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Routing and Wavelength Assignment in Multi-Segment WDM Optical Networks using Clustering Techniques

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Abstract. This paper studies the routing and wavelength assignment (RWA) problem in multi-segment optical networks. The notion of network segment is referred to any part of the network that requires special consideration of wavelength routing such as separate administrative domains in a large scale optical network, sub-networks run by various service providers, etc. In multi-segment optical networks, each segment has different resource availability or hardware characteristics. The differences between multi-segment optical networks and homogeneous optical networks are discussed. We then present a resource abstraction technique called blocking island and define a multi-segment blocking island graph (BIG) network model. Using a minimum splitting routing heuristic introduced in the context of the blocking island paradigm in conjunction with the multi-segment BIG model, we propose a general RWA algorithm that takes a combined view of the network resource to integrate routing, wavelength assignment and gateway selection in a single routing framework. In the simulation, we demonstrate the effectiveness of our proposed algorithm by comparing it with other state-of-the-art heuristics in this area.

Keywords: RWA, multi-segment, clustering, blocking island

1 Introduction

Wavelength division multiplexing (WDM) divides the capacity of a single mode fiber into different channels, each using a different wavelength. In a WDM optical network, given a request, we need to set up a lightpath (wavelength continuous path without processing at the intermediate nodes) between the source node and the destination node. If there are no wavelength converters in the optical network, besides the conventional routing scheme, we must also assign wavelengths to the route subject to the wavelength continuous constraint. Given a set of connection requests, the problem of setting up a lightpath by routing and assigning a wavelength to each connection is called the routing and wavelength assignment (RWA) problem. The RWA problem can be formulated as a combinatorial problem known to be NP-complete [2]. Many heuristic algorithms have been proposed and evaluated under different assumptions: the incoming traffic is static or dynamic; the physical connection between each node is single fiber or multiple fibers; whether wavelength converters are available or not, etc. For a recent survey on the RWA problem, please refer to Yoo and Banerjee [3] and Zhang et al. [4].

While most of the previous RWA investigations are focused on one homogeneous optical network with uniform hardware characteristics and resource management, little attention has been paid to the interconnected all-optical infrastructure with traffic adaptations at the gateways. These networks are known as multi-segment networks. The concept of network segments is first proposed in Zhu et al. [1]. It refers to a part of the network, whose resource management, hardware or technology characteristics are different from the other parts, for example, separate administrative domains in a large scale optical network, sub-networks run by various service providers with different hardware characteristics, etc. In such a large scale optical network, routing and wavelength assignment needs individual consideration on each segment. The optical end-to-end connections may traverse several optical segments connected by gateways. Although the conventional RWA heuristics can still be employed in each segment,

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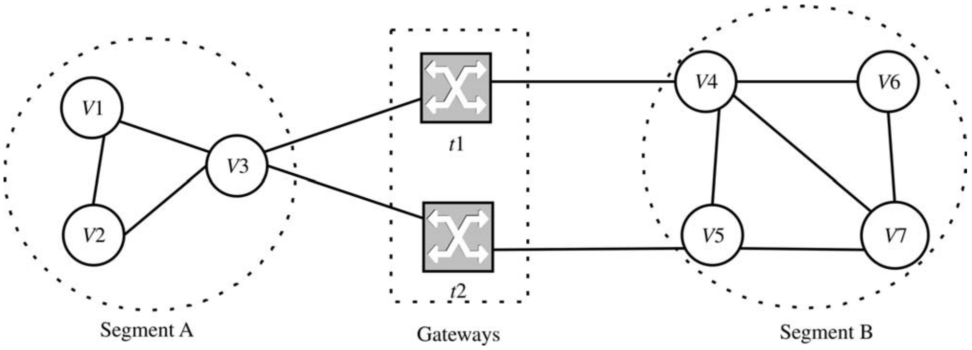

Fig. 1. A two segment interconnected optical network with two gateways $t1$ and $t2$. The number of wavelength in segment A is 2 and the number of wavelength in segment B is 3.

the final end-to-end route and wavelength selection will be far from optimal since the resource allocation is only optimized at the segment level. We here propose a simple and flexible algorithm which takes into account the global traffic as well as the local traffic and handles all the segment-specific topologies in a unified way.

To illustrate the issue to be addressed in this paper, let us consider a two-segment interconnected optical network as depicted in Fig. 1. There are two gateways $t1$ and $t2$. The number of wavelengths in segment A is 2 and the number of wavelengths in segment B is 3. If the source node and destination node in a request come from the same segment, the problem is a conventional RWA problem. While if the source node and destination node come from different segments, the RWA problem becomes more complicated by involving gateway selection and different wavelength numbers in different segments.

The concept of segments has been widely studied in ATM and Ethernet networks. In Somani and Azizoglu [9], it formulates the wavelength assignment issues in multi-segment optical networks. The difference between our study and Somani and Azizoglu [9] is that we mainly focus on wavelength routed optical networks while they only studied the optical broadcast star local area networks. Recently, Zhu et al. [1,5] studied the performance of multi-segment optical networks and several heuristics for multi-segment routing and wavelength assignment in large-scale optical networks were proposed. Based on notions proposed in Zhu et al. [1,5], we formulate the RWA problem in multi-segment optical networks and propose a new heuristic using the blocking island (BI) paradigm. Besides demonstrating the generality of our method (the same framework has been applied to a traffic grooming problem and a conventional RWA problem), we also show that our algorithm outperforms the state-of-the-art related algorithms.

The organization of this paper is as follows. In Section 2, we describe the RWA problem in multi-segment networks. In Section 3, some basic ideas about the clustering techniques called blocking island are introduced. We propose a new routing heuristic called minimum splitting. In Section 4, we define a multi-segment BIG network model, and a new RWA algorithm using blocking paradigm is proposed. The comparison and simulation results are discussed in Section 5. Section 6 concludes the paper.

2 Problem Statement

Let $G = (G^1, G^2, \ldots, G^k, T, TE)$ be a network graph consisting of K interconnected segments. T is the set of gateways and TE is the set of links which are directly connected to the gateways. For any segment $G^i, G^i = (N^i, A^i, W^i)$, where links $l \in A^i$, with $|A^i| = L$ and nodes $n \in N^i$. $|W^i|$ is the number of wavelengths per fiber. We assume all links in the same network segment have the same number of fibers and wavelengths. The network graph can also be represented as $G = (N, A, W, T, TE)$, where N is the set of all network nodes in the graph and A is the set of all links in the graph, $W = \{W^1, W^2, \ldots, W^k\}$, where W^i is referred to the number of wavelengths in segment i.

The gateway is a node that interconnects two segments. Without losing generality, we assume a gateway can only be an edge node in the segment. Because a gateway can be in two segments at the same time, we abstract the gateways between two segments to be a special independent segment. We also assume a gateway cannot be the source node or the destination node in a request. In our model, we do not allow multi-homing. Hence, the gateway can only support one-to-one connections. Based on this consideration, we characterize a gateway with the following parameters $T_k = (G^i, G^j, p)$, where G^i and G^j are two segments connected by gateway T_k and p is used to refer whether the gateway has an adaptation capacity or not.

We define two different types of traffic in multi-segment optical networks. The traffic whose source and destination nodes are in the same segment is called local traffic while the traffic that traverses multiple segments is called global traffic. For the local traffic, the conventional RWA heuristic can be applied. The end-to-end lightpath for the global traffic can be made up of several parts connected by gateways. We assume the number of lightpaths per fiber in each segment to be the same, but different segments may have different number of wavelengths. For example, in Fig. 1, the number of wavelengths in segment A is 2, while in segment B, the number of wavelengths is 3.

In our model, each traffic request occupies the bandwidth of a full wavelength. Because of the different number of wavelengths in each segment, we assume that the gateway at the boundaries has full adaptation and wavelength conversion capacity. That is, the traffic on one wavelength can be converted by the gateway to any other spare wavelength in another segment connected by this gateway.

Although it is desirable to have a distributed algorithm where each route and wavelength selection is computed at the local segments, here we assume the computation of the resource allocation to be done by a centralized server. In this paper, we will not discuss how the information is exchanged between the segments and the gateways (this is left to a sequel paper on the detailed implementation of our scheme and thus is beyond the scope of this paper).

It is well known that the complexity of the RWA problem in homogeneous optical networks is NP-complete. Since homogeneous optical networks are only a special case of multi-segment optical networks, it is easy to see that the RWA problem in multi-segment optical networks is also NP-complete. Although we can build an integer linear programming (ILP) formulation, it becomes unmanageable even for a very small network because of the exponentially increasing rate of the variables and equations. Besides, the ILP formulation will only be able to handle static traffic. We have to resort to heuristics to obtain fast and good solutions. In the next section, we first introduce the blocking island paradigm, and then we propose a heuristic using this paradigm to solve the RWA problem in multi-segment optical networks.

3 Blocking Island Paradigm

In this section, we assume all the network requests to be unicast traffic and the only QoS parameter taken into account is bandwidth. The network physical topology consists of m nodes arbitrarily connected by n bi-directional links. We depict it by a network graph $G = (V, L)$ as shown in Fig. 2, where $|V| = m, |L| = n$. A request is defined by a triple: $d_u = (x_u, y_u, \beta_u)$, where x_u and y_u are distinct nodes of the network and β_u is the bandwidth requirement.

Developed from artificial intelligence, namely constraint satisfaction and abstraction and the theory of phase transition, the BI [6] provides an efficient way of abstracting resources (especially bandwidth) available in a communication network. The goal is to find one and only one route for each demand so that the QoS requirements of the demand are simultaneously satisfied.

BI clusters parts of the network according to the bandwidth availability. A β-BI for a node x is the set of all nodes of the network that can be reached from x using links with at least β available bandwidth. For example, Fig. 2 shows a 40-BI for node $V1$.

β-BI has some very useful properties. Below we list a few without proof (for a proof, please refer to Frei [6]).

Unicity: There is one and only one β-BI for a node. Thus if S is the β-BI for a node, S is the β-BI for every node in S.

Partition: β-BI induces a partition of nodes in a network.

Route existence: Give a request $d_u = (x_u, y_u, \beta_u)$, it can be satisfied if and only if the node x_u and y_u are in the same β_u-BI.

Inclusion: If $\beta_i < \beta_j$, the β_j-BI for a node is a subset of the β_i-BI for the same node.

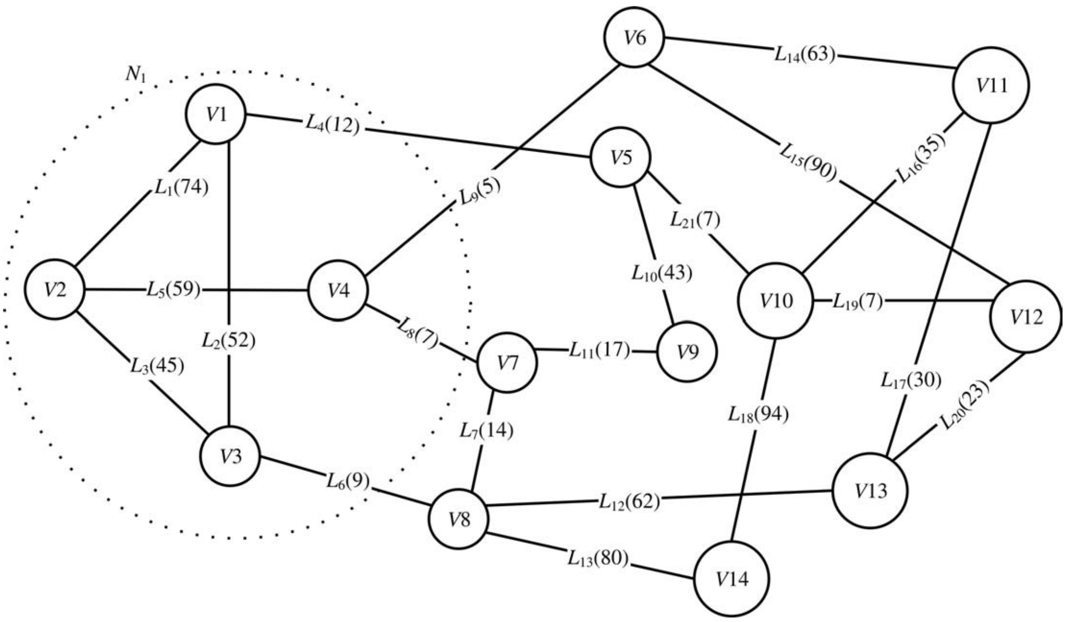

Fig. 2. The NSFNet topology. $N_1 = \{V1, V2, V3, V4\}$ is the 40-blocking island (40-BI) for node $V1$. The available bandwidth on a link is given in brackets.

Using the concept of β-BI, we can construct a recursive decomposition of BIGs in decreasing order of βs, e.g., $\beta_1 > \beta_2 > \ldots > \beta_n$. We call this layered structure of BIGs a blocking island hierarchy (BIH). For example, according to the demand $40 > 20 > 10$ and the network topology (Fig. 2), we have such a BIH (Fig. 7 later).

Given a request, using the routing existence property, we immediately know whether the request can be satisfied or not. It may be argued that a link-state routing protocol and Dijkstra's algorithm are also capable of checking the route existence. However, one of the key requirements of resource allocation in communications systems is the ability of responding very quickly to the question: can I have a route between *A* and *B* with a bandwidth *X* ? Thanks to the route existence property of the BIs paradigm, unlike the link-state routing, this question can be answered without having to compute a route.

After the allocation of a request, it is possible that some BIs in the BIH have to be split for there is not enough bandwidth left. For example, in Fig. 2, if we assign a route $V1 \rightarrow V3 \rightarrow V2$ with 40 bandwidth, the 40-BI N_1 will be split into two 40-BIs: $(V1, V2, V4)$ and $(V3)$. This splitting means that some requests that can be satisfied before the allocation of the route cannot be satisfied anymore. Based on analysis of the consequences that a given route has on the BIH, a routing heuristic called ''minimal splitting'' (MS) is proposed. The difference between this heuristic and others is that it tries to find a route which does not provoke a split in the BIH. We give an example to show the advantage of the MS heuristic.

In this example, we present two well-known heuristics (shortest path and widest path) and a new heuristic based on the BI characteristics (minimal splitting). We compare them on a single problem, depicted in Fig. 3. Fig. 4 is the corresponding BIH for bandwidth requirements $\{32, 9, 6, 0\}$. For instance, in the lowest level (when the bandwidth requirement is 32), we have three BIs: $N1$ which includes nodes *a, b, c* and *d*; $N2$ which includes *e* and *f*; and $N3$ which

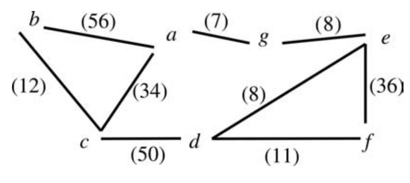

Fig. 3. A network where available bandwidths are given in parentheses.

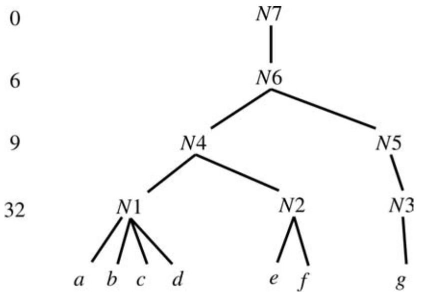

Fig. 4. The corresponding abstraction hierarchy for bandwidth requirements $\{32, 9, 6, 0\}$.

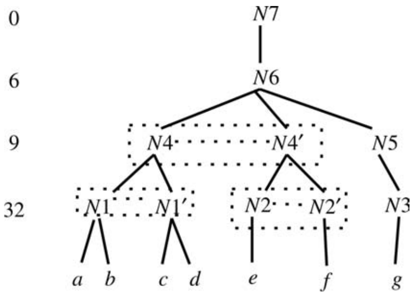

Fig. 6. The abstraction hierarchy after allocating request *d* by using the widest path heuristic.

includes g. The links are omitted for clarity of illustration.

Considering the problem of routing a single request $d = (a, e, 6)$, a is the source node, e is the destination node, 6 is the bandwidth requirement. One of the classical heuristics is to select a route that has enough resource and travels the least length (usually in terms of hops). That is called the shortest path (SP) heuristic. By employing the SP heuristic to allocate the request d in a network depicted in Fig. 3, we have the following route: $r_S: a \rightarrow g \rightarrow e$. Notice that 6-BI $N6$ is split into two if r_S is allocated to the request d, as shown in Fig. 5. That means node g is isolated from the rest of the network (assuming the bandwidth requirement is greater than or equal to 6). Any future request with g as an endpoint and with bandwidth requirement no less than 6 cannot be satisfied any more.

The widest path routing (WP) heuristic has been proposed as an alternative to SP, which tries to identify a route that has the maximum bottleneck bandwidth. The bottleneck bandwidth for a path is the lowest available bandwidth on the links composing the path. For the above request, we have the following route using the WP heuristic: $r_W: a \rightarrow c \rightarrow d \rightarrow f \rightarrow e$. Fig. 6 is the abstraction hierarchy after the route is allocated. Notice two 32-BIs has been split into two and one 9-BI has also been split into two. As a result, some requests that can be satisfied before the allocation of the route cannot be satisfied anymore.

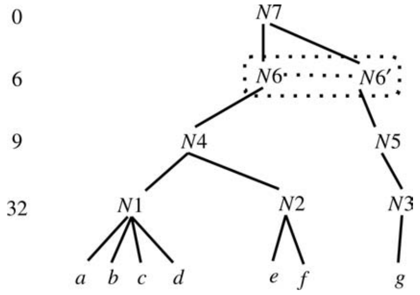

Fig. 5. The abstraction hierarchy after allocating request *d* by using the shortest path heuristic.

The MS heuristic is based on the analysis of the consequences the choice of a given route has on the BIH. If we could find a route which does not lead to a split in the BIH, that means any request which can be satisfied before can still be satisfied later. If the splitting is unavoidable, we would rather select a route which incurs the fewest splittings since the more splits that occur, the worse the situation gets in terms of future requests. Using the MS heuristic, first, we take the shortest route that does not affect the BIH. Second, if there is no such route, we take the route that causes the fewest splittings and also the lowest level splittings. For example, if we apply the MS heuristic, we have the following route: $r_M: a \rightarrow b \rightarrow c \rightarrow d \rightarrow e$. Notice the abstraction hierarchy will be the same as in Fig. 4 after the route is allocated. As illustrated by this example, the MS heuristic has a very good load balancing effect and in fact, the load balancing is the main objective of this heuristic by reserving the resource for the future requests.

For a general network, the implementation of the MS heuristic is difficult and time consuming since all routes must be computed in order to determine which one satisfies the requirement best. The level of BIH is usually decided by incoming bandwidth requirements. However, if there are too many different bandwidth values, we have to choose representative numbers either by simulation statistics or traffic analysis. We also propose to approximate this heuristic by combining it with another heuristic (in our case, we use the shortest path heuristic):

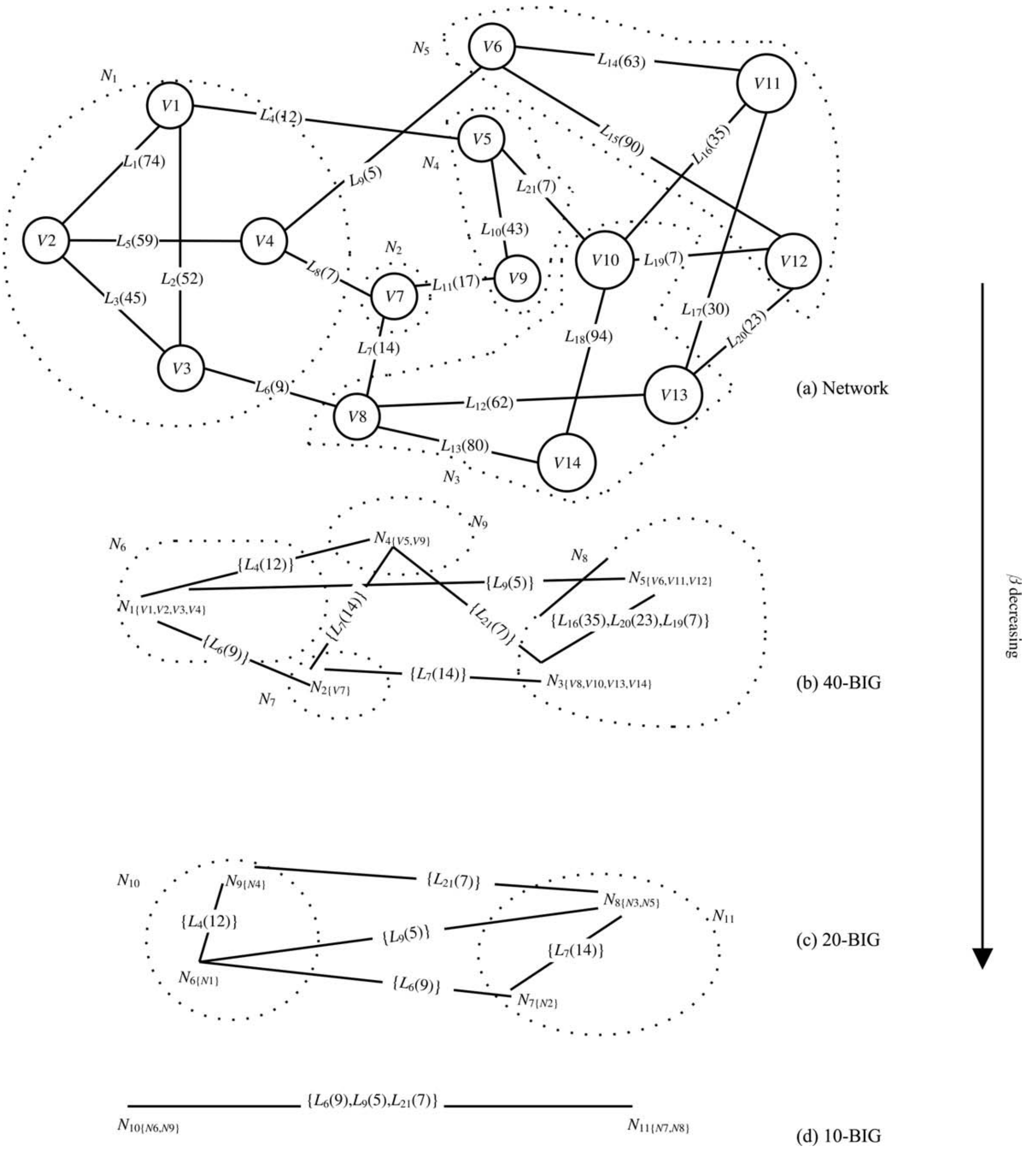

Fig. 7. The blocking island hierarchy for bandwidth requirement {40, 20, 10}. (a) Network graph, (b) 40-BIG, (c) 20-BIG, (d) 10-BIG.

1. Compute *n* different routes according to the shortest path heuristic (*K*-alternate shortest paths).
2. Order them according to the minimal splitting criterion.
3. If the routes have the same minimal splitting number, we use some other heuristics (such as the most loaded link heuristic) or select randomly.

By employing the minimal splitting heuristic, we also inherently balance the workload amongst each wavelength and each node; therefore, we implicitly reserve the largest possible resources for future requests. The most frequent operation in the process is to construct a BIG according to a certain β. It is obtained with a simple greedy algorithm. Starting with an arbitrary node x, we add all the nodes which can be reached by links with at least β available bandwidth to form a β-BI. Then start with another arbitrary node that is not in the previous β-BIs. Repeat the process until all the nodes in the network are included in one of β-BIs. The complexity of constructing BIG is $O(m)$ [6], where m is the number of links in the network.

In the next section, we show how to transfer the original network topology into a multi-segment BIG. Based on the multi-segment BIG network model, we propose a new multi-segment RWA algorithm.

4 Multi-Segment Big Model and the Proposed Algorithm

In this section, we present the BIG network model that represents a multi-segment optical network. Based on the BIG network model, we propose a simple and effective routing and wavelength assignment algorithm.

We consider a multi-segment optical mesh network interconnected by gateways. There are no wavelength converters, and the gateways have the full adaptation capacity. Define a network topology $G = (G^1, G^2, \dots, G^k, T, \mathrm{TE})$ for a given multi-segment optical network, where G^i is one segment of the network, T is the set of gateways and TE is the set of links directly connected to gateways. For any segment $G^i = (N^i, A^i, W^i)$, where N^i is the set of nodes in the segment, A^i is the set of links in the segment, W^i is the number of wavelengths in the segment i.

Assume the network is initially free of traffic and each connection request needs to be allocated over a route and assigned one wavelength subject to wavelength availability and continuous constraint. We have two abstraction phases. The first abstraction phase is to abstract the segment into one node. The gateway nodes and the links directly connected to the gateways are kept in the abstraction graph which is called BIG Layer 1. The bandwidth of the links is equal to the number of wavelengths of the connected segments. So the BIG layer 1 model G1 can be obtained from a given network topology G as follows: $G1 = (N1, A1)$, where $N1 = \{G^1, G^2, \dots, G^k\} \cup T, A1 = \mathrm{TE}$.

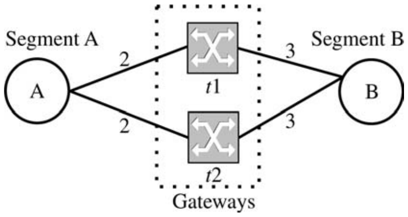

Fig. 8. The BIG layer 1 model of network graph shown in Fig. 1.

If the physical network representation is shown in Fig. 1, the BIG Layer 1 model of this network graph is given in Fig. 8. The bandwidth of link A-$t1$ is 2 and 2 is the number of wavelengths in segment A. The bandwidth of link B-$t1$ is 3 and 3 is the number of wavelengths in segment B.

In the second phase of the BI abstraction, each segment G^i is abstracted into a BIG with $|W^i|$ BIs. Each BI represents a wavelength and has the same topology as the original segment. The gateways connected to segment G^i are also replicated $|W^i|$ times and assigned one to each BI. Since the gateways have full adaptation capacity, we introduce a supernode for each gateway. All the replications of one gateway are directly connected to the corresponding supernode of the same gateway. We show an example in Fig. 9 which is the second phase of the abstraction for Fig. 1. Notice the bandwidth of each link is 1. This abstraction model is called BIG layer 2.

It is obvious that this BIG network model is a simplified BIG. All the properties such as unicity, partition and route existence still hold. Initially, we simply treat the whole BIG layer 2 as one BI with the bandwidth of each link as 1. The problem of setting up a end-to-end lightpath in the original network is transferred to a simple routing problem in the BIG model.

The second phase of the BIG abstraction is quite complicated. By using the BIG Layer 1, we can greatly simplify the BIG Layer 2. The main idea is that we first route the source segment and the destination segment in BIG Layer 1. Then, based on the route in BIG Layer 1, we construct the BIG layer 2 model. For example, assume we have found a route in figure: A → $t1$ → B, the BIG Layer 2 model will then be constructed as in Fig. 10 instead of Fig. 9. We then do the routing and wavelength assignment in Fig. 10.

A formal description of the algorithm is given below. We assume traffic is dynamic and our goal is to

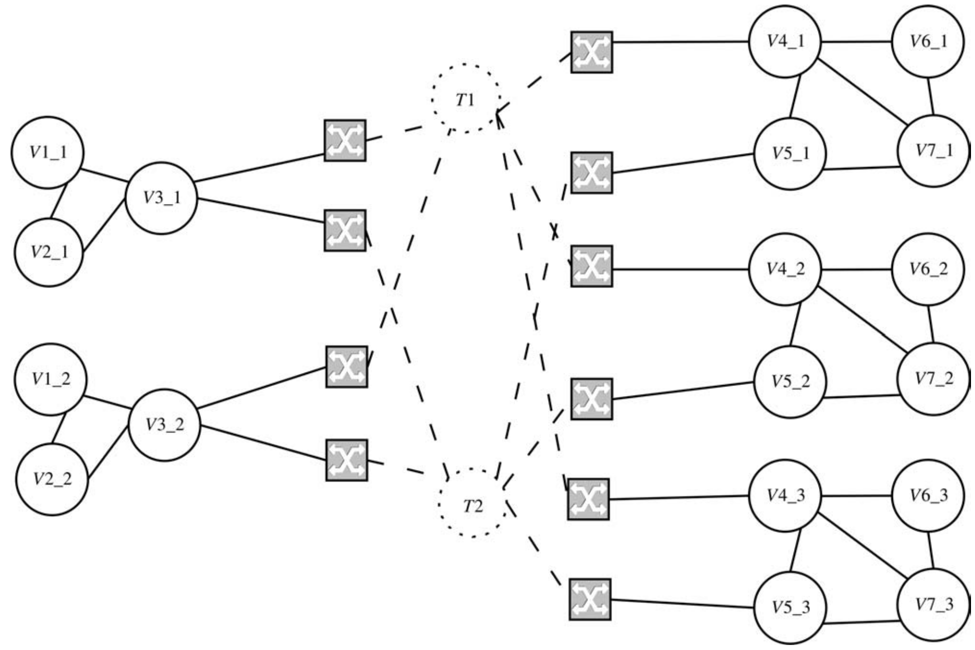

Fig. 9. The BIG layer 2 model of network graph shown in Fig. 1. $t1$ and $t2$ are supernodes.

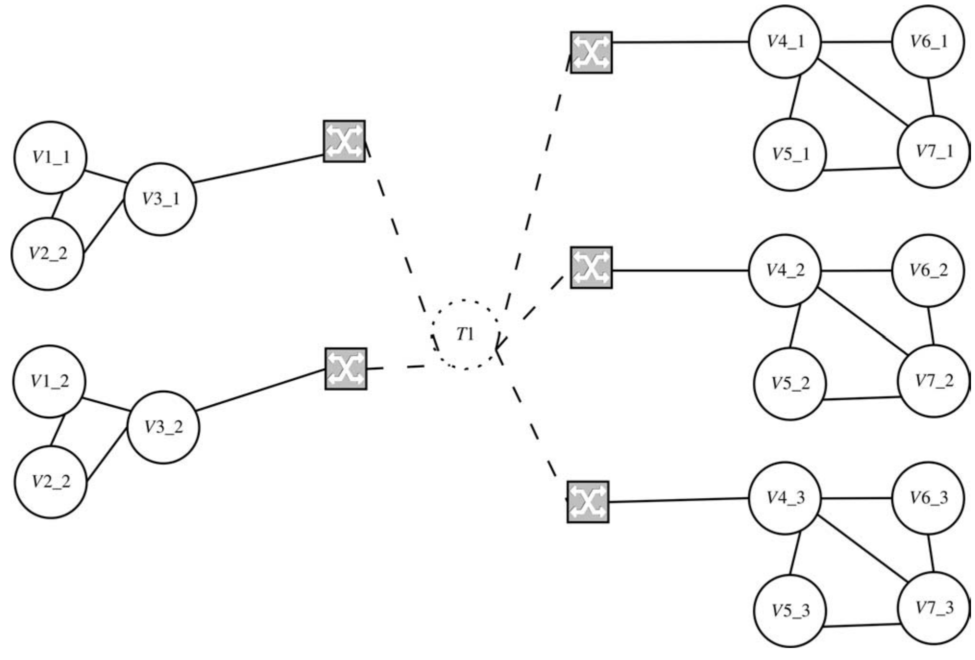

Fig. 10. The BIG layer 2 model of network graph shown in Fig. 1 after a route is identified in BIG layer 1. In this example, a route A → $t1$ → B is found in figure.

minimize the blocking probability. Our algorithm is divided into two parts: Phases 1 and 2.

Phase 1: Segment and gateway location
In Phase 1, we try to find the segments and gateways that constitute the final route.

Input: The network topology and a request $r = (s, d)$, s is the source node and d is the destination node.

1. Transform the network topology into a BIG Layer 1 model;
2. Notice the bandwidth of the links in this model is given by the number of wavelengths in the connected segments. We then build the BIH according to the decreasing order of the number of wavelengths of all the segments;
3. A connection request $r = (s, d)$ arrives. Notice the bandwidth requirement is always 1. We transform the node-to-node connection request into a segment connection request $r1 = (s1, d1)$, $s1$ and $d1$ are segment nodes in BIG Layer 1 model, which contain node s and d, respectively.
4. Use the blocking island minimum splitting heuristic to find the appropriate route. If there are several routes with the same MS number, find the shortest path.

In phase 1, we locate a route consisting of segment nodes and gateways. The route can be defined as $G^1T_1G^2T_2\ldots T_mG^{m+1}$, where $s \in G^1$ and $d \in G^{m+1}$. We separate the route form the original network and carry out Phase 2 computation.

Phase 2: Routing and wavelength assignment
Input: The segment and gateway route: $G^1T_1G^2T_2\ldots T_mG^{m+1}$;

1. Transform the segment and gateway route into the BIG Layer 2 model. Since the bandwidth of each link in the model is 1, we don't need the hierarchy construction.
2. Divide the segment and gateway route: $G^1T_1G^2T_2\ldots T_mG^{m+1}$ into $m+1$ sub-requests $\{(s, T_1), (T_1, T_2)\ldots(T_m, d)\}$.
3. Apply the dynamic BI_RWA algorithm proposed in Zhemin and Hamdi [8] to simultaneously route $m+1$ requests in the BIG Layer 2 model. If any sub-request cannot be satisfied, the original request is blocked.
4. Add up all the routes (with the wavelength) obtained in step 3 to get the end-to-end lightpath.

By employing the two-layer BIG model, we need less storage of routing information. The algorithm for the dynamic RWA case is not computationally intensive. Define a network topology $G(V, L, W)$ for a given WDM optical network, where V is the set of nodes, L is the set of links and W is the set of wavelengths per fiber link. Assume the set of wavelengths on each fiber link is the same. The most common operation in the dynamic RWA is the BI construction. The *β-BI* for a given node x of a network can be obtained with a simple greedy algorithm. Starting with an initial set $\{x\}$, we recursively add every node to the set, if this node can be reached from any node in the set by a link that has at least β available bandwidth. In the worst case, this construction process will examine all links. Therefore, the β-BI construction process is linear in $O(n)$, where n is the number of links in the network ($n = |L|$). If the request cannot be satisfied, it will be checked out immediately by using the route existence property. The computation time, in this case, is only the time of reconstructing the BIG, which is $O(|W|mn)$, where m is the number of nodes and n is the number of links in the network ($m = |V|, n = |L|$). $|W|$ is the number of wavelengths in the network. If the request can be satisfied, the running time is equal to the combination of (1) reconstruction time; (2) K alternate shortest paths; (3) route and wavelength selection; and (4) assign route and wavelength and reconstruction time. That is $O(|W|mn) + K|W| * O(nlg(m)) + K * O(|W|mn) + O(|W|mn)$, where K is a constant and $|W|$ is a constant.

For BIH maintenance, if the route is allocated, all the modification is only carried out within the specific BI. That means we don't need to compute the whole BIH again.

5 Simulation Results

In this section, we present the simulation results of blocking probability for multi-segment optical networks. The performance of the proposed algorithm is evaluated on a 3-segment interconnected network shown in Fig. 11, which has 14 nodes, 28 links and seven gateways. We employ a random dynamic traffic

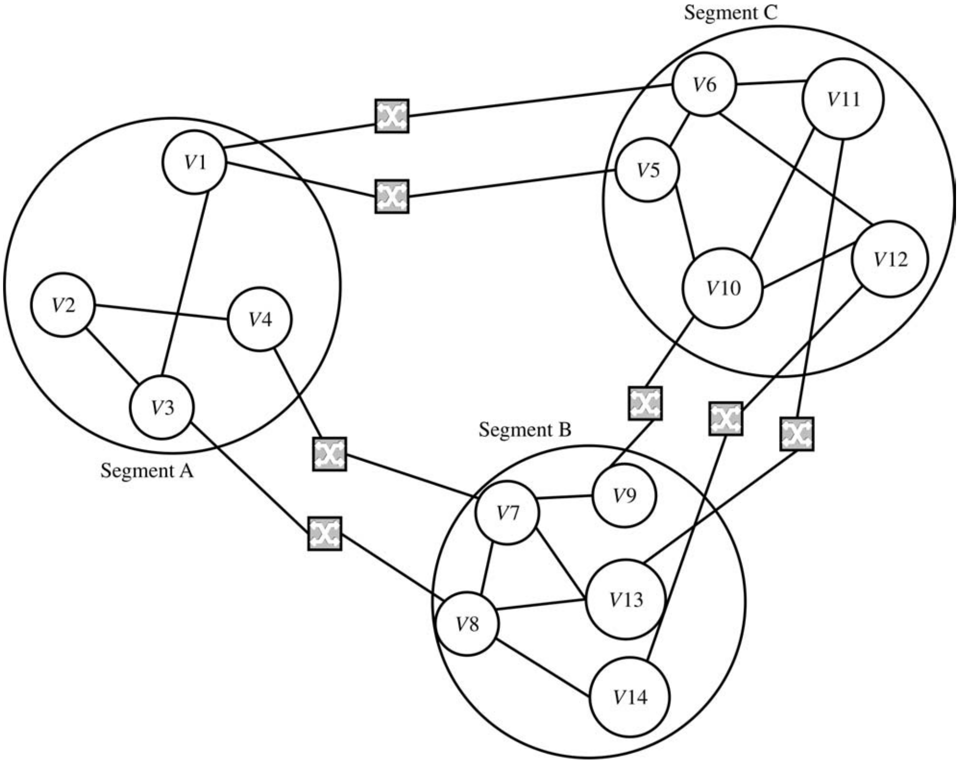

Fig. 11. The 3-segment interconnected optical network topology with 14 nodes, 28 links and seven gateways.

model to generate the incoming traffic. Calls (requests) arrive at each node according to an independent Poisson process with an arrival rate α. An arriving session is equally likely to be delivered to any node in the network. The session holding time is exponentially distributed with mean $1/\mu$. Thus the load per *s-d* node pair is $\rho = \alpha/N(N-1)\mu$, where N is the number of nodes in the network. Note that a node may engage in multiple sessions and several sessions may be simultaneously conducted between an *s-d* (source and destination) node. In our simulation, extensive tests are carried out to ensure a steady state is reached. Since an arriving request is equally likely to be delivered to any node in the network, the incoming traffic is mixed with local traffic as well as global traffic.

The other heuristics used in the simulation are proposed in Zhu et al. [5]: End-to-end shortest path (E2E), concatenated shortest path (CSR) and hierarchical routing (HIR). E2E treats all the segments in the network as one part and simply runs Dijikstra's shortest path algorithm on it to find the shortest route between the source node and the destination node. CSR routes the request segment by segment. When a request arrives, from the source segment, each segment independently decides the route. HIR employs a two-layered representation. The first layer contains all nodes and intra-segment edges. In the second layer, each single node represents a segment and only inter-segment edges are kept. The shortest path is computed in two layers. First, compute the shortest path on the second layer to find the segments (notice in this model, gateway nodes are treated the same way as the network nodes. They are included in the segment) along the end-to-end lightpath. Second, compute the shortest path in the segments which have been located in the first computation. In all three heuristics, after identifying the route, wavelengths are then assigned to the route subject to the availability and continuous constraint.

The gateway selection is a necessary process in HIR and CSR. In our case, we tested all three gateway

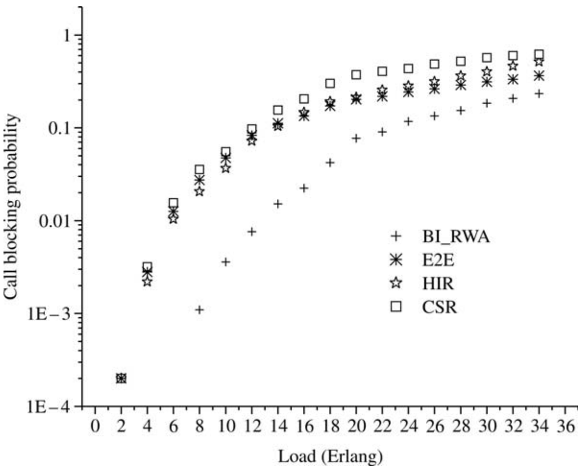

Fig. 12. Blocking probability of different RWA algorithms with network topology shown in Fig. 11. The number of wavelength in all segments is 4.

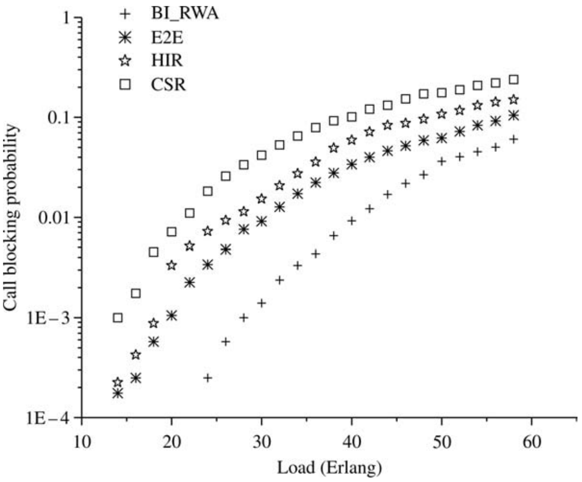

Fig. 13. Blocking probability of different RWA algorithms with network topology shown in Fig. 11. The number of wavelength in segment A is 8, in segment B is 12, and in segment C is 16.

selection rules with HIR and CSR [5]: random selection, shortest path selection and least utilized selection. We find the blocking probability performance is almost the same. For simplicity, only random selection rule is employed for comparison in the simulation.

In the first set of experiments, the number of wavelengths in all segments is four. Fig. 12 shows the performance comparison of different RWA algorithms, namely, BI_RWA, E2E, CSR and HIR on the network topology shown in Fig. 11. We can see the blocking probability increases as load increases, as expected. We also observe the heuristics used by the requests considerably affects the blocking probability experienced by the requests. Specially, for a given traffic load, the results show that the BI_RWA has the best performance, followed by E2E, HIR and CSR. BI_RWA has a much lower blocking probability under the same load than the other three heuristics while the performances of the other three heuristics are close. This is because in our algorithm, the wavelength assignment and gateway selection is integrated into the routing algorithm. This solution has the advantage of being sound and complete. By using the BI paradigm, we can better manage the available resource and handle the future requests. Among E2E, HIR and CSR, the performance of E2E is the best. The routing path in the E2E heuristic is globally optimized. But comparing to our algorithm it does not take into account the segment specific resource availability and traffic loads. Besides, each node has to acquire the global knowledge of other nodes in order to find the shortest path. It makes this heuristic less scalable. HIR is similar to our algorithm in terms of representing the network by means of two or more layers. But it only computes shortest paths in two layers. Although CSR is the most scalable heuristic, it performs worst in our simulation. CSR makes routing and wavelength assignment decisions only based on the segment knowledge. A request may be blocked even though there are enough resources.

In the second set of experiments, the number of wavelengths per link in each segment is different. There are eight wavelengths per link in segment A, 12 wavelengths per link in segment B, and 16 wavelengths per link in segment C. Fig. 13 shows the performance of all heuristics is improved by using more wavelengths. Note the performance of BI_RWA is still the best. The experiment is also run on some other network topologies, which lead to similar results.

To consider a case with more diversified bandwidth allocation between the links, in Fig. 14, we run simulation with four wavelengths per link in segment A, 12 wavelengths per link in segment B, and 24 wavelengths per link in segment C. The results prove the effectiveness of our algorithm.

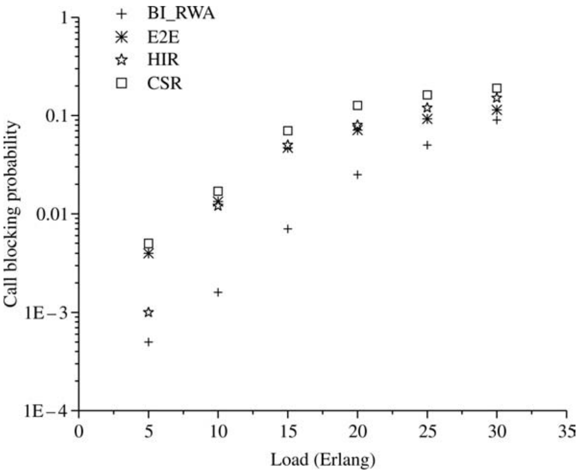

Fig. 14. Blocking probability of different RWA algorithms with network topology shown in Fig. 11. The number of wavelength in segment A is 4, in segment B is 12, and in segment C is 24.

6 Conclusions

The primary contribution of this paper is the development of a general routing and wavelength assignment algorithm for multi-segment optical networks. We discuss the differences between the multi-segment RWA problem and the conventional RWA problem. By using the concept of BI, a new routing heuristic called MS is proposed and a multi-segment BIG network model is defined. Based on the multi-segment BIG model, we propose a simple and flexible 2-phase BI RWA algorithm. After comparing the performance of blocking probability with other state-of-the-art algorithms, namely CSR, E2E and HIR, we demonstrated that our algorithm performs the best.

The main advantage of our algorithm is that it uses a combined view of the multi-segment network to do the routing, wavelength assignment and gateway selection in a single routing domain. In other words, the multi-segment BIG network model inherently integrates the routing, wavelength assignment and gateway selection problems into one routing problem. By using the MS heuristic, we balance the workload among each segment and reserve the largest possible resource for future requests.

Notice in the algorithm, we always assume the gateways to have full adaptation and wavelength conversion capacity. In practice, the gateways can be non-wavelength shifting, fully or selectively wavelength shifting. With the integration of IP layer and WDM layer, a request may only need a fraction of the bandwidth of a full wavelength, which may bring a new capacity to the gateways: wavelength merging (the function where the wavelengths can be merged in a new wavelength). In future work, we expect to extend our algorithm to include those properties and study the impact on the network performance.

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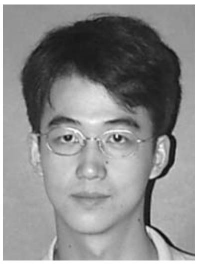

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