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Performance of Distributed Reservation Control in Wavelength-Routed All-Optical WDM Networks with Adaptive Alternate Routing

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***Abstract*—In this work, we consider the performance benefits of distribution reservation control schemes in partially-connected wavelength-routed all-optical WDM networks. In particular, we propose a new distributed reservation control scheme designed to work for general topology wavelength-routed WDM networks. In this new scheme, capacity reservation is invoked by always using the first shortest path if the direct route does not exist between all node (demand) pairs. Through our study, we show that our proposed scheme in the presence of distributed adaptive routing is much more fair on pairwise blocking than the conventional reservation method in general topology wavelength-routed WDM networks, especially in the presence of wavelength converters and overload situations.**

***Index Terms*—WDM; Capacity Reservation; Adaptive Routing; Wavelength Conversion; Integrated Control and Routing.**

I. INTRODUCTION

Wavelength-Routed All-Optical Wavelength Division Multiplexing (WDM) networks were designed and developed to accommodate increasing network traffic. WDM systems allow efficient utilization of a fiber bandwidth by dividing the bandwidth into smaller and manageable channels, each operating at an electronic speed and modulated at different wavelengths that are then combined and transmitted concurrently over the same fiber. This feature of multi-wavelength networks is capable of overcoming the shortfalls of single-wavelength networks (e.g. SONET) and makes them a candidate for the next generation backbone networks.

Generally, in these networks, the same wavelength must be used for each connection request on each fiber along the chosen path, but no two identical wavelengths can share the same fiber. These unique conditions of wavelength-routed WDM networks, *wavelength continuity constraint* and *distinct channel assignment*, exacerbate the difficulties of the routing and wavelength assignment (RWA) problem. However, the former restriction can be relaxed if a network's nodes are equipped with wavelength converters that can shift one wavelength to another at a converting node. The case when all nodes are capable of wavelength conversion is referred to as full conversion. In this case, any wavelength-routed all-optical WDM network is functionally identical to routing a request in a traditional circuit-switched network. This is because full conversion eliminates the *wavelength continuity constraint* which distinguishes routing in wavelength-routed WDM networks from circuit-switched networks.

Trunk Reservation (TR), also sometimes known as Bandwidth Reservation or State Protection, is a well-known distributed control technique used to prevent bistability at the time of congestion and to improve performance in a fully-connected circuit-switched voice network [1], [12], [18], [19]. It has been applied to other networking environments as well [8], [14]–[16]. Trunk reservation is a distributed capacity control scheme in which part of the capacity of a link for its direct calls is reserved when the used capacity of the link reaches a particular threshold. While TR has been extensively studied for dynamic routing circuit-switched networks, we note that the current literature on on-demand wavelength routing in WDM networks has essentially overlooked the consideration of the TR factor. While such reservation is considered in fixed routing WDM networks with no wavelength conversion [10], its scope is limited as no extensive understanding is addressed, nor how it compares when the network is not fully connected, especially for large networks.

In this paper, we investigate how such distributed capacity reservation affects the blocking performance of on-demand wavelength-routed all-optical WDM networks with dynamic routing capabilities in the presence of wavelength conversion. For dynamic routing, we use Adaptive Alternate Routing (AAR), a distributed routing method that we recently proposed [9]. It may be noted that the TR that is typically invoked in dynamic routing circuit-switched voice networks is for fully-connected network topologies. On the other hand, a WDM network is unlikely to be fully-connected in general and furthermore, only a subset of the nodes may have wavelength converters. Therefore, to understand the impact of the distributed capacity control in a general topology WDM network, we introduce a new distributed control that extends the classical trunk reservation approach by reserving some capacity on the first shortest paths for demand pairs that are not directly connected. We refer to this modification to the original TR scheme as *capacity reservation on the first shortest path* (CRoF). We then compare CRoF with the traditional notion of trunk reservation (henceforth, to be referred to as *trunk reservation on direct*, TRD) in our dynamic routing framework. Knowing that TR is used to prevent bistability and improve performance at the time of congestion, we observe that our CRoF is fairer than TR on pairwise blocking and more effective than TR in improving the overall performance under the same load conditions.

The rest of the paper is organized as follows. In Section II, we define the notation and assumptions used, and elaborate on the RWA employed in this study. In Section III, we introduce CRoF. In Section IV, we discuss our study scenarios and environment followed by a presentation of study results.

II. ADAPTIVE ALTERNATE ROUTING: OVERVIEW

We start with an overview on Adaptive Alternate Routing (AAR), which we recently proposed for WDM Networks [9]. Consider a WDM network consisting of N nodes and L fiber links where each link has W wavelengths labeled $w_1, w_2, ..., W$. The number of wavelength-converting nodes in the network will be indicated by c; clearly, $c \leq N$. Note that $c = 0$ refers to the case when none of the nodes are wavelength-converting nodes, while $c = N$ means that all nodes are wavelength-converting nodes.

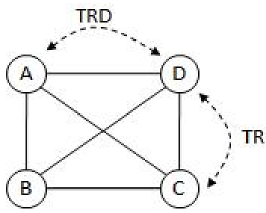
A node pair (or demand pair) u identifies traffic between the source node, S and the destination node, D. For each node pair u, $\{r_1^u, r_2^u, ..., r_{T_u}^u\}$ denotes the set of routes computed and ordered off-line where T_u is the total number of such computed routes for pair $u = (S, D)$ and $f(r_i^u)$ is the number of common idle wavelengths on a route r_i^u, $1 \leq i \leq T_u$, which can be chosen from in order to establish a lightpath. Note that the pre-computed route set serves as a basis for route selection at a coarse grain level. The very first path r_1^u is a direct-link path if the pair u is directly connected, else it is the shortest path (e.g., in terms of number of hops) for pair u consisting of multiple links—this path will be referred to as the *first shortest path*. We use K to be a system parameter to denote the number of routes allowable between (S, D) for a routing scheme at any time; clearly, $K \leq T_u$. In particular, $K = 1$ indicates that there is only one route allowable between S and D; this may or may not be a direct route. By direct route, we mean that S and D are directly connected by a link; however, in a general topology, not all sources and destinations will have direct connectivity.

Adaptive Alternate Routing (AAR) is an event-dependent routing scheme for general topology WDM networks. It is based on the sticky random principle of dynamic alternate routing (DAR) that was originally developed for fully-connected circuit-switched voice networks [6], [7]. However, unlike DAR, AAR has crankback capability [3], [13] and is designed for general topology WDM networks. Briefly, in AAR, for any pair u, if its end nodes are directly connected, then this direct-link path is always attempted first; on the other hand, if pair u does not have a direct link, then its first shortest path is attempted first. In addition, at any time, every demand pair u has at least an identified alternate path that can be attempted if an arriving request cannot find an available wavelength on the first path. Due to the crankback capability, our scheme checks if all links (segments) of such alternate paths (subject to satisfying the *wavelength continuity constraint*) have bandwidth available for an arriving request. If so, it is attempted; if not, the request proceeds to attempt the third route in the routing table. In the mean time, a new alternate path is randomly determined and stored in the second location (for use by future requests, not the current request). If the request is not successful in using the third route (e.g., due to the lack of wavelength continuity), it tries the fourth entry (while determining independently a new replacement randomly to take the position of the third route for use by future requests), and so on. If, after trying a maximum number of routes in the routing table, the request cannot go through, it is blocked and lost. Note that if a path is selected at any stage, we use a random wavelength selection algorithm to determine the wavelength to be used; i.e., whenever $f(r_i^u) \geq 1$, a wavelength is selected randomly.

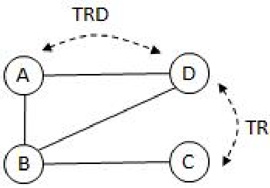
III. CROF: CAPACITY RESERVATION ON THE FIRST SHORTEST PATH

The classical trunk reservation concept works by reserving part of the capacity of a link for its direct calls when the used capacity of the link reaches a particular level. If R denoted the trunk reservation parameter on a link, then whenever the used capacity on the link reaches $W - R$, only the requests that are between the two ends of this link are allowed to use the remaining available R units; this is the basic idea of a classical TR scheme, which we will refer to as TRD (Trunk Reservation on direct path). Note that in the TRD scheme, only physically connected demand pairs u can take advantage of the TR feature; it does not help node pairs that are not directly connected. We briefly illustrate this feature using a 4-node WDM network. Assume that each node in Figure 1 has a full wavelength conversion capability. Now consider Figure 1(a) in which each node has direct links to all other nodes. TRD, with any assigned value of R $(< W)$, can be invoked whenever the network is congested, and still *all* node (demand) pairs will have some capacity reserved due to trunk reservation on their direct-link routes. On the other hand, consider Figure 1(b), which shows a 4-node partially-connected network where nodes D and C do not share a direct link. If we apply TRD in this network, node pair (D, C) would have no reserved lightpaths to avail in a congested situation. In a sparsely connected network, a significant number of demand pairs may not have direct link connectivity similar to this case.

To circumvent this situation, we introduce a modification to the TRD scheme so that it can be useful for general topology networks. The idea behind our modification is to make all demand pairs have some reserved capacity available, which would be invoked at the time of congestion. We call the proposed scheme, CRoF: *capacity reservation on the first shortest path*. As the name implies, for each demand pair u, we will apply a distributed capacity reservation on the first shortest



(a) 4-node fully-connected network



(b) 4-node partially-connected network

Fig. 1. Illustration of TRD and CRoF

path (r_1^u) whether it is a direct link path or not. By doing so, all demand pairs will have some reserved bandwidth reserved in a distributed manner when the network is congested and CRoF is invoked. Now consider again Figure 1(b) in which demand pair (D, C) is not directly connected. Our CRoF scheme allows (D, C) to have some reserved bandwidth on the first shortest path (D-B-C), which can be invoked at the time of congestion. Note that since path (D-A-B-C) is the *second* shortest path for pair (D, C), CRoF is not invoked on this path. It is to be understood that with CRoF, a link may have more than one reservation active at the time of congestion. Consider the point of view of direct link D-B; since it serves as the direct link for pair (D, B), it will have reserved bandwidth for itself (at the time of congestion), i.e., TRD is activated. At the same time, link D-B will have to cater to the reservation needed for pair (D, C), which is independent of the direct link reservation. Finally, it is worth noting that when the network is fully-connected, TRD and CRoF are the same.

IV. PERFORMANCE STUDY

The overall goal of this performance study is to understand the impact of the distributed control scheme, CRoF, in a general topology WDM network that has AAR in operation. In this context, we also want to understand the difference between CRoF and the classical scheme.

A. Study Environment

We developed a discrete-event routing simulator to simulate wavelength-routed all optical WDM networks for AAR. We implemented the capability that the network can have any number of wavelength-converting nodes and the option of using TR with any value specified for reservation parameter, R. The simulation tool is a call by call network simulator. For our study, request arrivals for wavelength services are assumed to follow the Poisson process, and the service duration time is assumed to be exponentially distributed; thus, the offered load can be represented in Erlangs. For each simulation scenario, we performed 11 independent simulation runs; the result reported is for the average of this value. We have also computed the 95% confidence interval and found that it stays typically within 1% of the average value.

First, consider the network topologies. We have selected three different topologies: a 14-node National Science Foundation network (NSFNET), a 25-node mesh-torus network, and a 36-node Sprint continental IP backbone (Figure 2), with varying degrees of connectivity. These topologies are selected as representative topologies to understand how the reservation schemes might be impacted differently when the number of demand pairs have differing spread of shortest-hop first paths; this will be explained further in Section IV-B3 (also see Table II). All links in these networks are assumed to be bidirectional multi-wavelength fibers with the same number of wavelengths in each fiber. For each topology, we consider two different load scenarios which we label as L1 and L2 to reflect moderate and high traffic loads, respectively. We started each network without any wavelength converters and determined a baseline load so that the call blocking probability is approximately 10% with two routes in the routing table; we call this load L1. We then increased the load proportionally to attain load L2 so that the blocking is progressively higher under the same topological scenarios and capacity. It is important to note that the moderate and the high load cases are chosen here since the general advantage of trunk reservation is found in such load cases (as opposed to a lightly loaded case) [13].

To generate traffic loads, we use the demand model of [5] to create asymmetric demands between node pairs. Information about network topologies and traffic scenarios is shown in Table I. From Table I(b), it is easy to see that the total traffic load simulated is quite significant, and the per pair traffic load varied from as low as 3 Erlangs to as high as 15 Erlangs to capture the load variations per pair.

The distributed capacity control schemes are invoked through parameter R in our approach. If it is the classical approach (i.e., TRD), then R refers to the capacity reserved only on the direct link for all traffic, while R refers to the capacity reserved in a distributed manner on the first shortest path for a demand pair for CRoF. We run each topology for a number of different values of R: for NSFNET, R=0, 1, 2, 4, 7, and 10; for Mesh-tours, R=0, 2, 3, 5, 8, and 11; for Sprint, R=0, 2, 3, 6, 9, and 12. We denote CRoF2 to mean CRoF with $R = 2$, and TRD2 to mean TRD with $R = 2$. Note that $R = 0$ means that TR is not used in this case, which will be referred to as *no reservation* (NR).

For clarity, we name each simulated scenario using the following convention: ("load level"-"topology"-"$c = n$"). For example, L1-NSFNET-c=0 refers to the scenario of traffic load L1, NSFNET network, and no coverter ($c = 0$).

The following factors were taken into account in our study:

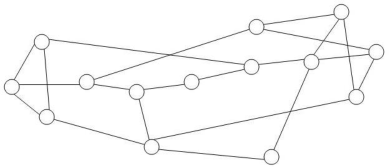
TABLE I
Topology Inforamtion

(a) Topology Summary

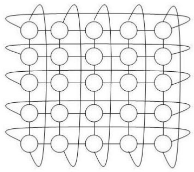
Network	No. of Nodes	No. of Links
NSFNET	14	21
Mesh-torus	25	50
SPRINT	36	54

(b) Topologies, Traffic patterns, Numbers of Wavelength, Loads

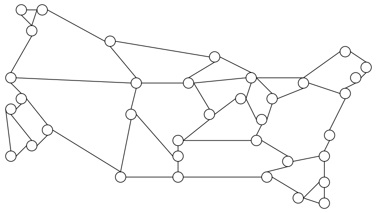
Case	Topology	Wavelengths per link	Total Load (in Erlangs)	Avg. Erlang Load per Demand pair
L1-NSFNET	14-NSFNET	140	1092	12
L2-NSFNET	14-NSFNET	140	1365	15
L1-Mesh	25-Mesh-torus	156	2700	9
L2-Mesh	25-Mesh-torus	156	3450.47	11.5
L1-Sprint	36-Sprint	260	1890	3
L2-Sprint	36-Sprint	260	2700	4.3



(a) 14-NSFNET



(b) 25-Mesh-torus



(c) 36-SPRINT

Fig. 2. Network Topologies

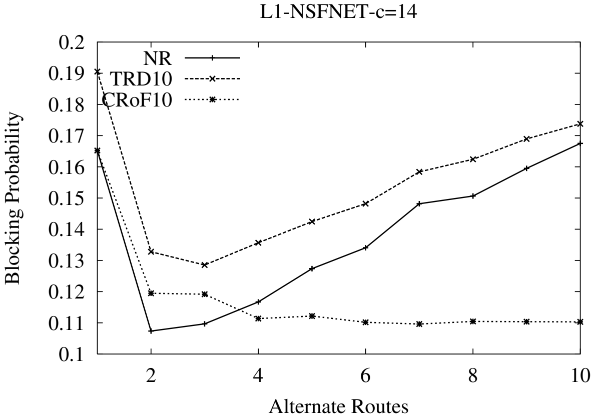


Fig. 3. Comparison of blocking performance of no reservation, TRD10, and CRoF10 as the number of routes in the routing table varied when $c = 14$ (L1, NSFNET).

1) the impact on network performance as the number of wavelength converters are varied, 2) the impact due to different number of alternate routes in the routing table (in figures, $K = 1$ means the case of the single fixed route in the routing table), 3) different offered load conditions, 4) the performance impact on different topologies, 5) different degrees of capacity reservation. These lead to a sizable number of scenarios due to the multiplicative nature. For brevity, we focus our discussion on a selective subset of scenarios out of the full list and remark where we noticed significant differences with the remaining scenarios.

In order to determine where to place the wavelength converters as we move from the no conversion case to the full conversion case, we use a simple heuristic given in [2] called Total Outgoing Traffic (TOT). The algorithm allows the placement of all given wavelength converters c at the nodes that have the highest outgoing traffic. The total outgoing traffic is defined by the entering traffic (the sum of the loads on all routes that originate at node v) plus the transit traffic (the sum of the loads on all routes that have v as an intermediate node). The choice of the wavelength converters placement algorithm is not expected to affect the general findings of this work. An inferior wavelength selection algorithm will only delay the significant reduction in the blocking probability until later stages, i.e., when almost all wavelength converters are already placed. However, the performance gap between TR and CRoF would be still preserved.

B. Study Results

1) Initial Justification of CRoF over Classical Capacity Reservation: For this illustration, we focus our results on the L1-NSFNET-c=14 case. Performance results are plotted in Figure 3. We can clearly see that the case of CRoF10 performs better than the case of TRD10 for all values of K and no reservation when $K > 3$. This shows the significant benefit of CRoF over TRD in partially-connected networks such as NSFNET. CRoF maintains the network connected at the time of congestion, whereas only the directly connected demand pair u are capable of establishing lightpaths under TRD.

2) Comparative Analysis of No Reservation, TRD, and CRoF: First consider the WDM networks with no converters; we found that the performance of no capacity reserved on any

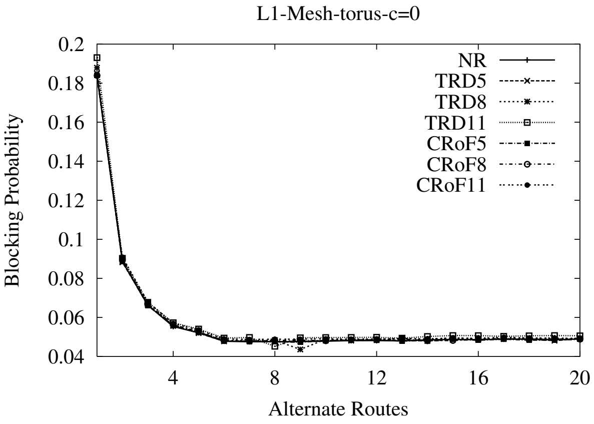


Fig. 4. Blocking performance of TR schemes for different values of R as the number of routes in the routing table varied when $c = 0$ (L1, Mesh-torus).

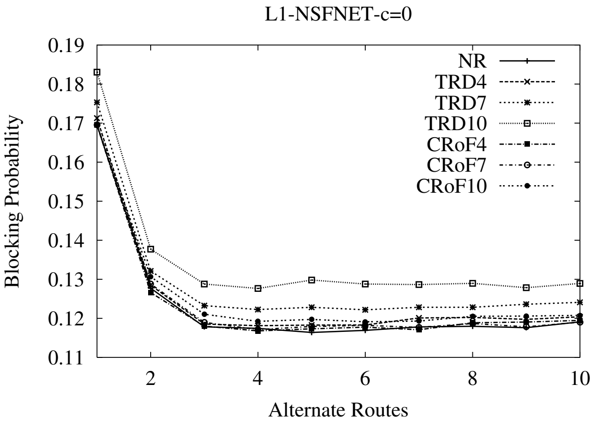


Fig. 5. Blocking performance of TR schemes for different values of R as the number of routes in the routing table varied when $c = 0$ (L1, NSFNET).

link (NR), TRD and CRoF are very similar for both L1 and L2 loads in a network with no converters. For instance, Figure 4 shows that there is no benefit of TRD or CRoF over NR. The exception is in the NSFNET network. In this scenario, NR and CRoF performance are close and better than TRD. The more loaded the network is, the more TRD becomes inferior as we see in Figures 5 and 6.

As we start placing wavelength converters in the networks, we see that the performance of CRoF gradually becomes better than NR and TRD. In a full conversion network, we observe the best case scenario of CRoF. We take the NSFNET example to show the increasing benefits of CRoF over NR and TRD as we place wavelength converters. Figures 6, 7, 8, and 9 show the performance of c=0, 2, 9, and 14 of the L2-NSFNET case (gradually moving form the no conversion to the full conversion network). This shows that the more wavelength converters are placed in the network, the greater benefit of CRoF is derived in terms of reducing and stabilizing the blocking probability. Clearly, there is a strong tie between the *wavelength continuity constraint* and the advantages of CRoF.

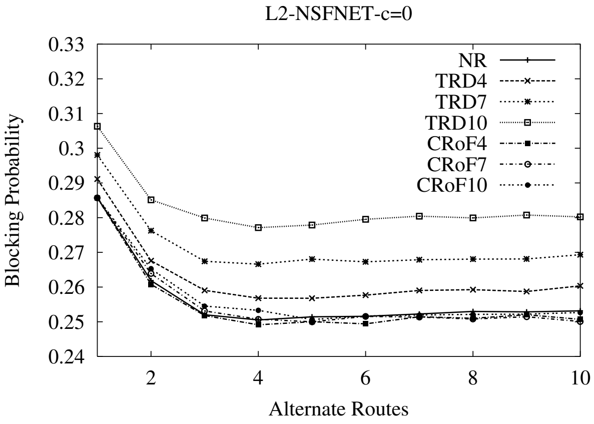


Fig. 6. Blocking performance of TR schemes for different values of R as the number of routes in the routing table varied when $c = 0$ (L2, NSFNET).

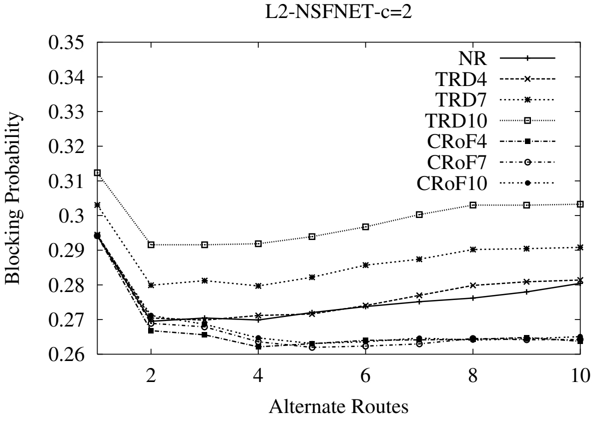


Fig. 7. Blocking performance of TR schemes for different values of R as the number of routes in the routing table varied when $c = 2$ (L2, NSFNET).

When the *wavelength continuity constraint* is strictly enforced (no wavelength conversion), CRoF is not useful. However, as the *wavelength continuity constraint* begins to loosen (by placing wavelength converters in the network), we observe the increasing benefits of CRoF.

While the gradual improvement is also the case in mesh-torus and Sprint networks, these benefits shrink. Figure 10 shows that while CRoF helps in stabilizing the performance, the blocking probability is lower only when $K > 3$.

The benefits of CRoF are also influenced by the load level. Our study shows that the CRoF performance gain in L2 is higher than that in L1. There is less benefit from CRoF in L1 NSFNET than in L2 NSFNET, especially when the number of alternate routes considered is small (compare Figure 3 with Figure 9). However, this is also dependent on the topology. There is no network-wide benefit of CRoF in Sprint for load L1 as shown in Figure 11.

3) Comparative Analysis at the Pairwise Level: So far, we have discussed performance results at the overall network-

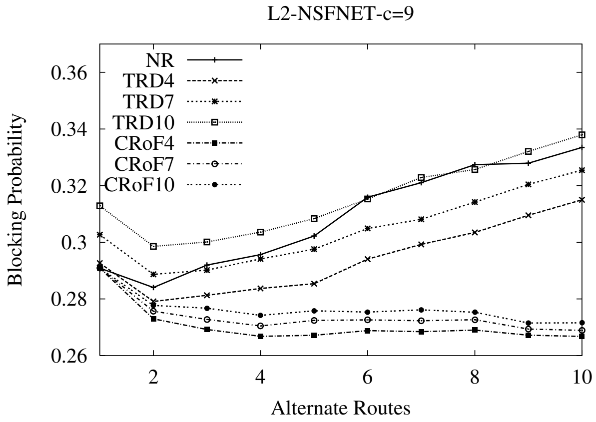


Fig. 8. Blocking performance of TR schemes for different values of R as the number of routes in the routing table varied when $c = 9$ (L2, NSFNET).

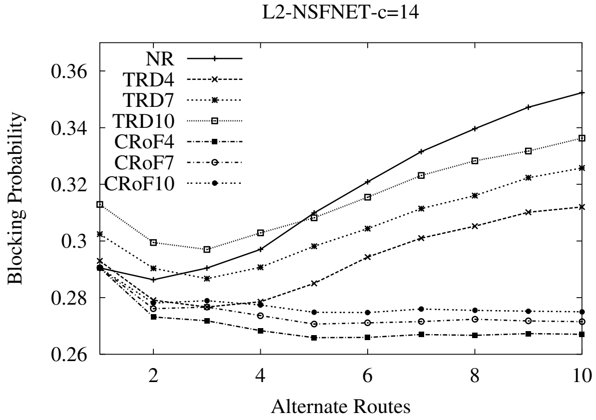


Fig. 9. Blocking performance of TR schemes for different values of R as the number of routes in the routing table varied when $c = 14$ (L2, NSFNET).

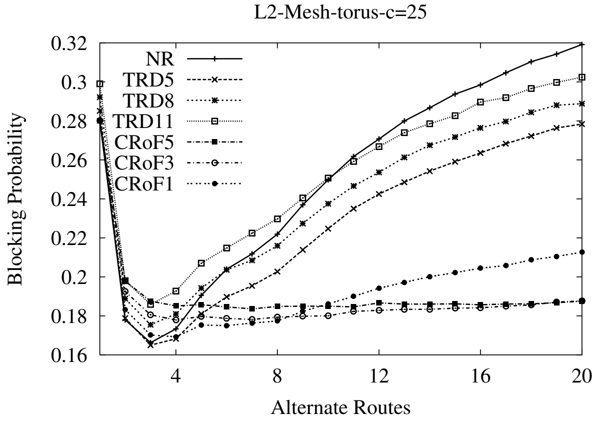


Fig. 10. Blocking performance of TR schemes for different values of R as the number of routes in the routing table varied when $c = 25$ (L2, Mesh-torus).

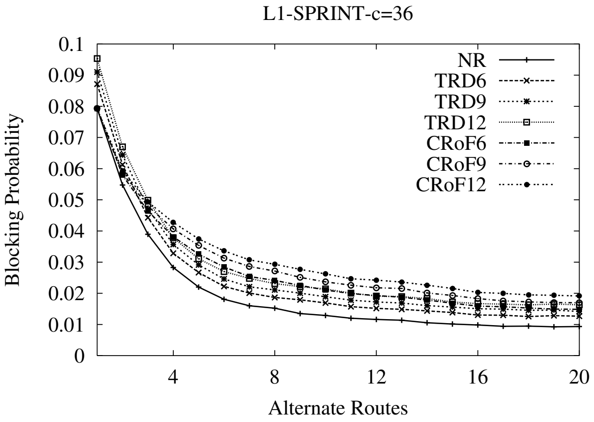


Fig. 11. Blocking performance of TR schemes for different values of R as the number of routes in the routing table varied when $c = 36$ (L1, SPRINT).

wide impact level. An attractive dimension of CRoF is to be able to provide some capacity reservation for non-directly connected pairs. Thus, we also delved into understanding the impact at the pair-wise demand pair level. In order to do that, we divided all the traffic demand pairs in the network into three different groups: pairs that are directly connected (P1), pairs for which the first shortest path consists of two links (P2), and the remaining pairs which have three or more links to travel on their first shortest paths (P3+).

For illustration, we take the scenario of TRD4 and CRoF4 in Figure 12 and break it into three groups; subsequent figures show a performance comparison between TRD4 and CRoF4 (i.e., with $R = 4$) for three groups of traffic node pairs. The first one, Figure 13, shows the blocking of node pairs in group P1. Note that these pairs are directly connected. The second one, Figure 14, shows the blocking of node pairs in group P2, and the third one, Figure 15, shows the blocking of node pairs that belong to group P3+. We find from Figure 13 that TRD4's performance is better than CRoF4 for group P1, i.e., for directly connected pairs. On the other hand, Figures 14 and 15 show that CRoF4 performs better than TRD4 for the other two groups. Not only does CRoF reduce the blocking probability for pair groups P2 and P3+, but it also stabilizes the network behavior as the number of alternate routes is increased. Moreover, CRoF provides *fairness* in the network by giving groups P2 and P3+ more bandwidth that was otherwise only reserved for directly connected node pairs in case of TRD, while still improving the overall performance as depicted in Figure 12. Results of Mesh-torus and Sprint networks show similar behavioral patterns. The basic advantages of CRoF over TRD are that CRoF provides more *fairness* among non-directly connected node pairs, and reduces and stabilizes the blocking performance as the number of alternate paths considered is increased.

Our study shows that NSFNET benefits the most from CRoF compared to Mesh-torus and SPRINT. The reason behind this is that the NSFNET topology has a higher percentage of direct routes than mesh-torus and Sprint. NSFNET has 11% of directly connected node pairs compared to 8% and 4% for mesh-torus and Sprint, respectively (Table II). Recall that TRD works well in fully-connected networks where direct

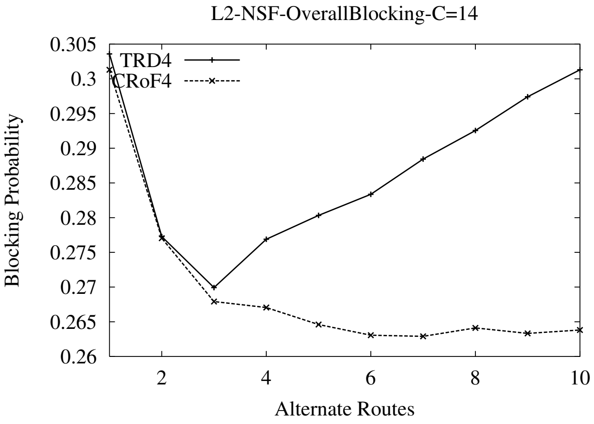


Fig. 12. Overall Blocking performance of TRD4 and CRoF4 schemes as the number of routes in the routing table varied when $c = 14$ (L2, NSFNET).

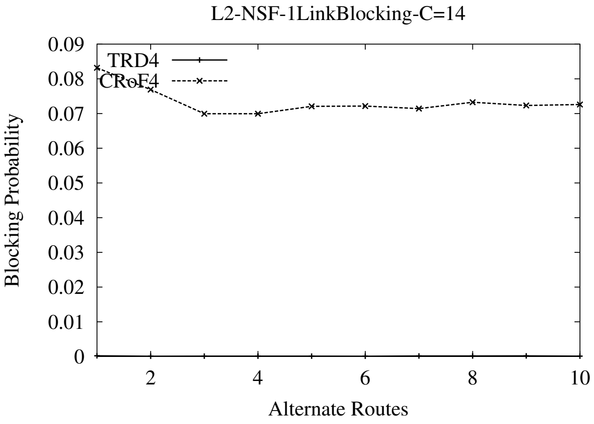


Fig. 13. Blocking performance of pair groups P1 with TRD4 and CRoF4 schemes as the number of routes considered in the routing table varied when $c = 14$ (L2, NSFNET).

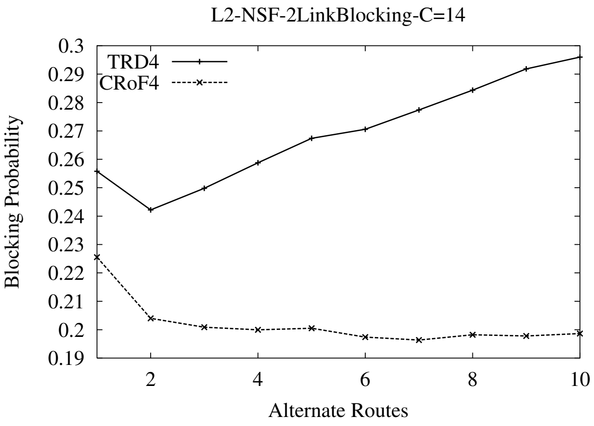


Fig. 14. Blocking performance of pair groups P2 with TRD4 and CRoF4 schemes as the number of routes considered in the routing table varied when $c = 14$ (L2, NSFNET).

routes exist between all pairs. Our modification of TRD is motivated by the observation that if TRD is applied in a

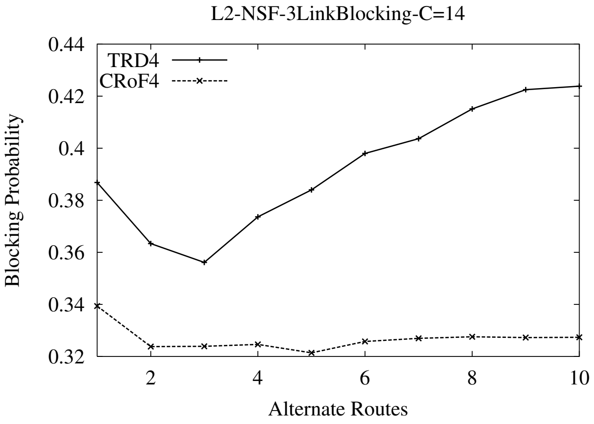


Fig. 15. Blocking performance of pair groups P3+ with TRD4 and CRoF4 schemes as the number of routes considreed in the routing table varied when $c = 14$ (L2, NSFNET).

TABLE II
TOPOLOGY INFORMATION: NUMBER OF PAIRS IN DIFFERENT PAIR GROUPS

Network	Group P1	Group P2	Group P3+
NSFNET	21	36	34
Mesh-torus	50	100	150
SPRINT	54	88	488

TABLE III
PERCENTAGE OF ERLANG LOAD FOR DIFFERENT PAIR GROUPS

Network	Group P1	Group P2	Group P3+
NSFNET	20.7	38.8	40.5
Mesh-torus	16.3	34.9	48.8
SPRINT	8.6	15	76.4

partially-connected network, a subset of node pairs will have no way of connecting to each other resulting in performance deterioration. Although CRoF avoids this problem by always using the first shortest path, it is still desirable to have more direct routes because of the obvious observation that the blocking probability of pairs in group P1 is less than the blocking probability of pairs in groups P2 and P3+, especially in a heavily loaded network. Thus, the more direct routes exist, the better CRoF performs since the first shortest path will likely be a direct route. The second reason is that the number of pairs in group P3+ in NSFNET is similar to the number of pairs in group P2, as shown in Table II. This is not the case in Mesh-torus or SPRINT where the number of pairs in group P3+ is significantly greater than the number of pairs in group P2.

V. CONCLUSION

In this paper, we introduce the concept of capacity reservation on the first shortest path for dynamic routing WDM networks in a general topology environment. For our study, we consider that the WDM network operates with adaptive alternate routing where a random wavelength selection algorithm is employed. Through our study, we find that CRoF is in general, more beneficial over TRD in improving the network performance. In particular, the advantages of CRoF are determined by three major factors: the wavelength conversion degree, the topology, and the load level. A major advantage of CRoF is that it is much fairer than no reservation and TRD in wavelength-convertible networks, which is further highlighted in higher loads. Naturally, networks that have a greater percentage of direct routes and also more pairs in groups P2 than P3+, benefit more from CRoF than networks with a less percentage of direct routes and less number of pairs in group P2.

For future work, we plan to examine the impact of various wavelength selection algorithms on capacityy reservation schemes. Secondly, in this work, we considered AAR, which is an event-dependent routing scheme. There are other dynamic routing schemes [4], [11], [17], [20] which fall under state-dependent routing. We intend to understand how capacity reservation might be influenced by several wavelength selection methods and different dynamic routing schemes in partially-connected wavelength-routed WDM networks.

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