Efficient Rerouting Algorithm for Optimizing Performances of WDM Transparent Networks Under Scheduled and Random Traffic

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***Abstract*—In this paper, we investigate further improvement in performances of Wavelength Division Multiplexing (WDM) transparent networks under scheduled and random traffic by applying traffic rerouting. Scheduled traffic corresponds to high priority traffic, whereas random traffic corresponds to best effort traffic. Indeed, in WDM transparent networks, the wavelength clash constraint along with the wavelength continuity constraint result in inefficient utilization of network resources and lead to higher rejection ratio. The traffic rerouting concept is a cost-effective and viable solution used to alleviate the inefficiency brought by the wavelength continuity, but it induces a service disruption period. Therefore, minimization of the incurred service disruption period is imperative. Our proposed rerouting algorithm proceeds in two separate phases. It first computes off-line the routing and wavelength assignment (RWA) for scheduled lightpath demands (SLDs) before considering random lightpath demands (RLDs) on the fly on the remaining network resources. Thus, if an incoming RLD cannot be established in the absence of a free wavelength-continuous path between its source and destination nodes, the proposed algorithm may reroute a minimum number of not yet routed SLDs and already routed RLDs. Rerouting of already routed SLDs is not allowed since they correspond to high priority guaranteed service. Allowing rerouting of not yet routed SLDs should lead to a shorter service disruption period. The performance of the proposed algorithm is evaluated and discussed through extensive numerical experiments. Significant improvements are demonstrated, either in terms of rejection ratio or in terms of service disruption period, in comparison with rerouting algorithms previously presented in the literature.**

***Keywords*–Routing and Wavelength Assignment (RWA); Service disruption period; Traffic rerouting; Wavelength continuity constraint; WDM transparent networks.**

I. Introduction

An optical network provides a common infrastructure over which a variety of services, such as video on demand, video conference, distance education can be delivered [1]. The requirement for networks with high capacity is increasing. There are many ways to increase the capacity of the optical fiber and one of the ways is Wavelength Division Multiplexing (WDM). In WDM networks, an optical communication path, referred to as lightpath, is set up to support a connection between two optical wavelength-routing nodes. 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]. The RWA problem has been extensively investigated in the literature and several approaches have been proposed either for static traffic or dynamic traffic (see [3], among others).

In the absence of wavelength converters, optical networks are referred to as transparent networks or all-optical networks [4]. In such networks, a lightpath is established before data can be transferred by allocating the same wavelength on all the fiber links in the route through which data traffic is transmitted. This constraint is called the wavelength continuity constraint [5]. Also, two lightpaths sharing at least one common fiber-link must be identified by different wavelengths to prevent the interference of the optical signals. This second constraint is called the wavelength integrity constraint. These limitations lead to inefficient utilization of wavelength channels which results in higher blocking ratios. Wavelength conversion and traffic rerouting are the two possible mechanisms that can increase the efficiency. Using wavelength converters potentially allows the network to support a larger set of Lightpath Demands (LDs). But, such converters remain too expensive. When wavelength conversion is not available, rerouting is used to improve network usage. It consists in rearranging certain existing lightpaths to free a wavelength-continuous path for the incoming LD. There are two ways to rearrange an existing lightpath. One is partially rearranging, which only changes the used wavelength and keeps the same physical route. This is also referred to as wavelength rerouting (WRR). Another is fully rearranging, which consists of finding a new physical path with possibly a new wavelength to replace the old path. This is referred to as lightpath rerouting (LRR). A taxonomy of rerouting schemes can be found in [6]. Transmission of the existing lightpaths to be rerouted must be temporarily shutdown to protect data from being lost or misrouted resulting in service disruption incurred by the longer propagation delay for transmitting signaling messages in transparent wide-area networks [7]. This period is referred to as the service disruption period. Therefore, in such networks, minimization of the incurred service disruption is imperative.

In this paper, we present a new rerouting algorithm in order to get further improvement either in terms of rejection ratio or in terms of service disruption period when two classes of traffic demands are considered:

- The first class is referred to as Scheduled Lightpath Demand (SLD). A SLD is a connection request with known setup and teardown times. The SLD model is deterministic since the demands are known in advance and is dynamic because it takes into account the evolution of the traffic load in the network over time.
- The second class is referred to as Random Lightpath Demand (RLD). A RLD, also called dynamic lightpath

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demand, is a connection request that arrives randomly.

Through numerical results, we outline that thanks to rerouting, the lightpath demands' rejection ratio is improved and that our LRR algorithm selects a minimum number of established RLDs to be rerouted which should hopefully lead to a short service disruption period.

The rest of this paper is organized as follows. Section II presents related work. In Section III, we summarize our main contributions. In Section IV, some notations are given. In Section V, we present in detail the proposed rerouting algorithm. Numerical results and concluding remarks are given in Sections VI and VII, respectively.

II. Related Work

The traffic rerouting concept has been applied to WDM transparent networks to alleviate the impact of the wavelength continuity constraint. In [7], Lee et al. introduced the WRR concept by studying the rerouting problem with the objective of minimizing the disruption incurred due to WRR. In [8], Mohan and Murthy proposed a time optimal wavelength rerouting algorithm based on the Parallel Move-To-Vacant Wavelength-Retuning (MTV-WR) rerouting scheme. In [9] and [10], the authors proposed two low complexity wavelength rerouting algorithms to improve throughput and to reduce blocking probability in wavelength division multiplexed networks. The former is called the Shortest Path Wavelength ReRouting (SPWRR) algorithm while the latter is called the Lightpath ReRouting Algorithm (LRRA). The authors also demonstrated that LRRA gives better results and can be implemented in huge networks for good blocking performance. Recently, a new lightpath rerouting scheme called Sequential Routing with Lightpath Rerouting (SeqRwLR) has been proposed in [11] to improve the rejection ratio while keeping a short service disruption period. In [12] and [13], the authors investigated hybrid rerouting to increase the network throughput and minimize the incurred service disruption period. In [14], the authors compared passive, active and hybrid rerouting. They demonstrated that when there is wavelength conversion, passive rerouting outperforms active rerouting, and hybrid rerouting can only improve the performance over passive rerouting slightly. Also, they demonstrated that, in the absence of wavelength converters, hybrid rerouting can improve the blocking performance significantly. Later, two RWA algorithms applying active lightpath rerouting are presented in [15]. The authors show that, in the absence of wavelength converters and in contrast to the results announced in [14], active rerouting works much better than passive rerouting but induces a longer service disruption period. Improving the performances of transparent optical networks in terms of rejection ratio by exploiting the set-up delay tolerance specification contained in the Service Level Agreement (SLA) has already been investigated in [1][16][17][18]. The basic idea is to delay LDs instead of rejecting them due to the current network state and try to establish them after some time, since other routed LDs may leave the network and its network resources are released. While in all of the above described algorithms dynamic traffic is considered, in [19], the authors proposed a new lightpath rerouting scheme to optimize network resources allocation considering scheduled and random lightpath demands. Their scheme prohibits SLD rerouting while the establishment of a new RLD may require the rerouting of one or several RLDs. To the best of our knowledge, this is the first attempt to apply rerouting of not already established SLDs to maximize the number of established RLDs and moreover, minimize the incurred service disruption period. The performances of the proposed algorithm either in terms of rejection ratio or in terms of service disruption period are demonstrated to be promising through illustrative simulation results.

III. Contribution of the Paper

In this paper, we present an efficient RWA algorithm for WDM transparent networks working under the wavelength continuity constraint without wavelength converters. We anticipate to alleviate the inefficiency brought by the wavelength continuity constraint by the use of an efficient lightpath rerouting strategy minimizing the number of rejected LDs. A combination of two traffic classes, namely, SLDs and RLDs are considered. Permanent lightpath demands (PLD) (i.e. static lightpath demands which are preknown connection requests and if accepted, remain in the network indefinitely) are not considered in this study because, once established, these demands remain in the network indefinitely. This can be considered as a reduction in the number of available wavelengths channels on some network fiber-links.

Our proposed scheme computes the RWA for the SLDs and the RLDs separately. First, it computes the RWA for the SLDs off-line, as SLDs correspond to preknown traffic, aiming at minimizing the number of blocked SLDs. Taking the assignment of the SLDs into account, the RWA for the RLDs is computed sequentially. When an incoming RLD cannot be established in the absence of a wavelength-continuous path between the source and the destination of the RLD, we try to reroute one or several SLDs in the set of SLDs that are not yet routed and/or a minimum number of already routed RLDs aiming hopefully at freeing a wavelength-continuous path to accommodate the incoming RLD. We assume that an already established SLD cannot be rerouted since SLDs correspond to high priority guaranteed service, and only SLDs that have not been routed yet can be rerouted. Unlike SLDs, already established RLDs may be rerouted to accommodate the new incoming RLD. In order to shorten the duration of the service disruption period, our rerouting algorithm promotes rerouting of not yet routed SLDs. This is because the service disruption period incurred by rerouting a not yet routed SLD is shorter than that incurred by rerouting an already established RLD. Theoretically, the service disruption period incurred due to rerouting a not yet routed SLD is very short since the SLD is not yet routed and the data transmission is not yet started. Our proposed algorithm differs from the previously published ones in the following aspects:

- First, it considers two classes of traffic demands. Only RLDs have been considered in all the others algorithms presented in the literature. In [19], two types of traffic demands are considered.
- Second, when a new RLD is to be rejected by the routing phase, the rerouting phase selects one or several RLDs and/or not yet routed SLDs to be rerouted in order to accommodate the new RLD. Whereas, in [19], the rerouting of SLDs is forbidden once the optimal RWA for the SLDs is computed off-line and only rerouting of already established RLDs is allowed. As mentioned above, rerouting not yet routed SLDs has a

direct impact on the duration of the service disruption period.

- Third, our proposed algorithm does not construct any auxiliary graph with crossover edges to determine the set of active lightpaths that should be rerouted as in [7][8][11]. Thus, our algorithm should be less Central Processing Unit (CPU) intensive than rerouting algorithms previously presented in [7][8][11].

IV. NOTATIONS

We use the following notations and typographical conventions:

- $G = (\nu, E, \vartheta)$ is an arc-weighted symmetrical directed graph representing the network topology with vertex set ν (representing the network nodes), arc set E (representing the network fiber-links) and weight function $\vartheta : E \rightarrow R+$ mapping the cost of the links set by the network operator.
- $N = |\nu|$, $L = |E|$ are respectively, the number of nodes and links in the network.
- D is the total number of LDs (SLDs and RLDs) which arrives at the network over the considered time period.
- W denotes the number of wavelengths per fiber-link.
- $\Lambda = \{\lambda_1, \lambda_2, ..., \lambda_W\}$ is the set of available wavelengths on each fiber-link of the network.
- The i^{th} LD, $1 \leq i \leq D$ (to be established), is defined by a $5-$tuple $(s_i, d_i, \pi_i, \alpha_i, \beta_i)$. $s_i \in \nu$ and $d_i \in \nu$ are the source and the destination nodes of the LD, respectively; π_i is the number of requested lightpaths; and α_i and β_i are the setup and teardown time of the LD, respectively. Here, for the sake of simplicity, we assume that each LD requires only one lightpath between the source and the destination nodes ($\pi_i = 1$).
- $P_{i,k}$, $1 \leq i \leq D$, $1 \leq k \leq K$, represents the k^{th} alternate shortest path in G connecting node s_i to node d_i (source and destination of the i^{th} LD). The hop count is used as the link metric and K-alternate (loop-free) shortest paths for each source$-$destination pair (LD) are computed beforehand according to the algorithm described in [20] (if as many paths exist, otherwise we only consider the available ones).
- P_i, $1 \leq i \leq D$, is the set of alternate shortest paths computed between the source and destination nodes of LD number i. Hence $|P_i| \leq K$. This computation is done in a preliminary step prior to any routing.
- P is the set of alternate shortest paths computed between the source and destination nodes of each possible node pair in the network. Clearly $|P| \leq N(N-1)K$.
- $c(i,k,w,t)$, $1 \leq i \leq D$, $1 \leq k \leq K$, $1 \leq w \leq W$ 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 LD numbered i at time t. The cost function of each considered path is determined as follows:

$$c(i,k,w,t) = \begin{cases} \varepsilon & \text{if } \lambda_w \text{ is path-free on } P_{i,k} \\ \infty & \text{if } \lambda_w \text{ is already used by another} \\ & \text{LD on at least on link of } P_{i,k} \end{cases}$$

  ε is a tiny positive value corresponding to the hop count on path $P_{i,k}$.
- $\theta(i,k,w,t)$, $1 \leq i \leq D$, $1 \leq k \leq K$, $1 \leq w \leq W$, denotes the set of LDs to be rerouted when serving the incoming RLD number i at time t using wavelength λ_w on $P_{i,k}$.
- $cr(j)$, $1 \leq j \leq |\theta(i,k,w,t)|$ is the cost of rerouting the j^{th} LD $\in \theta(i,k,w,t)$ in order to satisfy the incoming RLD on $P_{i,k}$, using wavelength λ_w.

$$cr(j) = \begin{cases} \tau, & \text{if the LD to be rerouted is a not} \\ & \text{yet established SLD} \\ \sigma, & \text{if the LD to be rerouted is an already} \\ & \text{routed RLD} \end{cases}$$

  τ is a tiny positive constant and σ is a positive weighting factor indicating the penalty of rerouting an already routed RLD to accommodate the new demand. σ is chosen such that $(\sigma \gg \tau)$ to promote rerouting of not yet routed SLDs. τ and σ are chosen such that the number of RLDs to be rerouted is minimized which should lead to the minimization of the service disruption incurred by rerouting.
- $cr(i,k,w,t) = \sum_{j \in |\theta(i,k,w,t)|} cr(j)$, $1 \leq i \leq D$, $1 \leq k \leq K$, $1 \leq w \leq W$ is the cost of rerouting to set up the incoming RLD number i at time t using wavelength λ_w on $P_{i,k}$.
- $cr^{min} = min_{1 \leq k \leq K, 1 \leq w \leq W} cr(i,k,w,t)$ is the minimum cost to satisfy the new RLD number i at time t on $P_{i,k^{min}}$ using wavelength $\lambda_{w^{min}}$.

V. THE PROPOSED SCHEME

Our proposed LRR algorithm called SepRwLR, for Separate Routing with Lightpath Rerouting, handles the SLDs and the RLDs separately, as shown in Figure 1. First, it considers the RWA for SLDs before considering the RLDs. The objective is to minimize the number of blocked SLDs. No rerouting is performed when computing the RWA for SLDs. Taking the RWA of the SLDs into account, the SepRwLR then tries to route sequentially the incoming RLDs in the following two phases:

- The first phase, also called routing phase, computes the RWA for a new RLD without considering rerouting.
- If Phase I fails, rerouting phase determines which LDs (already routed RLDs and not yet routed SLDs) are to be rerouted and how they will be rerouted to accommodate the incoming RLD.

Subsection V-A details the routing and wavelength assignment algorithm for LDs (be it scheduled or random) whereas Subsection V-B details the rerouting algorithm for RLDs.

A. Routing and Wavelength Assignment for LDs

At the incoming time of a new LD, we first try to establish it without rerouting any active lightpaths according to the traditional sequential Dijkstra based algorithm. The associated K-alternate shortest paths (computed off-line and denoted P_i) are considered in turn according to their number of hops. We look for the first path-free wavelength. The LD is hence set

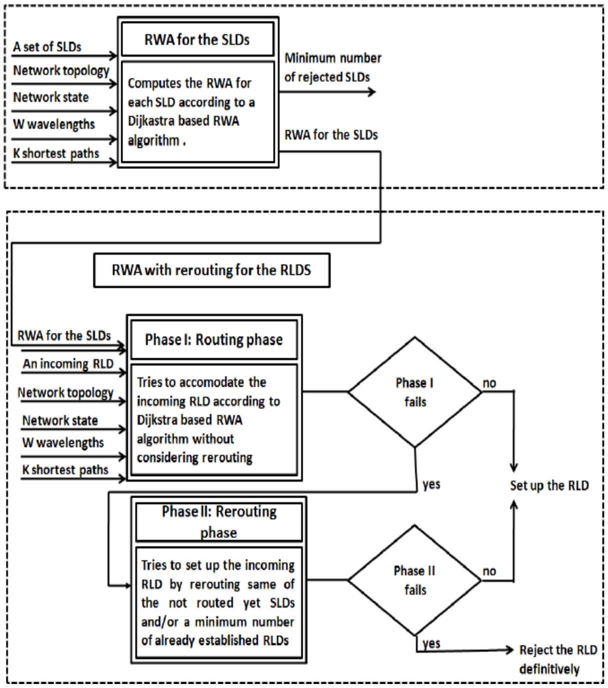

Figure 1. Block diagram of the SepRwLR algorithm.

up on the first met path-free wavelength among its K-shortest-paths if such path exists. The wavelength assigned to this path is selected according to a first-fit scheme [21] whenever multiple wavelengths are available on the considered path. If a path-free wavelength to satisfy the demand does not exist, two cases may happen: the demand is a SLD, in which case it is rejected since no rerouting is performed when computing the RWA for SLDs. The second case that may happen is that the demand is a RLD in which case the rerouting phase will be considered.

B. Rerouting algorithm for RLDs

We assume that a new RLD arrives at time t and that the routing phase fails to set it up. Thus, the rerouting phase is launched aiming hopefully to free a path along one of its K shortest paths as follows:

For each shortest path $P_{i,k}$, $1 \leq k \leq K$, associated to RLD numbered i, rejected by the routing phase, and for each wavelength λ_w, $1 \leq w \leq W$, we determine the set of RLDs, $\theta(i,k,w,t)$, that should be rerouted to establish the incoming RLD on the selected path and wavelength. The minimum cost of rerouting, cr^{min}, is then computed. If cr^{min} is finite, its associated k^{th}-alternate shortest path and the w^{th} wavelength are hence selected. Let θ^{min} denote the corresponding set of LDs to be rerouted. Two cases may happen: all the LDs in θ^{min} can be rerouted by only changing the used wavelength whilst keeping the same path or by changing the physical path and then possibly the used wavelength. In this case, the incoming RLD is established 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 $+\infty$, as well as the cost of all the paths in P that share at least one common link with $P_{i,k^{min}}$. We also update the costs of the new paths used by the rerouted LDs to $+\infty$ and to ε 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 LDs cannot be rerouted. In that case, $cr(i, k^{min}, w^{min}, t)$ is updated to $+\infty$ and the minimum cost is computed again. If cr^{min} is infinite, the incoming RLD numbered i is definitively rejected.

For an illustration, we consider a graph representing a network with five nodes and bidirectional fiber-links, as shown in Figure 2, and the set of LDs described in Table I. Two shortest paths ($K = 2$) are computed for each source destination pair as shown in Table I. We assume that each fiber has only one wavelength λ_0.

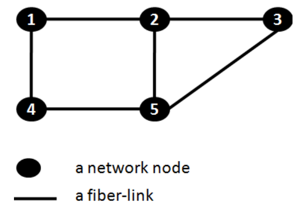

Figure 2. 5-node test network.

TABLE I. SET OF LDs TO BE SET UP.

Number	*s*	*d*	*π*	*α*	*β*	*K shortest paths*	*Nature*
1	5	3	1	100	808	5-3 / 5-4-1-2-3	RLD
2	2	5	1	303	1100	2-5 / 2-1-4-5	SLD
3	2	5	1	405	715	2-5 / 2-1-4-5	RLD
4	1	2	1	607	1118	1-2 / 1-4-5-2	SLD

The RWA for the SLDs is shown in Table II.

TABLE II. RWA FOR THE SLDs.

Number	*s*	*d*	*π*	*α*	*β*	*Path*	*Wavelength*
2	2	5	1	100	1100	2-5	λ_0
4	1	2	1	607	1118	1-2	λ_0

Now, we have to consider the RLDs taking into account the RWA for the SLDs. When RLD 1 arrives, λ_0 is selected to set it up on $P_{1,1} = 5-3$. SLD 2 arrives at time $t = 303$ and has to be set up on $P_{2,1} = 2-5$ using wavelength λ_0 according to Table II. At time $t = 607$, RLD 3 has to be set up. The routing phase fails to find a path-free wavelength and hence the rerouting phase is considered. On $P_{3,1} = 1-2-3$, the set of LDs to be rerouted is $\theta_{3,1,\lambda_0,607} = \{SLD4\}$. $SLD4$ is an SLD not routed yet, thus $cr_{3,1,\lambda_0,607} = \tau$. The set of LDs to be rerouted, on $P_{3,2} = 1-4-5-3$, is $\theta_{3,2,\lambda_0,607} = \{RLD2\}$. $RLD2$ is an already routed RLD hence $cr_{3,2,\lambda_0,607} = \sigma$. Since $\tau \ll \sigma$ the minimum cost $cr^{min} = cr_{3,1,\lambda_0,607}$ is selected and the algorithm selects the not yet routed SLD $1 \rightarrow 2$ to be rerouted on the following new physical path $1-4-5-2$. Then, it routes $RLD3$ on $P_{3,1} = 1-2-3$.

VI. Numerical Results

In this section, we attempt to experimentally evaluate and compare the performance of the SepRwLR scheme presented in the preceding section. We use the $14-$node network topology shown in Figure 3. The source and destination nodes for SLDs and RLDs are chosen according to a random uniform distribution in the interval $[1, 14]$. The RLDs requests arrive as independent Poisson processes with common arrival rate $\nu = 1$ and, once accepted, hold the network resources with independent exponential times with common mean holding time $\mu = 300$. The set-up and tear-down times for the SLDs are set according to a random uniform distribution in the same interval of RLDs arrivals. We compute $K = 5$ shortest paths between each node pair in the network if so many paths exist, otherwise we consider only the available ones. We assume also that there are $W = 32$ wavelengths on each fiber-link.

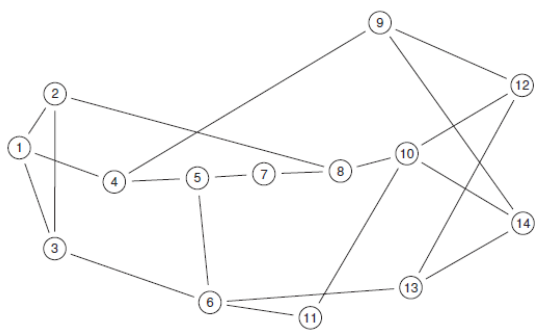

Figure 3. The 14-node network topology (NSFNET).

In order to evaluate the performance of our proposed scheme, we propose to compare the results obtained with the SepRwLR algorithm to those obtained with the following two algorithms:

- The separate routing algorithm (SepR) which computes separately the RWA for the SLDs and the RLDs according to the algorithm described in [22] without considering rerouting. The average rejection ratio obtained by this algorithm is considered in order to highlight the gain obtained thanks to rerouting.
- The separate routing with rerouting algorithm (SRWR) which routes in two separate phases the SLDs and the RLDs. To accommodate an incoming RLD rejected at the end of the first phase, the SRWR algorithm uses the rerouting algorithm described in [19]. SLD (be it routed or not yet routed) rerouting is forbidden. The SRWR algorithm is the only algorithm presented in the literature considering two types of traffic. All the others consider only random traffic.

Figure 4 shows the average rejection ratio computed when D, the total number of LDs arriving at the network during the observation period, varies. We notice that the rejection ratio increases with the traffic loading. This is because when the traffic loading increases, network resources decrease and therefore it becomes more difficult to serve a new incoming demand. The curves show that both of rerouting algorithms improve the rejection ratio significantly compared to the no-rerouting case. We also observe that the SepRwLR algorithm performs better than the SRWR algorithm. In fact, as the SepRwLR allows the rerouting of not yet routed SLDs (which is forbidden in SRWR) in addition to existing RLDs to set up an incoming RLD to be rejected by the routing phase, the number of rejected RLDs is hence minimized.

Figure 5 shows the average rejection ratio gain computed by the SepRwLR algorithm versus D. The rejection ratio gain

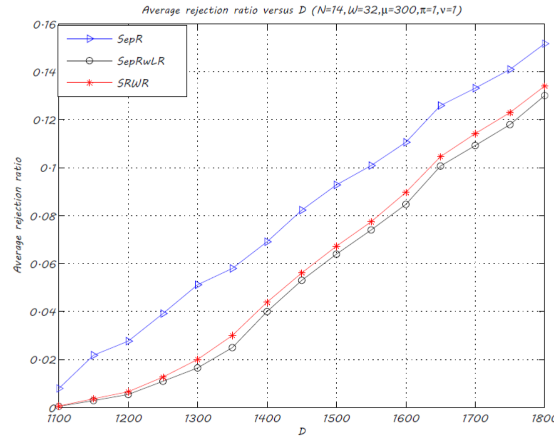

Figure 4. Average rejection ratio versus D.

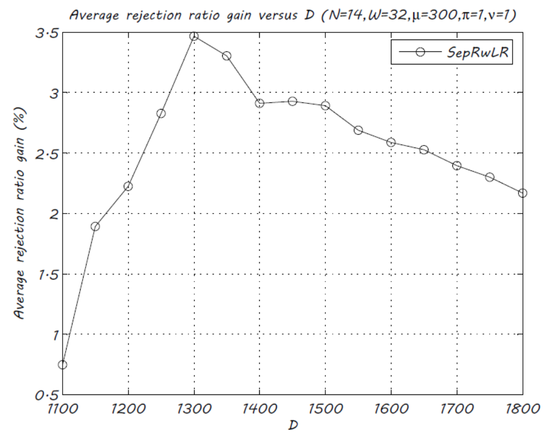

Figure 5. Average rejection ratio gain versus D.

has been computed as the difference between the average number of rejected LDs computed without rerouting i.e computed by the SepR algorithm and the average number of rejected LDs computed by the SepRwLR algorithm divided by D and multiplied by 100. A maximum rejection ratio gain of 3.5% is observed for $D = 1300$ under the aforementioned simulation parameters. The average rejection ratio gain decreases when D increases. This is mainly due to the fact that, when the number of LDs exceeds 1300 and since the number of wavelengths on each link is fixed, the network becomes saturated and it becomes impossible to accommodate more incoming LDs even by rerouting since no network resources are left.

Figure 6 shows the average number of rerouted LDs when D increases. Each group of two bars shows the average number of rerouted LDs by the SepRwLR (first bar from the left-hand side) and the SRWR algorithm (second bar), respectively. The height of the white segment indicates the average number of rerouted not yet routed SLDs whereas the height of the black one shows the average number of rerouted already routed RLDs. We observe that the SepRwLR algorithm requires fewer already routed RLDs to be rerouted than the SRWR algorithm. This is because the SepRwLR promotes rerouting of not yet routed SLDs at the expense of rerouting of already routed RLDs in order to reduce the service disruption period and that

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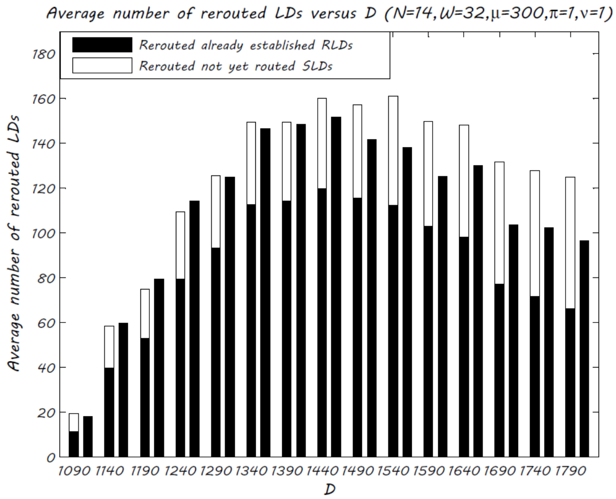

Figure 6. Average rerouted LDs versus D.

is why we can say that the service disruption period incurred by our rerouting algorithm is shorter than that of the SRWR algorithm. From Figure 6 we also notice that the number of LDs to be rerouted by the SepRwLR and the SRWR algorithms respectively decreases under heavy traffic load because the probability that an already routed RLD or a not yet routed SLD be retunable on the same path or on new path becomes infeasible. This is because the saturation regime of the network is achieved.

VII. Conclusion

In this paper, we propose a lightpath rerouting scheme to further improve the performances of transparent networks. Our algorithm considers both SLDs and RLDs. Our algorithm's objective is to further minimize the rejection ratio and the service disruption period. Simulation results show that our algorithm achieves better performance in terms of rejection ratio and reduces considerably the service disruption period since it promotes rerouting of not yet routed SLDs. Our forthcoming studies will investigate further improvement of WDM transparent networks performance by applying traffic rerouting and set up delay tolerance.

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