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Virtual topology reconfiguration in IP/WDM optical ring networks

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Abstract

Wavelength division multiplexing (WDM) has emerged as a promising technology for use in backbone transport networks. In an IP/WDM network, the optical layer provides circuit-switched lightpath services to the client Internet protocol (IP) layer. The set of all the lightpaths in the optical layer defines the virtual topology. Since the optical switches (cross-connects) are reconfigurable, the virtual topology can be reconfigured in accordance with the changing traffic demand pattern at the client layer in order to optimize the network performance. Although it is theoretically possible to implement any virtual topology on the physical topology, changing the virtual topology can be disruptive to the network since the traffic must be buffered or rerouted while the topology is being reconfigured. We develop a reconfiguration algorithm which is based on the concept of splitting and merging existing lightpaths, together with cost–benefit analysis to reduce the network reconfiguration cost. Our objective is to reduce the number of lightpaths that need to be reconfigured, while ensuring that the network congestion is low. The performance of the proposed algorithm for unidirectional and bidirectional ring networks is verified through simulation experiments. The experimental results show that the algorithm reduces the number of reconfiguration changes significantly while keeping the network congestion acceptably low.

Keywords: Wavelength division multiplexing; Ring networks; Virtual topology; Congestion; Generalized multiprotocol label switching

1. Introduction

Wavelength division multiplexing (WDM) and wavelength routing are becoming the technology-of-choice for use in the next generation backbone transport networks. A WDM optical network can utilize the large bandwidth available on an optical fiber by dividing the bandwidth into several hundreds of non-overlapping channels, each operating at a different optical wavelength. In a WDM optical network, wavelength routing nodes or optical cross-connects are interconnected by point-to-point fiber links. Electronic processing nodes such as Internet protocol (IP) routers with limited number of optical transmitters and receivers are connected to the cross-connects. Here, a *lightpath* is used for transmitting a message optically between its end nodes without requiring any electronic processing at the intermediate nodes. A lightpath must use the same wavelength on all the links along its physical route. This is known as *wavelength continuity constraint*. In a WDM-based transport network, the optical layer provides lightpath services to the client layer such as IP, SONET, and ATM. The set of lightpaths in the optical layer defines the virtual topology. In the graphical representation of a virtual topology, vertices correspond to wavelength routing nodes and the edges correspond to lightpaths.

With the IP playing a dominant role in the networking technology, there has been an increasing interest in IP/WDM networks [1–4]. In IP/WDM networks, the IP layer uses lightpaths in the optical layer as links. Two IP routers become neighbors when they are connected by a lightpath. A message from an IP router to another IP router may traverse one or more lightpaths. This is known as multi-(lightpath) hop communication. The IP layer is concerned with routing IP data traffic using packet switching-based statistical multiplexing technique over the virtual topology. On the other hand, the optical layer is concerned with routing lightpaths using wavelength-switching-based WDM technique over the physical topology.

There is an ongoing effort by IETF to standardize generalized multiprotocol label switching (GMPLS) as a means to control and manage IP and optical layers [2]. The GMPLS (also referred to as *multiprotocol lambda switching or lambda labeling*) can be used for routing, signaling, and management in IP/WDM networks by using enhanced open shortest path first (OSPF), resource reservation protocol

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(RSVP), and link management protocol (LMP) [2–4]. The usage information of resources, such as bandwidth on lightpaths, wavelengths on fiber links, optical transmitters and receivers at nodes, in IP and optical layers is exchanged among the nodes in order to route the IP traffic and lightpaths efficiently. When the traffic demand pattern changes in the IP layer, the network performance may become poor if the underlying virtual topology is unchanged. In order to improve the network performance, the virtual topology can be reconfigured to suit the changing traffic patterns [1,4]. Such a reconfiguration is feasible as the optical cross-connects are reconfigurable.

As network traffic varies over time, the optimal virtual topology varies accordingly. Although theoretically it is possible to implement any virtual topology on the physical topology, changing the virtual topology can be disruptive to the network since the traffic at each node must be buffered or rerouted while the topology is being reconfigured. In present day WDM networks, a typical reconfiguration process in the order of tens of milliseconds corresponds to tens of megabits of traffic that must be buffered or rerouted at each node that is being reconfigured [5]. It is therefore important to limit the network disruption during the reconfiguration process.

In this paper, we consider virtual topology reconfiguration in WDM optical ring networks. Due to the attractive features such as simple control and management, and fault tolerance, ring networks have been receiving more attention and several test-beds recognize the ring as a vital topology [6–9]. We develop a reconfiguration algorithm called merge –split reconfiguration (MSR) that restricts the virtual topology evolution to reduce the network disruption and reconfiguration cost. The algorithm is based on the concept of limiting the establishment of new lightpaths to splitting and merging of existing lightpaths. The reduction in virtual topology reconfiguration may be at the cost of higher average link load or maximum link load (congestion) in the network. The amount of traffic carried by a link (lightpath) on the virtual topology defines the link load. The maximum of the load on the links in the virtual topology defines congestion. Our objective is to ensure that the network congestion is low, while minimizing the number of lightpaths reconfigured. Reconfiguration using MSR algorithm results in low network congestion and reduced number of lightpath changes. MSR algorithm is computationally simple. It ensures that the number of optical cross-connects that need to be configured is limited. Also, it aids multistep reconfiguration wherein a few lightpaths are reconfigured in every step. This will reduce the overall network disruption at any instance of time. The performance of the proposed MSR algorithm is evaluated through simulation experiments. The simulation results confirm the effectiveness of MSR algorithm.

The rest of the paper is organized as follows. In Section 2, the related work on virtual topology and reconfiguration is presented. The proposed MSR algorithm is explained in Section 3. The concept of merge and split operations is explained with an illustration. The benefits of MSR algorithm are also presented. In Section 4, the performance study of the proposed algorithm on unidirectional and bidirectional ring networks through simulation is presented. Finally, some concluding remarks are made in Section 5.

2. Related work

The virtual topology design problem aims to minimize a certain objective function such as network congestion, weighted number of (lightpath) hops, and message delay. The network congestion is the maximum load offered to any lightpath. The weighted number of hops refers to the average number of lightpaths traversed by a unit traffic. The message delay includes the propagation delay and queuing delay. The problem of designing a virtual topology consists of four main subproblems [10]: (i) selection of lightpaths to be established, (ii) determining the physical route for each of the lightpaths, (iii) determining the wavelength for each of the lightpaths, and (iv) traffic routing over the virtual topology. In order to achieve the optimal topology, these subproblems should be solved jointly. However, the virtual topology design problem itself is NP-complete [10], thus the problems are more often solved separately. Although this may result in suboptimal solutions, it is acceptable for complexity reasons. Several heuristic solutions for the virtual topology problem have been proposed in the literature [10,11]. The heuristic proposed in Ref. [11] is based on sequentially assigning a single wavelength to all possible lightpaths in order of decreasing traffic before proceeding to the next wavelength. The objective is to maximize the single hop traffic, but the port availability and delay constraints have been ignored. The above constraints have been considered in the heuristics proposed in Ref. [10]. A survey of virtual topology design algorithms has been presented in Ref. [12].

There are several approaches to solve the virtual topology reconfiguration problem. In the first approach, the new virtual topology is designed considering only the new traffic demand thus ignoring the old (existing) traffic demand and virtual topology. This approach is simple as it can use any virtual topology design solution described above. However, the amount of changes required on the existing virtual topology is quite high. An important issue here is to transform the existing topology to the new one so as to reduce the disruption in the network.

The second approach is to design the new topology considering only the new traffic demand to obtain the optimum objective function value and select the one among several choices with the same optimum value that minimizes the number of changes in the topology. This approach is used in Ref. [13], where an integer linear programming (ILP) solution has been presented for the problem of virtual topology reconfiguration. The virtual topology reconfiguration problem has been shown to be NP-complete. The new virtual topology is computed based on

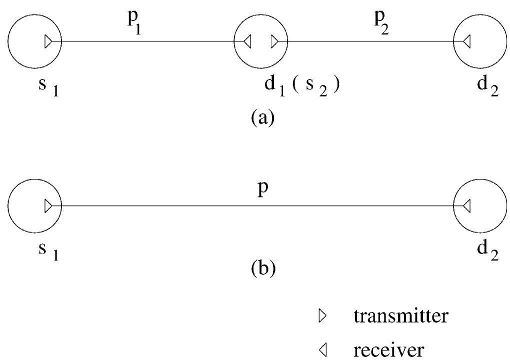

Fig. 1. Illustration of merge operation. (a) Before merging. (b) After merging.

optimizing a given objective function. Reconfiguration changes are minimized by choosing the optimal virtual topology that is closest in structure to the existing topology, among all such optimal virtual topologies. However, simplifying assumptions have been made for making the problem to be computationally tractable. Thus, the wavelength-continuity constraints are ignored.

The third approach is to make a small number of changes repeatedly, considering the new traffic demand and the present topology, to migrate towards the new topology without actually computing any optimal topology corresponding to the new traffic demand. Such an approach is followed in Refs. [5,14]. An algorithm called dynamic single-step optimization (DSSO) has been proposed for load balancing that tracks rapid changes in the traffic pattern. This reconfiguration strategy employs branch exchange sequences similar to the one presented in Ref. [15]. At each reconfiguration step, only a minimal change of a two- or three-branch exchange sequence is made to the network topology to minimize the disruption caused to the network. However, as the network size increases, the combinations of branch exchange sequences increase drastically. Thus, the order of computation at each step increases significantly. The algorithm may also settle at a topology that is locally but not globally optimal.

In Ref. [5], wavelength availability constraints have been considered and the impact of wavelength restrictions on the performance of the DSSO algorithm has been studied by creating ring logical topologies over the physical topology. It has been shown that a minimum of $P(N-P)$ wavelengths are required to establish all possible logical (virtual) topologies in a bidirectional ring network with N nodes and P ports per node. The results do indicate that most of the gain in DSSO algorithm performance can be achieved with approximately half the number of wavelength required to establish all possible logical topologies, or $P(N-P)/2$.

The last approach is to design the new topology taking the existing topology and new traffic demand as input with the objective of keeping the objective function value as close to the optimal value as possible while keeping the amount of virtual topology changes at a low value. It is basically a tradeoff between optimizing the objective function and minimizing the virtual topology changes. Our work uses this approach.

3. Proposed merge–split reconfiguration algorithm

Given a new traffic matrix and the existing virtual topology, the objective of our algorithm is to design a virtual topology which requires reduced number of changes to the existing virtual topology while keeping the network congestion as low as possible. The algorithm is based on splitting and/or merging existing lightpaths to establish lightpaths for the new traffic matrix. By doing so, the algorithm attempts to meet the following objectives:

1. Reduce the number of changes needed to establish each new lightpath.
2. Reduce the amount of computation needed to determine the new virtual topology.
3. Reduce the overall network disruption due to the reconfiguration process.
4. Respond to rapidly changing traffic patterns.
5. Allow for the flexible integration of any design algorithm which may consider different objective functions such as network congestion, weighted number of (lightpath) hops, and message delay.

3.1. Merge and split operations

We explain the merge and split operations which are used by the reconfiguration algorithm to choose lightpaths in the new virtual topology. We assume a unidirectional ring network with N nodes, W wavelengths per fiber, and P ports per node. This means that at most P lightpaths can start from a node and P lightpaths can end at the node. A transmitter/receiver pair is associated with every port. For the purpose of presentation, we consider unidirectional ring networks. However, our algorithm can be used in bidirectional ring networks also.

Two lightpaths p_1 and p_2 on a given wavelength w between node pairs $\langle s_1, d_1\rangle$ and $\langle s_2, d_2\rangle$, respectively, can be merged if $d_1 = s_2$ or wavelength w is free on all the links from node d_1 to node s_2. The merge operation can be performed for two purposes. The first purpose is to establish a new lightpath p that intersects both p_1 and p_2. The second purpose of performing merge operation is that the receiver (port) at node d_1 and the transmitter (port) at node s_2 can be freed. This may help to establish a new lightpath which terminates at d_1 or s_2 or both. The benefit of the merge operation is that the traffic between node pair $\langle s_1, d_2\rangle$ can be carried by the direct lightpath p which otherwise might require several lightpaths resulting in increased congestion. The merge operation incurs some cost due to the rerouting of traffic between node pairs $\langle s_1, d_1\rangle$ and $\langle s_2, d_2\rangle$ over a new set of multiple lightpaths (as against the earlier case of one

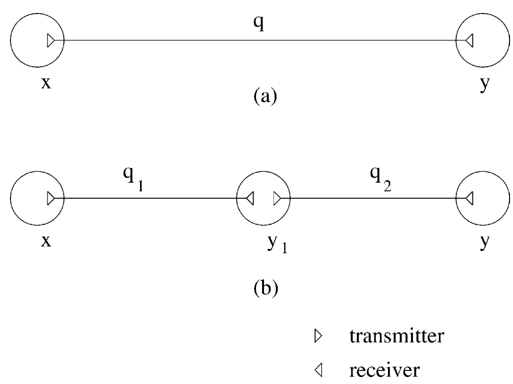

Fig. 2. Illustration of split operation. (a) Before splitting. (b) After splitting.

lightpath) which leads to increased load or congestion. The merge operation is illustrated in Fig. 1.

A lightpath q between node pair $\langle x, y \rangle$ can be split at node y_1 to create two lightpaths q_1 and q_2 whose end nodes are $\langle x, y_1 \rangle$ and $\langle y_1, y \rangle$, respectively. The split operation may become necessary when a new lightpath with y_1 as its end node is routed. The split operation incurs some cost as the original traffic on q has to be rerouted and it may use multiple lightpaths (as against the earlier case of one lightpath) resulting in increased load or congestion. As the result of split operation a new receiver (port) is used up for lightpath q_1 at node y_1 and a new transmitter (port) is used up for lightpath q_2 at node y_1. The split operation is illustrated in Fig. 2.

Reconfiguration using merge and split operations is illustrated in Fig. 3. An initial configuration of lightpaths on three wavelengths w_1, w_2, and w_3 on a 5-node unidirectional ring network is depicted in Fig. 3(a). For the purpose of clarity, the ring is stretched into a path starting from node 0 and ending with node 0. Every node is assumed to have two

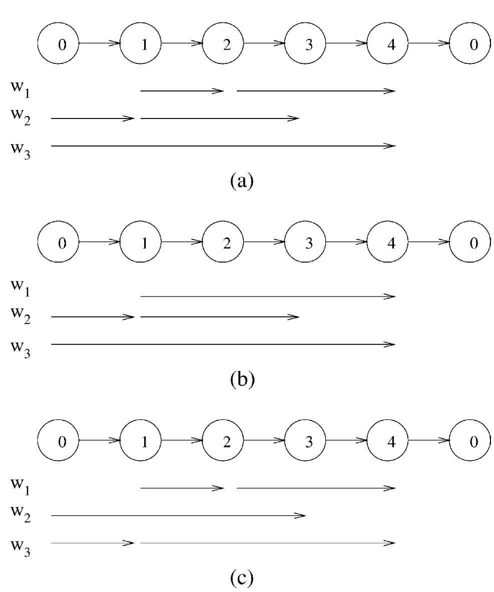

Fig. 3. Illustration of reconfiguration using merge and split operations. (a) Initial configuration. (b) Reconfiguration (case 1). (c) Reconfiguration (case 2).

ports (i.e. two transmitters and two receivers) and therefore at most two lightpaths may start and end at any node. It is required to establish a new lightpath from node 1 to node 4. For the given configuration, there are no ports available at the output of node 1 and input of node 4. Two of the possible ways of reconfiguring the initial topology to establish the new lightpath are shown in Fig. 3(b) and (c). In the first case, the new lightpath can be established on wavelength w_1 by merging the existing two lightpaths as shown in Fig. 3(b). In this case the traffic carried by each of the two lightpaths before merging need to be rerouted along other lightpaths incurring a certain cost. In the second case, the new lightpath can be established on wavelength w_3 by splitting the existing lightpath on w_3 at node 1. However, it requires a transmitter and receiver at node 1. Since no free transmitter/receiver is available, existing lightpaths on wavelength w_2 can be merged to free a transmitter and receiver. This is shown in Fig. 3(c). In this case, the traffic carried originally by the lightpath on w_3 before splitting and by each of the two lightpaths on w_2 before merging need to be rerouted along new lightpaths incurring a certain cost. We can note that the new lightpath cannot be established on wavelength w_2 as no receiver is free at node 4 and no receiver can be freed by merging lightpaths on wavelength w_1 and also on w_3.

3.2. Description of MSR algorithm

The reconfiguration algorithm takes the new traffic matrix and the existing virtual topology as input and generates the new virtual topology as output. It reserves one wavelength (say w_0) to establish lightpaths on each of the physical links. This is done for two reasons: (1) to ensure that the virtual topology is connected, and (2) to ensure that traffic between any node pair does not traverse the physical ring more than once; i.e. traffic is always routed through minimum number of physical links irrespective of the number of lightpaths traversed.

The algorithm considers the source–destination pairs in the non-increasing order of their traffic demand. Let the current node pair be $\langle s, d \rangle$ and the associated lightpath be p. The algorithm determines if the establishment of p is useful by considering the cost associated with the merge and split operations as discussed in Section 3.1. Lightpath p can be established between nodes s and d only if a free wavelength is available throughout the physical route of p or by merging and/or splitting some existing lightpaths. Also, it is required that a transmitter is available at node s and a receiver is available at node d. If it is not the case, some lightpaths can be merged to free a transmitter and receiver.

We explain now how the cost–benefit analysis is carried out to determine if lightpath p can be routed or not. The *path network of interest* in this case is the physical path traversing from node s to node d. Only those existing lightpaths which intersect the path network of interest are considered for possible merge and split operations. Two phases are involved in the analysis as explained below.

In our work, we measure the cost in terms of the increase in the load on lightpaths as a result of traffic rerouting. The benefit is measured as the reduction in lightpath load due to the establishment of a direct lightpath between a node pair when compared to the case where no direct lightpath is available. However, we note that any relevant metric could be used for cost–benefit analysis.

Phase-1 concerns with freeing the ports. This phase is executed if no ports (transmitters/receivers) are available at the end nodes of p. The cost of freeing ports by using merge operation at each of the W wavelengths is computed. For a given wavelength, at most two merge operations (one at s and another one at d) are performed and hence the cost function is used at most twice. The total number of times the cost function is used is $2 \times \min(W, P)$. For the uni-directional ring network, the number of ports P can be at most W. Therefore, the maximum number of lightpaths considered by Phase-1 is $2 \times P$.

Phase-2 concerns with the selection of wavelength for p. The benefit of establishing p on each of W wavelengths is determined in terms of reduction in congestion. The benefit is achieved because the traffic between node pair $\langle s, d \rangle$ is directly routed over p which otherwise would have been routed through a sequence of lightpaths. The cost of establishing p due to merging and splitting of lightpaths on each of the wavelengths is also determined. If ports need to be freed then its cost as computed in Phase-1 is also taken into consideration. The algorithm rejects the lightpath if the cost outweighs benefit. Otherwise, it chooses the best wavelength as decided in Phase-2 for routing p. The length of the path network of interest is at most $N-1$ and the total number of lightpaths considered by Phase-2 on all the wavelengths is $(N-1) \times P$.

We determine the computational complexity of MSR algorithm. The total number of lightpaths considered in Phase-1 and Phase-2 can be at most $2 \times P + (N-1) \times P$. Since there are $N \times (N-1)$ entries in the traffic matrix, the number of lightpaths examined for possible establishment, merging, and splitting by MSR algorithm in the worst case is $O(N^3 P)$.

We give below simple mathematical expressions to describe cost and benefit functions.

The cost of merging two lightpaths p_1 and p_2 is calculated as follows. Let t_1 and t_2 be the traffic being carried (current load) by p_1 and p_2, respectively. Let n_1 and n_2 be the number of lightpaths that need to be traversed after the merge operation, by t_1 and t_2, respectively. The cost of merge operation is then measured as $(n_1 - 1)t_1 + (n_2 - 1)t_2$.

The cost of splitting a lightpath q is calculated as follows. Let t' be the traffic currently carried by q and n' be the number of lightpaths that need to be traversed by t' after splitting q. The cost of the split operation is then calculated as $(n' - 1)t'$.

The benefit of directly establishing a lightpath p and routing traffic t on it is calculated as $(n-1)t$. Here, n is the number of lightpaths that need to be traversed by traffic t if the direct lightpath p is not established.

The pseudo-code to decide if a direct lightpath p be established from node s to node d, and to choose a good wavelength for p is given below. Let r be the route used by p.

1. *Wavelength availability*. Search all the wavelengths and choose the one which is free on all the links traversed by route r with a free transmitter at node s and a free receiver at node d. If no such wavelength can be found then proceed to next step. Otherwise, return success.
2. *Transmitter availability*. If a transmitter is free at node s then proceed to next step. Otherwise, for every wavelength i, determine the cost of freeing a transmitter port at node s, denoted as tp_i, by merge operation.
3. *Receiver availability*. If a receiver is free at node d then proceed to next step. Otherwise, for every wavelength i, determine the cost of freeing a receiver port at node d, denoted as rp_i, by merge operation.
4. *Wavelength selection*. For each wavelength i, determine (i) b_i, the benefit of routing p, (ii) m_i, the cost of merging lightpaths, if any, and (iii) s_i, the cost of splitting lightpaths, if any. If a transmitter needs to be freed at node s then choose wavelength $j (j \neq i)$ whose tp_j is minimum. Denote this value as tp'_i. If a receiver needs to be freed at node d then choose wavelength $k (k \neq i)$ whose rp_k is minimum. Denote this value as rp'_i.

   Choose wavelength u such that $b_u > (m_u + s_u + tp'_u + rp'_u)$ and $b_u - (m_u + s_u + tp'_u + rp'_u)$ is minimum among all candidate wavelengths. If such a wavelength can be found then return success; otherwise return failure.

3.3. Virtual topology realization

An important problem is to transform the current virtual topology to the new virtual topology. The MSR algorithm allows the realization of the new virtual topology from the current topology in multiple steps at a predetermined interval of time. This helps reduce the overall network disruption due to reconfiguration. The algorithm determines the set of lightpaths that need to be established in some order and the set of lightpaths that need to be merged or split. Different subsets of lightpaths from the above sets can be formed and in each step all the lightpaths from a subset can be realized.

3.4. Attractive features of MSR algorithm

We summarize below the attractive features of MSR algorithm.

1. By limiting the reconfiguration changes and virtual topology evolution to splitting or merging of existing lightpaths, the disruptive effect of reconfiguration can be isolated between the source and destination nodes of the

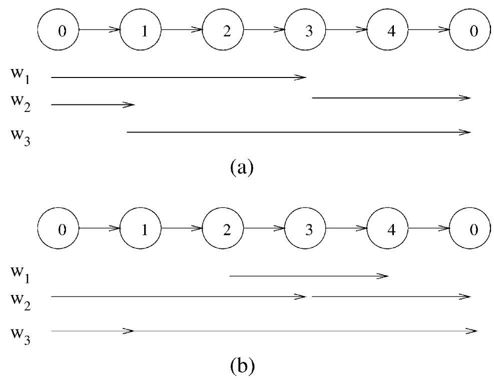

Fig. 4. Illustration of a reconfiguration operation that cannot be done by MSR algorithm. (a) Initial configuration. (b) Reconfiguration.

lightpath to be established and the existing intermediate lightpaths. Also, the switches (wavelength cross-connects) need to be configured only at the subset of nodes between the source and destination nodes.

2. The algorithm allows a lightpath to be established only when the cost–benefit analysis yields a favorable result. By doing so, the number of reconfiguration changes is restricted and the network congestion is kept low.
3. The cost–benefit function is inherently flexible in the sense that it may be based on any objective function such as network congestion, weighted number of (lightpath) hops, and message delay.
4. The algorithm aids multistep reconfiguration. Therefore, only a few lightpaths can be reconfigured at a time, thus providing better stability of lightpaths.
5. Since MSR does not exhaustively search all possibilities, the computational complexity is less. For example in Fig. 4(a), the lightpath from node 0 to node 1 on wavelength w_2 can be migrated to wavelength w_3 and then the lightpath from node 0 to node 3 on wavelength w_1 can be migrated to wavelength w_2 to establish a new lightpath from node 2 to node 4 on w_1 as depicted in Fig. 4(b). This possibility is not considered by MSR algorithm. We can observe that unlike MSR algorithm, in the above example, a lightpath (between nodes 0 and 1) which is outside the path network of interest needs to be disrupted.

4. Performance study

We study the performance of the proposed MSR algorithm through simulation experiments. We compare the performance of MSR algorithm with that of MLDA developed in Ref. [10]. Both HLDA and MLDA [10] have been shown to be good heuristics to design a virtual topology with the objective of reducing network congestion for a given traffic demand matrix. An important difference between MSR algorithm and HLDA/MLDA is that HLDA and MLDA algorithms do not consider the previous traffic matrix and existing virtual topology for designing the new topology. This will result in higher number of reconfiguration changes. Both HLDA and MLDA consider node pairs in the non-increasing order of traffic demand and establish lightpaths as long as sufficient wavelengths and ports are available. Unlike HLDA, MLDA ensures that a shortest propagation delay path exists between any node pair by reserving a wavelength for establishing lightpaths on every physical link.

Table 1
Performance of MLDA and MSR for the unidirectional ring network

Metric	MLDA	MSR	% Gain
Max. load	9.96	8.84	11.23
Ave. load	4.697	4.808	−2.36
No. of changes	40.21	3.73	90.73

Table 2
Performance of MLDA and MSR for the bidirectional ring network

Metric	MLDA	MSR	% Gain
Max. load	3.41	3.64	−6.58
Ave. load	1.43	1.69	−17.99
No. of changes	98.32	7.0	92.88

In our simulation we consider a 12-node ring network, 4 ports, and 8 wavelengths per link unless otherwise stated. The traffic matrix entries are generated randomly. The values are chosen uniformly in the range between 0 and 1. The traffic matrix changes to a new one according to a parameter p_t which controls the percentage of traffic change. An entry in the traffic matrix changes to a new value with probability p_t. Unless otherwise stated, p_t is assumed to be 100% in our experiments. In one simulation experiment, 20 traffic matrices are considered. The experiment is repeated several times to obtain accurate results. We analyze the performance in terms of number of changes and performance gain. Let a_1, b_1, and c_1 be the maximum load (congestion), average load, and number of changes experienced by MLDA, respectively. Let a_2, b_2, and c_2 be the maximum load (congestion), average load, and number of changes experienced by MSR, respectively. The performance gain in terms of maximum load is given by $(a_1 - a_2)/a_1$. The performance gain in terms of average load is given by $(b_1 - b_2)/b_1$. The performance gain in terms of number of changes is given by $(c_1 - c_2)/c_1$.

The performance gain obtained by MSR algorithm over MLDA is given in Tables 1 and 2 for the unidirectional ring and bidirectional ring network, respectively. The simulation results show that MSR performs significantly better than MLDA in minimizing the number of changes. Over 90% of the changes required by MLDA are avoided by MSR. At the same time, the maximum link load and average link load obtained by MSR algorithm are close to that obtained by MLDA. Since MSR algorithm resists the topological changes, its performance is poorer than MLDA in case of bidirectional ring network. However, MLDA performs

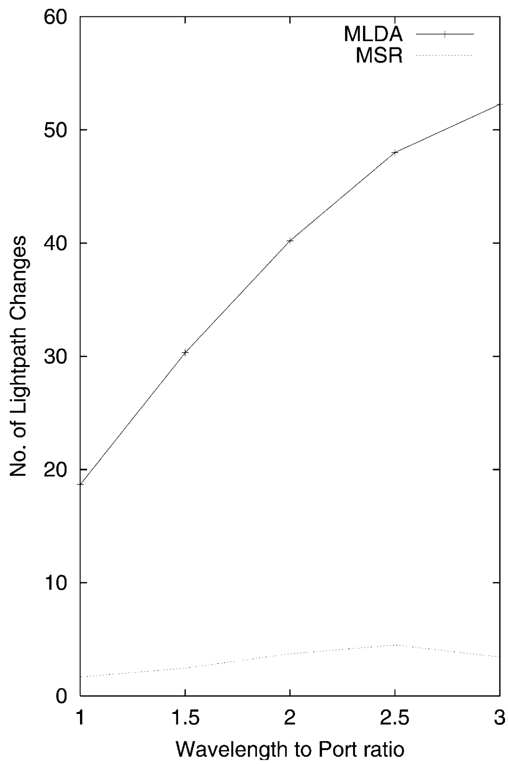

Fig. 5. Effect of varying wavelength-to-port ratio on number of lightpath changes in a unidirectional ring.

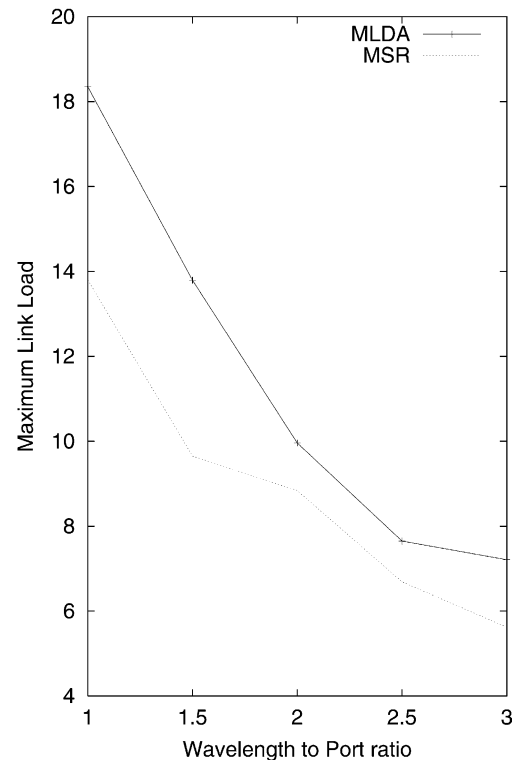

Fig. 6. Effect of varying wavelength-to-port ratio on maximum link load in a unidirectional ring.

poorer than MSR algorithm in minimizing link load in the unidirectional ring network. The reason for this behavior is explained below.

MLDA is unable to satisfactorily handle the wavelength constraints of a unidirectional ring network. In a unidirectional ring network, wavelength constraints have a greater effect compared to bidirectional rings. This is because the establishment of certain lightpaths may use much more physical hops in a unidirectional ring. Given that MLDA only attempts to maximize single hop direct traffic, the algorithm does not consider if the establishment of one lightpath is really beneficial and if it would affect the implementation of other lightpaths. Thus, depending on the traffic pattern, MLDA could be implementing lightpaths that require more physical wavelength resources on a unidirectional ring network compared to a bidirectional ring network. This limits the amount of lightpaths that can be established in a virtual topology designed using MLDA in a unidirectional ring network. The performance of the virtual topology would therefore become poor. On the other hand, MSR algorithm is able to make use of a cost–benefit strategy to weigh the cost of implementing such *wavelength-hungry* lightpaths. Thus, its performance in a unidirectional ring network is better than MLDA.

4.1. Effect of varying wavelengths–ports ratio

We study the effect of varying wavelength-to-port ratio on the performance of MSR algorithm and compares it with that of MLDA for both unidirectional and bidirectional ring networks. The number of ports is fixed to be four and the number of wavelengths is varied. The performance for the unidirectional ring network is shown in Figs. 5–8.

The effect of varying wavelength-to-port ratio on number of lightpath changes required by MSR and MLDA is depicted in Fig. 5. The curves show that MSR requires only a few changes and it increases slowly with the increasing wavelength-to-port ratio. On the other hand, the number of lightpath changes increases rapidly for MLDA. This is because, when the number of wavelengths increases the number of lightpaths also increases resulting in more number of lightpath changes. The rate of increase is slow in case of MSR because it limits the number of changes by performing cost–benefit analysis.

The effect of varying wavelength-to-port ratio on maximum link (lightpath) load and average link load is shown in Figs. 6 and 7, respectively. As noted earlier, the number of lightpaths established in the network increases with the increasing wavelengths. Therefore maximum link load as well as average link load decrease with the increasing wavelength-to-port ratio for both MSR and MLDA algorithms. It can also be observed from the figures that the performance of MSR is close to that of MLDA. We recall that the objective of our algorithm is to reduce the number of lightpath changes significantly while keeping the link load close to that of MLDA. The percentage of performance gain achieved by MSR algorithm over MLDA is more stable as seen from Fig. 8.

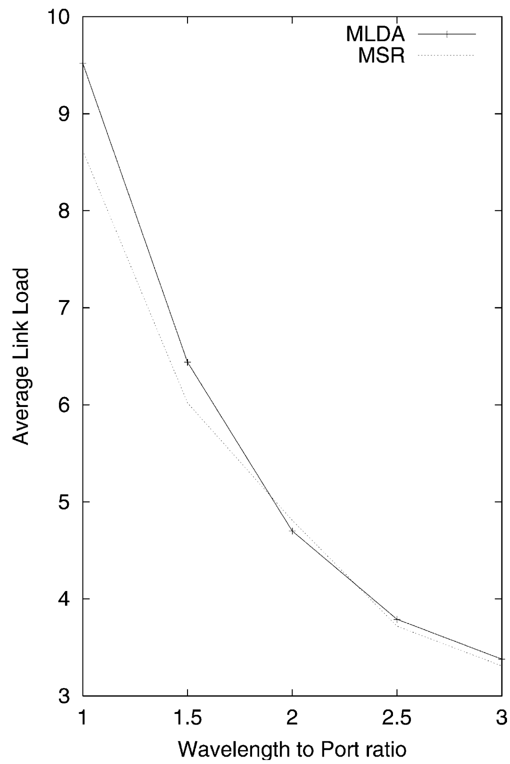

Fig. 7. Effect of varying wavelength-to-port ratio on average link load in a unidirectional ring.

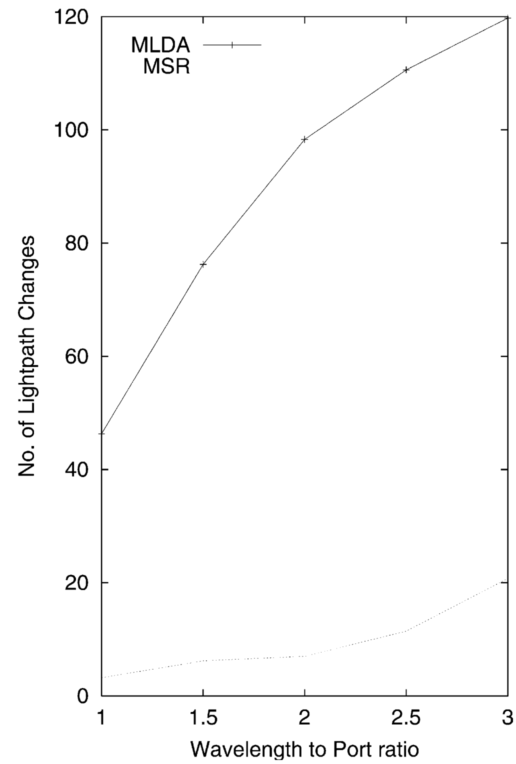

Fig. 9. Effect of varying wavelength-to-port ratio on number of lightpath changes in a bidirectional ring.

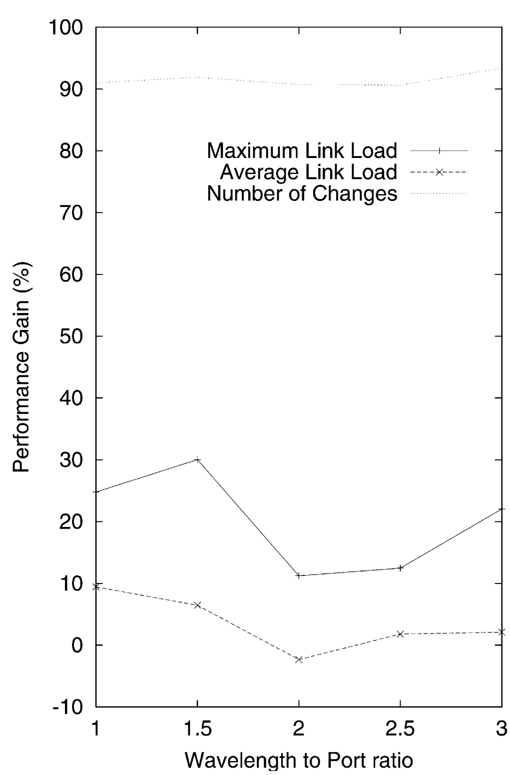

Fig. 8. Effect of varying wavelength-to-port ratio on performance gain in a unidirectional ring.

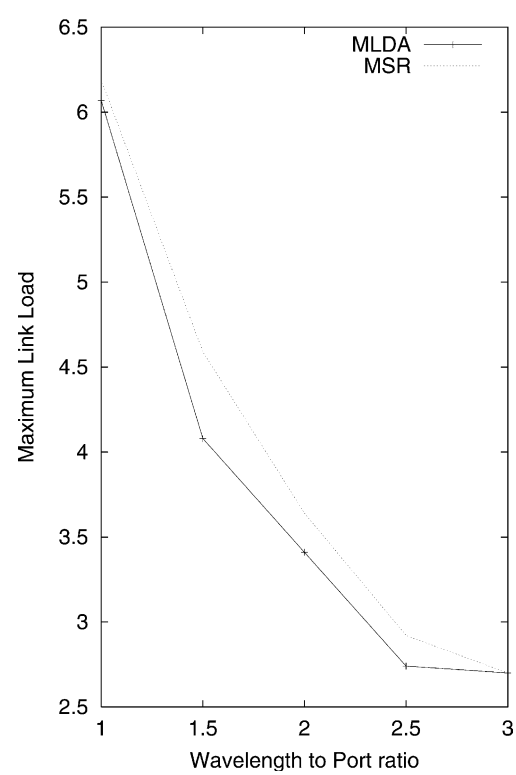

Fig. 10. Effect of varying wavelength-to-port ratio on maximum link load in a bidirectional ring.

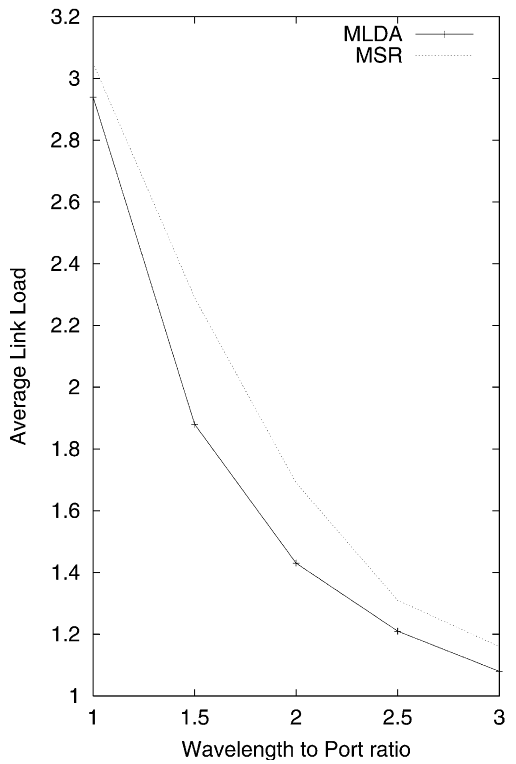

Fig. 11. Effect of varying wavelength-to-port ratio on average link load in a bidirectional ring.

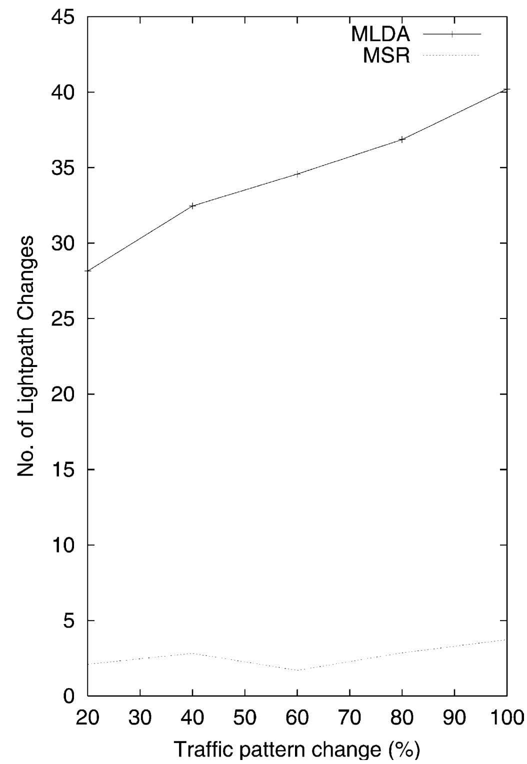

Fig. 13. Effect of varying percentage of traffic change on number of lightpath changes in a unidirectional ring.

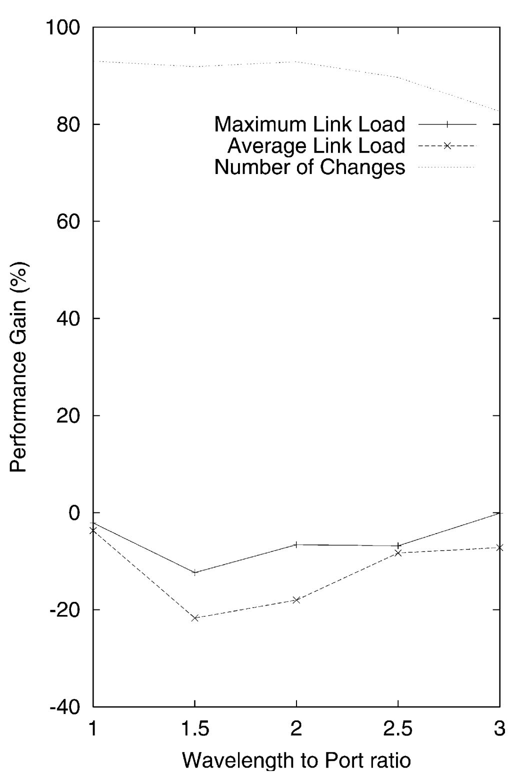

Fig. 12. Effect of varying wavelength-to-port ratio on performance gain in a bidirectional ring.

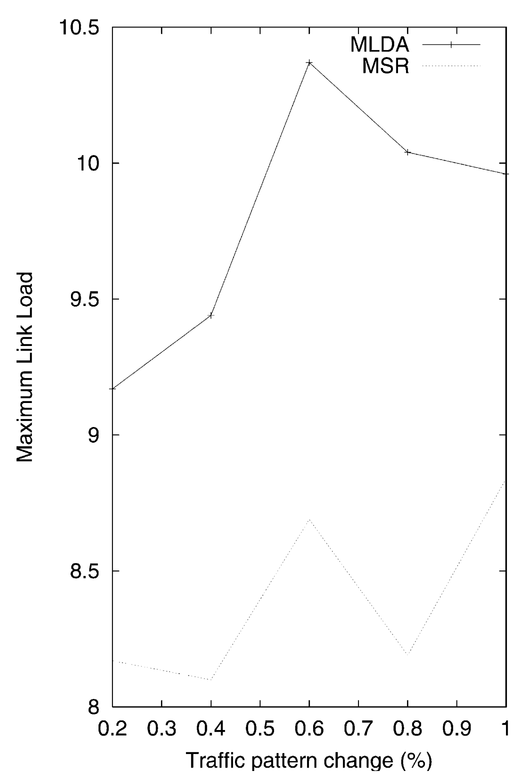

Fig. 14. Effect of varying percentage of traffic change on maximum link load in a unidirectional ring.

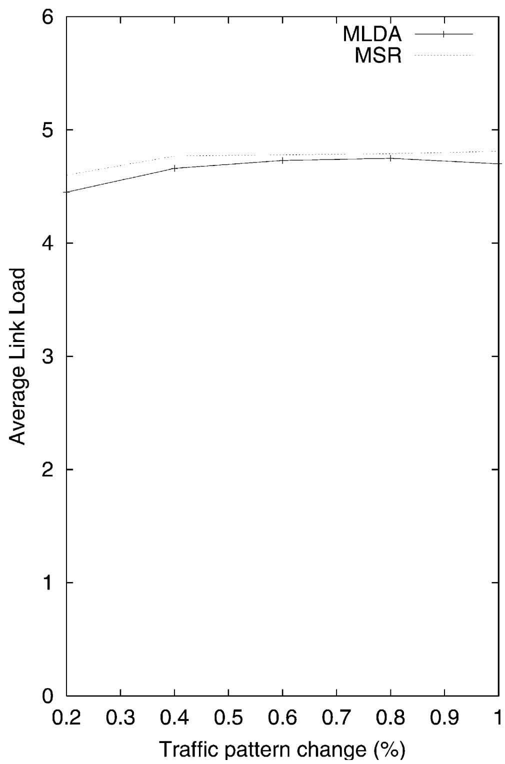

Fig. 15. Effect of varying percentage of traffic change on average link load in a unidirectional ring.

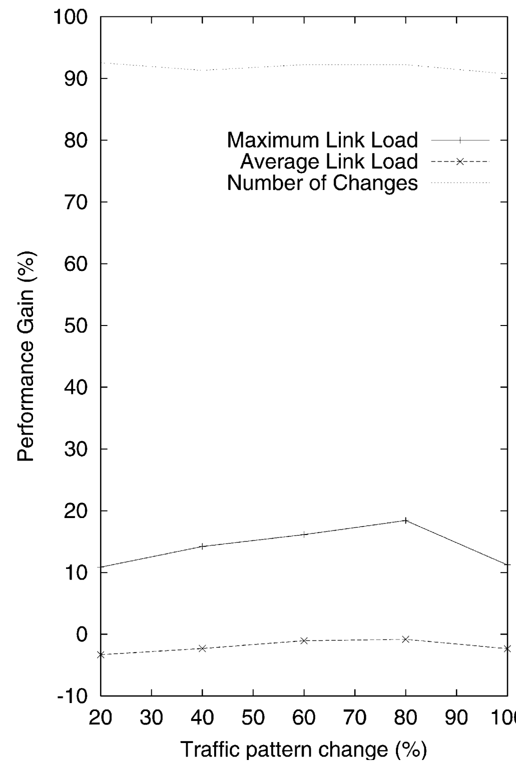

Fig. 16. Effect of varying percentage of traffic change on performance gain in a unidirectional ring.

The effect of varying wavelength-to-port ratio for the bidirectional ring network is shown in Figs. 9–12. It can be observed that the performance trend is similar to that of the unidirectional ring network. This confirms that our MSR algorithm performs well in case of bidirectional ring networks also.

4.2. Effect of varying percentage of traffic changes

We study the effect of varying percentage of traffic change on the performance of MSR algorithm and compares it with that of MLDA for both unidirectional and bidirectional ring networks. The number of ports is fixed to be four, the number of wavelengths is fixed to be eight, and the percentage of traffic change is varied. The performance for the unidirectional ring network is shown in Figs. 13–16.

The effect of varying percentage of traffic change on number of lightpath changes required by MSR and MLDA is depicted in Fig. 13. The curves show that MSR requires only a few changes and it increases slowly with the increasing percentage of traffic changes. The rate at which the number of lightpath changes increases with the increasing percentage of traffic changes is more for MLDA when compared to MSR. This is because, MSR algorithm is able to successfully track the changing traffic pattern and limits the number of changes by performing cost–benefit analysis.

The effect of varying percentage of traffic change on maximum link (lightpath) load and average link load is shown in Figs. 14 and 15, respectively. The figures show that maximum link load and average link load do not change significantly with the increasing percentage of traffic change for both MSR and MLDA algorithms. This is because the link load depends more on the number of lightpaths in the network than the change in the traffic pattern. It can also be observed from the figures that the performance of MSR is close to that of MLDA. The percentage of performance gain achieved by MSR algorithm over MLDA is more stable as seen from Fig. 16.

The effect of varying percentage of traffic change for the bidirectional ring network is shown in Figs. 17–20. It can be observed that the performance trend is similar to that of the unidirectional ring network. This confirms that our MSR algorithm performs well in case of bidirectional ring networks also.

5. Conclusions

In this paper, we have proposed a reconfiguration algorithm which is based on the concept of splitting and merging existing lightpaths to reduce the virtual topology reconfiguration cost in WDM optical ring networks. The objective of our algorithm is to design a new virtual topology so as to minimize the number of changes that need to be

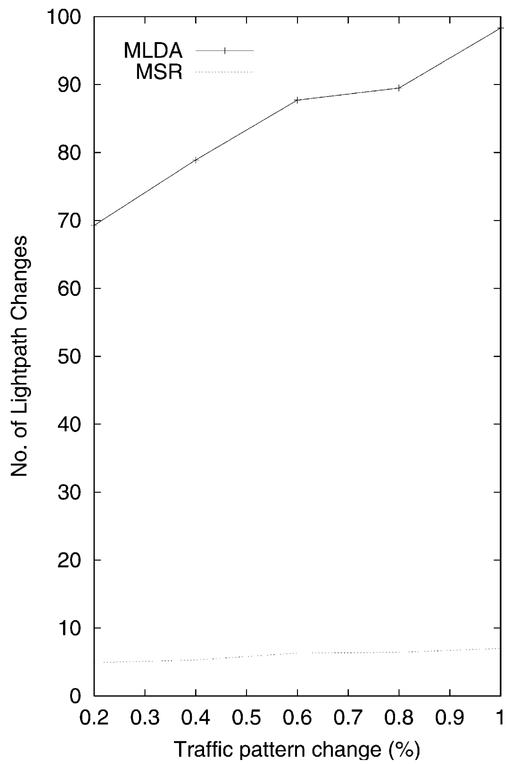

Fig. 17. Effect of varying percentage of traffic change on number of lightpath changes in a bidirectional ring.

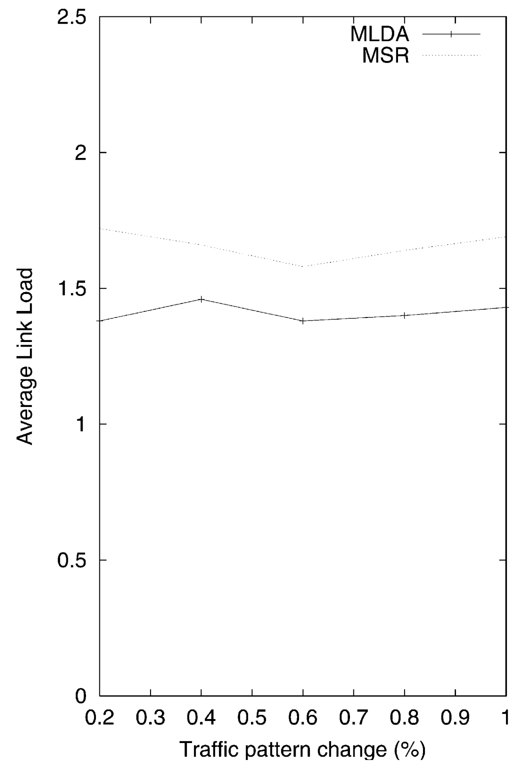

Fig. 19. Effect of varying percentage of traffic change on average link load in a bidirectional ring.

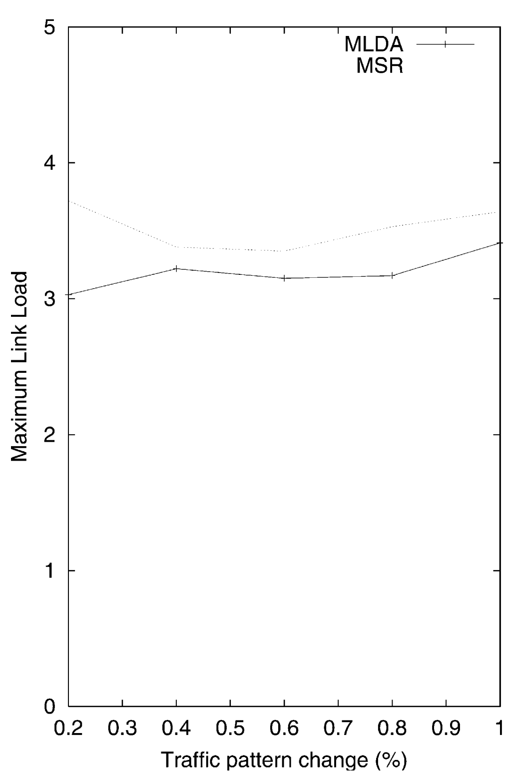

Fig. 18. Effect of varying percentage of traffic change on maximum link load in a bidirectional ring.

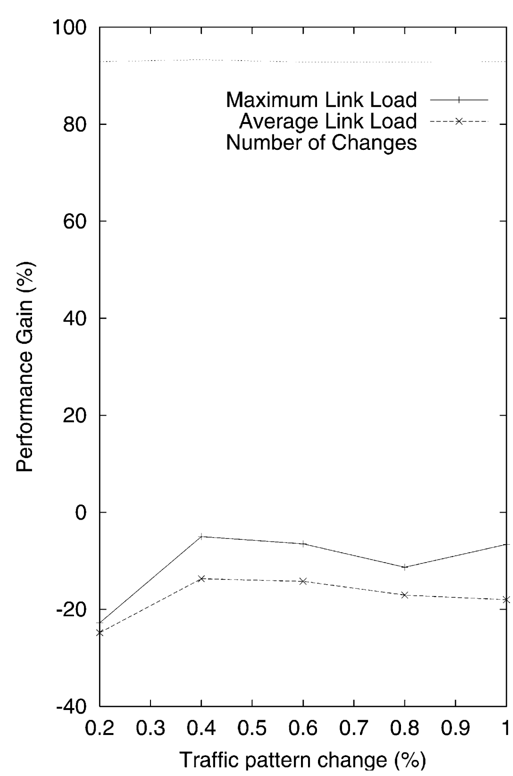

Fig. 20. Effect of varying percentage of traffic change on performance gain in a bidirectional ring.

made in the current virtual topology while keeping the network congestion as low as possible. The proposed MSR algorithm allows multistep reconfiguration in order to realize the new virtual topology in multiple steps with only a few lightpath changes in each step. The performance of the proposed algorithm has been studied through simulation experiments for unidirectional and bidirectional ring networks. The simulation results show that MSR algorithm is efficient as it reduces the number of lightpath changes significantly while keeping network congestion low.

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