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On the Impact of Lightpath Rerouting on Connection Provisioning with Transmission Impairments in WDM All-Optical Networks

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ABSTRACT

In transparent optical networks, signals can propagate over long distances without electrical regeneration, causing physical layer impairments to accumulate and make lightpaths' Quality of Transmission (QoT) become potentially unacceptable. Depending on the channel load and transmission distance some paths cannot be set up fully transparently because the transmission quality requirements (i.e. pre-FEC Bit Error Rate (BER) = 10^{-9} or Q-factor = 15.56 dB) cannot be fulfilled. This result might have a severe consequence on the performance of all-optical networks especially in terms of rejection ratios. In this paper, we propose a new lightpath rerouting algorithm to optimize network resources allocation in WDM all-optical networks in order to set up an incoming lightpath demand to be blocked for lack of resources or due to the absence of a suitable path and a suitable wavelength that meet the minimum QoT requirements. Rerouting aims at reassigning the wavelength and/or the path of one or several established connections in order to free enough wavelengths to satisfy the incoming demand. Rerouting refers implicitly to dynamic traffic. Simulation results show that our algorithm improves the rejection ratio and is less CPU time consuming than rerouting algorithms previously presented in the literature.

Keywords: *All-optical WDM networks, Routing and Wavelength Assignment (RWA), Lightpath ReRouting, Wavelength Continuity Constraint, Transmission Impairments, Quality of Transmission (QoT).*

1. INTRODUCTION

Wavelength Division Multiplexing (WDM) is the technology currently deployed to increase transmission bandwidth in optical networks. With bit rates of 2.5 Gigabit per second (Gbps) and 10 Gbps per channel currently being used, products with increasingly higher bit rates of 40 Gbps are beginning to appear on the horizon of optical systems. Transparent WDM also called all-optical WDM systems have the advantage of being independent of data format and bit rate so they are able to transport different protocols such as Synchronous Digital Hierarchy (SDH), Synchronous Optical Network (SONET), Internet Protocol over Wavelength Division Multiplex (IP over WDM), and Gigabit Ethernet (GE) [1].

In such networks, any connection request to be set up from a source node to a destination node (also called a lightpath) is subject to two main constraints: the former is called the wavelength continuity constraint and states that a lightpath should occupy the same wavelength on all the fiber-links it traverses on the route between the source and destination node pair [2]. The latter prohibits two lightpaths to use the same wavelength when they share at least one common fiber-link to prevent the interference of the optical signals. This constraint is called the wavelength contention constraint [3]. The problem of establishing lightpaths with the objective of optimizing the utilization of network resources is known as the Routing and Wavelength Assignment (RWA) problem also called the Lightpath Provisioning problem [4]. Many surveys have been carried out to investigate the RWA problem (see among others [4][5][6])..

In addition to the two aforementioned constraints, a third constraint cannot be neglected anymore. This constraint is related to the lightpaths' Quality of Transmission (QoT) which might become potentially unacceptable when the optical signal propagate through long distances. Indeed, in all-optical WDM networks, no signal regeneration at intermediate nodes is allowed. Thereby, noise and signal distortions incurred due to non-ideal transmission devices accumulate along the physical path. Since these impairments continue to degrade the signal quality as it progresses toward its destination, the received Bit Error Rate (BER) at the destination node might become unacceptably high [2][7][8].

Taking into account physical impairments, wavelength continuity constraint and wavelength contention constraint when solving the RWA problem leads to inefficient utilization of network resources and results in higher rejection ratios. Lightpath ReRouting (LRR) is a viable and cost effective solution to improve the network throughput conditioned by the aforementioned constraints. The main objective, in this paper, consists in maximizing the number of established Lightpath Demands (LD) satisfying the required QoT for a given physical network topology with a fixed number of wavelengths per fiber-links. LDs are assumed to be with random arrivals and departures. These LDs are referred to as RLDs. Four main transmission impairment effects are considered, namely Chromatic Dispersion (CD), Polarization

Mode Dispersion (PMD), Optical Signal to Noise Ratio (OSNR) and Nonlinear Phase Shift (φ_{NL}).

The rest of the paper is organized as follows. Section 2 describes briefly the investigated problem and presents related work. In Section 3, we present the four QoT parameters considered in this paper. In Section 4, we give the method we used to estimate the QoT of an optical signal, while, in Section 5, some notations are given. Section 6 presents in details our proposed lightpath rerouting algorithm. The results of the simulations carried out in order to highlight the efficiency of our algorithm are presented and analyzed in Section 7. Section 8 gives our conclusion and future work.

2. DESCRIPTION OF THE PROBLEM AND RELATED WORK

Considering the impact of physical layer impairments when dealing with the RWA problem is, recently, attracting more attention. Actually, several ongoing research studies [8], [10], [11], [12], [13] have pointed out the need for considering transmission impairments when solving the RWA problem in order to make the obtained solution more effective. Indeed, increased bandwidth means more data per unit time but also more impairments through higher power and increased channel counts. The higher the power and channel counts the more impairments become analog characteristics. Impairments for optical systems can be categorized into linear and non-linear effects [14]. There is some relation between limiting effects in optical systems and the optical power or number of wavelengths used. With less optical power and a lower number of channels the system performance suffers mainly linear effects. Linear impairment effects, such as noise of Erbium-Doped Fiber Amplifier (EDFA) and switches crosstalk investigated in [8] and [10], are generally considered as the predominant factors inducing signal degradation when evaluating network performance in low-speed transmission systems [9]. With higher optical power and more channels, non-linear effects play an increasingly significant role and could not be ignored anymore. Four-wave mixing (FWM), which was considered in [15], and Self-Phase Modulation (SPM) whose effect on network cost was investigated in [7], are some of the important nonlinear impairments affecting transmitted signal quality. Taking into account physical layer impairments should lead to lower network performance especially in terms of rejection ratios. That is why, we here propose to use rerouting to alleviate the effect of considering these impairments.

Rerouting (or repacking) is a concept originally introduced in the design of circuit-switched telephone networks [16][17]. It has also been applied to optical WDM networks recently to alleviate the effect of the wavelength continuity constraint when there is no wavelength conversion [18][19][20][21]. Rerouting occurs when an incoming LD is about to be rejected. It aims at rearranging a certain number of existing lightpaths to free one or several wavelengths for the incoming LD. There are two ways to rearrange an existing lightpath [22]. One is partially rearranging, which keeps the original path of the lightpath to be rerouted but reassigns a different wavelength to the fiber-links along the path. This is also referred to as Wavelength ReRouting (WRR). Another is fully rearranging, which consists in finding a new path with another wavelength to replace the old path. This latter one is referred to as Lightpath ReRouting (LRR). A comprehensive survey of rerouting techniques can be found in [23]. We focus on Lightpath ReRouting (LRR) strategies in rest of the paper. In [18][19], Lee and Li presented a wavelength rerouting scheme called Move-To-Vacant Wavelength-Retuning (MTV-WR). The main concern of this algorithm is to minimize the rejection ratio and the service disruption time. This algorithm is referred to as RRAlgo1. In [20], Mohan and Murthy proposed a time optimal wavelength rerouting algorithm based on the Parallel MTV-WR rerouting scheme. This second algorithm is referred to as RRAlgo2. In [24] and [25] Koubàa and al. later proposed an algorithm to improve the rejection ratio when scheduled and random lightpath demands are considered. This third algorithm is referred to as RRAlgo3. As mentioned before, all these studies, considered rerouting in order to alleviate the impact of the wavelength continuity constraint and assuming perfect physical layer conditions. To the best of our knowledge, this is the first attempt to use rerouting to maximize the number of established LDs satisfying the required quality of transmission (QoT) given a network topology with a fixed number of wavelengths on each fiber-link. The performance of our Impairment-Aware Lightpath ReRouting algorithm is demonstrated to be promising through simulation results.

3. PHYSICAL LAYER IMPAIRMENTS

Physical layer transmission impairments such as Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD), Optical Signal to Noise Ratio (OSNR), and NonLinear Phase shift (φ_{NL}) degrade the signal level in an optical fiber. These impairments limit the distance reached by the optical signal with acceptable Bit Error Rate (BER).

To investigate the impact of the aforementioned transmission impairments, we adopted the configuration illustrated in Figure 1 to model an all-optical WDM transmission system. We call a fiber-link the set of fiber-spans connecting two adjacent nodes in the network. Each fiber-span is composed of a single mode fiber (SMF) and an amplification site. Each amplification site, used to compensate fiber absorption losses, is composed of Erbium-doped fiber amplifier (EDFA) and a section of compensating dispersion fiber (DCF). Transmitted signals are modulated onto different wavelengths around the 1550 nm wavelength by transponders placed in every node in the optical system.

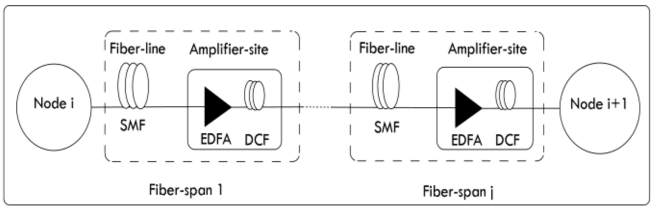

Figure 1: Typical configuration of a WDM transmission system

In the following subsections, we discuss the aforementioned four main quality of transmission parameters.

A. Chromatic Dispersion (*CD*)

The velocity of propagation of light in the core of an optical fiber depends on its wavelength. The degradation of lightwaves is caused by the various spectral components present within the wave, each traveling at its own velocity. The disparity in propagation velocity causes an optical pulse broadening in the time domain [28][29]. This phenomenon is called Chromatic Dispersion (*CD*). Many techniques exist to overcome the losses induced by *CD* in optical networks. One of these techniques consists in placing dispersion-shifted fiber (DSF) at every fiber-line. The *CD*s power penalty is given by Equation 1 [14]:

$$EOP_{DC} = 10\log\left(\sqrt{1+\left(DL\frac{\sigma_\lambda}{\sigma_0}\right)}\right) \qquad (1)$$

Where σ_0 is the pulse width, σ_λ is the spectral width, L is the fiber-line length and D represents the dispersion parameter characterizing the single mode fiber (SMF) used in the transmission system.

B. Polarization Mode Dispersion (*PMD*)

The fiber is not truly a cylindrical waveguide. Thus different polarizations of the analog propagate through the fiber with different velocities. This causes pulse broadening in the frequency domain often called polarization mode dispersion (*PMD*) [30]. The *PMD* at the end of the communication channel (destination node) is computed as given by Equations 2 and 3 [14]:

$$PMD_{link} = \left(\sum_{f\in spans}\left(PMD_{span}(f)\right)^2\right)^{\frac{1}{2}} \qquad (2)$$

$$PMD_{path} = \left(\sum_{f\in links}\left(PMD_{link}(f)\right)^2\right)^{\frac{1}{2}} \qquad (3)$$

Thus, the PMD's power penalty is evaluated according to Equation 4.

$$EOP_{PMD} = 5.1\left(\frac{PMD_{path}}{T_B}\right)^2 \qquad (4)$$

Where T_B is the bit time.

C. Optical Signal to Noise Ratio (*OSNR*)

Obviously, optical amplifiers enhance the transmission distance but they affect transmitted signal quality by their own component of noise known as amplified spontaneous emission (ASE). The OSNR, which represents the ratio of the average signal power to the average noise power, is the parameter used to evaluate the degradation due to ASE noise. The OSNR of each amplifier stage is computed as follows [28]:

$$OSNR_{span} = \frac{P_s}{P_{ASE}} = \frac{P_s}{NF_{stage}h\nu\Delta f} \qquad (5)$$

Where NF_{stage} is the noise figure of the stage, h is Plank's constant, ν is the optical frequency and Δf represents the bandwidth that measures the NF.

The final *OSNR* computed along a fiber-line composed of *M* amplifier stages is obtained according to the following Equation [28]:

$$\frac{1}{OSNR_{final}} = \sum_{1\le i\le M}\left(\frac{1}{OSNR_i}\right) \qquad (6)$$

D. Nonlinear Phase Shift φ_{NL}

The response of optical fibers to the light becomes nonlinear under strong optical intensity. In fact, the refractive index of an optical fiber has a strong nonlinear component that depends on the signal power level. Thus, enhancing the intensity of the optical signal propagating through the fiber raises the fiber nonlinearities which create a nonlinear phase shift φ_{NL} [30]. That is due to the interaction of optical amplifiers, used to compensate for fiber loss, and to the fiber Kerr effect. The nonlinear phase shift φ_{NL} is given by the Equation 7 [28]:

$$\varphi_{NL} = \gamma P_{in}\left(\frac{1-e^{\alpha L}}{\alpha}\right) \qquad (7)$$

Where α is the attenuation parameter and γ the nonlinear coefficient given by the following Equation:

$$\alpha = \frac{\eta_2\omega_0}{cA_{eff}} \qquad (8)$$

η_2 represents the cladding index while A_{eff} is the area of cross-section of the fiber core and ω_0 and c are respectively the frequency and the light velocity.

4. QUALITY OF TRANSMISSION COMPUTATION

The QoT, in WDM all-optical networks, is generally evaluated in term of BER. Generally, the required value of BER in optical networks is varying between 10^{-9} and 10^{-12}. Determining the BER value instantaneously may be sometimes difficult. That's why, another factor called Q-factor is used to estimate the QoT in the network. Equation 9 shows the relationship between Q-factor and BER [26], [27].

$$BER = \frac{1}{2}erfc\left(\frac{Q}{\sqrt{2}}\right) \qquad (9)$$

Where

$$erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^{+\infty} e^{-t^2}dt \qquad (10)$$

Since $erfc$, the complementary error function, is a decreasing function, the higher the Q-factor the lower the BER the better is.

To provide a qualitative description of the QoT in the network we have to evaluate the Q-factor considering *CD*, *PMD*, *OSNR*, and φ_{NL} parameters described above. The Q-factor is evaluated according to the following expression [31]:

$$Q = \left(\sqrt{\frac{OSNR\ \Delta f_{opt}\ EXTP}{EOP_{DC}\ EOP_{\varphi_{NL}}\ \Delta f_{elect}}}\right)\frac{1}{EOP_{PMD}} \qquad (11)$$

Where Δf_{opt} is the optical bandwidth, Δf_{elect} is the electrical bandwidth and *EXTP* is the extinction ratio which represents the ratio between the "one" level and the "zero" level.

5. NOTATIONS

We use the following notations and typographical conventions:

- $\boldsymbol{G = (\upsilon, E, \vartheta)}$ is an arc-weighted symmetrical directed graph representing the network topology with vertex set (representing the network nodes), arc set E (representing the network fiber-links) and weight function $\vartheta: E \rightarrow \mathbb{R}_+$ mapping the physical length of the links (or any other cost of the links set by the network operator).
- $\boldsymbol{N = |\upsilon|,\ L = |E|}$ are respectively, the number of nodes and links in the network.
- $\boldsymbol{D}$ is the total number of RLDs arriving at the network to be set up.
- $\boldsymbol{W}$ denotes the number of available wavelengths (i.e., optical channels) per fiber link. We assume that all the network links have the same number of available wavelengths.
- $\boldsymbol{\Lambda = \{\lambda_1, \lambda_1, \ldots, \lambda_W\}}$ is the set of available wavelengths on each fiber link of the network.
- The i[th] RLD, $1 \leq i \leq D$ (to be established), is defined by a 5-tuple $(s_i, d_i, \pi_i, \alpha_i, \beta_i)$. $s_i \in \upsilon$ and $d_i \in \upsilon$ are the source and the destination nodes of the lightpath demand, respectively; π_i is the number of requested lightpaths; and α_i and β_i are the setup and tear-down time of the lightpath demand, respectively. For the sake of simplicity, we here assume that, for each RLD, only one lightpath is required between the source and the destination nodes of the request ($\pi_i = 1$). This scheme can be generalized to consider traffic requests with a required number of lightpaths π_i ($\pi_i > 1$) by considering π_i simultaneous traffic requests between the same source and destination nodes with one required lightpath each.
- $\boldsymbol{P_{i,k}}$, $1 \leq i \leq D$, $1 \leq k \leq K$ represents the k[th] alternate shortest path in G connecting node s_i to node d_i (source and destination of the *i*[th] lightpath demand). We use the hop count as the link metric and compute beforehand K-alternate (loop-free) shortest paths for each source-destination pair according to the algorithm described in [32] (if as many paths exist, otherwise we only consider the available ones).
- $\boldsymbol{P_i}$, $1 \leq i \leq D$, is the set of alternate shortest paths computed between the source and destination nodes of RLD number i. Hence $|P_i| \leq K$. This computation is done in a preliminary step prior to any routing.
- $\boldsymbol{P}$ is the set of alternate shortest paths computed between the source and destination nodes of each possible node pair in the network. Clearly $|P| \leq N(N-1)K$.
- $\boldsymbol{c(i, kw, t)}$, $1 \leq i \leq D$, $1 \leq k \leq K$, $1 \leq w \leq W$ is the cost of using wavelength λ_w on the k[th] alternate shortest path in G from node s_i to node d_i of RLD i at time t. The cost function of each considered path is determined as follows:

$$c(i,k,w,t) = \begin{cases} \varepsilon & \text{if } \lambda_w \text{ is free on } P_{i,k} \\ +\infty & \text{otherwise} \end{cases}$$

  ε is a tiny positive value corresponding to the hop count on path $P_{i,k}$.
- $\boldsymbol{Q(i,k,w)}$ denotes the Q-factor of wavelength λ_w on the *k*[th] alternate path, $P_{i,k}$, of RLD number i.
- $\boldsymbol{Q_{threshold}}$ is the fixed threshold.

6. THE PROPOSED ALGORITHM

In this paper, we consider a transparent optical network, in which lightpath requests are dynamically set-up. Our proposed algorithm called IA-SeqRwLRR for Impairment-Aware Sequential Routing with Lightpath ReRouting aims at accommodating a maximum number of RLDs arriving at the network given a fixed number of wavelengths available per each fiber-link in the network. The IA-SeqRwLRR algorithm presented in [34] considers the RLDs sequentially, that is demand by demand at their arrival dates and computes for each RLD a suitable path and a suitable path-free wavelength that meet the minimum QoT requirement. Two separate phases, namely phase 1 and phase 2, are to be executed as shown in Figure 2. The first phase also called the routing phase computes the RWA for an incoming RLD without considering any rerouting. If phase 1 fails, due to lack of resources or in the absence of a path-free wavelength along one of the shortest paths associated to the RLD with a Q-factor higher than the fixed threshold ($Q_{threshold}$), the rerouting phase is launched. Phase 2 determines which active RLDs are to be rerouted and how they should be rerouted in order to set up the incoming RLD. If rerouting is unfeasible, the incoming RLD is definitively rejected. Our proposed algorithm differs from the previously published ones in the following aspects:

- First, when solving the RWA problem, we explicitly take into account the physical impairments imposed by the optical layer. However, RRAlgo1, RRAlgo2 and RRAlgo3 didn't consider any transmission impairments.
- Second, our algorithm does not construct any auxiliary graph with crossover edges to determine the set of existing lightpaths that should be rerouted as in RRAlgo1 and RRAlgo2. Also, it does not use a random search algorithm to compute the RWA for lightpath requests as in RRAlgo3. We hope, therefore, that our algorithm is less CPU consuming than rerouting algorithms previously presented in [18],[19],[20],[24] and [25].

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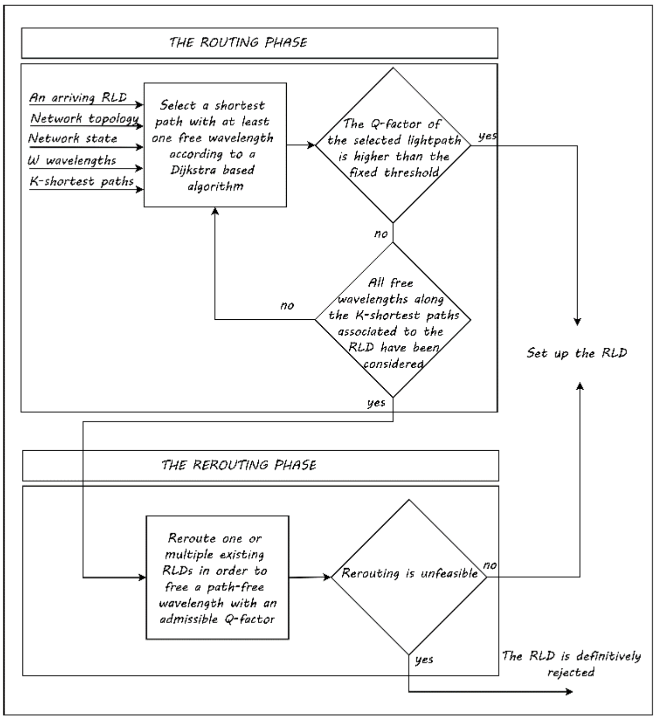

Figure 2: Schematic representation of the IA-SeqRwLRR algorithm

A. The routing algorithm

We use the Quality Path Selection Algorithm (QPSA) described in [14] as the routing algorithm. The approach is to compute the RWA for a given set of traffic demands sequentially without rerouting. Given a connection request, numbered i, to be set up at time t, the QPSA considers the K-alternate shortest paths in P_i (computed offline) in turn according to their number of hops. It looks for the first admissible path. We call an admissible path, a path with a path-free wavelength with a Q-factor higher than the fixed threshold, $\mathrm{Q_{threshold}}$. The Q-factor associated to each couple (path, wavelength) is estimated according to the expression given in Section 4. The RLD is hence established on the first met admissible path among its K-alternate shortest paths if such path exists, otherwise the rerouting phase is executed. It may happen that the number of available wavelengths with an admissible Q-factor on the selected path is higher than the number of requested lightpaths. In that case, the wavelengths are assigned according to a First-Fit scheme [33].

B. The rerouting algorithm

We need the following additional notations to describe the rerouting phase.

- $\boldsymbol{\theta}(\mathbf{i},\mathbf{k},\mathbf{w},\mathbf{t})$, $1 \le \mathrm{i} \le \mathrm{D}$, $1 \le \mathrm{k} \le \mathrm{K}$, $1 \le \mathrm{w} \le \mathrm{W}$, denotes the set of RLDs to be rerouted when serving the incoming RLD number i at time t using wavelength λ_w on $P_{i,k}$.
- $\mathbf{cr}(\mathbf{k},\mathbf{w},\mathbf{t}) = |\boldsymbol{\theta}(\mathbf{i},\mathbf{k},\mathbf{w},\mathbf{t})|$ is the cost of rerouting which is equal to the number of RLDs to be rerouted at time t in order to satisfy the incoming RLD number i on $P_{i,k}$ using wavelength λ_w.
- $\mathbf{cr^{min}} = \mathbf{min}_{1\le k\le K, 1\le w\le W}\, \mathbf{cr}(\mathbf{k},\mathbf{w},\mathbf{t})$ is the minimum cost to satisfy the new RLD number i at time t on $P_{i,k^{min}}$ using wavelength $\lambda_{w^{min}}$.

The rerouting phase, is launched whenever the routing algorithm fails in setting up the considered RLD. The rerouting phase aims at freeing as many path-free wavelengths as the number of lightpaths requested by the demand that meet the required QoT by rerouting a minimum number of already established RLDs:

For each shortest path $P_{i,k}$, $1 \le \mathrm{k} \le \mathrm{K}$, associated to RLD numbered i, rejected by the routing phase, and for each wavelength λ_w, $1 \le \mathrm{w} \le \mathrm{W}$, we determine the set of RLDs, $\theta(\mathrm{i},\mathrm{k},\mathrm{w},\mathrm{t})$, that should be rerouted when routing the incoming RLD on the selected path and wavelength. We then compute the corresponding cost of rerouting $cr(k,w,t)$. We then, compute cr^{min} (the minimum cost of rerouting). If cr^{min} is finite, the k^{th}-alternate shortest path and the w^{th} wavelength that require a minimum number of already established RLDs to be rerouted are hence selected. Let θ^{min} denote the corresponding set of RLDs to be rerouted. Two cases may happen: all the RLDs in θ^{min} can be rerouted either by only changing the used wavelength whilst keeping the same physical path or by changing both the physical path and then possibly the used wavelength. In this case, the incoming RLD is serviced using $P_{i,k^{min}}$ on wavelength $\lambda_{w^{min}}$. $c(i,k^{min},w^{min},t)$, the cost of using $P_{i,k^{min}}$ on wavelength $\lambda_{w^{min}}$, at time t is updated to $+\infty$. We also update the costs of the new paths used by the rerouted RLDs to $+\infty$ and to 0 the cost of the released lightpaths. The second case that may happen is that $P_{i,k^{min}}$ using $\lambda_{w^{min}}$ cannot be freed because one or several RLDs cannot be rerouted. In that case, we update $cr(k^{min},w^{min},t)$ to $+\infty$ and compute again the minimum cost. If cr^{min} is infinite, the incoming RLD numbered i is definitively rejected.

7. SIMULATIONS RESULTS

In this section, we present the numerical results obtained from the different simulation experiments that have been carried out to evaluate the performance of the IA-SeqRwLRR algorithm described in the previous section. We used the network topologies shown in Figures 3 and 4 with 15 and 16 nodes, respectively. The source and destination nodes of the RLDs arriving at the network are drawn according to a random uniform distribution in the interval [1, 15] for the 15-node network and in [1, 16] for the 16-node network. We assume that RLDs arrive at the network randomly according to a Poisson process with common arrival rate r and once accepted, will hold the circuits for exponentially distributed times with mean holding time equal to 10 much larger than the network-wide propagation delay and the connection set-up delay. We assume that W = 43 wavelengths are available on each fiber-link in the network and that K = 5 alternate shortest paths are computed between each source-destination pair in the network. The required value of the Q-factor (Q_threshold) is chosen equal to 6 which corresponds to a BER of 10^{-9}.

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Transmission system parameters are listed in Table 1:

Parameters	Value
SMF chromatic dispersion (ps/nm.km)	17
SMF polarization mode dispersion (ps/km$^{1/2}$)	0.1
SMF losses (dB/km)	0.2
DCF chromatic dispersion (ps/nm.km)	-90
DCF losses (dB/km)	0.6

Table 1: Transmission System Parameters

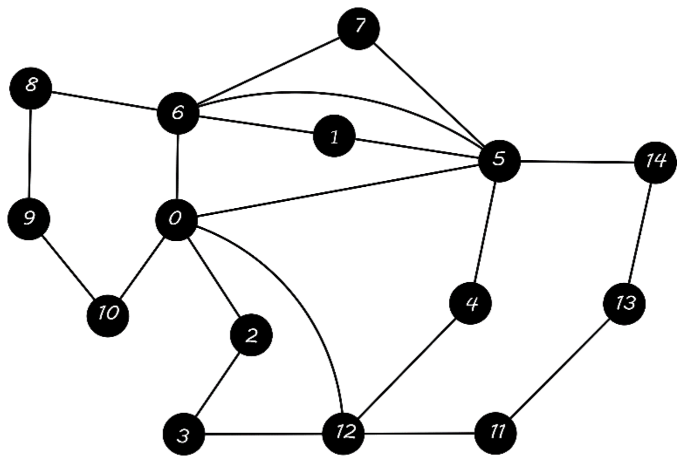

Figure 3: The 15-node Pacific Bell network topology

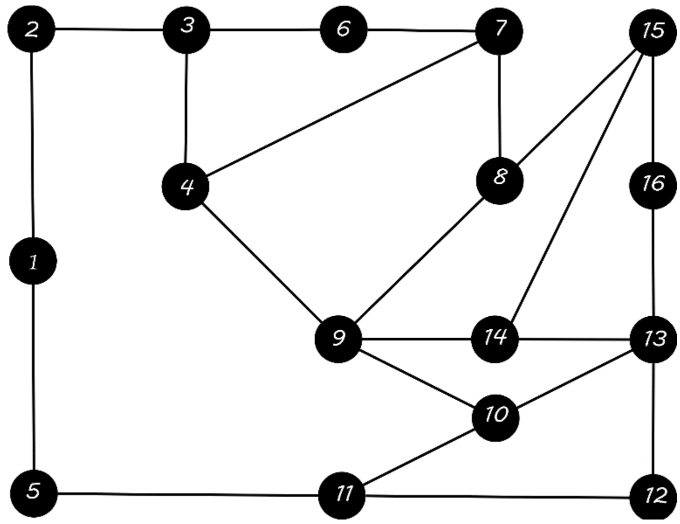

Figure 4: The 16-node Cost Core network topology

In order to point out the gain obtained thanks to rerouting, we propose to compare the results obtained with the IA-SeqRwLRR algorithm to those obtained with the following four routing algorithms.

- The simple traditional sequential RWA algorithm described in [24] and referred to as SeqR. The SeqR algorithm computes the RWA for the RLDs sequentially, at the arrival date of each RLD without any rerouting and assuming an ideal optical medium.
- The Quality Path Selection Algorithm (QPSA) described in [14]. The QPSA computes the RWA for the RLDs sequentially taking into account QoT requirements.
- The Worst Quality Path Selection Algorithm (WQPSA) which considers the incoming RLDs sequentially. It computes, for each incoming RLD, the set of admissible paths among its K-alternate shortest paths and selects the couple (path, wavelength) with the worst acceptable quality. A RLD is rejected if no admissible paths exit to carry the traffic request. Selecting worst acceptable wavelengths should, hopefully, lead to a minimal rejection ratio as wavelengths with higher quality are kept to be used by incoming RLDs.
- The Best Quality Path Selection Algorithm (BQPSA) computes the RWA for the RLDs the same way as the WQPSA. Conversely to WQPSA, the BQPSA selects the couple (path, wavelength) with the best acceptable quality among the computed admissible paths.

We generate 25 test scenarios, run the algorithms for each scenario, and compute rejection ratio averages for each algorithm. In the following, we only provide the curves obtained with the 15-node network as those obtained with the 16-node network present the same tendency.

Figure 5 and Figure 6 show the average number of rejected RLDs and the average rejection ratio respectively for various arrival rates per node (r). Each group of five bars in Figure 5 shows the average number of blocked demands computed using the seqR (first bar from the left-hand side), the QPSA (second bar), the WQPSA (third bar), the BQPSA (fourth bar) and the IA-SeqRwLRR (fifth bar) algorithms respectively. From Figure 5 and Figure 6, one may deduce four main observations. First of all, unexpectedly the QPSA has a rejection ratio that is lower than those computed by the WQPSA and BQPSA algorithms. This is mainly due to the fact that assigning worst or best acceptable wavelengths may lead to establish RLDs using longer paths and hence may consume more network resources. This may block up the establishment of future arriving LDs. Secondly, the average rejection ratio computed by the SeqR algorithm is lower than those computed by the QPSA, the WQPSA and the BQPSA algorithms. This is due to the fact that the SeqR does not consider any QoT constraint. In fact, by considering quality of transmission impairments more RLDs are rejected in the absence of admissible paths and wavelengths. This emphasizes, once again, the necessity to consider rerouting to improve the efficiency utilization of network resources. Third, the rejection ratio increases with the traffic loading per node due to the limited number of available resources with acceptable Q-factor. Finally, we notice that thanks to rerouting the network throughput conditioned by the wavelength continuity constraint and the QoT requirement constraint is improved. On the average, the number of blocked RLDs is reduced by 31% compared to QPSA and 36% compared to WQSPA and BQPSA respectively.

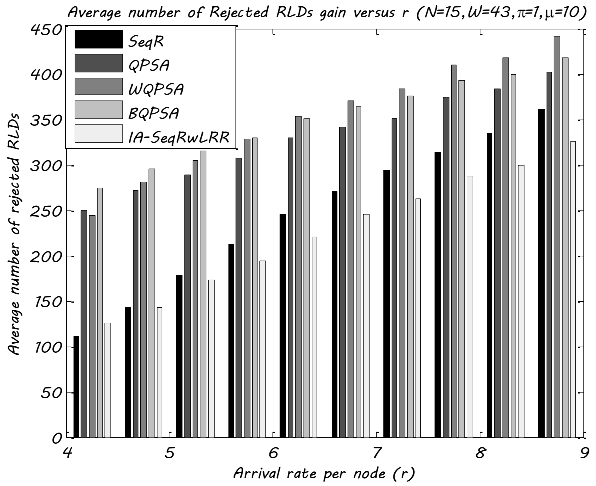

Figure 5: Average number of rejected RLDs w.r.t. r

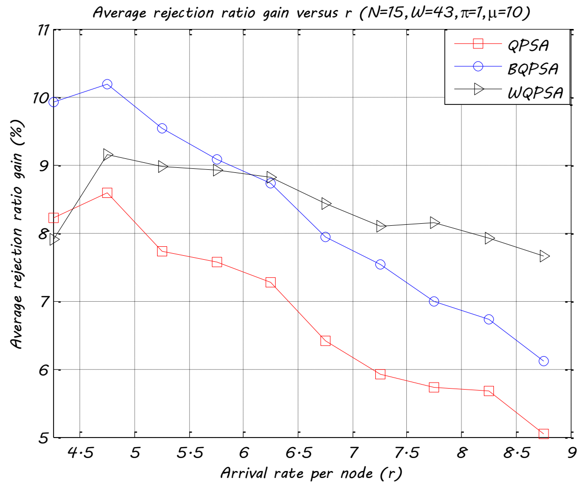

Figure 7: Average rejection ratio gain w.r.t. r

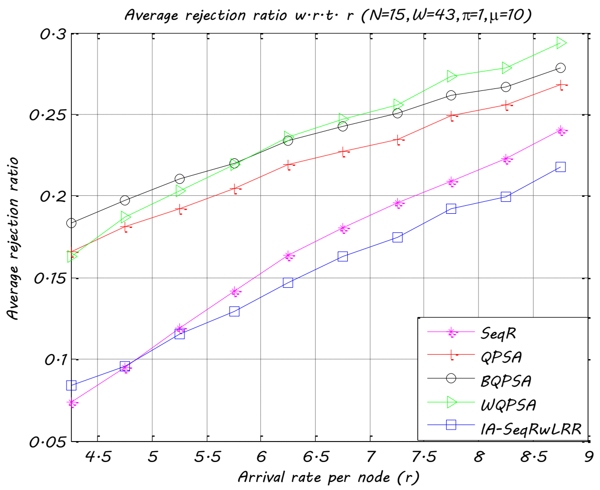

Figure 6: Average rejection ratio w.r.t. r

Figure 7 draws the average rejection ratio gains versus r. The rejection ratio gains have been computed as the difference between the average rejection ratios computed by the QPSA, the BQPSA and the WQPSA algorithms respectively and the average rejection ratio computed by the IA-SeqRwLRR algorithm multiplied by 100. Maximum rejection ratio gains of 8.58%, 10.18% and 9.15% (6.36%, 7.8% and 6.54% for the 16-node network) are observed under the aforementioned simulation parameters. The average rejection ratio gains fall down under heavy traffic load. This is because the saturation regime of the network is reached. When the traffic load increases, it becomes increasingly difficult to reroute some traffic demands taking into account quality of transmission impairments in order to set up more lightpath demands especially when the number of wavelengths per each fiber-link in the network is limited.

In Figure 8, each bar shows the average number of rerouted RLDs computed using the IA-SeqRwLRR algorithm with respect to r. The height of the white bar indicates the average number of rerouted RLDs using WRR whereas the height of the black one shows the average number of rerouted RLDs using LRR. We notice, obviously, that under low traffic load the IA-SeqRwLRR algorithm requires more RLDs to be rerouted when r increases. In fact, when the traffic loading per node at the network increases, more RLDs are to be rejected at their arrival dates due to lack of resources. Since, more existing RLDs need to be rerouted to set up the new RLD and consequently the number of RLDs to reroute increases. Under high traffic load, the average number of rerouted RLDs reaches an upper bound corresponding to network saturation.

We also notice that the average number of rerouted RLDs using LRR is much lower than the number of rerouted RLDs using WRR. This should, hopefully, lead to short disruption period when rerouting a set of RLDs to accommodate an incoming one.

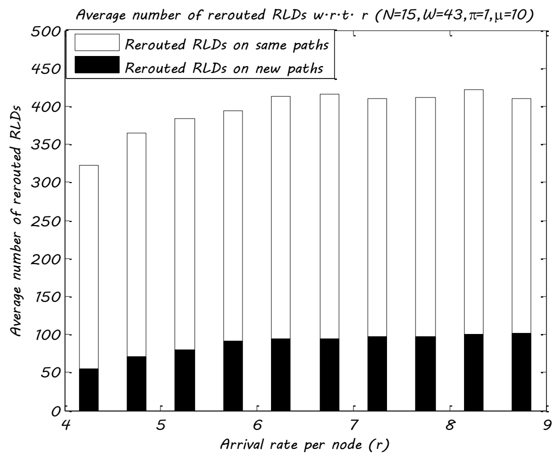

Figure 8: Average number of rerouted RLDs w.r.t. r

8. CONCLUSION

In this paper, we have investigated the RWA problem with signal-quality constraint for dynamic traffic in WDM all-optical networks. Our proposed RWA algorithm applies lightpath rerouting to alleviate the inefficiency brought by the wavelength continuity and the QoT requirement constraints. The efficiency of the proposed algorithm is highlighted by numerical simulations. Obtained results show that our algorithm reaches an average rejection ratio gain of 8.5%.

In this paper, we investigate a passive lightpath rerouting strategy. Passive rerouting means rerouting established lightpaths to accommodate new lightpath requests which will otherwise be blocked. Our forthcoming studies will investigate the RWA problem with signal-quality constraint applying intentional rerouting. Intentional rerouting is to intentionally reroute existing lightpaths during their life period without affecting other lightpaths, so as to achieve a better load balancing.

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