Quality of Transmission and Protection Schemes in Hybrid WDM Optical Networks

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Résumé

De nombreux travaux ont été réalisés dans le domaine de la protection et de la restauration dans les réseaux optiques WDM. La plupart des études négligent l'impact de la dégradation physique du signal sur les stratégies de routage et d'affectation de longueurs d'onde et en particulier sur celles faisant intervenir la protection. En fait, un signal optique subit de nombreuses dégradations sur son trajet. En l'absence de régénération 3R dans les nœuds traversés, le signal se dégrade et la qualité du signal est mesurée en terme de BER au niveau du récepteur.

Dans cet article, nous considérons un schéma de protection dédiée en prenant en compte les contraintes physiques subies par le signal. Étant donné un ensemble de demandes de trafic et une topologie de réseau, l'objectif est de minimiser le nombre de régénérateurs installés dans le réseau pour assurer la qualité de transmission (QoT) tant sur les chemins primaires que sur les chemins de secours. Nous proposons deux classes de protection selon la politique choisie (protection 1+1 ou protection 1:1). Dans le cas d'une protection 1+1, nous supposons que le même niveau de QoT est requis sur les chemins primaires et sur les chemins de secours. Dans le cas d'une protection 1:1, nous tolérons que le BER soit plus grand sur les chemins de secours que sur les chemins primaires. La QoT prend en compte quatre paramètres physiques, à savoir la dispersion chromatique, la dispersion modale de polarisation, la phase non linéaire et l'émission spontanée d'amplification. Dans les simulations numériques nous considérons deux valeurs pour le seuil de BER : 10^{-9} pour les chemins primaires et 10^{-6} pour les chemins de secours.

Ces travaux ont été réalisés dans le cadre du projet RNRT *RYTHME* et du réseau d'excellence *e-photon One*.

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Abstract— **Many investigations have been carried out in the field of path protection and restoration in WDM optical networks. Most of these studies neglect the impact of physical layer impairments on routing and wavelength assignment strategies, and more specifically on protection strategies. Actually, an optical signal undergoes throughout its route many transmission impairments. In the absence of `3R` regenerators at intermediate nodes, transmission impairments are accumulated at the receiver's side and translated in Bit Error Rate (BER). In this paper, we investigate a dedicated path protection scheme under physical layer constraints. Given a set of traffic demands and a network topology, our objective is to minimize the number of `3R` regenerators required to ensure the quality of transmission (QoT) on both primary and backup paths. According to the adopted policy (`1+1` or `1:1`), we propose two protection classes. In the case of `1+1` protection, we assume that the same QoT is required on both primary and backup paths whilst in the case of `1:1` protection, we tolerate a higher BER on backup paths. QoT is evaluated in considering four physical layer impairments, namely chromatic dispersion, polarization mode dispersion, non-linear phase shift and amplified spontaneous emission. In our numerical simulations, we consider two admissible BER: 10^{-9} for the primary paths and 10^{-6} for the backup paths.**

I. Introduction

WDM all optical networks are nowadays achievable thanks to the development of optical devices such as amplifiers and cross-connects. In such networks, data is transmitted from its source to its destination in optical form. Switching and routing operations are solely performed in the optical domain without underdoing any optical-to-electrical conversion. In the absence of any wavelength conversion, a connection, also called a *lightpath*, is supposed to use the same wavelength on all links along the chosen path. Because of the high data rate on lightpaths, it is imperative to develop appropriate protection and restoration schemes to prevent or reduce data losses [1][2]. In protection schemes, backup resources are pre-computed and reserved before a failure occurs whereas in restoration schemes, an alternate route is dynamically computed for each interrupted connection. Compared to restoration schemes, protection schemes have faster recovery time and provide guaranteed recovery ability but require more network resources. Protection schemes can be divided into *link protection*, *path protection* [3][4], and *partial path protection* schemes [5][6]. Path protection can be further subdivided into *dedicated path protection* and *shared path protection* [3][4]. In the dedicated path protection schemes, spare capacity is reserved for each individual end-to-end lightpath whilst in the shared path protection schemes, spare capacity is shared among multiple lightpaths, as long as those lightpaths do not fail simultaneously. Lightpaths sharing the same backup resources must be path-disjoint. Obviously, shared path protection requires less network ressources than dedicated path protection but requires more complex signaling and network management. Many strategies have been proposed in the literature to deal with the problem of protection in WDM all optical networks. Most of these strategies assume perfect physical layer conditions where physical layer impairments are neglected. Actually, since no `3R` regeneration is performed at intermediate nodes, the quality of transmission of the optical signal may be unacceptable at the destination node. The degradation of the transmitted signal is due to various physical layer impairments such as chromatic dispersion, polarization mode dispersion, non-linear phase shift and amplified spontaneous emission. Hybrid WDM optical networks are considered as a promising solution for meeting the QoT requirements while providing `3R` signal regeneration at intermediates nodes when necessary.

In the framework of hybrid WDM optical network, we proposed a novel algorithm called `LERP` (*Lightpath Establishment and Regenerators Placement*) to deal with the problem of routing and wavelength assignment (RWA) under physical layer constraints [7]. Given a set of traffic demands and a network topology, `LERP` proposes an RWA of the traffic demands and places `3R` regenerators at intermediates nodes of the established lightpaths for QoT purpose when necessary. `LERP` aims both at minimizing the number of rejected demands and the number of regenerators required to establish lightpaths under acceptable QoT conditions.

In this paper, we observe the behavior of `LERP` under `1+1` and `1:1` path protection schemes. In the case of `1+1` schemes, data is transmitted on both primary and backup paths simultaneously; the signal with the best quality being chosen at the receiver's side. Whereas, in the case of `1:1` schemes, data is rerouted on the backup path only when the primary path failed. According to the adopted policy (`1+1` or `1:1`),

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we propose two classes of protection. In the first class (1+1), we assume the same QoT requirements on both primary and backup paths. In the second class (1:1), we tolerate higher BER on backup paths. Numerical results are carried out to evaluate the network cost in terms of required regenerators w.r.t. the two protection policies aforementioned.

The remaining of the paper is organized as follows. In section II, we define the problem of RWA under physical layer constraints. In section III, we describe the LERP algorithm under dedicated path protection scheme. The obtained numerical results are presented in section IV and finally, we conclude this paper in section V.

II. Physical layer constraints aware RWA

In the last decade, much research work focuses on the RWA problem under physical layer constraints. A few RWA algorithms taking into account the impact of physical layer impairments have been proposed in the literature.

In [8], a BER-based RWA algorithm has been proposed. The authors employ appropriate models of multi-wavelength optical devices such that the BER of a candidate lightpath can be computed in advance to determine if this lightpath should be used for the call. The transmission impairments of physical layer include crosstalk in network nodes, wavelength dependence and saturation of amplifier gains as well as thermal noise components at the receiver. The impact of these impairments was taken into consideration in the wavelength assignment. In [9], the authors propose a simple model of the physical layer which considers both static noise due to optical components and nonlinearity effects due to the current wavelength allocation and usage. The proposed algorithm, called B-OSNR (*Best-Optical Signal to Noise Ratio*), aims at minimizing the effects of transmission impairments by choosing for each traffic demand the couple path/wavelength corresponding to the best OSNR. The problem of regenerator placement is addressed in [10]. The authors provide both minimal-cost and heuristic algorithms for locating signal regeneration nodes. For a minimal-cost algorithm, the problem is formulated using dynamic programming such that the blocking probability due to the lack of wavelengths is minimized throughout the network. In [11], the authors propose two heuristics for efficiently placing regenerators in the network. The MIR (*Maximum Infeasibility Reduction*) method is similar to maximum-descend algorithm. At each iteration, a regenerator is placed at the node which eliminates the maximum number of infeasible node pairs. MIR aims at minimizing the number of regenerators necessary to guarantee existence of at least two feasible disjoint paths between each source-destination pair. Instead of trying all nodes for each regenerator placement, the MDR (*Maximum Demand Regeneration*) algorithm determines two paths for each node pair so that the total number of required regenerators for both paths is minimized. After computing all paths for all node pairs, a regenerator is placed at the most demanding node.

III. LERP algorithm under protection schemes

The LERP algorithm, extensively described in [7], consists of two separate steps. In a first step, LERP computes an RWA for the demands according to an improved sequential RWA strategy. In the second step, each lightpath proposed by the first step is examined in terms of BER at the receiver's side. When necessary, regenerator is provided at intermediate nodes for the considered lightpath.

A. RS-based RWA

Our approach is based on a random search (RS) method. Given a set of traffic demands and a network topology, we consider for each demand k-alternate shortest paths computed off-line according to [12]. We aim at finding for each demand, among the corresponding k-shortest paths, two disjoint paths for establishing the primary and the backup paths. If the free resources (free wavelengths) are enough to establish the two disjoint lightpaths, the demand is considered as satisfied. The demand is blocked otherwise. Wavelength assignment is processed according to a standard first-fit scheme and the wavelength continuity constraint is imposed.

The RS method consists in finding a solution that minimizes the number of rejected demands. We define ρ_D as a D-dimensional vector generated randomly (D is the number of the demands). Vector ρ_D is a permutation of $\{1,2,\ldots,D\}$; it indicates the ranking according to which the demands are to be routed. The RS is performed as follows:

a. An initial solution is created by a function that defines the components of the vector ρ_D.

b. 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 demands) has not already been evaluated. In that case, another ranking vector is generated. 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***.

c. The objective function computes for a given value of vector ρ_D the number of rejected demands, denoted C. The demands are considered sequentially according to the ranking given by ρ_D. The ranking vector which reject a minimum number of demands 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 step.

B. QoT test and regenerator placement

The QoT of the established lightpaths is evaluated according to four transmission impairments, namely chromatic dispersion, polarization mode dispersion, nonlinear phase shift and amplified spontaneous emission. For this purpose, we developed a tool, called BER-Predictor [13]. Given a lightpath, BER-Predictor computes the four parameters aforementioned. According to a polynomial function, BER-Predictor computes the value of the Q factor taking into account the

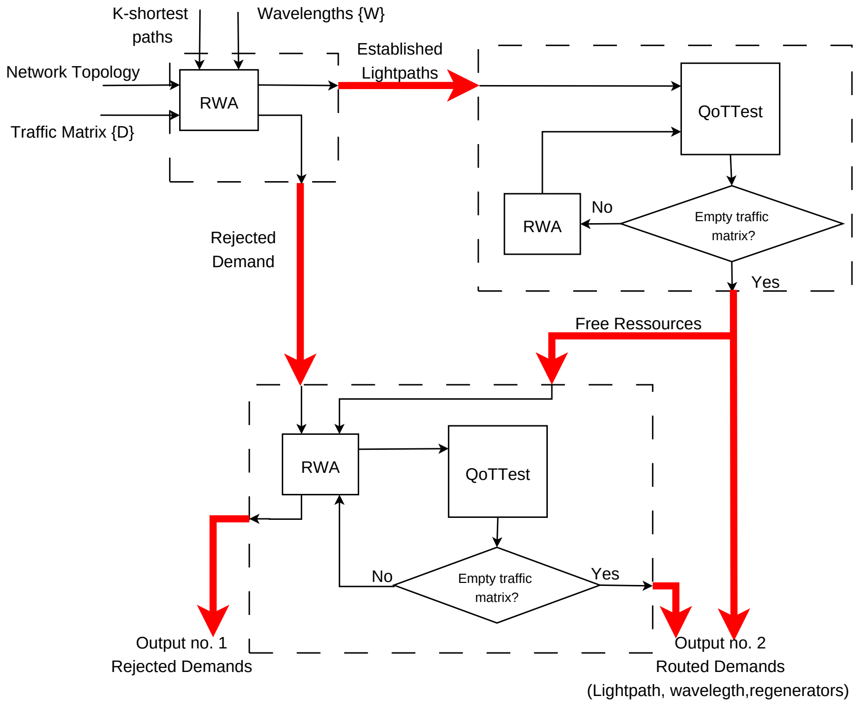

Fig. 1. LERP Synopsis

interaction between transmission impairments and deduces the corresponding BER. The QoT test is performed at intermediate nodes along the lightpath. If the BER exceed a certain admissible threshold at node i, the QoT is said unsatisfied and a regenerator is to be placed at the previous node. Note that a regenerator is associated at most to one demand.

At this stage of QoT test, LERP aims at optimizing the regenerator placement. For each demand between s and d, requiring a regenerator 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. The QoT of a lightpath ends if the destination node is reached without any signal regeneration necessity or if a regenerator is placed at a intermediate node. In the latter case, the first segment of the lightpath (origin, regenerator node) is stored and the assigned wavelength is reserved on this segment. The relative complementary sub-demand is added to new traffic matrix to be routed afterward. After testing all lightpaths, we obtain a new traffic matrix. The new traffic matrix contains sub-demands relative to demands that have needed signal regeneration. An RWA is computed for the new demands similarly to the first step. The QoT test is applied on the new established lightpaths. This procedure is repeated until QoT test doesn't return any sub-demand, which means that all established lightpaths satisfy the QoT constraint and no supplementary regenerators are necessary in the network.

At this stage, we try to route demands initially rejected because of the lack of network resources. The interest of resuming the phase of RWA after the regenerators placement phase is to potentially find shorter lightpaths for routed demands. In fact, once a regenerator is placed, the wavelength continuity constraint is relaxed. Thus the sub-demand (regenerator node, destination) can be routed using a new wavelength on a new lightpath. This would free WDM channels, and some demands which were initially rejected because of the lack of resources would be routed. The synopsis of LERP is given in Figure 1.

IV. Numerical Results

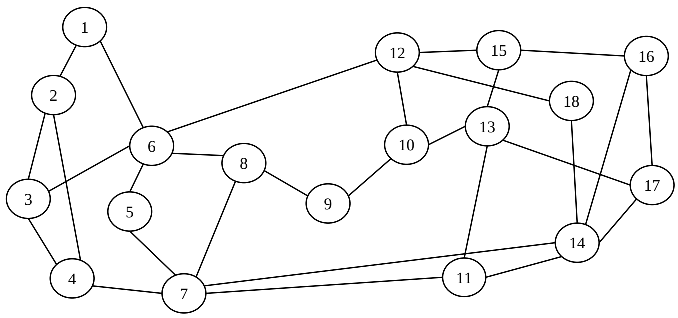

Fig. 2. The 18-nodes NSFNET backbone topology

In this section, we present some representative numerical results of our simulation experiments while considering the 18-nodes north American backbone shown in Figure 2.

The network nodes are assumed to be linked with standard single-mode fibers (SMF), with 40 wavelengths in the C-band at 100 GHz channel spacing. In order to recover the progressive losses incurred by the optical signal, erbium-doped fiber amplifiers (EDFA) are used every 80 km (see [13] for more detailed assumptions of the transmission system). In our

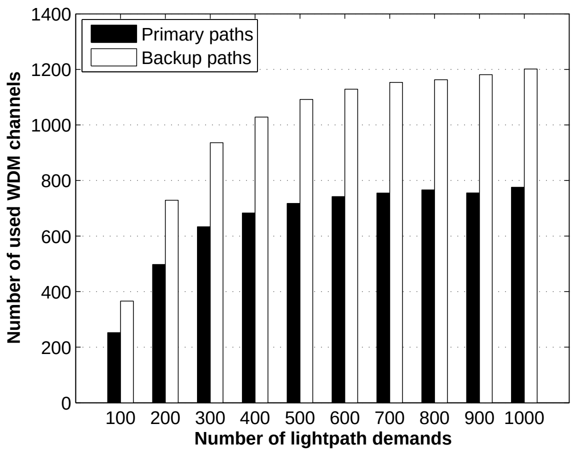

Fig. 3. Number of used WDM channels w.r.t. the number of lightpath demands for both primary and backup paths

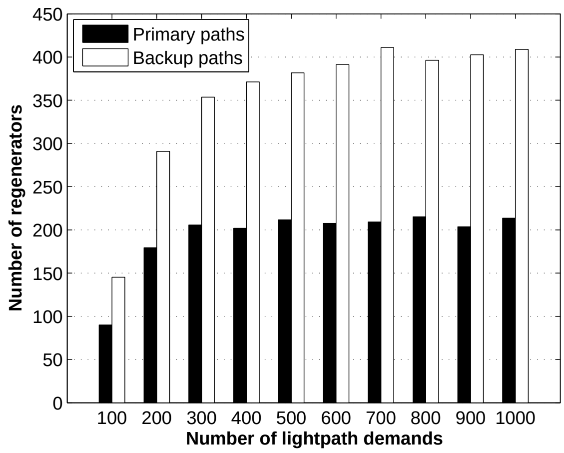

Fig. 4. Number of regenerators w.r.t. the number of lightpath demands when assuming $1+1$ protection scheme

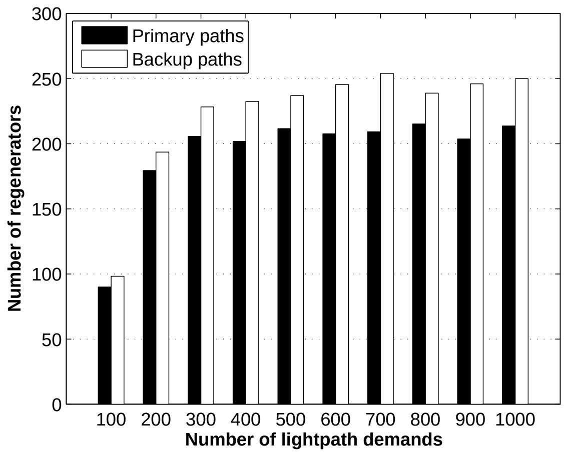

Fig. 5. Number of regenerators w.r.t. the number of lightpath demands when assuming $1:1$ protection scheme

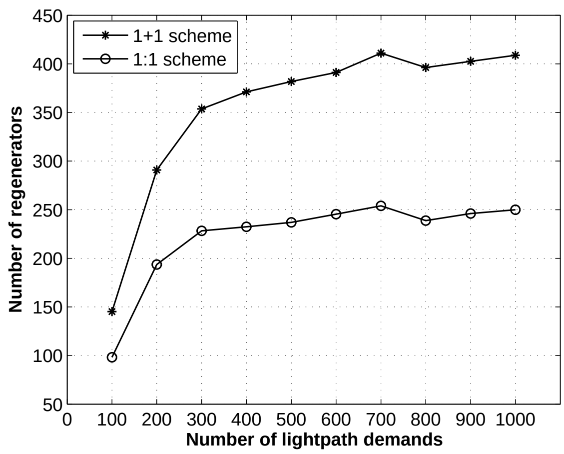

Fig. 6. Comparison between $1+1$ and $1:1$ schemes w.r.t. the number of lightpath demands

simulation scenarios, `10` different traffic matrices generated randomly according to a uniform distribution.

Figure 3 shows the mean value of the number of required WDM channels by both primary and backup paths w.r.t. the number of lightpath demands.

In Figure 4 and Figure 5, we compare between two dedicated path protection schemes: `1+1` and `1:1`. When `1+1` scheme is assumed, data is transmitted on the primary path and the backup path simultaneously. The signal with lower BER (best quality) being chosen at the receiver's side. Therefore, the QoT requirements are the same on both primary and backup paths. Figure 4 shows the number of `3R` regenerators required on primary and backup paths in the case of `1+1` scheme. We can notice that the number of regenerators to be placed on backup paths is quite higher. Indeed, the backup paths are longer than primary paths and consequently, more regenerators are placed to ensure the required QoT. In the case of `1:1` scheme, data is rerouted on backup path only after a failure occurs. Thus, we can tolerate higher BER on the backup paths. Figure 5 illustrates the number of required regenerators assuming two different admissible BER: 10^{-9} and 10^{-6} for the primary and the backup paths respectively.

In Figure 6, we plot the number of regenerators placed on backup paths under the different protection schemes. We notice that the `1:1` scheme with the differentiated admissible BER offer up to 38% reduction compared to the `1+1` scheme.

V. Conclusion

In this paper, we have discussed two dedicated path protection schemes in the framework of hybrid WDM optical network. Our algorithm, called `LERP`, ensures routing and wavelength assignment under physical layer constraints. `LERP` aims both at maximizing the resources utilization and at minimizing the number of `3R` regenerators required for establishing lightpaths so that the QoT requirements are met. We have observed the behavior of the `LERP` algorithm under two path protection schemes: `1+1` and `1:1`. Since in the case of `1+1` scheme, data are transmitted simultaneously on the primary and the backup paths, the same QoT requirements corresponding to BER of about 10^{-9} are assumed. Whereas in the case of `1:1` scheme, we tolerate a higher BER (10^{-6}) on backup paths. In the latter case, we have seen that for heavy traffic load the `1:1` scheme can offer up to 38% reduction in the number of regenerators required on backup paths.

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