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Rocco Cardillo, Vittorio Curri, Marco Mellia
Dipartimento di Elettronica - Politecnico di Torino - Torino, Italy
email: {cardillo,curri,mellia}@mail.tlc.polito.it

***Abstract*— We consider dynamically reconfigurable wavelength routed networks in which lightpaths carrying IP traffic are on demand established.**

We face the Routing and Wavelength Assignment problem considering as constraints the physical impairments that arise in all-optical wavelength routed networks. In particular, we study the impact of the physical layer when establishing a lightpath in transparent optical network. Because no signal transformation and regeneration at intermediate nodes occurs, noise and signal distortions due to non-ideal transmission devices are accumulated along the physical path, and they degrade the quality of the received signal. We propose a simple yet accurate model for the physical layer which consider both static and dynamic impairments, i.e., nonlinear effects depending on the actual wavelength/lightpath allocation. We then propose a novel algorithm to solve the RWA problem that explicitly considers the physical impairments.

Simulation results show the effectiveness of our approach. Indeed, when the transmission impairments come into play, an accurate selection of paths and wavelengths which is driven by physical consideration is mandatory.

I. Introduction

Wavelength Routed (WR) networks are considered the best candidate for the short-term implementation of a high-capacity IP infrastructure, since 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 are routed in the optical layer through the physical topology using a single wavelength (we do not assume to exploit wavelength conversion); at intermediate nodes, incoming wavelengths belonging to in-transit lightpaths are switched to outgoing fibers through an optical cross-connect that does not process in-transit information. At the IP layer, lightpaths are seen as data-link channels through which packets are moved from a router to another router toward their destinations following the classic IP forwarding procedure. Therefore, in a WR network, an *IP layer topology* (also called logical topology), whose vertexes are IP routers and whose edges are lightpaths, is overlayed to the *physical topology*, made of optical fibers and optical cross-connects (OXC). If the OXC node implementation requires opto/electronic conversions, the technology is usually called "opaque". Otherwise, if switching of lightpaths is fully performed in the optical domain, the term "transparent" is used. In this second case, the cost of switching a lightpath is almost independent on the transmission data-rate [1]. In this paper we consider the latter technology, which is also the most promising one.

Lightpaths can either be semi-permanent [2], or be allocated in on-demand fashion [3]. In the first case a static topology is seen at the IP layer, while in the second case more adaptivity can be gained at the cost of additional complexity both at the optical layer and the IP layer. In this paper we consider dynamically reconfigurable WR networks in which lightpaths are on demand established.

In classic WR networks that support the dynamic allocation of lightpaths according to user requests, the Routing and Wavelength Assignment (RWA) problem must be faced. Indeed, for each connection request, a route across the physical topology must be found, and a wavelength must be selected with the constrains that i) two (or more) lightpaths sharing the same fiber must be identified by two (or more) different wavelengths (also called "wavelength integrity constraint") and ii) a lightpath must be identified by the same wavelength on all the physical fibers along the path (also called "wavelength continuity constraint"). If such a path/wavelength exists, a point-to-point lightpath is established for the duration of the connection. On the contrary, the connection may be blocked given the limited number of wavelengths supported by fibers and OXCs. The goal of the RWA is therefore to minimize the connection blocking probability, and several algorithms have been proposed to address this problem [4].

RWA problem is a classic problem in the context of wavelength routed networks. However, despite several solutions have been proposed, most of them fail to consider the impact of the physical layer on the data transmissions. Indeed, in the definition of the RWA problem, only the *availability* of a wavelength is considered as constraint in the formulation of the problem itself. Considering opaque networks, this is

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a realistic assumption, as the optical signal is regenerated ad each node, and transmission impairments are therefore compensated at each node. But this is not anymore the case when transparent optical networks are considered.

In a transparent all-optical network, because no signal transformation and regeneration at intermediate nodes occurs, noise and signal distortions incurred due to non-ideal transmission devices are accumulated along the physical path, and they degrade the quality of the received signal. Noise accumulation actually decreases the Optical Signal to Noise Ratio ($OSNR$) increasing the corresponding Bit Error Rate (BER). Distortions due to fiber propagation modify the shape of the received pulse inducing performance impairments equivalent to a reduction of the $OSNR$. In this paper, besides considering the noise accumulation, we evaluate the impact of the linear and nonlinear fiber propagation with the purpose to obtain an equivalent $OSNR$ characterizing each lightpath of the considered transparent optical network. If for a certain lightpath the $OSNR$ is too low, the corresponding BER may exceed the maximum tolerable BER imposed by the transmission techniques employed. In that case the lightpath becomes not usable and such an information must be taken into account by the RWA algorithms. The $OSNR$ information can be also used as *soft* parameter giving a weight of the goodness of the a lightpath allowing to implement RWA algorithms based on the choice of the lightpath with the best $OSNR$ among all the usable ones.

In this paper, 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, for the first time to the best of our knowledge, 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.

In the remaining of the paper, Section II describes the physical layer model used to evaluate the transmission quality of a lightpath, including a brief comparison with related work. Section III focuses on the RWA algorithm adopted in this paper whose performance results are presented in Section IV. Finally, Section V summarizes our findings.

II. Physical model

In order to analyze the evolution of the electromagnetic 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. Since the optical fiber is a nonlinear medium, the wave equation that regulates the propagation is the so called Nonlinear Shroedinger Equation (NLSE) [5] whose expression is:

$$\frac{\partial A(z,t)}{\partial z} = -\alpha A(z,t) + \jmath \frac{1}{2}\beta_2 \frac{\partial^2 A(z,t)}{\partial t^2} - \jmath\gamma \left|A(z,t)\right|^2 A(z,t) \tag{1}$$

where $A(z,t)$ is the modal amplitude of the electromagnetic field propagating in the optical fiber, α is the fiber loss coefficient, β_2 is the dispersion coefficient, γ is the nonlinear coefficient, and z and t are the propagation direction and time, respectively. Note that $A(z,t)$ must include all the modulated signals associated to the wavelengths in use, because the nonlinear nature of the problem does not allow to solve separately - wavelength by wavelength - the signal propagation in optical fibers. Besides the model for the propagation of optical signals through the fiber, the other component that must be accurately considered is the optical amplifier, e.g., the Erbium-Doped Fiber Amplifier (EDFA). EDFA's are used to recover the fiber loss introduced by the fiber spans but impair the system performance by introducing a certain amount of noise, that is called Amplified Spontaneous Emission (ASE) Noise. Given the amount of gain G and the spontaneous emission factor n_{sp}, the power spectral density of noise introduced by the amplifier is [6]:

$$G_{ASE}(f) = 2\, n_{sp}(G-1)hf \tag{2}$$

where h is the Planck constant and f is the operation frequency.

The analysis presented in this paper is focused on the use of EDFAs to recover fiber attenuation, but it can be easily extended in order to include the use of the promising technology based on Raman Amplification [5], [6] or, in general, the use of mixed EDFA/Raman technologies [7].

As well as the transmission components, i.e., fiber and amplifiers, the transmitters and receivers should be modeled in order to include in the performance analysis their effects and potential system impairments.

The other network blocks to be modeled are the passive components such as filters, and, in general, all the elements performing optical network operations. For instance, the add-drop multiplexers and the optical cross-connects.

Due to the nonlinear nature of Eq. (1), the evolution of the optical signals along a transparent optical network should be studied as a single complex problem. Eq. (1) should be solved simultaneously for all the fiber links considering the boundary conditions, i.e., transmitters and receivers, and, in general, network nodes. Furthermore, Eq. (1) does not admit analytical solutions, therefore it must be integrated numerically using simulators that typically are based on the *Split-Step Fourier Method* [8], [9]. It means that the performance evaluation of a single network configuration could require a relevant computational effort, e.g., hours of CPU time with the present state-of-the-art computers. Hence, it is not possible to setup a RWA analysis that requires 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 introduced by the complexity of the exact analysis of the physical level of transparent optical networks, many approximated solutions were presented in the technical literature.

In [10], [11], the authors consider independently the impairments due to the effect of Polarization Mode Dispersion (PMD) and accumulated ASE noise. The authors considered the use of Raman amplifiers besides EDFAs. The analysis is done for each lightpath and they consider that lightpath performs well if both the requirements in terms of noise accumulation (ASE) and PMD are satisfied. In these works, the effect of fiber nonlinearities is not considered: it implies neglecting the fundamental trade off between increasing of transmitted power to overcome noise impairments and limiting the power to avoid the impact of nonlinearities. Similarly, in [12], [13] the authors considered only the impairments of optical ASE noise introduced by the in-line EDFAs and of electrical noise of the receivers. A different approach to the problem was presented in [14], the authors proposed to completely separate the transmission layer from control layer. The transmission layer was analyzed by the Optical Viability Engine (OVE) that gives to the control layer the binary information (connection viable or non-viable). The OVE can be a calculator, a rule-set or a complete simulator.

We target our analysis to the inclusion in performance evaluation of lightpaths the effect of accumulated ASE noise, linear and nonlinear propagation. To the best of our knowledge this is the first time nonlinear effects are included in the performance evaluation of physical layer of optical networks in order to drive the RWA algorithms with the physical impairments on each lightpath. The simplified model we propose is based on the separation of the effects impairing the signal propagation in order to evaluate the Optical Signal-to-Noise Ratio ($OSNR$) penalty induced by each effect. We start from the assumption that the performance in terms of Bit Error Rate (BER) of an optical link based on the optical amplification is well approximated by :

$$BER \approx \frac{1}{2}\mathrm{e}^{-\eta\,\mathrm{OSNR}} \tag{3}$$

where η is a coefficient assuming values in $[0, 1]$ that takes into account how close to the ideal one is the receiver used; $\eta = 1$ for the ideal receiver based on the optical filter matched to the transmitted pulse. Using Eq. 3 we neglected the influence of receiver electric noise. It is a reasonable assumption for optical networks based on the optical amplification, since the ASE noise is typically widely prevalent with respect to the electric noise. In case of studying networks without an extensive use of optical amplification, Eq. 3 can be replaced by a more complex one including the electric noise without varying the general structure of the presented analysis.

For the optimal receiver, the exact expression can be analytically derived and it is [15]:

$$BER = \frac{1}{2}\left\{\mathrm{e}^{-\phi}\left(1+\phi\right) + 1 - \mathrm{Q}_2\left(\sqrt{8\,\mathrm{OSNR}}, \sqrt{2\phi}\right)\right\} \tag{4}$$

where Q_2 is the Marcum Q-function of order 2 [15] and ϕ is the normalized decision threshold that must be optimized for each value of the $OSNR$. Eq. 3 derives from a fitting of Eq. 4 for optimal threshold and small (below 10^{-3}) BER. The $OSNR$ is given by:

$$OSNR = \frac{P_S}{P_N} \tag{5}$$

where P_S is the power of the modulated signal carrying the information and P_N is the overall power of the ASE noise introduced by the in-line optical amplifiers, i.e.,

$$P_N = \sum_{i=1}^{i=N_{span}} 2n_{sp,i}(G_i - 1)hfB_n \tag{6}$$

where M is the number of amplifiers for the lightpath under analysis, $n_{sp,i}$ is the spontaneous emission factor for the i-th amplifier, G_i is the gain for the i-th amplifier and B_n is the equivalent noise bandwidth of the receiver.

Using Eq. 3, BER of a lightpath is directly related to the $OSNR$. Therefore, if we define BER_{max} as the maximum error probability tolerable by the transmission technique used by the network under analysis, a lightpath can be considered as *in service* if presents a BER smaller than BER_{max}. Alternatively, the lightpath is *in service* if

$$OSNR \;>\; OSNR_{min} \;=\; \frac{1}{\eta}\ln\left(\frac{1}{2\,BER_{max}}\right)\,, \tag{7}$$

therefore, to distinguish between different lightpaths within the application of a RWA, the $OSNR$ is a parameter to be maximized in order to minimize the error rate. Furthermore, the use of a certain lightpath must be discarded if the related $OSNR$ results to be smaller than $OSNR_{\mathrm{min}}$. This approach is the one we followed in order to implement the RWA algorithms described in details in Sec. III.

In case of propagation impairments, besides the ASE noise accumulation, performance for each lightpath can be still evaluated using Eq. 3, substituting the Optical Signal-to-Noise Ratio with an *equivalent* coefficient $OSNR_{eq} < OSNR$ that wants to include the effects of the considered impairments. Therefore, the expression of $OSNR_{eq}$ in dB units can be described as follows:

$$OSNR_{eq,dB} = OSNR_{dB} - OSNR_{pen,l} - OSNR_{pen,nl} \quad (8)$$

where $OSNR_{dB}$ is 10 times the logarithm of the $OSNR$ value due to the ASE noise accumulation expressed in dB units. $OSNR_{pen,l}$ and $OSNR_{pen,nl}$ are the penalties - expressed in dB units as well - introduced by the linear (dispersion, PMD) and nonlinear (Kerr effect) propagation effects [5], [16], respectively. $OSNR$ penalties are caused by the pulse distortions induced by the propagation effects that impairs the decision signal - eye-diagram closure - inducing a performance impairments equivalent to a certain amount of extra noise. Either ASE noise accumulation, either the eye-diagram closure due to the propagative linear effects act separately on different wavelengths, independently of the number of wavelengths in use on the fiber span under analysis. Therefore, $OSNR_{dB}$ and $OSNR_{pen,l}$ depend only on the path π and on the wavelength λ (static network configuration), while $OSNR_{pen,nl}$ depends also on the number of wavelengths N_{λ} actually turned on - for the considered network configuration - per each fiber span used by the lightpath λ (dynamic network configuration). It means that the overall $OSNR_{eq,dB}$ function must be evaluated for each lightpath for each possible network configuration and not just for each lightpath independently of the network configuration. It is clearly understandable how the problem complexity dramatically grows with the inclusion of the propagation nonlinear effects.

A rigorous analysis of the physical effects on the performance of an optical network should require the simulation of the entire network for every possible configuration that the RWA algorithms may take into account. As previously explained, such a task should require millions of hours of computation time. Hence, we decided to evaluate separately the ASE noise accumulation, the impairments of linear effects and the impairments of nonlinear effects. Here is the description of the approximations we used in order to derive the impairments due to the considered effects.

- *ASE Noise accumulation.*
  The graph describing the network is analyzed in order to individualize the amplifiers, fiber losses, and lumped losses. Then, for each physical path, the accumulated ASE noise is evaluated together with the signal level. As a result, each lightpath is targeted with the corresponding $OSNR_{ASE}$.
- *Impairments of linear propagation effects.*
  In order to evaluate the impairments of linear effects (PMD and dispersion), for each lightpath the amount of accumulated dispersion and PMD is evaluated. Then, penalties are evaluated according to the results presented in [16], [17]. If the dispersion compensation is applied and the overall PMD is small with respect to the bit duration, impairments of linear propagation effects can be neglected. In general from the analysis of linear propagation the penalty $OSNR_{pen,l}$ is derived. In case of linear effects negligible, $OSNR_{pen,l} = 0$ dB.
- *Impairments of nonlinear propagation effects.*
  Nonlinearities in optical fibers are caused by the physical effect called *Kerr Effect*. Its effect is a locale change of the refractive index as a function of the overall propagating optical power. *Kerr effect* induces well know impairments on the propagating signal that can be classified as [5], [16]: Self Phase Modulation (SPM), i.e., the modulation of the phase of a signal induced by variation in time of the power of the signal itself; Parametric Gain (PG), i.e., the transfer of power from a signal to the adjacent spectral components; Cross-Phase Modulation (XPM), i.e., the modulation of the phase of a signal induced by variation in time of the the overall power of the comb of WDM channels propagating in the fiber; Four Wave Mixing (FWM), i.e., the generation of spurious tones at new frequencies. In commercial WDM systems, the nonlinear limiting effect is typically the XPM [18], [19], [20], [21]. Therefore, we focus our attention in the evaluation of the $OSNR$ penalty due to the XPM. In order to pursue such a target, we assume that this penalty is a monotone increasing function with number of wavelength actually in use on the fiber and with power per channel. Whereas we assume it decreases with the increasing of dispersion and channel spacing. These are well known general behaviors, but the exact expression of the function is not known. Therefore, we performed a series of Monte-Carlo simulations on a defined test-link using the optical system simulator *OptSim*^{TM} [22] [1]. 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. This function was actually a look-up-table derived from simulations. Using *OptSim* we evaluated the interference due to the non linear effect in several situations. We propagated an un-modulated (continuous wave) channel together with N_{ch} modulated channels, with $N_{ch} = 2, 4, 6, ..., 32$. We varied the channel power, channel spacing and dispersion. Furthermore, we carried out Monte-Carlo simulations in order to average the results with respect to the bit sequences and bit-edge alignments. The

[1] Note that *OptSim*^{TM} uses a propagation numerical model called *Time-domain split-step method* [8], [9], that is the time domain implementation of the well-know *Split-Step Fourier Method [5].*

resulting interference, as expected, was a monotone ”logarithm like” function with respect to the number of channels, whereas the interference decreases with the increasing of dispersion magnitude and channel spacing, and increases with the increasing of channel 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 for each fiber and with their spectral assignments. In the evaluation of non linear impairments we always considered the worst case situation in terms of channel spacing, i.e., given the number of channel turned on a fiber span, we considered that all the channels were uniformly spaced with the minimum channel spacing.

Considering the separate evaluation of impairments due to the considered effects, for each possible lightpath of the network, the physical layer analysis was able to provide to the RWA algorithms a function $OSNR(\pi, \lambda) = OSNR_{ASE} - OSNR_{pen,l} - OSNR_{pen,nl}$. The value of such a function, given a path π and a wavelength λ, is a constant for a static network, while changes in case of dynamic re-configuration of the network because it depends also on the number of wavelengths actually in use on each fiber span.

III. RWA ALGORITHMS

To gauge the impact of physical impairments on the RWA solution, we compare the performance of traditional RWA algorithms to the one obtained by a novel algorithm which considers the physical impairments when solving the RWA problem. We first describe traditional algorithms while also introducing the notation, and then describe the novel algorithm.

A. Traditional Algorithms

To solve the RWA problem, we selected two algorithms that were shown to give good performance: the *First Fit-Minimum Hop* (FF-MH) and *First Fit-Least-Congested* (FF-LC) [4]. These are traditional algorithm, 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.

In more details, when searching for available wavelengths on a given path, a First-Fit strategy is used: a lower numbered wavelength is considered before higher numbered wavelengths, and the first available wavelength is then selected by both algorithms.

As regards the path selection, for each source/destination pair, the FF-MH algorithm considers only one possible path, which has been preselected to be the minimum hop path. In case more than one minimum hop path is present between the same source/destination pair, only one is considered (in particular, the first minimum hop path found is selected). Dijkstra algorithm can be used to obtain the minimum hop path.

The FF-LC algorithm, instead, considers a pre-ordered list of available paths for each source/destination pair. Paths are dynamically sorted, so that always the least congested path is tested first. The “congestion” metric counts the number of wavelengths already used on a fiber, so that the path with the largest number of unused wavelengths is chosen. In case more than least congested path exists, (one at random among) the shortest path will be selected For the purpose of providing a formal description of the algorithms, we use a standard graph theory formalism. Thus, we refer to the generic physical network as a directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of vertexes (nodes, in our case), and $\mathcal{E}$ is the set of edges (links)[2].

A path $\pi(s, d)$ of length $n(\pi(s, d)) = ||\pi(s, d)||$ is defined as a sequence of n distinct edges e_i joining s and d, where $s, d \in \mathcal{V}$, $e_i \in \mathcal{E}$, $\pi(s, d) = \{e_1, e_2, ..., e_n\}$.

Let $\Pi(s, d) = \{\pi_i(s, d)\}$ be the set of available loop-free paths from node s to node d. Let $W(e_i)$ be the number of wavelength already allocated on link e_i.

Given those definitions, the Minimum Hop routing will select the path $\pi^{MH}(s, d)$ such that

$$\pi^{MH}(s, d) = \min_{\pi \in \Pi(s,d)} n(\pi)$$

On the contrary, the Least Congested path $\pi^{LC}(s, d)$ will be selected such that:

$$\pi^{LC}(s, d) = \min_{\pi \in \Pi(s,d)} \left(\max_{e_i \in \pi}(W(e_i)) + \frac{1}{c} n(\pi) \right)$$

The constant c must be selected such that

$$c > \max_{\pi \in \Pi(s,d)} (n(\pi))$$

Notice that the MH path selection can be performed off-line, being $n(\pi)$ constant with respect to wavelength allocation. On the contrary, the implementation of the LC path selection criterion requires each route to be selected for each lightpath request, thus entailing a much larger complexity, both in term of computational power and signaling.

Once a path has been selected, the wavelength allocation is performed using the first-fit approach by both algorithms. Let $\Lambda(e_i) = \{\lambda_j, j = 1, \ldots, L\}$ be the ordered set of supported wavelength on link e_i. Let $F(\lambda_j(e_i))$ take the value 0 if the j-th wavelength is free on link e_i, 1 otherwise. Then, the set $\mathcal{F}$ of available wavelength on path $\pi(s, d)$ is defined as

$$\mathcal{F} = \{\lambda_j \text{ such that } F(\lambda_j(e_i)) = 0 \ \forall e_i \in \pi(s, d)\}$$

[2]In this paper we interchangeably use the terms ‘edges’ and ‘links’ and the terms ‘vertexes’ and ‘nodes’.

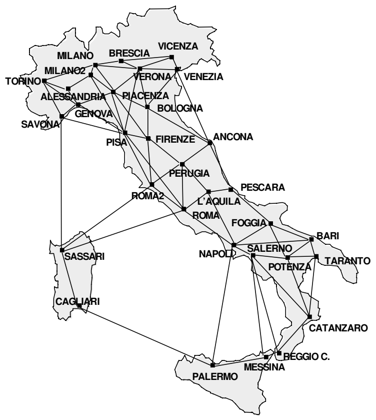

Fig. 1. Physical topology.

Then, lightpath request will be allocated using wavelength $\hat{\lambda}$ on path $\pi(s,d)$ such that:

$$\hat{\lambda} = \min_{j}(\lambda_j \in \mathcal{F})$$

B. B-OSNR algorithm

Traditional algorithms fails to consider the physical impairments that may affect the transmission on a given path/wavelength. We therefore 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. Let $OSNR(\pi(s,d),\lambda_j)$ be the OSNR on wavelength λ_j on path $\pi(s,d)$. $OSNR(\pi(s,d),\lambda_j) = -\infty$ if λ_j is not usable on path $\pi(s,d)$. Then, the path $\pi^{OSNR}(s,d)$ and the wavelength λ^{OSNR} will be selected such that:

$$(\pi^{OSNR}(s,d),\lambda^{OSNR}) = \max_{\pi\in\Pi(s,d)}\left(\max_{\lambda\in\Lambda} OSNR(\pi,\lambda)\right)$$

As can be noticed, the B-OSNR algorithm *jointly* assigns a path and a wavelength to a given lightpath request. Its complexity grows linearly with the number of paths and the number of wavelengths that must be checked to find the best solution.

IV. Performance Analysis

To gauge the impact of the physical constraints on the routing and wavelength assignment, we developed a simulator which implements all the RWA algorithms described in the previous section, and performs the evaluation of the OSNR as described in Section II. To this purpose, the description of the physical topology by means of a graph $\mathcal{G}$, which includes the definition of fibers, amplifiers, optical cross connects, etc., is given as input. In particular we assumed that the network is cabled using Non-Zero Dispersion Shifted fibers. In order to recover fiber losses we considered to use EDFAs spaced L_{span} km that perfectly recover the loss introduced by the fiber span. We supposed the employed EDFAs are perfectly spectrally equalized and have flat transfer functions, providing the same amount of gain for all the wavelengths. We explored different scenarios analyzing the network behaviors for L_{span} = 40, 60, 80 km. We assumed to use dispersion compensation techniques and that the PMD effect is negligible at the supposed bit-rate of 10 Gbit/s. Therefore, we supposed to be negligible the propagation linear effects focusing our analysis on considering the limiting effects of noise accumulation and impairments of fiber nonlinearities. Regarding the effects of passive components performing network operations within the nodes (filters, add-drop multiplexers, optical cross-connects, etc...) we considered the extra losses that they introduce. We did not include they filtering effect.

A description of the traffic pattern completes the scenario whose performance indexes will be analyzed during the simulation. The traffic description includes a traffic matrix $T = \{t_{s,d}\}$ whose elements $t_{s,d}$ represent the fraction of lightpath requests from node s to node d. Lightpath requests are generated according to a Poisson process of rate $\rho t_{s,d}$, in which ρ represent the average arrival rate in connection per seconds. Connection holding time is exponentially distributed, with average set to 1 which therefore fixes the time reference in the simulation.

Once a connection request is generated, the corresponding RWA problem is solved according to the selected algorithm. If a path π and a free wavelength λ are available, the corresponding OSNR is evaluated, and if it is above to a given $OSNR_{\min}$ threshold, then the lightpath is accepted, and the corresponding λ is allocated on all links of path π. Otherwise, the lightpath request is blocked and no reservation occurs. Allocated resources will then be released at the end of the connection lifetime.

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 $P_b = P_b^{OSNR} + P_b^{\lambda}$.

In the simulation result reported in this paper, we considered as physical topology the Italian Optical Network sketched in Fig. 1 which was derived from a possible evolution of the Telecom Italia network topology. Nodes reflect the real position of cities and link lengths reflect the

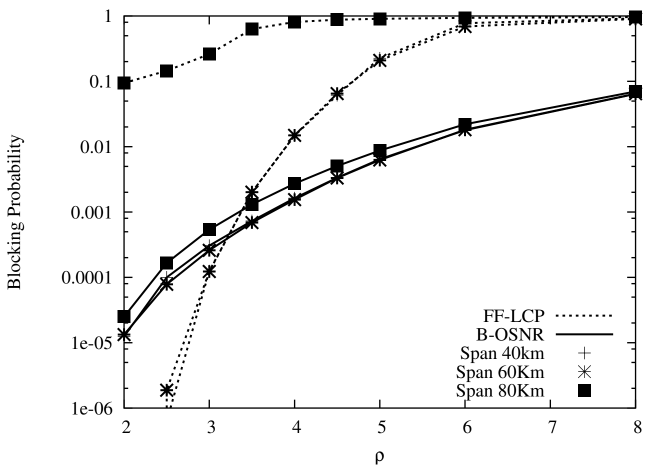

Fig. 2. Total average blocking probability versus offered load for different algorithms. Fiber span (L_{span} of 40 km, 60 km, 80 km are presented.

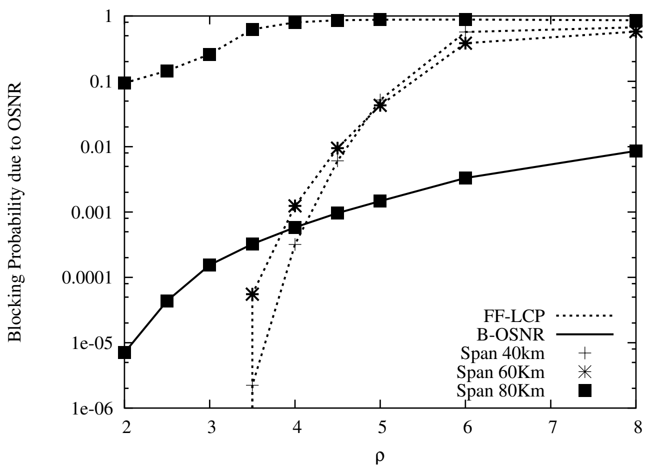

Fig. 3. Average blocking probability due to OSNR impairment versus offered load for different algorithms. Physical span of 40 km, 60 km, 80 km are presented.

real distances among cities. All fiber and nodes are assumed to be physically equal. Maximum number supported wavelength L is set to 16.

We consider three different physical configurations, which differ by the maximum *span* of fibers that is admissible without requiring regeneration, i.e, the maximum length of optical fiber between two adjacent amplifiers. In particular, spans of 40 km, 60 km, 80 km will be considered. The longer is the fiber span, the larger is the amount of gain required to recover fiber losses. Hence, the larger is the amount of noise introduced by the amplifiers. To restore the target $OSNR$ a larger amount of transmitted power can be employed, but with the increasing of transmitted power the effect of nonlinearities progressively grows inducing a stronger impairment on performance.

Regarding the traffic pattern, we consider in this paper a simple uniform traffic, in which all $t_{s,d} = 1$. We set $OSNR_{\min} = 20dB$, corresponding to $BER = 10^{-12}$ with an $OSNR$ margin of about 4 dB. During the path search phase, the sets $\Pi(s,d)$ are build by considering only those paths whose minimum OSNR is larger than $OSNR_{\min}$. The minimum OSNR of a given path is evaluated by not considering the nonlinearities, i.e., by considering $OSNR(\pi,\lambda)$ when no other lightpaths is established on any other paths. A limited number of path is considered for each source destination pair, so that the complexity of finding π^{LC} and π^{OSNR} is limited: paths in $\Pi(s,d)$ are sorted in decreasing number of hops, and then only the first 30 paths are considered [3].

Finally, to get accurate results, each simulation was ended when the performance indices were such that the 95% confidence interval was within 5% of the point estimate.

[3]We considered larger sets of paths, but without observing major differences on the results.

A. Blocking probability

In Figures reported in this section, dashed lines refers to the blocking probability obtained when the FF-LC algorithm is considered, while solid lines report results considering the B-OSNR. Different points are used to highlight different span values.

Figure 2 plots the average blocking probability versus offered load. Comparing the results obtained by the FF-LC or the B-OSNR algorithm, 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 80km, the B-OSNR algorithm clearly outperforms the FF-LC approach.

The intuition behind this is that the better allocation of wavelength used by the FF approach tends to better pack wavelength usage so that the change of obtaining a free wavelength is larger. On the contrary, the wavelength allocation performed by the B-OSNR algorithm tends to spread out the wavelength as much as possible, so to minimize the noise introduced by adjacent channels. This leads to a larger blocking probability when the cause of blocking is due to lack of wavelength.

On the contrary, for larger values of the offered load, the effects due to nonlinearities clearly affect the blocking probability faced by a FF-LC algorithm. Indeed, its more compact wavelength allocation criterion maximizes the noise due to interfering wavelengths. Therefore, when the

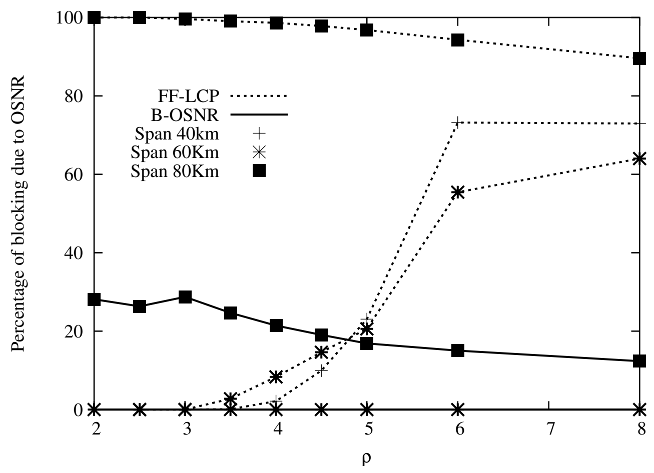

Fig. 4. Percentage of blocking probability due to OSNR degradation versus offered load for different algorithms. Physical span of 40km, 60km, 80km are presented.

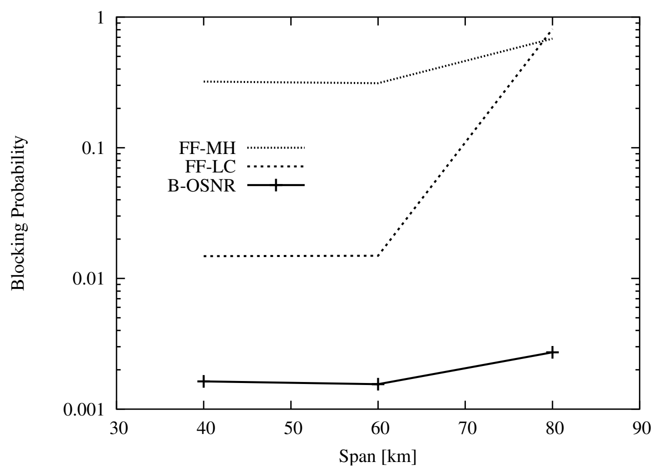

Fig. 5. Total average blocking probability versus physical span for different algorithms. Offered load set to 4.

blocking probability is largely due to physical impairments, the FF-LC algorithm cannot find any good solution.

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 present almost identical results when 40km and 60km span long networks are considered, while the 80km span network performance are much worse. This is due to the path selection choice, which allows the FF-LC algorithm to select longer paths which will cause larger transmission noise that will be accumulated along the path itself, finally resulting in a blocked lightpath due to lack of OSNR.

To better highlight this effects, Figure 3 plots the blocking probability due to physical impairments. Considering the 40km and 60km span, the B-OSNR presents no blocking due to lack of OSNR, while the FF-LC algorithm shows a steep increase of the blocking probability due to transmission impairments. This confirms the intuition the the nonlinearities faced by the FF-LC wavelength allocation (and path selection) are the largest cause of blocking.

Similarly, considering the 80km span long network, the FF-LC algorithm is not able to find any suitable path and wavelength solution to the RWA problem even when the nonlinearities are small, i.e., when then offered load is small so that few lightpath are present at the same time.

Finally, to gauge the ratio between the blocking due to wavelength lack or to OSNR lack, Figure 4 plot the percentage of blocking probability due to OSNR degradation versus the offered load. 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.

To better observe the effect of nonlinearities on the blocking probability, Figure 5 plots the total average blocking probability versus the span for offered load equal to 0.4. The plot also reports results considering the FF-MH algorithm. Its performance are in general limited when compared to algorithms that allow to test more than a single path, as already well-known [4]. The B-OSNR algorithm presents the best results, about one or two order of magnitude better than results presented by classic algorithms which fail to consider physical impairments.

In particular, considering span smaller than 80km, the static impairments due to the physical layer are negligible, as no major differences are observed moving from 40km long span to 60km long span physical configuration. Increasing the span length to 80km, on the contrary the blocking probability of the FF-LC algorithm increases. This performance downgrade is largely due to the selection of possibly longer and more noisy paths. The FF-MH algorithm is little affected by this, as it always select the minimum hop path which in general is also the shortest one and therefore the one which presents the smaller noise due to linear effects. Still, a little increase in the blocking probability is due to the smaller static OSNR ratio which, combined with the nonlinearity noise, increases the chance of observing a OSNR larger then $OSNR_{\min}$.

V. Conclusions

In this paper we considered a transparent optical network. By using wavelength routed technology, we considered the routing and wavelength assignment problem under transmission impairments. We considered a dynamic scenario, in which lightpath requests arrive and leave the network. Because in transparent optical network no signal transformation and regeneration at intermediate nodes occurs, noise and signal distortions due to non-ideal transmission devices are accumulated along the physical path, and they degrade the quality of the received signal. This affects the availability of the optical channel, and therefore must be considered during the RWA solution. 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 comes 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 fails to consider the physical impairments.

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