Wavelength and Waveband Assignment for Ring Networks Based on Parallel Multi-granularity Hierarchical OADMs

Yongmin Qi, Yikai Su, Yaohui Jin, Weisheng Hu, Yi Zhu, and Yi Zhang

In this paper we study the optimization issues of ring networks employing novel parallel multi-granularity hierarchical optical add-drop multiplexers (OADMs). In particular, we attempt to minimize the number of control elements for the off-line case. We present an integer linear programming formulation to obtain the lower bound in optimization, and propose an efficient heuristic algorithm called global bandwidth resource assignment that is suitable for the design of large-scale OADM networks.

Keywords: Integer linear programming (ILP), wavelength and waveband assignment (WBA), wavelength division multiplexing (WDM).

Manuscript received Mar. 02, 2006; revised May 18, 2006.

This work was supported in part by the National Natural Science Foundation of China under Grant 60407008/90304002, Shanghai Optical Science and Technology Grant 04dz05103, and Shanghai Rising Star Program 04QMX1413.

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I. Introduction

With the rapid development of wavelength division multiplexing (WDM) technology, optical networks could employ hundreds of wavelengths to support increasing traffic. In such dynamically re-configurable networks, routing and add-drop are performed for each individual wavelength in every node, thus resulting in increased complexity as well as capital and operational expenditures. To solve this problem, the concept of multi-granularity [1], [2] was proposed as an approach to reducing network complexity and cost. The key idea is to group multiple wavelengths into wavebands through the use of multistage sequential switches. Extensive studies have been performed on multi-granularity optical cross-connect (MG-OXC) networks [3]-[7]. In [3] and [4], various integer linear programming (ILP) models were developed to minimize the total number of ports in the multi-granularity optical cross-connect (MG-OXCs) networks based on different grouping strategies. Routing and wavelength (or waveband) assignment (RWA) for MG-OXCs based on space switches were studied under dynamic traffic conditions [5]-[7]. However, sequential MG-OXC exhibits high insertion loss and filtering penalties that could considerably impair the optical signals to be groomed due to the cascaded structure employing multiple stages of filters and switches. To solve these problems, Y. Su and others [8] proposed and experimentally demonstrated a novel parallel multi-granularity node in a hierarchical configuration for optical add-drop multiplexer (OADM) applications based on blocker filters [9]. Figure 1 illustrates that such a blocker filter is switched by a control element with on-

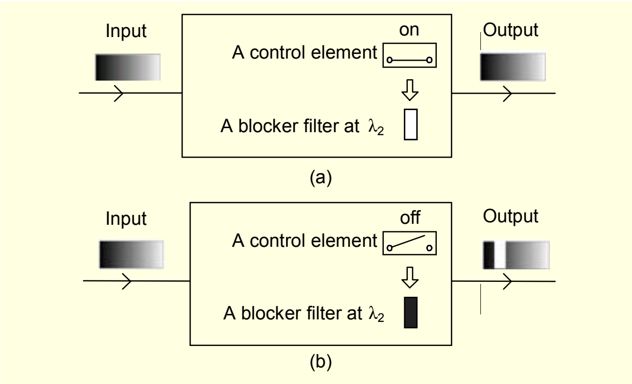

Fig. 1. Illustration of a blocker-filter controlled by a control element (a) a control element is in the on state and (b) a control element is in the off state.

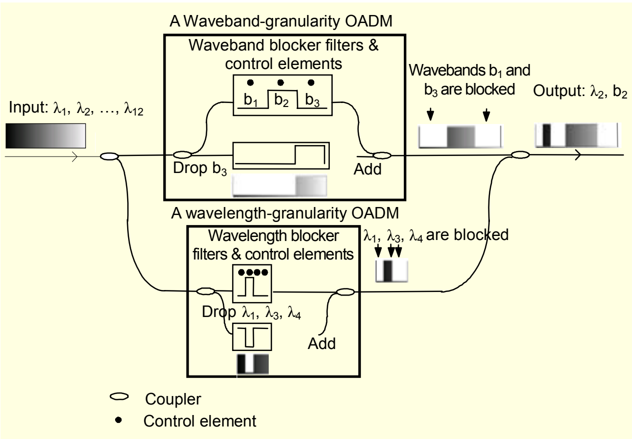

Fig. 2. The architecture of two-level parallel multi-granularity OADM node and a sample of λ_1, λ_3, and λ_4 in b_1 and b_3 to be dropped in the OADM node.

off states, which determines whether a signal at λ_2 either passes or is blocked by the blocker filter. The multi-granularity concept can then be introduced to blocker-based network nodes to form parallel multi-granularity OADMs, and therefore reduce the complexity and the size of the network node. This new parallel multi-granularity OADM architecture based on dynamic blocker filters consists of OADMs with wavelength granularity and waveband granularity, as shown in Fig. 2. There could be one or more wavelength-granularity OADM in parallel attached with a waveband-granularity OADM, depending on the traffic pattern as well as the wavelength and waveband assignment strategy.

The operation principle of the parallel OADM is explained as follows: incoming signals are power-split by a passive coupler and fed into the wavelength-granularity and waveband-granularity OADMs. At each granularity level, the OADMs operate in a broadcast-and-select manner for the input signals. The wavelength-granularity OADM handles input data traffic that is less than a waveband with a granularity of one wavelength and each filter element needs one control element. Once bundled traffic streams fill a waveband, they are directed through the waveband-granularity OADM. The total bandwidth of the system is divided into B wavebands, which are handled by the waveband-granularity OADM. The waveband-granularity OADM therefore has B control elements. Consequently, assuming that there are a total of W wavelengths available in the network, the number of control elements in a wavelength-granularity OADM is W/B and the bandwidth of a wavelength-granularity OADM is a waveband.

Note that when a wavelength is dropped by a wavelength-granularity OADM, the corresponding waveband should be blocked. The output signals from the wavelength-granularity and waveband-granularity OADMs are combined by a coupler. For example, in Fig. 2 we assume that there are 3 wavebands in the system and each contains 4 wavelengths (that is, $\lambda_1 \cdots \lambda_4 \in b_1$, b_1 denotes the first waveband). For a traffic distribution in the OADM network such that λ_1, λ_3, λ_4, and b_3 are dropped and other wavelengths pass, λ_1, λ_3, and λ_4 should be blocked and dropped by the wavelength blocker filters and the corresponding waveband b_1 should also be blocked by the waveband blocker. Only b_2 and λ_2 go through the OADM.

In contrast to the conventional cascading structure of OADMs, the parallel architecture significantly reduces the node loss and filtering effects and therefore ensures the quality of the signal when passing through the network nodes [8]. In addition to the above advantages, parallel multi-granularity OADMs also reduce node size and support data rate upgrade (for example, 10 Gbps, 40 Gbps, and 160 Gbps) with the same bandwidth efficiency and without replacing any optical components [8]. This is due to the fact that neighboring channels can be combined to form a new wider bandwidth to support higher data rates. Y. Su and others [10] proposed a heuristic algorithm to optimize the design of the multi-granularity OADM ring networks for the off-line case. The optimization objective for the parallel multi-granularity ring network is to minimize the number of control elements determined by the wavelength and waveband assignment (WBA) strategies, which could translate to the size and cost of the nodes in the network.

For dynamic scenarios, the study objective is to improve the performance of the existing network based on given resources, and generally, the optimization objective would be to minimize the blocking probability. In this paper, we focus on the optimization issue for off-line cases. We first present an integer linear programming (ILP) formulation to obtain the lower bound of the control elements needed. In addition, we propose an efficient WBA strategy called global bandwidth resource assignment (GBRA). This algorithm provides an effective design solution that reaches the lower bound of optimization in small ring networks, as indicated by ILP. It is also suitable for large-scale OADM networks, whose optimization would be challenging for ILP approaches. Compared with the algorithm in [10] termed as "node assignment first" (NAF) in this paper, GBRA minimizes waveband fragments and efficiently utilizes the waveband fragments that already exist, which are the key ideas in the optimization design.

II. ILP Formulation

Our objective is to achieve the least number of control elements in an N-node network via optimal assignment of wavelengths and wavebands to satisfy a given traffic demand matrix of the node pairs. In the following part, the problem formulations in the form of ILP are provided. An ILP program traverses all the values of integer variables in a given range to find all possible solutions satisfying the constraints and to provide the optimal solution (that is, the lower bound). Here, we present the integer constants and variables used in the ILP for this type of OADM given certain conditions, such as the architecture and the parameters of the network. Furthermore, we construct the constraints of the variables to satisfy the design requirements.

1. Notations

- N: number of nodes in the OADM ring network,
- W: total number of wavelengths,
- Bg: number of wavelengths per band (that is, waveband granularity),
- $T[n]$: set of total drop traffic demands of the nodes whose element t_n denotes total drop traffic demand in node n, which is obtained by summing the traffic demands of the corresponding node pairs,
- $A_b^w = \begin{cases} 1, \text{ Wavelength } w \text{ belongs to waveband } b, \\ \quad 1 \le w \le W,\ 1 \le b \le W/Bg \\ 0, \text{ Otherwise} \end{cases}$
- $B_n^w = \begin{cases} 1, \text{ Wavelength } w \text{ is dropped by a wavelength OADM} \\ \quad \text{in node } n,\ 1 \le w \le W,\ 1 \le n \le N \\ 0, \text{ Otherwise} \end{cases}$
- $C_n^b = \begin{cases} 1, \text{ Waveband } b \text{ is dropped by a waveband OADM} \\ \quad \text{in node } n,\ 1 \le b \le W/Bg,\ 1 \le n \le N \\ 0, \text{ Otherwise} \end{cases}$
- $WOADM_n$: the number of wavelength-granularity OADMs needed in node n, $1 \le n \le N$.

2. Objective Function

$$\min \sum_{n=1}^{N} CE_n \tag{1}$$

$$CE_n = W/Bg + WOADM_n \times Bg,\ 1 \le n \le N \tag{2}$$

$$\min_{Bg} \left\{ \min_{WOADM_n} \sum_{n=1}^{N} (W/Bg + WOADM_n \times Bg) \right\},\ 1 \le n \le N \tag{3}$$

$$\min \sum_{n=1}^{N} WOADM_n,\ 1 \le n \le N, \tag{4}$$

where CE_n is the number of control elements needed in node n, W/Bg is then the number of wavebands or the control elements in the waveband-granularity OADM. Each waveband or wavelength in the corresponding blocker needs one control element. The total number of control elements comes from two parts, one is the number of wavebands, while the other is the product of waveband granularity and the number of wavelength-granularity OADMs attached to node n. Here we illustrate the number of control elements in the node shown in Fig. 2: assuming that the node is numbered 3 in a network, the number of total available wavelengths is 12, the number of wavelengths per waveband is 4 (that is, $Bg = 4$), and there is one wavelength-granularity OADM (that is, $WOADM_3 = 1$), then the number of control elements in this node is $CE_3 = 12/4 + 1\times4 = 7$. Function (1) is the objective of optimization for the studied problem. We obtained function (3) by replacing CE_n with equation (2), where Bg and $WOADM_n$ are variables. Obviously, it is nonlinear. In other words, the number of control elements is related to both Bg and $WOADM_n$. Bg must be a factor of W (the number of wavelengths in the network) to guarantee W/Bg is an integer. In order to obtain the linear programming, we assume that Bg is a constant. Therefore, the objective is simplified to function (4) which satisfies the requirements of linear programming. Note that function (4) is the objective of the ILP model rather than the final goal. Given the parameters of the network, we perform the ILP many times according to different Bg values to achieve the optimal solution to function (3). In the ILP model, N, W, Bg, $T[n]$, and A_b^w belong to constants, B_n^w and C_n^b, and $WOADM_n$ are variables. In the optimization, we only consider drop traffic at each node (t_n, $1 \le n \le N$), which requires wavelength-granularity OADM(s) when assigning bandwidth resource, while add function can be realized by simply using passive combiners.

3. Constraints

We construct the constraints as follows:

$$\sum_{n=1}^{N} A_b^w \times B_n^w + \sum_{n=1}^{N} C_n^b \times A_b^w \le 1, \qquad \forall w=1,\cdots,W, \forall b=1,\cdots,W/Bg, \tag{5}$$

which prohibits space reuse of bandwidth resource for the purpose of comparison with the results in [10]. In other words, once a wavelength/waveband is assigned in a node, it cannot be reassigned in other nodes in the network.

$$\sum_{w=1}^{W} B_n^w + \sum_{b=1}^{W/Bg} C_n^b \times Bg = t_n, \ \forall n = 1,\cdots,N, \tag{6}$$

which describes the total drop traffic constraint in node n.

$$\sum_{w=1}^{W} B_n^w \times A_b^w < Bg, \ \forall b = 1,\cdots,W/Bg, \ \forall n = 1,\cdots,N, \tag{7}$$

which means that only the traffic of less than the waveband granularity can be dropped by a wavelength-granularity OADM.

$$WOADM_n = \sum_{b=1}^{W/Bg} \left\lceil \sum_{w=1}^{W} B_n^w \times A_b^w / Bg \right\rceil, \ \forall n = 1,\cdots,N, \tag{8}$$

which is the number of wavelength-granularity OADMs in node n.

III. Heuristic Design

Due to the complexity of the ILP presented in Section II, it is only preferred for small or medium-scale OADM networks where the computation complexity is not significant. However, for large-scale OADM networks, the ILP approach would be prohibitively time-consuming, thus efficient heuristics are desired. In this section, we propose an efficient heuristic assignment algorithm called GBRA to obtain a close-to-optimal solution.

The flowchart of the GBRA algorithm is shown in Fig. 3. The GBRA algorithm optimizes WBA from a global point of view, which is different from the NAF algorithm that optimizes the wavelength/waveband assignment based on each single node [10].

In brief, we discuss the procedure of the NAF algorithm as follows. There could be three cases to process the traffic drop in a node. In the first case, the NAF algorithm drops the traffic of one waveband if the traffic is larger than or equal to Bg and there is an empty waveband available. In the second case, for the remaining traffic, the NAF algorithm finds a waveband with minimum capacity to satisfy the traffic demand, and the number of wavelength-granularity OADM, $WOADM_n$ is added by 1. If this cannot be satisfied, the NAF algorithm assigns a waveband with the maximum bandwidth available

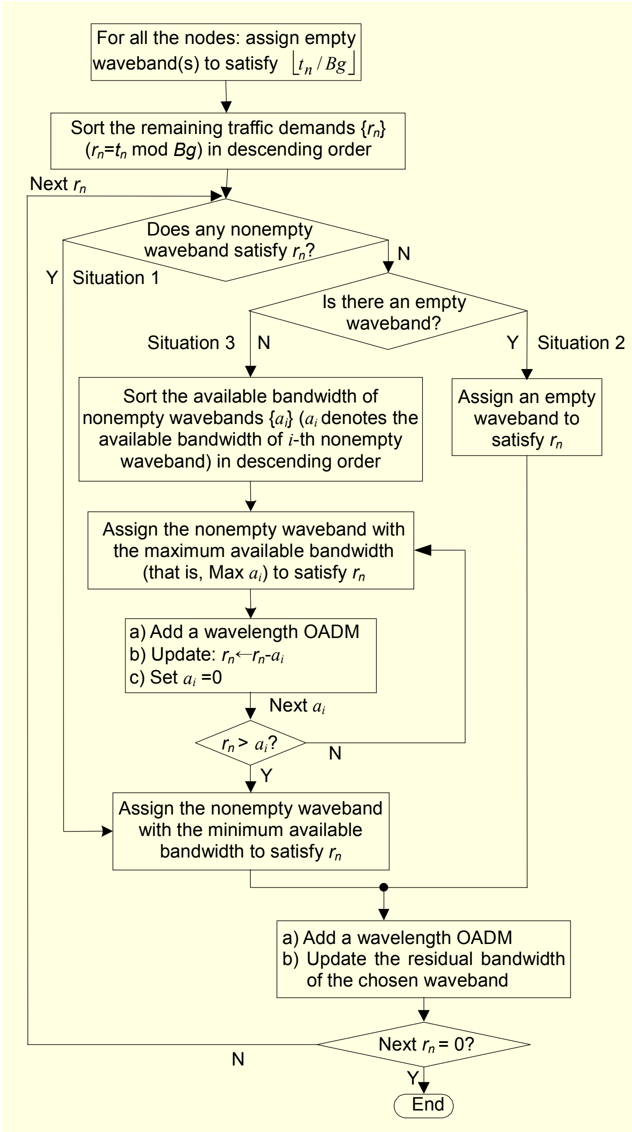

Fig. 3. Flowchart for the GBRA algorithm.

to satisfy the traffic demand and $WOADM_n$ is added by 1. The NAF algorithm repeats the above procedure until the traffic demand is satisfied for the node. The NAF algorithm assigns the bandwidth resource to satisfy the traffic demands node by node. However, for off-line cases, the global optimization schemes utilize the bandwidth resource more effectively for WBA compared to local optimizations. In addition, the GBRA algorithm minimizes the number of fragments in each waveband as well as the number of nonempty wavebands by an efficient assignment strategy utilizing existing nonempty wavebands which could lead to fewer wavelength-granularity OADMs and the associated control elements, thus contributing to the efficient optimization design.

The GBRA algorithm is explained as follows: first, the GBRA algorithm assigns empty waveband(s) to satisfy the

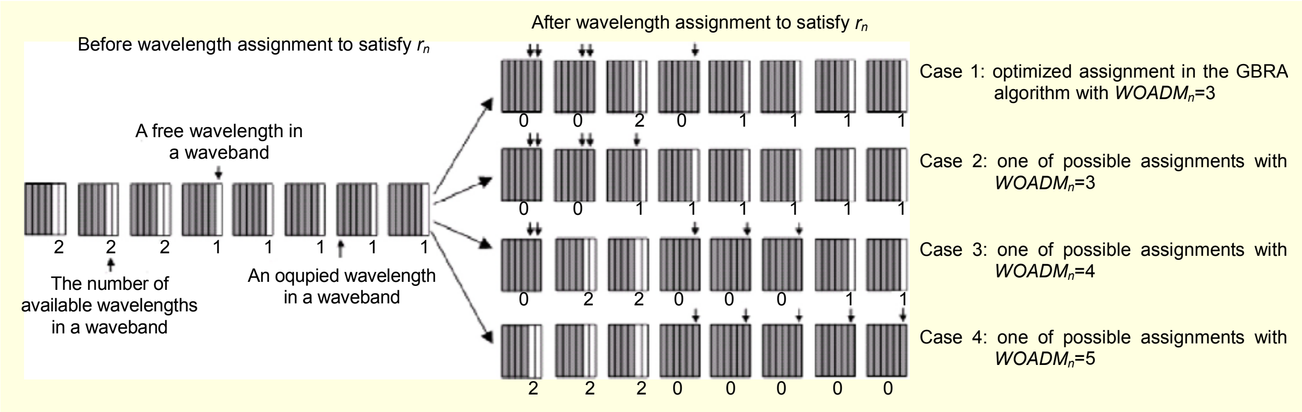

Fig. 4. The process of selecting available wavelengths of nonempty wavebands to satisfy r_n.

traffic bandwidth of $\lfloor t_n/Bg \rfloor$ if t_n is greater or equal to a waveband, where t_n is the traffic demand in n-th network node. Second, the remaining traffic demands of the nodes are sorted in descending order for bandwidth assignments. There could be three situations in the following process: in the first situation, there would be one or multiple nonempty wavebands that could satisfy the remaining traffic demand for node $n(r_n)$. Among them, the nonempty waveband with the minimum available bandwidth would be chosen to fit the demand. In the second situation, none of the nonempty wavebands would be able to satisfy r_n and there would be an empty waveband to accommodate r_n. Otherwise, r_n would have to be satisfied by multiple nonempty wavebands as in the third situation. After sorting the available bandwidth of nonempty wavebands $\{a_i\}$ in descending order (a_i denotes the available bandwidth of i-th nonempty waveband), the GBRA algorithm repeats satisfying part of r_n by selecting the nonempty waveband with the maximum available bandwidth (that is, Max a_i) to minimize the number of iterations, until in the last step, r_n is assigned to a nonempty waveband with the minimum available bandwidth to reduce the fragments. In each nonempty waveband assignment, the number of wavelength-granularity OADMs in node n should be added by 1 for the assigned wavelength(s). By the above means, the GBRA algorithm reduces the number of nonempty wavebands and efficiently utilizes existing bandwidth fragments in each waveband.

Here we provide an example to illustrate the third situation as shown in Fig. 4. Assuming that Bg is 6, the residual traffic demand in node n is 5 wavelengths (that is, $r_n = 5$). There are 3 nonempty wavebands with 2 available wavelengths and 5 nonempty wavebands with 1 available wavelength. Having sorted the remaining traffic demands in descending order, the GBRA algorithm selects one nonempty waveband with the maximum available bandwidth (that is, 2 free wavelengths). Consequently, the number of available wavelengths in the selected waveband becomes 0 after the assignment, while $WOADM_n$ is added by 1 and $r_n = 3$ after being updated. The process repeats one more time, therefore $WOADM_n$ is added by 1 and r_n becomes 1. Finally, it assigns a nonempty waveband with the minimum available bandwidth (that is, 1 free wavelength) to satisfy r_n, and eventually $WOADM_n$ becomes 3, and $r_n = 0$. We use "2-2-1" to denote the process of bandwidth assignment to satisfy r_n, as in case 1 in Fig. 4. Compared with the result of case 1, the number of wavelength-granularity OADMs in case 2 (2-2-2) is also 3, however, it introduces one more fragment in the third nonempty waveband, which could result in more wavelength-granularity OADMs being required to satisfy further traffic demand. Case 3 (2-1-1-1) and case 4 (1-1-1-1-1) are also two possible solutions; however, in cases 3 and 4, the number of wavelength-granularity OADMs are 4 and 5, respectively. Clearly, the GBRA algorithm performs the best in the wavelength and waveband assignments. The complexity of the sorting algorithm is $O(|W|^2/|Bg|^2)$; therefore, the complexity of the loop to process r_n is $O(|N||W|^2/|Bg|^2)$, which determines that the complexity of the GBRA algorithm is $O(|N||W|^2/|Bg|^2)$. It is equal to the complexity of the NAF algorithm as used in [10].

IV. Numerical Results and Discussions

In this section, we investigate some scenarios of uni-directional ring networks with different traffic distributions. We show the numerical results of both a small-scale (5-node) ring network and a large-scale (13-node) ring network. Numerical results of the ILP model are obtained by using the CPLEX solver.

We studied the 5-node ring network with 40 wavelengths (that is, N = 5, W = 40). Traffic demand of the node pairs follows a constant distribution of 2 and a uniform distribution between 0 and 4 wavelengths where Bg is 4, 5, 8, 10, and 20, respectively. Obviously, for constant traffic distribution, $t_n = 8$, $\forall n$. Table 1 shows numerical results of ILP, the GBRA algorithm and the NAF algorithm. From Table 1, we observe that, under constant traffic conditions, the minimal total

Table 1. Numerical results of 5-node networks with 40-wavelength.

Distributions of traffic demands	Waveband granularity (Bg)	Total number of control elements ($\sum_{n=1}^{N} CE_n$)		
		ILP	GBRA	NAF
Constant distribution (constant=2)	4	50	50	50
	5	75	75	80
	8	25	25	25
	10	70	70	100
	20	110	110	130
Uniform distribution [0,4]	4	66	66	68
	5	62	62	64
	8	63	63	67
	10	75	75	81
	20	110	110	126

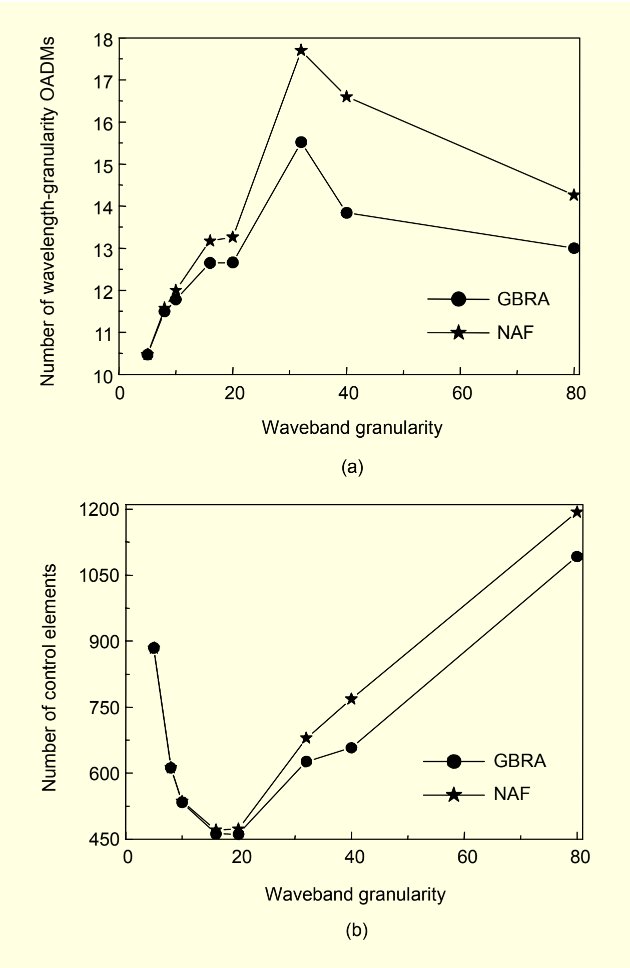

Fig. 5. 13-node ring network with 320 wavelengths (a) the number of wavelength-granularity OADMs, and (b) the number of control elements.

number of control elements can in general be achieved when the drop traffic at each node is equal to the waveband granularity. In addition, the GBRA algorithm reaches the lower bound as indicated by the ILP results for the 5-node case.

We next studied a large scale ring network in which $N = 13$ and $W = 320$. Assuming that traffic demands of the node pairs follow an exponential distribution with a mean value of 2, and Bg is 5, 8, 10, 16, 20, 32, 40, and 80, respectively. We ran the simulation 100 times and averaged the results, and the total running time on a typical PC was about 15 minutes. The results are shown in Fig. 5. For the GBRA algorithm, the optimal value of the control elements is 461.2 when the number of wavelength-granularity OADMs is 12.66 and Bg is 20, while those for the NAF algorithm are 470.72, 13.17, and 16, respectively. Figure 5 shows that the GBRA performs better than the NAF due to fewer waveband fragments during the WBA process. From Table 1 and Fig. 5, it can be seen that there is always an optimal Bg to achieve the minimal number of control elements. This can be explained according to function (3). If the Bg is set too small, the second term of function (3) will be reduced. On the other hand, a large Bg will make the first term of function (3) small.

V. Conclusion

In this paper, we presented an ILP formulation for optimizing parallel multi-granularity OADM networks to obtain the least number of control elements. We also proposed an efficient heuristic algorithm called GBRA to fulfill WBA in large-scale OADM networks. We demonstrated that WBA using the GBRA is more efficient than NAF for optimization.

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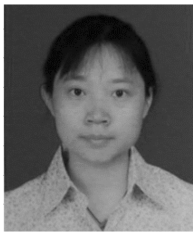

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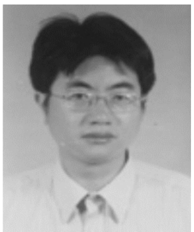

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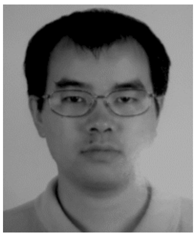

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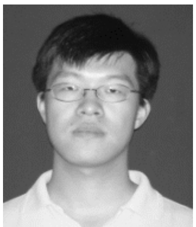

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