RESEARCH ARTICLE OPEN ACCESS

A Novel Timer-Based Hybrid Rerouting Algorithm for Improving Resource Utilization Efficiency and Shortening the Incurred Service Disruption Period in WDM Transparent Optical Networks

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ABSTRACT
In this paper we investigate hybrid rerouting and minimization of incurred service disruption period due to rerouting in Wavelength Division Multiplexed (WDM) transparent optical network. One limitation of such a network is the wavelength continuity constraint which does not allow a circuit to be placed on a non wavelength-continuous route. The impact of this constraint might have a severe consequence on the performance of transparent optical networks especially in terms of rejection ratio ant it is especially severe when traffic demands are unpredictable and characterized by random arrivals and departures. To alleviate the impact of these constraints, either wavelength conversion or traffic rerouting can be used. Since, in the foreseeable future, wavelength conversion is expected to remain an expensive technology, traffic rerouting is an attractive alternative solution. Thus, we here propose to employ hybrid rerouting to improve the network performances. Hybrid rerouting combines passive and active rerouting. Through simulation results, the performances of the proposed algorithm in terms of rejection ratio are demonstrated to be promising while rerouting a small number of already established lightpaths using Lightpath ReRouting (LRR). By rerouting a small number of existing lightpaths using LRR, we hope that the incurred service disruption period due to rerouting is minimized.
Keywords: Active Rerouting, Hybrid Rerouting, Lightpath ReRouting (LRR), Passive Rerouting, Routing and Wavelength Assignment (RWA), Wavelength Continuity Constraint, Wavelength ReRouting (WRR), WDM Transparent Optical Networks

I. INTRODUCTION

Multimedia applications such as peer-to-peer live media streaming, distance education, video-on-demand and video conference require networks with large amount of bandwidth. Wavelength Division Multiplexing (WDM) based optical net-working architectures using optical cross-connects (OXCs) are promising solutions [1]. An optical fiber, which uses WDM technology is capable of providing a large amount of bandwidth (nearly 50 Tb/s) [2]. Each fiber link can support a number of wavelength channels by using WDM. In a WDM network, data traffic is transported from one node to another in the form of optical pulses carried over an optical path, called lightpath. Today, a lightpath can carry approximately 40 Gbits/s of data traffic, and its holding period is usually very long. The problem of establishing lightpaths, with the objective of optimizing the network resource utilization is known as the Routing and Wavelength Assignment (RWA) problem [3]. The RWA problem has been extensively investigated in the literature and most of the proposed approaches considers either networks with wavelength conversion capabilities [4], [5] or networks without any wavelength conversion [6],[7], [8], [9], [10]. Using wavelength converters potentially allows the network to support a larger set of lightpaths. However, such converters remain too expensive [6].

Nowadays, WDM transparent optical networks, where all the switching, routing and intelligent control functions can be handled more effectively in the optical domain, turn out to be an efficient solution to overcome many problems arisen in traditional electronic networks such as the electronic bottleneck problem. These networks, also known as WDM all-optical networks [11], are widely recognized as the most promising candidates for next generation telecommunication networks that are expected to fulfill the tremendous bandwidth demand and enable the deployment of new network services. In such a network, a lightpath connecting the source node to the destination node of a lightpath demand and spanning a set of network fiber-links is established subject to the following two constraints:

Wavelength clash constraint: The wavelength clash constraint states that a wavelength may be used only once per fiber at a given instant.

Wavelength continuity constraint: A lightpath is set up by allocating the same wavelength on all the fiber links it traverses from its source node to its destination node.

The Wavelength continuity constraint reduces the possibility of successfully finding a free wavelength on a path and thus may force the lightpath to get blocked. Wavelength conversion is one technique to alleviate the inefficiency caused by wavelength continuity constraints but increases significantly the network design cost. Rerouting is a useful technique which also helps to increase the overall network resources utilization efficiency.

Rerouting (or repacking) is a concept originally introduced in the design of circuit-switched telephone networks [12]. It has been applied to WDM optical networks over the two past decades [7], [8], [9], [10]. Rerouting is defined as the action of rearranging an established circuit (or virtual path in ATM networks, lightpath in WDM networks) from one path to another path without changing the source and destination nodes. There are two ways to rearrange an existing lightpath [13]:

- 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.
- Lightpath ReRouting (LRR) which consists of finding a new path with possibly another wavelength to replace the old path.

In [8] authors demonstrate that LRR induces a service disruption period higher than that of WRR.

A comprehensive survey of rerouting techniques can be found in [14]. Rerouting in a WDM all-optical network can be divided into two categories with respect to the timestamp of initiating the rerouting procedure:

The first is passive rerouting: rerouting procedure is initiated 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 blocking performance.

In this paper we focus on hybrid rerouting, which combines passive and active rerouting to see whether a combination of these two rerouting concepts can further improve the blocking performance and minimize the incurred service disruption period due to rerouting when Random Lightpath Demands (RLDs) are considered.

The remainder of this paper is organized as follows. A summary of the related work is presented in Section 2. Then we explain in details the proposed algorithm in Section 3. The simulations are conducted and the results are discussed in Section 4. Finally, Section 5 concludes the paper.

II. RELATED WORK

A number of RWA schemes applying rerouting to alleviate the effect of the wavelength continuity constraint when there is no wavelength conversion have been proposed so far in the literature. Most of these schemes are based on passive rerouting concept. In [7], [8], authors first introduced the passive wavelength rerouting concept by proposing a wavelength rerouting scheme called Move To Vacant Wavelength Retuning (MTV-WR). The basic idea of this algorithm is that, in case a RLD gets blocked with normal assignment process, a few established lightpaths may be reassigned, if possible, to other wavelengths to enable the new RLD to get a wavelength-continuous route from its source to destination. While reassigning an existing lightpath it maintains the original path of the lightpath. Parallel MTV-WR deals with the rerouting of multiple lightpaths at the same time. The main concern of this algorithm is to minimize the rejection ratio and the service disruption period. A time optimal passive wavelength rerouting algorithm based on the Parallel MTV-WR rerouting scheme was presented later in [9]. Recently, a new passive lightpath rerouting scheme called Sequential Routing with Lightpath Rerouting (SeqRwLR) is proposed in [15] to improve the rejection ratio while keeping a small service disruption period.

All of the aforementioned rerouting algorithms use the passive rerouting concept i.e they only perform rerouting when a new RLD is to be blocked. In [10] and [17], authors proposed two active rerouting schemes which dynamically adjust physical paths of existing lightpaths according to some predefined criteria. The first scheme called Dynamic Least Congested Routing (DLCR) reroutes dynamically existing lightpaths to the vacant least congested route if a better load balancing can be achieved. The basic idea of the second algorithm is to reroute dynamically an existing lightpath to one of its K-shortest path with the highest weight value and the difference between the weight values is greater than the pre-defined threshold. The weight value associated to a path can be calculated by a pre-defined weight function. The design of the weight function could be very complicated. Usually it should consider lots of factors, e.g., the path hop-count, and the free wavelength distributions. Authors assume that a large weight value means a good candidate path [17]. Recently, new active lightpath rerouting schemes called the Timer-Based Active

Lightpath Rerouting algorithm (TB-ALR) and the Sequential Routing with Active Lightpath Rerouting algorithm (SeqRwALR), respectively, are proposed in [18]. The basic idea of both algorithms is to dynamically reroute some already established lightpaths to more appropriate physical paths so as to reduce the network resources consumption. The TB-ALR algorithm initiates the rerouting procedure at some predefined time instants whereas the SeqRwALR algorithm initiates the rerouting procedure at the end time of an established lightpath demand when its lightpath is released. Simulation results show that the two proposed active rerouting algorithms provide better blocking performances than previously presented passive rerouting algorithms but they introduce a higher service disruption period since they use only LRR. In [19], authors investigated hybrid rerouting. The proposed algorithm called Sequential Routing with Hybrid Lightpath Rerouting algorithm (SeqRwHLR). The basic idea of this algorithm is to dynamically reroute some already established RLDs to shorter physical paths so as to reduce the network resources consumption and perform a simple passive WRR procedure if a new incoming RLD is to be blocked due to lack of resources. The authors demonstrated that hubrid rerouting works much better than passive rerouting and incurs a service disruption period lower than that incurred by active rerouting.

III. THE PROPOSED ALGORITHM

This paper proposes a hybrid rerouting algorithm, namely, Sequential Routing with Timer-Based Hybrid Lightpath Rerouting (SeqRwTBHLR) algorithm to alleviate the inefficiency brought by the wavelength continuity constraint in WDM all-optical networks without any wavelength conversion capabilities. Lightpath demands are assumed to be with random arrivals and departures. The basic idea behind this algorithm is to combine passive rerouting and active rerouting to hopefully improve the network rejection ratio and minimize the incurred service disruption period due to rerouting. The SeqRwTBHLR algorithm computes the RWA for the RLDs sequentially that is demand by demand at their arrival dates. When an incoming RLD cannot be set up in the absence of network resources between its source and destination nodes, the SeqRwTBHLR algorithm performs passive WRR procedure aiming hopefully at freeing a wavelength-continuous route to service the new RLD. WRR concept is used here since it has the following attractive features. First, it has simple switching control because the old and new paths of rerouted lightpaths share the same switching nodes. Second, it provides shorter service disruption period that should be only of the order of microseconds [8]. Furthermore, our proposed algorithm dynamically reroutes some already established lightpaths from longer paths to vacant shorter ones so as to reduce the network resources consumption. This should hopefully lead to a better resource utilization efficiency. The SeqRwTBHLR algorithm allows active LRR of an existing RLD only once during its life period so as to reduce the service disruption period. The active LRR procedure is initiated periodically during the life period of an established RLD. Indeed, a timer is cocked at the setup time of the arriving RLD and the active LRR procedure is launched whenever the timer expires. In the following, we first define the notations used in the subsequent subsections. We then describe the routing and rerouting procedures in details.

3.1. Notations

We use the following notations and typographical conventions:

- $G = (\Psi, \mathrm{E}, \eta)$ is an arc-weighted symmetrical directed graph representing the network topology with vertex set Ψ , arc set E and weight function $\eta : \mathrm{E} \rightarrow \mathbf{R}_+$ mapping the physical length or any other cost of the links set by the network operator of each arc of E . We here assume that all fiber-links have the same cost equal to 1.
- $N = |\Psi|$ denotes the number of vertices (network nodes) of the directed graph representing the network topology.
- $L = |\mathrm{E}|$ denotes the number of arcs (network links) of the directed graph representing the network topology.
- $\Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_W\}$ is the set of available wavelengths on each fiber-link of the network.
- $W = |\Lambda|$ 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.
- D denotes the total number of RLDs to be set up.
- The i^{th} RLD, $1 \le i \le D$ (to be established), 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 RLD, respectively; π_i is the number of requested lightpaths; and α_i and β_i are the setup and teardown time of the RLD, 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 ($\pi_i = 1$).

- P_i , represents the shortest path already used by the RLD numbered i .
- μ_i , is a positive number that denotes the number of hops on P_i .
- R_i , represents the shortest path in G to be used by the rerouted RLD numbered i .
- ρ_i , is a positive number corresponding to the number of hops on R_i .

3.2. The routing procedure

The SeqRwTBHLR algorithm's routing procedure is based on the algorithm described in [8]. The approach is to transform the network to a graph. The graph's vertices correspond to the network nodes whereas the edges correspond to the fiberlinks. Each edge in the graph is associated a weight label representing the cost of routing a new lightpath on the corresponding fiber-link. To reduce the computational complexity and to simplify the notation, we decompose the graph into a few disjoint subgraphs, each corresponding to the network on a particular wavelength. The routing algorithm finds the shortest path on each subgraph and then chooses the least costly one among all the individual subgraphs. Smallest wavelength index is used to break a tie. The minimum-cost wavelength and its associated shortest path, if the routing of the demand is feasible, are selected according to the following three steps:

3.2.1. Step1: Graph transformation

- The network $G = (\Psi, \mathrm{E})$ with the wavelength set Λ is transformed into a collection of disjoint subgraphs $G = (\Psi^{\lambda}, \mathrm{E}^{\lambda}), \lambda \in \Lambda$, each corresponding to the network on a particular wavelength. For each wavelength $\lambda \in \Lambda$, the subgraph $G = (\Psi^{\lambda}, \mathrm{E}^{\lambda})$ is obtained by generating a vertex i^{λ} and an edge $\left(i^{\lambda}, j^{\lambda}\right)$ if $i \in \Psi$ and $(i, j) \in \mathrm{E}$, respectively. Thus the new graph is $\bigcup_{\lambda \in \Lambda} G\left(\Psi^{\lambda}, \mathrm{E}^{\lambda}\right)$ where:

$$\Psi^{\lambda} = \left\{i^{\lambda} : i \in \Psi\right\}, \lambda \in \Lambda$$

$$\mathrm{E}^{\lambda} = \left\{\left(i^{\lambda}, j^{\lambda}\right) : (i, j) \in \mathrm{E}\right\}, \lambda \in \Lambda$$

3.2.2. Step 2: Cost Labeling

$c\left(i^{\lambda}, j^{\lambda}\right)$ is the cost of using wavelength λ on link (i, j). The weight function of each edge of the graph is determined by whether a channel is free or busy, i.e.,

$$c\left(i^{\lambda}, j^{\lambda}\right) = \begin{cases} \varepsilon & \text{if } \lambda \text{ is free on link } (i, j) \\ +\infty & \text{otherwise} \end{cases}$$

Where ε is a tiny positive value.

3.2.3. Step 3: Route Searching:

For each $\lambda \in \Lambda$, the routing algorithm computes the shortest loop-free path with finite cost on each subgraph $G = (\Psi^{\lambda}, \mathrm{E}^{\lambda})$ according to the algorithm described in [16]. Let Ω be the set of all computed shortest paths. Two cases may happen:

- $\Omega = \infty$, no shortest paths with finite cost exist and the passive WRR procedure, described in subsection 3.3.1, will be considered.
- $\Omega \neq \infty$, which means that there is at least one available path-free wavelength along one shortest path connecting the source node to the destination node of the RLD to be set up. The least costly path and its corresponding wavelength are selected to break a tie. It may happen that two or multiple shortest paths have the same cost. In that case, the wavelength with the smallest index is used.

3.3. The rerouting procedures

3.3.1. The passive WRR procedure

We assume that a new RLD numbered i arrives at time t and that the routing procedure fails to establish it. The passive WRR procedure is hence launched to hopefully free a path-free wavelength for the incoming RLD after rerouting a minimum number of existing RLDs to a new vacant wavelength on the same path. It proceeds in three steps.

- Step 1: We need the following notations to explain the principles of the first step. Assume that an existing lightpath $u \in U$ (U is the set of existing lightpaths in the network), passes through the sequence of directed links $\left[i_j(u), i_{j+1}(u)\right], j = 1, \ldots, h(u)$ ($h(u) =$ the number of hops in u) , on the wavelength $\lambda(u)$. Define $g(u),\ u \in U$ as the retuning variable: $g(u) = \lambda$ if the lightpath u can be retuned to the vacant wavelength on the same path with the smallest index λ , i.e.,

$\lambda = \min\left\{\lambda' \in \Lambda : \left(i_j^{\lambda'}(u), i_{j+1}^{\lambda'}(u)\right) \text{ is free}\right\}$, $j = 1, \ldots, h(u)$ and $g(u) = Null$, otherwise. A returnable lightpath u is $g(u) \neq Null$ [8].

After identifying all the retunable lightpaths on same paths, step 2 begins.

- Step 2: It constructs an auxiliary graph by creating crossover edges for every retunable lightpath. A crossover edge between nodes n_1 and n_2 for a retunable lightpath p is created, if there exists a path of length two or more between n_1 and n_2 comprising only the edges of p. The cost for an idle edge is a tiny positive constant δ while the cost for a non-retunable edge and for an already rerouted edge on new physical path is infinite. Cost for a retunable edge associated with retunable lightpath u is c_u (c_u = number of WDM channel to be rerouted) which is a positive weighting factor indicating the penalty of rerouting an existing lightpath u to accommodate the new RLD.
- Step 3: The least costly shortest path and associated wavelength will be sought for serving the new RLD. If the resulting minimum cost is finite, the new RLD can be successfully accommodated after rerouting one or several existing lightpaths which are determined by the first phase of rerouting. Those existing lightpaths overlapping with the new RLD should be rerouted to the vacant wavelength on the same path as indicated by the retuning variable $g(u)$.

If no path with a finite cost can be found, the new RLD is definitively rejected.

3.3.2. The active LRR procedure:

When a new arriving RLD numbered i is successfully established on path P_i , a rerouting timer is started. This timer starts at a predetermined value κ and counts down over time. When the rerouting timer expires, the active LRR procedure is launched. If the existing RLD has not been already rerouted by the passive WRR procedure, two different situations may happen:

- If $\mu_i - \rho_i \geq \sigma$ i.e the difference between the number of hops of P_i and that of the new vacant path R_i is higher than the pre-defined rerouting threshold σ . The new path R_i is considered to be more suitable to carry the active RLD. The active RLD numbered i is hence rerouted from P_i to R_i. The cost of the edges on R_i is updated to $+\infty$ and that of the edges on the released path P_i is updated to ε .
- If $\mu_i - \rho_i < \sigma$, we here assume that it is not worthy to reroute the active RLD numbered i to R_i and no rerouting is performed. The timer is reinitialized to κ and the active LRR procedure is once again launched when the timer expires.

Transmission of the existing lightpaths to be rerouted must be temporarily shut-down to protect data from being lost or misrouted resulting in long service disruption incurred by the longer propagation delay for transmitting signaling messages in all-optical wide-area networks. Therefore, in such networks minimization of the incurred service disruption is imperative.

In order to shorten the duration of the service disruption period, one may notice that our proposed algorithm allows wavelength rerouting of an existing RLD several times but rerouting of an existing RLD on new physical path is allowed only once during its life period. This is because that, as theoretically demonstrated in [26], the service disruption period is lower for rerouting a RLD on new wavelength on the same physical path than for rerouting an existing RLD on new physical path and eventually a new wavelength.

IV. NUMERICAL RESULTS

To evaluate the performance of the proposed Timer-Based hybrid lightpath rerouting algorithm, we simulate it on the network topologies shown in Figures 1 and 2, respectively. The following assumptions are used. RLDs arrive according to a Poisson process with common arrival rate r and once accepted, will hold the network resources for exponentially distributed times with mean holding time equal to 1 much larger than the network-wide propagation delay and the connection setup delay. The source and destination nodes of the connection requests arriving at the network are chosen according to a random uniform distribution in the interval [1, 21] for the 21- node network and in [1, 29] for the 29-node network. Each fiber supports W = 13 wavelengths. Each node has enough transmitters and receivers such that a new connection request will not be blocked due to lack of transmitters and receivers. A blocked connection is cleared and will not retry.

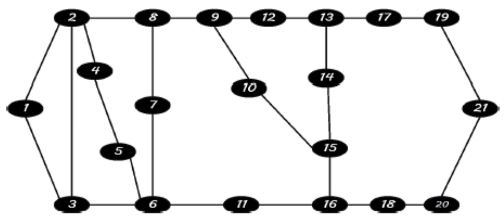

Fig.1: the 21-node network topology

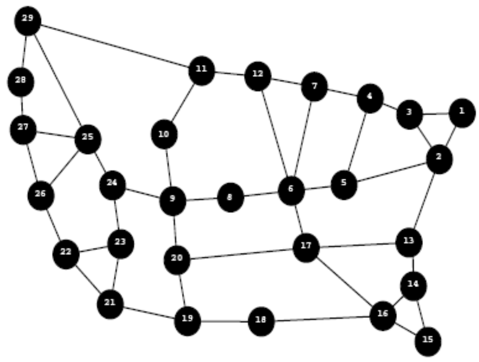

Fig.2: the 29-node network topology

We generate 25 test scenarios, run the algorithms for each scenario, and compute rejection ratio averages, rejection ratio gain averages and average ratios of rerouted connection for each algorithm.

We will merely report in the following the curves obtained with the 21-node network as those obtained with the 29-node network present the same tendency.

4.1. Discussion on the values of the rerouting timer's predetermined value (κ) and rerouting threshold (σ)

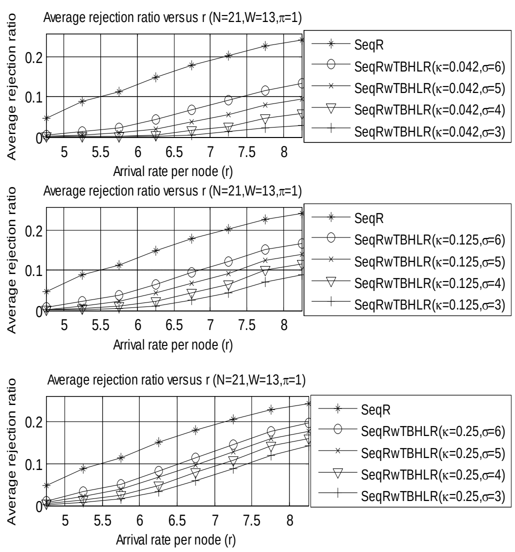

Fig 3: the SeqRwTBHLR algorithm's average rejection ratio w.r.t. r

Fig 3 draws the impact of the rerouting timer's predetermined value κ and the rerouting threshold σ on the SeqRwTBHLR algorithm's rejection ratio. The results join the intuition that small values of κ and σ give better performances in terms of rejection ratio. But with the decrease of κ , the signaling overhead will increase because the SeqRwTBHLR algorithm needs to refresh the information of network status more frequently. Also, with the decrease of σ , the average number of rerouted RLDs will increase leading to a higher service disruption period. In order to point out the gain obtained thanks to rerouting, we also plot on the same figure (first data curve) the average rejection ratio obtained by a traditional no-rerouting algorithm called the Sequential RWA algorithm (SeqR) which computes the RWA for the arriving RLDs on the fly without any rerouting according to the routing procedure described in Subsection 3.2.

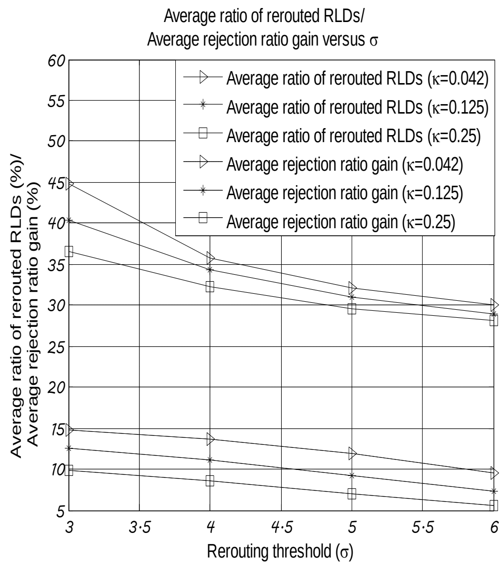

Fig 4: the SeqRwTBHLR algorithm's average ratio of rerouted connections /average rejection ratio gain versus κ and σ

In Fig 4, we plot the average ratio of rerouted connections and the average rejection ratio gain obtained by the SeqRwTBHLR algorithm w.r.t. κ and σ . The average ratio of rerouted RLDs has been computed as the average number of rerouted RLDs divided by the total number of RLDs arriving at the network and multiplied by 100. The average rejection ratio gain has been computed as the difference between the average number of rejected RLDs computed by the SeqR and the SeqRwTBHLR algorithms respectively, divided by the total number of RLDs arriving at the network and multiplied by 100. The results are shown in Table I.

Table I - Average ratio of rerouted RLDs /average rejection ratio gain versus κ and σ

κ \ σ	3	4	5	6
0.042	44.7/14.7	35.8/13.7	32.1/11.9	30.1/9.5
0.125	40.4/12.5	34.3/11.1	31.1/9.2	28.9/7.2
0.25	36.4/9.8	32.2/8.5	29.5/7.1	28.1/5.5

From Fig 4, we notice that smaller values of κ and σ lead to a better rejection ratio gain. But, if the value of κ and σ are too small, the average number of rerouted RLDs increases resulting in higher overall service disruption period incurred due to rerouting. From the preceding observations, one should notice that a trade-off arises between the rejection ratio gain and the rerouting timer's predetermined value κ and the rerouting threshold σ. A reasonable tradeoff is observed for $\sigma = 5$ hops and $\kappa = 0.042$, i.e, if the average lightpath holding time is one day, then κ can be set to 1 hour. By setting the value of κ to 0.042 and that of σ to 5, we achieve an average rejection ratio gain equal to 11.9% (respectively 11.2% for the 29-node network) while keeping the service disruption period at a very low level since the average ratio of rerouted RLDs is 32.1% (respectively 27.2% for the 29-node network) and only 15.7% of which are rerouted on new physical paths (respectively 14.4% for the 29-node network).

Furthermore, we notice that the three curves showing the variation of the average ratio of rerouted RLDs are so close when $\sigma = 5$ and in contrast the curves representing the average rejection ratio gain are not enough close. Indeed, we notice a significant reduction in terms of average rejection ratio gain (□ 3%) when $\kappa = 0.125$ and $\kappa = 0.25$ for a slight reduction in the average ratio of rerouted RLDs (□ 1%) compared to the case $\kappa = 0.042$. These results consolidate, once again, our choice for the values of κ and σ.

4.2. Rejection ratio

As already mentioned, we set, in the following, the value of σ to 5 and that of κ to 0.042 and propose to study the performances of our proposed algorithm, in comparison with those obtained by the traditional no-rerouting algorithm (SeqR) in order to assess the gain obtained thanks to rerouting, and the following four algorithms:

- The Parallel Move To Vacant Wavelength Retuning algorithm (Parallel MTV-WR) described in [8]. The Parallel MTV-WR algorithm is a passive wavelength rerouting algorithm that performs wavelength rerouting if an arriving RLD is to be rejected due to lack of resources.
- The Sequential Routing with Lightpath Rerouting algorithm (SeqRwLR) described in [15]. The SeqRwLR algorithm is a passive lightpath rerouting algorithm which initiates the rerouting procedure only when an incoming RLD is to be blocked due to lack of resources.
- The Timer-Based Active Lightpath Rerouting (TB-ALR) algorithm described in [18]. The TB-ALR algorithm is an active lightpath rerouting algorithm that dynamically reroutes some already established RLDs from longer paths to vacant shorter ones so as to reduce the network resources consumption and therefore provides a better network usage. It initiates the rerouting procedure every time a timer expires
- The Sequential Routing with Hybrid Lightpath Rerouting algorithm (SeqRwHLR) described in [19]. The SeqRwHLR algorithm establishes the RLDs sequentially. When an incoming RLD cannot be set up in the absence of path-free wavelengths between its source and destination nodes, it performs passive rerouting procedure aiming hopefully at freeing a path-free wavelength to service the new RLD. Furthermore, it reroutes some active lightpaths from longer paths to vacant shorter ones so as to reduce the network resources consumption when an existing RLD leaves and its lightpath is released.

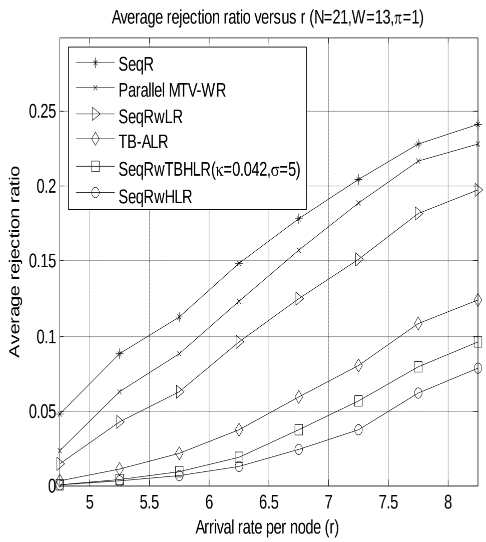

Fig 5: average rejection ratio w.r.t. r

Fig 5 draws the average rejection ratio computed by the above six algorithms with respect to traffic loading per node, r. From a first observation of the curves presented in this figure we can conclude that algorithms performing rerouting (be it passive, active or hybrid) improve the rejection ratio significantly compared to the no-rerouting case. On the average, the rejection ratio is reduced up to

13% with the SeqRwHLR algorithm (respectively 12% for the 29-node network), 12% with the SeqRwTBHLR algorithm (respectively 11.2% for the 29-node network), 10.1% with the I-MTVSP algorithm (respectively 10.4% for the 29-node network), 5% with the SeqRwLR algorithm (respectively 4% for the 29-node network) and 2% with the Parallel MTV-WR algorithm (respectively 1.2% for the 29-node network).

We can also observe that the passive rerouting algorithms (the Parallel MTV-WR and the SeqRwLR algorithms) have the worst connection requests rejection ratios. This is due to the fact that active rerouting can utilize wavelength resources more efficiently. In fact, these two algorithms perform only passive rerouting whereas all the other rerouting algorithms perform either active or hybrid lightpath rerouting. Furthermore, performing only WRR results in lower rejection ratio gain. Also, performing lightpath rerouting when a new RLD is to be blocked due to lack of network resources, may lead to rerouting several existing RLDs. These RLDs to be rerouted may use longer paths and hence may consume more network resources. This may block up the establishment of future arriving RLDs.

We also notice that hybrid lightpath rerouting algorithms are able to yield the smallest rejection ratios. This is due to the fact that hybrid rerouting combines passive wavelength rerouting and active lightpath rerouting and hence provides a better blocking performance. Indeed, reducing network resources consumption using active rerouting and performing passive wavelength rerouting when a new incoming RLD is to be blocked due to lack of resources lead obviously to a better rejection ratio.

Moreover, we notice that the SeqRwHLR algorithm outperforms slightly the SeqRwTBHLR algorithm. On the average, the former rejects 1% (respectively 0.8% for the 29-node network) fewer requests than the latter. This is mainly due to the fact that the SeqRwHLR algorithm initiates the active rerouting procedure at the departure of an existing RLD when its network resources are released and hence network resources reduction can be so impressive resulting in establishing furthermore incoming RLDs either without rerouting or by performing passive wavelength rerouting. Whereas, the SeqRwTBHLR algorithm launches the rerouting procedure at some predefined time instants which do no correspond necessarily to the departure times of already established RLDs. This causes the failure of the active rerouting procedure when no network resources are released and eventually the failure of the passive wavelength rerouting procedure. The impact of this becomes especially severe when the number of accepted RLDs increases in the network.

4.3. Rejection Ratio Gain

Fig 6 shows the average rejection ratio gain versus the traffic loading per node. We notice that the rejection ratio gain increases with the traffic load before it falls down under heavy traffic load. In fact, under low traffic load, our proposed algorithm still manages to satisfy a maximum number of arriving RLDs either by reducing network resources consumption by rerouting dynamically some of the established RLDs on shorter new physical paths or by partially rearranging some already established RLDs to set up a RLD to be rejected due to lack of resources. Whereas when r increases, the average rejection ratio gain falls down. This is because the saturation regime of the network is achieved and it becomes increasingly difficult to find new vacant shorter paths, satisfying the rerouting threshold constraint, on which the established RLDs can be rerouted in order to set up more RLDs and impossible to accommodate more RLDs even by performing passive rerouting as no network resources are left.

Note that the SeqRwTBHLR algorithm achieves a maximum rejection ratio gain equal to 14.9% (respectively 14.6% for the 29-node network) under the aforementioned simulation parameters.

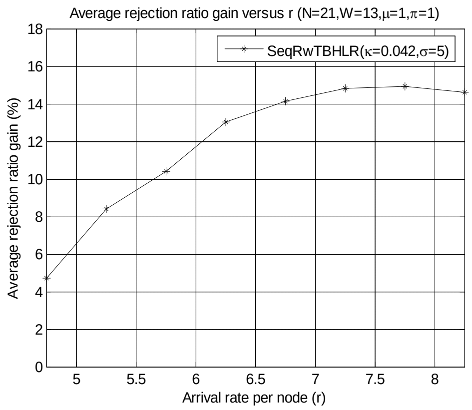

Fig 6: average rejection ratio gain w.r.t. r

4.4. Average Ratio of Rerouted RLDs

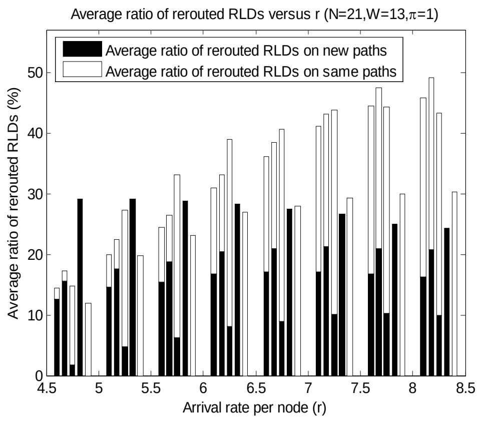

Fig 7: Average ratio of rerouted RLDs w.r.t. r

In Fig 7, each group of five bars shows the average ratio of rerouted already established RLDs computed using the SeqRwTBHLR algorithm (first bar from the left-hand side), the SeqRwHLR algorithm (second bar), the SeqRwLR algorithm (third bar), the TB-ALR algorithm (fourth bar) and the Parallel MTV-WR algorithm (fifth bar) respectively. The height of the black bar indicates the average ratio of rerouted RLDs on new paths whereas the height of the white one shows the average ratio of rerouted RLDs on same paths. Results are shown in details in Table II.

Table II - Average ratio of rerouted RLDs

Algorithms	Average ratio of rerouted RLDs using LRR (%)	Average ratio of rerouted RLDs using WRR (%)
SeqRwTBHLR	15.7	16.4
SeqRwHLR	19.5	15.1
SeqRwLR	7.5	28.2
TB-ALR	27.3	0
Parallel MTV-WR	0	24.8

From this Figure one may bring out the following main conclusions.

On the average, the Parallel MTV-WR and the TB-ALR algorithms require fewer RLDs to be rerouted than the others algorithms. But let us remind that the Parallel MTV-WR algorithm performs only WRR to minimize the incurred service disruption due to rerouting. On the opposite, the TB-ALR algorithm reroutes existing RLDs on new physical paths and its incurred disruption should be important. These observations can explain the fact that the TB-ALR algorithm outperforms the Parallel MTV-WR which presents the worst rejection ratio.

Also we notice that the SeqRwLR algorithm requires to reroute more existing RLDs than all the others algorithms whereas, this algorithm reroutes only 7.5% of existing RLDs on new physical paths. Therefore its incurred service disruption period should be little.

Hybrid lightpath rerouting algorithms require to reroute more RLDs than active lightpath rerouting algorithm but reroutes fewer RLDs on new physical paths than the TB-ALR. This is mainly due to the imposed rerouting rule. Let us remind that an active RLD rerouted by the active rerouting procedure cannot be rerouted by the passive rerouting procedure and vis-versa.

Our proposed algorithm reroutes less RLDs on new physical paths than the SeqRwHLR algorithm. This should hopefully lead to a shorter service disruption period.

For small values of *r*, active lightpath rerouting algorithm requires more active RLDs to be rerouted than passive and hybrid rerouting algorithms. Whereas hybrid and passive rerouting algorithms reroute slightly the same number of existing RLDs. Under high traffic load and unlike passive and hybrid rerouting algorithms, the TB-ALR algorithm reroutes fewer existing RLDs than passive and hybrid rerouting algorithms. This can be explained by the fact that when the network reaches its saturation regime, it becomes difficult to reroute an active RLD to a new path with σ hops lower than the number of hops on its already used path. That's why hybrid rerouting algorithms have to reroute more RLDs using WRR. Moreover, passive rerouting algorithms require to reroute a large number of existing RLDs under high traffic load when it becomes difficult to set up an arriving RLD without rerouting existing RLDs as the amount of available network resources become very low.

V. CONCLUSION

In this paper, we proposed a simple hybrid lightpath rerouting algorithm for WDM transparent optical networks when considering random traffic. Simulation results show that the proposed algorithm provides important rejection ratio gain. Moreover, it reroutes a minimum number of existing RLDs using LRR. We hope, thus, that it achieves minimum service disruption period.

Our forthcoming studies will investigate the RWA problem with signal-quality constraint applying hybrid rerouting.

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