Virtual Fiber Configuration Method for Dynamic Lightpath Establishment in Large–Scaled WDM Networks

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***Abstract*— Recently, progress has been made in the Generalized Multi–Protocol Label Switching (GMPLS) and Automatic Switched Optical Networks (ASON) standardizations. These technologies realize construction of large–scaled optical networks, interconnection between single–domain Wavelength Division Multiplexing (WDM) networks, and direct communication over multi–domain WDM networks. Meanwhile, it is known that the topology of the Internet exhibits the power–law attribute. Since the topology of the Internet, which is constructed by interconnecting ASs, exhibits the power–law, there is a possibility that large–scale WDM networks, which are constructed by interconnecting WDM networks, will also exhibit the power–law attribute. One of the structural properties of a topology that adheres to the power–law is that most nodes have just a few links, although some have a tremendous number of them. Another property is that the average distance between nodes is smaller than in a mesh–like network. A natural question is how such a structural property performs in WDM networks.**

In this paper, we first investigate the property of the power–law attribute of physical topologies for WDM networks. We compare the performances of WDM networks with mesh–like and power–law topologies, and show that links connected to high–degree nodes are bottlenecks in power–law topologies. To relax this, we introduce a concept of virtual fiber which consists of two or more fibers and propose its configuration method to utilize wavelength resources more effectively. We compare performances of power–law networks with and without our method by computer simulations. The results show that our method reduces the blocking probabilities by more than one order of magnitude.

I. INTRODUCTION

The rapid growth in the Internet's traffic volume has led to demands for backbone networks with higher capacities. Wavelength Division Multiplexing (WDM) is one approach that is expected to satisfy such demands. The technology multiplexes different signals with exclusive wavelength bandwidths on a single fiber. WDM networks with OXCs (optical cross connects) have a wavelength–routing capability. In this network, a wavelength channel, called a lightpath, is established from a source node to a destination node for data transmission [1], [2]. Progress has been made in Generalized Multi–Protocol Label Switching (GMPLS) [3] and Automatic Switched Optical Networks (ASONs) [4] which realize interconnections of lightpaths over heterogeneous or multi–domain optical networks. By utilizing these, optical networks employing WDM technology have been adopted to improve the Internet for example cores of Wide Area Networks (WANs) [1], [2], [5]–[8] and Metropolitan Area Networks (MANs) [9], [10], which form large–scale optical networks.

What kind of topologies do the large–scale optical networks have? It is difficult to assure the topologies of the future optical networks. Looking at the current Internet, recent studies demonstrate that the Autonomous System (AS)–level and router–level topologies exhibit the power–law attribute [11], [12]. In such networks, the probability $p(k)$ that a node is connected to k other nodes follows this relationship: $p(k) \sim k^{-\gamma}$ (γ is a constant number such as $2 < \gamma < 3$); therefore, most nodes have just a few links, although some have a tremendous number of them. An extreme scenario for constructing large–scale optical netowrks is that the current routers are replaced by OXCs or optical switches. In this case, the backbone of the Internet will be a large–scale WDM network and the topology shall take over the power–law attribute.

One might think that, since optical networks are carefully planned, their topologies will not follow the power–law. It may be true for intra–domain optical networks (corresponding to the router–level topology of the Internet) because it is well designed by their own network operators. However, an inter–domain network that is constructed by interconnecting intra–domain networks (corresponding to the AS–level topology of the Internet) will not be in the similar situation since there is no coordinator for the entire network. Refs. [13]–[15] also present speculations and discussions about the origin of the property of the Internet topology. Barabási and Albert propose the BA model to explain the power–law attribute [13]. They present that a simple heuristic policy that new nodes tend to be connected with nodes having many links forms a power–law network (See Sec. II for details). This approach makes distances (hop counts) between nodes short. Another model, Highly Optimized Tolerance (HOT), is introduced in [14]. That model produces the power–law attribute as a result of designing a robust structure. In [15], the authors show that the costs for last mile connections and the hop distances have the potential possibilities of being the origins of the power–law attribute. In summary, the power–law property is likely embedded in an large–scale inter–domain optical network as a result of the probable ways of adding new AS interconnections.

Conventional studies on WDM–based networks have focused on relatively small networks, such as single–domain backbone networks with tens of nodes or random networks that have at most 100 nodes or so. Furthermore, although there is much researches available about the performance on large–scale network with power–law properties [16], [17], the effort has focused on packet–switched networks, not focused on circuit–switched networks and wavelength–routed networks. We therefore investigate the performance of large–scale optical networks for *both* random and power–law topologies, and show how the structural properties of topology affects the performance of WDM networks.

In this paper, we first show the differences of the topological properties between random and power–law networks. Because of the differences, the performances of WDM networks constructed on those topologies are quite different; traditional lightpath setup methods for random networks cannot demonstrate their performances in power–law networks. Then we propose a new method to accelerate their performances in power–law networks. Our method is based on *quasi–static lightpath* and *virtual fiber*. Quasi–static lightpath is not a traditional lightpath to transmit data from a source node to a destination node but a virtual link to change topologies for wavelength routed networks. Virtual fiber is a bundle of quasi–static lightpaths. We construct logical topologies over physical topologies of WDM networks by configuring virtual fibers and setup lightpaths on the logical topologies. We evaluate our method by computer simulations and the results show that our method reduces more than one order of magnitude of the blocking probability in some cases.

This paper is organized as follows. In Sec. II, we show the attributes of the physical topologies of the random network (used in traditional studies) and the power–law network upon which this paper focuses. Additionally, we compare the performances of blocking probabilities in those two types of networks. In Sec. III, we introduce the concepts of quasi–static lightpath and virtual fiber. We also describe a method to configure virtual fibers to revise the blocking probability in power–law networks in the section. We evaluate the performance of our method with computer simulations in Sec. IV. Finally, we summarize our paper in Sec. V.

II. Topology Models

While the current topology of the Internet has been investigated for actual trace data, there are many studies that focus on modeling methods for Internet topology. In this section, we first describe the ER (Erdös–Rényi) model [18] in which links are randomly placed between nodes (Fig. 1(a)). We then introduce the BA (Barabási–Albert) model [13] in which the topology grows incrementally and links are placed based on the connectivities of the topologies to form power–law networks (Fig. 1(b)).

A. ER (Erdös–Rényi) Model

The ER model was designed by Erdös and Rényi to describe communication networks. They assumed that such systems could be modeled with connected nodes of randomly placed links usually called random networks. In this model, the number of nodes N is given at first, and every two nodes are connected with the fixed probability p. Thus, the ER model generates a random network. The probability $P(k)$ that a node has degree (number of links) k is given as

$$P(k) = \binom{N-1}{k} p^k (1-p)^{N-1-k}. \tag{1}$$

In addition, with large N and small p, Eq. (1) becomes

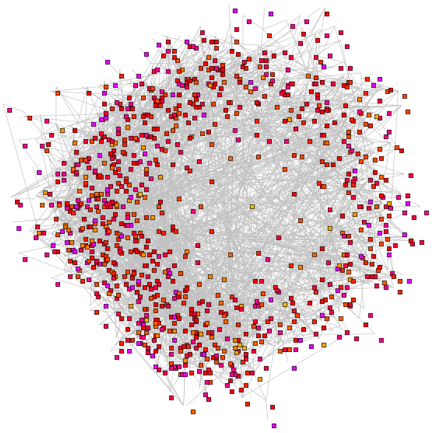
$$P(k) = \lambda^k e^{-\lambda}/k!, \tag{2}$$

where $\lambda = pN$. From Eq. (2), the distribution of the degrees of the nodes in a random network generated by the ER model follows a Poisson distribution [19].

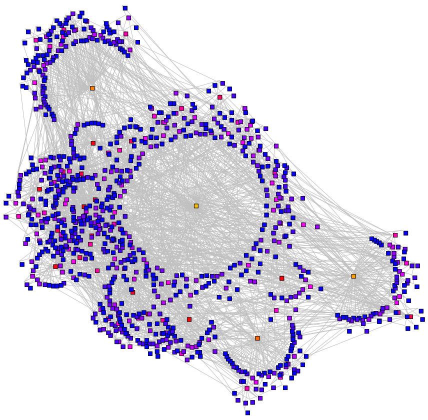
B. BA (Barabási–Albert) Model

Barabási and Albert designed their model to emulate the growth of such large–scale networks as the Internet. The BA model is characterized by two features that the ER model does not have: *Incremental Growth* and *Preferential Attachment*. Generating a topology is started with a small number of nodes m_0.

1) *Incremental Growth*: Add a new node at each timestep.



(a) Random network



(b) Power–law network

Fig. 1. Topologies of a random network and a power–law network

2) *Preferential Attachment*: Connect the new node with two other different nodes, which are chosen with the probability Π (k_i is the degree of node i).

$$\Pi(k_i) = k_i / \sum_j k_j. \tag{3}$$

C. Properties of Random and Power–Law Networks

Figure 2 shows cumulative distribution functions $F(d)$ of node degrees d of nodes in the topologies generated by the ER and BA models. There are 1,000 nodes. The connection probability of the ER model is 0.002 and 2,066 links are generated. The number of nodes at the initial phase and the number of links added at each timestep in the BA model are set as $m_0 = m = 2$ and 1,997 links are generated.

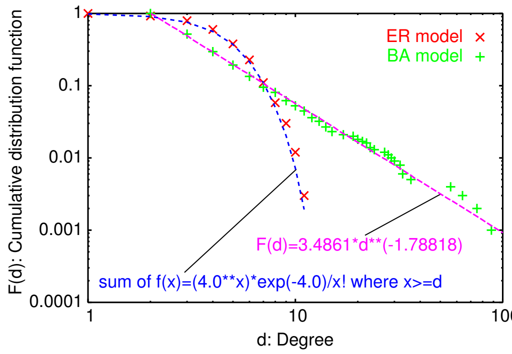


Fig. 2. Cumulative distribution functions of node degrees in topologies generated with the ER and BA models

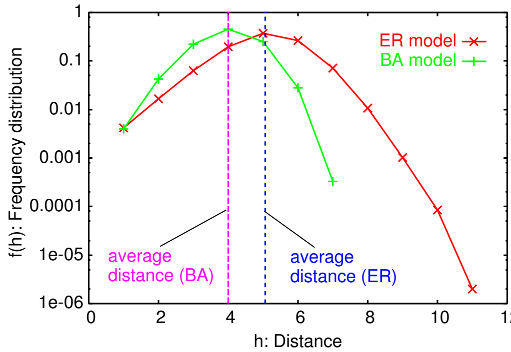


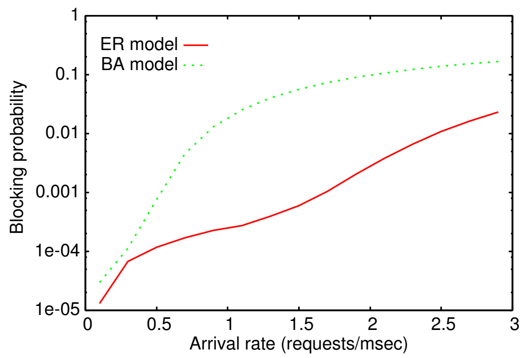
Fig. 3. Distributions of distances between nodes in topologies generated with the ER and BA models

This figure shows that the distribution of node degrees of the random network approximately follows a Poisson distribution. On the other hand, distribution of the degrees of the power–law network is approximately aligned on a log–log plot, which indicates the distribution follows the power–law. Distributions of distances between nodes in the random network and the power–law network are shown in Fig. 3. The horizontal axis represents distance; we mean distance is number of hops between a pair of nodes. The vertical axis represents frequency of node pairs whose distances are h. The variance of the distances in the random network is larger than that in the power–law network. In addition, the average distance of the power–law network is smaller than that of the random network.

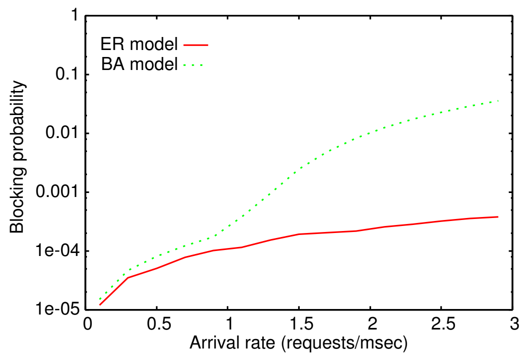
D. Performances of Random and Power–Law Networks

If the physical topology of a WDM network is power–law, a large variance of node degrees strongly affects the performance of the network, such as its blocking probability. In this subsection, we investigate the performances of blocking probability in random and power–law WDM networks.

We measured the blocking probabilities of lightpath establishment by computer simulations with the topologies which



(a) 16 wavelengths



(b) 32 wavelengths

Fig. 4. Blocking probabilities in random and power–law networks

we use for the comparisons of properties in the previous subsection. In addition, we assume the following conditions and restrictions:

- The number of physical links between a pair of two adjacent nodes is one.
- Each link is a bi–directional (i.e., it is composed of an in–coming and an out–going fibers).
- Propagation delays of the fibers are uniformly 0.1 msec.
- Processing delays at the nodes are ignored.
- Arrival of demands between all of the node pairs follows a Poisson process with an average rate λ.
- Holding time of the lightpaths follows an exponential distribution with an average rate of $1/\mu$.
- The shortest–hop routes are used for routes of lightpaths.
- Wavelengths are assigned by the backward reservation protocol [20].
- Wavelength conversion is not available at any node.

Figure 4 shows the results of simulations with 8, 16, and 32 multiplexed wavelengths. The horizontal axes represent arrival rate. The vertical axes represent blocking probability.

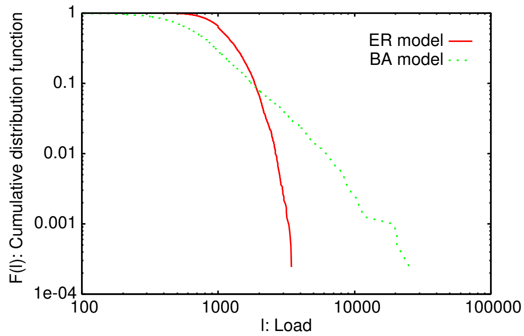


Fig. 5. Distributions of link loads in topologies generated with the ER and BA models

λ is changed from 0.1 requests/msec to 2.9 requests/msec and μ is set to 1.0 /sec. From these results, it is found that power–law networks cannot accommodate still less traffic demands than random networks when the traffic load is not light. This is because many requests compete for wavelength resources around hub (i.e., high–degree) nodes. Because of the different properties as described above, traditional lightpath establishment methods for random networks cannot demonstrate their abilities in power–law networks. To see this more clearly, we show the number of the shortest paths passing through a link, called link load hereafter, in Fig 5. From this figure, the link load distributions show much the same tendency to the node degree distributions. That is, there are some heavy–loaded links in power–law networks and they make the blocking probability rise. Based on the observations, we propose a new method to setup lightpaths more efficiently in power–law networks.

III. Proposal of Lightpath Configuration Method for Virtual Fibers

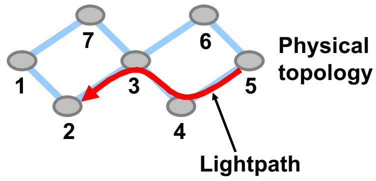
In Sec. II, we showed that the power–law attribute of physical topologies in WDM networks increases the blocking probabilities. The attribute leads most of the shortest path routes between the nodes to pass across hub nodes, and therefore reservation requests conflict at hub nodes. In this section, we bring in the concepts of *quasi–static lightpath* and *virtual fiber*. We also propose a virtual fiber configuration method to improve blocking probability in power–law networks.

A. Concept of Quasi–Static Lightpath

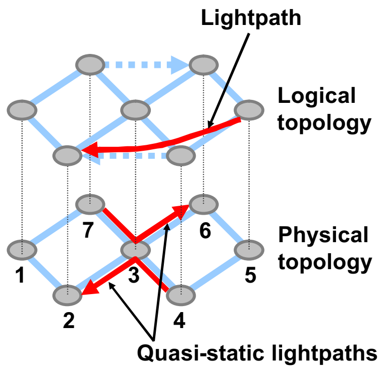
In dynamic–wavelength routing networks, lightpaths are established on a demand basis and released after data transmission. However, the more hops (fibers) that lightpaths pass through, the more difficult setup becomes because of the inherent nature of a circuit–switch–based network (i.e., the lightpath with more hops requires more wavelength resources), and this is exacerbated by the wavelength continuity constraint.

To resolve the inequality of blocking probabilities between short–distance and long–distance node pairs, we prepared some lightpaths beforehand. We refer to such pre–configured lightpaths as quasi–static lightpaths. Quasi–static lightpaths are different from conventional lightpaths designed for transporting IP packets or communications of other upper layers. Quasi–static lightpaths are reserved as part of lightpaths. Figure 6 illustrates the concept of quasi–static lightpath. In traditional wavelength–routed networks, lightpaths are set up on physical topologies composed of nodes and fibers, as shown in Fig 6(a). On the other hand, quasi–static lightpath behaves as a single hop link to upper wavelength routed networks. That is, wavelength routing protocols perceive quasi–static lightpaths as fibers whose available wavelengths are only what are reserved as wavelength resources for the lightpaths (the dotted arrows in Fig. 6(b)). When a lightpath request arise between node 5 and node 4, the request traverses $5 \longrightarrow 4 \longrightarrow 3 \longrightarrow 2$ in the case of traditional lightpath establishment approach. However, if there are quasi–static lightpaths between node 4 and node 2, the length of the lightpath gets shorter by one hop; the request traverses $5 \longrightarrow 4 \longrightarrow 2$.

As noted above, quasi–static lightpaths are reserved as part of lightpaths. Lightpaths are released after the data transmission, but quasi–static lightpaths keep their configurations. Quasi–static lightpaths may not be reconfigured unless the traffic pattern is changed. In this sense, the pre–configured lightpaths are quasi–static.



(a) Traditional lightpath establishment



(b) Logical topology construction with quasi–static lightpaths

Fig. 6. Concept of quasi–static lightpath (The links without arrows are bi–directional.)

B. Virtual Fiber: Bundle of Quasi–Static Lightpaths

There are two benefits of quasi–static lightpaths. First, the fragmentation of wavelength resources can be avoided by setting up quasi–static lightpaths. When a network is congested, the remaining free wavelength resources are too fragmented to be utilized to establish lightpaths due to the wavelength continuity constraint. However, the constraint is always satisfied at the parts consisting of quasi–static lightpaths. Therefore, quasi–static lightpaths can promote an effective utilization of resources. Second, quasi–static lightpaths shorten the distance between nodes. Viewing from the upper layer, the source node of a quasi–static lightpath is directly connected to the destination nodes of the quasi–static lightpath, which reduces the number of hop–counts between nodes.

There is a disadvantage of quasi–static lightpath configurations. A fiber that quasi–static lightpaths pass through loses some of available wavelengths since the fiber devotes its wavelengths to the quasi–static lightpaths. In Fig. 6(b), when two quasi–lightpaths ($7 \longrightarrow 3 \longrightarrow 6$) and ($4 \longrightarrow 3 \longrightarrow 2$) are configured using one wavelength (say λ_1), the fibers $3 \longrightarrow 2$, $4 \longrightarrow 3$, $3 \longrightarrow 6$, and $7 \longrightarrow 3$ on the logical topology cannot use the λ_1. Furthermore, only one wavelength, λ_1 can be used for the virtually constructed links $7 \longrightarrow 6$ and $4 \longrightarrow 2$. We can use much more wavelengths for quasi–static lightpaths, however, the remaining wavelengths on fibers may not be enough resources to handle lightpath requests. Thus, for effectively utilizing the quasi–static lightpaths, it is necessary to append routing mechanisms with traffic engineering, i.e., route selection based on the number of available wavelengths. This requires higher complexity of route calculation, which may not be suitable for large–scale WDM networks. Instead, we configure quasi–static lightpaths using all the wavelengths on fibers and bind wavelengths to form a *virtual fiber*. This configuration is illustrated in Fig. 7. In this figure, by configuring quasi–static lightpaths using all the wavelengths on the fibers $4 \longrightarrow 3$ and $3 \longrightarrow 2$, a virtual fiber appears between the node 4 and the node 2. Data from the node 4 to the node 2 cuts through the intermediate node 3. We call this operation *cut–through* hereafter. The fibers devoting their wavelengths to quasi–static lightpaths become uni–directed. This means that cut–through operation reduces in–degree and out–degree of a node by one. In the case of Fig. 7, the cut–through operation is also applied for the node 3 so that virtual fiber is configured for the node 7 to the node 6.

As we refer in Sec. II, node degree is associated with load

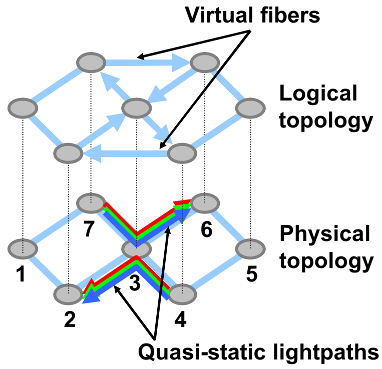


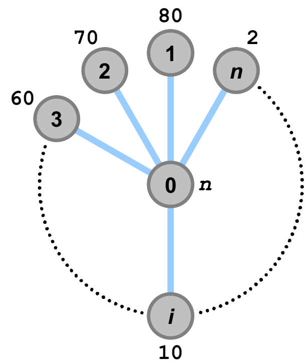
Fig. 7. Concept of virtual fiber (The not arrow links are bi–directional.)

and performance of blocking probability. Hence this degree reduction can lead reduction of link load and blocking probability. Of course, virtual fibers are likely to make the performances of logical topologies worse if they are not configured appropriately. In the next subsection, we consider a heuristic approach to effectively set up virtual fibers in order to improve the performances of blocking probabilities of logical topologies.

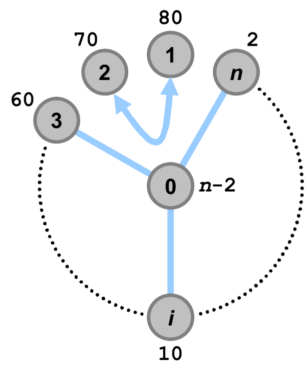
C. Degree–Based Method for Virtual Fiber Configuration

Here we discuss how to configure virtual fibers in order to reduce loads for fibers around hub nodes. Imagine such a situation as Fig. 8(a). The hub node 0, which has the highest degree in the network, is connected with n nodes on a physical topology of a power–law network. Node IDs 1 to n are assigned in degree–descending order and the corresponding degrees are put at the sides of the nodes in the figure.

Since the node with higher degree tends to have more connections that pass through the node, the majority of lightpath requests in the network pass through the fiber from node 1, which has the second–highest degree, to the hub–node 0 and vice versa. That is, the most congested link in the network is the fiber between the nodes 0 and 1. In a similar way, the next congested link in the network is the fiber between node 0 and 2. In order to reduce the load of these links, we consider applying the cut–through operation on the node 0 to configure a virtual fiber between the node 1 and the node 2 (Fig. 8(b)). Due to the virtual fiber, the nodes 1 and 2 cannot communicate with the other adjacent nodes 3 to n via the hub node 0. Lightpath requests from the nodes 1 (or node 2) to nodes 3 to n take other routes not through the hub node 0, which we expect that the load of links around the hub node is reduced. Therefore the blocking probability is improved. Note that, in the above example, we have to confirm there is no direct fiber between the nodes 1 and 2. If there exists one, there will be no effect on reducing the load.



(a) Physical connectivity of a hub node



(b) Set a virtual fiber through the hub node

Fig. 8. Virtual fiber configuration around a hub node: Arrows mean virtual fibers.

Based on the above heuristic, we propose a degree–based virtual fiber configuration method. The details of our method are described below.

1) Notations: We use the following notations to explain our method.

N:	Set of the nodes in a network.
F:	Set of the fibers in a network, including the virtual fibers.
$F(n_1, n_2)$:	Set of the fibers placed from a node n_1 to a node n_2 on a logical topology.
$d(n)$:	Degree of a node $n \in N$.
$A_{in}(n)$:	Set of the adjacent nodes which are connected to a node n.
$A_{out}(n)$:	Set of the adjacent nodes which are connected from a node n.
$Cut(f_1, f_2)$:	Cut–through operation from a fiber f_1 to a fiber f_2.

2) Degree–Based Virtual Fiber Configuration Methods: Here we describe a heuristic algorithm for virtual fiber configurations. It tries to decrease the maximum degree of nodes in a network by using the cut–through operation. The terminal condition is that the maximum degree of nodes is less than a given parameter th.

Step 1: Make a list of the degrees of the nodes. Set the value of th such that $th > 2$. Go to Step 2.

Step 2: If the top of the degree lists satisfies the condition $max\ d(n) > th$ ($n \in N$), $n_0 \leftarrow n$ and go to Step 3. Otherwise, go to Step 5.

Step 3: Select a node n_1 from $A_{in}(n_0)$ and another node n_2 from $A_{out}(n_0)$. The node pair (n_1, n_2) has to satisfy these conditions; $F(n_1, n_2) = \phi$, $n_1 \neq n_2$, and $d(n_1)+d(n_2) \geq d(n_{in})+d(n_{out})$ for any node pair (n_{in}, n_{out}) such that $n_{in} \in A_{in}(n_0)$, $n_{out} \in A_{out}(n_0)$, $F(n_{in}, n_{out}) = \phi$, and $n_{in} \neq n_{out}$. If such a pair of nodes is found, go to Step 4. Otherwise, go to Step 5.

Step 4: Do $Cut(f_1, f_2)$ ($f_1 \in F(n_1, n_0), f_2 \in F(n_0, n_2)$). Update the degree lists and go back to Step 2.

Step 5: Quit setting virtual fibers.

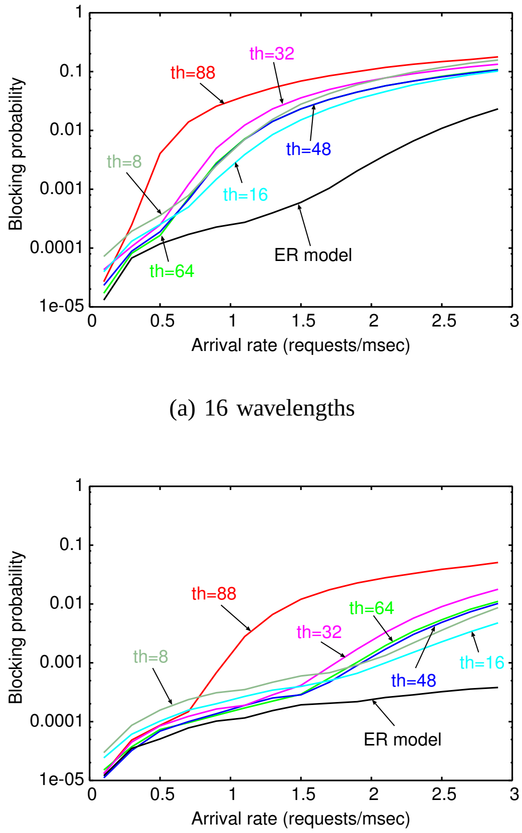
In Step 1, the threshold th is set. If the floor of th is one, generated logical topologies are ring networks. Therefore the minimum value of th should be more than 2. In Step 3, we select the edge nodes of a virtual fiber through nodes n_0, n_1 and n_2, with the heuristic approach. Adjacent node pairs (n_1, n_2) directly connected via physical or virtual fibers are excluded in the selection. And we set a virtual fiber on a route $n_1 \rightarrow n_0 \rightarrow n_2$ in Step 4. Thus, the in–degree and out–degree of a node n_0 are decremented by one for each.

IV. Numerical Evaluation

We evaluate the performance of the degree–based virtual fiber configuration method with the same simulation model in Sec. II. The maximum degree of the power–law network topology is 88. The values of the threshold th are 88, 64, 48, 32, 16, and 8. Therefore, $th = 88$ means that our proposed method is not applied. Figure 9 illustrates the simulation results. The results with 16 wavelengths are shown in Fig. 9(a). Figure 9(b) shows the results with 32 wavelengths. In both of the figures, the horizontal axes represent arrival rate for each node–pair and the vertical axes represent blocking probability.

From these figures we observe that our proposed method reduces the blocking probability of lightpath requests for the moderate and high arrival rates, comparing with $th = 88$. It also mitigates the sharp rise of blocking probability as appeared for $th = 88$. Among the examined threshold values, the method with $th = 16$ shows the best results for high arrival rate; it reduces more than one order of magnitude of the blocking probability when the number of wavelengths is 32. However, for the lower arrival rate, the results with $th = 16$ get worse than the results with $th = 88$. Only the methods with $th = 48$ or $th = 64$ always show better performance than the results with $th = 88$.

This fact can be easily explained by using Table I, which



(a) 16 wavelengths

(b) 32 wavelengths

Fig. 9. Variation of blocking probabilities for different thresholds th in power–law networks

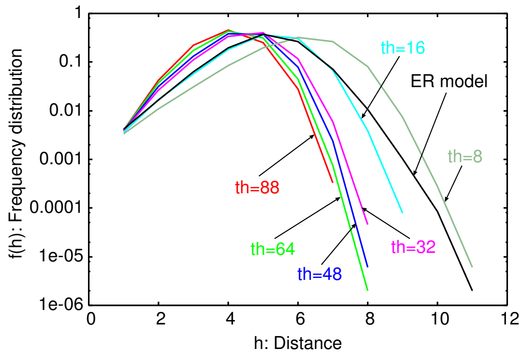


Fig. 10. Distributions of distances between nodes on logical topologies

TABLE I

AVERAGE DISTANCE AND AVERAGE/MAXIMUM/MINIMUM LINK LOAD

Topology	$th = 88$	$th = 64$	$th = 48$	$th = 32$	$th = 16$	$th = 8$	ER
Average distance	3.99	4.15	4.33	4.47	5.09	5.92	5.06
Average load	998.89	1046.0	1107.1	1166.0	1406.9	1787.1	1222.5
Maximum load	25120	12905	11863	11786	9993	8745	3442
Minimum load	15	48	62	55	117	325	414

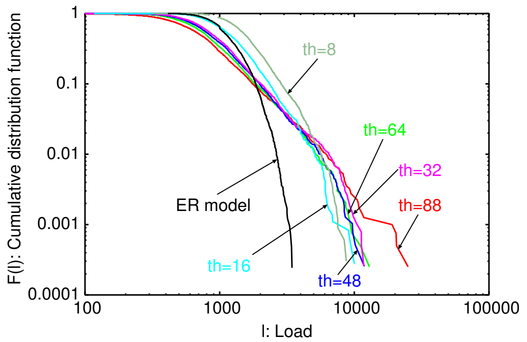


Fig. 11. Distributions of link loads distances between nodes on logical topologies

shows the average distance, the average load, the maximum load, and the minimum load for each threshold value. Note again that the values with $th = 88$ corresponds to the physical topology. The values of the random network topology are also put in the table for comparison. Focusing on the maximum load, the methods with $th = 64$ and $th = 48$ significantly reduce the maximum load, with less increase of the average load. The method with $th = 16$ certainly reduces the maximum load. However, the reduction requires sacrifices from the average load and the average distance. When the arrival rate of requests is low, the blocking probability is much affected by the distance rather than by the link load since arrivals of lightpath requests to fibers are also low. On the other hand, when the arrival rate is high, the link load, especially for the maximum link load, affects the blocking performance. Therefore, the method with $th = 16$ shows best performance for the moderate and high arrival rate.

To explain the above discussions more clearly, we show the distributions of the distance and loads for each threshold in Figs. 10 and 11, respectively. Figure 10 shows that the distribution of the distance spreads to the right as the value of the threshold becomes smaller. When th is 8, the distances between the nodes become longer than any other topologies due to excess operations of cut–through. Therefore, blocking probability with $th = 8$ increases when comparing to the results with $th = 16$. From Fig. 11, the variance of the loads generally becomes small, as the threshold value decreases down from 88 to 16. However, when th is 32, the tail of the load distribution becomes heavier, i.e., shifts to the right. This is because that our heuristic method does not explicitly include the route selection mechanism of upper layer protocol, so the maximum link load could not be reduced whereas the average link load increases.

V. CONCLUSION

According to the trend of technological development of optical networks, large–scale optical networks will be constructed by interconnecting a number of local optical networks in the future. There is a possibility that topologies of such large–scale optical networks exhibit the power–law attributes rather than the properties of random networks. However in traditional studies on WDM–based networks, the objective physical topologies are not large and rely on random networks. We investigated the performance of large–scaled WDM networks whose topologies follows the power–law. The results show that high–degree nodes in the power–law networks are easy to be congested and that the congestion at those nodes causes the decline of performance of blocking probability. To resolve this problem, we proposed a virtual fiber configuration method to accelerate the performance of WDM networks with physical topologies following the power–law. We evaluated our method by simulation and confirmed that our proposed method is efficient for power–law networks to improve the blocking probability.

For future research work, we plan to consider the way to determine thresholds of maximum degree. One possible candidate is to use the results of analyzing the structural properties of the topologies exhibiting the power–low attributes.

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