Gain equalization and electrical regeneration in hybrid WDM networks

Compromis entre égalisation en ligne et régénération électrique dans les réseaux WDM hybrides

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Résumé

L'évolution de composants optiques, comme les commutateurs optiques ou les amplificateurs optiques, permet un accroissement des distances parcourues par le signal optique sur les fibres optiques. Toutefois, cette évolution conduit aussi à augmenter le déséquilibre dans la répartition de la puissance sur les différentes longueurs d'onde parcourant la fibre ce qui se traduit par de fortes dégradations sur les signaux transmis. Des travaux récents montrent comment on peut modifier des réseaux optiques transparents pour qu'ils puissent traiter les problèmes inhérents à la dégradation du signal optique lorsqu'il parcourt de grandes distances.

Dans un réseau transparent, en l'absence de régénération électrique 3R aux nœuds intermédiaires, les dégradations physiques s'accumulent tout au long du parcours du signal et conduisent parfois à des valeurs de BER élevées du côté du récepteur. En permettant une régénération partielle, les réseaux hybrides deviennent une solution prometteuse pour prendre en compte la dégradation physique du signal optique et ainsi obtenir des résultats qualitativement proches de ceux obtenus par les réseaux opaque à moindre coût. Dans nos précédents travaux, nous avons proposé de nouveaux outils logiciels pour la planification de réseaux optiques hybrides avec garantie de qualité de transmission.

Jusqu'à présent, nous n'avions pas considéré l'égalisation en ligne dans nos travaux, l'égalisation de gain dynamique n'étant effectuée que dans les noeuds du réseau. Dans cet article, nous étudions l'effet que peut avoir le déploiement de régénérateurs en ligne dans le réseau, en terme de réduction du nombre de régénérateurs installés et en terme de coût d'équipement du réseau. Nous proposons aussi une nouvelle stratégie d'affectation de longueur d'onde qui prend en compte la qualité de transmission dans le réseau. Nous présentons des résultats de simulations qui montrent qu'une stratégie d'affectation de longueur d'onde bien choisie peut compenser l'absence d'égalisation en ligne.

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Abstract— **The evolution of optical network devices such as optical cross-connects and optical amplifiers has provided a huge increase in the transmission capacity of optical links. However, this evolution also brings problems such as the large power imbalance arising with the transmission of several wavelengths that impose a severe degradation to the optical signal. Recent research work shows how to adapt (transparent) all-optical WDM networks to cope with transmission impairments induced by long-haul optical components on long spans. Since no electrical 3R regeneration is performed at intermediate nodes in a transparent network, transmission impairments accumulate along the signal route and may result in high BER values at the receiver's side.**

Since they provide sparse regeneration, hybrid WDM networks are considered as a promising solution to overcome the transmission impairments and achieve performance measures close to those obtained by fully opaque networks at a much lesser cost. In previous work, we addressed the design of hybrid WDM network and proposed a novel tool for routing, wavelength assignment, and regenerator placement so that the quality of transmission is guaranteed.

Up to now, we did not consider any in-line gain equalization scheme, i.e. dynamic gain equalizers are only deployed at the network nodes. In this paper, we investigate the impact of deploying in-line dynamic gain equalizers in terms of the number of required regenerators to meet QoT and in terms of cost tradeoff. We also propose a novel wavelength assignment strategy that takes into account the quality of transmission. Simulations show that using an adequate QoT-aware wavelength assignment strategy may compensate for the absence of in-line equalization.

I. Introduction

Wavelength division multiplexing (WDM) is considered as a cost-effective mean to increase the capacity of long-haul transmission systems in order to keep up with explosive growth of the traffic demand. All-optical WDM networks are nowadays achievable thanks to the development of long-haul optical components such as optical cross-connects and optical amplifiers. Nevertheless, such components may induce different problems like the large power imbalance arising with the propagation of several wavelengths that impose a severe degradation to the optical signal. Among the causes of such imbalance, one may enumerate the unequal gain profile of erbium doped fiber amplifier (EDFA), the non-flat response of optical multiplexer/demultiplexer at their wavelength band edges, the influence of nonlinearities, and the dynamic nature of all-optical switches [1]. Usually, one deals with such an imbalance by employing gain controllers in EDFA amplifiers or power equalizers at adequate sites in the network.

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More generally, (transparent) all-optical WDM networks must cope with transmission impairments induced by long-haul optical components. Actually, the optical signal undergoes through its route various transmission impairments like attenuation, dispersion, nonlinearities, etc. In fully opaque networks, the signal quality is always considered as acceptable since electrical 3R regeneration (Re-amplifying, Re-shaping, and Re-timing) is provided at each node (in the rest of the paper, *regeneration* will refer to electrical 3R regeneration). However, providing regeneration at each node is very expensive.

Hybrid WDM networks are considered today as a promising solution to meet the fully opaque performances at a much lesser cost. In such networks, electrical regenerators are used at intermediate nodes only when it is necessary. In previous work, we proposed a tool called QWP (Quality of transmission dependent WDM network Planning), to deal with the problem of routing, wavelength assignment and regenerator placement considering physical layer constraints. Our tool consists of two modules, namely BER-Predictor (Bit Error Rate-Predictor) and LERP (Lightpath Establishment and Regenerator Placement). Given a network topology, BER-Predictor provides an estimation of the BER on any lightpath taking into account the simultaneous effects of four transmission impairments, namely chromatic dispersion (CD), polarization mode dispersion (PMD), nonlinear phase shift (ϕ_{NL}), and amplified simultaneous emission (ASE). For a given lightpath, the estimated value of the BER provides an indication of the intermediate nodes at which the signal must be regenerated. Whenever the BER value exceeds a certain threshold, one or more regenerators may be needed along the path. The LERP algorithm aims both at minimizing the number of rejected demands and at minimizing the number of regenerators required to establish lightpaths under acceptable QoT conditions. It first solves the routing and wavelength assignment (RWA) problem associated to the traffic demands and then checks for the signal quality and places regenerators when necessary.

In this paper, we focus on in-line equalization as a solution that might compete with regeneration under some operating conditions. Indeed, in-line equalizers are optical components that, to some extent, may help in dealing with the long-haul signal degradation. We investigate the impact of in-line optical gain equalization on the network performances measures in terms of the number of required regenerators. We use an in-line gain equalization scheme that deploys a gain equalizer every 5 spans, i.e. after a cascade of 5 optical amplifiers. Furthermore, we propose a new QoT-aware wavelength assignment (WA) strategy called Min-BER-Fit that chooses among the available wavelengths the one leading to the smallest BER value on the considered path.

This paper is organized as follows. In section II, we providea brief review of related studies on hybrid WDM network design considering physical layer issues. In section III, we describe the QWP tool and the new WA strategy. Simulation results are discussed in section V. Our conclusions are drawn in section VI.

II. An Overview of Related Work

Recent research work in the field of optical network planning focuses on the problem of RWA considering physical impairments arising the transmission system.

A critical issue in WDM systems with cascaded amplifiers is the flatness of the EDFA amplifiers. The amplifier gain is not exactly the same for each wavelength. A small imbalance in gain between channels at some stage may cause a large imbalance in power between channels at the output of the chain. Various strategies have been proposed to deal with such imbalance. In [2], the authors suggest employing controllers in EDFA amplifiers or to employ power equalizers at convenient sites in the network. Generally, gain control is applied individually in each amplifier, nevertheless, a recent study [3] proposes also the usage of control system techniques for handling the gain behavior in a long cascade of amplifiers. On the other hand, the employment of in-line dynamic gain equalizers makes only sense if they are used in adequate locations [4]. However, the literature is not conclusive as to with technique is best suited for fighting the imbalance problem.

Several studies support the idea of sparse regeneration in long-haul and ultra-long-haul WDM networks. As it has been surveyed in [5], the 600 km reach distance usually used is far from the average connection distance for Internet traffic. Considering a large set of network topologies and traffic scenarios, the authors demonstrate that even a system of 3000 km reach distance can only satisfy 60% of all Internet connections. However, today's technologies have difficulties in extending the reach distance to more than 2000 km. In [6], the authors suggest to establish sub-connections between regeneration sites using "islands of transparency" so that the QoT requirements are met. An architecture of the regeneration capable node has been proposed and validate in [7] and [8]. The authors propose regenerator placement algorithms that are carried out the network planning stage based on the prediction of future demands. Simulations results show the tradeoff between the blocking probability and the total number of used regenerators under the light and heavy traffic loads. In each experiment case, the total number of used regenerators is normalized to the number of regenerators in a fully opaque network (e.g. the fully opaque 53-node, 68-link, 16-wavelength USA network needs 2176 regenerators(see [9])). It has been showed that when the number of used regenerators exceeds 20% of the number of regenerators in a fully opaque network, adding extra regenerators only provides a little additional improvement in the blocking probability.

Other studies evoke the dependency of performance measures on the used wavelength. In [10], the authors study the impact of the crosstalk on the blocking performance of all-optical WDM networks. They propose four crosstalk-aware WA algorithms as variants of the well-known First-Fit, Random-Pick, Most-Used, and Least-Used WA strategies so that the crosstalk factor is taken into consideration. The proposed strategies aim at minimizing the crosstalk effect in the network: they choose the available wavelength that creates as little crosstalk on the new and existing lightpaths as possible to reduce the blocking probability. Simulation results show that, compared to their traditional counterparts, the proposed algorithms can significantly reduce the blocking probability due to QoT purpose. Nonlinear effects have been also considered in [11]. The authors propose an algorithm, called B-OSNR (Best-OSNR), which aims at minimizing the effect of transmission impairments when solving the RWA problem. B-OSNR chooses the wavelength that provides the maximum OSNR. Simulations results showed that, when transmission impairments come into play, the B-OSNR outperforms traditional algorithms (for instance First-Fit) in terms of blocking probability.

In our studies ([12], [13], and [14]), we propose methods and algorithms to tackle the RWA problem while meeting the QoT requirements for the established lightpaths. Our approach assumes that it is possible to set up a regenerator for a demand at any intermediate node if necessary. We deal with static traffic (permanent demands) and aim at minimizing the number of rejected demands. Our algorithms take into account four parameters describing the transmission impairments in order to estimate the signal quality (see below). In this paper, we propose some improvements of the transmission system by employing an in-line gain equalization scheme. Also, we propose a novel WA strategy that takes into account the signal quality.

III. The QWP Tool

The QWP tool deals with the problem of routing, wavelength assignment, and regenerator placement. It consists of a BER prediction tool and a dimensioning tool (Figure 1).

A. BER-Predictor

Given a lightpath $(route, \lambda)$, BER-Predictor provides an estimate of the optical signal quality at the destination node. This is done by computing the physical parameters we have chosen to estimate the Q-factor. The Q-factor is a quantitative description of the optical signal quality and is related to the

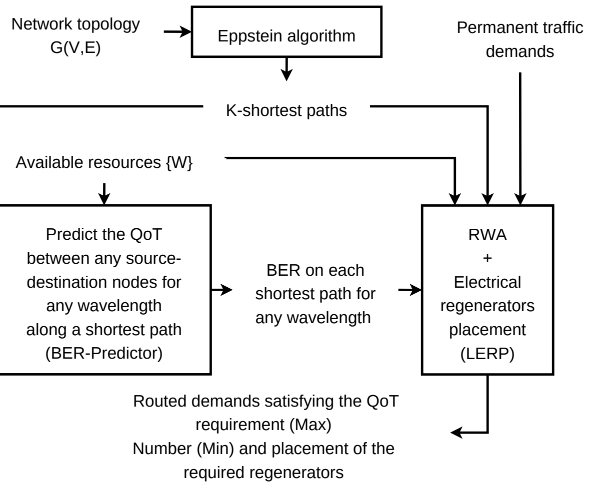


Fig. 1. The QWP tool

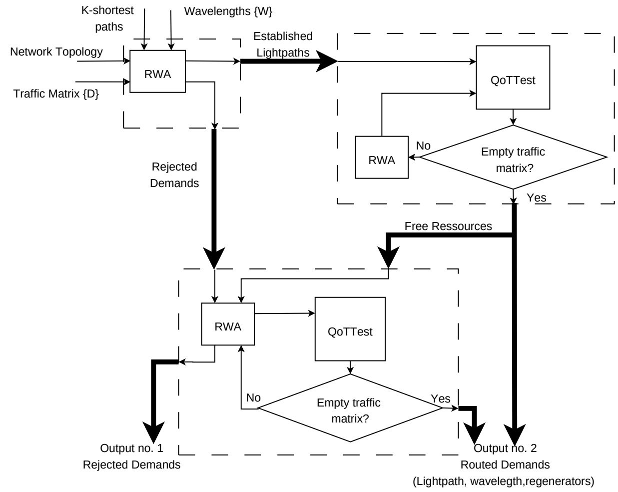


Fig. 2. The LERP algorithm

BER according to the following equation:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \quad (1)$$

where:

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

Various techniques have been proposed to model the signal degradations considering one or more physical impairments such as chromatic dispersion, polarization mode dispersion, amplified spontaneous emission, crosstalk and nonlinear effects ([11], [10], and [15]). One originality of our approach is to take into account interactions between four physical parameters considered as relevant to describe the signal quality, namely chromatic dispersion (CD), polarization mode dispersion (PMD), nonlinear phase shift (Φ_{NL}), and amplified spontaneous emission (ASE). In our study, the Q-factor estimation is computed as a function of these four parameters, i.e. $Q = f(CD, PMD, OSNR, \Phi_{NL})$ where f has been derived both from equations describing the physical phenomena and experimentation ([12] and [13]).

B. LERP

The LERP algorithm is twofold. First, it solves the RWA problem associated to the traffic demands. Second, it verifies the QoT requirement and places regenerators when necessary.

The RWA problem is solved using a sequential algorithm based on a random search (RS) method [14]. The RS method considers randomly several orderings according to which the demands have to be routed, so as to choose an ordering that hopefully minimizes the number of rejected demands. The routes are chosen among the k-shortest paths computed according to Epstein's algorithm [16] whilst the wavelengths are assigned according to the First-Fit.

The RWA problem being solved, the LERP algorithm addresses regenerator placement via a second step called QoT-Test. QoT-Test places regenerators so that the QoT requirements are met on all established lightpaths. Lightpaths composed of at least two hops are tested one by one. Considering a lightpath connecting node s to node d, the test begins at the third node. If the Q-factor is less than a certain threshold, the signal has to be regenerated at the previous node of the lightpath. Otherwise, we proceed to the same test at the next node. For each lightpath, the test ends if the destination node is reached or if a regenerator is placed at some intermediate node i. In the latter case, we define a new sub-demand whose source is i and whose destination is d. The route of the first segment of the lightpath (s,i) is stored and the used wavelength is reserved. The relative complementary sub-demand is added to a new traffic matrix to be routed afterwards. Once all the lightpaths have been tested, a new traffic matrix has been defined: it contains the sub-demands relative to demands that undergo signal regeneration. An RWA solution is computed for this new traffic matrix just as done in the first step taking into account the already allocated resources for the lightpaths established in the first step. Thus, we obtain a new routing scheme. The QoT-Test is performed for these newly established lightpaths. This procedure is repeated until no more signal regeneration is necessary, i.e. QoT-Test does not return any sub-demand. Processing new RWA steps after the regenerator placement steps makes it possible to find shorter paths for the routed demands and, as such, minimizes the number of required regenerators [14].

At this stage, we try to route the initially rejected demands. Indeed, once a regenerator is placed, the wavelength continuity constraint is relaxed. Thus, the sub-demand (i,d) can be routed using a different wavelength from the one used by the (s,i) segment. This may free several WDM channels, and some demands, initially rejected because of lack of resources, may now be routed [14]. Figure 2 gives the synopsis of the LERP algorithm.

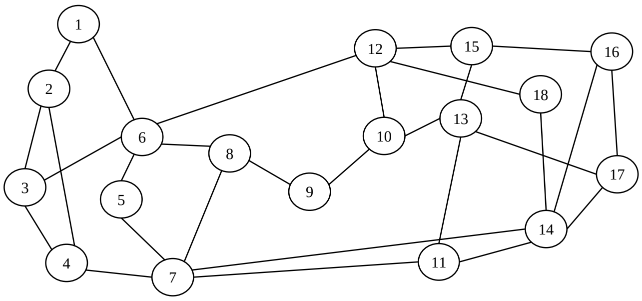


Fig. 3. The American NSF backbone network topology

TABLE I

A SET OF THREE TRAFFIC DEMANDS

Demand (δ_i)	*Source* (s_i)	*Destination* (d_i)	*Route* ($\mathcal{P}_i$)
δ_1	2	4	$2-3-4$
δ_2	1	6	$1-2-3-6$
δ_3	3	7	$3-4-7$

IV. In-Line Equalization vs. Regeneration

The aim of this study is to investigate the impact of employing an in-line gain equalization scheme. We want to assess the economical benefit of using equalization as a complement to regeneration. We will compare the number of required regenerations in the considered example optical network with and without in-line equalization and try to evaluate the cost ratio between the two solutions.

Equalization provides a better homogeneity in the BER distribution over the wavelengths on the considered path. It hence makes it easier for LERP to choose a wavelength. Hence, the study led us to try to find WA strategies (better than the basic Firs-Fit strategy used up to now) as an alternative to equalization to ease the wavelength choice in LERP.

A. Wavelength Assignment Strategies

Here we describe the Min-BER-Fit strategy as well as the standard First-Fit used in our previous work and that will serve as a basis for comparisons.

1) First-Fit: All the available wavelengths are indexed according to their position in the frequency spectrum. The wavelength with the lowest index is selected from the set of available wavelengths.

2) Min-BER-Fit: All the available wavelengths are sorted according to the Q-factor value they lead to on the considered path. The wavelength with the highest value of Q-factor is selected from the set of available wavelengths.

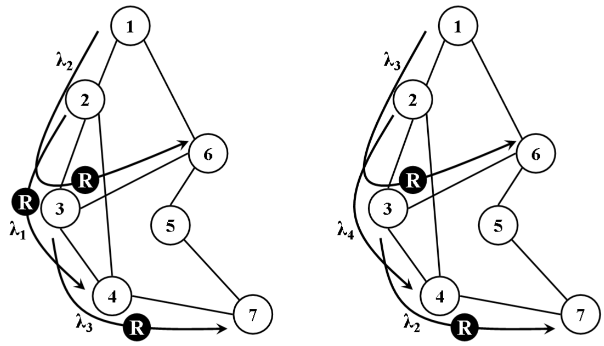
B. Numerical Example

A numerical example may clarify how the different strategies work with and without employing in-line gain equalizers. Considering the 18-node north American backbone network (Figure 3) and the set of demands described in Table I), we assume that four wavelengths are available on each fiber-link, namely $\lambda_1 = 1561.41$ nm, $\lambda_2 = 1553.32$ nm, $\lambda_3 = 1545.32$ nm, $\lambda_4 = 1540.55$ nm. For each route $\mathcal{P}_i$, we compute the Q-factor corresponding to each wavelength as shown in Table II.

TABLE II

Q-FACTOR VALUE W.R.T. THE USED WAVELENGTH

Demand (δ_i)	*Route* ($\mathcal{P}_i$)	λ (nm)	Q_{WE} (dB)	Q_E (dB)
δ_1	$\mathcal{P}_1$	1561.41	11.42	14.17
		1553.32	14.95	17.26
		1545.32	15.77	17.93
		1540.55	17.49	18.09
δ_2	$\mathcal{P}_2$	1561.41	5.71	10.03
		1553.32	11.49	13.92
		1545.32	12.19	14.36
		1540.55	13.19	13.71
δ_3	$\mathcal{P}_3$	1561.41	-0.24	5.70
		1553.32	6.92	13.50
		1545.32	9.39	14.56
		1540.55	12.69	13.83

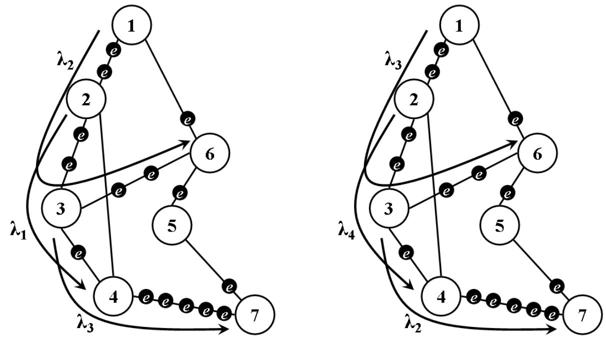


(a) First-Fit (b) Min-BER-Fit

Fig. 4. Solutions computed without in-line gain equalization

In Figures 4 and 5, black disks labeled with an "R" stand for requested regenerators at intermediate nodes. For example, the solution computed with First-Fit and represented in Figure 4 require two regenerators at node 3 (one for the demand routed on λ_1 and one for the demande routed on λ_2) and one regenerator at node 4 (for the demand routed on λ_3. Black disks labeled "e" stand for in-line equalizers. One can notice that once the equalization scheme has been set, the number of equalizers is set once for all in the network. Figure 5 show, for example, that the equalization scheme requires 5 equalizers between node 5 and node 7. The BER threshold is assumed to be 10^{-5} which corresponds to a Q-factor value of about 12.6 dB.

Solutions computed according to the two strategies are given in Figures 4 and 5. Whithout in-line gain equalization, the solution obtained with First-Fit requires 3 regenerators whereas the solution obtained with Min-BER-Fit only requires 2 regenerators (Figures 4(a) and 4(b) respectively). From this example it is possible to expect that the Min-BER-Fit strategy may lead to an improvement in the number of regenerators



(a) First-Fit (b) Min-BER-Fit

Fig. 5. Solutions computed with in-line gain equalization

required to meet QoT constraints.

Using an in-line gain equalization scheme, both the First-Fit and the Min-BER-Fit solutions do not require any regenerator at intermediate nodes (Figures 5(a) and 5(b) respectively). From the example it becomes understandable that using in-line equalization may higly reduce the number of regenerators required to ensure QoT. Now we would like to get some insight in the economical tradeoff between the two ways of improving the signal QoT in the network.

V. Numerical Results

Several numerical simulations have been carried out to show the effect of employing in-line gain equalization as well as to assess the improvement provided by the new WA strategy. These simulations have been achieved considering the 18-node north American backbone network (NSF) shown in Figure 3.

The network is assumed to be deployed using standard single-mode fibers (SMF) covering the C-band with 100 GHz spacing (providing 40 wavelengths on each fiber-link). In order to recover the fiber losses, double-stage EDFA (Erbium-Doped Fiber Amplifier) amplifiers are deployed every 80 km. The amplifiers characteristics, namely the gain and the noise figure are assumed to be wavelength dependent. Gain equalizers are deployed every 5 spans, i.e. every 400 km. As already mentioned, the number of equalizers installed in the network only depends on the network topology and on the equalization scheme. Hence, this number (here 122 equalizers) is set once for all. Chromatic dispersion is dealt with dispersion compensating fibers (DCF) which are deployed at the amplification sites. Further details about the transmission system's assumptions are given in [12].

Simulation results have been obtained considering static (also said permanent) traffic matrices generated randomly according to a uniform distribution. In our simulation scenarios, we consider various traffic loads where matrices of 100 to 700 demands are used. For each traffic load, we deal with 10 different matrices. Hence, each result presented in this paper is the mean value of the results gathered 10 different experiments.

First, we are interested in the impact of employing an in-line gain equalization scheme on the number of required regenerators. Figure 6 shows the mean values of the number of regenerators required to establish lightpaths for various traffic loads for First-Fit with and without equalization. Vertical lines refer to the confidence intervals, i.e. mean value $\pm$ standard deviation. Regenerators are placed considering a typical BER threshold value of 10^{-5}. We assume that the system uses a forward error code (FEC), therefore the system can achieve an end-to-end BER of about 10^{-20} whilst the effective BER is of about 10^{-5}. Figure 6 shows that in-line gain equalization becomes more interesting for heavy traffic loads. Using equalization leads to a gain of about 30% in the number of required regenerators for low traffic loads whereas this gain is of about 40% for heavy traffic loads (Figure 7). This can be explained by the fact that an equalizer is servicing all the wavelengths that cross it, hence, a single equalizer improves the whole bunch of wavelengths as opposed to the regenerators that we consider (in our work we consider that a regenerator is set up to service one demand at a specific intermediate node).

Figure 8 shows the mean values of the number of regenerators required to satisfy 600 demands for various values of the BER threshold. In both cases (with/without gain equalization), the number of regenerators increases as the QoT requirement become stronger which is to be expected. We see that the gain in the number of regenerators becomes of about 10% (compared to 40%) considering lower BER threshold values.

In Figure 9, we observe the gain in the network cost offered by in-line gain equalizers. The cost ratio has been computed as follows. We first define some variables:

- C_E is the cost of a gain equalizer;
- C_R is the cost of a regenerator;
- α is the ratio of an equalizer's cost to a regenerator's cost, and as such $\alpha = C_E/C_R$;
- M_E is the number of equalizers deployed in the networks (for the considered example network and equalization scheme $M_E = 122$);
- N_R is the number of regenerators required when no equalizers are used;
- N_{RE} is the number of regenerators that are required when using equalizers;

We define Γ as the gain in the network cost achieved by using in-line gain equalizers. Therefore, Γ can be defined as:

$$\Gamma = \frac{C_R N_R - C_R N_{RE} - C_E M_E}{C_R N_R}$$

Thus,

$$\Gamma = 1 - \frac{N_{RE}}{N_{Rwe}} - \alpha \frac{M_E}{N_R}$$

Figure 9 shows the value of the gain Γ as a function of α, still for First-Fit WA, and for various traffic loads. One can notice that for heavy traffic loads and for α of about 0.1, the use of in-line gain equalizers can achieve a benefit of about 37% in the network cost whereas the benefit is null for $\alpha = 1$. It is understandable that heavy traffic loads lead to

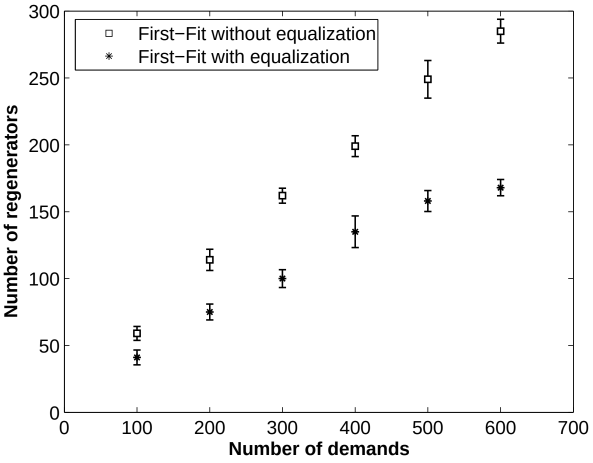


Fig. 6. Number of regenerators w.r.t. traffic load for First-Fit with and without equalization

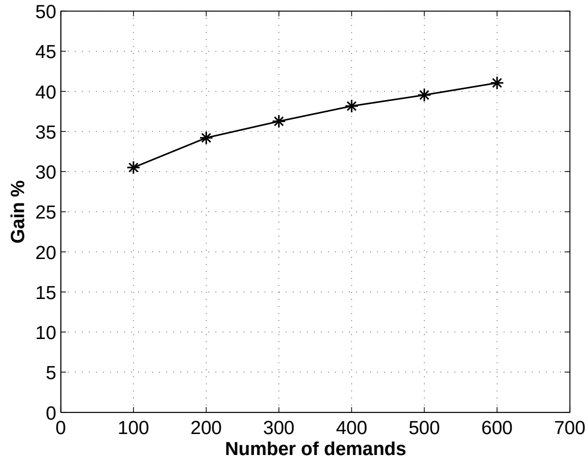


Fig. 7. Gain (First-Fit with equalization vs. First-Fit without equalization) in the number of regenerators w.r.t. traffic load

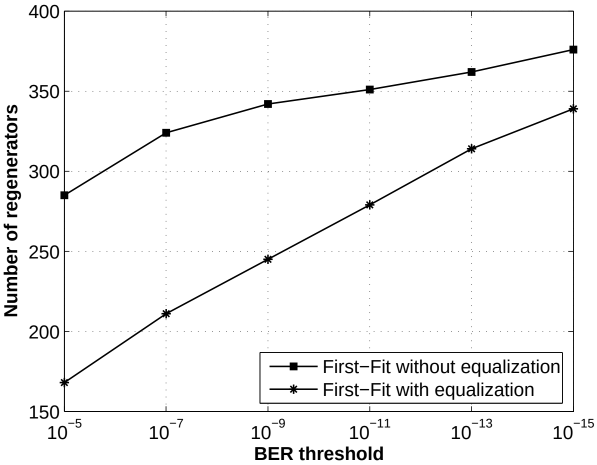


Fig. 8. Number of regenerators w.r.t. BER-threshold for First-Fit with and without equalization

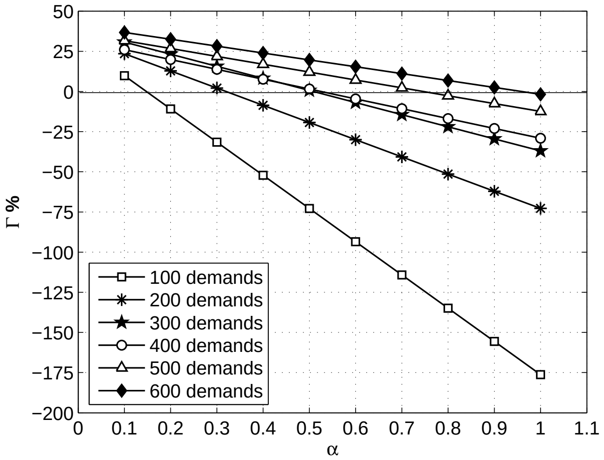


Fig. 9. Network cost gain (equalization+regeneration vs. regeneration) w.r.t. device cost ratio (equalizer cost vs. regenerator cost)

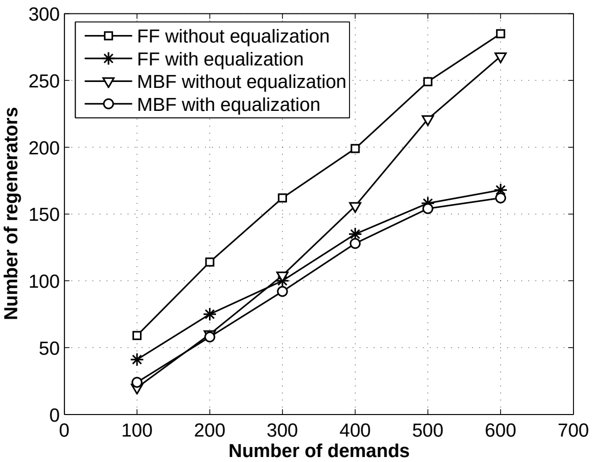


Fig. 10. Number of regenerators w.r.t. traffic load for First-Fit and Min-BER-Fit with and without equalization

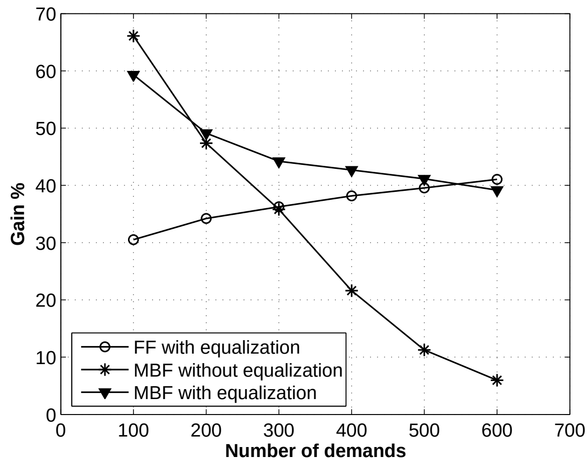


Fig. 11. Gains (various strategies vs. First-Fit without equalization) in the number of regenerators w.r.t. traffic load

better benefits when using in-line equalization. Indeed, again, an equalizer improves the full bunch of wavelengths so that the highest the traffic, the more an equalizer is shared by different wavelengths (the more the equalizer is profitable).

In Figure 10, we compare the First-Fit and Min-BER-Fit strategies in terms of the number of required regenerators. When no equalizers are used, the Min-BER-Fit strategy outperforms the First-Fit strategy, achieving respectively benefits of 66% and 6% for low and high traffic loads respectively 11. When equalizers are deployed, First-Fit and Min-BER-Fit achieve very close performances.

Figure 11 shows the gain in terms of required regenerators obtained with First-Fit with equalization, Min-BER-Fit without equalization and Min-BER-Fit with equalization w.r.t. First-Fit without equalization. From Figures 10 and 11, we can see that for low traffic loads, for which the deployment of in-line equalizers is not profitable, a QoT-aware WA strategy may compensate for the absence of gain equalizers.

VI. Conclusion

In this paper we have investigated the impact of in-line gain equalization in terms of the number of regenerators required to ensure QoT and in terms of economical benefits. We have also proposed a new wavelength assignment strategy that takes into account the quality of the optical signal. Simulation results show that, using the standard First-Fit strategy, in-line gain equalization may lead to an average 40% reduction in the number of required regenerators for heavy traffic loads. In absence of in-line gain equalizers, Min-BER-Fit outperforms First-Fit. Even more interesting, for low traffic loads, Min-BER-Fit achieves performances very close to those obtained by First-Fit when in-line gain equalization is used. Therefore, the deployment of in-line gain equalizers becomes interesting when the traffic load is heavy whereas the use of a QoT-aware WA strategy is more interesting for a low traffic load. Our current work focuses on new wavelength assignment strategies that further improve the results otbained with the Min-BER-Fit strategy proposed in this paper.

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