A Simple and Intelligent Routing and Wavelength Assignment Algorithm for All-Optical Networks

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Abstract

In this paper we consider the routing and wavelength assignment problem in a wavelength routed all optical network. Inspired by techniques from artificial intelligence, in particular the *Blocking Island* (BI) abstraction, we propose a simple and intelligent routing and wavelength assignment (RWA) algorithm: BI_RWA. This algorithm can be used in arbitrarily connected optical networks. In addition, it is general enough such that with some simple modifications, it can be applied to different optical networking scenarios: static or dynamic traffic, single or multiple fiber links between node pairs, with or without wavelength converters. We have conducted simulation experiments to evaluate the performance of our algorithm. The simulation is carried out in two parts: static traffic and dynamic traffic. The results will demonstrate that our RWA algorithm outperforms state-of-the-art related algorithms.

1. Introduction

With the rapid growth of bandwidth demand in today's Internet, more and more people believe that optical WDM (Wavelength Division Multiplexing) is the most promising solution for setting up next generation networks. An optical link has a huge bandwidth capacity: a single mode fiber's potential bandwidth can reach up to 50Tb/s using WDM [1]. In WDM transmission, each data channel is carried on a unique wavelength (or optical frequency) and a single optical fiber has many different wavelengths. WDM technology is being extensively deployed in transport networks while with the development of optical cross-connects, high-speed, end to end connections called lightpaths can be routed from sources to destinations, simplifying network management and processing. Networks which use optical cross-connects to route lightpaths through

the network are referred to as wavelength routed networks. In a wavelength routed WDM network, a lightpath (e.g., wavelength continuous path without processing in the intermediate nodes) is established between two communication nodes. A lightpath may span multiple fiber links and must occupy the same wavelength on all the fiber links it traverses if there is no wavelength converter. This property is known as *the wavelength continuity constraint*. In order to satisfy a lightpath request in a wavelength routed WDM network, we not only need to consider routing but the wavelength selection as well. 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 RWA problem. It can be formulated as a combinatorial problem which is known to be NP-complete [2]. A lot of heuristic algorithms have been proposed and evaluated under different assumptions. The traffic assumptions generally fall into one of two categories: 1) static traffic, where all the connection requests are already known; 2) dynamic traffic, where connection requests arrive in a dynamic manner and lightpaths are setup on demand. Most previous work focuses on single-fiber networks where each node pair is connected by a single fiber link while recently more and more research is carried out on multiple-fiber networks. The benefit of adding wavelength converters has also been studied. For a recent survey on the RWA problem, please refer to [3] [4].

In this paper, we address the RWA problem using techniques from AI (Artificial Intelligence). Specifically we borrow the idea from the BI (Blocking Island) abstraction technique to solve the RWA problem. BI is proposed in [5] to solve the RAIN (Resource Allocation in Networks) problem. It is an abstraction technique of available resources in a network. It can efficiently plan the allocation of network resources to connection requests and provides a novel way of identifying the bottlenecks in a network. Our proposed BI_RWA algorithm is very flexible and robust, which can be used to solve the RWA problem under different networking scenarios. In the simulation, we will demonstrate that our results compare favorably to other heuristic algorithms.

The paper is organized as follows: in section 2, we introduce the basic idea of BI. In section 3 we apply the BI to solve the RWA problem and a RWA algorithm is proposed. In section 4 we extend the BI_RWA algorithm to solve the RWA problem under different assumptions: static or dynamic traffic, single or multiple fiber links between node pairs, with or without wavelength converters. Simulation results are presented in section 5. Section 6 is the conclusion.

2. Background

Developed from Artificial Intelligence techniques, namely constraint satisfaction and abstraction and the theory of phase transition, the BI (blocking island) provides an efficient way of abstracting resources (especially bandwidth) available in a communication network.

The central problem in the communication field is the RAIN problem. [5] proposes a framework of using BI to solve the RAIN problem. Before discussing the BI technique, we first define the RAIN problem.

Given a network composed of nodes and bi-directional links, where each link has a given resource capacity and a set of communication demands to allocate, where each demand is defined by a source and destination node and a set of QoS requirements. The goal is to find one and only one route for each demand so that the QoS requirements of the demands are simultaneously satisfied.

We assume all demands are unicast and the only QoS parameter taken into account is bandwidth. The network physical topology consists of V nodes arbitrarily connected by L bi-directional links. We model it as a network graph $G = (V, L)$. Fig. 1 depicts such a network graph.

Fig. 1: An example network topology (NSFNet) where the available bandwidth on a link is given in brackets.

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. A set of requests is noted by D that can be represented by a matrix or a table (Table 1).

Request	x_u	y_u	β_u
1	V1	V4	40
2	V8	V11	20
3	V5	V12	10

Table 1. An example set of requests D .

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 $V1$.

Fig. 2. A network topology (NSFNet). $N_1 = \{V1, V2, V3, V4\}$ is the 40-blocking island (40-BI) for node $V1$.

β -BI has some very useful properties. Below we list a few without proof (for a proof, please see [5]).

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 the node y_u are in the same β_u -BI.

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

Using the concept of β -BI, we can construct a recursive decomposition of Blocking Island Graphs (BIG) in decreasing order of β s, e.g., $\beta_1 > \beta_2 > \dots > \beta_n$. We call this layered structure of Blocking Island Graphs a Blocking Island Hierarchy (BIH). For example according to the demand table (Table 1) and the network topology (Fig. 1), we can have such a BIH (Fig. 3).

Given a request, using the *routing existence* property, we immediately know whether the request can be satisfied or not. With the abstraction technique, instead of studying the whole network topology, we focus our attention only on a small part. For example, given a demand (V1, V4, 40), according to the BIH, it is in 40-BI N_1 . In the N_1 Blocking Island, different routing heuristics can be employed. If the route is allocated, the BIH may need to be modified. In this case route V1V2V4 is assigned. The available link capacity is less than 40 so we should reconstruct the BIH. Notice although lower levels may be affected, all the modification is actually carried out within the N_1 Blocking Island.

The most frequent operation in this 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 starting with another arbitrary node that is not in the previous β -Bs, we repeat the process until all the nodes in the network are included in one of the β -BIs. The complexity of constructing a BIG is $O(m)$ [5], where m is the number of links in the network.

BI is a natural abstraction of network resources. A β -BIG allows us to get a clear picture about the traffic loads as nodes and links with enough resources are hidden behind

an abstract node. In particular, bottlenecks are identified by the interlinks between the Blocking Islands.

Fig. 3. The blocking island hierarchy for bandwidth requirement $\{40, 20, 10\}$. (a) the network graph (b) the 40-BIG (c) the 20-BIG (d) 10-BIG

3. BI_RWA

In this section, we propose a new routing and wavelength assignment algorithm using BI. The proposed algorithm can be applied to any optical network with an arbitrary topology. In addition, it can be applied under different networking scenarios.

3.1 Problem Formulation and BIG Network Model

A RWA problem can be formulated as follow: given a set of connection requests and given a constraint on the number of wavelengths, we need to determine the routes and assign the wavelengths so that a maximum number requests are accepted (or minimize the number of required wavelengths or minimize the request blocking probability). Usually a RWA algorithm is divided into two parts: the routing algorithm and the wavelength assignment algorithm. In our algorithm the wavelength assignment is integrated into the routing algorithm. This solution has the advantage of being sound and complete compared to previous solutions.

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 bidirectional links and W is the set of wavelengths per fiber link. Assume this is a single fiber network without wavelength converters. The set of wavelengths on each fiber link is the same. Each connection request needs to be allocated over a route and assigned one wavelength. The network can be abstracted into a blocking island graph (BIG) with $|W|$ blocking islands. Each blocking island represents a wavelength and has the same topology as the original WDM optical network. The BIG network model $BIG(m_1, m_2, \dots, m_{|W|})$ can be obtained from a given network topology G as follows. The topology of G is replicated $|W|$ times denoted by $m_1, m_2, \dots, m_{|W|}$. Each blocking island m_i represents a wavelength and the link capacity is 1. An example is shown in Fig. 4.

It is obvious that this BIG network model is a simplified blocking island graph. All the properties such as Unicity, Partition and Route Existence still hold. For example, when there is a lightpath (r, λ) where r is the route and λ is the selected wavelength, the *route existence* property can be interpreted as whether the route r exists in blocking island λ or not. For a connection request, instead of routing and assigning wavelengths, we try to find a “best” route in different blocking islands.

Fig. 4. (a) A network topology G with 3 wavelengths on each fiber link (b) The corresponding blocking island graph (BIG) with 3 blocking islands, where all links have a capacity of 1.

3.2 The Proposed Algorithm

The RWA problem can be solved based on the BIG model. A formal description of the proposed algorithm is given below. We first assume the traffic is static. So we know all the connection requests at the beginning. Our goal is to maximize the number of accepted requests given a fixed number of wavelengths per fiber link.

- Step 1:** Transform the network topology into a BIG network model.
- Step 2:** Order all the connection requests in decreasing length of their MNH (Minimum Number of Hops) distance (MNH distance is calculated using any shortest path algorithm, e.g., Dijkstra). Paths with equal lengths are ordered randomly.
- Step 3:** Select an unallocated request d , $D = D - \{d\}$, if the request set D is empty then go to step 8.
- Step 4:** Use the Route Existence property to check if all the requests in D can be satisfied individually. If it can, assign the request d to every blocking island and calculate K alternate shortest paths. If can't, go to step 8.
- Step 5: (Route and Wavelength selection.)**
- 1) Now we have a set of candidate routes in different blocking islands. Compute the splitting numbers if the corresponding route is selected and removed from the blocking islands. Find the route(s) with the minimum splitting numbers.
 - 2) If there are several routes, pick up one with the shortest MNH distance.
 - 3) If there are still a few routes, choose one whose congestion of the most loaded link is lower than the congestion of the most loaded link in other routes. Then if there is more than one route left, randomly select one.
- Step 6:** Allocate the route in corresponding blocking island. Reconstruct the blocking island graph (BIG).
- Step 7:** Add the route to the result set R , go to step 3.
- Step 8:** If the request set is empty, output the result set. Otherwise, output "Requests can't be satisfied."

In step 4, "all the requests in D can be satisfied individually" means we sequentially pick up requests from D , and test it on the current BIG. The topology of the current BIG is not changed.

In order to get the optimal result, a *Backtracking Scheme* is added to the algorithm as long as time is allowed. In step 4, if not all the requests can be satisfied individually, instead of going to step 8, we backtrack to a previous request and try an alternate route. We repeat the process until we succeed or all the alternate routes of previous requests are tried. In step 4, the Route Existence property checks whether the current available

resource can satisfy any single request in D . Using the backtracking process, it provides an early warning of selecting the wrong route and wavelength.

In step 5, several heuristics are employed to get the “best” route and wavelength. The first heuristic tries to keep the integrity of the blocking islands. It is equivalent to keeping the connectivity of each node pairs since the link capacity is 1. The second heuristic is to reduce the resource consumption by picking up the shortest path. The third heuristic balances the network load by adjusting the most loaded links (most number of wavelengths in the link has been used). We find that the combination of the three heuristics in this order gives the best performance in our simulation.

If we don’t take into account the backtracking scheme, the computation complexity of the algorithm is dominated by the shortest path algorithm and the BIG construction algorithm.

4. Extensions of BI_RWA

In section III, we assume a single fiber wavelength routed optical network without wavelength converters and the traffic is static. In this section, we show how to relax those constraints using our BI_RWA algorithm.

4.1 Dynamic Traffic

If the connection requests arrive dynamically, we need to do a few modifications to the original algorithm. For example, we can’t order the requests and the backtracking scheme is impossible.

Step 1: Transform the network topology BIG network model.

Step 2: A connection request d arrives. Based on the arriving time of the request, reconstruct the BIG.

Step 3: Check the request d using the Route Existence property in each blocking island. If it exists in some blocking island, calculate k alternate shortest paths; if it doesn’t exist in any blocking island, it is blocked.

Step 4: Route and wavelength selection. (The same as the static case)

Step 5: Allocate the request and go to step 2.

Because of the dynamic traffic and the different holding times of each session, we need to update the BIG every time a new request arrives in Step 2.

4.2 Wavelength Converters

In simple WDM networks, a connection must be established along a route using a common wavelength on all of the links along the route. This constraint may be removed by the introduction of wavelength converters, which are devices that take the data modulated on an input wavelength, and transfer it to a different output wavelength. Obviously, wavelength converters improve network blocking performance. However the introduction of wavelength converters also increases the hardware cost and complexity and it has been shown that wavelength converters offer only modest performance improvements in many networks [12].

There are two cases of wavelength conversion: 1) Full conversion. Any wavelength can be converted into any other wavelength and such wavelength converters exist in every node. This means there is no wavelength assignment problem. We treat the network as one blocking island with the link capacity equal to the number of wavelengths. 2) Limited number of converters and limited range of conversion. This means only part of the network nodes has wavelength converters and those wavelength converters may only have limited range of conversion. We simply replace the original BIG with the modified BIG as the initial input Graph in this case. For example, in Fig. 4, if we have a converter on node A that can convert wavelengths between 1 and 3 and a converter on node C that can convert wavelengths between 2 and 3, a converter on node B that can convert wavelengths among 1, 2, 3. The modified BIG network model is illustrated in Fig. 5.

Fig. 5. The BIG network with converters.

Five converter links A1A3, B1B2, B2B3, B1B3 and C2C3 are added into the original BIG. Here we assume the converter is used exclusively. That means when there is one route using the converter converting wavelength from a to b , any other route can't use it converting wavelength from b to a at the same time. So the converter links are bi-directional and the capacity is 1. Notice in calculating the shortest path, the weight of the converter links is 0.

4.3 Networks with Multiple-fiber links

Most of the previous work on RWA problem focuses on single fiber networks. There has been a recent interest in deploying multiple fiber links between node pairs. A multifiber network is an attractive alternative to a network with wavelength conversion capability. An M -fiber W -wavelength network is functionally equivalent to an MW -wavelength network with partial wavelength conversion of degree M [6]. Because of the expensive cost of wavelength converters, multifiber networks may become a viable and economic alternative solution.

Previous research work assumes the same number of fiber links between each node pairs. In our algorithm, we can easily relax this assumption. Again, we simply replace the original BIG with the modified BIG as the initial input Graph. For example, if there are 5 fiber links between AF, AD and BC and there are 3 fiber links between DC, DG, DE and FE. The modified BIG network model is illustrated in Fig. 6. Each fiber link has 3 wavelengths.

Fig. 6. The BIG network with multiple fibers.

We modify the link capacity between each node pairs. The link capacity is equal to the number of fiber links. The rest of the algorithm can still apply to the new topology.

5. Numerical Results

We evaluate the performance of the proposed BI_RWA algorithm on two types of connection requests: static and dynamic.

5.1 Static Traffic

For static traffic, one of the most important goals is to minimize the number of wavelengths needed to accommodate the requests. The goal is equivalent to maximizing the number of accepted demands given a fixed number of wavelengths. The proposed BI_RWA algorithm is applied to several existing or planned network topologies to verify its efficiency. The networks considered are the ARPANet [8], NSFNet [9], the European Optical Network (EON) proposed in [10] and a hypothetical UK topology reflecting the current BT-networks [11]. Noted those topologies are also evaluated in [7] and results in [7] are near optimal.

Given a fixed number of wavelengths, the BI_RWA algorithm tries to accommodate as many requests as possible. So we can't use it directly to calculate the required number of wavelengths. In the last few years, theoretical lower and upper bounds on the required number of wavelengths have been established. We select a higher limit and, if a solution is found, then try the lower limit progressively.

In our simulation, we assume the incoming connection requests are uniform. There is a single-fiber WDM optical network without wavelength converters. Table 2 gives the simulation result.

Network	N	L	W_{LL}	[7]	BI_RWA
ARPANet	20	31	33	34	34
UKNet	21	39	19	22	20
EON	20	39	18	18	18
NSFNet	14	21	13	13	13

Table 2. The simulation result. N is the number of nodes in the network. L is the number of links in the network. W_{LL} represents the lower limit on the number of wavelength. [7] is the result of our implementation of the algorithm in [7].

As to ARPANet, although in [7], it claims to get the optimal result of 33 (we simulated the same algorithm in [7] and we were not able to get this result. We asked the author about his result, but he declined to answer), we could only get 34 in our implementation. BI_RWA outperforms [7] on the UKNet topology. The two algorithms both get the optimal result on the other network topologies. We expect the BI_RWA algorithm to outperform [7] in more complicated topologies. In addition, the algorithm in [7] can only be applied to static traffic. In other words, it is not as flexible as our proposed algorithm. The running time of our BI_RWA is fairly fast. It takes at most 15 minutes (using a PIII450, 128M memory PC) to solve those problems. However, for the static traffic condition, time usually is not a big concern. In some cases, if necessary, we may give a time constraint to BI_RWA algorithm and try to get the best result in this period.

5.2 Dynamic Traffic

We use the same Dynamic Traffic Generator model employed in [6]. Calls (requests) arrive at each node according to an independent Poisson process with arrival rate β . 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 $\rho = \beta/N(N-1)\mu$, 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 node pair. In our simulation, extensive tests are carried out to ensure a steady state is reached.

We evaluate the performance of the proposed Dynamic BI_RWA algorithm on NSFNet shown in Fig.1, which has 14 nodes and 21 links. The heuristic Dynamic RAW algorithms used in the simulation are fixed routing with first-fit wavelength assignment (FR/FF); fixed routing with most used/pack wavelength assignment (FR/MU); alternate routing with most used/pack wavelength assignment (AR/MU); alternate routing with random wavelength assignment (AR/RAN).

In our simulation, we assume there is a single-fiber WDM optical network without wavelength converters.

Fig. 7 and Fig. 8 compare the call blocking probabilities for BI_RWA, FR/FF, FR/MU, AR/MU, AR/RAN using the NSFNet network. In the alternate routing algorithm, all the shortest paths are calculated for each node pair. In Fig.7, the number of wavelengths on each link is 4. In Fig.8, the number of wavelengths on each link is 8. Results show that in

all cases, the BI_RWA has the best performance, followed by AR/MU, AR/RAN, FR/MU and FR/FF. For example, in the case $|w| = 4$, at a blocking probability of 0.01, the network throughput can be increased by 50% over FR/FF, FR/MU and by nearly 40% over AR/MU and AR/RAN. In the case $|W| = 8$ and the total load $\beta/\mu = 38$ Erlang, the blocking probability for BI_RWA is only 4.85×10^{-2} , compared to 1.18×10^{-1} for FR/FF, 1.15×10^{-1} for FR/MU, 9.175×10^{-2} for AR/MU, and 9.9×10^{-2} for AR/RAN.

Fig. 7. Blocking probabilities for the NSFNet with four wavelengths.

Fig. 8. Blocking probabilities for the NSFNet with eight wavelengths.

6. Conclusion

In this paper, inspired by some artificial intelligence abstraction concepts, we have proposed a new RWA algorithm called Blocking Island RWA (BI_RWA), which is simple, flexible, intelligent and robust. We have shown that this algorithm can be applied to any network with any topology. In addition, with a few modifications, this algorithm can also be used under different networking parameters, namely static or dynamic traffic, single or multiple fiber links between node pairs, with or without wavelength converters. Simulation results have demonstrated that our algorithm outperforms state-of-the-art algorithms in this area using both static and dynamic traffic.

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