LERP : a Quality of Transmission Dependent Heuristic for Routing and Wavelength Assignment in Hybrid WDM Networks

LERP : une heuristique pour le routage et l'affectation de longueurs d'onde tenant compte de la qualité de transmission dans les réseaux WDM hybrides

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Titre :
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Résumé :

Plusieurs algorithmes de routage et d'affectation de longueurs d'onde (RWA) ont été proposés ces dernières années pour la planification des réseaux WDM optiques. Néanmoins, dans la plupart de ces algorithmes, la dégradation de la qualité des signaux optique due aux paramètres physiques de la transmission a été ignorée. Dans cette publication, nous présentons un nouvel outil appelé LERP *(Lightpath Establishment with Regenerator Placement)* permettant de résoudre le problème de routage et d'affectation de longueurs d'onde tout en garantissant une qualité de transmission (QoT) satisfaisante pour les chemins optiques établis. LERP a pour objectif de minimiser le nombre de demandes de trafic rejetées par manque de ressources dans le réseau. Les ressources du réseau correspondent au nombre de longueurs d'onde disponible sur chaque lien du réseau. Un chemin optique est considéré comme admissible si le BER *(Bit Error Rate)* du signal optique au niveau du nœud destination reste inférieur à un certain seuil donné. Dans le cas où le BER dépasse le seuil considéré, un ou plusieurs régénérateurs doivent être placés sur les nœuds intermédiaires du chemin optique. La principale originalité de notre approche réside dans la minimisation simultanée du nombre de demandes de trafic rejetées et du nombre de régénérateurs requis. La deuxième originalité de LERP réside dans l'estimation du BER qui prend en compte simultanément la dispersion chromatique, la dispersion modale de polarisation, l'émission spontanée des amplificateurs et la phase non linéaire. L'efficacité de notre démarche est mise en évidence à travers des simulations numériques permettant de comparer les performances de LERP à celles d'un algorithme proposé dans la littérature.

Mots clés :

Réseaux optiques, WDM, QoT, régénérateurs, planification, BER.

LERP: a Quality of Transmission Dependent Heuristic for Routing and Wavelength Assignment in Hybrid WDM Networks

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***Abstract*— Numerous Routing and Wavelength Assignment (RWA) algorithms have been developed these last ten years for WDM optical networks planning. In most cases, these algorithms neglect the impact of physical layer impairments on the feasibility of the obtained optical circuits or lightpaths. In this paper, we introduce a new quality of transmission (QoT) dependent tool called LERP (Lightpath Establishment with Regenerator Placement) enabling to solve the RWA problem in guaranteeing the feasibility of the obtained solution. The LERP tool tends to minimize the amount of rejected lightpath demands due to a lack of network resources. Network resources correspond to the amount of available wavelengths in each fiber-link. A lightpath is said admissible if BER at its destination node remains under a given threshold. In case on BER non-admissibility, one or several electrical regenerators may be inserted along the lightpath. The first originality of our approach consists in minimizing simultaneously the amount of rejected traffic demands and the amount of required regenerators. For that purpose, one considers a much larger combinatoric in lightpaths' selection and regenerators' placement. The second originality of the LERP tool relies on BER evaluation in considering simultaneously chromatic dispersion, polarization mode dispersion, amplified spontaneous emission and non-linear phase shift. The efficiency of the LERP heuristic is underlined via a numerical comparison with one of the alternative solutions proposed in the literature in the context of the NSFNET network.**

I. Introduction

Thanks to optical amplifiers and to optical cross-connects (OXC), all-optical (or transparent) networks are today achievable. For a given a set of traffic demands and a given transparent network topology, the Routing and Wavelength Assignment (RWA) problem consists in associating to each traffic demand an all-optical circuit (or ligthpath). In general, wavelength continuity constraint is imposed to each lightpath since optical wavelength converters remain too costly. Two independent lightpaths sharing a common optical fiber must use two different wavelengths. A lightpath is then characterized by its computed route in the physical topology and by its assigned wavelength. Many RWA techniques have been proposed in the literature. The great majority of these techniques assume ideal physical layer conditions ([1], [2]). In that sense, all the lightpaths obtained by means of RWA are considered a priori achievable in terms of BER. Perfect optical transmission is in fact never achieved because of multiple physical layer impairments. The degradation of BER inherent to propagation is mainly due to four physical effects known as Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD), Amplified Spontaneous Emission (ASE) and Nonlinear Phase shift (ϕ_{NL}). These recent years, a few RWA algorithms taking into account the impact of physical layer impairments on the feasibility of the obtained lightpaths have been proposed in the literature ([3],[4],[5],[6]). Most of these studies consider the QoT problem separately from the RWA problem. At the best of our knowledge, none of the proposed QoT dependant RWA algorithms takes into account the simultaneous impact of CD, PMD, ASE and ϕ_{NL}.

In this paper, we propose an innovative QoT dependant RWA algorithm called LERP (Lightpath Establishment with Regenerator Placement). We have developed a tool called BER-predictor enabling to compute for any lightpath the BER value at each of its intermediate nodes. The BER-predictor tool is part of the LERP algorithm. It takes into account the simultaneous effect of CD, PMD, ASE and ϕ_{NL}. For a given lightpath, an electrical regenerator is required whenever the BER goes below a certain threshold. In practice, several electrical regenerators may be needed along a lightpath. The LERP algorithm enables to optimize network resources utilization and to minimize the amount of required regenerators.

This paper is organized as follows. In Section II we define the RWA problem. In Section III we describe the four QoT parameters considered in this paper. In section IV we present the notations that will be used for the description of the LERP algorithm. In order to outline the efficiency of this algorithm, we have carried out numerical evaluations based on the NSFNET North-American backbone topology. These results are compared to those obtained by another QoT dependant algorithm from the literature. Compared to LERP, this existing algorithm proceeds with a reduce combinatoric for lightpath selection and regenerator placement and is referred in the remaining of the paper as sLERP for simple LERP. Sections V and VI describe the sLERP and the LERP algorithms respectively. Finally we present in section VII the obtained numerical results. We conclude the paper in section VIII.

II. Routing and Wavelength Assignment problem

The RWA algorithms proposed in the literature differ in their performance metrics or PM ([7], [8]) and traffic assumptions or TA ([1], [9]):

- PM_1 : considering an unlimited network capacity, the number of wavelengths required to establish a given set of lightpath demands
- PM_2 : considering a limited amount of optical channels per fiber, the lightpath demands rejection ratio.
- TA_1 : each traffic demand is permanent. In that case, RWA considers all the possible routing and wavelength assignment combinatorics (Static Lightpath Establishment (SLE)).
- TA_2 : connection requests arrive sequentially. The established lightpaths for each connection remains in the network indefinitely (Incremental Lightpath Establishment (ILE)).
- TA_3 : lightpath requests arrive one by one and have a finite life duration (Dynamic Lightpath Establishment (DLE)).

In this paper, only PM_2 and TA_1 are considered.

III. Transmission impairments in WDM networks

Impairments like attenuation, amplified spontaneous emission, dispersion and nonlinear effects degrade QoT. These impairments limit the range of a lightpath with acceptable Bit Error Rate (BER). In the following sections, we define the four main qualities of transmission parameters Q_i (i$\in\{1,2,3,4\}$) and the global QoT associated parameter Q_g gathering them. We have presented in [10] a tool designated by BER-predictor enabling to deduce from the value of Q_g at an intermediate node along a lightpath the BER value at this node. We briefly describe below the four physical layer impairments considered in the following of the paper [11]:

- Chromatic Dispersion (CD): It is caused by the disparity in propagation velocity between the various spectral components of the optical signal. CD induces pulse broadening in the time domain.
- Polarization Mode Dispersion (PMD): The core of the fiber is not truly a cylindrical waveguide. Thus different polarizations of the analog optical signal travel with different group velocities creating pulse spread in the frequency domain.
- Amplified Spontaneous Emission (ASE): Optical amplification is used to compensate for the attenuation of the optical signal along its propagation. Optical amplifiers generate random noise known as ASE that degrades the Optical Signal to Noise Ration (OSNR) [11]. OSNR is the measurement at the receiver of the ratio of the average signal power to the average noise power.
- Non Linear Phase Shift ϕ_{NL}: The response of optical fibers to the light becomes nonlinear under strong optical intensity. The refractive index of optical fiber increases with optical intensity to slow down the propagation speed, inducing a dependency between the optical power and nonlinear phase shift. That is due to the interaction of optical amplifiers, used to compensate for fiber loss, and to the fiber Kerr effect.

IV. Notations

We use the following notations in the rest of this paper:

- N is the number of nodes in the network.
- $G=(V,E,\xi)$ is an arc-weighted symmetrical directed graph representing the network topology with vertex set V (representing the network nodes), arc set E (representing the network fiber-links) and weight function $\xi: E \rightarrow R_+$ mapping the physical length of the links (or any other cost of the links set by the network operator). The cardinal of V is N.
- W denotes the common maximum number of available wavelengths (i.e., WDM channels) per fiber-link. $\Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_W\}$ is the set of the available wavelengths on each fiber-link of the network.
- D denotes the total number of permanent lightpath demands (PLD) to be set up.
- δ_i, $1 \leq i \leq N(N-1)$, is the i-th traffic demand to be satisfied in the network. It is defined by a tri-tuple (s_i, d_i, π_i). $s_i \in V$, $d_i \in V$ are respectively the source node and destination node of the demand, π_i is the number of requested lightpaths to be established from s_i to d_i. In the following, one assumes that π_i equals either "0" or "1". Under this assumption of single PLD traffic demands, we can set $D = N(N-1)$.
- p_i, $1 \leq i \leq D$, is the i-th PLD to be set up in the network. Because of our assumption of single PLD traffic demand, we assimilate in the following δ_i and p_i. We have:

$$D \geq \sum_{i=1}^{N(N-1)} \pi_i \tag{1}$$

- R_i denotes the set of available routes connecting the source node and destination node of PLD p_i. For each PLD p_i, $1 \leq i \leq D$, we compute beforehand K-alternate shortest paths connecting the source node to the destination node of the PLD according to the algorithm described in [12] (if as many paths exist, otherwise we consider the available ones).
- $P = \cup_{1 \leq i \leq D} R_i$ is the set of all the available routes considering all the K-alternate shortest paths computed between all the PLDs to be set up.
- $c_j^\omega \in \{1, +\infty\}$ is the cost of using wavelength λ_ω on link $j \in E$. $c_j^\omega = 1$ if wavelength λ_ω is free on link j; $c_j^\omega = +\infty$ if a lightpath has already been set up and uses λ_ω on link j.
- $C_{i,k}^\omega = \sum_{j \in P_{i,k}} c_j^\omega$ is the cost of using wavelength λ_ω on $P_{i,k}$, the k^{th} alternate shortest path in R_i connecting the source node to the destination node of PLD p_i. $C_{i,k}^\omega < +\infty$ if λ_ω is a path-free wavelength on $P_{i,k}$; $C_{i,k}^\omega = +\infty$ otherwise.

- $\gamma_{i,k}^{\omega} = 1$, $1 \leq i \leq D$, $1 \leq k \leq K$, $1 \leq \omega \leq W$, if wavelength λ_{ω} is a path-free wavelength along the k^{th} alternate path, $P_{i,k}$, connecting the source to the destination node of PLD p_i ($C_{i,k}^{\omega} < +\infty$). $\gamma_{i,k}^{\omega} = 0$ otherwise ($C_{i,k}^{\omega} = +\infty$) .
- $\sigma_{i,k} = \sum_{\omega=1}^{W} \gamma_{i,k}^{\omega}$, $1 \leq i \leq D$, $1 \leq k \leq K$, is the number of path-free wavelengths along $P_{i,k}$.

V. The simple Lightpath Establishment with Regenerator Placement algorithm (sLERP)

The sLERP algorithm computes RWA and Regenerator Placement in two separate phases. The first phase corresponds to RWA based on a Random Search (RS) algorithm. The second phase, referred to as the QoT test phase, performs the QoT-test and places regenerators when necessary. The QoT-test phase was adopted from the Trace-back Regenerator Allocation Strategy proposed in [4].

A. RWA phase

This section describes the random RS algorithm used to compute the RWA for the PLDs. Before explaining the principles of the RS algorithm, we first describe the sequential RWA (seqRWA) algorithm. We assume that for each couple of nodes in the network, K-alternate shortest path (if as many paths exist) are computed off-line before any routing according to [12]. The sequential RWA algorithm (seqRWA) considers in turn the K-alternate shortest paths associated to any PLD. On each shortest path, we look for as many path-free wavelengths as the number of requested lightpaths. Two cases arise depending on the fact it exists or not paths with as many path-free wavelengths as the number of requested lightpaths. In the negative case, some PLDs may be rejected. It may happen that the number of available wavelengths on a shortest path $P_{i,k}$ is higher than the number of requested lightpaths. In that case wavelengths are assigned according to a First-Fit scheme [13]. The assigned wavelengths are reserved on $P_{i,k}$ and on all the lightpaths sharing a common link with $P_{i,k}$. The pseudo-code of the seqRWA function is presented in Table1.

The random search consists in finding a solution that minimizes the number of rejected demands among solutions obtained by the sequential RWA (seqRWA). ρ_D is a D-dimensional vector. ρ_D is a permutation of $\{1, 2, \ldots, D\}$. Vector ρ_D is generated randomly. It indicates the ranking according to which the PLDs are to be routed.
The RS is computed as follows:

1) An initial solution is created by a function that defines the components of the vector ρ_D.
2) A random function generates random values for ranking vectors ρ_D. Note that one has to verify that the cost of the generated vector ρ_D (number of rejected PLDs) has not already been evaluated. In that case, another ranking vector is generated randomly using the random function. For this purpose we keep trace of a certain number of already visited ρ_D vectors by updating a list we called the *BLACK LIST*.
3) The objective function computes for a given value of vector ρ_D the number of rejected PLDs, C. The PLDs are considered sequentially according to the ranking given by ρ_D. The ranking vector which reject a minimum number of PLDs is retained.

It may happen that several vectors ρ_D reject the same number of demands. In that case, one may prefer a solution that minimizes the number of used WDM channels. Once the RWA is computed, the quality of transmission of all established lightpaths is tested in the second phase.

B. Quality of Transmission Test phase

The Q_g factor is evaluated according to a polynomial function of the QoT parameters Q_i. It has been obtained from equations of both physics and experimentation [14][15]. BER can be deduced from the Q_g factor by the relation:

$$BER = \frac{1}{2}\ erfc\ \frac{Q_g}{\sqrt{2}}$$

where

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{+\infty} e^{-t^2}\ dt$$

For each lightpath Q_g is computed off-line, thus we obtain a data base containing Q_g values of all the lightpaths $R_i \in P$. We

```
ALGORITHM    the sequential RWA algorithm
Input: ρ, D, R_i, W
Output: computes the number of rejected PLDs
   (* According to ρ, compute the number of rejected PLDs when routed sequentially *)
1    rejectedPLDs:=0
2    for each item in ρ do
2.1      Find the corresponding PLD p_i, 1 ≤ i ≤ D
         (* Consider in turn the K-alternate shortest paths associated to PLD p_i and
         compute the number of path-free wavelengths on each path until the PLD is
         set up or rejected *)
2.2      k:=1
2.3      FLAG:=0
2.4      while (k ≤ K) and (FLAG = 0) do
2.5           for ω := 1 to W do
2.6                Compute γ^ω_{i,k}
              endfor
              if σ_{i,k} ≥ π_i then
2.7              FLAG:=1
              endif
2.8           k:=k+1
         endwhile
2.9      if (FLAG=0) then
            (* The PLD cannot be set up. There are not enough path-free wavelengths
            on any of the considered shortest paths associated to PLD p_i *)
2.10        rejectedPLDs:=rejectedPLDs+1
         else
            (* The PLD is set up. Instantiate the lightpaths. Update paths' cost. In the
            case when σ_{i,k} > π_i, the wavelengths are selected according to a First-Fit
            scheme *)
2.11        ω := 1
2.12        p := 1
2.13        while (ω ≤ W) and (p ≤ π_i) do
2.14             if C^ω_{i,k} ≤ +∞ then
2.15                C^ω_{i,k−1} := +∞
2.16                p := p+1
                 endif
2.17             ω := ω+1
            endwhile
         endif
     endfor
end. the sequential RWA algorithm
```

TABLE I

PSEUDO-CODE OF THE SEQUENTIAL RWA ALGORITHM refer to his data base every time we need to test the quality of transmission on a certain lightpath.

The QoT test phase treats sequentially established lightpaths composed at least of two hops. Single hop lightpaths are directly considered as satisfying the QoT constraint. We test the quality of transmission at the $n-1$-hops lightpath nodes i, $i = 1,..,n$, $n > 2$, from node $i = 3$ to the destination node ($i = n$). If the quality is lower than the threshold, a regenerator has to be placed on the previous node $i-1$ else we test the next node $i+1$. We repeat this operation until $i = n$. This phase returns for each established PLD intermediate nodes where the signal should be regenerated.

VI. Lightpath Establishment with Regenerator Placement algorithm (LERP)

The RWA is computed with the RS algorithm like in the first algorithm. The rejected demands are stocked, they will be treated at the last phase of the algorithm. The difference with sLERP consists in using a more sophisticated function, called QoT-Test, which try to optimize regenerator placement. For each demand between s and d requiring a regeneration at intermediate node i we define a relative sub-demand. The sub-demand has for origin the node i and for destination the node d. Established lightpaths composed of two hops at least, are tested sequentially by the QoT-Test function. The test begins at the third node on of the lightpath. If Q_g at node i goes below the threshold, the regeneration of the signal is necessary at the previous node of the lightpath. Otherwise the same test is made for the following node. The test of a lightpath ends if the destination is reached without any necessity to regenerate the signal or if a regenerator is placed in a node of the lightpath. In that case, the first section of the lightpath (origin, regenerator node) is stored and the wavelength used on this lightpath section is reserved. The relative complementary sub-demand is added to a new traffic matrix to be routed afterward. Once all the lightpaths are tested, we obtain a new traffic matrix containing sub-demands relative to demands that have needed regeneration. RWA is computed for this matrix like in the first phase. Thus we obtain a new routing scheme. QoT-Test is computed for the new established lightpaths. This procedure is repeated until QoT-Test doesn't return any sub-demand, which means that no more regeneration is necessary.At this stage, we try to route demands which were initially rejected by the RWA. In LERP the RWA phase and the QoT test phase are computed several times until what we obtain an empty new traffic matrix in the output of the QoT-Test function. When an empty matrix is obtained, it means that all the established lightpaths satisfy the quality of transmission constraint and that no supplementary regenerators are needed in the network. The interest of resuming the phase of RWA after the regenerators placement phase is to try to find shorter lightpaths for routed PLDs. In fact, once a regenerator is placed, the wavelength continuity constraint is relaxed thus the sub-demand (regenerator node - destination) can be routed in a new lightpath on a new wavelength. This would free WDM channels, and some demands which were initially rejected because of the lack of

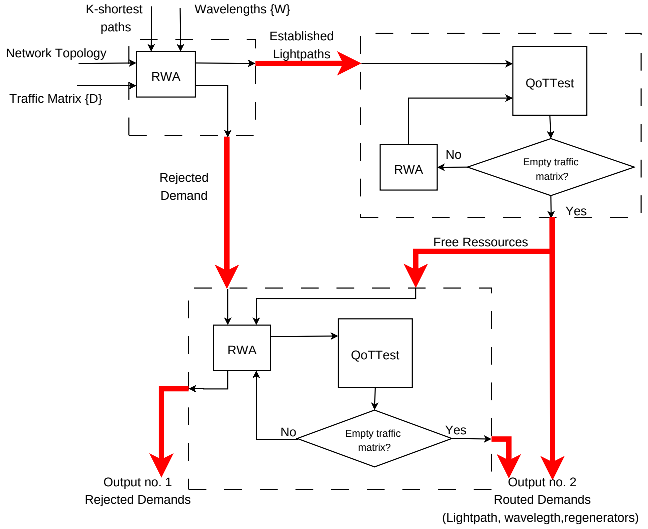

Fig. 1. LERP Synopsis

resources would be routed. The LERP flow-chart is described by the diagram on Fig. 1.

VII. Experimental results

Let us consider the network depicted in Fig. 2; the NSFNET-18. We have chosen this network to test our algorithms since it includes very long links. The minimal threshold of the Q_g considered in this study is 12 dB.

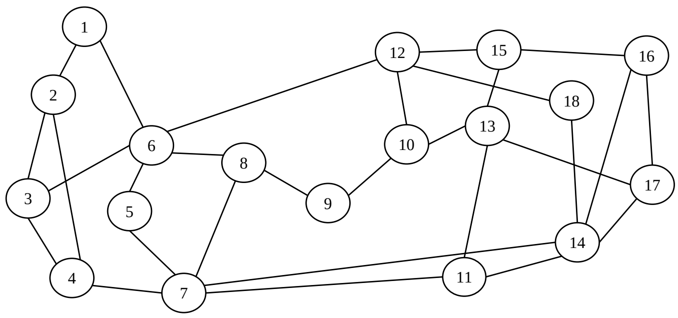

Fig. 2. The NSFNET backbone topology

In order to show the interest of using a random search for RWA computation, we compare the RS algorithm to a simple seqRWA which treats the PLDs in sequentially in their initial order. We consider traffic matrices generated randomly according to a uniform distribution containing 100 demands. We compute the number of rejected demands with the two algorithms and the number of used WDM channels per demand. We notice on Fig. 3 that the random search algorithm rejects less demand than the seqRWA. This improvement of performance can reach an order of 20 %. For W = 5, the seqRWA throws back 50 demands, while with the RS 40 demands are rejected. We can notice on Fig. 4 that for a small W the difference in the number of used WDM canals is high; with the random search, lightpaths are one to two hops shorter. For larger number of available wavelengths the performances of the two approaches become comparable in

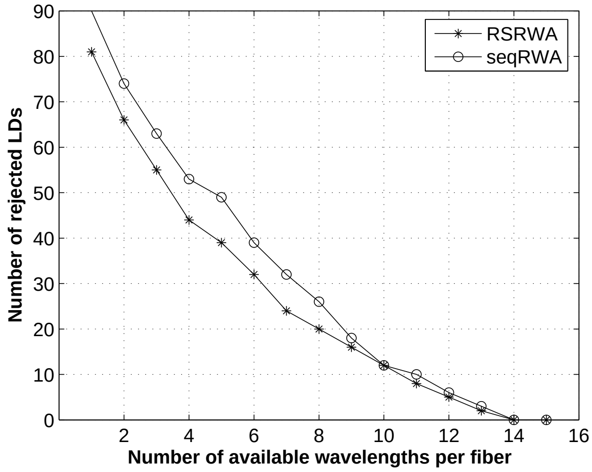

Fig. 3. Number of rejected demands

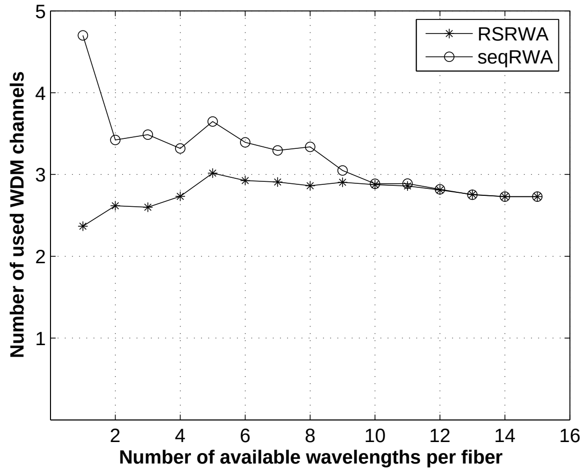

Fig. 4. Number of used WDM channels per demand

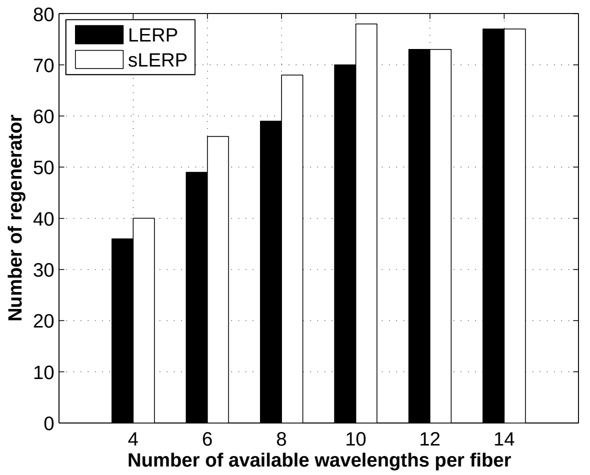

Fig. 5. Number of regenerator

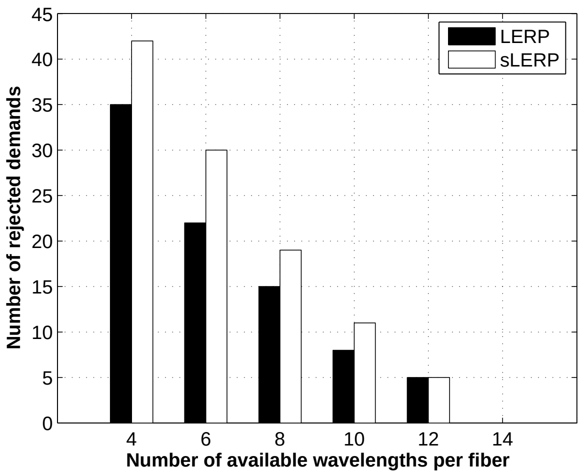

Fig. 6. Number of rejected demands

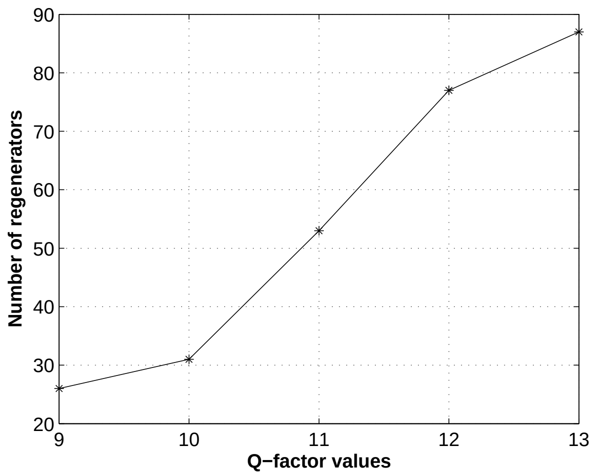

Fig. 7. Impact of the Q_g threshold variation

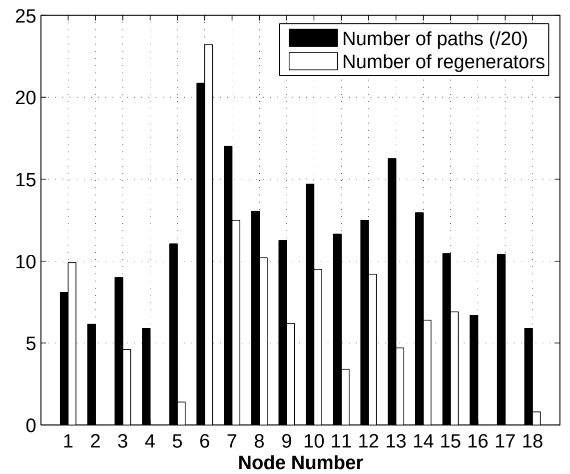

Fig. 8. Regenerator repartition in the network

term of number of rejected demands and average number of used WDM channels per demand. In fact, in presence of a sufficient number of wavelengths, demands can be routed on short lightpaths since the probability to find a free wavelength on theses lightpaths becomes important, and thus the order of treatment of demands has no more a major importance.

In Fig. 5 we vary the value of W and we compute the number of regenerators to be placed in the network using sLERP and LERP algorithms. Fig. 5 shows that this number is smaller with LERP. Indeed, the segmentation of lightpaths and the new routing computed for the segments of lightpaths which require regeneration, allow to forward demands on shorter lightpaths. This implies that there is less chance that the quality of transmission degrades too much, and consequently, the number of regenerators to place is smaller.

In Fig. 6 we present the number of rejected demands using sLERP and LERP. We notice that LERP provides better results. In fact, some rejected demands due to luck of wavelengths, can be routed after the regenerator placement phase. When placing regenerators, the continuity wavelength constraint is relaxed. In the LERP, we can relax this constraint thanks to the rerouting phase, where connections needing regeneration can change wavelength. However in sLERP, the lightpaths established by the RS don't change, and no wavelength conversion can be operated even at nodes presenting regenerators.

The Q_g threshold is a parameter which determines the required Quality of Service (QoS). For an important threshold, the required quality is more important, and consequently, the number of necessary regenerators in the network is bigger. In the Fig. 7, we present the impact of the Q_g threshold variation on the number of regenerators required. In that case we consider 100 lightpath demands and 10 available wavelengths.

The number of rejected demands grows with the Q factor threshold. In fact, when the threshold increases, it means that we require better quality of the optical signal. So we may have additional demands that may need regeneration and which would have been routed without any regeneration for a smaller threshold. We notice besides on this curve, that the slope is more important 10 and 12, so the increase of the number of regenerators is more important for variations of the threshold in this interval. This shows that the greatest number of lightpaths in the network has a value of the Q_g between 10 and 12 dB.

In Fig. 8 we compute the LERP algorithm for W=40. Fig. 8 presents the geographical repartition of regenerator placement. In order to outline the impact of physical topology on regenerator placement, we also represent the number of K-shortest paths $R_i \in P$ traversing each node i. We notice that nodes 6 and 7 contain the higher number of regenerators. We can notice that these nodes have the highest physical degree (5). They are traversed by large number of routes. Moreover, links connecting nodes 6 and 7 to their neighbours have an important length especially links 7-14, 7-11 and 6-12. The signal crossing these links has of high probability to require regeneration. In fact, other factors as BER and traffic matrices also have a strong impact on regenerator placement strategy.

VIII. CONCLUSION

In this paper, we have presented a new heuristic ensuring routing and wavelength assignment with regenerator placement taking into account physical layer impairments. This algorithm called LERP includes an original function called BER-predictor allowing an exact evaluation of the optical signal quality. The LERP tool enables to minimize lightpath demands rejection ratio and the amount of required regenerators. Numerical results applied to the NSFNET-18 network compares the efficiency of LERP with a simplified version from the literature called sLERP. They outline an average benefit of 25% on rejected demands and of 14% on the amount of regenerators due to LERP over sLERP. These benefits are obtained thanks to a larger combinatoric in lightpath routing and colouring and in regenerator placement. Our coming studies will consider via the BER-predictor tool the impact of wavelength on Q_g in order to proceed to a more efficient wavelength assignment strategy.

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