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# Routing and wavelength assignment in hierarchical WDM networks

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**Abstract** A new routing and wavelength assignment method applied in hierarchical wavelength division multiplexing (WDM) networks is proposed. The algorithm is called offline band priority algorithm (offline BPA). The offline BPA targets to maximize the number of waveband paths under the condition of minimum number of wavelengths, and solve the routing and wavelength assignment (RWA) problem with waveband grooming to reduce cost. Based on the circle construction algorithm, waveband priority function is introduced to calculate the RWA problem. Simulation results demonstrate that the proposed algorithm achieves significant cost reduction in WDM network construction.

**Keywords** routing and wavelength assignment (RWA), waveband grooming, waveband path

## 1 Introduction

In a hierarchical optical switching wavelength division multiplexing (WDM) network, hierarchical optical cross-connects (H-OXC) can aggregate contiguous wavelengths into a waveband that can be switched as a single unit, which results in a simplified implementation of OXC and reduced node cost in network construction [1,2]. However, as far as we know, there are no mature solutions of the routing and wavelength assignment (RWA) problem in hierarchical WDM networks. We have proposed a band priority algorithm (BPA) [3] that combines integrated dynamic IP/WDM routing with hierarchical multiplexing architecture

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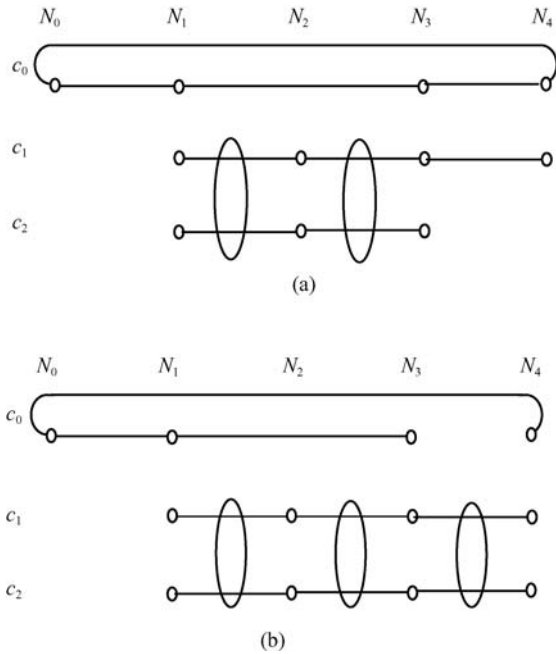
to maximize the number of grouped wavelengths into wavebands under dynamic request circumstances. The BPA introduces a waveband grooming related cost function called “waveband priority” into routing calculation to obtain the optimal route. In this paper, we propose an offline BPA for the waveband construction problem in WDM rings with arbitrary traffic requests between the nodes. Our simulation shows that on average, 30% reduction of the total number of optical ports can be achieved.

## 2 Problem statement

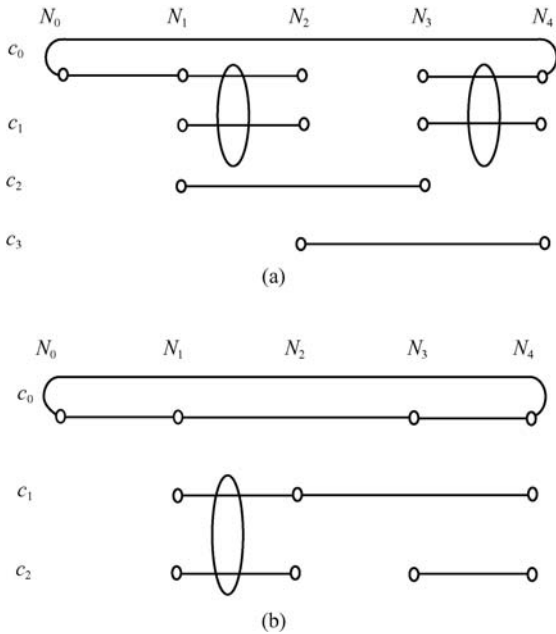
We assume that there are  $N$  optical add/drop multiplexer (OADM) nodes in a WDM ring, labelled from 0 to  $N - 1$ , and use a traffic request matrix  $\{r_{ij}\}$  to represent arbitrary traffic requests, where  $i$  and  $j$  are the ingress/egress nodes, and  $r_{ij}$  is the requested bandwidth between node  $i$  and node  $j$  in a unit of wavelength. The offline model assumes that all requests are given in advance.

In the waveband formation process, we employ the scheme that groups the light-paths with the same source-destination pairs into a waveband. We call a grouped path a “waveband path”. A waveband path can be switched optically as a single unit, thus reducing the number of optical ports required for processing individual wavelengths. The circle construction method proposed in Ref. [4] solves the conventional RWA problem in a WDM ring. The circle construction algorithm aims to minimize the total number of wavelengths to layout a cost-efficient network. However, it does not automatically generate the maximum number of waveband paths. Here is an example. Figure 1(a) shows that for the given traffic matrix, the circle construction algorithm in Ref. [4] leads to two waveband paths. Figure 1(b) shows that the optimum solution can have three waveband paths.

On the other hand, if we start by maximizing the number of waveband paths, we cannot guarantee the minimum number of wavelengths, as shown in Figs. 2(a) and 2(b). We can see from Fig. 2 that minimizing the number of



**Fig. 1** Sample A of circle construction algorithm. (a) Result of circle construction method in Ref. [4]; (b) optimal result of RWA combined with waveband grooming



**Fig. 2** Sample B of circle construction method. (a) Result of circle construction method for maximum waveband number; (b) result of circle construction method for minimum wavelength number

wavelengths and maximizing the number of waveband paths can be contradictory under certain circumstances.

The objective of our algorithm is to maximize the number of waveband paths under the condition of minimized number wavelengths, thus to minimize the number of optical ports to further reduce node costs. There are two

main steps in our offline BPA algorithm. The first step uses the circle construction algorithm to minimize the total number of wavelengths required to satisfy the given traffic matrix. The second step uses a waveband construction algorithm to find the optimum grouping of wavelengths into wavebands to maximize the number of waveband paths. Note that in the second step, we must keep the total number of circles unchanged. So the optimized solution we obtain will have a minimum number of wavelengths and a maximum number of waveband paths.

### 3 Offline band priority algorithm

In this section, we describe our offline BPA to assign wavelengths for a given arbitrary traffic matrix  $\mathbf{R} = \{r_{ij}\}$ .

#### 3.1 Applying circle construction algorithm

Applying circle construction algorithm, we obtain the minimum number of wavelengths to satisfy  $\mathbf{R}$ . Suppose  $C$  is the number of circles (or wavelengths). For each request  $r_{ij}$ , it corresponds to  $r_{ij}$  “routed paths” in the constructed circles.

#### 3.2 Using waveband construction algorithm to maximize number of waveband paths

The waveband construction algorithm based on the result of circle construction rearranges the grouping of connections among different circles, with the target of maximizing the number of waveband paths while keeping the number of wavelengths unchanged. The waveband construction algorithm is composed of the following steps.

##### 3.2.1 Computing “degree function” of each circle

We introduce a degree function that reflects the importance of each circle to waveband grooming. The degree function can be obtained through the following calculations.

First, we compute a  $\mathbf{P}$  matrix according to the given request matrix  $\mathbf{R}$ .

$$p_{ij} = \begin{cases} 1, & \text{if } r_{ij} \geq 2, \\ 0, & \text{if } 0 \leq r_{ij} < 2, \end{cases} \quad (1)$$

where  $i$  and  $j$  are the source and destination nodes of a request.

Also, according to the output of circle construction, a  $\gamma$  function can be defined as:

$$\gamma_{ij}^{(k)} = \begin{cases} 1, & \text{if } r_{ij} \in c_k, \\ 0, & \text{if } r_{ij} \notin c_k, \end{cases} \quad k=0,1,\dots,C-1, \quad (2)$$

where  $k$  is the circle identifier, and  $c_k$  is the  $k$ th circle.

The degree function is computed based on the matrix  $\mathbf{P}$  and function  $\gamma$ :

$$D(c_k) = \sum_i \sum_j [p_{ij} \gamma_{ij}^{(k)}], \quad k=0,1,\dots,C-1. \quad (3)$$

### 3.2.2 Grouping circles into circle groups

Assume that at most  $B$  wavelengths can be aggregated into one waveband in the given WDM network. Two circles are more “similar” if there are more wavelength paths with the same ingress-egress pair belonging to them.

$c_k (k = 0, 1, \dots, C - 1)$  can be ordered by degree function  $D(c_k)$  in descending order. For  $c_0$  that has the largest degree function, we search  $(B - 1)$  circles that are the most “similar” to  $c_0$ . Group these  $(B - 1)$  circles and  $c_0$  into a “circle group”. Circles that belong to the same circle group will be assigned to contiguous wavelengths. Then we look for a circle that has the largest degree function in the remaining  $(C - B)$  circles. Group the next circle group. Repeat the grouping step until all circles are grouped into circle groups.

### 3.2.3 Computing “isolated path set” and “base circle group” to form waveband path

Consider a request  $2 \leq r_{ij} \leq B$ . If its corresponding  $r_{ij}$  “routed paths” all belong to the same circle group, the  $r_{ij}$  routed paths will be grouped into one waveband path. If not, we look for the circle group that has the most routed paths among  $r_{ij}$  routed paths. This circle group is called the “base circle group”. The routed paths that are not in the base group will be placed in an “isolated path set”. For  $r_{ij} \geq B$ , similar procedures will be applied to form several waveband paths or base circle groups.

### 3.2.4 Circle rearrangement

Check each path in the isolated path set one by one to see whether it can be exchanged with another path within the base circle group. If yes, exchange them and update the “isolated path set”. The following algorithm helps to analyze whether an ungrouped  $l_a$  can be rearranged into another circle  $c_m$ , so that the ungrouped path could be grouped into a waveband path.

In the following cases as shown in Figs. 3 and 4(a), we can exchange the paths of isolated path set into the base circle group.

1)  $l_a$  does not belong to the base circle group  $(c_1, c_2)$ . The corresponding connection in  $c_2$  is a vacancy  $l_c$ , as shown in Fig. 3. Then  $l_a$  and  $l_c$  can be exchanged. Therefore,  $l_a$  and  $l_b$  can be groomed into a waveband path, as shown in Fig. 1(b).

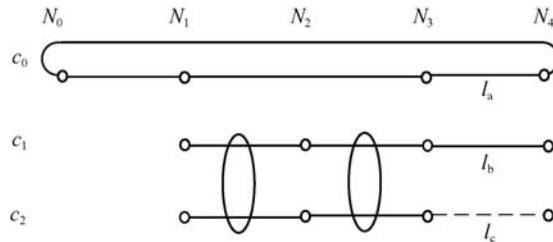


Fig. 3 Optimization of waveband grooming based on Fig. 1(a)

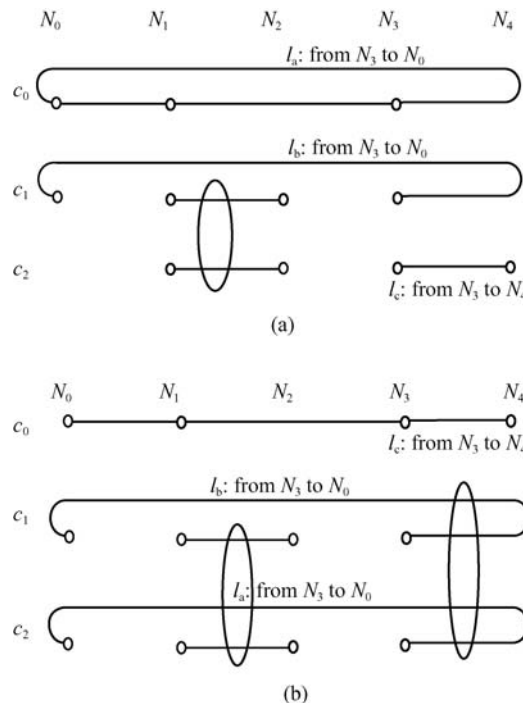


Fig. 4 Sample of static waveband priority algorithm. (a)  $l_a \notin (c_1, c_2)$ ; (b) exchange  $l_a$  and  $l_c$

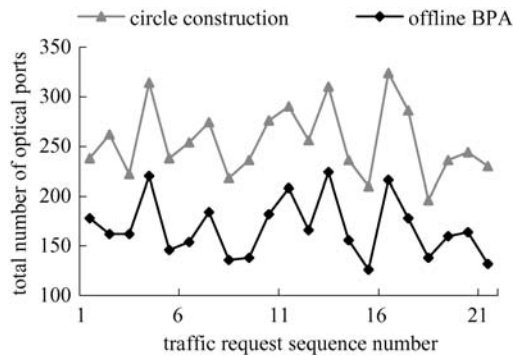
2)  $l_a$  does not belong to the base circle group  $(c_1, c_2)$ . The corresponding connection in  $c_2$  is occupied by  $l_c$ , as shown in Fig. 4(a).  $l_c$  is not vacant but it is exchangeable with  $l_a$  without destroying the other connections on  $c_0$  and  $c_2$ . In this case, we can exchange  $l_a$  with  $l_c$  and groom  $l_a$  and  $l_b$  into a waveband path (see Fig. 4(b)).

Through rearrangement, we increase the number of waveband paths while keeping the total number of wavelengths unchanged.

## 4 Simulation results

In our simulation, the traffic matrix  $\{r_{ij}\}$  is generated randomly. Both circle construction without BPA and circle construction with our offline BPA are simulated. We also simulate the waveband formation process after applying these two algorithms. Then we calculate the total optical

port numbers needed by the two ways. Figure 5 shows the comparison result when  $N = 10$  and  $B = 4$ . The  $X$ -axis is the sequence number of the randomly generated traffic requests. The  $Y$ -axis represents the number of optical ports needed to satisfy the traffic request. We can see that the offline BPA improves the efficiency of waveband formation process and results in significant savings in the total number of optical ports in every simulated case, thereby reducing the total cost in the hierarchical-switching WDM networks. The average savings in the number of optical ports is above 30%.



**Fig. 5** Number of optical ports needed when  $N = 10$  and  $B = 4$

## 5 Conclusions

In this paper, we propose an offline BPA that solves the RWA and waveband grooming problem in a WDM ring network. The BPA maximizes the number of waveband paths while minimizing the number of wavelengths to satisfy any traffic request matrix. The simulation result shows a reduction of the total number of optical ports by more than 30%, which demonstrates the contribution of the BPA to the subsequent waveband formation process.

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