we describe in detail the generic architecture of a node as it is considered in our study. From this architecture, we precise the parameters upon which the CapEx and OpEx costs of a switching node depend. Section 4 describes and justifies the various steps of the COR2P heuristic. In Sect. 5, we discuss regenerator concentration that represents the original aspect of our strategy. We also compare the performance of the aforementioned algorithms (COR2P to LERP and RP-CBR+). Our conclusion of this study is presented in Sect. 6 where we provide guidelines for future work.

2 Survey of related work

In traditional RWA algorithms, the blocking probability of a lightpath depends on resource availability, whereas IA- RWA algorithms consider the signal quality as well.

As a comprehensive parameter taking all the impairment effects into consideration, BER is an appropriate criterion to evaluate the signal quality of a lightpath [12,13]. Statistical models of the physical impairments and their effects on optical signals have been developed in order to estimate the BER in the routing process since its measurement is only possible once the lightpath is operational.

2.1 IA- RWA in transparent networks

In the context of transparent WDM networks under dynamic traffic, Deng et al. propose in [14] crosstalk-aware wavelength assignment (WA) algorithms as variants of the well-known *first-fit* (FF), *random-pick*, *most used*, and *least used* WA algorithms. Crosstalk-aware WA algorithms choose the available wavelength that minimizes crosstalk between the new and existing lightpaths reducing thereby the blocking probability. If multiple candidate wavelengths provide the same crosstalk factor for a new lightpath, one of them is selected according to the aforementioned schemes. Simulation results show that compared to their traditional counterparts, the proposed algorithms can significantly reduce blocking caused by poor QoT.

Non-linear effects have been considered under dynamic traffic in [15]. Cardillo et al. propose an algorithm that jointly solves the routing and wavelength assignment sub-problems. Upon the arrival of a lightpath request, all possible lightpaths are examined in terms of optical signal-to-noise ratio (OSNR) values perceived at their destination. The solution guaranteeing the maximum OSNR is then selected. Simulation results show that when transmission impairments come into play, the Best-OSNR algorithm outperforms traditional

[1] In the following, *regeneration/regenerator* will refer to electrical 3R regeneration/regenerator.

algorithms (e.g., FF) in terms of blocking probability. Huang et al. propose in [16] IA- RWA algorithms based on the traditional Best-Path (BP) and FF algorithms. When a lightpath is to be established, a network-layer module searches for a candidate lightpath. If no route and/or wavelength is available, the lightpath request is blocked. If a solution exists, a physical-layer module is invoked to verify the signal quality of the candidate lightpath. If the QoT requirements are not met, the network-layer searches for another solution. This operation is repeated until a solution is found. Otherwise, the lightpath request is blocked. Simulation results show that in realistic networks, the proposed algorithms can achieve a significant improvement in blocking probability with respect to their traditional counterparts.

2.2 IA- RWA in translucent networks

The idea of sparse regeneration has been supported by several studies and reported in the literature. Kim et al. deal with the problem of regenerator placement considering physical layer constraints [6]. For each lightpath, the authors verify whether the signal quality is acceptable at the destination or not with respect to QoT requirements. Three heuristics are proposed to choose the adequate sites for regeneration. Simulations carried out in [6] compare the proposed algorithms to a dynamic programming approach for minimal-cost placement (MCP). Simulation results show that the MCP algorithm outperforms the other heuristics in terms of blocking performance and especially when the lightpath requests have a long average distance expressed in hops.

In [5,17], Ramamurthy et al. deal with sparse regeneration in translucent WDM networks assuming a limited regeneration capacity. Four regenerator placement algorithms are proposed, based on either the network topology or a traffic prediction. The authors in [5] investigate the proposed algorithms considering different network topologies. Simulation results show that for medium-sized networks, the topology-based regenerator placement algorithm yields better results than the signal quality prediction and the traffic load prediction algorithms. However, for large-sized networks, the signal quality prediction algorithm yields the best performance.

In [8,18,19], Al Zahr et al. proposed and investigated an algorithm dealing with translucent WDM network design under static traffic. Assuming that it is possible to deploy, if necessary, a regenerator for a request at any intermediate node along its path, the proposed algorithm aims at minimizing both the number of rejected requests and the number of regenerators. In [18], the impact of deploying in-line equalizers on the number of required regenerators is investigated. Simulation results show that the usage of an equalization scheme can significantly improve performance throughout the network. Moreover, under low traffic load, the absence of in-line equalizers may be compensated by the use of a QoT-aware WA strategy, namely the Min-BER-Fit strategy (MBF). An enhanced QoT-aware WA strategy, called Best-BER-Fit (BBF), can furthermore improve network performance under heavy traffic loads [19].

In [9,10], Pachnike et al. propose an approach aiming to limit the regeneration to some network nodes considering the impact of both linear and non-linear impairments on QoT. They propose a double-stage algorithm for routing and regenerator placement. Their proposal relies on a topology-driven strategy for regenerator placement followed by a constraint-based algorithm for routing and wavelength assignment.

3 Investigated network

3.1 Network characteristics and parameters

Considering a translucent network, Fig. 1 describes the architecture of a node equipped with a pool of 3R regenerators. Different technologies are available for optical switching fabrics such as micro-electro-mechanical mirrors (MEMS) or wavelength selective switch (WSS). Nowadays, WSS-based ROADMs (reconfigurable optical add-drop multiplexers) are progressively deployed in core networks because of their relatively low cost. An optical signal that transit through a translucent node can either continue its path to the next node transparently (see lightpath l_1), or be subject to regeneration. In the latter case, the considered optical signal is extracted from the switching fabric to be redirected toward an available regenerator in the pool (see lightpath l_2). A regenerator proceeds to three operations: opto-electrical (O- E) conversion, bit regeneration, and electro-optical (E- O) conversion. The regenerated signal is then re-injected into the switching fabric to join the next node along its route.

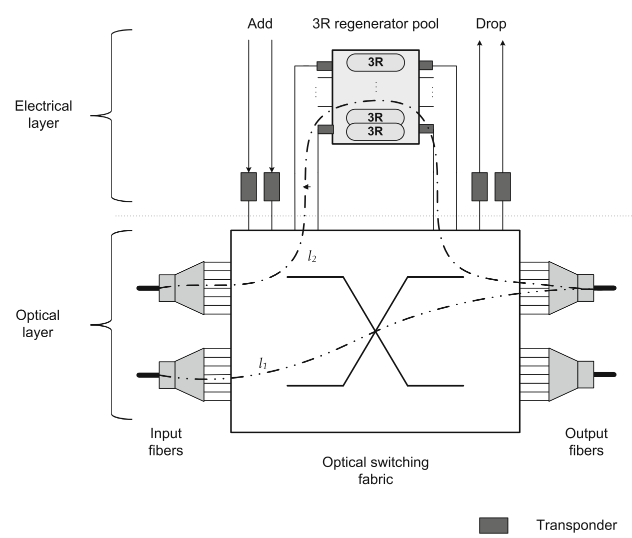

Fig. 1 Translucent node architecture

In practice, two types of regenerators must be distinguished: tunable and fixed regenerators. The former use tunable transceivers and thus can serve any optical connection. The latter, at the opposite, use fixed transceivers and thus can only serve optical connections operating at a specific wavelength. As long as only permanent traffic is considered, using fixed or tunable regenerators only impacts the unit cost of a regeneration site. In the context of dynamic traffic, using fixed or tunable regenerators differently impacts the connections' rejection ratio. In this paper, we consider tunable regenerators enabling wavelength conversion under permanent traffic. The conversion capability increases the network resources utilization.

Adjacent network nodes are connected by two contra-directional fibers. Fiber-links are deployed using standard single-mode fibers (SMF). In order to recover from fiber losses, double-stage erbium-doped fiber amplifiers (EDFA) are deployed every fiber-span, i.e., typically every 80 Km. However, one drawback of EDFAs is their non-flat spectral response. In other terms, the EDFA's gain depends on the considered wavelength. In [18], it has been shown how deploying dynamic gain equalization scheme can significantly improve the performance in the network. In this paper, we assume the deployment of dynamic gain equalizers every three spans. In order to compensate for chromatic dispersion, dispersion compensating fibers (DCF) are deployed systematically in the amplification sites. Further details about the transmission parameters can be found in [2].

3.2 Physical layer impairments

In most studies dealing with translucent network design, regeneration's decision relies on a linear approximation. In other terms, the quality of transmission of a lightpath is evaluated with respect to an average transparent distance, i.e., the optical reach distance. In this work, our regenerator placement strategy is based on a realistic estimation of the $\mathcal{Q}$-factor, related to the BER as follows:

$$\mathrm{BER} = \frac{1}{2}\left(\frac{\mathcal{Q}}{\sqrt{2}}\right) \tag{1}$$

Actually, the $\mathcal{Q}$-factor provides a quantitative description of the absolute quality of an optical signal. In this paper, we use a prediction tool, called BER-Predictor [2], to estimate the $\mathcal{Q}$-factor values. Given a lightpath, identified by a physical route and a specified wavelength, BER-Predictor computes the $\mathcal{Q}$-factor value taking into account four transmission impairments simultaneously, namely chromatic dispersion (CD), polarization mode dispersion (PMD), non-linear phase-shift (Φ_{NL}), and amplified spontaneous emission (ASE) [2]. Indeed, the $\mathcal{Q}$-factor value is a function of the penalties induced by the aforementioned parameters as proposed in [13]. It is worth noting that the analytical model, described in [13], has been obtained by extrapolation of experimental results assuming 40/80 wavelengths per link, covering the C-band with 100/50 GHz spacing. Each wavelength is assumed to carry a capacity of 10 Gbps.

In practice, under IA- RWA and static traffic, a potential route satisfying the wavelength continuity constraint is subject to a QoT-admissibility test. The QoT is estimated at each intermediate node from source to destination. When the estimated QoT is not acceptable at a certain node, a regeneration of the signal should be considered in a preceding node. The QoT-admissibility threshold may differ depending on the carrier. Meanwhile, in most cases, a residual BER at destination of 10^{-9} is adopted. Such a BER may be obtained thanks to the use of error correction techniques such as Reed-Solomon encoding relaxing the BER threshold to a value of 10^{-5}, i.e., a $\mathcal{Q}$-factor of 12.6 dB.

3.3 Regeneration's cost

In this work, we propose to jointly solve the IA- RWA and regenerator placement problems. For that purpose, two types of cost are considered, one related to the availability of physical resources at the optical layer and another one related to the availability of physical resources at the electrical layer. Concerning the cost inherent to electrical resources, i.e., to the usage of regenerators, two aspects must be considered namely CapEx and OpEx [4]:

- CapEx (Capital Expenditures)

Regenerators are not installed one by one but by pools of size X. On one hand, the regenerators of a pool are activated, i.e., power supplied, only if a connection requires such a regeneration. On the other hand, air conditioning for cooling a regeneration pool is provided systematically whatever the number of activated regenerators within the pool. In that sense, air conditioning is considered as a fixed cost per regeneration pool and then as a CapEx cost. For a given connection, the CapEx cost inherent to regeneration is proportional to the number of regeneration sites to be installed at the different nodes along the route assigned to this connection. If several connections need regeneration at a same node, the CapEx cost inherent to regeneration for all these connections is a unique cost $\mathcal{C}_C$.

- OpEx (Operational Expenditures)

Once a pool of regenerators is installed at a site, this pool has to be operated and supervised. We consider in this paper a supervision staff per regeneration site. The higher the number x of activated regenerators at the considered site, the lower the operation and maintenance cost of this site with respect to all operator's OpEx cost. Indeed, managing two regenerators at the same location is more cost-effective than to manage two regenerators at two distant sites. This is the reason why we choose to weight the OpEx cost by a negative exponential factor $e^{-\frac{1}{X}}$.

Equation (2) expresses the definition of the OpEx and CapEx costs inherent to a regeneration site v_i. x is the number of regenerators deployed at V_i.

$$\mathcal{C}(v_i) = \mathcal{C}_O \cdot e^{(-\frac{x}{X})} + \mathcal{C}_C \quad (2)$$

4 Cross-optimization for translucent network design

In the context of network dimensioning, permanent traffic is considered. A permanent lightpath demand (PLD) is a connection request having a data rate equal to the full capacity of a wavelength channel, thus established through a full lightpath.

4.1 Problem statement

Given

- a physical network topology wherein switching nodes are a-priori transparent;
- a set of wavelengths, available per fiber-link;
- a set of permanent lightpath demands (PLDs): the offered traffic;
- an admissible BER threshold in the network BER_{th}.

Objective

The aim of translucent network design is to satisfy the maximum number of PLDs while minimizing the network cost. This depends on the policy of choosing the nodes which will be equipped with regeneration facilities, i.e., those that will "become" translucent as in Fig. 1. As aforementioned in Sect. 3, we consider a twofold regeneration cost: CapEx and OpEx. Consequently, our objective is to minimize the number of required regenerators and to urge their concentration into a reduced number of nodes.

Subject to

Quality of transmission requirements: for any lightpath in the network, the corresponding BER value should not exceed the BER threshold at its destination node.

Wavelength continuity constraint: in the absence of any wavelength conversion, an established lightpath should be routed using the same wavelength along its route. Introducing regenerators slightly relaxes this constraint since electrical regeneration allows wavelength conversion.

Regeneration capacity per site: the number of regenerators that can be deployed in a regeneration site is limited to an upper bound X due to power supply or space constraints or any other motivation according to the carrier's strategy.

4.2 COR2P

As a solution for the translucent network design problem, we introduce our tool named COR2P for *Cross-optimization for RWA and Regenerator Placement*. COR2P is a heuristic-based algorithm that aims to find an RWA solution to a set of PLDs and places regenerators in appropriate nodes in order to satisfy the quality of transmission. Its originality consists not only in minimizing the number of required regenerators in the network but also in minimizing the number of regeneration sites. COR2P can be described in three consecutive steps as follows.

4.2.1 Step-1: Preliminary routing

In this step, we only consider the network resources and the wavelength continuity constraint.

First, for each PLD we compute an estimate of the BER over all of its shortest paths (K-shortest paths in Km) assuming flat transmission systems, i.e., the network elements have a flat spectral response. Then, considering the " best" path giving the best BER, we sort the PLDs in the decreasing order of BER. Subsequently, PLDs that are most affected by transmission impairments will be processed first. We recall that the"best" path is not necessarily the shortest path since the BER estimation depends on the transmission elements over the routes. Indeed, the higher the number of nodes over a path, the higher the non-linear impairments added by switching nodes, regardless of the distance in km of the path.

Second, we consider the ordered PLDs one by one. We scan each of a PLD's K-shortest paths for a solution that provides a path-free wavelength until one is found. If no solution is available by lack of resources over some of the paths' links, the processing of the PLD is postponed to Step-3. Such PLDs may then be satisfied thanks to the placed regenerators that relax the wavelength continuity constraint.

4.2.2 Step-2: Potential regenerator placement

In this step, we determine the nodes that are most likely to become regeneration sites. In this respect, each node is assigned a counter reflecting the need for regeneration at its level.

We consider the lightpaths obtained in Step-1 and follow the QoT of each lightpath hop-by-hop. Whenever the QoT drops, the counter of the preceding node is incremented and the quality test is resumed from that node until the lightpath's destination and so forth. Once all the lightpaths are processed, we sort the network nodes in decreasing order of counters. Introducing the parameter R as the initial number of regen-

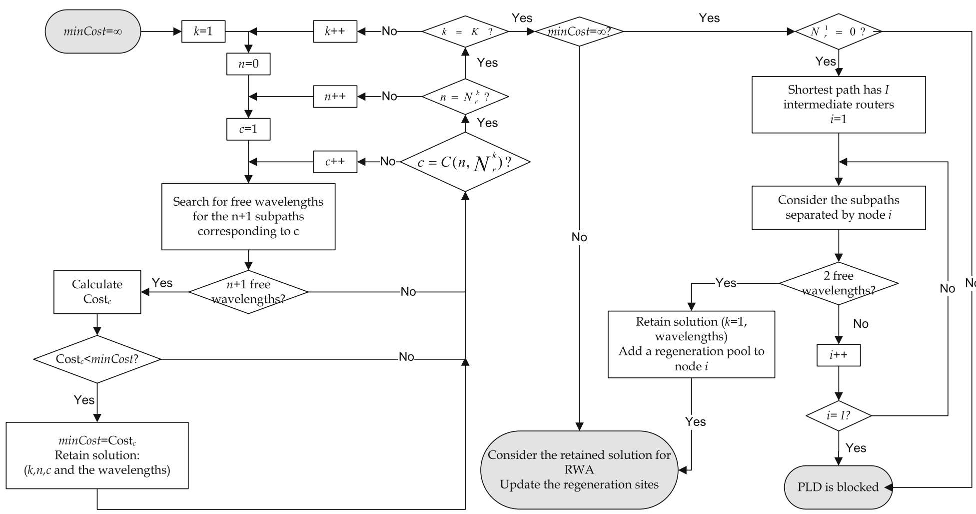

Fig. 2 PLD processing in Step-3

eration sites in the network, the first R nodes of the sorted list are thus qualified as those where regeneration is most likely needed. The number of regeneration sites at the end of Step-3 is not restricted to R as we explain in the following.

4.2.3 Step-3: Effective RWA and regenerator placement

In this step, we assume a real transmission system wherein the signal quality depends on the chosen wavelength. First, we consider the PLDs that have been routed in Step-1. We assign to each PLD an adequate wavelength according to the best-BER-fit (BBF) strategy. Given a path and a set of wavelengths, BBF consists in choosing the first available wavelength that guarantees the quality of transmission requirements [19]. Subsequently, BBF saves the better suited wavelengths in terms of BER for possible longer/weaker PLDs. If no available wavelength can satisfy the quality of transmission requirements, the lightpath requires one or more signal regenerations. In addition, PLDs that found no path-free wavelength in Step-1 benefit from the relaxation of the constraint of wavelength continuity using regenerators.

Second, PLDs that remain with no RWA solution are processed as follows. For each PLD, COR2P first verifies whether it can be routed without the need for any regeneration on any of its K-shortest paths. Otherwise, COR2P tries all possible combinations of regeneration over these paths. For each combination, a test for available wavelengths over the transparent subpaths is performed. These subpaths are separated by regeneration sites corresponding to each combination. If multiple possible solutions exist, they are compared one to the others by means of an original multi-constraints cost function (detailed in Sect. 4.2.4) that aims not only to optimize the number of deployed regenerators but also to concentrate them in several nodes in order to reduce

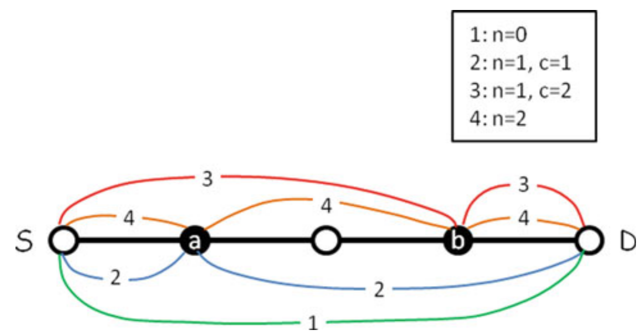

Fig. 3 Regeneration possibilities

the network's management cost. The retained solution is the one that costs less for the operator.

One regeneration site may be added if there is no way of routing the PLD on any of its K-shortest paths, even with regeneration in existing sites. This is only possible over the shortest path of the PLD.

Figure 2 depicts the flowchart according to which the PLDs that remain unrouted are processed in Step-3. We assume N_r^k regeneration sites over the path of index $k (1 \leq k \leq K)$, thus $C(n, N_r^k)$ combinations of n regeneration sites $(0 \leq n \leq N_r^k)$. Figure 3 presents an assimilation of the different regeneration possibilities over the kth path of a PLD from source S to destination D. The path passes by two regeneration sites a and b, thus the four possibilities of regeneration. The figure shows the subpaths corresponding to each regeneration possibility.

4.2.4 Cost function

The global cost of an end-to-end connection is twofold: the network resources cost and the regeneration cost. In our consideration, we weight these two costs by α and $(1-\alpha)$, respectively, as depicted in Eq. (3) ($\alpha \in [0, 1]$). According to the operator's preference, the regeneration cost is given more importance than the resource cost and vice versa by changing the value of α.

$$\mathcal{C}_{\text{connection}} = \alpha \cdot \mathcal{C}_{\text{resources}} + (1-\alpha) \cdot \mathcal{C}_{\text{regeneration}} \quad (3)$$

On one hand, as aforementioned in Sect. 3, the regeneration cost takes into account two aspects, namely CapEx and OpEx. We assume that regenerators are not installed individually but by pool of size X. Let v_i be a regeneration site used by a connection. Respecting the cost depicted in Eq. (2), the regeneration cost $\mathcal{C}_R(v_i)$ relative to v_i takes into account the CapEx/OpEx duality as follows:

$$\mathcal{C}_R(v_i) = \begin{cases} \mathcal{C}_O \cdot \mathrm{e}^{-\frac{1}{X}} + \mathcal{C}_C & \text{if } v_i \text{ is a new site,} \\ \mathcal{C}_O \cdot \mathrm{e}^{-\frac{x_0+1}{X}} & \text{if } 1 \le x_0 < X, \\ \infty & \text{if } x_0 = X \end{cases} \quad (4)$$

In the first case, we consider the installation of a regenerator pool in v_i and the activation of a first regenerator in it. In this case, $\mathcal{C}_C$ illustrates the carrier's investment to install the regeneration pool at node v_i while $\mathcal{C}_O \cdot \mathrm{e}^{-\frac{1}{X}}$ corresponds to the cost to manage a single active regenerator at v_i. The second case refers to the activation of a new regenerator in a site that already has x_0 active regenerators. We notice that the higher x_0, the lower the OpEx cost as aimed in our considerations (Sect. 3). The third case corresponds to the case where the maximum number of regenerators X is already reached in v_i and the site can no longer be used for further regeneration, thus the infinite regeneration cost.

Finally, the regeneration cost of an end-to-end connection is the sum of the costs of all regeneration sites used on the path.

On the other hand, the network resources cost is related to optical channels consumed by the connection and therefore to the number of hops of the connection. We formulate the network resources cost by:

$$\mathcal{C}_{\text{resources}} = \frac{H}{\mathbb{E}[H]}, \quad (5)$$

where H is the number of hops of the assigned path and $\mathbb{E}[H]$ is the mean number of hops of the K-alternative shortest paths. The objective of Eq. (5) is to keep resources cost and regeneration cost at comparable orders of magnitude (Eq. (3)).

From Eqs. (5) and (4), Eq. (3) can be developed as follows:

$$\mathcal{C}_{\text{connection}} = \alpha \cdot \frac{H}{\mathbb{E}[H]} + (1-\alpha) \cdot \sum_i \mathcal{C}_R(v_i) \quad (6)$$

such that v_i is a regeneration site used by the connection.

5 Results and discussion

In this section, we first precise our simulation environment and characteristics and then discuss the regeneration concentration provided by COR2P before ending with the comparison with the two algorithms: RP-CBR+ and LERP.

5.1 Simulations' assumptions

In this work, we investigate the 18-node, 29-link NSF-Net backbone network illustrated in Fig. 4. We assume 40 wavelengths per link (100 GHz channel spacing) carrying a capacity of 10 Gbps each. In the current study, the $\mathcal{Q}$-factor threshold ($\mathcal{Q}_{th}$) takes the value of 12.6 dB which corresponds to a BER of 10^{-5} considering forward error correction (FEC) at the destination. We also consider the ratio $\mathcal{C}_C/\mathcal{C}_O$ to be equal to 1 without loss of generality since the OpEx cost cannot be evaluated explicitly, according to the statement of different carriers. K is set to 5 for the computation of the K-shortest paths.

Simulations cover five traffic loads ranging from 100 to 500 connection requests. For each traffic load, ten static traffic matrices generated randomly according to a uniform distribution. Therefore, all the presented results are mean values of ten simulations.

5.2 Regeneration concentration

In this section, we emphasize the cross-optimization provided by COR2P in the context of regenerator placement. Indeed, COR2P aims at minimizing not only the number of required regenerators in the network, but also the number of regeneration sites.

As detailed in Sect. 4.2.4, the cost function used by COR2P when faced with several possibilities for routing/ regeneration takes two costs into account: a regeneration cost and a resources cost (Eq. 3). When we set α to a small value, the regeneration cost becomes more eminent than the resources cost. In this case, COR2P prefers to activate regenerators from the most used sites as much as possible, because of the exponential form of the OpEx cost which is the

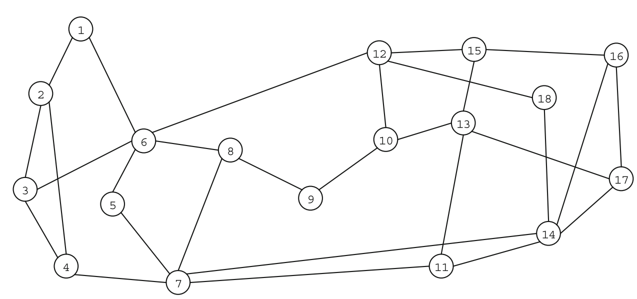

Fig. 4 The American 18-node NSF backbone network topology

considered cost after installing the regeneration pool in the node. This is possible on condition of admissible resources. When existing regeneration sites cannot provide a solution for the establishment of a lightpath, one and only one regeneration site can be added over the shortest path, trying to release the wavelength continuity constraint. We also recall that COR2P chooses in Step-2 (Sect. 4.2.2) a certain number R of regeneration sites. We do not take the CapEx cost of the installation of their regeneration pools into account when they are first used; only new regeneration sites are considered so that regeneration stays concentrated in the present sites. According to the choice of R, we define our flexibility toward the concentration of regenerators. But it is worth noting that even with $R = N$ with N being the number of nodes of the network, COR2P does not use all of them, since it always tries to activate regenerators in the most previously used sites. In [20], we discussed the regenerator concentration according to the choice of the value of $\rho = \frac{R}{N}$ being the ratio of sites chosen a-priori to the total number of network nodes. We also outlined the impact of ρ over the regenerator pool's size. We choose in the following results $\alpha = 0.1$ in order to favor regeneration concentration.

Figure 5 illustrates the distribution of regenerators over the sites for a traffic load of 400 requests. The considered values of ρ are 0.167 and 1 corresponding to R values of 3 and 18, respectively. We set X to 100. We notice that when allowing a flexible number of regeneration sites, some are used for a very small number of regenerators (small bars on the figure) which can be costly for an operator: first for the installation cost of the regenerator pools and second for the monitoring and maintenance of a reduced number of regenerators in more sites than those that constitute hotspots for regeneration. It is worth noting that the predominantly used sites (sites 6, 7, 12, and 14) have the highest nodal degrees and longest average distance with their first neighbors (*Cf.* Fig. 4).

Figure 6 depicts the number of effectively used regeneration sites with regard to the traffic load and ρ. We first notice that for $\rho = 1$ and for the highest considered traffic load (500 PLDs), an average of 8.2 sites is effectively used, i.e., even when the heuristic allows the use of all of the network nodes without taking into account the CapEx cost of pool installation. Less than half of the network nodes are effectively used which highlights the concentration of the regenerators urged by the form of the cost function. Second, for $\rho = 0.167$ and for a traffic load of 500 PLDs, an average of 4.4 (>3) sites is effectively used meaning that COR2P allowed the installation of pools of regenerators in new sites than those considered at the end of Step-2, in order to successfully establish the lightpaths.

These scenarios give acceptable blocking ratios (<1%). The percentages in Fig. 6 are the non-zero blocking ratios corresponding to the respective traffic load and ρ value on the figure. In [20], we found that the value $\rho = 0.167$ respects

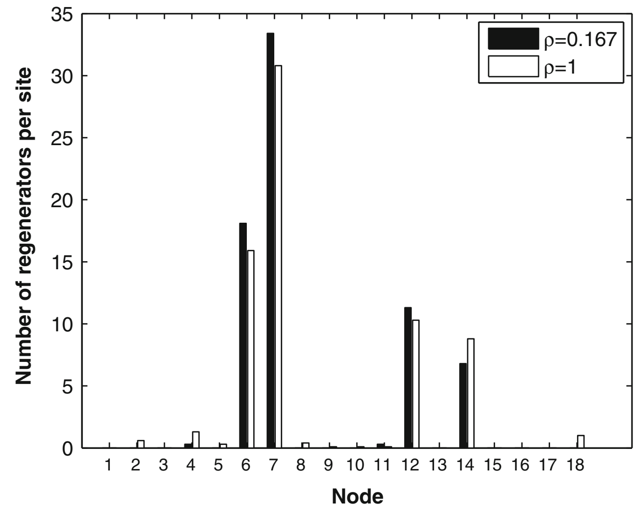

Fig. 5 Regenerator distribution for a traffic load of 400 PLDs

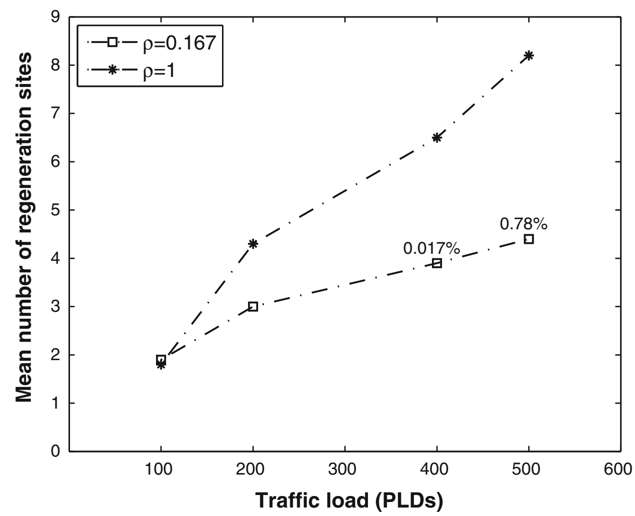

Fig. 6 Effective number of regeneration sites versus ρ

acceptable blocking ratios and provides the optimum concentration for the given network and traffic loads ($\rho = 0$ gives higher effective numbers of regeneration sites and higher blocking ratios than those of $\rho = 0.167$).

Figure 7 depicts the impact of α over the effective number of regeneration sites for a traffic load of 400 PLDs. We considered $\rho = 0.167$ and $\rho = 1$ (the optimum and worst scenarios in terms of the number of effective regeneration sites and with respect to an acceptable blocking ratio). For $\rho = 1$, all network nodes are regenerating, thus the CapEx cost related to the installation of a pool of regenerators does not exist, which explains how α barely impacts the number of effectively used regeneration sites. On the other hand, for $\rho = 0.167$, the concentration due to the value of α is eminent. Small values of α, e.g., $\alpha = 0.1$, concentrate better the regenerators because the CapEx cost of installing new regeneration

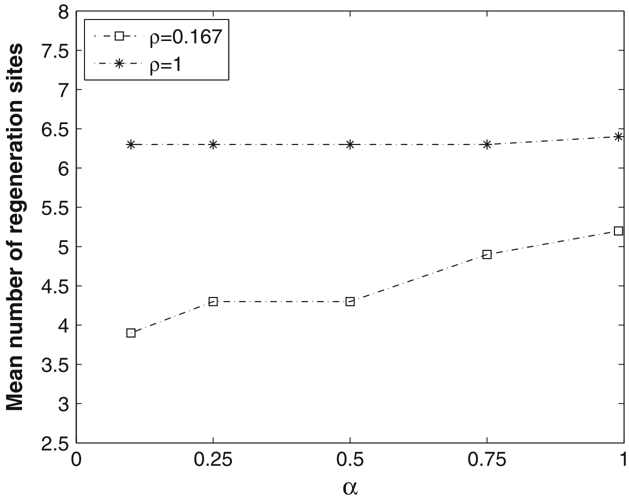

Fig. 7 Effective number of regeneration sites versus α

pools weights more than it does when α takes higher values. Indeed, the values of α and ρ jointly affect the concentration of regenerators in a limited number of regeneration sites.

5.3 Performance analysis via comparison

In this section, we provide a performance analysis of COR2P with means of comparison with two other regenerator placement algorithms, namely RP-CBR+ and LERP. In this respect, we shortly describe in Sect. 5.3.1 the two algorithms and provide in Sect. 5.3.2 a comparative summary of the essential characteristics of COR2P RP-CBR+, and LERP, before proceeding to numerical results in Sect. 5.3.3.

5.3.1 Description of RP-CBR+ and LERP

RP-CBR+

In [9,10], Pachnike et al. propose a regenerator placement (RP) and a constraint-based routing (CBR) strategies. They first define a set of regeneration sites in the network. Then, they proceed to RWA for regenerator assignment in the sites predefined in the previous step. In [11], we proposed an improved version of Pachnicke's algorithm, called RP-CBR+. In its first phase, Pachnicke's algorithm relies on a heuristic proposed in [21] to determine regeneration sites. Connection requests between all node pairs are considered assuming unlimited network capacity under flat systems. In other terms, each of these traffic requests is routed over its shortest path. At this step, the algorithm computes for each node the number of non-QoT-admissible connections that could be established if the considered node was equipped with an infinite-size regeneration pool. Let ϕ_n be the set of such connections for node n. Once all the nodes have been investigated, the node n_1 with the highest $|\phi_{n_1}|$ is considered as an effective regeneration site. The operation of computing ϕ_n for all nodes then choosing a regeneration site is repeated each time for the set of requests that remain non-QoT-admissible until all the PLDs become QoT-admissible, i.e., $\phi_n = \emptyset, \forall n$. In the second phase, all the PLDs of a given traffic matrix are routed in an arbitrary order. Regenerator assignment occurs along with RWA under limited network capacity. We have improved Pachnicke's original algorithm in order to minimize the number of regenerators. The K-shortest paths are computed for each request, and starting from the first path, different regenerator placement combinations are investigated. more regeneration sites exist over the path. The first QoT-admissible combination providing the least number of regenerators is considered as the retained solution. For each combination, the algorithm tries to find free wavelengths over the resulting transparent sections of the path, the FF strategy being adopted under non-flat systems. The Q-factor is evaluated at the end of each section. In case of non-admissible QoT for all the combinations inherent to the k-th shortest path, the $(k + 1)$-th shortest path is considered.

LERP

In [8], authors introduce a heuristic-based algorithm called LERP for Lightpath Establishment and Regenerator Placement. LERP aims at minimizing the number of required regenerators in the network while optimizing the resource utilization with respect to QoT requirements. In a first step, LERP uses a random-search-based (RS-based) scheme to find an RWA solution for a given set of static traffic requests. Rejected requests due to lack of network resources are stored for processing in a third step. In a second step, LERP runs a QoT-Test over the lightpaths given out in the previous step respecting the order provided by the mentioned RS scheme. Each lightpath is tested hop-by-hop and when a regeneration is required, the lightpath is dispatched into two lightpaths: an established lightpath prior to regeneration and a residual lightpath. The residual lightpath is added to a new traffic matrix made of only residual lightpaths. After all lightpaths provided by the first step are tested, the residual lightpaths matrix constitutes an input for another run of the RS-based RWA module. This operation is repeated each time for the new RWA solution respecting the updated set of available resources until no more residual lightpaths exist. Indeed, inserting regenerators for previous connection requests releases some network resources that can be used to route additional requests. This how, the rejected requests at the first step can be reconsidered under the same iterative operation as the second step.

5.3.2 Comparative summary

Table 1 summarizes the essential differences between COR2P, RP-CBR+ and LERP. It is important to note how RP-CBR+ restricts the regenerator placement to the sites that

Table 1 Comparative summary of RP-CBR+ COR2P and LERP

Criterion	RP-CBR+	COR2P	LERP
Dedicated phase for choosing regeneration sites?	Yes	Yes ($\rho \leq 1$) No ($\rho = 1$)	No
Number of regeneration sites	Fixed (restricted to the first phase's result)	Adaptive with pertinent values of ρ and α, regeneration concentration in some sites is manageable -Choosing $\rho < 1$ and α near 0 urges COR2P to stay as much as possible within the first R sites. -Choosing $\rho = 1$ and α near 1 gives COR2P more freedom in terms of regenerator placement in all the network nodes, but still respects concentration.	All nodes are potential regeneration sites
Processing order of requests	Arbitrary	-QoT-dependent order for requests successfully routed in Step-1 -Arbitrary order for demands rejected in Step-1 due to capacity limitations	Random search chooses best sequence of requests providing lowest rejection ratio
Wavelength assignment strategy	FF	BBF	BBF

it determines in its first phase, while LERP allows inserting regenerators in any site of the network. COR2P, in comparison, can be adapted to each of the two scenarios. On one hand, choosing α near 0 urges COR2P to respect as much as possible the regeneration sites (R) assigned before Step-3. On the other hand, choosing α near 1 allows more freedom for regenerator placement even in new sites if needed. In the following, we will highlight the different parameters considered within COR2P in order to be comparable to the two algorithms.

5.3.3 Numerical results

Simulations run over the NSFNet-18 (Fig. 4) under RP-CBR+ define six regeneration sites: 4, 6, 7, 12, 14, 17. For $\rho = 0.33$ ($R = 6$), the first phase of COR2P provides the same set of sites. Moreover, RP-CBR+ assumes unlimited-size regeneration pools, thus, for comparable scenarios, we have chosen $X = 100$ and set α to 0.1 under COR2P.

Figure 8 illustrates the blocking ratio versus the traffic load for both algorithms. The values attached to each point of the figure represent the average numbers of regenerators. Figure 9 depicts the regenerator distribution over the nodes of the network under 400 PLDs. We notice a big difference between COR2P and RP-CBR+ in terms of blocking ratio. On one hand, for a traffic load of 200 PLDs, COR2P accepts all traffic requests whereas RP-CBR+ presents a blocking ratio of 2.5% while having the same number of regenerators. On the other hand, under high traffic loads, COR2P keeps reasonable blocking ratios while they reach 11% and 15% for 400 and 500 PLDs, respectively, under RP-CBR+. This gap of blocking ratios between the two algorithms is compensated by regenerators in the network; COR2P inserts more regenerators than RP-CBR+. It is worth noting that for 400 PLDs, COR2P does not add regeneration sites beside the first fixed six (*Cf.* Fig. 9). In this case, we justify the flexibility in terms of succeeded lightpath establishment by two important features adopted in COR2P: first, the order by which the requests are processed (decreasing order of QoT over the best path (Step-1 in 4.2.1)) and second, the wavelength assignment strategy (BBF vs. FF [19]). At last, for traffic loads higher than 500 PLDs, COR2P adds isolated regenerators in new nodes (e.g., for 500 PLDs, nodes 8 and 10 hold a regenerator each), which also helps establishing lightpaths.

As a conclusion, COR2P presents a blocking ratio 100 times lower than RP-CBR+ under high traffic loads, a benefit obtained at the price of a greater number of regenerators.

Comparison with LERP

In order to compare COR2P to LERP, COR2P's parameters should meet LERP's environment. Thus, since LERP does not consider a limited regeneration capacity per site, we

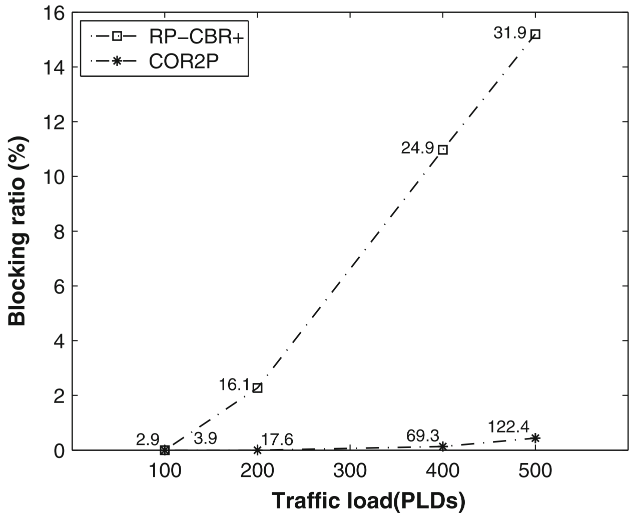

Fig. 8 COR2P versus RP-CBR+: blocking ratios versus traffic load

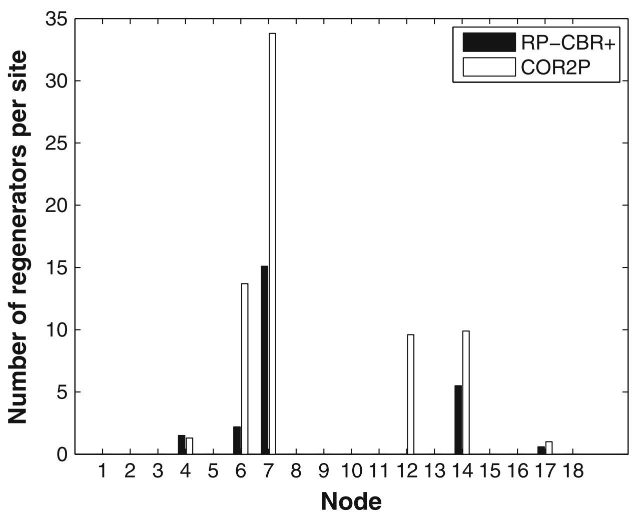

Fig. 9 COR2P versus RP-CBR+: regenerators distribution under 400 PLDs

choose to set X to 100 in COR2P. This ceiling is not reached for the traffic matrices considered in our simulations. Moreover, since LERP does not concentrate the regenerators, we consider $\alpha = 0.99$.[2] ρ is also set to 1.

Figure 10 shows the distributions of the regenerators over the network nodes for both COR2P and LERP. The considered traffic load is 400 PLDs. We notice that LERP places 16 regenerating nodes while the mean number of effective sites in COR2P over the ten matrices is 6.4, i.e., saving 60% of regeneration sites. The total number of regenerators under COR2P is equal to 89.7 regenerators whereas it is equal to 135 under LERP.

[2] We do not choose $\alpha = 1$ in order to save the comparison between the alternative paths.

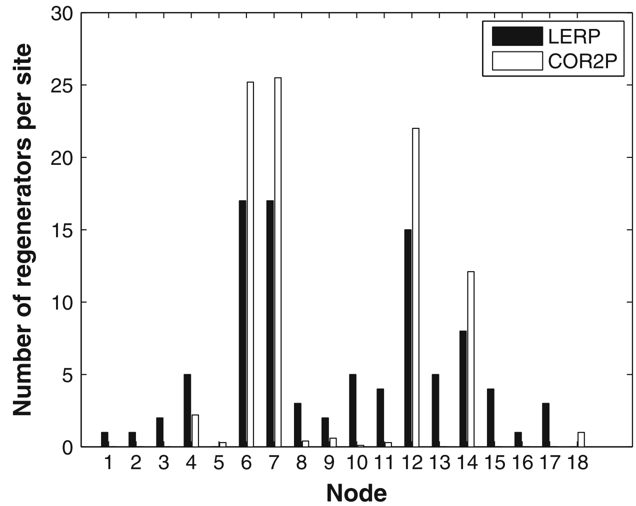

Fig. 10 COR2P versus LERP: regenerators distribution under 400 PLDs

Figure 11 shows the evolution of the mean number of required regenerators with respect to traffic load. This figure shows the limits of the QoT-dependent order adopted for RWA in COR2P. For low and moderate traffic loads (i.e., less than 500 PLDs), sorting the requests in the aforementioned order allows better use of network resources than LERP. Therefore, the number of PLDs needing regeneration is minimized relatively to LERP, and the resulting number of required regenerators is also minimized. As for high traffic loads, this QoT-dependent order is not very effective since the network is overloaded and faces blocking due to the lack of resources. In this case, LERP outperforms COR2P for the reason that it uses the best combination for the RWA solution in order to minimize the number of regenerators, while COR2P processes the requests needing regeneration sequentially in its third step.

We conclude that for identical scenarios, and for low or moderate traffic loads, COR2P reduces both the total number of regenerators and the number of sites compared to LERP. As for higher traffic loads, COR2P's feature of ordering requests in a QoT-dependant order has negligible effect.

6 Conclusion

In this paper, we introduced a new approach for translucent WDM network design consisting in optimizing CapEx and OpEx network costs. On one hand, considering a new regeneration site at a network node involves equipment positioning (a pool of regenerators per site), powering and cooling, considered as a fixed CapEx cost. The added CapEx cost inherent to regeneration is then proportional to the number of regeneration sites to be deployed. On the other hand, a regenerator pool needs supervision and maintenance which adds a new

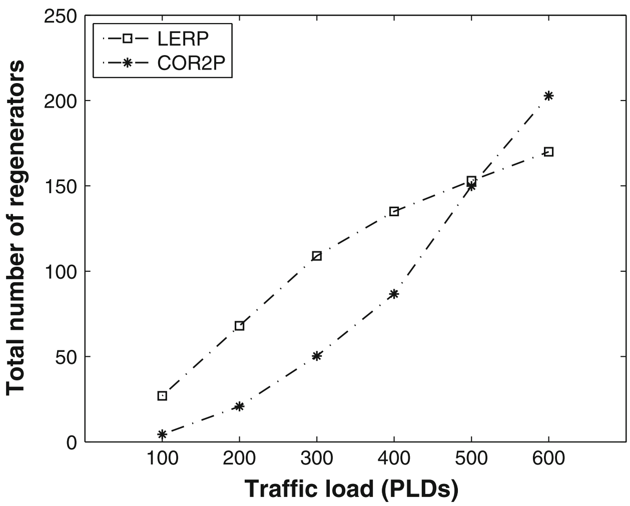

Fig. 11 COR2P versus LERP: total number of regenerators versus traffic load

component to network's OpEx cost. Considering supervision staff at each regeneration site implies that the fewer the sites, the lesser the regeneration OpEx. In addition, activating as much regenerators as possible in existing pools in order to avoid new pools' installation helps reducing the OpEx cost (CapEx too). It is also worth noting that the more supervised regenerators by a supervision team, the more rendering this latter is.

The proposed heuristic, COR2P, translates our CapEx/OpEx perspective, resulting in regenerator concentration in some network nodes. We note that nodes with higher connectivity are most favored for regeneration.

Among COR2P's different parameters, the initial number of potential regeneration sites can be adjusted to allow flexibility toward the regeneration at the network nodes. Thus, the value of ρ (ratio of this number to the total number of nodes in the network) determines the number of regeneration sites to be actually deployed. We found that a value of $\rho = 0.167$ is the best compromise between rejection ratio and network cost inherent to regeneration, for the examined topology (NSFNet-18).

In addition, we compared COR2P to two other heuristics: RP-CBR+ and LERP. Compared to RP-CBR+, COR2P presents satisfying blocking ratios (<1%) while they reach 15% for 500 PLDs in RP-CBR+, revealing the importance of requests ordering with respect to QoT as well as the adaptability of the BBF WA strategy compared to the FF strategy. Compared to LERP, COR2P presents a drawback at high traffic loads where PLDs in need for regeneration become numerous and are processed sequentially whereas the best processing order to optimize the use of network resources is a key feature in LERP.

In our assumption, we considered power supply and cooling to be fixed by regeneration sites. In practice, power supply is proportional to the number of activated regenerators in a pool. Moreover, generated heat is proportional to the number of activated regenerators. Thermal management for heat dissipation in order to prevent component failure adds more power consumption to that used for activating regenerators. Our proposed approach concentrates regenerators while it might be more efficient from a green perspective to distribute the power consumption over the network nodes. In future work, we will consider translucent network design from a green perspective including component and dissipation technique's powering.

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