Regenerator Allocation in WDM networks with uncertainties in the Q factor

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Abstract— **The performance of the regenerator allocation algorithms in WDM networks strongly depends on the accuracy of the physical-layer information such as the Q factor. In a translucent WDM network the already installed regenerators along the lightpath are allocated based on the physical information (Q factor) in order to maximize the quality of the optical signal while minimizing the opaqueness of the network. The Q factor used by the IA-RWA algorithms is usually inaccurate due to the drift suffered by the physical-layer parameters during the operation of the optical network. In this scenario the allocation of regenerators is not optimized and then the performance of the network is worsened. New regenerator allocation schemes should be proposed in order of counteracting the inherent and unpredictable uncertainty in the physical-layer information.**

I. Introduction

In a completely transparent network, the optical signal travels from the source to the destination node entirely in the optical domain without the need of optical-electronic-optical (OEO) conversion; whereas, in an opaque network an OEO conversion is performed at every switching node. The OEO conversion enables re-amplifying, re-shaping, and re-timing (i.e., 3R regeneration) the optical signal. The complete transparency is always desirable because the savings in electronic devices. However, the maximum transmission distance that an optical signal can reach without 3R regeneration is limited by the Physical-Layer Impairments (PLIs). When traversing the optical devices the optical signal suffers different PLIs that affect the signal intensity level, as well as its temporal, spectral and polarization properties. This degradation of the optical signal can make it illegible at destination. Moreover, nowadays optical networks usually operate at 2.5 Gps or 10 Gps, but in the near future, they are expected to work at 40 Gbps. Most of the PLIs have a higher effect when the network operates at higher rates (10 Gps and 40 Gps).

In order to deal with the degradation produced by the PLIs while limiting the number of OEO conversions, a solution is the translucent network. In a translucent network, some of the nodes are equipped with 3R regenerators. The optical signal can be regenerated at some intermediate node along the end-to-end path. This causes that the provisional end-to-end path is divided into two or more transparent sub-paths. The regenerator allocation consists on dynamically selecting which of the already installed regenerators may be used for each optical connection request. However, the optimization of regenerator allocation depends on the accuracy of the physical information known by the routing algorithm. In this paper, we propose a novel parametric regenerator allocation scheme that takes into account the inaccuracy of the physical information.

The rest of the paper is structured as follows. Section 2 reviews the recent work addressing the regenerator allocation, Section 3 describes the physical model utilized in our proposal, Section 4 presents the new proposed scheme. Section 5 evaluates and validates our proposal by simulation; and finally Section 5 concludes the paper.

An extended version of this paper has been presented in the 15th European Conference on Networks and Optical Communications (NOC 2010).

II. Impairment Aware Routing and Wavelength Assignment (IA-RWA) Algorithms with Regenerator Allocation Schemes

Only few works in the literature address the problem of regenerator placement and allocation. The regenerator placement is performed in the planning phase, and it consists of selecting which nodes of a translucent network have regeneration capabilities, and how many signals can be regenerated at those nodes. The regenerator allocation, on the other hand, determines how the already placed regenerators are used in a dynamic scenario. Designing a smart regenerator allocation policy has different advantages; first, when the usage of regenerators is optimized, more connections can be set up with enough quality; second, there is an energy saving if only the needed regenerators are working at any moment of time; and finally, it reduces the delay introduced by the regenerators due to the time necessary for the OEO conversion. In this scenario, upon receiving a connection request, the IA-RWA algorithm performs an on-line routing and wavelength selection, and also decides whether to use or not the regenerators already placed along the nodes of the selected path.

The allocation of regenerators is proposed in [1], [2] and [3]. In [1] the Least-Cost Impairment Aware Routing algorithm utilizes the constraints of maximum number of nodes and maximum distance between nodes with regeneration. The nodes with regenerator capabilities have a cost associated; then the IA-RWA algorithm selects among the K-Shortest Paths (K-SP), the lightpath minimizing the cost. Finally, the IA-RWA algorithm chooses the nodes where regeneration is performed. In [2], the Efficient Regeneration-Aware algorithm minimizes the number of used regenerators along the selected lightpath as well as the PLI constraints. The novelty of this proposal consists of sharing the transmitters, receivers and electronic interfaces with the access functions at any node with regenerator capabilities. Some nodes must have spare T-R (transmitter-receiver) pairs and electronic interfaces remaining for the regeneration function. The DWP (Distributed Discovery of wavelengths Paths) method [3] aims to minimize either the minimum usage of electronic regeneration or the delay introduced by the regenerators in the OEO conversion. The route decision is taken at destination, and if the criterion is the minimum number of used regenerators, the lightpath using the least number of regenerators is selected.

All these previous proposals of regenerator allocation schemes consider that the physical information is completely accurate. In [4] authors evaluate the impact of having inaccurate physical information on an optimized regenerator allocation scheme. Authors compare the MINCOD-Q algorithm without regenerator allocation optimization (all the regenerators on the nodes along the candidate path are allocated) with the MINCOD-Q-REG algorithm that optimizes the allocation of regenerators. The conclusion for the MINCOD-Q-REG algorithm is that when the degree of inaccuracy of the physical information is greater than 0.5 dB, the optimization of regenerator allocation is not useful; hence, it is better to use all the regenerators found along the selected route.

III. PHYSICAL MODEL

1) Q Personick's factor

An optical signal is subject to PLIs (linear and non-linear) which degrade its quality as it transparently propagates through the network. Due to this degradation, some connections are unfeasible to be set up completely in transparency. Hence, a regenerator is needed in an intermediate node dedicated to the connection; otherwise, if there are no available regenerators, the connection cannot be set up. At the end of each sub-path (except the last one), a regenerator renews the signal. The regeneration operation implies a complete loss of memory of the history of the signal along the path followed to reach the regenerator, because we consider that 3R regenerators fully restore the optical signal. A PLI model allows us to relate the signal degradation to the physical parameters of the network elements crossed along the path. It must be simple enough to be useful in practice, where a limited number of input parameters should be sufficient to characterize each optical link. It is also desirable to have a single output parameter which collects all the PLI effects as suggested in [5], [6] and [7]. This can be carried out by different methods, from analysis in the simplest cases, to physical-layer simulations in the most complicated ones. The Bit Error Rate (BER) is considered as the main performance parameter to measure the optical signal quality at the receiver of an optical connection. An optical connection can be set up if the BER at the receiver is above a threshold.

A BER value can be translated by well-known relations into a quality factor value of the so-called *Personick Q factor* [5]. The Q Personick's factor can be evaluated as a function of the transmission-system parameters (i.e. optical bandwidth, electrical bandwidth, power level at the signal launch, etc) and PLIs (ASE, loss (linear); self- and cross-phase modulation (non-linear)). In particular, we have adopted the model proposed in [8]. Let us consider a h-hop sub-path p, crossing h links. The Q factor at the end of the sub-path is given by the equation:

$$Q_p[dB] = a_0 + a_1 OSNR_p + a_2 N_p + a_3 (P_0 N_p)^B \quad \text{Eq. 1}$$

The coefficients a_0, a_1, a_2, a_3, and B, depend on the type of used equipment, and should be tuned by an on-field measurement campaign [8]. The third and fourth terms of the equation take non-linear effects into account. $P_0[dB]$ is the power level at the sub-path channel-signal launch. N_p is the total number of EDFA-amplifier spans crossed by the sub-path. $OSNR_p$ is the optical signal to noise ratio over a fixed optical bandwidth (dependent on the bit rate and the modulation format of the transmitters). A minimum threshold value of Q, called Q_{th} is required at the end of each sub-path. Typically, the requirements for the minimum value of the signal Q at the receiver are about 17 dB without error correction mechanism.

$$Q_p \geq Q_{th} \quad \textbf{Eq. 2}$$

2) Uncertainties in the physical parameters

Authors in [9] propose a physical model that interpolates the BER from experimental measurements. This interpolation introduces uncertainties which have to be considered when evaluating the feasibility of a lightpath. In [10], these uncertainties are considered by means of an extra fixed margin. A lightpath is only considered feasible if its quality factor, Q, is higher than the Q threshold plus this extra fixed margin. This fixed value is computed from the standard deviation of the difference between the real BER and the interpolated BER values. Finally, in [11] this extra margin is proposed to be variable and it is based in the amount of residual chromatic dispersion and nonlinear phase experimented by the signal.

The above proposals consider that the PLI model is not completely accurate. In concrete for the Q *Personick's* model, apart from other sources of inaccuracy, it does not take into account PLIs that depend on the traffic load. The effect of this is the drift suffered by the Q values from their nominal values during the operation of the optical network. Then, the performance of the IA-RWA process might drop sharply when either assigning routes and wavelengths or when allocating regenerators, since the real Q value differs from the Q factor used by the IA-RWA algorithms.

IV. PARAMETRIC K-SHORTEST PATH REGENERATOR IA RWA AND REGENERATOR ALLOCATION ALGORITHM

In our study, the discrepancies between both the computed and the real *Q* values are random values. We associate a random error value to each one of the candidate sub-paths between nodes with 3R regenerators. This random error is uniformly distributed between 0 and a maximum error value (*error_max*). We consider that the real *Q* value of a lightpath, which is denoted by Q_{real}, is the *Q* value obtained using the *Q Personick's* methodology, which is denoted by $Q_{computed}$, minus an error value:

$$Q_{real} = Q_{computed} - error \qquad \text{Eq. 3}$$

This approach of considering a random error in Q on each sub-path is simple but effective in producing a degradation of the network blocking performance. Obviously, we assume that this error value is unknown to the IA-RWA algorithm and, as a result, the algorithm may make a wrong routing/wavelength assignment or regenerator allocation decision. Results in [4] show the effects on the performance due to this error in two IA-RWA algorithms, with and without regenerator allocation optimization. We propose two new algorithms taking into account the inaccuracy in the Q value. Both algorithms select the lightpath among the K shortest paths and they select the first-fit (FF) wavelength in each one of the sub-paths. Moreover, we consider that both new algorithms know statistically [10] the value of the maximum error (*error_max*) of Q of any of the lightpaths, although they do not know the exact error for each one of the lightpaths. The first algorithm, called Worst-K-SP, utilizes this maximum value as an extra margin. A lightpath is not selected if its Q is lower than the Q threshold plus this extra margin.

$$Q_p \geq Q_{th} + error\_\max \qquad \text{EQ. 4}$$

Whereas, in the second algorithm, called (Parametric) Par-K-SP, the Q value of a lightpath has to be higher than the Q threshold plus a parametric margin, which is a percentage, *par*, of the maximum error (*error_max*).

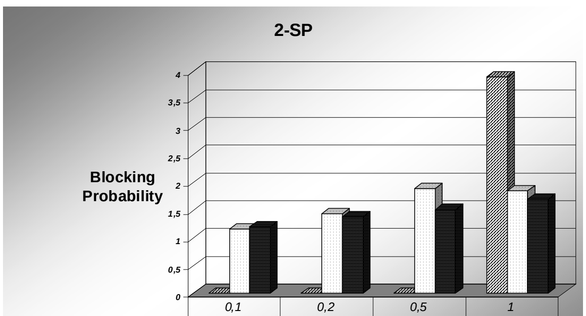
$$Q_p \geq Q_{th} + par * error\_\max \qquad \textbf{Eq. 5}$$

V. PERFORMANCE EVALUATION

Evaluation trials are performed on the Pan European network formed by 28 nodes and 41 links. The number of wavelengths on each link and regenerators in each node is calculated in a previous planning phase. More detailed information about the planning phase can be found in [8]. However, according to [12] there is a significant improvement in terms of the resource consumption when using an optimized regenerator allocation scheme and hence we reduce the number of installed regenerators (14) with respect to those obtained in the planning phase (129). We carry out a set of simulations under dynamic traffic conditions: from 0.1 to 1 Erlang between each pair of nodes of the network The *Q* threshold utilized in all the following simulations is 17 dB. In order to evaluate the effect of having inaccurate information, the random error value of each sub-path is between 0 and 1 dB (with an average value of 0.5 dB). We only consider the case of underestimation of the *Q* value.

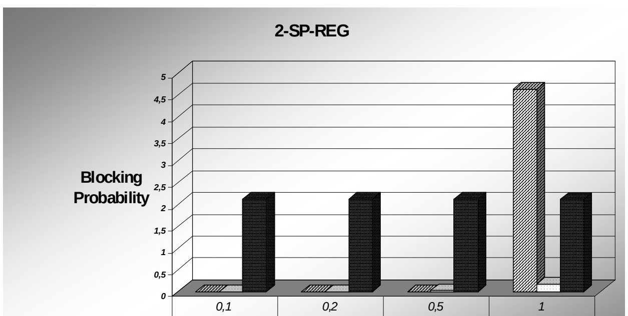
In our evaluation we compare the K-SP algorithm without regenerator allocation optimization, with the K-SP-REG algorithm (both with FF wavelength assignment) where the regenerator allocation is optimized according to [12]. We compare them with the two new proposed algorithms, Worst-K-SP and Par-K-SP without and with (-REG) regenerator optimization, all of them with K=2. Figure 1 shows the blocking probability produced by resource (wavelength) unavailability, physical unavailability (there is not any lightpath with enough Q) and finally due to inaccurate Q value, for the K-SP and K-SP-REG respectively. The inaccuracy in the computed Q may produce that a lightpath is selected with a $Q_{computed}$ higher than 17 dB, but due to the error the lightpath can be blocked in the setup process because it does not have enough quality (Q_{real}< 17 dB). From Figure 1 we observe that for low traffic load the K-SP-REG eliminates the blocking due to physically unfeasible lightpaths with respect to K-SP because K-SP-REG optimize the use of regenerators. However it does not take into account the inaccuracy of Q and it does not solve this problem.

Figure 2 shows the blocking probability versus traffic load for Worst-K-SP and Worst-K-SP-REG. When we add and extra-margin to the Q threshold (higher than the error of any lightpath) we eliminate the blocking probability due to inaccuracy in the Q value. But we increase the number of physically 'unfeasible' lightpaths because now the Q threshold is



	0,1	0,2	0,5	1
BP resource unavailability	0	0	0	3,896825397
BP physical (Q) unavailability	1,164021164	1,436507937	1,886243386	1,843915344
BP Q error	1,203703704	1,378306878	1,510582011	1,693121693

Traffic load (Erlangs)



	0,1	0,2	0,5	1
BP resource unavailability	0	0	0	4,62962963
BP physical (Q) unavailability	0	0	0,026455026	0,164021164
BP Q error	2,116402116	2,116402116	2,121693122	2,103174603

Traffic load (Erlangs)

Figure 1. Blocking probability versus traffic load for K-SP and K-SP-REG

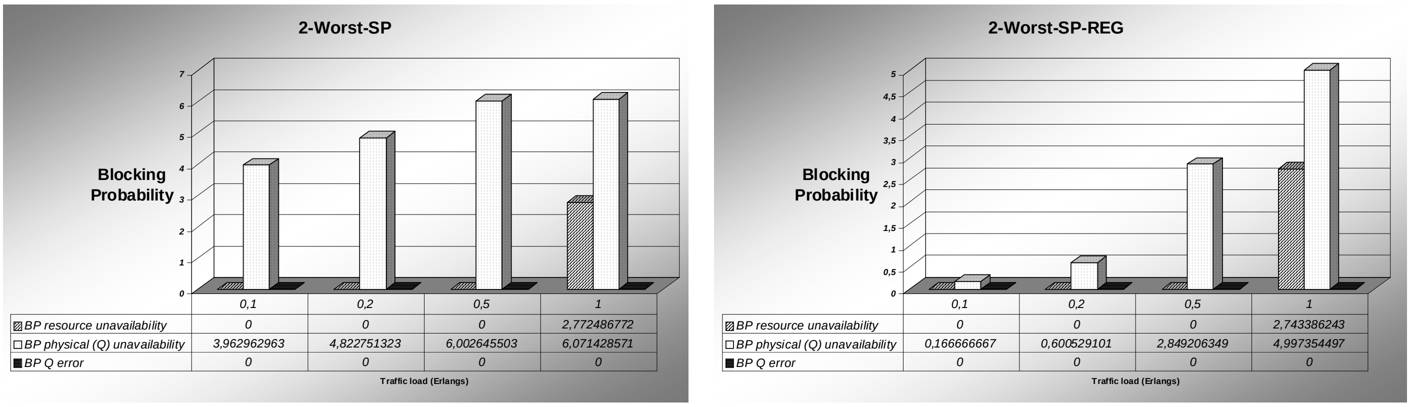


Figure 2. Blocking probability for Worst-2-SP and Worst-2-SP-REG

18 dB. On the other hand, from both figures we also observe that for 1 Erlang a high percentage of blocked connections is due to wavelength unavailability. Moreover, in general algorithms with regenerator optimization (-REG) perform better than without. Results for the Par-K-SP algorithm show the improvement of using a parametric margin when allocating regenerators. In the simulations with different parametric margins (0.25, 0.5 and 0.75) we obtain the best performance for the Par-K-SP-REG with par=0,25, that is with an extra margin of a 25% of the *error_max*. Figure 3 shows results for this case and we observe that Par-K-SP-REG (0.25) eliminates for low traffic load the blocking probability due to physical unfeasibility and also due to uncertainties in Q.

VI. Conclusions

In this paper, we have analyzed new regenerator allocation schemes taking into account the inherent inaccuracy in the physical information. The best performance is obtained with the scheme that adds a parametric margin to the quality factor threshold. This parametric margin depends on of the maximum quality factor inaccuracy in the network. When the IA-RWA algorithm and regenerator allocation scheme know this maximum value of inaccuracy [10], the blocking probability can be reduced around a 90%.

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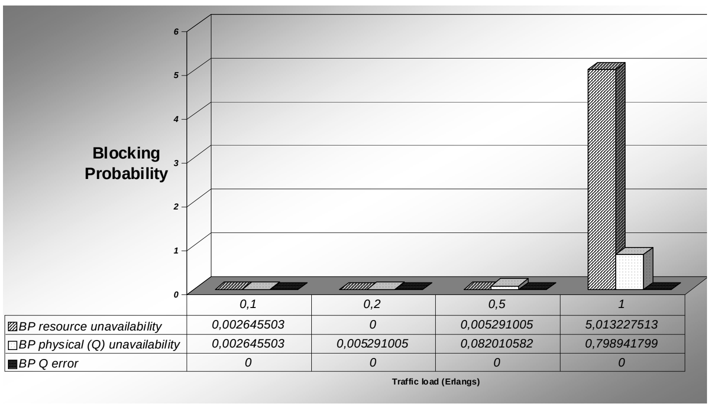

Figure 3. Blocking probability for Par-2-SP with par=0.25