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大規模 WDM ネットワークにおける光パス設定手法の提案

石田　晋哉[†]　荒川　伸一[††]　村田　正幸[†††]

† 大阪大学大学院 情報科学研究科 〒 560–0043 大阪府豊中市待兼山町 1–32
†† 大阪大学大学院 経済学研究科 〒 560–0043 大阪府豊中市待兼山町 1–7
††† 大阪大学大学院 情報科学研究科 〒 565–0871 大阪府吹田市山田丘 1–5

あらまし　GMPLS (Generalized Multi–Protocol Label Switching) の標準化により，複数の WDM (Wavelength Division Multiplexing) ネットワーク間の接続が可能となりつつある．現在のインターネットでは AS (Autonomous System) 階層のトポロジーがべき乗則に従うことが示されていることから，複数の WDM ネットワークで構成される大規模ネットワークのトポロジーも同様に，べき乗則に従うと考えられる．本稿では，このようなネットワークにおいて，波長資源をより有効に利用し，棄却率を改善するための新たな光パス設定手法を提案する．計算機シミュレーションにより，この手法を適応した場合としない場合で性能評価を行った．その結果，本手法を用いることで，棄却率を 80% 以上改善できることが分かった．

キーワード　波長分割多重, べき乗則, スケールフリーネットワーク, 大規模ネットワーク

Quasi–Static Lightpath Configuration Method in Large–Scaled WDM Networks

Shinya ISHIDA[†], Shin'ichi ARAKAWA[††], and Masayuki MURATA[†††]

† Graduate School of Information Science and Technology, Osaka University,
Machikaneyama 1–32, Toyonaka, Osaka, 560-0043 Japan
†† Graduate School of Economics, Osaka University, Machikaneyama 1–7, Toyonaka, Osaka, 560–0043 Japan
††† Graduate School of Information Science and Technology, Osaka University,
Yamadaoka 1–5, Suita, 565–0871 Japan

Abstract　Recently, progress has been made in the Generalized Multi–Protocol Label Switching (GMPLS) standardization lets WDM (Wavelength Division Multiplexing) networks be interconnected. As known that the Autonomous System (AS)–level topologies of the current Internet are found to exhibit the power–law, large–scale WDM networks constructed by interconnecting local WDM networks will also exhibit the power–law attribute. In this paper, we propose a quasi–static lightpath configuration method to utilize the wavelength resources more effectively and to reduce blocking probability in such networks. We compared our method with one not using a pre–determined lightpath by computer simulation. The results show that our method reduces the blocking probabilities by more than 80%.

Key words　WDM (Wavelength Division Multiplexing), Power–Law, Scale–Free Network, Large–Scaled Network

1. 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. For this reason, optical networks employing WDM technology have been adopted to improve the backbone networks of large networks such as the Internet [1–4]. In addition to high transmission capacity, WDM networks have a wavelength–routing capability. In this network, a wavelength channel, called a lightpath, is established from a sender node to a destination node for data transmission [5]. Progress has also been made in Generalized Multi–Protocol Label Switching (GMPLS) standardization, a technology that realizes interconnections between WDM networks and other optical domains, such as

Syncronous Digital Hierarchy (SDH) [6].

On the other hand, recent studies of the Internet topology demonstrate that the Autonomous System (AS)–level and router–level topologies exhibit the power–law attribute. In such networks, the probability $p(k)$ that a node is connected to k other nodes follows this relationship [7,8]: $p(k) \sim k^{-\gamma}$; 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* [9]. The Internet is constructed by interconnecting ASs, and each AS is independently planned and designed by its operators. Therefore, it is 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 transport network, which is composed of SDH circuits, as reported in [10], and the authors consider that these properties are not arbitrary but function to accommodate new demands.

According to the discussion above, it is likely that the physical topologies of future large–scale WDM networks to be constructed by interconnecting local WDM networks, will also exhibit the power–law attribute. However, traditional 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. Hence, the properties of WDM networks whose physical topology has the power–law attribute have not yet been determined.

In this paper, we first investigate the relationship between the number of blocks of requirements for establishing lightpaths and the power–law attribute in large–scale WDM networks. The results show that many more wavelength reservations are blocked at the high–degree nodes in the physical topologies that follow the power–law because the high–degree nodes are probably included in the shortest routes of node pairs and because such nodes are congested with requests for wavelength resources. To reduce the blocks, our method utlizes the wavelength resources more effectively. First, we introduce the concept of a quasi–static lightpath whose entity is a static lightpath to provide a logical single link. By preparing quasi–static lightpaths, a logical topology is constructed on a physical topology, and lightpaths for transmitting data are dynamically established on the logical topology, which means that lightpaths for communication are established with wavelength resources of one or more quasi–static lightpaths. Based on this concept, we propose a configuration method for the quasi–static lightpaths to utilize wavelength resources more efficiently. We evaluated our method by computer simulations with different numbers of multiplexed wavelengths. The results shows that our method reduces the blocking probability to less than 10% in some cases.

This paper is organized as follows. In Section 2, we show the attributes of the physical topologies of the random network (used in traditional studies) and the scale–free network upon which this paper focuses. In Section 3, we investigate the distribution of reservation blocks. We describe a method to configure quasi–static lightpaths to revise the blocking probability and evaluate the performance of our method with numerical simulations in Section 4. Finally, we summarize our paper in Section 5.

2. Topology Models

Although 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 [11] in which links are randomly placed between nodes. We then introduce the BA (Barabási–Albert) model [8] in which the topology grows incrementally and links are placed based on the connectivities of the topologies to form scale–free networks.

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 k is given as

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

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

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

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 [12].

2. 2 BA (Barabási–Albert) Model

Barabási and Albert designed their model to emulate the growth of such large–scaled 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.

(2) *Preferential Attachment*: Connect the new node

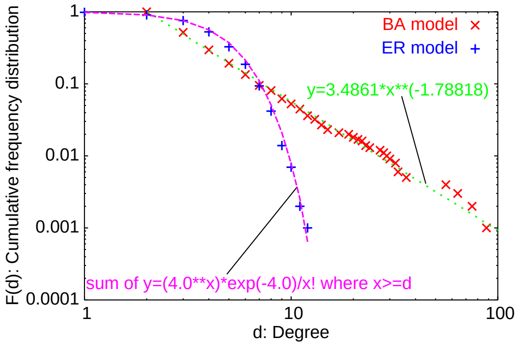


Figure 1 Cumulative frequency distribution of outdegrees in topologies generated with the ER and BA models

with two other different nodes, which are chosen with the probability Π (k_i is the outdegree of node i).

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

Figure 1 shows the cumulative frequency distribution of outdegrees (number of linkages) 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. The number of nodes at the initial phase and the number of links added at each timestep in the BA model are set as $m_0 = m = 2$. This figure shows that the distribution of the outdegrees of the random network approximately follows a Poisson distribution. That is, many nodes have outdegrees around their mean. Distribution of the outdegrees of the scale–free network is approximately aligned on a log–log plot, which indicates the distribution follows the power–law attribute.

3. Performance of Scale–Free WDM Networks

If the physical topology of a WDM network is scale–free, a large variance of outdegrees strongly affects the performance of the network, such as its blocking probability. In this section, we investigate the distribution of blocking probabilities.

3. 1 Distribution of the Blocking Probabilities in Physical Topology with Scale–Free Properties

We measured the blocking probabilities of lightpath establishment by computer simulations. The physical topologies we employed in these simulations were generated with BA models. In addition, we assume the following conditions and restrictions:

- The maximum number of fibers between a pair of nodes is one.
- The propagation delay of each fiber is 0.1 m sec, processing delays at the nodes are ignored.
- Arrival of demands between a node pair follows a Poisson process with an average rate λ.

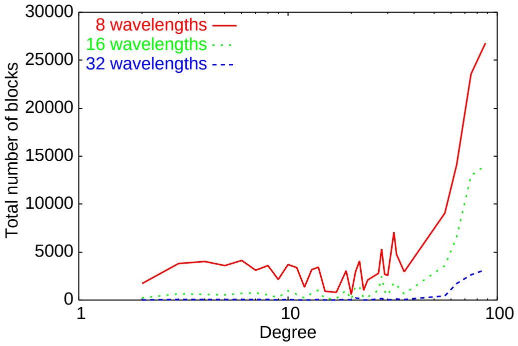


Figure 2 Distribution of blocks

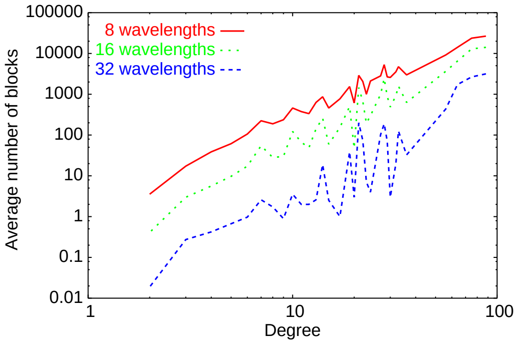


Figure 3 Average number of blocks

- Lifetime of lightpaths follows an exponential distribution with an average rate of $1/\mu$.
- Routes of lightpaths are the shortest–hop routes.
- Wavelengths are assigned by the backward reservation protocol [13].

In addition, we set the parameters as follows: the number of nodes in a physical topology N is 1,000. 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 0.004 requests/m sec, and the mean lifetime of the lightpaths $1/\mu$ is 1.0 sec.

Figure 2 shows the results of simulations with 8, 16, and 32 multiplexed wavelengths. The vertical axis represents the total number of blocks that occurred at the nodes having the same degree. The horizontal axis represents the node degree. This figure illustrates that most of the blocks occur at the high–degree nodes. This is because the nodes that have many linkages are likely to include minimum hop routes among the nodes in scale–free networks, and conflicts of wavelength resources tend to occur there. On the other hand, blocks seldom happen at the low–degree nodes in Fig. 3. The horizontal axis represents the node degree, and the vertical axis represents the average number of blocks that occurred at the nodes with the same outdegree. These results show that the high–degree nodes result in major bottlenecks in communication. Therefore, we focused on the hub nodes to reduce the blocking occurrences and in the next section suggest an approach to eliminate blocks at those nodes.

4. Proposal of Lightpath Configuration Method for Quasi–Static Lightpaths

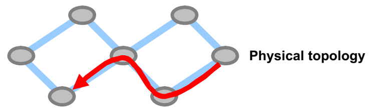
In Section 3, we showed that the power–law attribute of physical topologies in WDM networks increases the blocking probabilities. The attribute leads most of the shortest path routes between the nodes to pass across the hub (i.e., high–degree) nodes, and therefore reservation conflicts occur at the hub nodes. In this section, we propose to resolve those problems by decreasing blocking probabilities with *quasi–static lightpaths*.

4.1 Concept of Quasi–Static Lightpaths

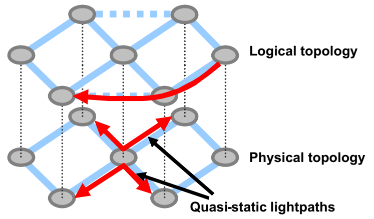
In dynamic–wavelength routing networks, lightpaths are established on a demand basis and released after data transmission. However, the more hops (fibers) that lightpaths pass through, the more difficult to setup becomes because of the inherent nature of a circuit–switch–based network (i.e., the lightpath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

To resolve the unequal number of blocking probabilities with different numbers of hop–counts, we prepared several lightpaths beforehand. We refer to such pre–configured lightpaths as quasi–static lightpaths. A quasi–static lightpath behaves as a single hop link to the upper–layer protocol; it is reserved as 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 longer than usual lightpaths. In this sense, the pre–configured lightpaths are quasi–static; they are different from conventional lightpaths which are designed to transport IP packets. Figure 4 illustrates the concept of quasi–static lightpaths. In traditional wavelength routing networks, lightpaths are set up on physical topologies composed of nodes and fibers, as in Fig 4(a). Quasi–static lightpaths behave as virtual fibers on the logical topology (the dotted lines in Fig. 4(b)). Only the wavelengths assigned to the quasi–static lightpaths are free in the virtual fibers. Lightpaths for communication are dynamically established between communicating nodes on the virtual topology, and a quasi–static lightpath is handled as a fiber in the routing protocol and in the wavelength reservation protocol. The state of the physical topology is hidden against the upper layers, and only the information contained in the logical topology is utilized to establish lightpaths. In the case of Fig. 4(b), the hop–counts between the left and right nodes are decreased from 4 to 3.

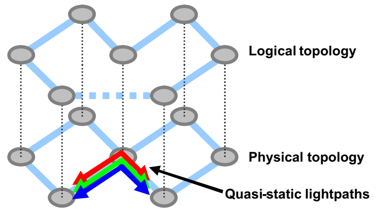
There are two benefits of quasi–static lightpaths. First, the fragmentation of wavelength resources can be avoided by setting up quasi–static lightpaths. When a network is congested, the remaining free wavelength resources are too fragmented to be utilized to establish lightpaths because of the wavelength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



(a) Traditional lightpath establishment



(b) Logical topology construction with quasi–static lightpaths



(c) Reduction of node degree with quasi–static lightpaths

Figure 4 Concept of quasi–static lightpaths

Furthermore, we can logically reduce the degrees of nodes by configuring quasi–static lightpaths to all wavelengths in a fiber. Hereafter, we call this operation *cut–through*. If quasi–static lightpaths are configured to all the wavelengths, as in Figure 4(c), the two fibers whose wavelengths are utilized to set up the quasi–static lightpaths have no available wavelengths on the logical topology. Therefore, the intermediate node of the quasi static lightpaths loses two fiber connections on the logical topology.

On the other hand, if a quasi–static lightpath is not utilized to establish a lightpath for data transmission, the wavelength resources reserved for the quasi–static lightpath are not utilized for communication. This is a drawback of quasi–static lightpaths. Accordingly, where to settle quasi–static lightpaths and how many of them to prepare are crucial problems before adopting 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, a scale–free network has a main area of bottleneck or blocking occurrences; at the highest–degree nodes. Since high–degree nodes are likely to include minimum hop routes among the nodes, conflicts of wavelength resources tend to occur there. Furthermore, in WDM networks, the wavelength continuity constraint makes the establishment of lightpath difficult as the number of hops increases that lightpaths pass through. Our lightpath configuration method intends to ease the concentration of the load at the high–degree node as well as to reduce the number of hops.

4. 2. 1 Notations

We introduce 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.
$d(n)$:	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.
$CutThrough(f_1, f_2)$:	Cut–through operation from a fiber f_1 to a fiber f_2.

4. 2. 2 Heuristic Methods for Quasi–Static Lightpath Configuration

Here we describe a heuristic method for quasi–static lightpath 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 $thres$.

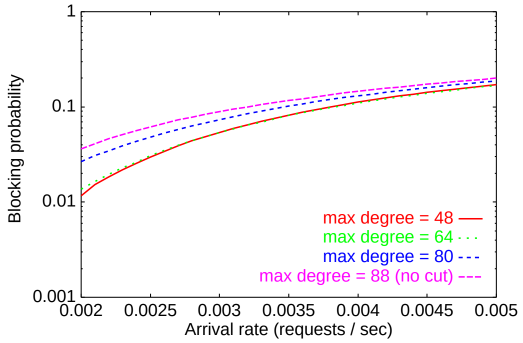


Figure 5 Blocking probability with 16 multiplexed wavelengths

a) Degree–Based Configuration Method

Step 1: Set the value of $thres$ such that $min\ d(n) \leqq thres \leqq max\ d(n)$ $(n \in N)$. 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 with the maximum degree and set to n_0. Formally, $n_0 \leftarrow n$, where n satisfies $d(n) = max\ d(n)$ $(n \in N)$. Go to Step 2.2.
- Step 2.2: Select two different nodes, n_1 and n_2, among sets of neighbor nodes of node n_0, $A_{in}(n_0)$ and $A_{out}(n_0)$, so that $F(n_1, n_2)$ is ϕ, and $d(n_1)$ and $d(n_2)$ are the highest–degree in the sets $A_{in}(n_0)$ and $A_{out}(n_0)$ respectively. 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: $CutThrough(f_1, f_2)$ $(f_1 \in F(n_1, n_0)$, b$f_2 \in F(n_0, n_2))$ 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 has the highest degree and try to cut through the node. Step 2.2 selects two nodes to which 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. This is because configuring a virtual fiber between two nodes that are already connected does not conduce to reduction of hop counts.

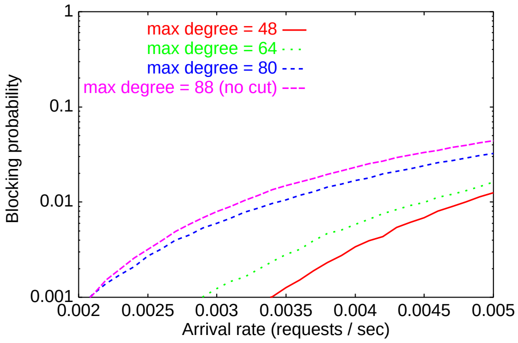


Figure 6 Blocking probability with 32 multiplexed wavelengths

4. 3 Numerical Evaluation

We evaluated the performance of the degree–based configuration method by the same simulation model in Sec. 3.1. We simulated the situations where the highest degree of nodes in a network is set to 48, 64, and 80. The results are presented in Figs. 5 and 6. The horizontal axes represent arrival rate of requests between a node pair per sec and the vertical axes represent blocking probability. Note that the highest degree in the physical topology is 88, so the results of the conventional approach are denoted as “88”.

when the arrival rate of requests is low. The blocking probability is reduced by 16%, when the arrival rate of requests is 0.005 (requests / sec) and the highest degree is reduced to 64, to 67%, when the arrival rate is 0.002 and the highest degree is reduced to 48. Figure 6 illustrates that the results when the number of multiplexed wavelengths is 32. This figure shows that setting the highest degree to 48 greatly reduces the blocking probabilities. When the arrival rate is 0.005, the blocking probability is reduced by 71%. Additionally, the blocking probability is reduced by more than 90% when the arrival rate is from 0.0025 to 0.0036. From these results, our method promotes more effective utilization of wavelength resources.

5. Conclusion

In traditional studies on WDM–based networks, the objective physical topologies are relatively small and rely on random mesh networks. In this paper, we investigated the properties of large–scale and scale–free physical topologies and evaluated the influence of those properties on the performance of WDM networks. The results of numerical simulations in scale–free physical topologies showed that wavelength requests for establishing lightpaths are gathered at the high–degree nodes in the network, so those nodes became the source of reservation blocks. To ease the concentration of lightpaths at high–degree nodes, we introduced a quasi–static lightpath and proposed its configuration method. We evaluated our method with scale–free physical topologies, confirming that our proposed method decreases the blocking probability, especially for large–scale networks.

Issues for research remain. In this paper, a centralized computation is assumed for the quasi–static lightpath configuration. However, to apply to much more large–scale networks, a distributed configuration method should be considered. Another issue in our method is related to such parameter setting as the threshold of the maximum degree. One possible approach is to use the mathematical results of structural properties on scale–free networks, but that is a topic for future research.

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References

[1] R. Dutta and G. N. Rouskas: “A survey of virtual topology design algorithms for wavelength routed optical networks”, Optical Networks Magazine, **1**, 1, pp. 73–89 (2000).
[2] B. Mukherjee, D. Banerjee, S. Ramamurthy and A. Mukherjee: “Some principles for designing a wide–area WDM optical network”, IEEE/ACM Transactions on Networking, **4**, 5, pp. 684–695 (1996).
[3] R. Ramaswami and K. N. Sivarajan: “Design of logical topologies for wavelength–routed optical networks”, IEEE Journal on Selected Areas in Communications, **14**, pp. 840–851 (1996).
[4] J. Bannister, J. Touch, A. Willner and S. Suryaputra: “How many wavelength do we really need? a study of the performance limits of packet over wavelength”, Optical Networks Magazine, **1**, 2, pp. 11–28 (2000).
[5] I. Chlamtac, A. Ganz and G. Karmi: “Lightpath communications: An approach to high bandwidth optical WAN’s”, IEEE Transactions on Communications, **40**, 7, pp. 1171–1182 (1992).
[6] E. Mannie: “Generalized multi–protocol label switching architecture”, Internet Draft draft–ietf–ccamp–gmpls–architecture–07.txt, Internet Engineering Task Force (IETF) (2003).
[7] M. Faloutsos, P. Faloutsos and C. Faloutsos: “On power–law relationships of the Internet topology”, Proceedings of ACM SIGCOMM ’99, Vol. 29, Cambridge, Massachusetts, USA, pp. 251–262 (1999).
[8] A.-L. Barabási and R. Albert: “Emergence of scaling in random networks”, Science, **286**, 15, pp. 509–512 (1999).
[9] A. L. Barabási and E. Bonabeau: “Scale–free networks”, Scientific American, **288**, 5, pp. 60–69 (2003).
[10] J. Spencer and L. Sacks: “On power–laws in SDH transport networks”, Proceedings of IEEE ICC 2003, Anchorage, Alaska, USA (2003).
[11] P. Erdös and A. Rényi: “On the evolution of random graphs”, Publications of the Mathematical Institute of the Hungarian Academy of Sciences, **5**, pp. 17–61 (1960).
[12] M. E. J. Newman: “Random Graphs as Models of Networks”, chapter 2, pp. 35–68, WILEY–VCH, Berlin, 1 edition (2002).
[13] X. Yuan, R. Gupta and R. Melhem: “Distributed control in optical WDM networks”, Proceedings of IEEE Conference on Military Communications (MILCOM’96), Vol. 3, pp. 100–104 (1996).