Virtual Fiber Configuration for Dynamic Lightpath Establishment in Large–Scaled Optical 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, interconnections among 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 performance 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.

Index Terms

WDM (Wavelength Division Multiplexing), lightpath, large–scaled network, power–law

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1. INTRODUCTION

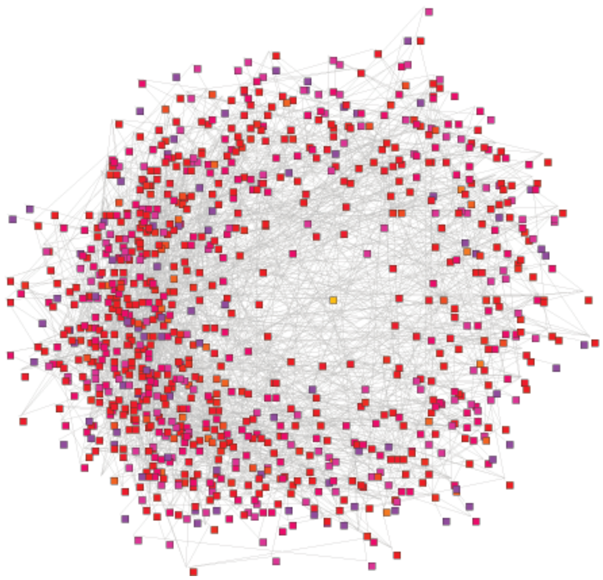
The rapid growth in the traffic volume of the Internet has led to demands of higher capacities for backbone networks. Wavelength Division Multiplexing (WDM) technology multiplexes different signals with exclusive wavelength bandwidths in a single fiber. Therefore, WDM is expected as an approach to satisfy those demands and optical networks employing the technology has been employed to improve cores of Wide Area Networks (WANs) [1–6] and Metropolitan Area Networks (MANs) [7, 8]. WDM networks with OXCs (optical cross connects) have the wavelength–routing capability. In these networks, a wavelength channel, called a lightpath, is established from a source node to a destination node for data transmission [1, 2, 9]. Related to WDM networks, progress has been made in Generalized Multi–Protocol Label Switching (GMPLS) [10] and Automatic Switched Optical Networks (ASONs) [11]. These new architectures realize communications over heterogeneous and multi–domain optical networks. By utilizing these, optical networks of WANs and MANs will be interconnected with each other and form large–scale optical networks.

Here we have a question. What kind of topologies do the large–scale optical networks have? It is difficult to assure the topologies of the future optical networks. To speculate about the answer, we refer to the topology of the Internet because, although it is a packet–switched network, it is constructed by interconnections between quite a number of ASs (Autonomous Systems) as large–scale WDM networks will be composed of a number of optical WANs and MANs. The topology of the Internet has attracted attention of researchers and it is known that the AS–level topology has the power–law connectivity [12, 13]. The power–law connectivity means that the probability $p(k)$ that a node is connected to k other nodes is proportional to $k^{-\gamma}$ (γ is a constant number such as $2 < \gamma < 3$). Briefly, most nodes have just a few links although some nodes have a number of links. This property is quite different from that of random network; each node has almost same number of connections in a random network.

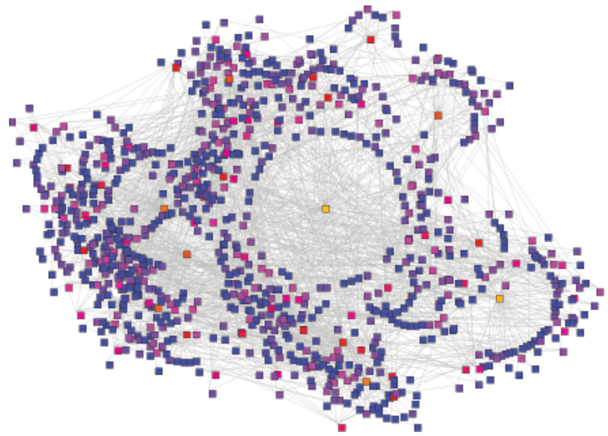
One might doubt that large–scale WDM networks will have the power–law connectivity since optical networks are carefully planned. It is true that intra–domain optical networks would be well planned and designed by their planners and operators. However, there are no coordinators for an entire inter–domain optical network, which is constructed by interconnections between lots of intra–domain optical networks. An extreme scenario for constructing large–scale optical networks 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 connectivity. In [14], Barabási and Albert have discussed about the origin of the property of the Internet topology and proposed the BA model to explain it. They have presented that a power–law network would be formed by a simple stochastic policy; new joining nodes tend to be connected with high–degree nodes (see Section 2 for detail). Node placement and locality of connections are pointed out as additional factors for the power–law in [15]. It means that the geographical distribution of nodes is practically not uniformly random in space but heavy–tailed and that nodes tend to connect to close nodes instead of far–away nodes in distance. Another model, Highly Optimized Tolerance (HOT), has been introduced in [16]. That model produces the power–law network as a result of designing a robust structure. In [17], the authors have showed that the costs for last mile connections and the hop distances have the potential possibilities of being the origins of the power–law. In summary, the power–law connectivity is likely embedded in an large–scale inter–domain optical network as a result of the probable ways of adding new AS interconnections.

On the other hand, WDM–based networks focused in previous studies are relatively small (tens of nodes) and single–domain mesh–like or random networks that are supposed to be managed and controlled by their operators. Furthermore, although performances of large–scale networks with the power–law properties have been researched in [18, 19], those efforts are focused on packet–switched networks, not on circuit–switched networks and wavelength–routed networks. We therefore investigate performances of large–scale optical networks with *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 and evaluate the performances of those two types of topologies. Node degrees in random networks are almost uniform while those in power–law networks are biased as described above. Because of the biased degree distribution, distributions of loads on links in power–law networks are also unbalanced; some links are heavily loaded while most links are lightly loaded. As a result, blocking performance of power–law networks are worse than those of random networks. There are some way to resolve this problem. The simplest solution is enhancement of network equipments; installing or upgrading OXCs and fibers at heavily loaded parts. However, this solution requires too much investment in equipments to resolve the problem by itself. Next solution is using a link state based routing. Such a routing realizes well–balanced load distributions. But, meanwhile, it requires to distribute link state information and to update routing tables at each node frequently so as to perform well. This penalty is undesirable in particular for large–scale networks. Then we propose another solution based on *virtual fiber* configuration. We construct logical topologies over physical topologies by configuring virtual fibers and route lightpaths in logical topologies, not in physical topologies as in the normal way. By adopting our method, performances of WDM networks with the power–law connectivity are improved without any cost for network equipments and link state based routings. We evaluate our method by computer simulations and the results show that our method reduces more than one order of magnitude of blocking probability.



(a) Random network



(b) Power–law network

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

This paper is organized as follows. In Section 2, we show the difference of topological properties and performance between random and power–law networks. In Section 3, we introduce the concepts of virtual fiber. We describe and evaluate two types of methods to configure virtual fibers to revise the blocking probability in power–law networks in Section 4 and Section 5, respectively. Finally, we summarize our paper in Section 6.

2. 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 [20] in which links are randomly placed between nodes (Fig. 1(a)). We then introduce the BA (Barabási–Albert) model [14] 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)).

2.1 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

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

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 [21].

2.2 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.

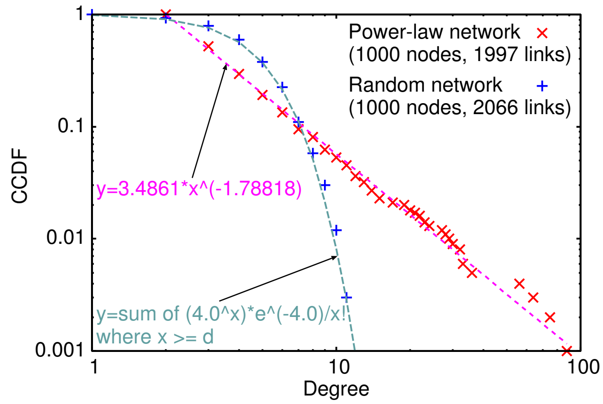


Fig. 2. Complementary cumulative distribution of node degrees in topologies generated with the ER and BA models

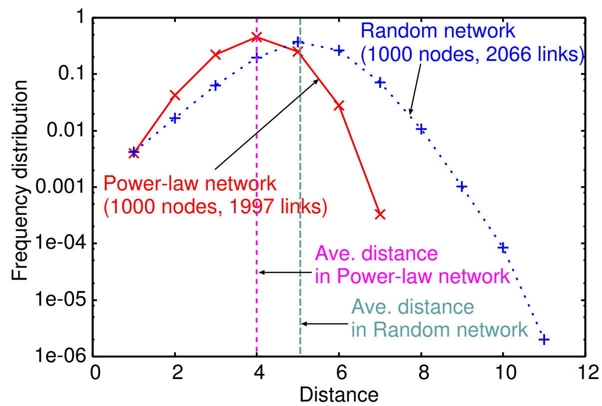


Fig. 3. Distributions of distances between nodes in topologies generated with the ER and BA models

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).

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

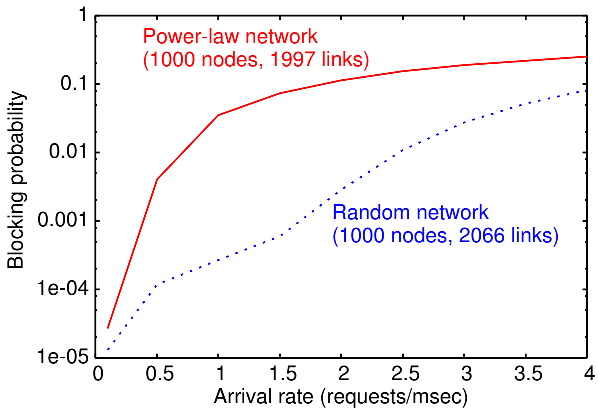
2.3 Properties of Random and Power–Law Networks

Figure 2 shows complementary cumulative distribution of node degrees in the topologies generated by the ER and BA models. The number of nodes is 1,000. 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. 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 due to the existence of hub nodes.

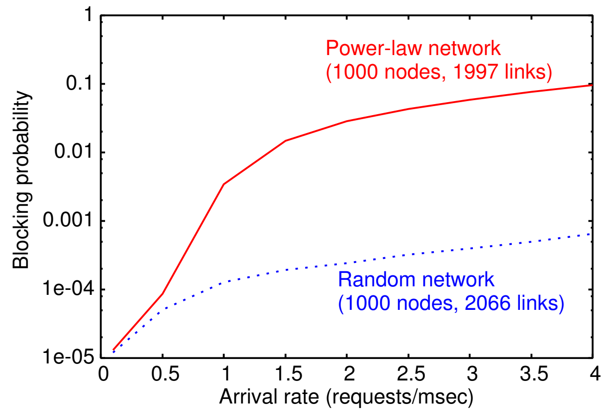
2.4 Performances of Random and Power–Law Networks

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



(a) 16 wavelengths



(b) 32 wavelengths

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

- 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 incoming and an outgoing 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 [9].
- Wavelength conversion is not available at any node.

Figure 4 shows the results of simulations with 16 and 32 multiplexed wavelengths. The horizontal axes represent arrival rate. The vertical axes represent blocking probability. λ is changed from 0.1 requests/msec to 4.0 requests/msec and μ is set to 1.0 per second, i.e., average holding time is 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. To see this more clearly, we measure load L_e on link e $(\in E)$. L_e means the number of node pairs whose lightpaths go through link e and given by Eq. (4). V is a set of the nodes in a network and E is a set of the links. $\pi_{i,j}$ is a set of the links included in the route of lightpaths from node i to node j. x_e is defined as Eq. (5).

$$L_e = \sum_{i,j \in V, i \neq j} x_e(\pi_{i,j}) \tag{4}$$

$$x_e(\pi) = \begin{cases} 1 & (e \in \pi) \\ 0 & (otherwise) \end{cases} \tag{5}$$

We show the complementary cumulative distributions of L_e for a power–law network and a random network in Fig 5. From this figure, the link load distributions show much the same tendency to the node degree distributions; the link load distribution for a power–law network has heavy tail. That is, there are some heavy–loaded links in power–law networks and they increase the blocking probability. Based on the observations, in the following sections, we propose a new method to setup lightpaths more efficiently in power–law networks.

3. Virtual Fiber Configuration

In Section 2, we showed that the power–law connectivity of physical topologies in WDM networks increases blocking probabilities. The topological property 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 consider some approaches to moderate load concentration at hub nodes and introduce a solution using *virtual fiber*.

3.1 Approaches to Moderate Load Concentration

There might be some solutions to the load concentration in power–law networks. Here we pick up and discuss two main solutions. After that, we bring on our approach.

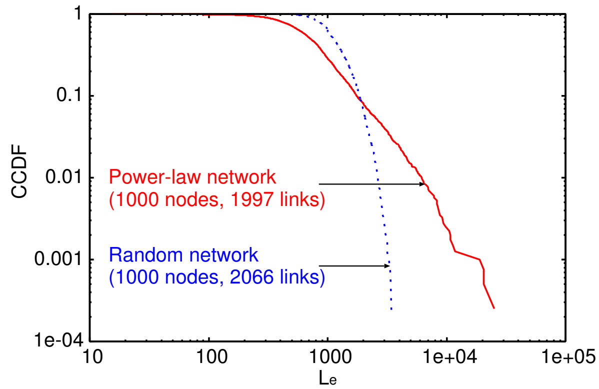


Fig. 5. Complementary cumulative distributions of link loads in topologies generated with the ER and BA models

1) Enhancement of Network Equipments: The simplest solution is enhancement of network equipments, i.e., installing more OXCs and fibers into heavily loaded parts in a network or upgrading those equipments. By adopting this, the amount of traffic that a network can accommodate is increased and, as a result, blocking probabilities for the network is improved. However, installing or upgrading network equipments requires much more investment. From a viewpoint of cost, we think it is difficult to moderate the load concentration by only this approach.

2) Link State Based Routings: Using link state based routings is a second solution. By utilizing link–state based routing, routes of lightpaths are diverted from heavily loaded links. Consequently, we realize load distribution in a network and decrease the blocking probability. But this kind of routing strategy requires newest link state information to perform well. Hence, we must frequently distribute link state information about all of the links and update a routing table at each node. It means that we have to prepare extra capacity for distributing link state information and that each node has overhead to calculate contemporary routes. This penalty is undesirable in particular for large–scale networks.

3) Changing topologies: To improve blocking probabilities of power–law networks without equipment investment and routing overhead, we consider another approach. In our approach, we logically change a topology having the power–law connectivity into another one that is more similar to a random network. How to change topologies logically is described in the following subsections.

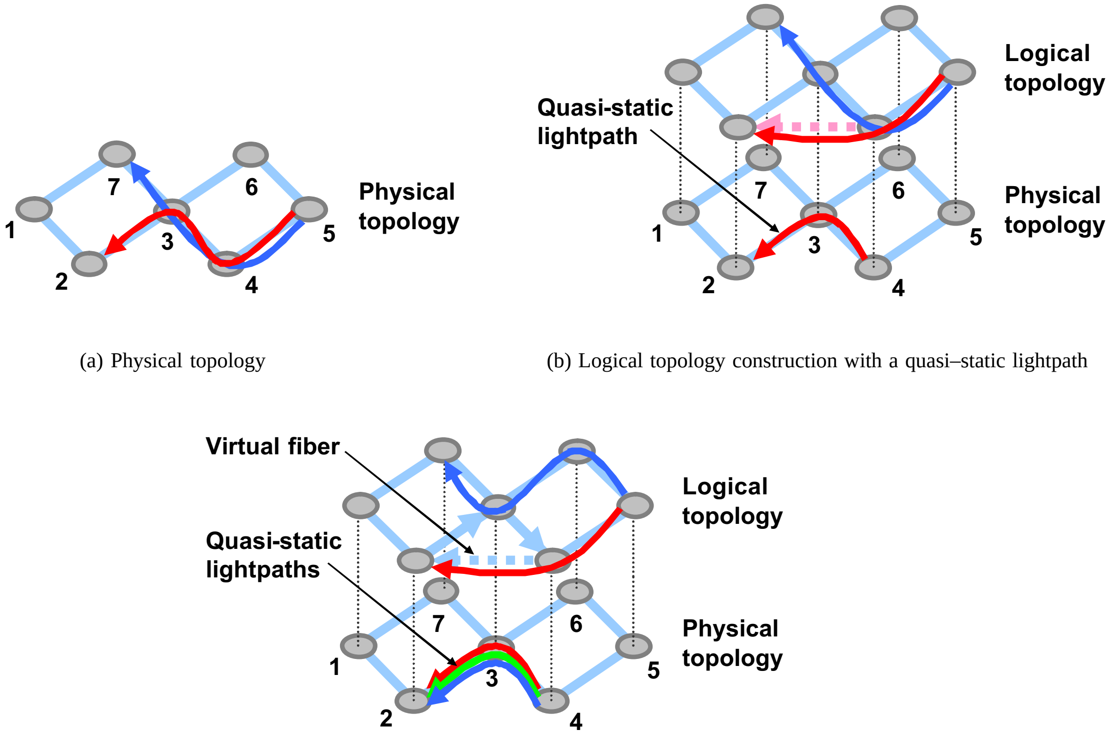
3.2 Concept of Quasi–Static Lightpath

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 static lightpaths designed for transporting IP packets or communications of other upper layers. Quasi–static lightpaths are reserved as parts of lightpaths. Those lightpaths are released after data transmission, but quasi–static lightpaths keep their configurations. Quasi–static lightpaths may not be reconfigured unless the traffic pattern is substantially changed. In this sense, the pre–configured lightpaths are quasi–static.

Figure 6(b) illustrates the concept of quasi–static lightpath. In traditional wavelength routing networks, lightpaths are routed and set up in 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 those reserved for the quasi–lightpaths. Then a logical topology is constructed over a physical topology as shown in Fig. 6(b) (the dotted line is a logical link by a quasi–static lightpath). In the situation of Fig. 6(a), when a lightpath from node 5 to node 2 is requested, we have to reserve a same wavelength in the three links, $5 \rightarrow 4$, $4 \rightarrow 3$, and $3 \rightarrow 2$ to establish it. However, in the case of Fig. 6(b), we have to reserve a same wavelength in only two links, $5 \rightarrow 4$ and $4 \rightarrow 2$, due to a logical link by a quasi–static lightpath.

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



(a) Physical topology

(b) Logical topology construction with a quasi–static lightpath

(c) Logical topology construction with a virtual fiber

Fig. 6. Logical topology construction (The links without arrows are bi–directional.)

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.

However, quasi–static lightpath configuration has a disadvantage that it makes vulnerable parts to traffic load in a network. Each of logical links by quasi–static lightpaths has only one available wavelength while fibers, which devote their wavelengths to quasi–static lightpaths, lose some of available wavelengths. In the case as in Fig. 6(b), link $4 \rightarrow 2$ can accommodate only one request at a time. At the same time, links $4 \rightarrow 3$ and $3 \rightarrow 2$ has only $w-1$ available wavelengths, assuming that the total number of wavelengths is w; those links can accommodate only $w-1$ requests at a time. Thus, for effectively utilizing the quasi–static lightpaths, it is necessary to append traffic engineering mechanisms to a routing architecture, i.e., we have to use link state based routings. Therefore, we use *virtual fibers* instead of quasi–static lightpaths in order to construct logical topologies.

3.3 Virtual Fiber: Bundle of Quasi–Static Lightpaths

Virtual fiber is equivalent to a bundle of quasi–static lightpaths for all of the wavelengths. Virtual fiber configuration is illustrated in Fig. 6(c). Quasi–static lightpaths from node 4 to node 2 via node 3 are configured for all of the wavelengths (here we assume $w = 3$). We regard a set of these quasi–static lightpaths as a fiber in a logical topology. We call this operation *cut–through* hereafter. Then, node 4 gets a fiber to node 2, which has w available wavelengths. Instead of the virtual fiber, node 4 loses a fiber to node 3 in the logical topology and node 2 loses a fiber from node 3. As for node 3, it loses an incoming fiber and an outgoing fiber. That is, the degrees of intermediate nodes of a virtual fiber are reduced by one for each.

Since fibers reserved for virtual fibers vanish in a logical topology, some node pairs have to change routes of lightpaths. In Fig. 6(a) and Fig. 6(b), the route of a lightpath from node 5 to node 7 is $5 \rightarrow 4 \rightarrow 3 \rightarrow 7$. But, in Fig. 6(c), fiber $4 \rightarrow 3$ disappears in the logical topology. The route of a lightpath from node 5 to node 7 is changed to $5 \rightarrow 6 \rightarrow 3 \rightarrow 7$ in that case. Although this seems a demerit of virtual fiber configuration at first glance, it is useful for load distribution. For example, in Fig. 6(a) and Fig. 6(b), fiber $4 \rightarrow 3$ is heavily loaded. However, this load concentration is moderated by a cut–through operation as in Fig. 6(c).

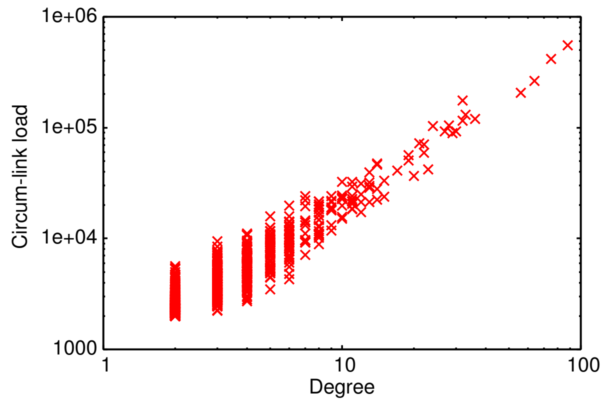


Fig. 7. Correlation between degree and circum–link load

4. Virtual Fiber Configuration Method

In this section, we propose two types of virtual fiber configuration method, degree based and load based. The basic strategy of our method is reducing degrees of heavily loaded nodes, which would mainly be hub nodes, by cut–through operations and bypassing some of the heavy traffic. In degree based method, we regard high degree nodes as heavily loaded nodes since shortest paths between nodes tend to pass through hub nodes in power–law networks. In load based method, we utilize circum–link load as the metric. Circum–link load of a node i, c_i defined by Eq. (6), means the sum of loads on the links connected with a node i.

$$c_i = \sum_{(i \to j) \in E} L_{(i \to j)} + \sum_{(j \to i) \in E} L_{(j \to i)} \tag{6}$$

To configure virtual fibers efficiently, circum–link load is more suitable for the metric than node degree because the purpose of virtual fiber configuration is load distribution. But circum–link load is so variable by change of traffic pattern that we have to recalculate it after every cut–through operation. On the other hand, degree is independent of traffic pattern and correlated closely with circum–link load as shown in Fig. 7. Thus, we consider degree based and load based methods.

We explain the outline of our methods with an instance illustrated in Fig. 8. Here we use degree as the metric. Figure 8(a) shows a hub node 0 and its adjacent nodes 1 to 80 in a power–law network (the other nodes and links are omitted here). The numbers described beside nodes are degree. Supposed that the degree of node 0 is maximum in the network. It is reasonable to expect that larger amount of traffic is transmitted through higher degree (i.e., more heavily loaded) nodes. If so, for node 0, incoming traffic from node 1 is heavier than those from the other adjacency nodes. In the same way, for node 0, outgoing traffic to node 2 is heaviest among those to the other adjacency nodes except to node 1. Then we prepare a virtual fiber from node 1 to node 2 via node 0 and construct a logical topology like Fig. 8(b). This cut–through operation splits traffic through node 0 into two factions, i.e., traffic from node 1 to node 2 and the other by the virtual fiber. Additionally, this operation diverts traffic from node 1 to the other adjacent nodes and from the other adjacent nodes to node 2 from node 0, as a result. Thus, load on node 0 is reduced and distributed.

Our proposed method repeats the above heuristic process. The details of our method are described below.

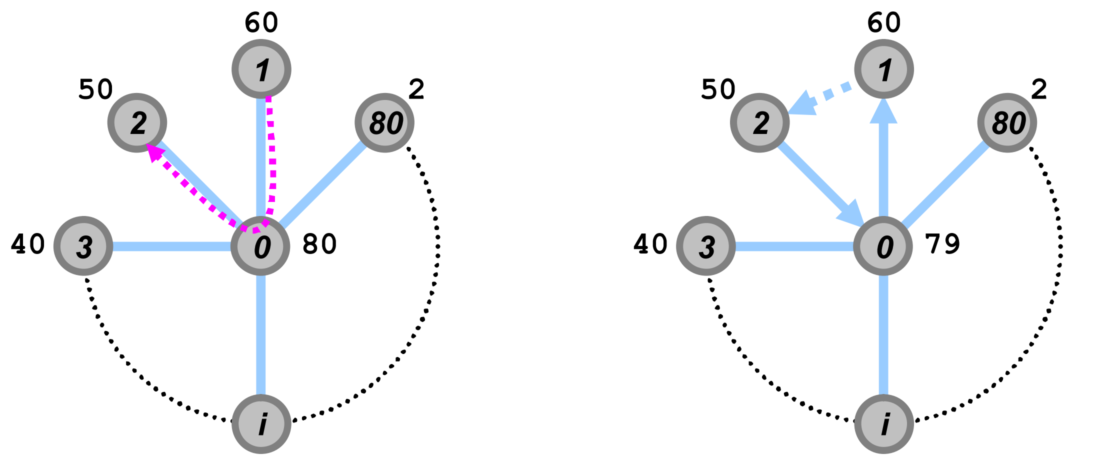
4.1 Notations

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 in a logical topology.
A^n_{in}:	Set of the adjacent nodes, which are connected to a node n.
A^n_{out}:	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.
d_n:	Degree of a node $n \in N$.
c_n:	Circum–link load of a node $n \in N$.

4.2 Degree Based Virtual Fiber Configuration Method

Step 1: Set the value of th such that $th > 2$. Go to Step 2.
Step 2: If $max\ d_n > th$ $(n \in N)$, then $n_0 \leftarrow n$ and go to Step 3. Otherwise, go to Step 5.



(a) Physical connectivity of a hub node

(b) Cut–through a hub node (A dotted arrow is a virtual fiber.)

Fig. 8. Virtual fiber configuration around a hub node (Numbers described beside nodes are degree.)

Step 3: Search such a node pair (n_{in}, n_{out}) that $d_{n_{in}} + d_{n_{out}}$ is maximum where $n_{in} \in A_{in}^{n_0}$, $n_{out} \in A_{out}^{n_0}$, $n_{in} \neq n_{out}$, and $F_{n_{in},n_{out}} = \phi$. If it is found, ($n_1$, n_2) $\leftarrow$ (n_{in}, n_{out}) and go to Step 4. Otherwise, go to Step 5.

Step 4: $Cut(f_1, f_2)$ ($f_1 \in F_{n_1,n_0}, f_2 \in F_{n_0,n_2}$). go back to Step 2.

Step 5: Quit virtual fiber configuration.

In Step 1, we set the threshold th to determine a terminal condition. If the maximum degree is equal to or less than th, this method quit configuring virtual fibers. This evaluation is done in Step 2. The floor of th is two because, if $th = 1$, a generated logical topology is an uni–directed cycle graph. In Step 3, we select edge nodes of a virtual fiber via node n_0, n_1 and n_2, by the heuristic approach described above. Note that node 1 and node 2 must not be connected by a physical or virtual fiber yet at this point. This is because, if there is already a direct link between node 1 and node 2, a virtual fiber configured from node 1 to node 2 would have almost no effect for load distribution and be just waste of wavelength resources. If a node pair (n_1, n_2) satisfying the restriction is found, we operate cut–through from node n_1 to node n_2 via node n_0 and iterate a same process from Step 2. Thus, a maximum degree in a network decreased by one at every iteration.

4.3 Load Based Virtual Fiber Configuration Method

The algorithm of this method is almost the same as degree based method. Only one difference is that the metric is replaced with normalized circum–link load by the number of node pairs, $\tilde{c}_i = c_i/|N|(|N|-1)$, where $|N|$ is the number of nodes in a network. The restriction against the threshold th in degree based method is removed.

Step 1: Set the value of th. Go to Step 2.

Step 2: If $max\ \tilde{c}_n > th$ ($n \in N$), then $n_0 \leftarrow n$ and go to Step 3. Otherwise, go to Step 5.

Step 3: Search such a node pair (n_{in}, n_{out}) that $\tilde{c}_{n_{in}} + \tilde{c}_{n_{out}}$ is maximum where $n_{in} \in A_{in}^{n_0}$, $n_{out} \in A_{out}^{n_0}$, $n_{in} \neq n_{out}$, and $F_{n_{in},n_{out}} = \phi$. If it is found, ($n_1$, n_2) $\leftarrow$ (n_{in}, n_{out}) and go to Step 4. Otherwise, go to Step 5.

Step 4: $Cut(f_1, f_2)$ ($f_1 \in F_{n_1,n_0}, f_2 \in F_{n_0,n_2}$). go back to Step 2.

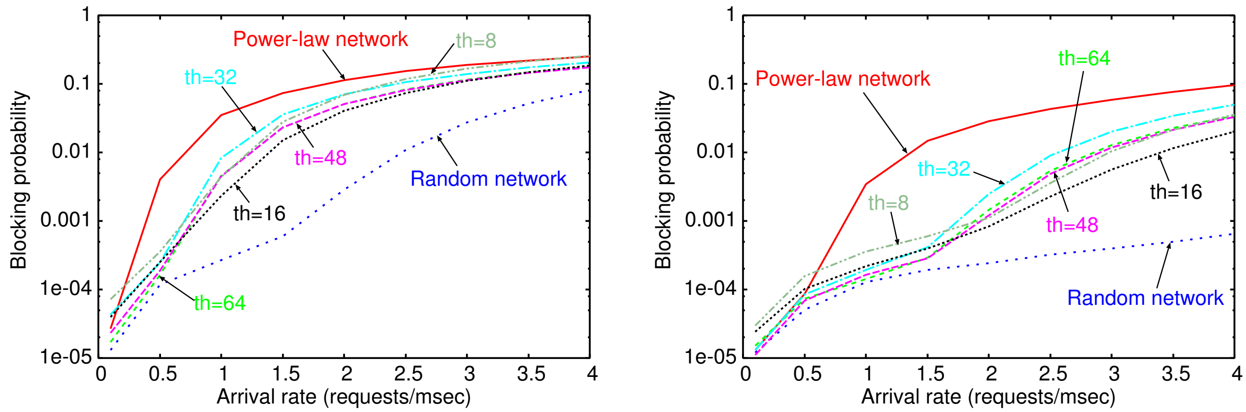
Step 5: Quit virtual fiber configuration.

5. Numerical Evaluation

We evaluated the performances of degree based and load based virtual fiber configuration methods with the same simulation model in Section 2.

5.1 Performance of Degree Based Virtual Fiber Configuration Method

The results of degree based virtual fiber configuration method are illustrated in Fig. 9. The maximum degree of the power–law network topology is 88. The degree thresholds we examined are 64, 48, 32, 16, and 8. Our proposed method reduces more than one order of magnitude of the blocking probability when the arrival rate is moderate. For lower arrival rates, our method performs best when th is 48 or 64. The performances for these thresholds are almost same all through



(a) 16 wavelengths (b) 32 wavelengths

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

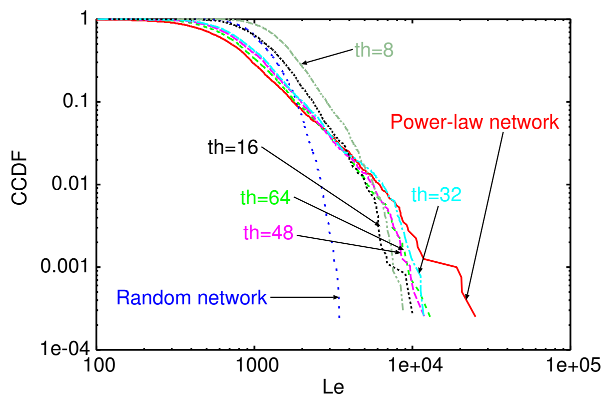


Fig. 10. Complementary cumulative distributions of link loads distances between nodes on logical topologies

the arrival rate. For higher arrival rates, $th = 16$ lets the degree based method perform better than the other thresholds. An optimal degree threshold depends on arrival rate.

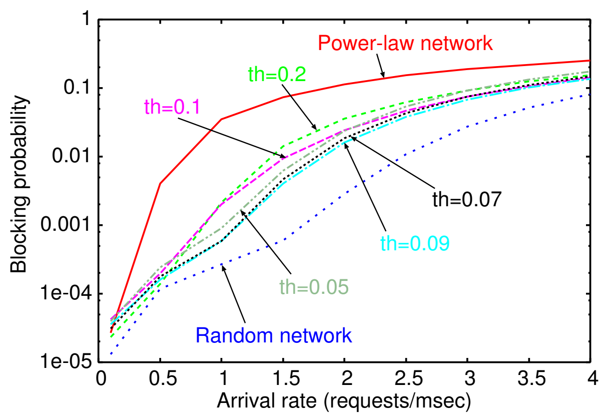
This fact is explained by the changes of distance and link load distribution. Table I shows average distance, average/maximum/minimum link load L_e, and number of links for each threshold. Note that a bi–directional link is counted as two uni–directional links here. Difference of the number of links in the power–law network, 3994, and a number of links in a logical topology is the number of cut–through operations. Cut–through operations reduce maximum or higher load. However, the reduction requires sacrifices from average load and average distance. This is because those operations logically decrease the number of links and make shortest paths through hub nodes unusable, i.e., link utilization becomes easier to be increased. When arrival rate of requests is low, blocking probability is much affected by distance rather than by link load L_e since offered load is also low. On the other hand, when arrival rate is high, link load, especially for maximum link load, affects the blocking probability: The higher link load L_e is, the more offered load for link e is likely to be increased. Therefore, the degree based method with $th = 16$ shows best performance for the moderate and high arrival rate while it performs better with $th = 64$ or $th = 48$ when the arrival rate is low.

When th is 8, since the distances between the nodes become longer than any other topologies due to excess operations of cut–through, blocking probability with $th = 8$ increases when comparing to the results with $th = 16$. In Table. I, it seems that there is little difference between $th = 48$ and $th = 32$. But as in Fig. 9, $th = 32$ is not a good threshold. Figure 10 shows the L_e distribution of each threshold. From this figure, although the maximum link load is decreased by reducing the degree threshold from 64 or 48 to 32, the frequency of heavily loaded nodes is higher. We consider this is because some links connected to nodes around hub nodes are overloaded. By configuring virtual fibers, routes between some node pairs passing through hub nodes are diverted and load originally for links connected to hub nodes is distributed. However, when th is 32, this load distribution does not work well and diverted routes from hub nodes tend to pass through certain links. The degree based virtual fiber configuration method decides where to be cut–through with only node degree information. But, instead of the simplicity and heuristics, it sometimes carries out unprofitable configurations. The other

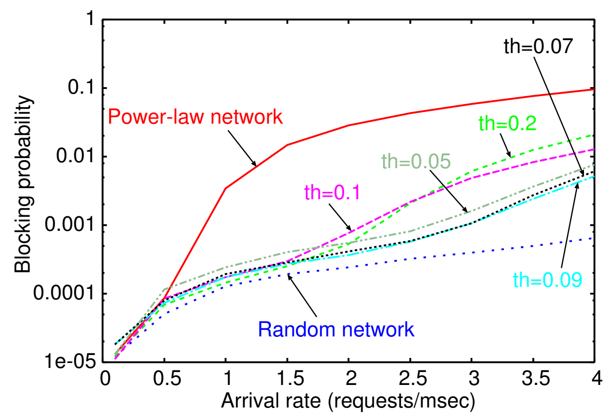
TABLE I

AVERAGE DISTANCE, AVERAGE/MAXIMUM/MINIMUM LINK LOAD, AND NUMBER OF LINKS OF LOGICAL TOPOLOGIES GENERATED BY DEGREE BASED VIRTUAL FIBER CONFIGURATIONS (A BI–DIRECTIONAL LINK IS COUNTED AS TWO UNI–DIRECTIONAL LINKS.)

Topology	Power–law network	$th = 64$	$th = 48$	$th = 32$	$th = 16$	$th = 8$	Random network
Average distance	3.99	4.15	4.33	4.47	5.09	5.92	5.06
Average L_e	998.89	1046.0	1107.1	1166.0	1406.9	1787.1	1222.5
Maximum L_e	25120	12905	11863	11786	9993	8745	3442
Minimum L_e	15	48	62	55	117	325	414
Number of links	3994	3959	3903	3834	3613	3314	4132



(a) 16 wavelengths



(b) 32 wavelengths

Fig. 11. Variation of blocking probabilities for different thresholds th in power–law networks

proposed method, load based virtual fiber configuration method revises this defect.

5.2 *Performance of Load Based Virtual Fiber Configuration Method*

We examined the performance of the load based virtual fiber configuration method when the normalized load threshold is 0.2, 0.1, 0.09, 0.07, and 0.05. The maximum normalized circum–link load of the power–law network is 0.552384. The simulation results are illustrated in Fig. 11. This method performs better than the degree based method when arrival rate is moderate or high. The results of $th = 0.09$ and $th = 0.07$ are similar all through the arrival rate. When the threshold is higher, i.e., 0.2 or 0.1, the blocking probability is worsen at high arrival rates. This is because the number of configured virtual fibers is not enough. Compared to the cases with the other thresholds, heavily loaded links still remain in a logical topology as illustrated in Fig. 12.

The maximum link load of the logical topology generated with load threshold 0.1 is higher than that of the logical topology generated with load threshold 0.2. Hence, the former topology is more sensitive to increase of arrival rate and its blocking probability gets higher than the blocking probability of the latter topology at moderate arrival rate. But this relation turns back at high arrival rate since link load is totally more well–balanced when th is 0.1. Relatively heavily loaded links (the middle of L_e distribution in Fig. 12) also affect increase of blocking probability at high arrival rate because offered load for those links becomes high. On the other hand, when the threshold has a lower value, 0.5, too many virtual fibers are configured and the blocking probability is also slightly increased. The performance of load based method is stable when th is about 0.09. It means that we do not need to reconfigure a logical topology so much according to the change of arrival rate of lightpath setup requests.

To compare the efficiency of our two methods, we list maximum degree, average distance, average/maximum/minimum link load, and number of links for each load threshold in Table II. Focusing on the load threshold is 0.09, the load based method reduces the maximum link load lower than the degree based method with less number of cut–through operations. In addition, the load based method keeps average distance and average link load lower not only than the degree based method with $th = 8$ but with $th = 16$. Thus, the load based method achieves better performance when arrival rate is high.

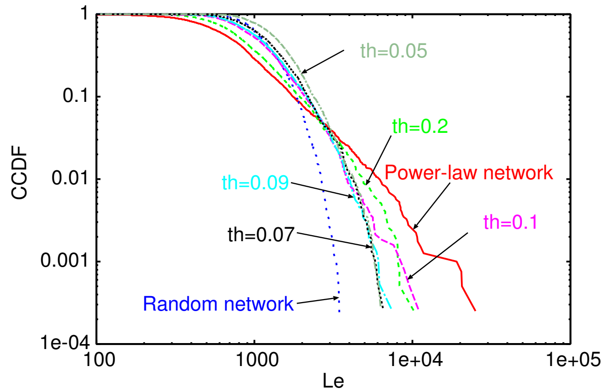


Fig. 12. Complementary cumulative distributions of link loads distances between nodes on logical topologies

TABLE II

MAXIMUM DEGREE, AVERAGE DISTANCE, AVERAGE/MAXIMUM/MINIMUM LINK LOAD, AND NUMBER OF LINKS OF LOGICAL TOPOLOGIES GENERATED BY LOAD BASED VIRTUAL FIBER CONFIGURATIONS (A BI–DIRECTIONAL LINK IS COUNTED AS TWO UNI–DIRECTIONAL LINKS.)

Topology	$th = 0.2$	$th = 0.1$	$th = 0.09$	$th = 0.07$	$th = 0.05$
Maximum degree	59	35	30	24	16
Average distance	4.24	4.66	4.75	4.95	5.38
Average L_e	1075.7	1229.1	1264.8	1345.3	1532.0
Maximum L_e	10182	10893	7315	6491	6281
Minimum L_e	53	86	40	56	104
Number of links	3934	3784	3750	3673	3510

6. 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 two 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 or maximum link load L_e. 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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REFERENCES

[1] I. Chlamtac, A. Ganz, G. Karmi, "Lightpath communications: An approach to high bandwidth optical WAN's," *IEEE Transactions on Communications*, vol. 40, pp. 1171–1182, July 1992.

[2] R. Dutta, G. N. Rouskas, "A survey of virtual topology design algorithms for wavelength routed optical networks," *Optical Networks Magazine*, vol. 1, pp. 73–89, Jan. 2000.

[3] B. Mukherjee, D. Banerjee, S. Ramamurthy, A. Mukherjee, "Some principles for designing a wide–area WDM optical network," *IEEE/ACM Transactions on Networking*, vol. 4, pp. 684–695, Oct. 1996.

[4] R. Ramaswami, K. N. Sivarajan, "Design of logical topologies for wavelength–routed optical networks," *IEEE Journal on Selected Areas in Communications*, vol. 14, pp. 840–851, June 1996.

[5] J. Bannister, J. Touch, A. Willner, S. Suryaputra, "How many wavelengths do we really need? A study of the performance limits of packet over wavelength," *Optical Networks Magazine*, vol. 1, pp. 11–28, Apr. 2000.

[6] R. H. Cardwell, O. J. Wasem, H. Kobrinski, "WDM architectures and economics in metropolitan areas," *Optical Network Magazine*, vol. 1, pp. 41–50, July 2000.

[7] "Comparing metro WDM systems: Unidirectional vs. bidirectional implementations," White paper, Cisco Systems, Inc., Jan. 2001.
[8] F. Bruyére, "Metro WDM," Alcatel telecommunications review, Alcatel, Mar. 2002.
[9] X. Yuan, R. Melhem, R. Gupta, "Distributed path reservation for multiplexed all–optical networks," *IEEE Transactions on Computers*, vol. 48, pp. 1355–1363, Dec. 1999.
[10] L. Berger, "Generalized Multi–Protocol Label Switching (GMPLS) signaling functional description," *RFC 3471*, Jan. 2003.
[11] S. Tomic, B. Statovci-Halimi, A. Halimi, W. Muellner, J. Fruehwirth, "ASON and GMPLS – overview and comparsion," *Photonic Network Communications*, vol. 7, pp. 111–130, Mar. 2004.
[12] M. Faloutsos, P. Faloutsos, C. Faloutsos, "On power–law relationships of the Internet topology," in *Proceedings of ACM SIGCOMM '99*, (Cambridge, MA, USA), pp. 251–262, Aug.–Sept. 1999.
[13] G. Siganos, M. Faloutsos, P. Faloutsos, C. Faloutsos, "Power laws and the AS–level Internet topology," *IEEE/ACM Transactions on Networking*, vol. 11, pp. 514–524, Aug. 2003.
[14] A.-L. Barabási, R. Albert, "Emergence of scaling in random networks," *Science*, vol. 286, pp. 509–512, Oct. 1999.
[15] A. Medina, I. Matta, J. Byers, "On the origin of power laws in Internet topologies," *ACM SIGCOMM Computer Communication Review*, vol. 30, pp. 18–28, Apr. 2000.
[16] J. M. Carlson, J. Doyle, "Highly optimized tolerance: A mechanism for power laws in designed systems," *Physical Review E*, vol. 60, pp. 1412–1427, Aug. 1999.
[17] A. Fabrikant, E. Koutsoupias, C. H. Papadimitriou, "Heuristically optimized trade–offs: A new paradigm for power laws in the Internet," in *Proceedings of 29–th International Colloquium on Automata, Languages, and Programming (ICALP 2002)*, (Málaga, Spain), pp. 110–122, July 2002.
[18] L. Qiu, Y. R. Yang, Y. Zhang, S. Shenker, "On selfish routing in Internet–like environments," in *Proceecdings of SIGOMM 2003*, (Karlsruhe, Germany), 2003.
[19] C. Gkantsidis, M. Mihail, A. Saberi, "Conductance and congestion in power law graphs," in *Proceedings of SIGMETRIC*, (San Diego, CA, USA), June 2003.
[20] P. Erdös, A. Rényi, "On the evolution of random graphs," *Publications of the Mathematical Institute of the Hungarian Academy of Sciences*, vol. 5, pp. 17–61, 1960.
[21] M. E. J. Newman, *Random Graphs as Models of Networks*, ch. 2, pp. 35–68. Berlin: WILEY–VCH, 1 ed., Nov. 2002.