# A wavelength-switched time-slot routing scheme for wavelength-routed networks

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*Abstract*— **Optical time division multiplexing (OTDM) is an effective approach to improve the performance of wavelength-routed (WR) networks. Implementation of all-optical time-slot routing in OTDM-WR networks is difficult owing to the lack of practical optical buffer and sophisticated optical processing devices. In this paper, we proposed a wavelength-switched time-slot routing scheme that can be implemented with fast wavelength converters only. Simulation results demonstrate that the performance of the proposed scheme is much better than that of WR networks and is comparable to OTDM-WR networks with time-shared space switching.**

## I. INTRODUCTION

Wavelength-routed (WR) optical networks are one of the important networking platforms for providing broadband services [1]. In WR networks, the maximum transmission rate is mainly determined by the data processing capability of the source and destination nodes. WR networks divide fiber bandwidth into wavelength channels and use them for communications between users. Users are guaranteed their transmission bandwidth once they get connected, and are blocked if their bandwidth requirements cannot be satisfied [1]. To reduce user blocking probability, it is recognized that bandwidth utilization improvement is as important as bandwidth increment. For examples, wavelength channel assignments using network status information serve more users than fixed assignments. Adaptive routing algorithms utilize wavelength channels more efficiently than fixed routing [2]. Wavelength converters improve the availability of wavelength channels by allowing the channels to be made up of segments with different wavelengths [1]. These approaches utilizate the wavelength channels more efficiently while others solve the problem by providing wavelength sub-channels.

Optical time division multiplexing (OTDM) provides time division wavelength sub-channels to match the processing speed of electronic devices, and allows users to access the sub-channels individually [3]. Users can have better chance of being served in OTDM-WR networks because multiple users can share the same wavelength channel. Traditional TDM networks take advantage of both time slot interchanging and time-shared space switching technologies. Time slot interchanging switches data between time division sub-channels while time-shared space switching transfers data at a node input to the same time division sub-channel at any output of the node. As the transmission rate in WR-OTDM networks increases up to hundreds of gigabits per wavelength channel, the routing at intermediate nodes will have to be carried out all-optically. Most proposed OTDM-WR networks rely on time-shared space switching because time slot interchanging is understandably difficult for all-optical implementation [4]–[7]. Currently available optical signal processing power is rather limited, however, neither all-optical time slot interchangers nor large fast optical switches are really feasible yet. In spite of such limitations, we can benefit from optical time division switching at the expense of complexity of routing control and slot assignment. Moreover, technologies such as fast wavelength converters [8], [9] and micro-electro-mechanical system (MEMS) optical switches [10] can greatly improve the network performance if we carefully manipulate the operation of OTDM-WR networks. In this paper we investigate the performance of OTDM-WR networks constructed with fast wavelength converters only. We show that the performance of the proposed networks is comparable to those with only time-shared space switching and much better than that of wavelength routed networks. Thus one can add OTDM to WR networks using present day technology.

The paper is organized as follows. In Section II we review the time division switching in OTDM-WR networks, and discuss the difficulties of all-optical implementation. We then describe the proposed wavelength-switched routing node architecture in Section III-A. The time-slot routing scheme for the proposed networks are discussed in Section III-B. We compare the performance of different kinds of time-slot routing schemes by simulations in Section IV. We demonstrate that the proposed time-slot routing scheme can provide significant performance improvement on current WR networks. Finally, we give the conclusion in Section V.

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## II. Optical time division multiplexed wavelength-routed networks

OTDM-WR networks are connection-oriented networks. A user requests for a connection by sending the destination address and the required quality of service such as transmission bandwidth to the network. The network then searches for a suitable path to fulfill the request. If a path is found, one or more time division wavelength sub-channels at each link on the path are reserved for the user. The user is granted the right to send out his data to the assigned wavelength channels within the particular time slots of the periodic time frames. The path searching algorithm may determine the path by looking up precomputed records [4], [5], or by computing the path using current information of the network status [7]. The required time for path searching and time division sub-channel reservation is in general not critical and electronic processing can be used. Once the sub-channel reservation process is completed, intermediate nodes lookup the routing paths according to the input ports, wavelength channels, and time division sub-channels associated to the user data. Because of the simplicity, the route lookup at intermediate nodes can be processed very fast even if optical processing is not used. However, the switching of data from the input ports to the output ports has to be done all-optically to avoid conversion of the data between the optical domain and the electrical domain which will significantly slow down the switching process.

The requirement for all-optical switching of data and the limited optical signal processing power renders some traditional time division switching approaches infeasible in OTDM-WR networks. For example, optical time slot interchange is not feasible yet. However, features unique to optical networks such as wavelength conversion/switching allow new functions of time division switching to be developed in OTDM-WR networks. We may manipulate data with time division switching in the wavelength domain in addition to the domains of time and space. We can have very different time-slot routing schemes in OTDM-WR networks if different considerations of the optical processing power in the following three switching categories are assumed.

### A. Time switching

In traditional time division switching networks, one is able to arbitrarily modify the time division sub-channel allocation of a data with time slot interchangers (TSI) [11]. As shown in Fig. 1, data $a$ is switched from slot 1 of input 1 to slot 2 of output 1 with a TSI being installed on input 1. TSIs are one of the key devices in traditional time division switching networks, but TSIs for optical networks are not feasible yet because of the lack of practical optical buffer and sophisticated optical processing devices. Most proposed time-slot routing schemes do not assume TSIs in OTDM-WR networks.

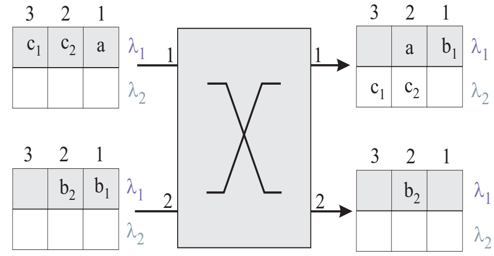


Fig. 1. An optical time division multiplexed wavelength-routed (OTDM-WR) node with routing processing in space, time, and wavelength domains. The node has two input ports and two output ports. Two wavelength channels ($\lambda_1$ and $\lambda_2$) are available for each input/output port. Each wavelength channel is further divided into three time division sub-channels.

### B. Space switching

Time-shared space switching is another powerful switching mechanism in traditional time division switching networks [11]. Data in adjacent time slots in a data stream at the input of a node can be switched to different output ports. For example, data $b_1$ and $b_2$ from input 2 in Fig. 1 are switched to different output ports but their associated wavelengths and time division sub-channels remain unchanged as $(\lambda_1, 1)$ and $(\lambda_1, 2)$, respectively. Time-shared space switching is traditionally used with TSIs to build large switches in time division switching networks. It is not recommended to build switches with only time-shared space switching because the blocking probability will be large [11], *e.g.,* data $b_1$ and $b_2$ in Fig. 1 cannot be switched correctly if data $a$ has not been moved to time slot 2 at output 1. In addition, fast optical switches are available in small size only, *e.g.,* $2 \times 2$. In spite of this, time-shared space switching is commonly assumed to be available in OTDM-WR networks in the derivation of time-slot routing schemes [4]–[7].

### C. Wavelength switching

In basic wavelength routed optical networks, data streams are transmitted in different wavelength channels and do not interfere with each other. This greatly simplifies the bandwidth utilization and data streams routing. However, the sharing of bandwidth is also prohibited. Owing to the non-overlap wavelength channels, WR networks are occasionally underutilized. Wavelength conversion overcomes this by allowing data streams to change their wavelength channels at intermediate nodes to improve the bandwidth utilization [1], [8]. Similarly, wavelength conversion reduces the blocking in OTDM-WR networks by directing data to time division sub-channels on different wavelength channels. Data $c_1$ and $c_2$ in Fig. 1 are relocated from wavelength channel $\lambda_1$ at input 1 to $\lambda_2$ at output 1. Otherwise, data $a$, $b_1$ and $b_2$ cannot be switched to their desired time division sub-channels. Wavelength conversion has been heavily investigated since the early proposals of WR networks [1], and technologies have been developed for applications including fast wavelength switching and contention resolution in optical switches [8]. Most time-slot routing schemes

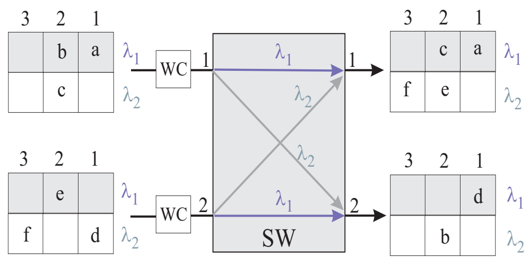


Fig. 2. A basic wavelength switched time-slot routing node. SW is a wavelength routed optical switch which has been configured to route data in $\lambda_1$ and $\lambda_2$ from input $x$ to output ports $x$ and $y$, respectively, where $x = 1, 2$ and $y \neq x$. WCs are wavelength converters that convert data slot-by-slot into other wavelengths so that data can be wavelength-routed to the desired output ports.

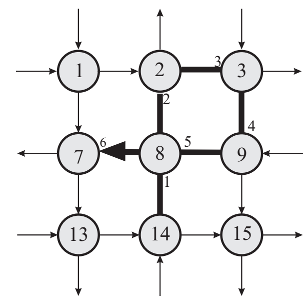


Fig. 3. A possible shortest path in a $6 \times 6$ MSN network. Each fiber have a single wavelength channel with multiple time division sub-channels. Connections with sub-channels on paths of (14-8-2) and (9-8-7) already exist when we search for the shortest path from nodes 14 to 7.

in OTDM-WR networks, however, treat wavelength conversion as an option in reducing the blocking probability [4]–[7].

## III. Wavelength switched time-slot routing

### A. Routing node architecture

In this paper, we consider an OTDM-WR network in which each node is assumed to have slot-by-slot fast wavelength converters and a wavelength routed switch only. No fast optical time-shared space switches are required. Figure 2 shows such a basic wavelength-switched time-slot routing node. The wavelength converters are installed at each input of the switch to modify the data associated wavelengths so that the data can be routed by the switch to their desired outputs. In Fig. 2, switch SW has been configured to route data in $\lambda_1$ and $\lambda_2$ from input $x$ to outputs $x$ and $y$, respectively, where $x = 1, 2$ and $y \neq x$. The wavelength converters at input 1 convert data into $\lambda_1$ if their desired outputs are output 1, and convert data to $\lambda_2$ if otherwise. The wavelength converters at input 2 operate similarly. Hence, the associated wavelengths of data $b$, $e$, and $c$, $d$ are changed from $\lambda_1$ to $\lambda_2$ and $\lambda_2$ to $\lambda_1$, respectively. The associated wavelengths of data $a$ and $f$ remain unchanged.

The performance of the proposed routing node relies on the availability and capability of the wavelength converters as well as the effectiveness of wavelength routing in switch SW. In general, the number of wavelength converters at an input should be equal to that of wavelengths in use for transmission between nodes. The conversion capability of the wavelength converters should cover all these wavelengths. Otherwise, we will have severe performance degradation. To improve the performance, we have to reduce the internal blocking caused by the insufficient of wavelength connections in switch SW. We can solve this problem by adding extra wavelength converters at both inputs and outputs but this increases the node complexity further. The wavelength routing in switch SW is also critical. For example, data $b$ and $c$ cannot be switched to output 1 simultaneously even if input 2 is idle with the switch SW configuration in Fig. 2. An adaptive algorithm for wavelength assignment and connection management in switch SW can further improve the system performance but also increases the wavelength channel routing complexity between nodes. Detail about the wavelength channel routing is discussed in Section III-B.

The proposed routing node requires $\mathcal{O}(KW)$ of fast wavelength converters, where $K$ and $W$ are the numbers of input/output ports and wavelengths per fiber, respectively. If compared with that of a time-shared space switching routing node, the proposed routing node requires more wavelength converters. Provided that fast wavelength converters are feasible, the proposed optical routing node should have hardware complexity equal to that of a time-shared space switching node that has complexity of $\mathcal{O}(KW \log_2 KW)$ [11].

### B. A shortest path searching algorithm

Traditional TDM networks assume time switching and space switching at each node. We can therefore search the shortest path between two nodes with methods similar to Dijkstra's shortest-path algorithm. These methods assume that the shortest path from $s$ to $t$ is equal to the shortest paths from $s$ to $x$ and $x$ to $t$ if the sum of the distances from $s$ to $x$ and $x$ to $t$ is the minimum. This assumption, however, is invalid for the proposed OTDM-WR networks. Figure 3 shows part of a $6 \times 6$ Manhattan Street Network (MSN). We assume that each fiber has a single wavelength channel with multiple time division sub-channels. Sub-channel connections on paths (14-8-2) and (9-8-7) already exist when we search the shortest path from nodes 14 to 7. Since the proposed routing node has no fast space switching capability, no sub-channel exchanging is permitted inside a node between wavelength channels. A connection of path (14-8-7) is not allowed because we cannot make it without breaking the existing connections on paths of (14-8-2) and (9-8-7). Path (14-8-2-3-9-8-7) can be the shortest path under such situation but it would not be reported as such by algorithms with node by node searching.

The shortest path searching algorithms for the proposed OTDM-WR networks should search the paths input by input or link by link. Node by node algorithms assume that the most appropriate output of an intermediate node is always available regardless what the upstream nodes are. In the proposed networks, paths with different source nodes can have rather different path lengths even if they have common second and destination nodes. For example, the shortest paths of source-destination pairs (9, 7) and (14, 7) in Fig. 3 have path lengths of 2 and 6, respectively, although both use node 8 as the second node on the paths. To find the shortest path from nodes $s$ to $t$ in the proposed OTDM-WR networks, we first find the $k$ node inputs that are closest to node $s$. These $k$ inputs can belong to the same or different nodes. Let $x$ be the node that one of these $k$ inputs, say $i$, belongs to. Similarly, $y$ is the node that a potential $(k+1)$-th closest input, say $j$, belongs to. We observe that the shortest path from node $s$ to the $j$-th input of node $y$ is equal to the shortest paths from node $s$ to the $i$-th input of node $x$ and to the $j$-th input of node $y$. Hence, we find the $(k+1)$-th closest node input according. This procedure repeats until the $(k+1)$-th closest input belongs to node $t$. Owing to page limitation, we omit the detail of the algorithm here.

We are required to search the path in all combinations $x$ out of $T$ time division sub-channels if the user demands $x$ sub-channels and there are $T$ sub-channels per wavelength. Since there is no time switching in the proposed networks, different paths may be obtained in the search with different sets of sub-channels used for communication. Path searchings in all combinations of time slot are therefore required. In each path search, we need $\mathcal{O}(L^2)$ computations where $L$ is the total number of node inputs in the network. Heuristic may be required to reduce the computational complexity in networks with large $T$ and $L$.

## IV. Performance Evaluation

Three different network topologies have been used in simulations: a 24-node bi-directional ring network, a $6 \times 6$ Manhattan Street Network, and the 27-node network of topology shown in Fig. 4. New users are randomly generated in Poisson probability distribution and arrive at the system with random source-destination pairs. In the simulations, each user demand one time slot bandwidth and the holding time is an exponential random variable with a mean of one time unit. If the path searching algorithm cannot find a path with sufficient bandwidth for a call, the call is blocked immediately. The number of wavelength per fiber $W$ and the number of sub-channels per wavelength $T$ are set to the relatively small values of 4 and 20, respectively. Hence, we can easily determine the performance between different OTDM-WR time-slot routing schemes. However, similar results have been observed on systems with larger number of wavelengths, *e.g.,* 8 and 16. We use the batched mean method to compute the results. The batch size is $10^4$ time units. The first batch result is discarded. The 95% confidence intervals are less than 5% of the results.

We simulate the proposed routing scheme in two settings: *normal* and *ideal*. The *normal* setting assumes that the number of wavelength converters at each input of a node is equal to the number of wavelengths in use for transmission between nodes. The wavelength converters have full conversion capability among these wavelengths. The *ideal* setting assumes that

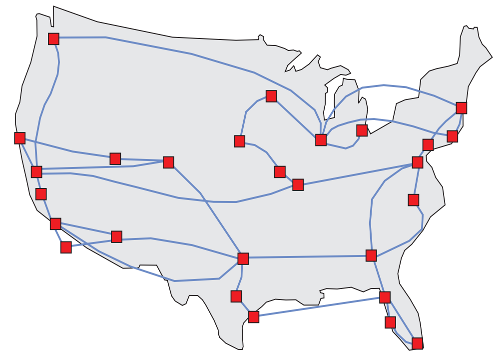

Fig. 4. The AT&T North America OC-48 fiber network. The network topology was obtained from the URL http://www.ipservices.att.com/backbone/bbone-map.cfm in March 2001.

the wavelength converters cover a much larger number of wavelengths than that of normal setting. In ideal setting, the switch SW is sufficient large such that there is no internal blocking. Two time-slot routing schemes are included for comparison. The first is *basic wavelength routing* in which there is no time-slot switching or wavelength conversion at intermediate nodes. To search for the shortest path in a basic OTDM-WR network, we use the algorithm in Section III-B with no data exchanging between different wavelength channels. The next is *space-switched routing* which is similar to the OTDM-WR networks assumed in [4]–[7]. A data can be switched from an input to any output with the same associated wavelength and time division sub-channel. An OTDM-WR network of space-switched routing is equivalent to $W \times T$ identical single channel circuit-switched networks joining the source and destination nodes. The shortest path searching in such networks is equal to choosing the 'shortest' path from the set of 'shortest paths' of each of the $W \times T$ equivalent networks.

Figures 5, 6, and 7 show the blocking probabilities of the routing schemes in a 24-node bi-directional ring, a $6 \times 6$ MSN, and the 27-node network of irregular topology shown in Fig. 4, respectively. The $x$-axis is the total number of users arriving in unit time while the $y$-axis shows the average blocking probability of all users. Crosses, asterisks, circles, and squares represent the results of the basic wavelength routing, space-switched routing, the proposed routing scheme in normal and ideal settings, respectively. We observe that at low arrival rate, all four types of routing perform similarly. When the arrival rate increases, the proposed scheme in ideal setting performs better than the space switched routing which in turn is better than the proposed scheme in normal setting for the MSN and the irregular topology network. All four routing schemes use alternate paths to prevent blocking at low user arrival rate and cause network congestion when user arrival rate is high. the basic wavelength routing scheme performs the worst among the four schemes. Since the average node degree of the irregular topology network is larger than that of MSN, more alternate paths are available. Hence, the blocking probabilities shown in Fig. 7 for all the routing schemes at the same user arrival rate are smaller

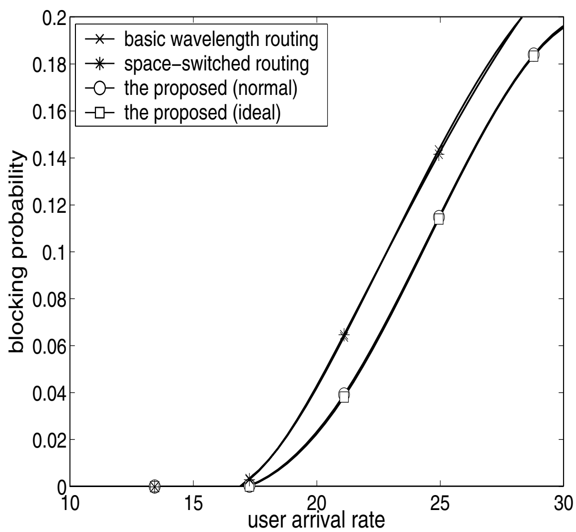


Fig. 5. Blocking probabilities of the routing schemes in a 24-node bi-directional ring OTDM-WR network.

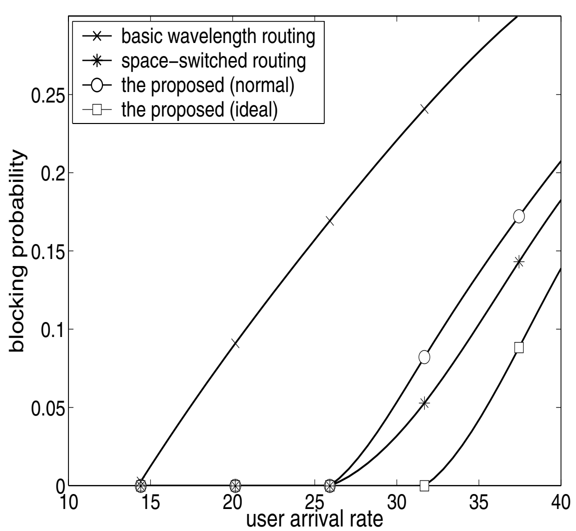


Fig. 6. Blocking probabilities of the routing schemes in an OTDM-WR network with the topology of a $6 \times 6$ MSN.

than that shown in Fig. 6. In ring networks, there is few alternate paths. All four routing schemes have similar routing paths. The two proposed schemes have better performance because of the wavelength conversion.

## V. Conclusion

Optical time division multiplexing (OTDM) is an effective approach to improve the performance of wavelength routed (WR) networks. Owing to lack of practical optical buffer and sophisticated optical processing devices, however, implementation of all-optical time-slot routing in OTDM-WR networks is difficult. In this paper, we have demonstrated that OTDM-WR

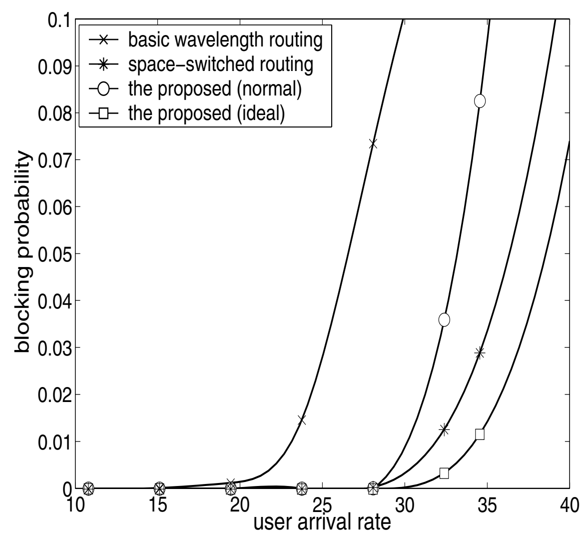


Fig. 7. Blocking probabilities of the routing schemes in a 27-node OTDM-WR network of topology of AT&T OC-48 fiber network shown in Fig. 4.

networks utilizing fast wavelength converter instead of time-shared space switches have much better performance than that of basic WR networks. When compared to OTDM networks with time-shared space switching only, the proposed network will have better performance if additional wavelength converters are used in the node to remove internal blocking. Otherwise, the former will have slightly better performance.

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