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A novel load-balanced fixed routing (LBFR) algorithm for wavelength routed optical networks

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ABSTRACT

In the wavelength-routed optical transport networks, fixed shortest path routing is one of major lightpath service provisioning strategies, which shows simplicity in network control and operation. Specifically, once a shortest route is found for a node pair, the route is always used for any future lightpath service provisioning, which therefore does not require network control and management system to maintain any active network-wide link state database. On the other hand, the fixed shortest path routing strategy suffers from the disadvantage of unbalanced network traffic load distribution and network congestion because it keeps on employing the same fixed shortest route between each pair of nodes. To avoid the network congestion and meanwhile retain the operational simplicity, in this study we develop a Load-Balanced Fixed Routing (LBFR) algorithm. Through a training process based on a forecasted network traffic load matrix, the proposed algorithm finds a fixed (or few) route(s) for each node pair and employs the fixed route(s) for lightpath service provisioning. Different from the fixed shortest path routes between node pairs, these routes can well balance traffic load within the network when they are used for lightpath service provisioning. Compared to the traditional fixed shortest path routing algorithm, the LBFR algorithm can achieve much better lightpath blocking performance according to our simulation and analytical studies. Moreover, the performance improvement is more significant with the increase of network nodal degree.

Keywords: Wavelength routed optical networks, wavelength assignment, fixed routing, load-balanced fixed routing

1. INTRODUCTION

With the rapid growth of Internet traffic, the technology of Wavelength Division Multiplexing (WDM) is widely employed to construct large-scale optical transport networks interconnecting a large number of optical switch nodes. In a WDM network, end nodes communicate with each other via lightpaths, which are found by an appropriate routing strategy. Various lightpath routing algorithms were proposed for the wavelength-routed optical networks in the literature. These algorithms include the simplest ones such as Dijkstra's fixed shortest path routing algorithm [1-5] and more efficient ones such as alternate and adaptive lightpath routing algorithms [6-11]. Interested readers may refer to paper [12] for a good survey on these lightpath routing algorithms.

Under the fixed shortest path routing strategy [1-5], the network control system can be very simple, not requiring maintaining any network link state database as in some traditional routing protocols such as OSPF-TE. Rather, each node only needs to maintain the route information to all the other nodes in the network, and each time when there is a lightpath request, the node looks up its route table to retrieve a corresponding route and establish a lightpath along the route. Because all the routes are fixed, the route table is static. In addition, the network control system only needs to maintain local link capacity availability information at the end nodes of the links. No link state information needs to be advertised around the network as in the OSPF-TE protocol. Despite simplification in network control and operation, fixed shortest path routing often suffers from network congestion due to unbalanced traffic load distribution.

In order to avoid the network congestion, adaptive routing algorithms that are aware of link load when dynamically selecting a route between a pair of nodes were developed to achieve balanced network traffic load distribution [6-11]. However, this type of routing strategies needs to maintain a network-wide link state information database (on each node) and a complicated network control system that supports Link State Advertisement (LSA) is required. An OSPF-based network control system is a typical example of such a kind of network control system, in which resource availability

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information on each link is broadcasted around the network periodically. Thus, the adaptive routing strategies is thus to show better network performance, which is however at the cost of more complicated network control system and higher network control overhead.

Viewing the above tradeoff between network performance and the complexity of network control system by the two types of network routing strategies, in this study we develop a kind of route-selection approach, called Load-Balanced Fixed Routing (LBFR) algorithm, which is dedicated to the fixed path routing strategy. Through a pre-training process based on a forecasted traffic load matrix, this routing algorithm can select a (few) fixed route for each node pair that can ensure a well-balanced traffic load distribution if they are used for lightpath service provisioning, and therefore can overcome network congestion suffered by the traditional fixed shortest path routing strategy.

We also extend the reduced load approximation (also referred to as Erlang fixed point approximation) approach [2][4][13-14] to analytically estimate lightpath blocking performance. The extension is general to model network scenarios where multiple parallel routes with each following a certain selection probability are employed to serve lightpath requests between each node pair.

The rest of this paper is organized as follows. Section II introduces the proposed LBFR algorithm. Section III presents the extended reduced load approximation approach and discrete-event-driven simulation. Results of the analytical models and the simulations are reported in Section IV. We conclude the paper in Section V.

2. LOAD-BALANCED FIXED ROUTING (LBFR) ALGORITHM

The LBFR algorithm is proposed based on the assumption that the traffic load between each pair of nodes is known a priori, which can be obtained by traffic demand forecast or history traffic demand data. With such a given traffic load matrix, the key idea of the algorithm is to perform a load-based routing training process to select a (few) route(s) for each node pair that can balance traffic load if they are employed as fixed route(s) to serve dynamic lightpath service demand. The training is a converging process. The routes between node pairs eventually converge to certain ones; these are the fixed routes between node pairs used for lightpath service provisioning.

Fig. 1 shows the flowchart of the proposed LBFR algorithm. The detailed steps of the algorithm are described as follows:

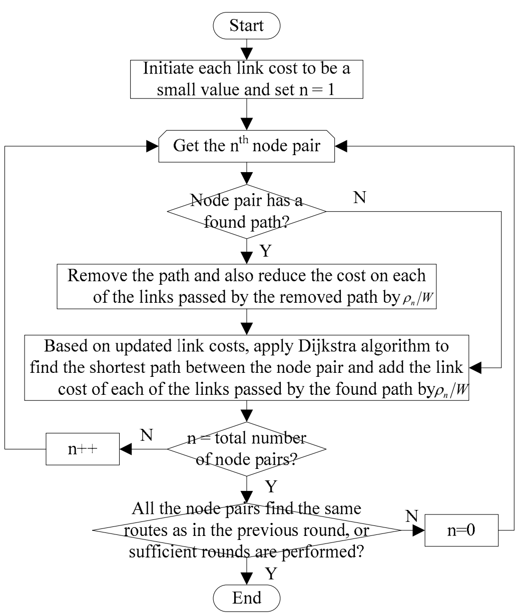

Figure 1: Flowchart of the LBFR algorithm

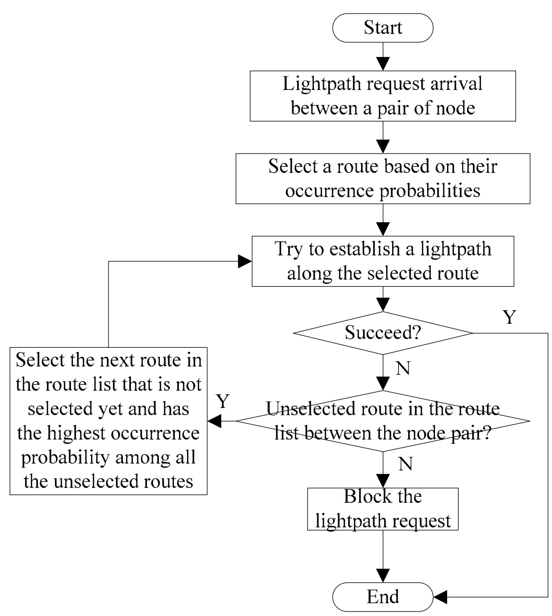

Figure 2: Flowchart of the route selection on a pair of nodes upon a new lightpath service arrival

Step 1: Initiate all the link costs in the network to be a small value ε (e.g., 10^{-4}) and set a counter n = 1.

Step 2: Get the nth node pair. If the node pair has a previous found route, remove the route and reduce the cost of each link traversed by the route by ρ_n / W, where ρ_n is the forecasted traffic load between node pair n and W is the maximum number of available wavelengths on each link. Otherwise, directly proceed to Step 3.

Step 3: Based on the current network link costs, apply Dijkstra's algorithm to find the shortest path for the nth node pair and add the cost of each link traversed by the new path by ρ_n / W.

Step 4: If n is still smaller than the total number of node pairs (not all the node pairs are visited), then set n = n+1 and go back to Step 2; Otherwise, if all the node pairs have the same found routes as before or each of the node pairs has been visited for a sufficient number of times (iterations), terminate the algorithm and output the route(s) for each node pair; otherwise, set n to be zero and return to Step 2 to repeat the previous iteration.

The LBFR algorithm will converge to a (few) fixed routes between each pair of nodes after several training iterations (we will show this in the result section later). The converged route sets are affected by the node-pair-based traffic load distribution within the network. Different traffic load distributions may lead to different final converged route sets.

Though in the most cases, there is only one converged route between a pair of nodes, situations also exist that a node pair may flip between two or even more than two routes (but very rare) during the training process. Moreover, the occurring probabilities of these flipping routes are also different, with one major route appearing frequently and remaining ones occasionally. This implies that this type of node pairs needs to store two or more than two fixed routes for selection to establish lightpaths. Specifically, when a lightpath request arrives, based on the occurring probabilities of the routes in the training process, we choose one of them to establish a lightpath. Such a process is different from another routing approach called alternate routing [6], in which route selection on a pair of nodes follows a fixed order, i.e., only a previous route in the route list is not available, is the next route attempted to establish a lightpath.

3. ANALYSES AND SIMULATIONS

3.1 Analytical Model

To evaluate the performance of the proposed routing algorithm, we employ the reduced load approximation approach to estimate lightpath blocking performance. In this study, we only apply the analytical model to the optical network with full wavelength conversion capability (i.e., a virtual wavelength path (VWP) network), in which all the nodes have full wavelength conversion capability of converting an input wavelength to any other output wavelength. Our future study will also consider the analytical model for the optical network with the constraint of wavelength continuity (i.e., a wavelength path (WP) network).

Analytical models for the VWP optical network under the assumption of a single fixed shortest route between each pair of nodes have been reported [4][14]. In the current study, after the pre-training process by the LBFR algorithm, there can be multiple fixed routes between a pair of nodes and each of the routes is selected with a certain probability for new lightpath establishment. An extension to the existing single fixed route analytical models is thus necessary to support the case of multiple fixed routes. Next we describe the detail of the analytical model. The notations of the model are as follows:

S: the set of links in the network, indexed by *s*;

L: the set of node pairs in the network, indexed by *l*;

$\mathbf{R}^l$: the set of fixed routes between node pair *l*, index by *r*;

β_r^l : the probability that the *r*th route between node pair *l* is selected to serve a lightpath request, where for any node pair *l*, the relationship $\sum_{r \in \mathbf{R}^l} \beta_r^l = 1$ holds.

$\Phi_s^{l,r}$: takes the value of one if the *r*th route between node pair *l* traverses link *s*, zero, otherwise. Thus, $\sum_{r \in \mathbf{R}^l} \beta_r^l \Phi_s^{l,r}$ indicates the probability of link *s* traversed by the traffic flows between node pair *l*. In the single-fixed route analytical model, this term is a binary to indicate whether the fixed route between a pair of nodes traverses link *s*.

However, in the context of multiple routes, this term becomes a real number to sum the possibilities of the routes that traverse the link.

B_s : the blocking probability on link *s*;

L_s : the offered load on link *s*;

A^l : the offered load between node pair *l*;

P^l : the blocking probability between node pair *l*;

P_B : the overall blocking probability of the network;

Consider a VWP network with dynamic traffic load and let *W* be the maximum number of wavelengths on each link. According to Erlang B formula, the blocking probability B_s on link *s* can be calculated as

$$B_s = E(L_s, W) = \frac{L_s^W / W!}{\sum_{j=0}^{W} L_s^j / j!} \tag{1}$$

If there is any link that is part of a lightpath that has no free wavelength to assign, the lightpath has to be blocked. Based on equation (1), the blocking probability of a lightpath P^l is

$$P_r^l = 1 - \prod_{s \in \mathbf{S} : \Phi_s^{l,r} = 1} (1 - B_s)$$

(2)

where $s \in \mathbf{S} : \Phi_s^{l,r} = 1$ is the set of links traversed by the *r*th route between node pair *l*.

The offered load L_s on link *s* can be calculated as

$$L_s = \sum_{s \in \mathbf{S}, r \in \mathbf{R}^l, l \in \mathbf{L}} A^l \beta_r^l \Phi_s^{l,r} \frac{1 - P_r^l}{1 - B_s}$$

(3)

We substitute (3) into (1) to obtain the Erlang fixed-point equation as

$$B_s = E(L_s, W) = E\left(\sum_{s \in \mathbf{S}, r \in \mathbf{R}^l, l \in \mathbf{L}} A^l \beta_r^l \Phi_s^{l,r} \frac{1 - P_r^l}{1 - B_s}, W \right)$$

(4)

Given the blocking probability on each route as (2), the lightpath blocking probability on each node pair is

$$P^l = \sum_{r \in \mathbf{R}^l} \beta_r^l P_r^l \tag{5}$$

The network average lightpath blocking probability P_B is

$$P_B = \frac{\sum_{l \in \mathbf{L}} P^l A^l}{\sum_{l \in \mathbf{L}} A^l}$$

(6)

To solve the analytical model, the fixed-point relaxation method is applied. Specifically, we define the terms of $B_s(n)$, $P^l(n)$, $P_r^l(n)$, $L_s(n)$ and $P_B(n)$ as the values of B_s, P^l, P_r^l, L_s and P_B in the *n*th iteration, respectively. A recursive process for the solution is as follows:

Step 1: Let $B_s(0)=0$, $P^l(0)=0$, $P_r^l(0)=0$, $P_B(0)=0$ and $L_s(0)$ be an arbitrary value; set n =1;

Step 2: Calculate $L_s(n)$ using (3) and $B_s(0)$ using (1);

Step 3: Calculate $P_r^l(n)$ using (2), $P^l(n)$ using (5), and $P_B(n)$ using (6);

Step 4: Comparing $P_B(n)$ and $P_B(n-1)$, if their difference is smaller than a predefined small value ε, then stop. Otherwise, set $n = n+1$ and go back to Step 2.

3.2 Simulations

To evaluate the performance of the proposed routing algorithm as well as the accuracy of the extended reduced load approximation analytical model, discrete-event-driven simulations were performed. We assume that the arrival of lightpath service request follows a Poisson distribution and the holding time of each established lightpath follows a non-exponential distribution.

For each node pair, when a new lightpath request arrives and the node pair has multiple fixed routes (including the case with a single route) with different selection probabilities, the detailed route selection principle is shown by the flowchart in Fig. 2. Specifically, we first randomly select a route from the route list of the node pair based on the routes' individual selection probabilities β_r^l. We then try to establish a lightpath on the selected route. If there are no sufficient wavelength resources along the route, we try the other routes in the route list following their selection probabilities from the highest to the lowest. If one of the trials succeeds, we establish a lightpath; otherwise, we block the lightpath request.

For lightpath service release, the simulation just removes an existing lightpath and releases all the network resources occupied by the lightpath. Through keeping on simulating the events of lightpath request arrival and lightpath release, we count the total number of blocked lightpath requests. After a certain number (e.g., one million) of lightpath requests is simulated, a lightpath blocking probability is calculated.

The above simulation process is applicable to both of the VWP and WP optical networks. The only difference is that in the VWP network, when using a route to establish a lightpath, we only check whether there is at least one free wavelength on each of the links along the route, while in the WP networks, we consider the constraint of wavelength continuity, that is, all the links along the route must have the same free wavelength(s) to enable lightpath establishment. For the WP networks, our simulations have employed the first-fit algorithm [1] for wavelength assignment due to its simplicity and efficiency.

4. NUMERICAL RESULTS

We evaluate the performance of the proposed LBFR algorithm on three test networks. The first network is the ARPA-2 network as shown in Fig. 3, which has 21 nodes and 26 links (average nodal degree = 2.5). The second network is the NSFNET network as shown in Fig. 4, which has 14 nodes and 21 links (average nodal degree = 3.0). The third network is the SmallNet network, which has 10 nodes and 22 links (average nodal degree = 4.4).

We assume that the maximum number of wavelengths on each link is W=80. We use a dynamic traffic model in which lightpath requests arrive on each node pair according to a Poisson process with an arrival rate λ (though it is possible to allow different node pairs to have different arrival rates, we assume that all the node pairs have the same arrival rate in this study). The lightpath holding time is exponentially distributed with mean $1/\mu$ = 1.0. Thus, the offered load between node pair is $\rho = \lambda/\mu = \lambda$. For each simulation result point, at least a total of 10^6 lightpath requests (i.e., arrival events) were simulated to calculate a final blocking probability.

For the VWP optical network, its blocking performance was evaluated by both of the analytical model and the discrete-event-driven simulation, while for the WP optical network, only simulation study was performed. Both of the analytical model and the discrete-event-driven simulation were implemented in JAVA and executed on a desktop PC.

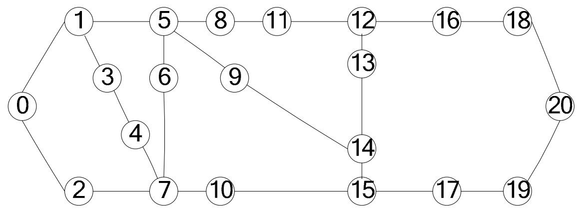

Figure 3: ARPA-2 network

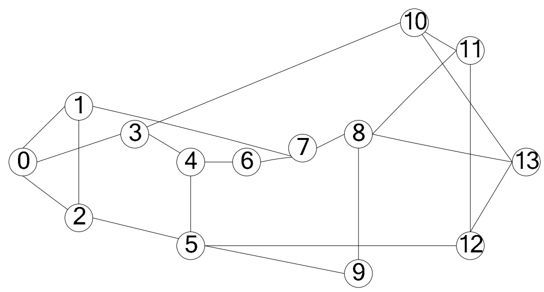

Figure 4: NSFNET network

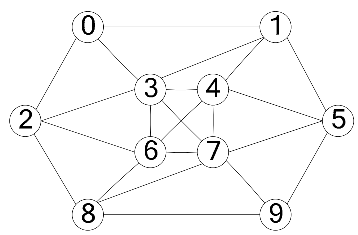

Figure 5: SmallNet network

4.1 Load-Balanced Fixed Routes

Based on the above simulation parameters, we first run the LBFR algorithm to find the fixed routes between node pairs. The pre-training process as described is terminated when all the routes selected for the node pairs are converged or a certain number of iterations (here we set the maximal number of iterations to be 10,000) reaches. Meanwhile, for the case that there are multiple converged routes flipping on a node pair during the pre-training process, we counted their numbers of occurrence and calculated their selection probabilities by dividing the total number of iterations, i.e., 10,000. These probabilities are just the ones used for route selection during lightpath service provisioning.

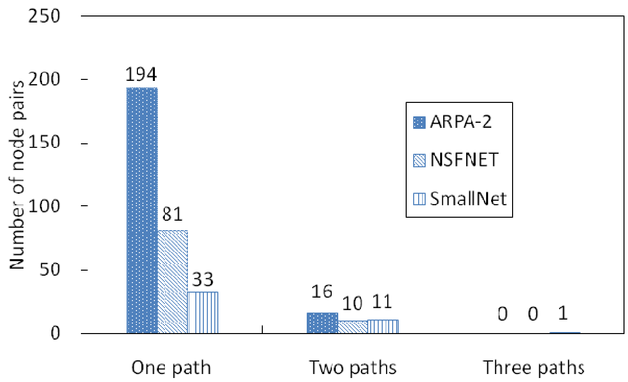

Figure 6: The distributions of the numbers of node pairs that have different numbers of converged routes found by the LBFR algorithm.

For the three test networks, Fig. 6 counts the numbers of node pairs that have different numbers of fixed routes when the pre-training process stops. Specifically, on most node pairs, there are only one fixed routes, and on some node pairs, there are two flipping routes. The situation that there are three flipping routes or even more is very rare. Only in the SmallNet network, there is one node pair that has three converged routes when the training process stops. Note that if a node pair has only a single converged route, the route is not necessarily a shortest one, but one that can balance the traffic load in the network.

Specifically, in the ARPA-2 network, 92.4% node pairs each has a single route, and the remaining 7.6% node pairs each has two routes; in the NSFNET network, 89.0% node pairs each has a single route, and the remaining 11.0% node pairs each has two routes; in the SmallNet network, 73.3% node pairs each has a single route, 24.4% node pairs each has two routes, and the remaining 2.2% node pairs each has three routes. Consider the average nodal degrees of the three test networks. It is interesting to see that with the increase of nodal degree, the percentage of node pairs that have more than one route becomes higher. This is reasonable since a higher nodal degree provides more routes between each pair of nodes, which also provides more options for route convergences.

4.2 Lightpath Blocking Performance

Based on the route selected by the LBTR algorithm, we evaluated the lightpath blocking performance for the three test networks. For the VWP network, both of the analytical model and simulations were implemented, while for the WP network only simulations were performed.

A) VWP network

Fig. 7 shows the results of the LBFR algorithm in comparison with traditional Dijkstra's shortest path routing algorithm. The x-axis shows the traffic load in Erlang on each node pair and the y-axis shows the network-wide lightpath blocking probability. There are four performance curves. The first two are the blocking results of Dijkstra's shortest path routing algorithm with one obtained from the simulation and the other calculated by the analytical model. The second two are the blocking results of the proposed LBFR algorithm. Comparing these two routing algorithms, we can see that though both of them are static fixed routing, which provides simplicity for network control and operation, the proposed LBFR algorithm can achieve much better blocking performance than that of Dijkstra's algorithm. In addition, comparing the results obtained by the analytical model and simulation, we see that the analytical model can accurately model the blocking performance based on fixed routing, no matter a single shortest fixed route, or multiple load-balanced fixed routes.

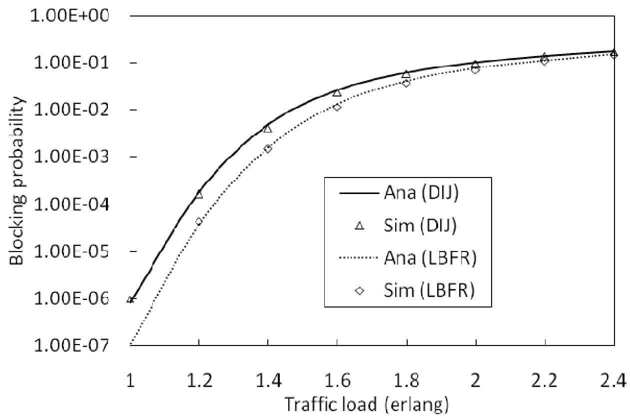

Figure 7: The blocking probabilities in the ARPA-2 network (VWP) with the fixed routing algorithms: Dijkstra's versus LBFR ($W = 80$)

Similar studies were also performed for the second test network, i.e., the NSFNET network, which is shown in Fig. 8. Similar observations and phenomena are found except that the performance difference between the two algorithms become even larger. The NSFNET network has a higher average nodal degree than that of the ARPA-2 network. This implies that with the increase of network nodal degree, the proposed LBFR algorithm can perform better. Such better performance is also reasonable since a higher nodal degree means more eligible routes between each pair of nodes that allow the LBFR to select. More route options enables to select better load balanced routes, thereby achieving better network blocking performance.

Such a nodal degree-related phenomenon is also observed in the results of the SmallNet network as shown in Fig. 9, in which only analytical result curves are presented. The SmallNet network has an even higher average nodal degree. Thus, the proposed LBFR algorithm can achieve even better performance than that of Dijkstra's algorithm. For example, when the traffic load on each node pair is 14.0 Erlang, the performance difference is significant, around 5,000 times.

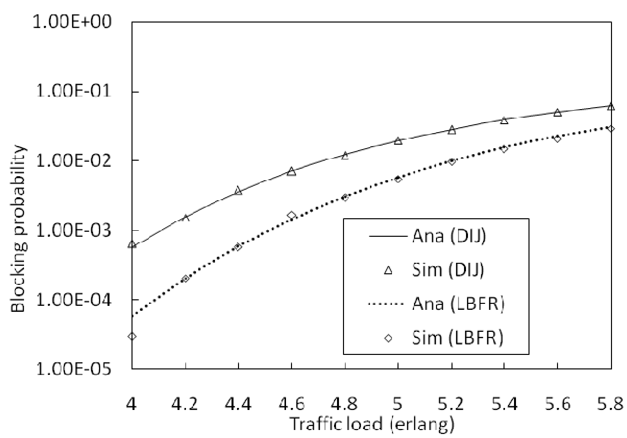

Figure 8: The blocking probabilities in the NSFNET network (VWP) with the fixed routing algorithms: Dijkstra's versus LBFR ($W = 80$)

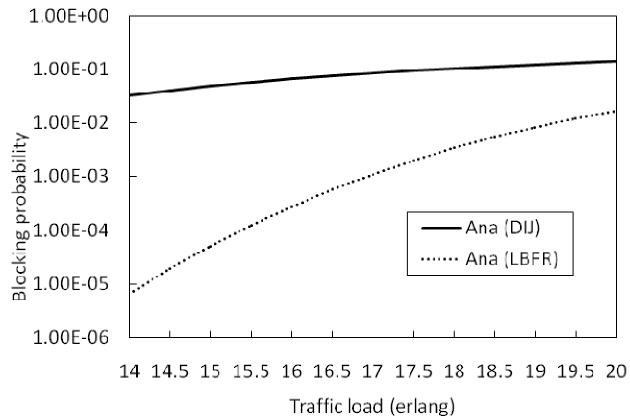

Figure 9: The blocking probabilities in the SmallNet network (VWP) with the fixed routing algorithms: Dijkstra's versus LBFR ($W = 80$)

We also evaluate how the proposed LBFR algorithm performs under different number of wavelengths on each link. Under the SmallNet network with each node pair having 18.0 Erlang traffic load, Fig. 10 shows how the blocking performance (obtained from the analytical model) changes with different numbers of link wavelengths. We can see that with the increase of number of wavelengths on each fiber link, the proposed LBFR algorithm performs even better than Dijkstra's algorithm, which implies that we can benefit more to apply the LBFR algorithm under a larger link wavelength number.

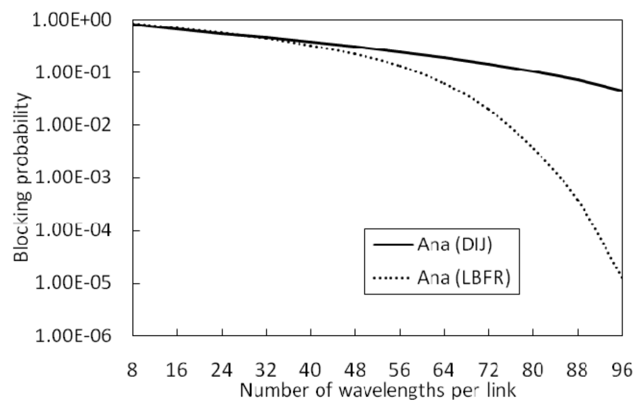

Figure 10: The blocking probabilities in the SmallNet network (VWP) with the change of wavelength number on each fiber from $W = 8$ to 96 (traffic loads per node pair: 18.0 Erlang)

B) WP network

For the WP network, we ran simulations for the three test networks. We do not provide results of analytical model, which is our future research work. Figs. 11-13 show the lightpath blocking performance of the three test networks under the two lightpath routing algorithms, namely Dijkstra's and the LBFR algorithms. Similar to the results of the VWP network, we can see that the LBFR algorithm can perform much better than Dijkstra's algorithm. Moreover, with the increase of network average nodal degree, the performance difference between the two routing algorithms becomes even larger. This implies that the LBFR algorithm is also valid to find load-balanced routes for the WP network.

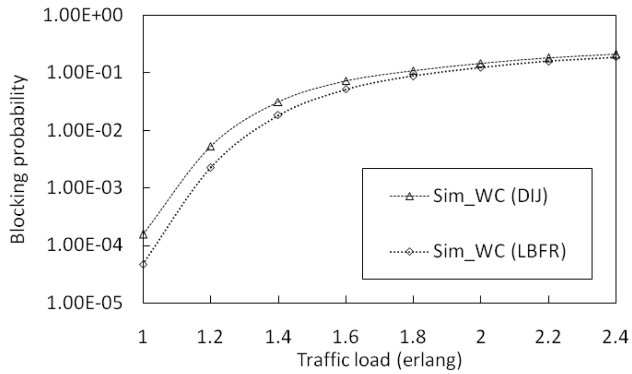

Figure 11: The blocking probabilities in the ARPA-2 network (WP) with the fixed routing algorithms: Dijkstra's versus LBFR ($W = 80$)

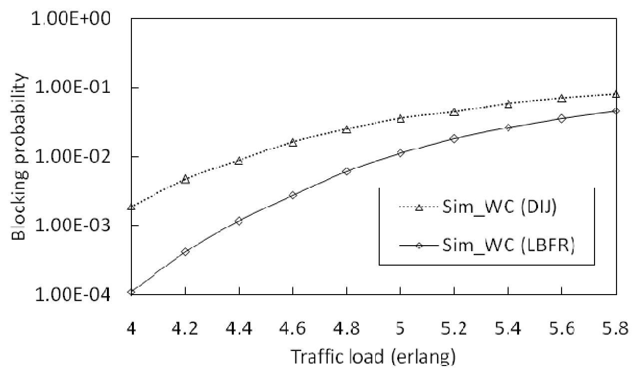

Figure 12: The blocking probabilities in the NSFNET network (WP) with the fixed routing algorithms: Dijkstra's versus LBFR ($W = 80$)

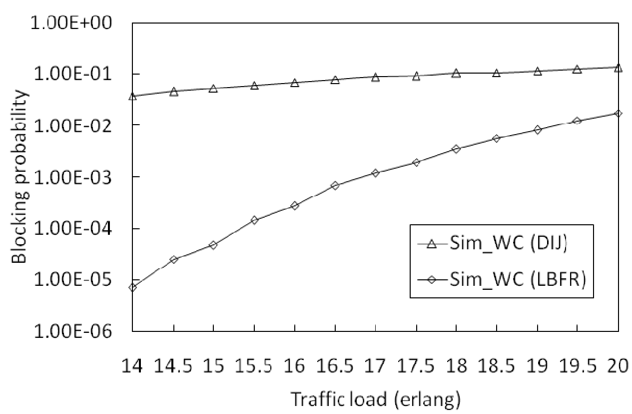

Figure 13: The blocking probabilities in the SmallNet network (WP) with the fixed routing algorithms: Dijkstra's versus LBFR ($W = 80$)

5. CONCLUSION

Traditional fixed shortest path routing is advantageous of simple network control and operation, which is however suffered from unbalanced network traffic load distribution and network congestion. This study developed a new load-balanced routing algorithm to find a (few) fixed routes between each pair of nodes. These routes are used as fixed routes in the fixed path routing operation. These routes can evenly distribute network traffic load and remedy network congestion suffered by traditional single fixed shortest path routing. Moreover, to estimate lightpath blocking performance for node pairs that have multiple fixed routes, we extended the traditional reduced load approximation analytical model to support the multi-route scenario. Simulation studies indicated that the analytical model is accurate to evaluate network blocking performance. Also, the proposed LBFR algorithm can perform better than the traditional fixed shortest path routing algorithm and their performance difference becomes larger with the increase of network nodal degree and number of wavelengths on each fiber link for both of the VWP and WP optical networks.

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