A Wavelength Assignment Scheme for WDM Networks with Limited Range Wavelength Converters

Sho SHIMIZU, Yutaka ARAKAWA, Naoaki YAMANAKA
Department of Information and Computer Science, Faculty of Science and Technology
Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, 223-8522, Japan
Email: shimizu@yamanaka.ics.keio.ac.jp

Abstract—In this paper, we propose a new wavelength assignment scheme that improves the blocking probability of WDM networks that use limited-range wavelength converters. Limited-range wavelength converters are attractive for wavelength-routed networks given current technology since they offer good utilization of the wavelength resource and improved blocking probability. However, their conversion ranges are limited, the maximum difference between the input and output wavelengths is restricted. Thus, we must take into account the existence of these limited-range wavelength converters. In our proposed scheme, each connection request is assigned a different wavelength according to its hop number. We tend to use different wavelengths for connection requests with different hop numbers. As a result, we can reduce the blocking probability by two decades compared to simply assigning the shortest available wavelengths. In addition, it allows the number of wavelength converters used in each node to be reduced with almost no degradation in blocking probability. Simulation results show that the proposed scheme can reduce the wavelength converters by about 20%.

I. INTRODUCTION

Wavelength-routed networks are attractive for realizing the next generation wide-area networks since they offer a data transmission scheme for WDM all-optical networks [1], [2]. In wavelength-routed networks, data is transferred on lightpaths. A lightpath is an optical path established between the source node and the destination node. When a connection request arrives, a lightpath is set up. This involves routing and signaling to reserve a wavelength on each link along the path selected. The benefit of wavelength-routed networks is the ability to more fully utilize the bandwidth of optical fibers since they do not require processing, buffering, and opto-electronic-optic (O/E/O) conversions at intermediate nodes.

The simplest wavelength-routed networks assigns one wavelength to all links of the connection between the source node and the destination node. This requirement is known as the wavelength continuity constraint. The constraint can be avoided by the use of wavelength converters at intermediate nodes. A wavelength converter is a device which converts the input wavelength $\lambda_i$ into a different wavelength which is then output $\lambda_o$. In wavelength-routed networks with wavelength converters, a lightpath can be established even though there is no common wavelength on all links along the path. This approach can improve the blocking probability and the efficient utilization of wavelengths [3]. The wavelength converters assumed in [3] provide full-range wavelength conversion capability. This means that any input wavelength can be converted to any output wavelength. While it is possible to realize full-range wavelength converters optoelectronically, such means that the networks lose the benefit of optically-transparent wavelength-routed networks. Given current technologies, one of the most popular all-optical wavelength conversion techniques is four-wave mixing (FWM) [4]. In FWM based wavelength converters, the output signal power is significantly degraded as the difference between the input wavelength and the output wavelength increases [5]. Therefore, realistic wavelength converters have limited wavelength conversion capability, and the difference between the input and output wavelengths is limited. It follows that we need a wavelength assignment scheme that considers the existence of limited-range wavelength converters [6].

Routing and wavelength assignment (RWA) is a very important issue since it decides the wavelength utilization efficiency and blocking probability. Many papers on routing and wavelength assignment have been published [6]–[9]. First-fit assignment has been researched as a wavelength assignment scheme for networks with limited-range wavelength converters [5]. Starting with the assumption that all nodes can get global information on all links in the network, first-fit assignment achieves almost the same blocking probability as a network with full-range wavelength converters. However, it is not practical to share the global information on all links in real time to realize adequate scalability. We need to assign wavelengths in a distributed manner based on information on neighboring links. If the nodes have limited-range wavelength conversion capability, wavelength assignment on a link limits the wavelengths assigned to the other links along the path. For this reason, it is expected that the blocking probability in networks with limited-range wavelength converters will increase compared to networks with full-range wavelength converters.

In this paper, we propose a distributed wavelength assignment scheme that considers the number of hops under the existence of limited-range wavelength converters. In order to allocate different wavelengths as the search area for connection requests with different numbers of hops, the proposed scheme proceeds as follows. The proposed scheme identifies available
wavelengths starting from a different initial area according to the number of hops in the request. That is, nodes start the wavelength search from a wavelength closer to the center wavelength when the path has large number of hops. On the other hand, when it has a small number of hops, the search starts from a wavelength far from the center. This decreases the blocking probability and the number of wavelength conversions needed.

The rest of this paper is organized as follows. Section II denotes the system model considered in this paper. In Section III, we propose a wavelength assignment scheme for wavelength-routed networks with limited-range wavelength converters. Section IV presents the simulation results of the blocking probability and the average number of wavelength conversions. Finally, in Section V, we conclude this paper.

II. SYSTEM MODEL
A. Wavelength reservation protocol

Figure 1 illustrates an example of the wavelength reservation protocol. In this paper, we assume the forward reservation scheme. When a connection request arrives at a source node, the node determines the path used for the lightpath, and sends a RESERVE signal to the next node along the path to reserve a wavelength for the first link, as shown in Figure 1(a). When an intermediate node receives a RESERVE signal, it sends a RESERVE signal to the next node to reserve a wavelength based on the link state information. When a RESERVE signal reaches the destination node, it sends an ACK signal to the source node, which indicates the success of wavelength reservation on all links. The source node starts to send data after it receives the ACK signal. On completing data transmission, the source node sends a RELEASE signal toward the destination node along the path. A node receiving a RELEASE signal releases the wavelength on the lightpath used for the data transmission. If there is a link with no wavelength available in a path, wavelength reservation fails. In this case, the node that failed to reserve a wavelength sends a NACK signal toward the source node as shown in Figure 1(b). Upon receiving the NACK signal, a node releases the wavelength and resends the NACK signal until the NACK signal reaches the source node.

B. Limited-range wavelength converter

A major problem of wavelength-routed networks is their inefficient utilization of the wavelength resource and the high blocking probability due to the constraint that the same wavelength must be used on all links along the path. This is known as the wavelength continuity constraint. The solution is the use of wavelength converters. A wavelength converter is a device that can convert the wavelength input to another wavelength that is then output. Full-range wavelength conversion can be achieved optoelectronically [3]. However, this approach loses one key advantage of wavelength-routed networks, optically-transparent processing. We assume that this weakness is not acceptable and focus our attention all-optical wavelength converters. Wavelength converters based on FWM (Four-Wave Mixing) are becoming extremely popular [5]. Unfortunately, as shown in Figure 2, the output signal strength of such a wavelength converter degrades as the difference between the input wavelength and the output wavelength increases. Current technologies restrict the range over which an optical wavelength conversion is possible. The relation between the input wavelength and the output wavelength is modeled as the following equation [5].

\[ \lambda_{\text{max}}(j,k) \leq \lambda_o \leq \lambda_{\text{min}}(j,k) \]  

where \( W \) wavelengths, \( \lambda_1 \) to \( \lambda_W \), are multiplexed into an optical fiber, wavelength conversion range is \( k \), the wavelength input to the wavelength converter is \( \lambda_i \), and the wavelength output by the wavelength converter is \( \lambda_o \). Figure 3 illustrates an example where \( W = 7, k = 1, \) and \( i = 3 \). The output wavelength is limited to \( \lambda_3 \) to \( \lambda_5 \) for input wavelength \( \lambda_4 \).

C. First-Fit assignment

First-Fit assignment has been proposed as a wavelength assignment scheme for wavelength-routed networks with limited-range wavelength converters [5]. In this scheme, the shortest of the available wavelengths is assigned to a new connection request. The behavior of First-Fit assignment in our system model is expressed as follows. A node assigns
the shortest wavelength among all available wavelengths to a new connection request when it is a source node. When a node is intermediate node, it assigns the same wavelength assigned to the previous link if the wavelength is available. Otherwise, it assigns the shortest wavelength among other wavelengths limited by Equation (1). Reference [5] shows that the blocking probability of First-Fit assignment is reasonable, but this approach assumes that each node can get the link states of the entire network. If this assumption is incorrect and the states of only the neighboring links is known, the blocking probability degrades dramatically.

### III. Proposed Scheme

In this paper, we propose a wavelength assignment scheme that considers the number of hops in a connection. The blocking probability can be reduced by the proposed scheme since the wavelength search area depends on the number of hops in the connection. In the following, we denote the number of wavelengths as \( W \), the maximum number of hops in a network as \( H_{\text{max}} \), the wavelength conversion range is \( k \), and the number of hops in a connection request as \( h \). Furthermore, we assume each node knows the maximum number of hops in the network and that it can get adjacent link states. The source node can select any of the wavelengths in the search area, but intermediate nodes must select one the wavelengths that satisfy Equation (1) where the input wavelength is the wavelength assigned to the previous link. That is, wavelength assignment at the source node differs from that at an intermediate node.

#### A. Wavelength assignment at the source node

We assume that \( W = 14 \) and \( k = 2 \). When the input wavelength is \( \lambda_1 \), Equation (1) indicates that there three wavelengths are possible, \( \lambda_1 \) to \( \lambda_3 \). When the input wavelength is \( \lambda_7 \), five wavelengths, \( \lambda_3 \) to \( \lambda_8 \), can be output. The number of output wavelengths possible varies with the input wavelength and the conversion range. When the input wavelength is near the center wavelength, the number of possible wavelengths is maximized. On the contrary, when it is distant from the center wavelength, the number is minimized. The necessity of wavelength conversion increases with the number of hops, as does the blocking probability. The goals of our proposed scheme are to reduce the blocking probability and the number of wavelength converters needed. Our approach is to vary the search area of available wavelengths with the number of hops; increasing the number of hops increases the search area. The initial search area is allocated from both ends of the wavelength range. As a result, a connection request with a large number of hops tends to use wavelengths near the center wavelength. If there are vacant wavelengths in the search area, assignment starts from the wavelength nearest the center wavelength and the first available wavelength is assigned. In this way, connection requests that have many hops are more likely to be assigned wavelengths near the center wavelength. Requests with few hops tend to be assigned wavelengths far from the center. This procedure can improve the blocking probability of connections with many hops, which reduces the blocking probability of the entire network, as well as the number of wavelength converters needed.

Figure 4 shows the search area and the search order of our proposed scheme where \( W = 8 \), and \( H_{\text{max}} = 4 \). The numerals in this figure indicate the search order of wavelengths. As shown in Figure 4, \( \lambda_1 \) and \( \lambda_3 \) are the search area of a 1-hop connection. \( \lambda_1 \) to \( \lambda_3 \) and \( \lambda_6 \) to \( \lambda_8 \) are the search areas of a 3-hop connection. The search area contains as many wavelengths as there are hops from either end of the wavelength range. This symmetry makes the proposed scheme is effective regardless of the number of hops.

#### B. Wavelength assignment at intermediate nodes

The wavelength conversion range follows Equation (1) where the wavelength assigned to the previous link is \( \lambda_i \). Figure 5 shows the search order of the proposed scheme at an intermediate node. If available, the input wavelength \( \lambda_i \) is assigned to the next link. Otherwise, we start the search from the wavelength most distant from the center wavelength. Next, the node checks the wavelength nearest the center. The first available wavelength is assigned to a connection request. In the example in Figure 5, the node searches for a wavelength in the order \( \lambda_3, \lambda_1, \lambda_1, \lambda_4, \lambda_5 \). As a result, fewer wavelengths near the center are selected which leaves them available for assignment to connections with many hops. Moreover, the number of wavelength conversions for a connection with large number
of hops is also reduced. Consequently, the proposed scheme can reduce the impact of eliminating underutilized wavelength converters.

We show an example of the effect of the proposed scheme in Figure 6. In this figure, we assume that the wavelength conversion range, \( k \), is two, there are three existing connections between Node 4 and Node 5. When a new connection request from Node 1 to Node 8 arrives, in First-Fit assignment, we assign the shortest available wavelength. Wavelength assignment fails because of existence of short-hop connections between Node 4 and Node 5. On the contrary, in the proposed scheme, we assign the center wavelength and the wavelength assignment succeeds. The center wavelength is available for the new connection, and no wavelength conversion is required at intermediate nodes in this example.

**IV. PERFORMANCE EVALUATION**

Computer simulations were conducted to evaluate the blocking probability and the average number of wavelength conversions. It is assumed that the network topology is a unidirectional ring with eight nodes as shown in Figure 7, the number of wavelengths is fourteen, the connection requests arrive at each node independently following a Poisson process, and source-destination pairs were uniformly distributed. We compared three wavelength assignment schemes: First-Fit assignment, Random assignment, and the proposed scheme. Random assignment assigns a wavelength from available wavelengths randomly. It should have lower blocking probability than First-Fit assignment since it assigns wavelengths with uniform distribution, but the number of wavelength conversions is expected to be increased.

Figure 8 shows the blocking probability versus the network load where each node has a limited-range wavelength converter. In this simulation, we generate 1 million connections. When wavelength converters have limited-range wavelength conversion capability, First-Fit assignment greatly increases the blocking probability compared to full-range conversion. The proposed scheme and Random assignment better suppress the impact of limited-range wavelength conversion on the blocking probability than First-Fit assignment. If the wavelength conversion range, \( k \), is large, the blocking probability is decreased. In the following evaluations \( k = 1 \) which is the most strict case for limited-range wavelength conversion. We see that the proposed scheme and Random assignment have almost same blocking probability. Given the above results, we compared the proposed scheme with Random assignment which has better blocking probability than First-Fit assignment.

Figure 9 shows the average number of wavelength conversions needed versus the number of hops. We assume that each
node has sufficient wavelength converters to handle all input wavelengths. The proposed scheme requires fewer on average wavelength conversions than Random assignment. The key point is that the proposed scheme makes it more likely that connections with many hops will undergo fewer wavelength conversions; this suggests that some wavelength converters will be underutilized.

Figure 10 shows the blocking probability versus the wavelength converter density. "All" indicates all nodes have sufficient numbers of limited-range wavelength converters to handle all input wavelengths. "Case 1", "Case 2", and "Case 3" represent the situations in which some wavelength converters are eliminated. The percentage of eliminated wavelength converters in Case 1, Case 2, and Case 3 is about 7%, 14%, and 21%, respectively. In the proposed scheme, the utilization of wavelength converters whose input wavelength lies on the side or the center is lower than that of other wavelength converters. There is almost no difference in the blocking probability of the proposed scheme even though some wavelength converters were eliminated. On the other hand, Random assignment allowed the blocking probability to rapidly increase as the number of wavelength converters eliminated was increased.

Figure 11 shows the increase ratio of the blocking probability versus the network load. We define the increasing ratio of the blocking probability as the ratio of the blocking probability with wavelength converters for all input wavelengths to that with fewer wavelength converters whose input wavelengths were $\lambda_1, \lambda_8, \lambda_{14}$, were eliminated. It is found that the blocking probability is only slightly degraded in the proposed scheme when underutilized wavelength converters are eliminated. We also observe that the increase ratio decreases as the network load increases. At high network loads, the blocking probability is also high regardless of the existence of wavelength converters. In this case, the impact on the blocking probability of using wavelength converters is small.

V. CONCLUSION

This paper introduced a wavelength assignment scheme for wavelength-routed networks with limited-range wavelength converters. The proposed method uses a center wavelength for a long hops connection and an edge wavelength for a short hops connection. First-Fit assignment does not consider wavelength conversion, and its blocking probability is high. The proposed scheme considers the number of hops in a
connection request, and so offers lower blocking probability than First-Fit assignment. Moreover, we showed that it can reduce the number of wavelength converters needed.

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