New QoT-Aware Rerouting Algorithms in WDM All-Optical Networks

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***Abstract*—The wavelength continuity constraint and the wavelength integrity constraint imposed by Wavelength-Division Multiplexing (WDM) all-optical networks have been, for a long time, the main constraints to be considered when solving the Routing and Wavelength Assignment (RWA) problem in such networks. However, 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 propagates through long distances. Indeed, in WDM all-optical networks, no signal regeneration at intermediate nodes is allowed which induces some impairments in the transmission signal. 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. This result might lead to inefficient utilization of network resources resulting in higher rejection ratios. This is especially severe when dynamic lightpath demands are considered. In this paper, we propose to use rerouting as a solution to improve the network throughput. We investigate and compare three different rerouting categories, namely, passive rerouting, active rerouting and hybrid rerouting. To the best of our knowledge, this is the first attempt to use active and hybrid rerouting for optimizing WDM all-optical network throughput with transmission impairments consideration. Multiple simulation studies have been carried out on different network topologies to evaluate and compare the performance of the proposed algorithms.**

Keywords–WDM all-optical networks; passive, active and hybrid rerouting; Wavelength continuity constraint; Quality of Transmission (QoT); Service disruption period.

I. INTRODUCTION

WDM [1] optical networks are promising candidates that are expected to satisfy the continually evolving requirements for higher bandwidth services. Nowadays, 40 and 100 Gbps connections are used thanks to WDM all-optical networks, also known as WDM transparent optical networks, in which the signals remain in the optical domain. In such a network, data traffic is transported from one node to another in the form of optical pulses carried over an end-to-end optical path, called lightpath. A lightpath, generally spanning several fiber-links, is established by allocating the same wavelength on all the fiber links it traverses. This requirement is referred to as the wavelength continuity constraint. Also, two lightpaths sharing the same fiber must be identified by different wavelengths. This requirement is called wavelength integrity constraint. 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 [2]. Many surveys have been carried out to investigate the RWA problem assuming an ideal optical medium [2]. But such a perfect optical transmission could never be achieved in a realistic WDM network where fibers and non ideal components induce multiple transmission impairments which affect significantly the quality of transmission. Indeed, to ensure the feasibility of proposed algorithms, in addition to the two aforementioned constraints, a third constraint cannot be ignored anymore. This constraint is related to the lightpaths' QoT, which might become potentially unacceptable when the optical signal propagates over long distances without electrical regeneration.

Taking into account physical layer impairments, wavelength continuity constraint and wavelength integrity constraint when solving the RWA problem leads to inefficient utilization of network resources and results in higher rejection ratios. Traffic rerouting is a viable and cost effective solution to improve the network throughput conditioned by the aforementioned constraints. There are two ways to rearrange an existing lightpath. One is wavelength rerouting (WRR), which keeps the original path of the lightpath to be rerouted but reassigns a different wavelength to the fiber links along the path. Another is lightpath rerouting (LRR), which consists of finding a new path with possibly another wavelength to replace the old path. A comprehensive survey of rerouting techniques can be found in [3]. Transmission of the existing lightpaths to be rerouted must be temporarily shut-down to protect data from being lost or misrouted. This period is referred to as the service disruption period. It has been demonstrated in [4] that WRR induces a service disruption period shorter than that induced by LRR. Traffic rerouting can be divided into three categories with respect to the timestamp of initiating the rerouting procedure. The first is passive rerouting, which initiates the rerouting procedure when an incoming lightpath demand is about to be rejected due to lack of resources. It aims at rearranging a certain number of existing lightpaths to free a wavelength-continuous route for the incoming lightpath demand. The second category is active rerouting, also called intentional rerouting, which reroutes dynamically existing lightpaths to a more suitable physical path according to some predefined criteria, without affecting other lightpaths, so as to achieve a better rejection ratio performance. The third category is hybrid rerouting which combines passive rerouting and active rerouting. In this paper, the main objective consists in applying active and hybrid rerouting to maximize the number of established lightpath demands satisfying the required QoT for a given physical network topology with a fixed number of wavelengths per fiber-links and minimize the incurred service disruption period. Lightpath demands are assumed to be with random arrivals and departures and referred to as Random Lightpath Demands (RLDs). Four main physical layer impairment effects are considered as dominating factors that affect signal quality, namely Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD), Optical Signal to Noise Ratio (OSNR) and Nonlinear Phase Shift (ϕ_{NL}).

The remainder of this paper is organized as follows. In Section II, we briefly describe the investigated problem and present related works. In Section III, the QoT computation as well as the four QoT parameters considered in this paper are presented. In Section IV, we present in details our proposed QoT-aware rerouting algorithms. Performance results are presented and analyzed in Section V. Finally, Section VI concludes the paper.

II. DESCRIPTION OF THE INVESTIGATED PROBLEM AND RELATED WORK

Taking into account the impact of physical layer impairments when solving the RWA problem in order to make the proposed RWA algorithms more effective has been, recently, extensively investigated in the literature [5]. Impairments can be classified into linear and non-linear effects [5]. Linear effects are independent of signal power and affect wavelengths individually. Amplifier Spontaneous Emission (ASE), PMD, and CD investigated in [5][6][7], are generally considered as the predominant factors inducing signal degradation when evaluating network performance in low-speed transmission systems. However, in high-speed optical networks non-linear impairments as well as linear ones become more prominent and could not be ignored anymore. Self-Phase Modulation (SPM), considered in [8], and Four Wave Mixing (FWM) investigated in [9], are some of the important non-linear impairments affecting transmitted signal quality. Taking into account physical layer impairments should lead to lower network performance especially in terms of rejection ratio. That is why, we propose here to use traffic rerouting to alleviate the effect of considering these impairments.

The traffic rerouting concept has been applied to WDM all-optical networks to alleviate only the impact of the wavelength continuity constraint. Different rerouting techniques have been proposed so far in the literature [3]. But, they assumed perfect physical layer conditions. To the best of our knowledge, the first attempt to use rerouting as a solution to maximize the number of established RLDs satisfying the required QoT is found in our studies presented in [10][11][12], where passive lightpath and/or wavelength rerouting was considered. In this paper, we investigate active and hybrid rerouting to alleviate the transmission impairments consideration effect and minimize the incurred service disruption period. The performances of our QoT-aware rerouting algorithms are evaluated and compared to those of our impairment-aware passive lightpath rerouting algorithm previously published in [10] through illustrative numerical examples.

III. QUALITY OF TRANSMISSION COMPUTATION

In WDM all-optical networks, the QoT is generally evaluated in terms 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 very difficult. That is why another factor called Q-factor is used to estimate the QoT in the network.Equation (1) shows the relationship between $Q-$factor and BER.

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

To provide a qualitative description of the QoT in the network, the Q-factor is estimated by combining four linear and nonlinear effects. The effects considered in this study are respectively: CD, PMD, SNR and ϕ_{NL}. In the following subsections, we discuss the aforementioned four main quality of transmission parameters and estimate the associated Q-factor based on the models proposed in [5].

A. Chromatic Dispersion

The disparity in propagation velocity causes an optical pulse broadening in the time domain. This phenomenon is called CD. The CD's power penalty is given by (2) [5].

$$EOP_{DC} = 10log \left(\sqrt{1 + (DL\frac{\sigma_\lambda}{\sigma_0})} \right) \tag{2}$$

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

B. Polarization Mode Dispersion

Different propagation velocities cause pulse broadening in the frequency domain called PMD. The PMD's power penalty is evaluated according to (3), where T_B is the bit time.

$$EOP_{PMD}{=}5.1 \left(\frac{\left(\sum_{f \in links} (\left(\sum_{f \in spans} (PMD_{span}(f))^2 \right)^{\frac{1}{2}} (f))^2 \right)^{\frac{1}{2}}}{T_B} \right)^2 \tag{3}$$

C. Optical Signal to Noise Ratio

The amplification site, used to compensate fiber absorption losses, consists of Erbium-doped fiber amplifier (EDFA) and a section of compensating dispersion fiber (DCF) [5]. Optical amplifiers affect transmitted signal quality by their own component of noise known as 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 computed along a fiber-line composed of M amplifier stages is obtained according to the following equation [5]:

$$\frac{1}{OSNR} = \sum_{1 \leq i \leq M} \left(\frac{1}{\frac{P_s}{P_{ASE}}} \right) = \sum_{1 \leq i \leq M} \left(\frac{NF_{stage} h\nu\Delta f_i}{P_s} \right) \tag{4}$$

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.

D. Nonlinear Phase Shift ϕ_{NL}

Enhancing the intensity of the optical signal propagating through the fiber raises the fiber nonlinearities which create a nonlinear phase shift ϕ_{NL} computed according to Equation 5 [5]:

$$\phi_{NL} = \frac{n_2 \omega_0 P_{in}}{cA_{eff}} \left(\frac{1 - e^{\alpha L}}{\alpha} \right) \tag{5}$$

where α is the attenuation parameter, n_2 represents the cladding index, 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.

E. Q-factor Estimation

The Q-factor considering the four impairment parameters described above is estimated according to the following expression:

$$Q = \left(\sqrt{\frac{OSNR \Delta f_{opt} EXTP}{EOP_{DC} EOP_{\phi_{NL}} \Delta f_{elect}}} \right) \frac{1}{EOP_{PMD}} \tag{6}$$

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.

IV. THE PROPOSED ALGORITHMS

In this section, we describe our QoT-aware rerouting algorithms called the *QoT-Aware Active Rerouting* algorithm and the *QoT-Aware Hybrid Rerouting* algorithm and referred to as the *QoT-AAR* and the *QoT-AHR* algorithms, respectively. Our proposed algorithms aim to optimize the network throughput in WDM all-optical networks with QoT consideration and minimize the incurred service disruption period. Both algorithms use the same routing and active rerouting procedures. They consider the RLDs sequentially, that is demand by demand at their arrival dates and compute for each RLD a suitable path-free wavelength that meets the required QoT without considering any rerouting. Also, both algorithms execute an active rerouting procedure when an established RLD leaves the network. Already established lightpaths that can be set up on a new vacant shorter path are selected to be rerouted by the active rerouting procedure in order to improve the network resources utilization efficiency. The main difference between the two proposed algorithms is that the QoT-AHR algorithm launches a passive wavelength rerouting procedure to hopefully free a wavelength-continuous route with an acceptable QoT to accommodate an incoming RLD which will otherwise be blocked by the routing procedure. On the other hand, the QoT-AAR algorithm rejects any RLD failed to be set up by the routing procedure.

Our proposed algorithms differ from the previously published ones in the following aspects: First, when solving the RWA problem, they explicitly take into account the physical impairments imposed by the optical layer. However, rerouting algorithms previously presented in the literature did not consider any transmission impairments. Second, our algorithms do not construct any auxiliary graph with crossover edges to determine the set of existing lightpaths that should be rerouted. Also, they do not use a random search algorithm to compute the RWA for lightpath requests. We hope, therefore, that our algorithms are less Central Processing Unit (CPU) intensive than rerouting algorithms previously presented in the literature.

In the following subsections, first we define some notations. Then, we detail the routing and rerouting procedures, respectively.

A. Notations

- $\Lambda = \{\lambda_1, \lambda_2, ..., \lambda_W\}$ is the set of available wavelengths on each fiber link. W denotes the number of available wavelengths per fiber link. We assume that all the network links have the same number of available wavelengths.
- The i^{th} RLD, is defined by a $5-$tuple $(s_i, d_i, \pi_i, \alpha_i, \beta_i)$. s_i and d_i are the source and the destination nodes of the lightpath demand, respectively; π_i is the number of requested lightpaths. For the sake of simplicity, we assume here that $\pi = 1$. α_i and β_i are the setup and teardown times of the lightpath demand, respectively.
- $P_{i,k}$, $1 \leq i \leq D$ (D the total number of RLDs), $1 \leq k \leq K$, represents the k^{th} alternate shortest path connecting node s_i to node d_i. We use the hop count as the link metric and compute beforehand K-alternate (loop-free) shortest paths for each source-destination pair (if as many paths exist, otherwise we only consider the available ones).
- $C_{i,k,w}$ is the cost of using wavelength λ_w on $P_{i,k}$. The cost function is determined as follows:
  $C_{i,k,w} =$
  $\begin{cases} \varepsilon, & if\ \lambda_w\ is\ path-free\ on\ P_{i,k} \\ +\infty, & if \lambda_w\ is\ already\ used \end{cases}$
  ε is a tiny positive value corresponding to the hop count on $P_{i,k}$.

B. The routing procedure

The routing procedure uses the Quality Path Selection Algorithm (QPSA) described in [5]. To establish an incoming RLD, the QPSA considers the K-alternate shortest paths (computed offline) in turn according to their number of hops. It looks for the first path-free wavelength with a Q-factor higher than the fixed threshold, $Q_{threshold}$. The Q-factor associated with each couple (path, wavelength) is estimated according to the expression given by (6). The RLD is hence established on the first met suitable path among its K-alternate shortest paths if such path exists.Otherwise, we distinguish two cases: the QoT-AAR algorithm rejects the RLD definitively, or, the QoT-AHR algorithm executes a passive wavelength rerouting procedure.

C. The active rerouting procedure

Both algorithms execute the active rerouting procedure every time an established RLD leaves the network. The active procedure first computes ϕ_i^t, the set of existing RLDs that should be rerouted when the i^{th} RLD leaves the network at time t knowing that the rerouting of an existing RLD is allowed once during its life period in order to avoid the rerouting of an active RLD multiple times as the RLDs departure times may be very close. By doing so, we reduce the number of RLDs to be rerouted and consequently the overall service disruption period. Once ϕ_i^t is computed two cases may happen:

- $\phi_i^t = \emptyset$: None of the existing RLDs satisfy the preceding constraints. No rerouting is to be executed.
- $\phi_i^t \neq \emptyset$: Each RLD in ϕ_i^t is hence rerouted to a vacant shorter path using the routing procedure described in Subsection IV-B. The costs of the new path's edges used by the rerouted RLD are updated to $+\infty$ and to 1 the costs of the released path's edges.

D. The passive rerouting procedure of the QoT-AHR algorithm

The QoT-AHR algorithm launches the passive rerouting procedure whenever the routing procedure fails to satisfy an incoming RLD. It aims at freeing a wavelength-continuous route that meets the required QoT as follows:
For each shortest path k, $1 \leq k \leq K$, associated to the incoming RLD numbered i and for each wavelength λ_w, $1 \leq w \leq W$, we determine the set of RLDs that should be rerouted $\phi_{i,k,w}$ to set up the incoming RLD numbered i. We then compute the corresponding rerouting cost $RC_{k,w} = |\phi_{i,k,w}|$. After that we compute RC^{min} the minimum rerouting cost to satisfy the new RLD on $P_{i,k^{min}}$. If RC^{min} is finite, the k^{th}-alternate shortest path and the w^{th} wavelength that requires a minimum number of already established RLDs to be rerouted is hence selected. Let ϕ^{min} denote the corresponding set of RLDs to be rerouted. Two cases may happen: all the RLDs in ϕ^{min} can be rerouted by only changing the used wavelength whilst keeping the same physical path. In this case, the incoming RLD is serviced using $P_{i,k^{min}}$ on wavelength $\lambda_{w^{min}}$. $C_{i,k^{min},w^{min}}$ is updated to $+\infty$. We also update the costs of the new paths used by the rerouted RLDs to $+\infty$ and to 1 the cost of the released paths. 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 $RC_{k^{min},w^{min}}$ to $+\infty$ and compute again the minimum cost. If RC^{min} is infinite, the incoming RLD is rejected definitively.

V. SIMULATIONS RESULTS

In order to evaluate the performance of the QoT-aware rerouting algorithms presented in the previous section, we carried out multiple simulation experiments on the $15-$node Pacific Bell network topology and the $16-$node Cost Core network topology, respectively. We assume that 43 wavelengths are available on each fiber-link of the network $(W = 43)$. Also, $5-$alternate shortest paths $(K = 5)$ are computed for each possible source-destination pair in the network. We assume that RLDs arrive at the network randomly according to a Poisson process with common arrival rate per node 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. The source and destination nodes of the RLDs are drawn according to a random uniform distribution in the intervals $[1, 15]$ and $[1, 16]$ for the $15-$node network and the $16-$node network, respectively. The required value of the $Q-$factor is chosen equal to 6 which corresponds to a BER of 10^{-9}.

We generate 25 test-scenarios, that is, 25 different traffic matrices, run algorithms for each scenario, and compute mean values. The QoT-aware rerouting algorithms performances are measured in terms of average rejection ratio and average ratio of rerouted RLDs. The average rejection ratio is defined as the ratio of the average number of rejected RLDs to the total number of RLDs arriving at the network. The average ratio of rerouted RLDs is computed as the average number of rerouted RLDs divided by the total number of RLDs arriving at the network. 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.

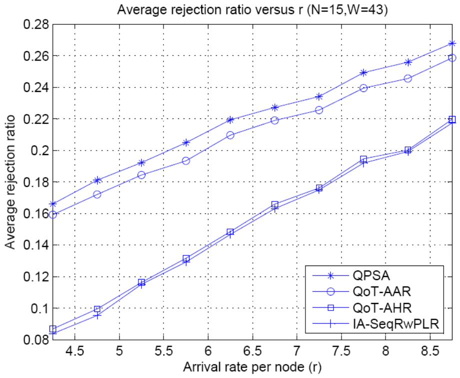

Figure 1. Average rejection ratio versus r.

In the following, we propose to compare the average rejection ratios, computed by our proposed QoT-aware rerouting algorithms to those computed by the Quality Path Selection Algorithm (QPSA) described in [5] which computes the RWA for RLDs sequentially taking into account QoT requirements and our Impairment-Aware Sequential Routing with Passive Lightpath Rerouting (IA-SeqRwPLR) algorithm described in [10]. The IA-SeqRwPLR algorithm considers the RLDs sequentially and computes for each RLD a suitable path and a suitable path-free wavelength that meet the minimum QoT requirement. The rerouting procedure is launched whenever the routing procedure fails in setting up the considered RLD. The rerouting procedure aims at freeing a path-free wavelengths that meets the required QoT by rerouting a minimum number of already established RLDs either by only changing the used wavelength whilst keeping the same physical path or by changing the physical path and then possibly the used wavelength.

In Figure 1, we draw the average rejection ratios computed by the four algorithms described above for various arrival rates per node, r. From Figure 1, one may deduce three main conclusions.

- The average rejection ratios increase with r due to the limited number of available resources with acceptable Q-factor. Thanks to rerouting (be it passive, active or hybrid), the average rejection ratio is improved. On the average, the rejection ratio is reduced up to: 8.58% (respectively 6.55% for the 16-node network) with the IA-SeqRwPLR algorithm, 8.16% (respectively 6.12% for the 16-node network) with the QoT-AHR algorithm and 1.5% (respectively 1.3% for the 16-node network) with the QoT-AAR algorithm.
- The IA-SeqRwPLR and the QoT-AHR algorithms outperform the QOT-AAR algorithm, outlining a significant improvement in term of average rejection ratio. In fact, the QOT-AAR algorithm has the worst rejection ratio performance because it is so difficult, for a given established RLD, to find a new shorter

physical path satisfying the required QoT among its K shortest paths. Also, imposing that an established RLD can be rerouted on new physical path only once during its life period results in decreasing the number of rerouted RLDs and hence the network resources consumption reduction becomes limited.

- Unexpectedly the IA-SeqRwPLR algorithm has a rejection ratio that is slightly lower than that computed by the QoT-AHR algorithm despite the fact that the QoT-AHR algorithm applies both active and passive rerouting procedures. This is mainly due to the fact that when applying passive rerouting procedure LRR rerouting is not allowed which causes the failure of the passive wavelength rerouting procedure to free a wavelength-continuous route to set up an incoming RLD. Also, the active procedure does not provide an impressive network resources consumption reduction as discussed above.

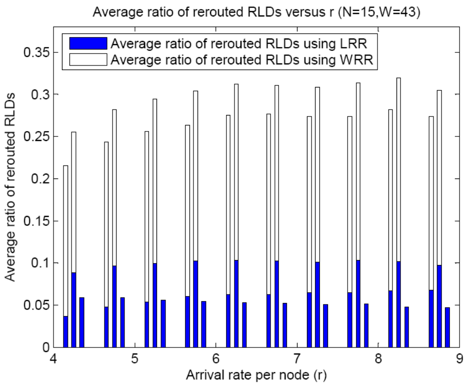

Figure 2. Average ratio of rerouted RLDs versus r.

In Figure 2, each group of three bars shows the average ratio of rerouted RLDs computed using the IA-SeqRwPLR, the QoT-AHR and the QoT-AAR algorithms respectively with respect to r. The height of the blue bar indicates the average ratio of rerouted RLDs using LRR whereas the height of the white one shows the average ratio of rerouted RLDs using WRR.

We notice, obviously, that the IA-SeqRwPLR and the QoT-AHR algorithms require more RLDs to be rerouted when r increases. In fact, when r increases, the probability that an incoming RLD be rejected is higher and hence, more existing RLDs have 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 the network saturation. Unlike those algorithms, the average ratio of RLDs to be rerouted by the QoT-AAR algorithm decreases when r increases. Indeed, when the network reaches its saturation regime, it becomes difficult to reroute an active lightpath to a shorter path satisfying the required QoT.

We also notice that the average ratios of rerouted RLDs by the IA-SeqRwPLR and the QoT-AHR algorithms using LRR are much lower than the average ratios of rerouted RLDs using WRR. This should, hopefully, lead to short service disruption period.

VI. CONCLUSION AND FUTURE WORK

In this paper, we have investigated the RWA problem with signal-quality constraint for dynamic traffic in WDM all-optical networks. Our proposed RWA algorithms apply active or hybrid rerouting to alleviate the inefficiency brought by the wavelength continuity and the QoT requirement constraints. Obtained results show that passive and hybrid rerouting work much better than active rerouting. Passive lightpath rerouting is an efficient way to improve the rejection ratio performance with a short service disruption period. Our forthcoming studies will consider more physical layer impairment effects to make the proposed algorithms more effective.

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