

# Adaptive Alternate Routing in WDM Networks and its Performance Tradeoffs in the Presence of Wavelength Converters

Iyad Katib and Deep Medhi<sup>1</sup>

Computer Science & Electrical Engineering Department

University of Missouri–Kansas City

Kansas City, MO 64110 USA

email: {IyadKatib, DMedhi}@umkc.edu

**Abstract** Routing in wavelength-routed all-optical WDM networks has received much attention in the past decade for which fixed and dynamic routing methods have been proposed. Taking into account the observation that wavelength-routed all-optical WDM networks are similar to circuit-switched voice networks, except with regard to wavelength conversion, we propose an adaptive alternate routing (AAR) scheme for wavelength-routed all-optical WDM networks. A major benefit of AAR is that it can operate and adapt without requiring an exchange of network status, i.e., it is an information-less adaptive routing scheme. The scope of this work is to understand this scheme on its own right since no other dynamic routing schemes are known to have the information-less property. In this paper, we conduct a systematic study of AAR with regard to factors such as the number of converters, load conditions, traffic patterns, network topologies, and the number of alternate paths considered. We observe that the routing scheme with multiple alternate routes provides more gain at a lower load instead of requiring any nodes to be equipped with wavelength converters. On the other hand, the availability of wavelength converters at some nodes, along with adaptive routing, is beneficial at a moderate to high load without requiring all nodes to be equipped with wavelength converters. We also observed that a small number of alternate routes considered in a network without wavelength converters gives a much better performance than a network with full wavelength converters and fewer alternate routes. Through this study, we observed that the proposed adaptive alternate routing scheme adapts well to the network traffic condition.

## Keywords:

Routing in WDM Networks, Wavelength Converters, Adaptive Alternate Routing.

---

<sup>1</sup> Corresponding Author

## 1 Introduction

Wavelength-routed all-optical wavelength division multiplexing (WDM) networks are designed and developed to accommodate perpetually 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. Wavelengths are combined and transmitted concurrently over the same fiber.

Normally, the same wavelength must be used for each connection request on each fiber along the chosen path. At the same time, two identical wavelengths cannot share the same fiber. These unique conditions of wavelength-routed WDM networks, referred to as the *wavelength continuity constraint* and the *distinct channel assignment*, make the routing problem (called routing and wavelength assignment, RWA) more complicated than routing in traditional circuit-switched voice networks, and fundamentally different than routing in packet-switched networks. However, the former restriction can be somewhat relaxed if a network's nodes are equipped with wavelength converters that can shift one wavelength to another at a converting node. In fact, if all nodes in a network are equipped with full conversion capability, then the routing in the WDM network is similar to dynamic call routing in the circuit-switched voice network. However, wavelength converters are costly and a network provider either may not be able to or may not want to replace all non-converted nodes to fully converted nodes in a single installation cycle. However, the problem of wavelength converter placement raises many questions. Does a given network need wavelength converters for a given traffic load if quality of service can be met without converters? How do additional wavelength converters improve network performance? Where should they be placed? How is this related to network traffic load? What effects do routing techniques have on the wavelength conversion (WC) gain?

While there have been significant works on routing in WDM networks (see Section 2 for related work), we have found that several angles have not been addressed before or are not discussed in one place to see how these are related. For instance, there have been significant works on dynamic call routing for circuit-switched voice networks [15]. However, such schemes have not been explored much for wavelength-routed WDM networks in the presence of the wavelength continuity constraint. At the same time, dynamic call routing, which was developed originally for circuit-switched voice networks, has been studied primarily for fully connected networks. It is not clear how well they work in a general topology network, especially in the presence of the wavelength continuity constraint and/or with some nodes having converters. Furthermore, most studies on wavelength-routed WDM networks have been primarily devoted to considering either small topologies or symmetric traffic along with the total load being considered quite low (for instance, about 1 Erlang traffic load per pair, in many studies), or for fixed routing.

For our work, we propose an adaptive alternate routing (AAR) scheme for WDM

networks, which is extended from dynamic alternate routing [13, 14] developed originally for full-connected circuit-switched voice networks. The key advantage of DAR (and thus, AAR) is that it is an information-*less* routing; that is, the scheme adapts to selecting alternate routes *without* requiring an exchange of status information on links by the different nodes. The primary scope of our work is to study and understand AAR in its own right for WDM networks such as how well it adapts in an information-less environment under various conditions. For this, we consider a number of factors. Specifically, we consider wavelength converters along with adaptive alternate routing for three different network topologies under a set of load conditions, with the intent to see where and how wavelength converters might benefit and how the consideration of multiple alternate routing entries in the routing table impact network performance. Our goal is to shed some light on various inter-related aspects in a comprehensive manner for AAR. For instance, we wish to observe how the usefulness of wavelength converters is influenced by the traffic patterns (i.e. symmetric vs. asymmetric at low, medium, and high loads) and the number of alternate routes considered in the routing table. An important goal is to identify the cases in which wavelength converters can significantly effect the performance for AAR. Moreover, we compare the benefits of wavelength converters with the availability of multiple alternate routes in the routing table in the absence of wavelength converters to examine the real exigencies of wavelength converters in wavelength-routed WDM optical networks. We wish to point out that this study does not compare AAR with any other dynamic routing schemes that requires the exchange of status information. Since DAR is also an information-less routing scheme, we also include a brief comparison to show how AAR differs from DAR. In general, the focus remains on understanding AAR, in the same spirit as one tries to understand physical systems.

The rest of the paper is organized as follows. In Section 2, we present related work. In Section 3, we discuss the routing framework for wavelength-routed WDM networks along with our proposed adaptive alternate routing scheme. In Section 4, we discuss our study scenarios followed by a presentation of study results.

## 2 Related work

Routing in circuit-switched voice networks has been a major research direction in the past several decades. Ash and Chemouil [6] provided an overview of routing algorithms in circuit-switched networks. They categorized routing algorithms into four types: fixed routing, time-dependent routing, state-dependent routing, and event-dependent routing. In fixed routing, the routing table is fixed for a call and the route selection order is predetermined based on this table; an alternate route from the table is attempted if the first path is not available, and so on. In time-dependent routing, the routing table is updated at a certain point of time during the day or week, and then the route selection order is based on the current routing table. In state-dependent routing, the routing table is updated automatically according to the

current state of the network and may require periodic flooding of network status information. In event-dependent routing, the routing table is altered locally based on whether a request is blocked. While each of the above routing categories have their pros and cons, Ash [4] found that the performance of event-dependent routing to be close to, or better than, state-dependent routing with flooding. An advantage of event-dependent routing is that it avoids the information flooding associated with state-dependent routing. While routing in wavelength-routed all optical networks has been examined in the past decade, most considered fixed alternate path routing [17,25], or dynamic routing [11,22,30,36] that fall under state-dependent routing, but none considered event-dependent routing. Because of the success of event-dependent routing in circuit-switched voice networks and the lack of current work on event-dependent routing in WDM networks, we proposed an event-dependent routing scheme that can be used in WDM networks.

If we now consider the benefits of wavelength converters, which have been extensively investigated for WDM networks with fixed routing, we find that the gain of wavelength converters in minimizing the call blocking probability depends on several factors. These are as follows:

- Network topology and size: It has been shown that [7–9,23,32] when the connectivity of the network is low, e.g. a ring topology, the conversion capability is not very advantageous because of the high load correlation. Also, when the connectivity is high, such as in a hypercube topology, conversion gain is small because of the short length of the routes. In contrast, if the connectivity is medium, such as in the mesh-torus topology, wavelength converters are useful due to the low load correlation and longer hop-counts.
- The RWA used: The conversion gain in fixed routing, in which only one fixed route is available between a source and destination, is low compared to fixed alternate routing, especially when a packing wavelength selection scheme such as fixed fit (FF), most used (MU), or least used (LU) is used. When more alternate paths are available, higher benefits of conversion can be derived. Moreover, dynamic alternate routing techniques can achieve better performance [29] and [19]. Other studies, [19] and [28], investigated the performance of wavelength selection algorithms. It has been shown that the MU wavelength selection scheme may achieve better performance than other wavelength selection algorithms, especially when the number of wavelengths per link is large. Barry [7] claimed that a good routing algorithm in wavelength-continuous networks should consider the hop-count ( $H$ ), interference lengths ( $L$ ), and link congestion. The claim is that minimizing the ratio of  $H/L$  would provide better performance and reduce the benefits of wavelength converters. Ramamurthy and Mukherjee [29] showed that the presence of wavelength converters significantly improves the performance in networks that employ alternate routing when compared to networks that use (single) fixed routing. They also show that the benefits of adding an alternate route is more than the benefits of adding a wavelength converter at low loads when the number of alternate routes between node pairs does not fully

exploit the connectivity of the network topology. Karasan and Aynoglu [19] showed that FF or MU wavelength selection algorithms produce a low conversion gain compared to other algorithms when the shortest path routing algorithm is used.

- Traffic load: [33] shows that WC may not improve the performance in some cases. As wavelength converters solve the conflict of the wavelength continuity constraint, placing wavelength converters in a network prompts the network to accept longer paths compared to the same network without wavelength converters. This means that when the network is heavily loaded, longer paths can be accommodated subject to bandwidth availability. In turn, more subsequent shorter paths will be rejected, resulting in higher blocking performance.
- The number of wavelengths per link: It has been shown that [31] when the number of wavelengths increases, wavelength converters become more useful since this leads to the mixing of more connections. However, after a certain point, increasing the number of wavelengths does not produce new conversion benefits.
- The number of fibers per link: [18] showed that the benefits of wavelength converters decrease as the number of fibers per link increase. [33], however, showed that wavelength converters can improve the performance in multi-fiber ring networks with a moderate number of wavelengths more than in single-fiber ring networks. The authors reported that the reason for this was unclear and subject to further investigation.

It may be noted that most previous works examined the interaction between wavelength converters and fixed alternate routing assuming symmetric traffic. Often, such studies have been analyzed for small numbers of wavelengths with low Erlang loads. From Erlang-B loss formula [15], it is known that when the load to the number of wavelengths is kept fixed, the statistical multiplexing gain of low load to a small number of wavelengths is less than the gain of high load and a large number of wavelengths. As wavelength-routed all-optical WDM systems are suitable for backbone networks, it is important to understand the system dynamics for larger network load values and a large number of wavelengths. Furthermore, trunk reservation, also known as bandwidth reservation or state protection, is a well-known control technique used to prevent bistability at the time of congestion in a circuit-switched voice network and to improve network performance [1, 24, 34, 35]. It works by reserving part of a capacity of a link for its direct calls when the used capacity of the link reaches a particular level. We also note that current literature on routing in WDM networks has not considered the impact of the trunk reservation factor and its interaction in the presence of wavelength conversion.

While there have been analytical models developed to understand performance of WDM networks [9–11], such models are mostly for fixed routing with a single (shortest) path between each pair of nodes. As is known from studies of alternate routing for circuit-switched voice networks, analytical models in the presence of alternate routing require assuming that the overflow traffic is Poisson, while in

reality there is peakedness in overflow traffic. Thus, such models [15] typically assume link independence and use reduced load approximation approaches; however, such models do not always lead to results that accurately reflect the system dynamics depending on the offered load to the capacity ratio. For instance, it was reported in [16] that for a nominal load, there is a good match between simulation and analytical models; however, the difference can be noticeable at a moderately higher load (while keeping the same capacity). Recall that our primary interest is to conduct a study on adaptive alternate routing for WDM networks in the presence of wavelength converters and the number of alternate routes considered; thus, we wanted the comparison to be accurate, not dissuaded by any artificial gap that may be induced due to the approximation in an analytical model. Therefore, development of an analytical model for event-dependent routing for WDM networks in the presence of wavelength continuity constraint is outside the scope of the present paper and will be considered independently.

### 3 Routing and Wavelength Assignment with Wavelength Conversion

Before we describe the routing framework, we define the notation and assumptions used in this discussion. Consider a WDM network consisting of  $N$  nodes and  $L$  fiber links where each link has  $W$  wavelengths labeled  $w_1, w_2, \dots, w_W$ . We denote the number of wavelength-converting nodes in the network by  $c$ ; clearly,  $c \leq N$ . Here,  $c = 0$  means that none of the nodes are wavelength-converting nodes, while  $c = N$  means that all nodes are wavelength-converting nodes.

A node pair  $u$  is denoted by the pair  $(s, d)$ , where  $s$  is the source node and  $d$  is the destination node. For each node pair  $u$ ,  $\{r_1^u, r_2^u, \dots, r_{T_u}^u\}$  denotes the set of routes computed and ordered off-line where  $T_u$  is the total number of such computed routes between  $(s, d)$ . Note that this pre-computed set serves as a basis for route selection at a coarse grain level. We use  $K$  to be the number of routes available 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 available 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, a source and a destination may not necessarily be directly connected. We denote  $f(r_i^u)$  to be the number of common idle wavelengths on a route  $r_i^u$ ,  $1 \leq i \leq T_u$ , that can be chosen from in order to establish a lightpath. Finally,  $L(r_i^u)$  denotes the number of links of route  $r_i^u$ , and  $l_h(r_i^u)$  is link  $h$  on  $r_i^u$ , where  $1 \leq h \leq L(r_i^u)$ .

#### 3.1 Wavelength Converters

We now formally present wavelength converters and their impact on path selection. Let  $N(s_j, r_i^u)$  denote the number of segments  $s_j(r_i^u)$  on the route  $r_i^u$ , where  $1 \leq j \leq L(r_i^u)$ . Consider  $c(r_i^u)$  to denote the number of wavelength-converting

nodes on  $r_i^u$ . If, for instance,  $r_i^u$  consists of four nodes (also referred to as wavelength cross-connects, WXC) and only one is a wavelength-converting node (also called wavelength-interchanging cross-connects WIXCs), then  $c(r_i^u) = 1$ , and the other are non-converting nodes (also called wavelength-selective cross-connects WSXCs). Here,  $N(s_j, r_i^u) = 2$  with segments ( $s_1(r_i^u)$  and  $s_2(r_i^u)$ ) as shown in figure 1. That is,  $(N(s_j, r_i^u) = c(r_i^u) \text{ (excluding } s \text{ and } d) + 1)$ . Each segment  $s_j(r_i^u)$  still must follow the *wavelength continuity constraint*.

To establish a lightpath, two sub-problems need to be solved. First, a path from source to destination must be chosen from the allowable paths; this will be discussed in detail in the next section. Second, a wavelength must be selected for the chosen path. This is the wavelength selection part performed by any of the wavelength selection algorithms such as *most used* (MU), *least used* (LU), *fixed fit* (FF), and so on. In this work, we use a random wavelength selection algorithm. That is, whenever  $f(r_i^u) \geq 1$ , a wavelength is selected randomly. The random selection of wavelengths equally distributes the load on the wavelengths and therefore balances the wavelength utilizations. This allows us to focus our work on the routing algorithm aspect and the role of the wavelength conversion.

There are three possible scenarios to consider in order to find  $f(r_i^u)$ . The first is when the network has no converters. In this environment, each  $r_i^u$  consists of one segment  $s_1(r_i^u)$  that must have at least one idle common wavelength on all its links  $l_h(r_i^u)$  to establish a lightpath. The second is when the network uses *sparse wavelength conversion*. In this case, paths are divided into numbers of segments  $s_j(r_i^u)$  determined by the number of  $c(r_i^u)$  on each path as we saw in Figure 1. Each segment  $s_j(r_i^u)$  must have at least one idle common wavelength to establish the lightpath. For example, let  $r_i^u$  consist of three segments  $s_1(r_i^u)$ ,  $s_2(r_i^u)$ , and  $s_3(r_i^u)$ . Let  $w_1$ ,  $w_2$ , and  $w_3$  be common idle wavelengths on  $s_1(r_i^u)$ ,  $s_2(r_i^u)$ , and  $s_3(r_i^u)$ , respectively. Then, a lightpath could be established using  $w_1$  on  $s_1(r_i^u)$ ,  $w_2$  on  $s_2(r_i^u)$ , and  $w_3$  on  $s_3(r_i^u)$ . The third is when all nodes are wavelength-converting nodes. In this case, the wavelength continuity constraint is utterly diminished, each link becomes a segment by itself, and any idle wavelength can be used on each  $l_h(r_i^u)$ . In general,  $f(r_i^u)$  is positive if the following logic condition is satisfied by the  $m$  segments:

$$(f(s_1(r_i^u)) \geq 1) \wedge (f(s_2(r_i^u)) \geq 1) \wedge \dots \wedge (f(s_m(r_i^u)) \geq 1) \equiv 1$$

The three scenarios can then be represented by  $m = L(r_i^u)$  (full conversion),  $m < L(r_i^u)$  (partial conversion), and  $m = 1$  (no conversion).

### 3.2 RWA

We propose here an event-dependent adaptive routing scheme. We shall refer to this scheme as *Adaptive Alternate Routing* (AAR). It is based on the principle of dynamic alternate routing (DAR) for fully-connected circuit-switched voice networks

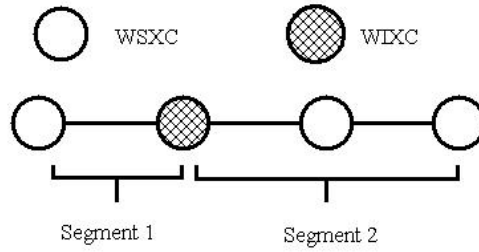


Fig. 1. Path segments for wavelength continuity.

---

**Algorithm 1** Wavelength Assignment

---

INPUT:

A route  $r_i^u$ .

OUTPUT:

A wavelength to be used on  $r_i^u$ .

PROCEDURE:

**for**  $s_j(r_i^u)$  **do**

    find all idle wavelengths

**end for**

find common wavelengths  $f(r_i^u)$  between  $s_j(r_i^u)$

**if**  $f(r_i^u) > 1$  **then**

    select one wavelength randomly

**else if**  $f(r_i^u) = 1$  **then**

    use this wavelength

**else**

    no common wavelength found

**end if**

---

in [13, 14]. Note that DAR falls in the category of event-dependent routing, and so does AAR. In DAR, the direct link route, which exists in a fully-connected network, is always attempted first—this route is listed as the first route in the routing table; then, the alternate routes (beyond the first route) in the routing table are updated locally on the basis of whether the call is blocked on the selected alternate route. If a connection request is blocked, the current alternate route is replaced by randomly selecting a new alternate route; however, if a request is successfully connected on this route, it remains in the routing table for future calls between the same node pairs. This scheme is also referred to as the sticky random principle.

While AAR is an event-dependent routing scheme, it is fundamentally different than other event-dependent or state-dependent schemes in the following sense: it is an information-less routing scheme. What this means is that to make a routing decision, this scheme does not require an exchange of any information (such as link state) between any nodes. Thus, a major goal, within this context, is to understand how well the schemes adapt under a variety of conditions.

---

**Algorithm 2** Adaptive Alternate Routing

---

INPUT:

The node pair  $u$ .Routing table of the  $s$  node of size  $K$ .No. of attempts  $a$  to route the call. $2 \leq i \leq K$ 

OUTPUT:

A route between  $s$  and  $d$ .

PROCEDURE:

**if**  $a = 1$  **then**    use  $r_1^u$  if  $f(r_1^u) \geq 1$ ; exit**end if****while**  $a \geq 2$  and  $a \leq K$  **do**    use  $r_a^u$  if  $f(r_a^u) \geq 1$ ; exit    **if** no capacity on  $r_a^u$  **then**        reset alternate path entry for  $r_i^u$  randomly (for use by future calls)         $a = a + 1$     **end if**    **end while**No route found; the call is blocked

---

Since we want to consider routing in a general topology network, the direct link route as used in DAR may not always exist. Furthermore, in DAR, alternate paths are limited to paths that consist of at most two links. In our scheme, for pairs that do not have a direct link path, the shortest-hop path for this pair is considered as equivalent to the fixed first path in the routing table, which is always to be attempted first whenever a request arrives for this pair. We also allow any alternate routes to not be limited to just a maximum of two links—in fact, in a general topology network, a pair may not always even have a two-link route. It may be noted that in DAR, the number of attempts to route a call is typically two, the direct and the alternate path; this is partly influenced by a lack of crankback [3, 5, 27] capability. That is, if a call cannot find available capacity on the second link of a two-link alternate path, the call is blocked and lost and it cannot be tried on a third path even if this is listed in the routing table. Rather, the third path is attempted only when a call cannot find available bandwidth on the first link of the first alternate path. In AAR, we allow crankback capability; therefore, our scheme checks if all links (segments) of an alternate path (subject to satisfying the wavelength continuity constraint) have bandwidth available for an arriving call. If so, it is attempted; if not, the call proceeds to attempt the third route in the routing table. In the meantime, a new alternate path is randomly determined and stored in the second location (for use by future calls). If the call is not successful in the third route, it tries the fourth entry (while determining independently a new replacement randomly for the location of the third route), and so on. If, after trying a maximum number of routes in the routing table the call cannot go through, it is blocked and lost.

Note that AAR retains the basic principle of DAR, which is sticky random; i.e, if an entry in a routing table is capable of completing a request, it is not changed. Change occurs only if such a route cannot accommodate a newly arriving call. In this case, a newly arriving call attempts the next entry in the routing table, while a new random route is selected from cached alternate paths and placed in the location of the unsuccessful route.

Our modification to DAR is motivated by the following: DAR is efficient in fully connected networks where each node pair  $u$  has a direct path. We found that it does not perform well in wavelength-converting networks in its native form when a pair does not have a direct path (this will be discussed with numerical results in the results section). Also, the shortest-hop path is used as the fixed first path in the routing table. We also allowed routes to be selected from multiple alternate paths for each attempted call by incorporating the crankback feature. Furthermore, AAR is chosen since, by being an event-dependent routing, it avoids the information flooding associated with state-dependent routing. It may be noted that the performance of event-dependent routing was found to be better than state-dependent routing for circuit-switched voice networks; however, performance of event-dependent routing has not been studied so far for WDM networks.

We now comment on where the adaptive alternate routing scheme for WDM networks falls under the general notion of dynamic quality-of-service routing. A framework for dynamic quality-of-service routing can be found in [26, 27], which discusses three phases: 1) the preliminary path caching (PPC) phase, 2) the updated path order (UPO) phase, and 3) the actual route attempted (ARA). For adaptive alternate routing, the PPC phase determines up to  $K$  paths for consideration in the routing table—these are candidate paths based on coarse-grain information; however, the UPO phase for adaptive alternate routing is event-dependent—that is, if a particular path in the routing table cannot accommodate an arriving call, then this path is dropped and an alternate path is randomly determined that now takes the location of the rejected path in the routing table (for future call attempts). The actual route attempted is influenced by this sticky random nature since the route located in the routing table for a future call could be different; certainly, the first path remains fixed as we discussed earlier.

## 4 Performance Studies

### 4.1 Study Environment

We developed a discrete-event 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. 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.

The following factors were taken into account in our study: 1) impact on network performance as the number of wavelength converters are varied, 2) 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 under both symmetric and asymmetric traffic cases, 4) the performance impact on different topologies. We also considered the role of trunk reservation. These then lead to a sizable number of scenarios due to the multiplicative nature. For brevity, we focused our discussion on a selective subset of scenarios out of the full list of scenarios and remarked where we noticed significant differences with the rest of the scenarios.

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). These topologies were selected as representative topologies to understand how routing performance might be impacted differently on different topologies. All links in these networks were assumed to be bidirectional multi-wavelength fibers with the same number of wavelengths in each fiber. For each topology, we considered two traffic cases: symmetric traffic and asymmetric traffic. In each case, we considered three different load scenarios, which we label as L1, L2, L3 to reflect low, medium and high traffic loads, respectively. For asymmetric traffic cases, we used the demand model of [12] to create demands between node pairs while keeping the average load the same as the corresponding symmetric cases. Information about network topologies and traffic scenarios are shown in tables 1 and 2. From Table 2, it is easy to see that the total traffic load simulated is quite significant, and per pair traffic load varied from as low as 2 Erlangs to as high as 15 Erlangs to capture load variations per pair.

We briefly comment on the selection of network loads L1, L2, and L3. We started each network with no wavelength converters and determined a baseline load such that the call blocking probability is approximately 1% with two routes in the routing table for the symmetric traffic case; we call this load L1. Then we increased the load proportionally to two different levels so that the blocking was progressively higher under the same topological scenarios and capacity.

In order to determine where to put wavelength-converting nodes as we moved from the no conversion case to the fully converted case, we used a simple heuristic given in [2] called Total Outgoing Traffic (TOT). This algorithm allows the placement of all given wavelength converters  $c$  at once at the nodes that have the highest outgoing traffic. The total outgoing traffic was 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 transit traffic component was calculated so that for each chosen  $r_i^u$ , whether a direct or an

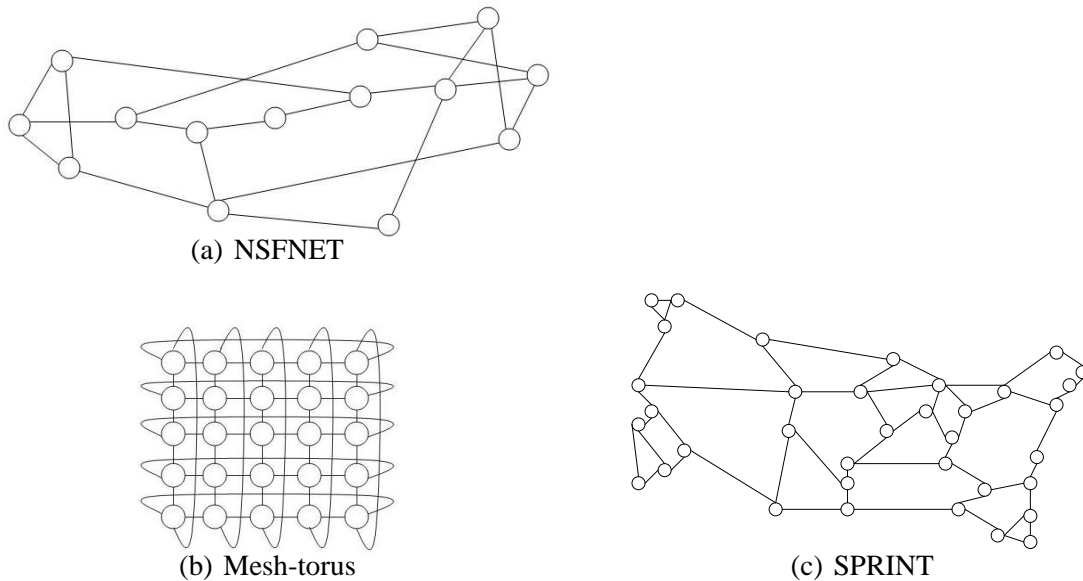


Fig. 2. Network Topologies.

alternate route, each intermediate node  $v$  on  $r_i^u$  records the load passing through it.

## 4.2 Study Results

We earlier commented about the difference between DAR and AAR. We now start with a numeric comparison between DAR and AAR. This is followed by our detailed study on AAR under various scenarios.

### 4.2.1 Comparison of DAR and AAR

Recall that DAR was developed originally for fully-connected circuit-switched voice networks where routes were limited to at most two links and crankback was not allowed. For our comparison, we allowed a route in DAR to have an arbitrary number of links so that it can be used in a general topology network; since a pair of nodes may not be directly connected, it then used the sticky random principle to pick a path from a set of candidate routes. A minor change of DAR was considered by allowing crankback; the modified version will be referred to as DAR+. Finally,

Table 1  
Topology information.

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

Table 2  
 Simulated Topologies, Traffic patterns, Numbers of Wavelength, Loads.

Case	Topology	Wavelengths per link	Total Load (in Erlangs)	Erlang Load per Demand pair
L1-Asymmetric-NSF	14-NSFNET	140	819	Avg=9
L2-Asymmetric-NSF	14-NSFNET	140	1092	Avg=12
L3-Asymmetric-NSF	14-NSFNET	140	1365	Avg=15
L1-Symmetric-NSF	14-NSFNET	140	819	9
L2-Symmetric-NSF	14-NSFNET	140	1092	12
L3-Symmetric-NSF	14-NSFNET	140	1365	15
L1-Asymmetric-Mesh	25-Mesh-torus	156	1800	Avg=6
L2-Asymmetric-Mesh	25-Mesh-torus	156	2700	Avg=9
L3-Asymmetric-Mesh	25-Mesh-torus	156	3450.47	Avg=11.5
L1-Symmetric-Mesh	25-Mesh-torus	156	1800	6
L2-Symmetric-Mesh	25-Mesh-torus	156	2700	9
L3-Symmetric-Mesh	25-Mesh-torus	156	3450.47	11.5
L1-Asymmetric-Sprint	36-Sprint	260	1260	Avg=2
L2-Asymmetric-Sprint	36-Sprint	260	1890	Avg=3
L3-Asymmetric-Sprint	36-Sprint	260	2700	Avg=4.3
L1-Symmetric-Sprint	36-Sprint	260	1260	2
L2-Symmetric-Sprint	36-Sprint	260	1890	3
L3-Symmetric-Sprint	36-Sprint	260	2700	4.3

AAR has both crankback and one fixed shortest path that is attempted before any alternate route is considered through the sticky random principle.

For our comparison of DAR, DAR+, and AAR, we focused our results for NSFNET with asymmetric traffic load L1. Performance results are plotted in Figure 3 for the case when the network has no wavelength-converting nodes and when the network is fully converted by varying the number of routes considered in the routing table. When only a single route is considered ( $K = 1$ ), then blocking is lower with a network being fully converted compared to the network where no nodes are converted. As expected, this is the result of wavelength continuity constraint being relaxed in the case of fully converted nodes allowing more bandwidth. It may be noted that  $K = 1$  means fixed routing (with one route).

The situation became interesting when we considered alternate routes in the routing

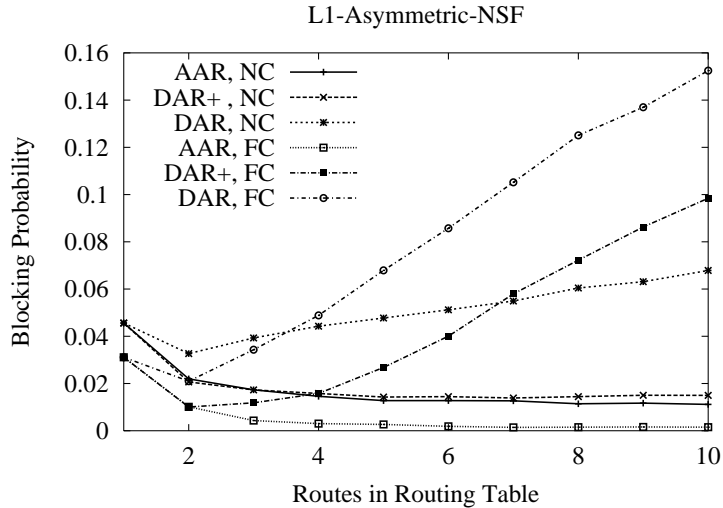


Fig. 3. Comparison of DAR, DAR+, and AAR for NSFNET for load L1 (asymmetric case).

table. We note that for the full conversion case, both DAR and DAR+ performed poorly as the number of alternate routes considered increased, while AAR’s performance remained better throughout. When the network has no converted nodes, the behavior of DAR was not as poor when the number of alternate routes increased compared to the fully converted case. On the other hand, both DAR+ and AAR performed about the same (while both being better than DAR) for the non-converted case. While the graph does not include the case of some nodes being converted, the result rested somewhere in between the non-converted and the fully converted case for DAR and DAR+. We conclude that at the nominal load, the more stable behavior of AAR is due to the first path being fixed, coupled with crankback. Starting in the next section, our discussion will be limited to AAR.

#### 4.2.2 Alternate Routing and Wavelength Conversion

As a continuation from above, we first discuss the results for the asymmetric case for NSFNET topology. Later, we will point out where and whether the other topologies differ from NSFNET and by how much.

We first considered varying the number of wavelength converters for different values of alternate routes (see Figure 4). We can see that converting as few as two nodes to fully converted nodes results in performance improvement. This improvement continues until eight nodes are being converted, at which point no further improvement is noticed as more nodes are converted. By comparing the different values of the routes kept in the routing table, we note that by going from  $K = 1$  to  $K = 2$  (that is, from fixed routing to adaptive alternate routing with one alternate path besides the fixed first path), the blocking drops significantly from about 4.5% to 2.1% for the no-converter case while no such improvements can be achieved with additions of converters if the number of paths is kept fixed at  $K = 1$  (i.e., single fixed routing). To see another view of this observation, we plotted performance un-

der a different number of converters as the number of alternate routes considered in the routing table was varied (Figure 5). This result is significant since in operational networks, the cost of adding converters is expensive. The fact that a significantly better performance can be observed by simply increasing the number of alternate routes in the routing table is important from an operational point of view; in other words, this shows the benefit of alternate routing even in non or partially converted scenarios.

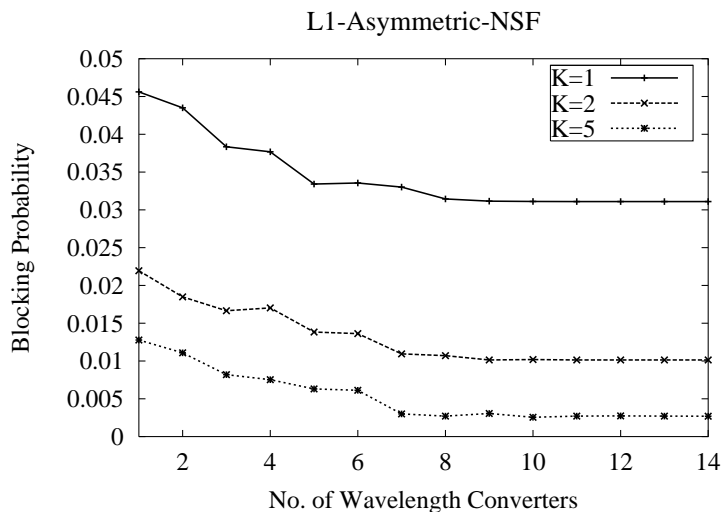


Fig. 4. AAR performance for different values of the number of routes in the routing table as the number of converters is varied (NSFNET, L1, asymmetric case).

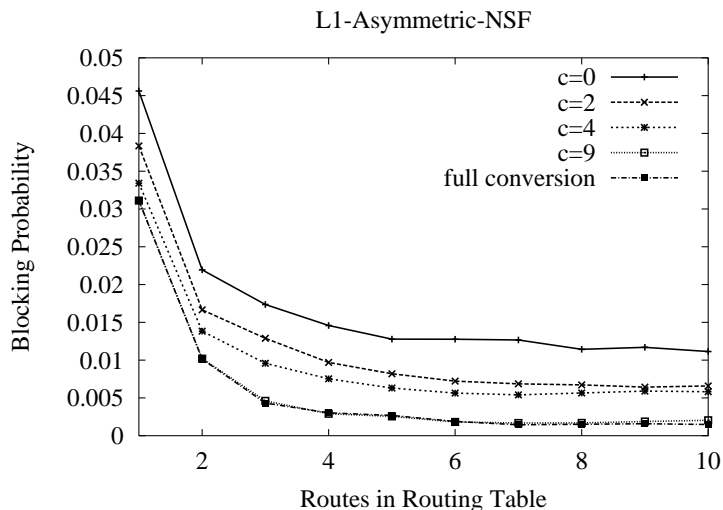


Fig. 5. AAR performance for different values of the number of wavelength converters as the number of routes in the routing table varied (NSFNET, L1, asymmetric case).

The next issue we wanted to understand is, if this behavior is maintained when the load was significantly increased. For this, we considered asymmetric load L2 for the same NSFNET topology (see Figure 6). We made an interesting observation: for the no converter case, the performance improved as the number of alternate

routes is increased; however, this was not so for the partially converted case or the fully converted case when the number of alternate paths increased beyond  $K = 4$ . Rather, limiting the alternate paths between 2 and 4 gave the best result. Similar observations were also found when the load is further increased to L3 (see Figure 7). Combining these observations with observations for load L1, we can say that having multiple alternates in the routing table improves network performance, but the number of such routes to be considered in the routing table should be restricted since the blocking increases for networks with some of the nodes converted with the increase in load. In particular, for many cases, only a few wavelength converters are needed with only a few alternate routes considered in the routing table to achieve the optimal performance.

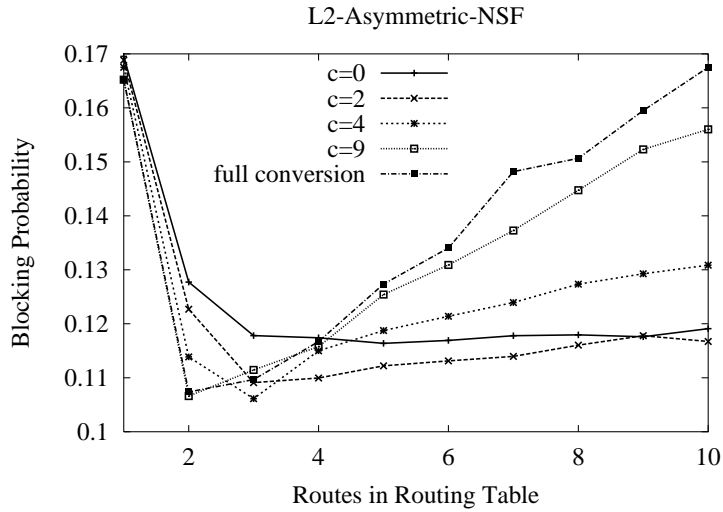


Fig. 6. AAR performance for different values of the number of wavelength converters as the number of routes in the routing table varied (NSFNET, L2, asymmetric case).



Fig. 7. AAR performance for different values of the number of wavelength converters as the number of routes in the routing table varied (NSFNET, L3, asymmetric case).

We next conducted the same experiments on the other two topologies, by varying loads from L1 to L3. Unlike NSFNET, for the Mesh-torus network and SPRINT at L1, only a minimal number of alternate routes were needed to be considered before reaching zero blocking. Certainly, for the fixed routing case (i.e.,  $K = 1$ ), performance gain with converters was much greater than without converters, but this became not as pronounced when converters were introduced. More importantly, there was practically no gain going from a network with about a third of the nodes converted to the fully-converted case (Figures 8 and 9). Our conclusion is that for mesh-torus and SPRINT, being more connected and larger networks (than NSFNET), and having a small number of converters can create a good set of alternate routes that helps in minimizing blocking.

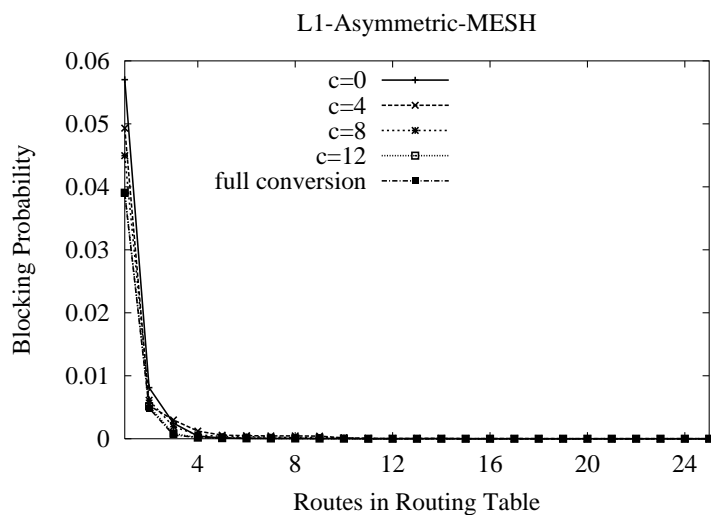


Fig. 8. AAR performance for different values of the number of wavelength converters as the number of routes in the routing table varied (Mesh-torus, L1, asymmetric case).

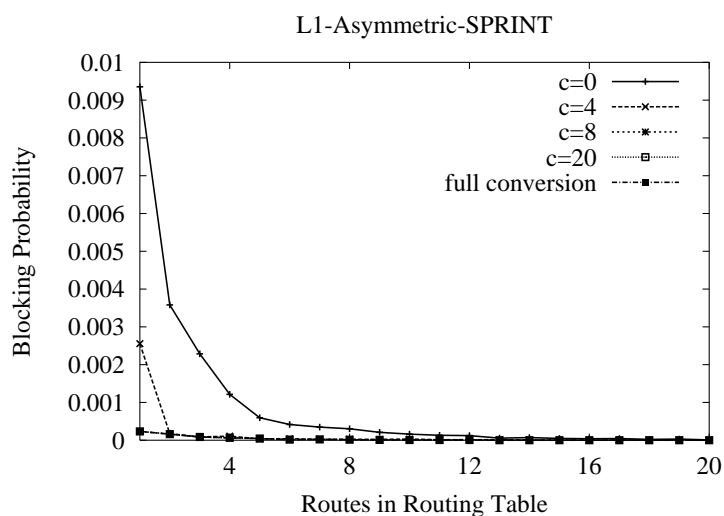


Fig. 9. AAR performance for different values of the number of wavelength converters as the number of routes in the routing table varied (SPRINT, L1, asymmetric case).

Consider now load L2. Our simulations showed that adaptive alternate routing was also beneficial even in a mesh-torus topology as it can improve the performance much more than having a fixed route with full conversion. To illustrate, consider Figure 10 for L2 for the mesh-torus topology; we can see that the case of  $K = 2$  and no WC has a much lower blocking than the case of  $K = 1$  and full conversion. Similarly, the case when  $K = 5$  and no WC achieves better performance than the case when  $K = 2$  with full conversion, although the difference is not as significant as in the former comparison between ( $K = 1, c = \text{full conversion}$  vs.  $K = 2, c = 0$ ). Now, if we take the view of performance as the number of alternate routes is varied for different values of  $c$ , we note that much like the NSFNET with load L2, the performance deteriorates here too if the number of alternate routes considered is too high (see Figure 11). Rather, for a 25-node mesh-torus network, around two to four alternate routes gave the best performance when the network was partially converted.

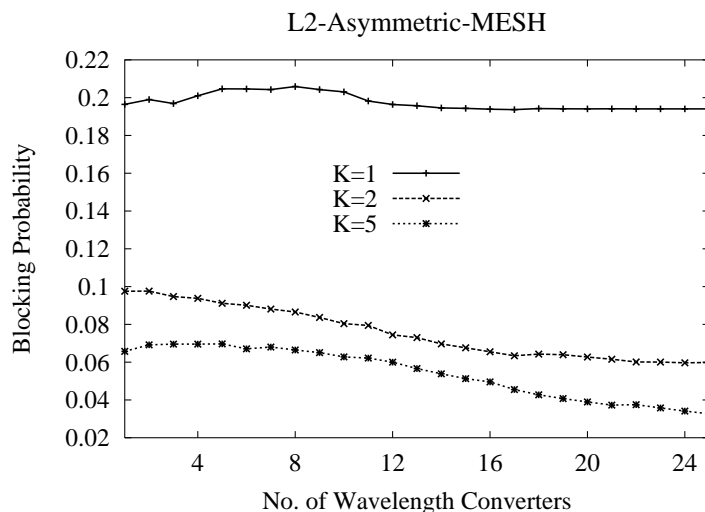


Fig. 10. AAR performance for different values of the number of routes in the routing table as the number of converters varied (Mesh-torus, L2, asymmetric case).

Next, we consider SPRINT at L2. We note that results for SPRINT differ from that for NSFNET and Mesh-torus. However, it should be noted that L2 for one topology is not the same as for another topology (unlike L1). L2 used for SPRINT exerted much less blocking than L2 in NSFNET and Mesh-torus (Figure 12). In fact, at this blocking range, we saw a gain as the number of alternate routes increased. To see the impact due to load, we next considered L3 on SPRINT; here we started to see that the blocking went up again when the number of alternate routes increased (Figure 13). Incidentally, at this load, the SPRINT network showed significant gain with the network being fully converted compared to the partially converted case. Furthermore, we observed a similar pattern to NSFNET and Mesh-torus at L3 (Figure 14), although the degradation in performance for the fully converted case was not as pronounced as other topologies when the number of alternate paths is increased. Thus, a general conclusion is that as the load increases, the number of alternate

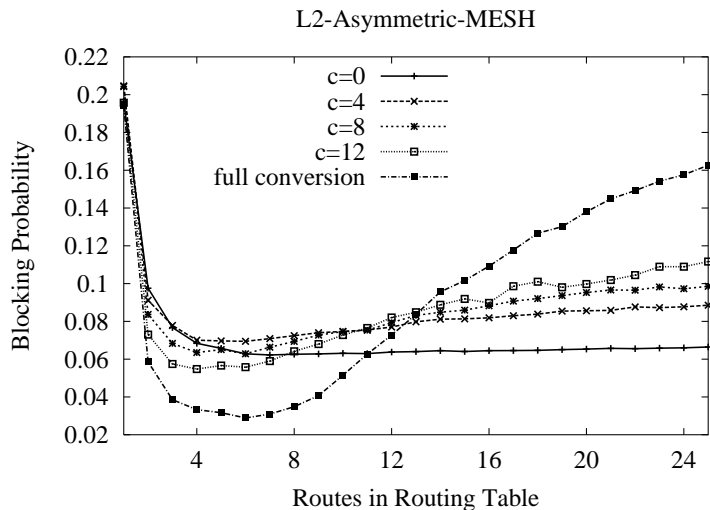


Fig. 11. AAR performance for different values of the number of wavelength converters as the number of routes in the routing table varied (Mesh-torus, L2, asymmetric case).

routes should be limited and the network can give optimal performance with *some* nodes converted rather than having all nodes converted. The significance of this result is that since deployment of wavelength-converting nodes is costly, a network can be better utilized by intelligently converting some of the nodes to wavelength-converting nodes to maintain the best network performance.

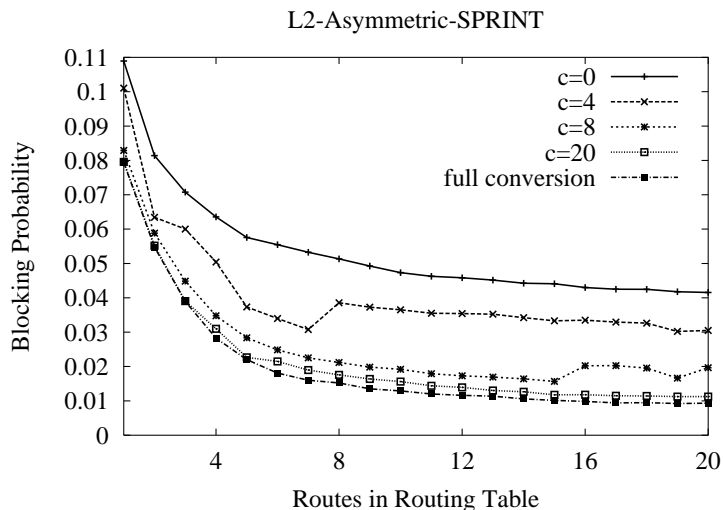


Fig. 12. AAR performance for different values of the number of wavelength converters as the number of routes in the routing table varied (SPRINT, L2, asymmetric case).

We now comment on the implication of these results from a network operation as well as a network evolution point of view. Since a network is dimensioned for operational use to keep the blocking at a low value such as 1%, we expect a network to be operationally designed for a load like L1. What loads such as L2 and L3 allow us to understand, is how change in the network is to be handled; if it is a sudden

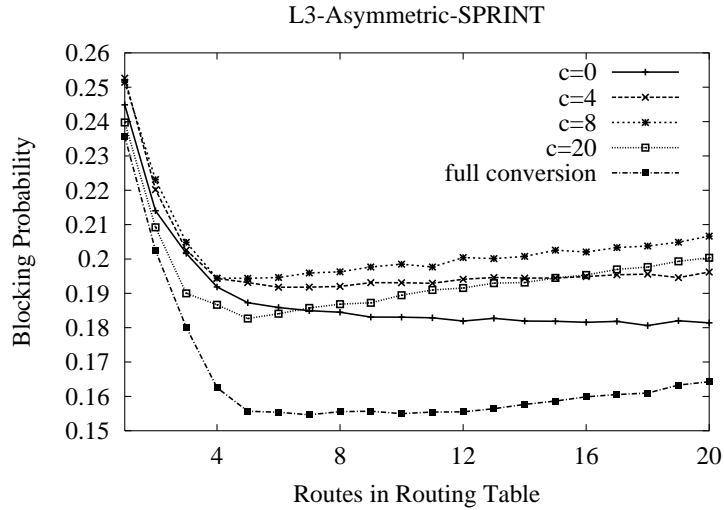


Fig. 13. AAR performance for different values of the number of wavelength converters as the number of routes in the routing table varied (SPRINT, L3, asymmetric case).

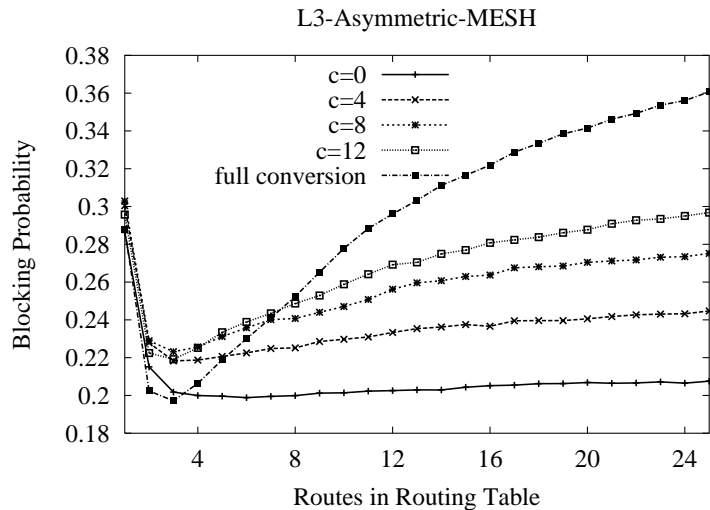


Fig. 14. AAR performance for different values of the number of wavelength converters as the number of routes in the routing table varied (Mesh-torus, L3, asymmetric case).

surge temporarily, then it is preferable to limit the number of alternate paths during the period of surge. If the network traffic is observed to increase over a time horizon, a decision to add converters without adding capacity can be considered depending on the cost trade-off, since adding converters at strategic locations often results in low blocking.

### 4.3 Trunk Reservation Factor

Another factor we studied is trunk reservation (TR), which has been rarely investigated so far in wavelength-routed WDM network studies. The only discussion of

TR for WDM networks was by [21], which considered TR in fixed routing WDM networks with no wavelength conversion. This model, however, is not applicable to AAR. We simulated the same set of cases, as shown in Table 2, by allowing trunk reservation. We uniformly reserved 6,7, and 8 wavelengths in NSFNET, Mesh-torus, and SPRINT topologies, respectively, for trunk reservation on each link. The choice of these numbers was based on observations from operational networks that the rule of thumb for trunk reservation is approximately  $(\sqrt{W}/2)$  [27].

An important reason to introduce trunk reservation in a fully-connected circuit-switched voice network was to avoid bistability [24], while improving performance. Greenberg and Srikant [16], however, noted the lack of bistability in a general topology circuit-switched network, implying that trunk reservation may not be necessary. While we did not observe any bistability, we found that trunk reservation indeed provides limited benefits in certain situations in a general topology wavelength-routed WDM network.

When the network is fully wavelength convertible, there is some gain with trunk reservation, which is only for high load such as L3 (Figures 15 and 17). Figure 15 also shows that with sparse wavelength conversion, Mesh-torus network may benefit from TR.

To summarize, it is known from circuit-switched dynamic routing that TR does not provide benefit in low to moderate loads; thus, it is not surprising that we also made similar observations for low to moderate load cases in WDM networks.

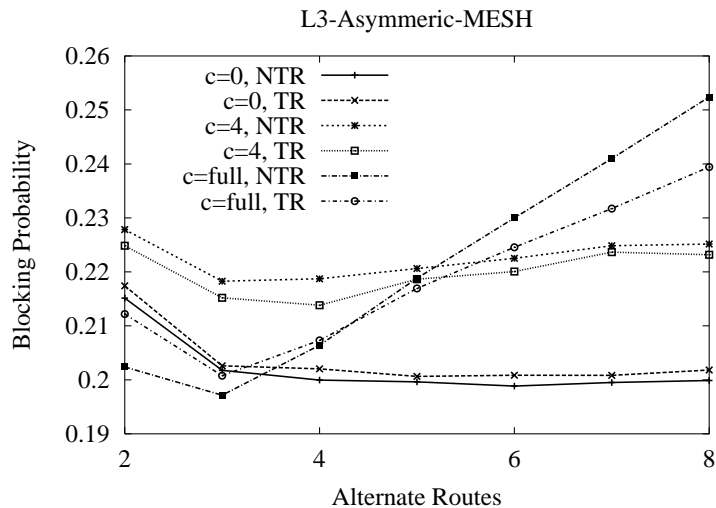


Fig. 15. Trunk Reservation Effect: Asymmetric L3 MESH-torus.

#### 4.4 Asymmetric vs. Symmetric traffic

Finally, we comment on the relation between symmetric and asymmetric traffic. We also studied symmetric against asymmetric traffic to see how the result influ-

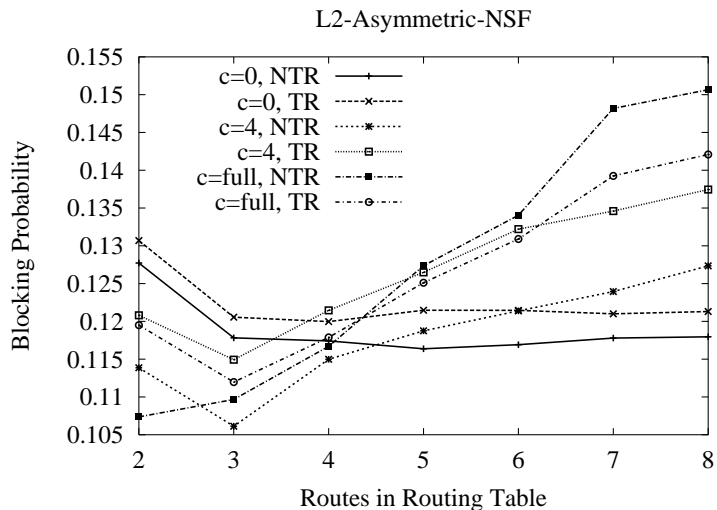


Fig. 16. Trunk reservation effect: Asymmetric L2 NSFNET.

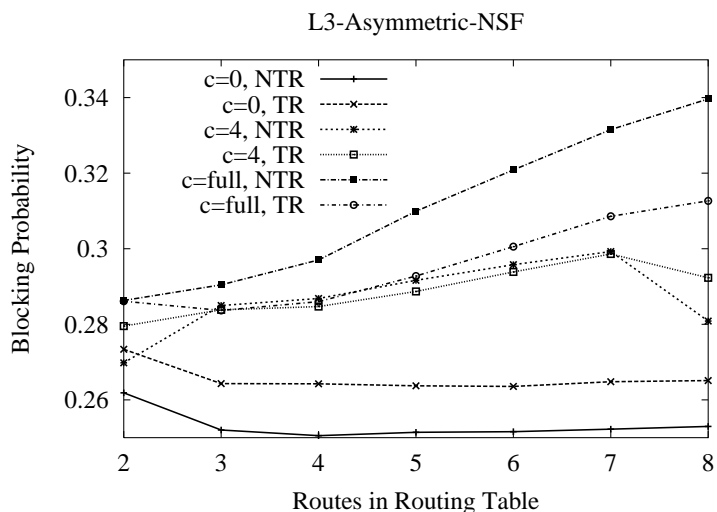


Fig. 17. Trunk reservation effect: Asymmetric L3 NSFNET.

enced for any of the topologies. Consider, for instance, load L2, which is a moderate load level on SPRINT topology. We note that although the offered load was the same, the performance with asymmetric traffic was better than with symmetric traffic (see Figure 21). For moderate load, this can be attributed to the fact that the network can take advantage of some slack due to asymmetry by completing more calls through parts of the network where capacity is available. However, when the network load was very high, we found that asymmetric traffic load could no longer find such space, and in fact, resulted in higher blocking than symmetric traffic. In other words, asymmetric traffic is likely to give lower blocking than symmetric traffic in a moderately low load scenario, but it may not be so at a higher load.

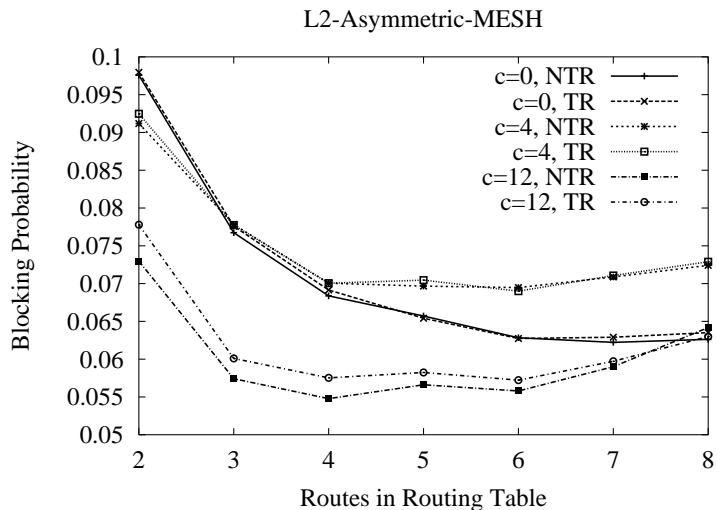


Fig. 18. Trunk reservation effect: Asymmetric L2 MESH-torus.

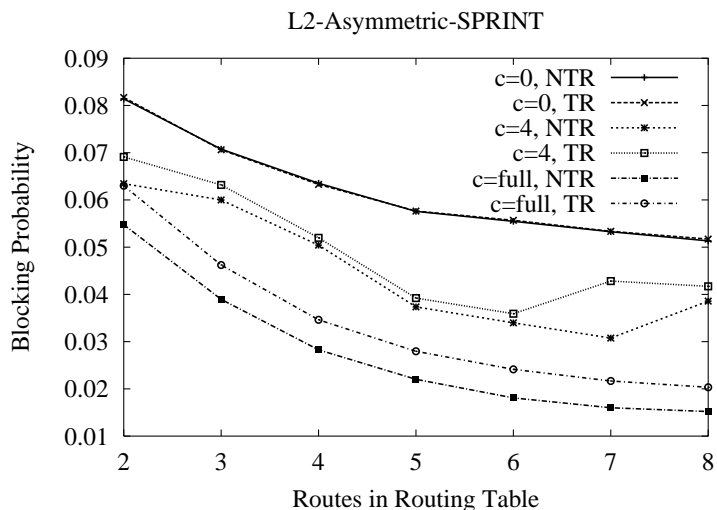


Fig. 19. Trunk reservation effect: Asymmetric L2 SPRINT.

## 5 Summary

In this paper, we proposed an event-dependent, information-less adaptive alternate routing (AAR) scheme for a WDM network by extending a well-known event-dependent scheme for circuit-switched voice networks. Our scheme also considered wavelength assignment as well as the wavelength continuity constraint. Our interest was to understand how it performed compared to fixed (single path) routing, and the trade-offs of considering a number of alternate paths as opposed to a number of nodes in the network with wavelength converters. For our work, we considered three different network topologies. We further considered three different sets of loads both for the asymmetric and the symmetric traffic case. Our study also considered whether there is any role for trunk reservation, a well-known control

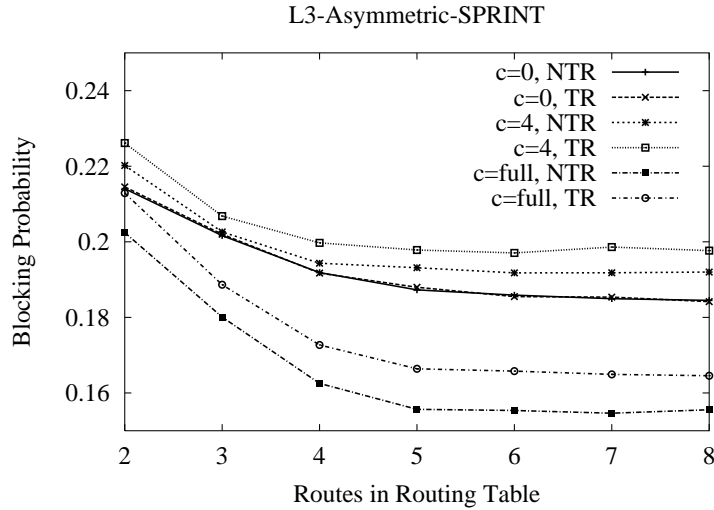


Fig. 20. Trunk reservation effect: Asymmetric L3 SPRINT.

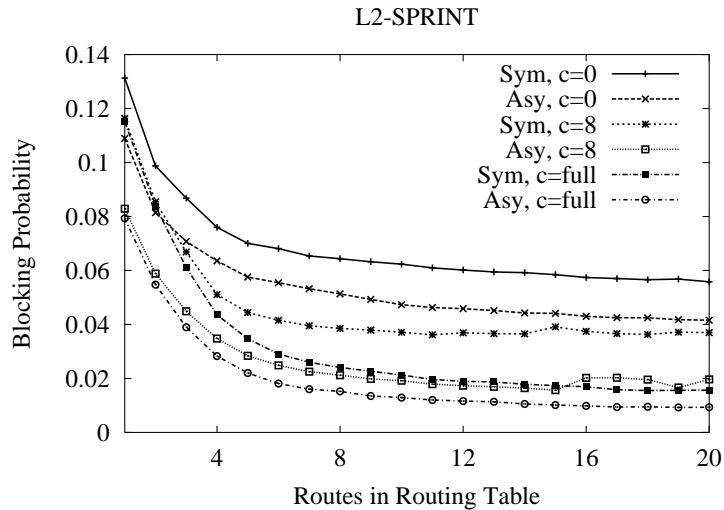


Fig. 21. Comparison of symmetric and asymmetric traffic for different values of the number of wavelength converters as the number of routes in the routing table varied (L2, SPRINT).

used in circuit-switched voice networks. We developed a simulator where various factors can be considered.

Through an extensive set of simulation studies, a number of observations have been made. Below, we summarize the key observations from our study:

- Significant performance gain is observed when we go from fixed single-path routing to adaptive alternate path routing.
- At low load, having many alternate routes in the routing table is helpful.
- In a low load environment, having at least some wavelength-converting nodes significantly reduces blocking. In the absence of any WC, consideration of many alternate paths can reduce blocking and is helpful. This serves as a trade-off in

terms delaying the cost of WC by increasing the number of paths to be considered. It is important to note that at high load, an increase in the number of alternate paths does not negatively affect performance when there is no WC. In a minimal number of WC environment, the increase in the number of alternate paths is not as detrimental to performance compared to if the network were fully converted.

- At a very high load, having many alternate paths in the routing table is detrimental to the performance even if the network connectivity is not fully exploited. This is regardless of whether the network has no WC or full conversion; thus, for such situations, the number of alternate routes should be restricted. This is less of a problem on a no-conversion environment as we observed this behavior for all topologies.
- The degree of a network's connectivity is an important factor in determining whether a certain level of WC at a particular load is beneficial.
- Trunk reservation may be helpful in an overloaded network, but not always for all topologies or scenarios.
- The difference in blocking between symmetric and asymmetric scenarios originally exists because of the traffic pattern nature and its interplay with the network. WC merely receives the difference and preserves it.

As a future work, we plan to further explore trunk reservation when different values of reservation levels are considered as well as when adaptive trunk reservation or other reservation schemes might be useful. Our preliminary work [20] suggests that end-to-end trunk reservation for pairs that are not directly connected results in fairness on equitable pairwise blocking more so than with the conventional reservation method. As we stated in the introduction, this paper focuses on a systematic study of adaptive alternate routing as this is the only known information-less dynamic routing scheme. In the future, we plan to consider a detailed performance comparison between the proposed scheme with other dynamic routing schemes for WDM networks.

## References

- [1] J. M. Akinpelu, The overload performance of engineered networks with nonhierarchical and hierarchical routing, *AT&T Bell Labs Technical Journal* 63 (1984) 1261–1281.
- [2] A. S. Arora, S. Subramaniam, Converter placement in wavelength routing mesh topologies (2000) 1282–1288.
- [3] G. R. Ash, *Dynamic Routing in Telecommunications Network*, McGraw-Hill, 1997.
- [4] G. R. Ash, Performance evaluation of QoS-routing methods for IP-based multiservice networks, *Computer Communications* 26 (2003) 817–833.

- [5] G. R. Ash, *Traffic Engineering and QoS Optimization of Integrated Voice & Data Networks*, Morgan Kaufmann Publishers, 2006.
- [6] G. R. Ash, P. Chemouil, 20 years of dynamic routing in telephone networks: Looking backward to the future, *IEEE Global Communications Newsletter* (2004) 1–4.
- [7] R. A. Barry, P. A. Humblet, Models of blocking probability in all-optical networks with and without wavelength changers, *IEEE Journal of Sel. Areas. Comm.* 14(5) (1996) 858–8867.
- [8] A. Birman, Routing and wavelength assignment methods in single-hop all-optical networks with blocking, *Proc. IEEE INFOCOM* (1995) 431–438.
- [9] A. Birman, Computing approximate blocking probabilities for a class of all-optical networks, *IEEE Journal of Sel. Areas. Comm.* 14(5) (1996) 852–857.
- [10] X. Chu, J. Liu, B. Li, Z. Zhang, Analytical model of sparse-partial wavelength conversion in wavelength-routed WDM networks, *IEEE Communications Letters* 9 (2005) 69–71.
- [11] A. Ding, S. Tan, G. Poo, Blocking performance analysis on adaptive routing over WDM networks with sparse wavelength conversion, *Proc. 28th Annual IEEE International Conference on Local Computer Networks* (2003) 187–193.
- [12] B. Fortz, M. Thorup, Internet traffic engineering by optimizing OSPF weights, *Proc. IEEE INFOCOM* (2000) 519–528.
- [13] R. J. Gibbens, F. P. Kelly, Dynamic routing in fully connected networks, *IMA Journal of Mathematical Control and Information* 7 (1990) 77–111.
- [14] R. J. Gibbens, F. P. Kelly, P. B. Key, Dynamic Alternate Routing—modeling and behaviour, *Proc. 12th International Teletraffic Congress (ITC12)* (1988) 3.4A3.1–3.4A3.7.
- [15] A. Girard, *Routing and Dimensioning in Circuit-Switched Networks*, Addison-Wesley, 1990.
- [16] A. Greenberg, R. Srikant, Computational techniques for accurate performance evaluation in multirate, multihop communication networks, *IEEE/ACM Trans. on Networking* 5 (1997) 266–290.
- [17] P. Ho, H. Mouftah, An approach for enhancing fixed alternate routing in dynamic wavelength-routed WDM networks, *Proc. of IEEE GLOBECOM 2002* (2002) 2792–2797.
- [18] G. Jeong, E. Ayanoglu, Comparison of wavelength-interchange and wavelength-selective cross-connects in multiwavelength all-optical networks, *Proc. IEEE INFOCOM* (1996) 156–163.
- [19] E. Karasan, E. Ayanoglu, Effects of wavelength routing and selection algorithms on wavelength conversion gain in WDM optical networks, *IEEE/ACM Transaction on Networking* 6(2) (1998) 186–196.

- [20] I. Katib, D. Medhi, Performance of distributed reservation control in wavelength-routed all-optical WDM networks with adaptive alternate routing, in: Proc. of Mini-conference, with 11th IFIP/IEEE International Symposium on Integrated Network Management (IM'2009), 8 pages, New York, 2009.
- [21] A. Khalil, C. Assi, M. Ali, Analytical modeling of block probabilities in WDM-based optical networks with fixed alternate routing and trunk reservation, in: Proc. International Conference on Communications and Computer Networks (CCN'2002), 6 pages, Cambridge, MA, 2002.
- [22] J. Kim, D. C. Lee, H. Sridhar, Route-metric-based dynamic routing and wavelength assignment for multifiber WDM networks, *IEEE Journal on Selected Areas in Communications* 24(12) (2006) 56–68.
- [23] M. Kovacevic, A. Acampora, Benefits of wavelength translation in all-optical clear-channel networks, *IEEE Journal of Sel. Areas. Comm.* 14(5) (1996) 868–880.
- [24] R. S. Krupp, Stabilization of alternate routing networks, *Proc. IEEE ICC'82* (1982) 31.2.1–31.2.5.
- [25] H. Lin, S. Wang, C. Tsai, Traffic intensity based fixed-alternate routing in all-optical WDM networks, *Proc. IEEE International Conference on Communications* (2003) 2439–2446.
- [26] D. Medhi, Quality of Service (QoS) routing computation with path caching: A framework and network performance, *IEEE Communications Magazine* 40 (12) (2002) 106–113.
- [27] D. Medhi, K. Ramasamy, *Network Routing: Algorithms, Protocols, and Architectures*, Morgan Kaufmann Publishers, 2007.
- [28] A. Mokhtar, M. Azizoglu, Adaptive wavelength routing in all-optical networks, *IEEE/ACM Transactions on Networking* 6(2) (1998) 197–206.
- [29] R. Ramamurthy, B. Mukherjee, Fixed-alternate routing and wavelength conversion in wavelength-routed optical networks, *IEEE/ACM Transaction on Networking* 10(3) (2002) 351–367.
- [30] K. Roy, M. Naskar, U. Biswas, Adaptive dynamic wavelength routing for wdm optical networks, *Proc. IFIP International Conference on Wireless and Optical Communications Networks*.
- [31] S. Subramaniam, M. Azizoglu, A. Somani, All-optical networks with sparse wavelength conversion, *IEEE/ACM Transactions on Networking* 4(4) (1996) 544–557.
- [32] S. Subramaniam, M. Azizoglu, A. Somani, Connectivity and sparse wavelength conversion in wavelength-routing networks, *Proc. IEEE INFOCOM'96* (1996) 148–155.
- [33] S. Subramaniam, R. Barry, Wavelength assignment in fixed routing WDM networks, *Proc. IEEE Int'l Conf. on Communications* (1997) 460–410.

- [34] J. H. Weber, Some traffic characteristics of communication networks with automatic alternate routing, *Bell Systems Technical Journal* 41 (1962) 769–792.
- [35] J. H. Weber, A simulation study of routing and control in communication networks, *Bell Systems Technical Journal* 43 (1964) 2639–2676.
- [36] W. Xu, Y. Hua, C. Wu, Adaptive open capacity routing in WDM networks with heterogeneous wavelength conversion capabilities, *Proc. IEEE The 9th Asia-Pacific Conference on Communications* (2003) 325–329.