Master's Thesis

Title

A Study on the Quasi–Static Lightpath Configuration Method in Large–Scaled WDM Networks

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Abstract

It is revealed that the AS (Autonomous System)–level and router–level topologies of the current Internet exhibit the *power–law*. In previous researches on optical networks constructed with WDM (Wavelength Division Multiplexing) technologies, relatively small networks with tens of nodes, that have at most 100 nodes, have been the objects of interest. And blocking performances have been performed with small numbers of nodes as physical topologies that do not follow the power–law. Recently, progress has been made in GMPLS (Generalized Multi–Protocol Label Switching) standardization, a technology which realizes interconnections of wavelength channels (lightpaths) between WDM networks. Therefore, as the topology of Internet constructed by interconnecting ASs exhibit the power–law, large–scale WDM networks, which are constructed by interconnecting local WDM networks, are also likely to exhibit the power–law attribute.

One of the structural properties of the topology that follows the power–law is that most nodes have just a few links, although some have a tremendous number of them. Because of this property, it is known that the shortest path route between nodes to pass across the high–degree nodes, and therefore requests of lightpaths conflict at the high–degree nodes. Furthermore, the circuit–switched nature of the WDM network has an inherent drawback that the performance such as blocking probability of requests is much dependent on the number of hops (i.e., the number of links that requests experience).

In this thesis, we first investigate the property of the power–law attribute of physical topologies for WDM networks. Our simulation results show that the required number of wavelengths multiplexed in the physical topologies that follow the power–law is much greater than that which follows an exponent, due to the wavelength continuity constraint. We therefore propose a quasi–static lightpath configuration method to utilize the wavelength resources more effectively for reducing blocking probability. In our method, the wavelength channels are prepared for cutting through the high–degree nodes, and for long–hop paths by which the actual number of hop counts can be decreased. We compare our method with no pre–determined lightpath by the computer simulation. The results shows the blocking probabilities are reduced more than 80% by adopting our method, and the method is effective especially when the arrival rate of lightpath establishment requests is relatively low.

Keywords

WDM (Wavelength Division Multiplexing), power–law, scale–free, lightpath, wavelength–routing, logical topology, distributed lightpath establishment

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1 Introduction

The rapid growth in Internet's traffic volume has led to demands for higher capacities in the backbone networks. WDM (Wavelength Division Multiplexing) is one approach expected to satisfy such demands. The technology multiplexes different wavelength channels with exclusive wavelength bandwidths on a single fiber. Recent developments in WDM technologies make it possible to multiplex more than 200 wavelengths, each of which has a transmission capacity of more than 10 Gbps, on a fiber [1]. For this reason, optical network employing WDM technology have been investigated and improved for adoption to backbone networks of large networks such as the Internet [2–5].

In addition to the high transmission capacity, WDM network has a wavelength–routing capability. In this network, each node has optical switches directly connecting an input wavelength to an output wavelength, by which no electronic processing is necessary at the node (Fig. 1). The incoming multiplexed signals are divided into each wavelength at the wavelength demux. Then, each signal is routed to an optical switch. The optical switch switches incoming signals to a preconfigured outgoing port. Finally, signals routed to wavelength mux are again multiplexed and transmitted to the next node. Then, the wavelength channel can be set up directly between two nodes via one or more optical switches (Fig. 2). Hereafter, we will call the wavelength channel directly connecting two nodes as a *lightpath* [6]. Viewing from the upper layer than the optical layer (e.g., IP layer), the nodes are directly connected via the lightpath (Fig. 3).

There are two approaches to establishing lightpaths. The one is a centralized approach where a special node sets up and tears down lightpaths. The other is a distributed approach where each node sets up and tears down lightpaths. In the centralized approach, by establishing "static" lightpaths, another topology is embedded over the physical topology, and it is called a *logical topology*. Many researchers have developed design methods for

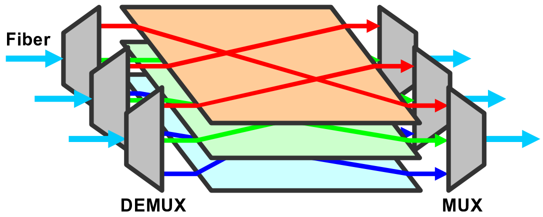


Figure 1: Node architecture

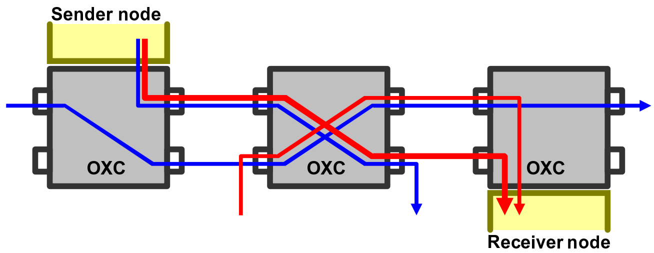


Figure 2: Lightpath establishment between nodes

the logical topology for transporting data packets [2–4]. For example, in [4], the authors consider the logical topology design problem together with packet routing problem so as to maximize the network throughput. Since the combined problem is computationally hard to solve, several heuristics are proposed to relax the computational burden [7].

In the distributed approach, when a data transfer request arrives at the sender node, one wavelength is reserved along the route between the sender and receiver nodes. After the data has been transferred using the lightpath, the reserved wavelength is released immediately. The centralized approach is suitable for networks in which traffic demands are not changed intensively. However, the centralized approach cannot deal with large–scale networks because the amount of state information of network components is enormous and much time is required to construct logical topologies. The distributed approach relaxes computational burden. Furthermore, because the distributed approach establishes lightpaths dynamically, effective use of the wavelength resources in the network is expected,

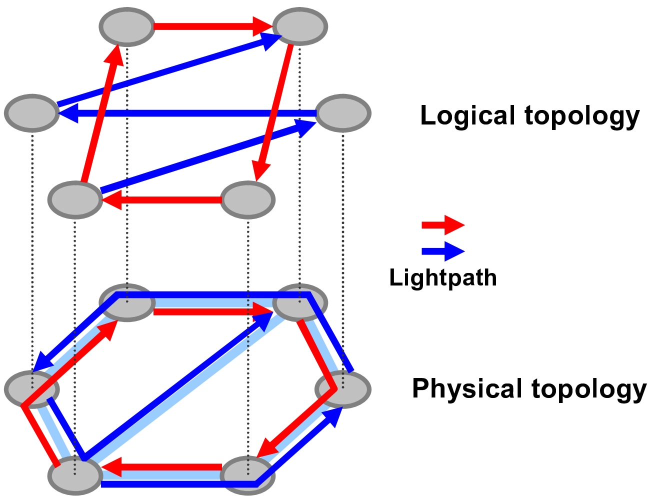


Figure 3: A network as seen from upper layer protocol

and therefore, actively investigated in recent papers [8, 9].

On the other hand, recent studies on Internet topology demonstrate that AS (Autonomous System)–level and router–level topology exhibit the power–law attribute. In such networks, the probability $p(k)$ that a node is connected to k other nodes follows this relationship [10, 11]: $p(k) \sim k^{-\gamma}$, therefore, most nodes have just a few connections, although some have a tremendous number of them. In that sense, such networks are called *scale–free* [12]. The Internet is constructed by interconnecting ASs, and each AS is independently planned and designed by its operators. It is, therefore, reasonable to assume that the network exhibits the AS's attributes. However, even if the entire design is carefully planned, similar attributes to the Internet emerge in such a network. This fact is investigated in a large–scale SDH (Synchronous Digital Hierarchy) transport network, which is composed of SDH circuits, and reported in [13, 14]. The authors consider that the properties are not unintended but originated by accommodating new demands. On the other hand, progress has also been made in GMPLS (Generalized Multi–Protocol Label Switching) standardization, a technology which realizes interconnections between WDM networks and other optical domains such as SDH [15].

According to the discussion above, it is predictable that the physical topologies of future large–scale WDM networks, which are constructed by interconnecting local WDM networks, are also likely to exhibit the power–law attribute. However, in traditional studies on WDM–based networks, relatively small networks, such as backbone networks with tens of nodes or random networks that have at most 100 nodes, have been the objects of interest. Hence, the properties of WDM networks whose physical topology has the power–law attribute have not yet been revealed.

In this thesis, we first investigate the relations between the required number of wavelengths to accommodate demands and the power–law attribute in large–scale WDM networks. The results show that the required number of wavelengths multiplexed in the physical topologies that follow the power–law is much greater than that which follows an exponent (that is the attribute of physical topologies targeted previous researches), due to the wavelength continuity constraints (see Sec. 3 for details).

Based on the observation, we propose a method to utlize the wavelength resources more effectively. For this purpose, we first introduce a concept of quasi–static lightpath which provides a logical single link to the dynamic establishment of a ligthpath, which means a lightpath between nodes consists of several quasi–static lightpaths. The lightpaths are quasi–static in a sense that it stays in a network for relatively long periods of time between the path setup requests. After introduction of the concept, we propose a lightpath configuration method for the quasi–static lightpaths. We evaluate our method by computer simulations with different topology models and the number of wavelengths multiplexed on a fiber.

This thesis is organized as follows. In Section 2, we show the attributes of physical topologies of random networks and scale–free networks. In Section 3, we investigate the distributions of demand by examining the required number of wavelengths for those networks with and without wavelength conversion, assuming infinite wavelengths. After that, we investigate the distributions of blocking probabilities with finite wavelength restriction. Section 4 describes a method for configuring quasi–static lightpaths to revise the blocking probability and we evaluate the performance of our method with numerical simulations. Finally we summarize our thesis in Section 5.

2 Topology Models

Though 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 [16], in which links are randomly placed between nodes. We then introduce the BA (Barabási–Albert) model [11], in which the topology grows incrementally and links are placed based on the connectivities of the topologies, thus forming the scale–free networks.

2.1 ER (Erdös–Rényi) Model

The ER model was suggested by Erdös and Rényi in order to describe communication networks. They considered that such systems could be modeled with connected nodes by randomly placed links. Those networks are usually called random networks. Therefore, the ER model is one that generates random networks, and this model requires that the number of nodes (N) in a network to be generated be fixed in advance. And every two nodes are connected with the same and fixed probability (p) that is a fixed value.

N: The number of nodes in a network to be generated ($N > 0$).

p: The probability that every two nodes will be connected ($0 < p < 1$).

The ER model generates topologies of random networks with those two parameters as follows.

Step 1: Locate N nodes.

Step 2: Connect every two nodes with the probability p.

Fig. 4 shows the cumulative distribution function of outdegrees of nodes in the topology of a random network generated by the ER model. The dumulative distribution function

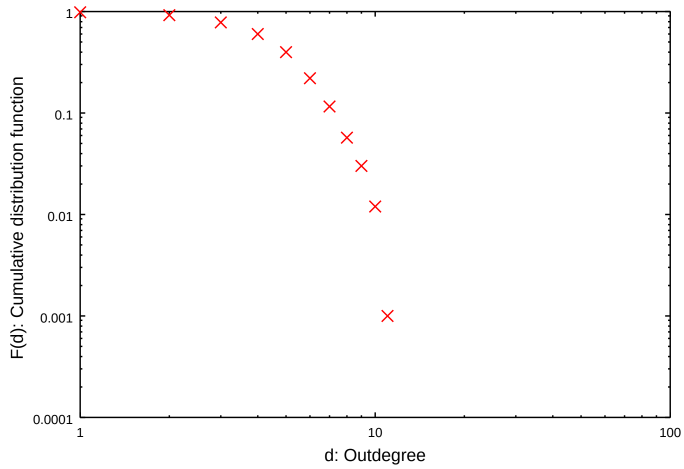


Figure 4: Cumulative distribution function of outdegrees in a topology generated with the ER model

$F(d)$ of variable d is defined as:

$$F(d) = \sum_{d}^{\infty} f(d). \tag{1}$$

There are 1,000 nodes present and the connection probability is 0.002. This figure shows that the distribution of outdegrees approximately follows an exponential distribution. That is, most of the outdegrees are gathered around the mean of the outdegrees.

2.2 BA (Barabási–Albert) Model

Barabási and Albert designed their model to emulate the growth of networks. The BA model includes two features, consequently, that the ER model does not have: *Incremental Growth* and *Preferential Attachment*. In this model, these following parameters are defined.

N: The number of nodes in a network to be generated ($N > 0$).

m_0: The small number of nodes initially placed.

m: The number of links appended when a node is added ($m \geq m_0$).

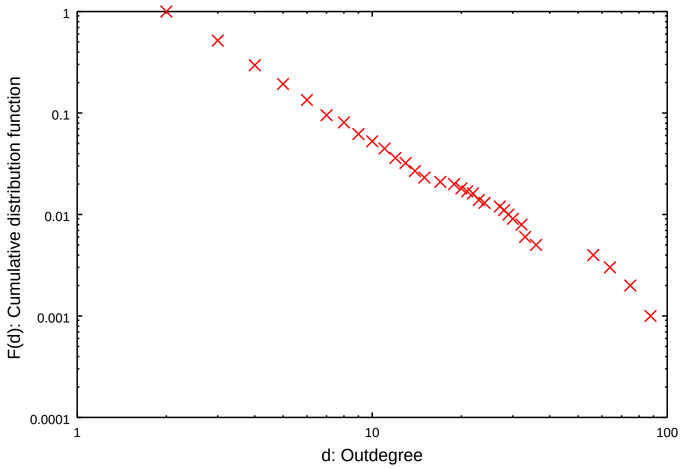


Figure 5: Cumulative distribution function of outdegrees in a topology generated with the BA model

k_i: The outdegree of node i.

$\Pi(k_i)$: The probability that a new node will be connected to node i. The value of the probability is given as:

$$\Pi(k_i) = k_i / \sum_j k_j. \tag{2}$$

The BA model generates scale–free network topology as follows.

Step 1: Place m_0 nodes.

Step 2: If the number of nodes is smaller than N, go to Step 3. Otherwise, quit the generation.

Step 3: Add a node (*Incremental Growth*).

Step 4: Connect the added node to other m ($\leq m_0$) different nodes with the probabilities (2) (*Preferential Attachment*). Go to Step 2.

Figure 5 presents the cumulative distribution function of outdegrees of nodes in the topology of a scale–free network generated by the BA model. There are 1,000 nodes present and $m_0 = m = 2$. This figure shows that the distribution of outdegrees is approximately aligned on a log–log plot, which indicates the distribution follows the power–law.

3 Performance of Scale–Free WDM Networks

If the physical topology of a WDM network is scale–free, a large variance on outdegrees strongly affects the performance of the network, such as in blocking probability. In this section, we investigate the distributions of the number of required wavelengths to accommodate demands and distributions of blocking probabilities.

3.1 Simulation Model

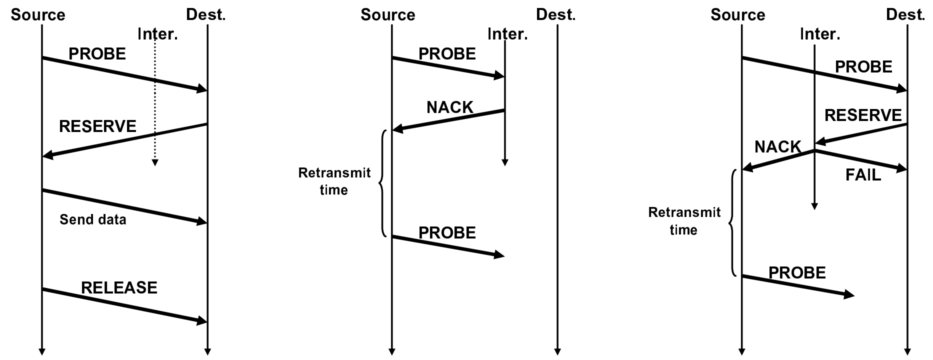
Physical topologies we employ in these simulations are generated with the ER and BA models. In addition, we assume the following conditions and restrictions:

- The number of fibers between a pair of nodes is one at most.
- Propagation delays of fibers and processing delays at nodes are ignored.
- A wavelength can be converted into any other wavelength at nodes if wavelength conversion is assumed.
- Arrivals of demands throughout the network follow a Poisson process with the average rate λ.
- Lifetimes of lightpaths follow an exponential distribution with the average rate $1/\mu$.
- Routes of lightpaths are shortest–hop routes.
- Wavelengths are assigned by the backward reservation protocol [17] (details are described in Sec. 3.1.1).

In addition, we set the parameters as follows: the number of nodes in a physical topology N is 1,000, and the connection probability of the ER model p is 0.002. The BA model starts with $m_0(= 2)$ nodes, and appends $m(= 2)$ fibers when a node is added to the physical topology. The arrival rate of demands λ is 1 request/sec, and the mean of lifetimes of lightpaths $1/\mu$ is 1.0 sec.

3.1.1 Wavelength reservation method

When a lightpath request arrives at the sender node, the wavelength must be reserved for the lightpath. Because several lightpaths cannot share a wavelength on a fiber, a method is needed to control the process of lightpath establishment in lightpath networks. The backward reservation is one of the methods for wavelength reservation [17]. The sender node generates a PROBE signal containing a set of available wavelengths on the next link, and transmits it to the receiver node. When an intermediate node receives the PROBE signal, it intersects the sets of available wavelengths on the next link and contained in the PROBE signal, and write in the PROBE signal. After updating the PROBE signal, the node transmits the signal to the next node. The set of wavelengths in the PROBE signal contains available wavelengths on the route when the PROBE signal arrives at the receiver node. The receiver node selects a wavelength from the available wavelengths in the PROBE signal, and transmits a RESERVE signal to reserve the wavelength on the path. Upon receiving the RESERVE signal at the sender node, the sender node acknowledges that the lightpath establishment has been successfully completed, and starts transferring the data. After the data have been transferred, the reserved wavelength is released via a RELEASE signal. Figure 6(a) shows a case of successful wavelength reservation. There are two cases when a request for wavelength reservation is rejected with the backward reservation protocol (Figs. 6(b) and 6(c)); one is when during the available wavelengths are being probed (a PROBE sequence), and the other is when the wavelength has already been reserved (a RESERVE sequence). Rejection upon the receipt of a PROBE sequence occurs when the set intersected by the intermediate node is empty. In this case, there are no available wavelengths on the route, and the intermediate node sends a NACK



(a) Case 1: Reservation success

(b) Case 2: Reservation failure (in probing)

(c) Case 3: Reservation failure (in reserving)

Figure 6: Backward reservation protocol

signal to the sender node. Rejection upon the receipt of a RESERVE sequence occurs when wavelength reservation conflicts with the establishment of another lightpath. When the wavelength reservation fails, a NACK signal is transmitted to the sender node, and a RELEASE signal is transmitted from the intermediate node to the receiver node to release the reserved wavelength.

3.2 Distribution of the Number of Required Wavelengths

Here we evaluate the number of required wavelengths to accommodate traffic demands in physical topologies with random connectivity and with scale–free properties. In this simulation, we assume that the number of wavelengths per fiber is infinite. Therefore, no demands are blocked. The results for the wavelength conversion and no–wavelength conversion are presented.

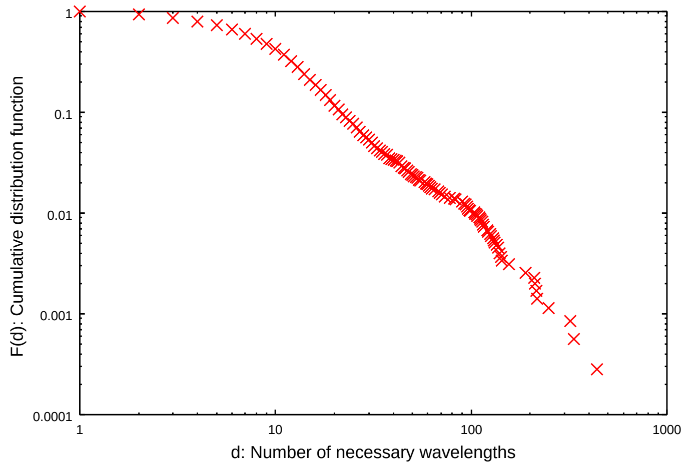


Figure 7: Distribution of the number of required wavelengths: the BA model with wavelength conversion

3.2.1 The Number of Required Wavelengths in Physical Topology with Scale–Free Properties

The cumulative distribution functions of the number of required wavelengths on each fiber in scale–free topology are shown in Figs. 7 and 8. Figure 7 shows the result with wavelength conversion, whereas Fig. 8 illustrates the result with no conversion. The vertical axis $f(d)$ represents the ratio of the number of fibers which are required at least d wavelengths.

Figure 7 shows that the distribution of required wavelengths follows the power–law. When wavelength conversion is available and wavelengths are allocated by the First–Fit method, wavelengths are reserved from those having the minimum ID in ascending ID order. Therefore, in this case, the number of required wavelengths equals the maximum number of lightpaths passing through.

In contrast, the case without wavelength conversion (Fig. 8), requires that many more fibers be used for a large number of wavelengths. The maximum numbers of required wavelengths in the two cases, plotted at lower–right in each figure, are almost same. Without wavelength conversion, every lightpath has to satisfy the wavelength continuity

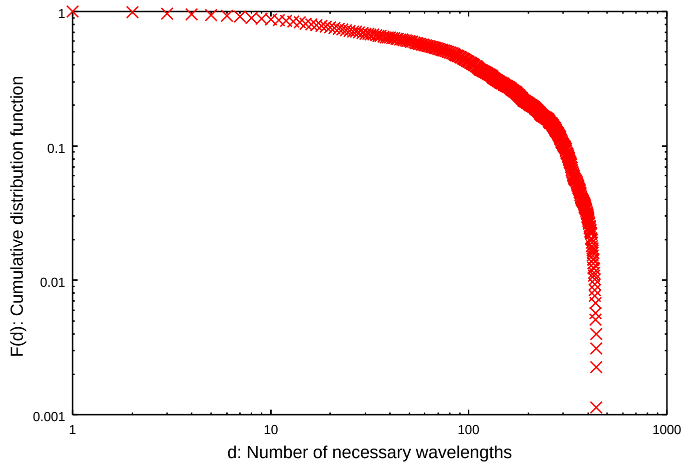


Figure 8: Distribution of the number of required wavelengths: the BA model without wavelength conversion

constraint on the fibers through which it passes, and this constraint causes an enormous increase in the required wavelengths in the fibers. However, each fiber accommodate the same number of lightpaths as wavelength conversion. Hence, the difference between the two distributions shown in Figs. 7 and 8 implies the quantity of free wavelength resources not used. Moreover, from these two figures indicate that the influence of the wavelength continuity constraint in scale–free WDM network is heavy.

3.2.2 The Number of Required Wavelengths in Physical Topology with Random Connectivity

We next show the results of simulations in physical topology with random connectives. The physical topologies are generated with the ER model. Figure 9 is the result with wavelength conversion and Fig. 10 is the one without. In each case, the maximum number of required wavelengths is smaller than that in scale–free topology. This is because the variance of outdegrees is small (in Fig. 4); in other words, each node is relatively uniformly connected to others. Therefore, there are few fibers needed for many lightpaths to pass

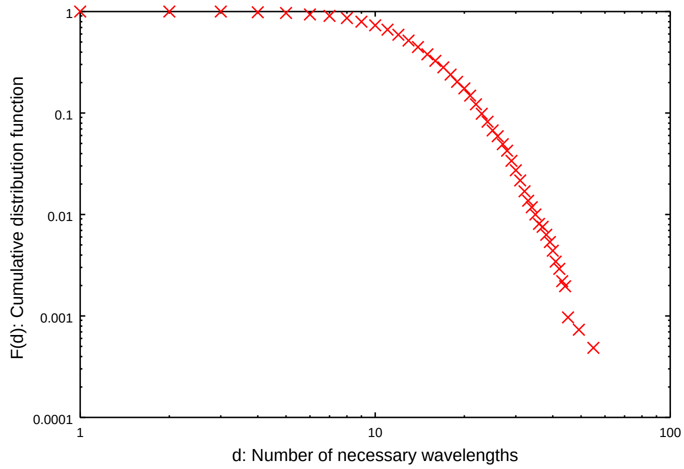


Figure 9: Distribution of the number of required wavelengths: the ER model with wavelength conversion

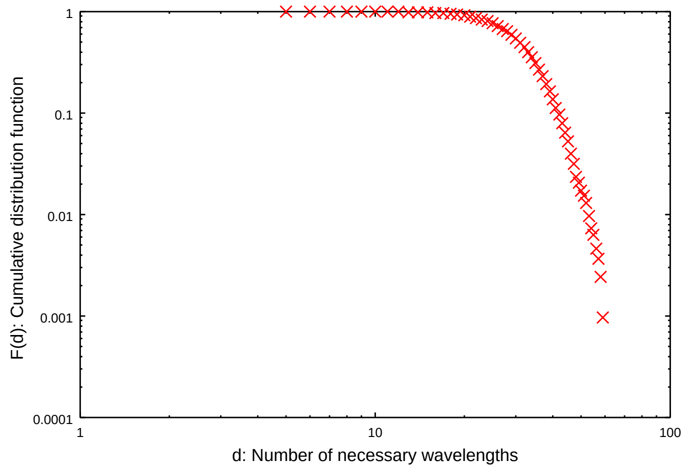


Figure 10: Distribution of the number of required wavelengths: the ER model without wavelength conversion

through, and the influence of the wavelength continuity constraint diminishes.

3.3 Distribution of the Blocking Probabilities

We next limit the number of wavelengths per fiber and evaluate the distribution of blocking probabilities at each node. Hereafter, we discuss the cases without wavelength conversion

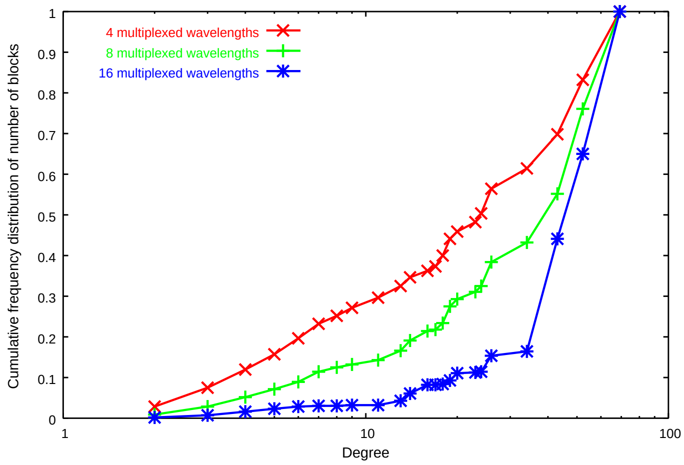


Figure 11: Cumulative frequency distribution of number of blocks

since wavelength continuity constraint is the fundamental problem of managing WDM networks to be resolved. Additionally, installation of wavelength converters takes much higher cost.

3.3.1 The blocking probabilities in physical topology with scale–free property

We measure the blocking probabilities of lightpath establishments by computer simulations. We use a scale–free topology which 500 nodes including a 69 degree node as the highest degree node. Requests arrives in a Poisson process with rate 1.0 requests /msec and the holding time of lightpaths follows an exponential distribution with the average 1.0 sec.

Figure 11 shows the results of simulations with 4, 8, and 16 multiplexed wavelengths. The horizontal axis represents node degree and the vertical axis represents the cumulative frequency distribution of number of blocks occurred at nodes that have the corresponding node degree. According to this figure, most of blocks are occurred at the high–degree nodes. This is because nodes which have many linkages are likely to be included minimum hop routes among nodes in scale–free networks, conflicts of wavelength resources tend to

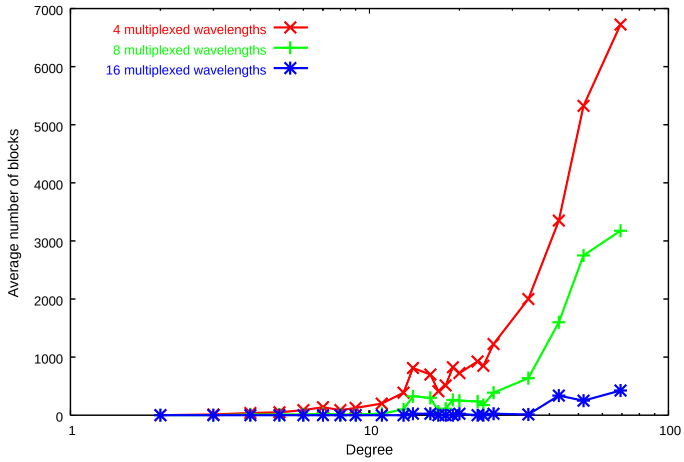


Figure 12: Average number of blocks

be occurred there. On the other hand, blocks are seldom happened at lowest–degree nodes. However, because there are many nodes with few connectivity in scale–free networks, the total number of blocks becomes large. To show this fact clearly, we show the average number of blocks happened at each degree node in Fig. 12. This result indicates that high–degree nodes are major bottlenecks in communication. Therefore, we focus on a few of the high–degree hub nodes to reduce the blocking occurrences and suggest an approach to eliminate blocks at those nodes in the next section.

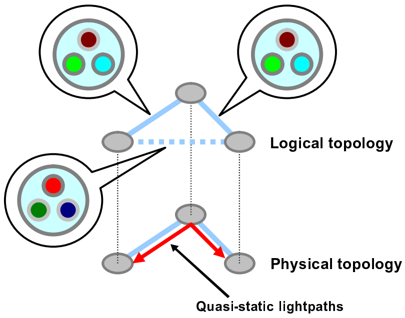
4 Proposal of Lightpath Configuration Method for Quasi–Static Lightpaths

In Section 3, we show that the power–law attribute of physical topologies in WDM networks makes blocking probabilities worse. The attribute leads most of the shortest path route between nodes to pass across the hub (i.e., high–degree) nodes, and therefore reservation conflicts occurs at the hub nodes. Further decline of the performance occurs in WDM networks with no wavelength conversion. This is mainly due to the wavelength continuity constraint that poses the use of the same wavelength along the path. In this section, to resolve those problems, we propose one approach to improve blocking probabilities by using *quasi–static lightpaths*.

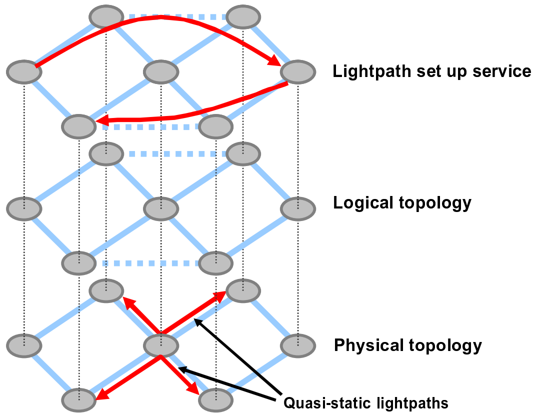
4.1 Concept of Quasi–Static Lightpath

In dynamic wavelength routing networks, lightpaths are established on demand basis and released after data transmission. However, the longer the number of hops (fibers) that lightpaths pass through, the harder to set up them because of inherent nature of the circuit–switch–based network (i.e., the lightpath with longer hops reserve more wavelength resources), and the wavelength continuity constraint strengthen the nature.

To resolve the unfairness of blocking probabilities against the different number of hop–counts, we prepare several lightpaths beforehand. We refer to the pre–configured lightpaths as quasi–static lightpaths. A quasi–static lightpath behaves a single hop link to the upper layer protocol: the quasi–static lightpath is reserved as a part of a lightpath. The lightpath is released after the data transmission, but the quasi–static lightpath keeps its configuration. The pre–configured lightpaths stay in a network for longer periods of time than lifetimes of usual lightpaths. In this sense, the pre–configured lightpaths are quasi–static. Quasi–static lightpaths are different from the conventional lightpaths which



(a) Quasi–static lightpath



(b) Structure of the service architecture

Figure 13: Concept of quasi–static lightpath

are considered to transport IP packets. Figure 13 illustrates the concept of quasi–static lightpaths. Quasi–static lightpaths behaves as a virtual fiber on the logical topology (the dotted lines in Fig. 13(a)). The wavelengths assigned the quasi–static lightpaths are free in the virtual fiber. Figure 13(b) shows the structure of a service architecture for lightpath establishments. The bottom of the figure represents the actual physical topology. Then, quasi–static lightpaths are configured to form virtual fibers and construct the logical topology. The top of Fig. 13(b) represents the service layer where lightpaths are dynamically established between communicating nodes and its wavelength reservation protocol is shown in Fig. **??**. The state of the physical topology is hidden against the upper layers and only the information of the logical topology is referred to establish lightpaths. In this case, the hop–counts between the left and the right nodes are decreased from 4 to 3.

There are two benefits of quasi–static lightpaths. First, fragmentation of wavelength resources can be avoided by setting up quasi–static lightpaths. When a network is congested, remaining free wavelength resources are too fragmented to be utilized to establish lightpaths because of wavelength continuity constraint. However, the constraint is always satisfied in the part of quasi–static lightpaths. Therefore, quasi–static lightpaths promotes the effective resource utilization. Second, quasi–static lightpaths make the distance between nodes shorter. 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. On the other hand, configuring the quasi–static lightpaths has a drawback that the flexibility of on–demand wavelength reservation may be lost.

On the other hand, quasi–static lightpaths have a drawback that the wavelength resources reserved for them lose flexibility because the wavelength resources of quasi–static lightpaths are kept reserved if quasi–static lightpaths are reserved or not. It is not allowed to reserve a part of quasi–static lightpaths. According to this drawback, where quasi–static lightpaths are settled and how many prepared are crucial problems to adopt quasi–static lightpaths. We, consider a heuristic approach to effectively set up quasi–static lightpaths in Section 4.3.

4.2 Degree–Based Method for Quasi–Static Lightpath Configuration

As we discussed in Section 3, there are mainly two bottleneck, i.e., blocking occurrence, parts in the scale–free network; lowest–degree nodes and highest–degree nodes. Since high–degree nodes are likely to be included minimum hop routes among nodes, conflicts of wavelength resources tend to be occurred there. Furthermore, in WDM networks, the wavelength continuity constraint makes the lightpath establishment difficult as the number of hops that lightpaths pass through increase. Our lightpath configuration method is intended to relax the concentration of load at high–degree nodes as well as to reduce the number of hops.

4.2.1 Notations

We introduce following notations for explaining our method.

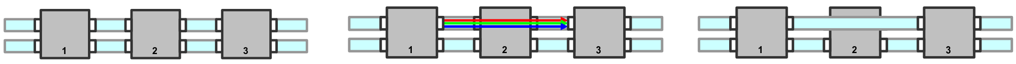
N:	Set of the nodes in a network.
F:	Set of the fibers in a network. This set includes the virtual fibers.
$F(n_1, n_2)$:	Set of the fibers placed from the node n_1 to the node n_2.
$d(n)$:	Degree of the node $n \in N$.
$A_{in}(n)$:	Set of the adjacent nodes which are connected to the node n.
$A_{out}(n)$:	Set of the adjacent nodes which are connected from the node n.

4.2.2 Cut–Through Operation

Before explaining our algorithm, we introduce an operation, which we call *cut–through*, used in our algorithm. This operation decreases the degrees of nodes by configuring quasi–static lightpaths using all wavelength resources. The process of this operation is illustrated in Fig. 14. Here we reduce the degree of the node 2 by establishing quasi–static lightpaths from the node 1 to the node 3 (Fig. 14(a)). The quasi–static lightpaths are configured using all wavelengths at two fibers: from the node 1 to the node 2 and from the node 2 to the node 3 (Fig. 14(b)). Then, two fibers form a virtual fiber (Fig. 14(c)). This operation decreases the in–degree and out–degree of the node 2 by 1. Hereafter, we denote the operation which merge two fibers, say f_1 and f_2, $CutThrough(f_1, f_2)$.

4.2.3 Heuristic Methods for Quasi–Static Lightpath Configuration

Here we describe two heuristic methods for quasi–static lightpath configuration. Both methods try to decrease the maximum degree of nodes in a network by using the cut–



(a) Before an cut–through operation

(b) Setup quasi–static lightpaths of all wavelengths

(c) Two merged fibers handled as a virtual fiber

Figure 14: Cut–through operation

through operation. The terminal condition is that the maximum degree of nodes is less than a given parameter $thres$.

Degree–Based Configuration Method

Step 1: Set the value of $thres$ such as $min\ d(n) \leq thres \leq max\ d(n)$ $(n \in N)$. Go to Step 2.

Step 2: If $max\ d(n) = thres$, go to Step 3. Otherwise, go to Step 2.1.

Step 2.1: Select a node that has the maximum degree and set to n_0. Formally, $n_0 \leftarrow n$, where n satisfy $d(n) = max\ d(n)$ $(n \in N)$. Go to Step 2.2.

Step 2.2: Among a set of neighbor nodes of node n_0, select two nodes, n_1 and n_2, so that $d(n_1)$ is the highest–degree in the set, $d(n_2)$ is the second highest, and $F(n_1, n_2)$ is ϕ. Then go to Step 2.3. If there are no nodes that satisfy this condition, go to Step 3 and stop the configurations.

Step 2.3: $CutThrough(f_1, f_2)$ $(f_1 \in F(n_1, n_0), f_2 \in F(n_0, n_2))$ and go back to Step 2.

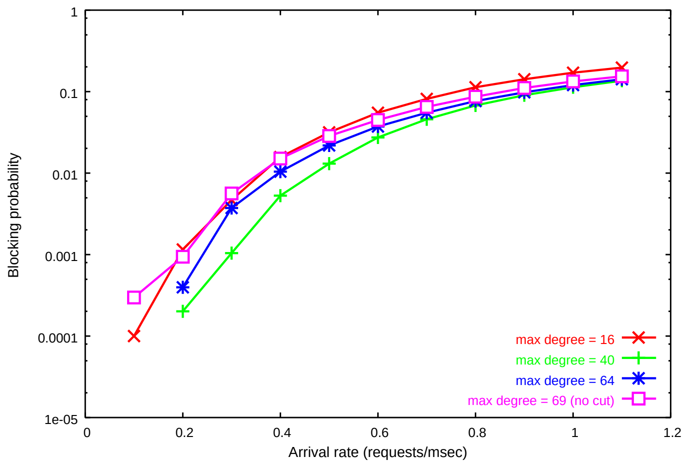
Step 3: Stop the quasi–static lightpath configurations.

Step 1 sets the threshold *thres*. In Step 2, the maximum degree in a network is compared with *thres*. If the terminal condition is satisfied, go to Step 3 and stop the lightpath configurations. In Step 2.1, we find a node that is the highest degree and tries to cut through the node. Step 2.2 selects two nodes to which the the virtual fiber is provided. When selecting two nodes, the condition that the fiber or virtual fiber has not been configured between two nodes is posed so as not to generate a self–loop. This is because two fibers that traverse different path cannot be used by the upper layer protocol.

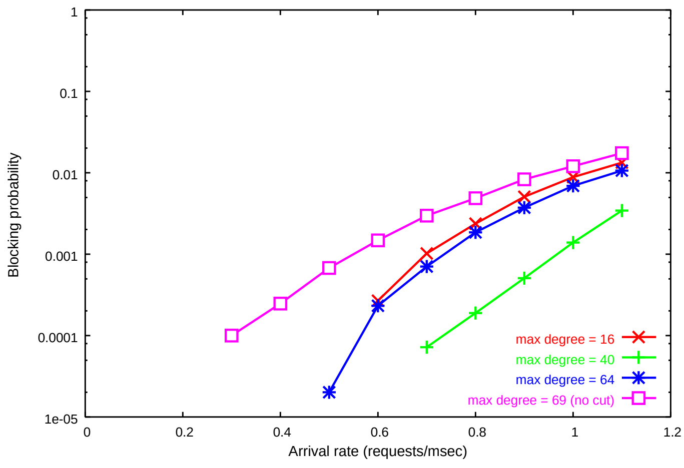
4.3 Numerical Evaluation

We evaluate the performance of degree–based configuration method by computer simulations. We use the same topology and lifetime distribution in Sec. 3.3.1. We simulate the situations that the highest degree of nodes in a network is set to 16, 40, 64. The results are presented in Fig. 15. Note that the highest degree in the physical topology is 69, so the results of conventional approach are denoted as "69".

In Fig. 15(a), when 8 wavelengths are multiplexed and the highest degree is set to 40, the result of our method shows better performance especially when requests arrival rate is low. However, when the highest degree is set to 16, the blocking probabilities get worse at the rates over 0.5 requests /msec than the blocking probabilities by no cut–through operation. Figure 15(b) represents the results when the number of multiplexed wavelengths is 16. This figure also shows that setting the highest degree to 40 greatly reduces the blocking probabilities. Blocks are not occurred when the arrival rate of requests is less or equal to 0.6 requests /msec. Moreover, even when the arrival rate is over 0.6 requests /msec, about 97% (at which the arrival rate 0.7 requests /msec) to 82% (at which the arrival rate 1.1 requests /msec) of the blocking probabilities are reduced by our method.



(a) Blocking probability with 8 multiplexed wavelengths



(b) Blocking probability with 16 multiplexed wavelengths

Figure 15: Performance of the degree–based method

5 Summary

In traditional studies on WDM–based networks, the objective physical topologies are relatively small and random mesh networks. In this thesis, we investigated the properties of large–scale and scale–free physical topologies and evaluated the influence of those properties with respect to the performance of WDM networks. The results of numerical simulations in scale–free physical topologies showed that, when wavelength conversion is possible, the distribution of the number of lightpaths passing through per fiber follows the power–law. It was also shown that lightpaths are gathered at some high-degree nodes, hence, for more wavelength resources are required at some hub nodes to accommodate demands. Furthermore, if the wavelength conversion is not allowed in a WDM network, the wavelength continuity constraint spreads out the influence around the hub nodes. To relax the concentration of lightpaths at high–degree nodes, we introduce the idea of a quasi–static lightpath and propose its configuration method. We evaluated our method with the scale–free physical topologies and we confirmed that our proposed method decrease the blocking probability, especially for large–scale networks.

There still remain some research issues. In this thesis, the centralized computation is assumed for the quasi–static lightpaths configuration. However, to apply much further large–scale networks, the distributed configuration method should be considered. Another issue is related to the parameter settings, such as the threshold of the maximum degree, in our method. One possible approach is to use the mathematical results of structural properties on scale–free networks, but it is left for our future research topics.

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