Considering transmission impairments in configuring wavelength routed optical networks

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Abstract: We face the Routing and Wavelength Assignment (RWA) problem considering as constraints the physical impairments that arise in all-optical networks. We propose a simple model for the physical layer considering both static and dynamic impairments.

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1. Introduction

Wavelength Routed (WR) networks are considered the best candidate for the short-term implementation of a high-capacity IP infrastructure, because they permit the exploitation of the huge fiber bandwidth, but do not require complex processing functionalities in the optical domain.

In WR networks, remote high-capacity (electronic) routers are connected through IP-tunnels. IP tunnels are implemented by optical pipes called *lightpaths* that may extend over several physical links. Lightpaths can either be semi-permanent [1], or be allocated in on-demand fashion [2]. In the first case a static topology is seen at the IP layer, while the second case is more adaptive at the cost of additional complexity both at the optical layer and the IP layer.

In this work, we consider a transparent optical network, in which lightpath requests are dynamically set-up. When solving the RWA problem, we explicitly take into account the physical impairments imposed by the optical layer. In particular, we consider the effect of *nonlinearities* which arise when considering dynamic wavelength allocation on optical fibers. In particular, nonlinearities strongly depend on the current allocation of wavelength on a given fiber (and path), and therefore on the current status of allocated lightpaths on the top of the physical topology.

This intuitively affects the RWA problem solution of new lightpath requests: the selection of a suitable path and suitable wavelength may fail to meet the minimum transmission requirement. But it may also affect already established lightpaths whose transmission properties are negatively affected by the new establishing lightpath. Hence, we propose a novel routing and wavelength assignment algorithm (called Best-OSNR) which explicitly tries to minimize the impact of physical impairments.

2. Model of physical layer

In order to analyze the evolution of the signals through a transparent optical network based on the Wavelength Division Multiplexing (WDM) technique, the wave equation for the fiber optic propagation should be solved for every optical link, together with mathematical models of optical components. Due to the nonlinear nature of the problem, and to the absence of analytical solutions, a rigorous analysis could need hundreds of hours of CPU time. Hence, it is not possible to setup a RWA analysis that may require to evaluate the network performance for possible millions different network configurations, i.e., millions extremely time consuming simulations of the physical layer.

In order to overcome the computational limits many approximated solutions have been presented in the technical literature (e.g., [3], [4]), but most of them do not include the impact of fiber *nonlinearities*.

We target our analysis to the inclusion in performance evaluation of lightpaths the effect of accumulated ASE noise, *linear* and *nonlinear* propagation. The simplified model we propose is based on the separation of the effects impairing the signal. To define the goodness of a lightpath we estimate the related *Optical Signal-to-Noise Ratio* (OSNR) and its penalties due to linear and nonlinear propagation effects, defining for each lightpath:

$$OSNR = OSNR_{ASE} - OSNR_{pen,lin} - OSNR_{pen,nl} \text{ [dB]}$$

where $OSNR_{ASE}$ is the value deriving from the noise accumulation, whereas $OSNR_{pen,lin}$ and $OSNR_{pen,nl}$ are penalties deriving from linear and non-linear propagation impairments, respectively.
It is well known that in ASE noise limited system, the *Bit Error Rate* (BER) for the considered lightpath can be directly related [5] to the *OSNR*, therefore, establishing that a lightpath can be reliably used if $BER \leq BER_{max}$ implies to impose $OSNR \geq OSNR_{min}$, where the threshold $OSNR_{min}$ is the one corresponding to maximum tolerable BER_{max}.
OSNR penalties are derived using semi-analytical models of impairments (PMD, dispersion, SPM and XPM [6]) based on simulations. In particular, in order to evaluate $OSNR_{pen,nl}$ we performed a series of Monte-Carlo simulations on defined test-links using the optical system simulator *OptSim*™. From the results of these simulations we deduced an empirical function giving $OSNR_{pen,nl}$ from the knowledge of the fiber characteristics, the number of wavelengths turned on, the length of the fiber span and the transmitted power. From this function, knowing the network characteristics from its graph description and the wavelength assignment, $OSNR_{pen,nl}$ is evaluated. Of course this penalty depends on the dynamic reconfiguration of the network because it varies with the number of wavelengths in use per each fiber and on their spectral assignment; therefore it depends on dynamic network configuration. Main approximation is given by the separation of effects in the propagation impairment analysis.

3. Application of RWA algorithms

To solve the RWA problem, we started selecting two algorithms that were shown to give good performance: the *First Fit-Minimum Hop* (FF-MH) and First Fit-Least-Congested (FF LC) [7]. These are traditional algorithms, which split the RWA problem into two simpler sub-problems: first a suitable path is selected, and then a suitable wavelength is allocated, if available on the selected path. An event driven simulator has been written to get numerical results.
Traditional algorithms fail to consider the physical impairments that may affect the transmission on a given path-wavelength. Therefore, we propose a novel algorithm, called *Best-Optical Signal* Noise Ratio (B-*OSNR*), which will jointly assign to a given request a path and a corresponding wavelength. In particular, the path/wavelength solution which will present the maximum *OSNR* will be selected.
As performance indexes, the average blocking probability P_b is evaluated. In particular, to asses the impact of the *OSNR* limitation, the simulator evaluates the blocking probability due to physical impairments P_b^{OSNR} and the blocking probability due to lack of available wavelength P_b^{λ}. The first one is defined as the ratio between the number of lightpath requests which were blocked because the *OSNR* level on the selected (free) wavelength was below the minimum threshold with respect to the total number of lightpath requests. P_b^{λ} accounts for blocked lightpath requests due to lack of available free wavelength. Clearly $P_b = P_b^{OSNR} + P_b^{\lambda}$.
We considered as physical topology the Italian Optical Network which was derived from a possible evolution of the *Telecom Italia Spa* network topology. We assumed that the network is cabled using *Non-Zero Dispersion Shifted fiber*. In order to recover fiber losses, we considered to use EDFAs spaced L_{span} km that perfectly recover the loss introduced by the preceding fiber span. We explored different scenarios analyzing the network behaviors for L_{span} = 40, 60, 80 km. We assume to use dispersion compensation techniques and that the *PMD* effect is negligible at the supposed bit-rate of 10 Gbit/s. The maximum number of supported wavelengths is set to 16.
Fig.1a plots the average blocking probability versus offered load ρ. For simplicity, we considered a uniform traffic pattern. Comparing the results obtained by the FF-LC with the *B-OSNR* algorithm ones, it can be noticed that when the impact of the *OSNR* introduced by the physical layer is negligible, the FF-LC algorithm performs better than the *B-OSNR* approach. Indeed, for small values of the offered load and for small span values the FF-LC takes the lead, while for both larger values of ρ and for span value set to 80 km, the *B-OSNR* algorithm clearly outperforms the FF-LC approach.
The intuition behind this is that the allocation of wavelength used by the FF approach tends to pack wavelength usage and therefore to maximize the noise due to interfering wavelengths. Therefore, when the blocking probability is largely due to physical impairments, the FF-LC algorithm cannot find any good solution. The *B-OSNR* algorithm on the contrary shows much better results.
Similarly, considering different network span configuration, the *B-OSNR* approach shows little differences, showing that it is able to overcome physical configuration which offers worse *OSNR*. On the contrary, the

FF-LC algorithm presents much worse results when considering the 80 km span network. This is due to the path selection choice, which allows the FF-LC algorithm to select longer and noisier paths. Finally, to gauge the ratio between the blocking due to wavelength lack or to *OSNR* lack, Fig. 1b plots the percentage of blocking probability due to *OSNR* degradation versus the offered load ρ. It confirms the previous observation, by showing that the B-OSNR algorithm is only marginally affected by the lack of *OSNR*. On the contrary, the FF-LC approach faces the majority of blocking probability because the selected wavelength and path cannot offer an adequate *OSNR* level. This is particularly true when considering the 80 km span length.

4. Conclusions

We presented a novel simple physical model to evaluate the OSNR ratio which considers both static noise due to optical components and nonlinearity effects due to the current wavelength allocation and usage. We then presented a novel algorithm which tries to minimize the effect of transmission impairments when solving the RWA problem for each lightpath requests. Simulation results showed that, when the transmission impairments come into play, an accurate selection of path and wavelength which is driven by OSNR is mandatory. In particular, both static effects and nonlinearities can largely affect the blocking probability: the first one depend on the physical configuration and must be considered for any offered load to the network; the latter one rapidly degrades the quality of the transmission layer when the number of lightpath already established is large, i.e., when the offered load is higher. In such scenarios, the proposed B-OSNR algorithm outperforms traditional algorithms which fail to consider the physical impairments.

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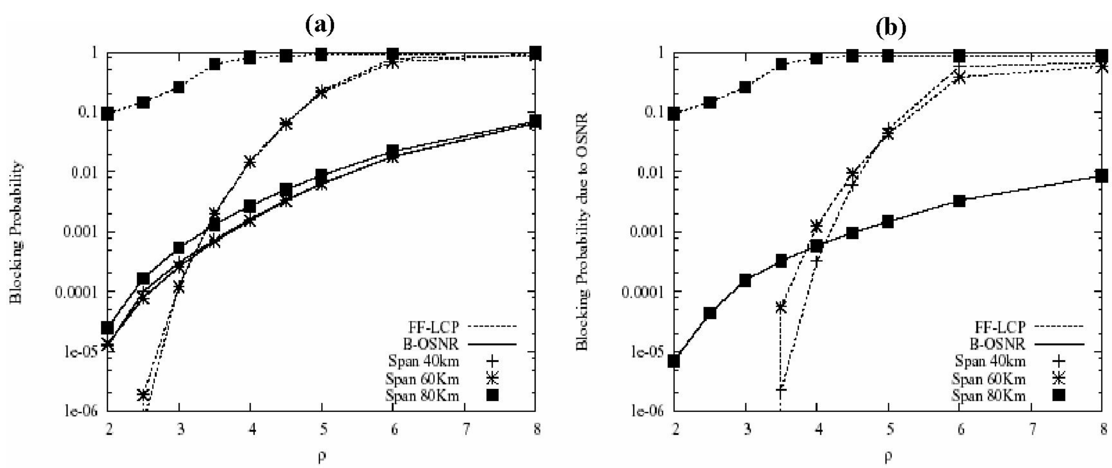

Fig. 1 (a) Blocking probability versus ρ for different algorithms. Fiber span L_{span} of 40 km, 60 km, 80 km. (b) Percentage of blocking probability due to OSNR degradation versus ρ for different algorithms. Physical span of 40 km, 60 km, 80 km are presented.