논문 13-38B-06-01
한국통신학회논문지 '13-06 Vol.38B No.06
http://dx.doi.org/10.7840/kics.2013.38B.6.417

Study on the Characteristics of the Korea Internet AS-Level Topology Using Node Degree and Node Connectivity Metrics

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ABSTRACT

The Korea Internet AS-level topology was constructed using three data sources: Border Gateway Protocol (BGP) trace collector, Internet Routing Registry (IRR), and Internet Exchange Point (IXP). It has 685 nodes and 1,428 links. The Korea Internet AS-level topology is a small regional subgraph of the massive global one. We investigate how well the Korea Internet preserves the topological characteristics of the global one or how different they are. We carefully select several topology metrics that can analyze the characteristics of the Korea Internet AS-level topology. We also investigate how well Internet topology generators can represent the characteristics of the Korea Internet AS-level topology.

Key Words : Autonomous System, Internet Topology, BGP, Node Degree Metrics, Connectivity Metrics

Ⅰ. Introduction

The proliferation of the Internet has been accompanied by a wide range of internetworking problems related to the Border Gateway Protocol (BGP), multicasting, robustness of the network under the attack, and administration. The study of algorithms and policies to address such problems often involves simulations or analyses using an abstraction or model of the actual Internet structure. Recently, the analysis and modeling of the Internet AS-level topology have been investigated in a number of studies [1,2,3,4,5,6,7,8] because the AS-level topology is an abstraction of the Internet, commonly used to analyze its macro-level characteristics. It can be also used to simulate the performance and scalability of new protocols and applications.

Various sources of Internet topology data obtained using different methodologies yield substantially different views of the Internet AS-level topology. Faloutsos et al. [9,10,11] examined the AS-level topology of the Internet using data collected by a route server from the BGP routing table of multiple geographically distributed routers with BGP connections to the server. They showed empirically that certain properties of the AS-level Internet topology are well described by power-laws. These power-laws capture concisely the highly skewed distributions of the graph properties. For example, for a particular snapshot of the Internet topology in 1998, 85% of the nodes had degrees less than the average. Several studies [12,13,14] have investigated power-laws in the AS-level topology, most of which were able to discern power-laws. However, Chen et al. [15] and Mahadevan et al. [4] found that the AS degree distributions constructed from the BGP table and extended data sources are slightly different from the strict power-law curves. The extended data sources include Traceroute [16], Internet Routing Registry (IRR) [17], and

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논문번호 : KICS2013-03-132, 접수일자 : 2013년 3월 11일, 최종논문접수일자 : 2013년 5월 23일

other publicly available full BGP routing tables. Mahadevan et al. [4] attempted to provide an analytical comparison of the most important properties of the topologies of Internet AS-level graphs extracted from the three commonly used data sources: (1) BGP table and update messages, (2) Traceroute measurement, and (3) IRR. They found that the BGP and Traceroute topologies are similar to one another, but differ substantially from the IRR. They also found that the node degree distribution of the IRR topology does not follow a power-law at all.

Despite a significant effort to obtain an accurate picture of the Internet AS-level topology, much remains unknown about the quality of inferred AS-level topology. Several studies have attempted to access the quality of inferred AS-level topology and unearth the missing links. Oliveira et al. [5,6] investigated which parts of the actual topology may be missing from the inferred ones. They found that inferred AS maps based on a single–period snapshot of publicly available BGP-based data are typically of low quality. They also provided evidence that the bulk of missing connectivity involves peer links, typically between stub ASes and small ASes, as well as among stub ASes. He et al. [11] suggested a framework for identifying the AS links that are missing in the AS-level topologies extracted from the commonly used data sources. They found that IXP (Internet Exchange Point) hides significant topology information and most of the newly discovered peer-to-peer AS links were incident at IXP.

Over the last decade, the Internet in Korea has developed rapidly. The number of ASes in Korea is 800 [18]. There were pioneering works [8,19], which investigated the node degree distribution of Korea Internet topology and power-law properties. However, no study has tried to answer the questions, “Are there any topological properties that characterize Korea Internet?” and “How can I generate Internet-like graphs for my simulation?”.

In this paper, we attempt to present the first and most complete picture of the Korea Internet AS-level topology. In our previous study [19] we critically reviewed the commonly used data sources and selected the most suitable ones to enhance the quality of inferred AS-level topology graphs. Using them we constructed the Korea AS graph. The objective of this study is to identify the topological properties which characterize the Korea Internet AS-level topology based on the Korea AS graph constructed in [19]. The Korea Internet AS-level topology is a small regional subgraph of the massive global one. We also want to see how well the Korea Internet preserves the topological characteristics of the global one or how different they are. For this purpose we introduce the following topology metrics and use them to try to characterize the Korea Internet AS-level topology: 1) node degree metrics (average, maximum, and distribution), and 2) node connectivity metrics (clustering coefficient, assortative coefficient, rich club connectivity, and distance distribution). In this study we also investigate how well Internet topology generators can represent the characteristics of the Korea AS graph. For this purpose the topology metrics of generated models are compared with those of Korea AS graph.

The remainder of this paper is organized as follows. In Section 2, data sources and the inferred AS graphs are presented, which is a brief review of our previous study [19]. In Section 3, we present the set of topology metrics and explain what they measure and why they are important. Using the estimated values of the proposed topology metrics, we analyze the topological characteristics and diagnose the efficiency of the Korea Internet. In Section 4 we discuss Internet topology generators. Finally, the conclusions are stated in Section 5.

Ⅱ. Data Sources and Korea Internet S-level Graph

2.1. Data Sources

In our previous study [19] we carefully reviewed all the available data sources [20,21,22,23,24,25,26] and selected three data sources for constructing Korea Internet AS-level graph: BGP data, IRR data, and IXP data.

1) BGP data: We used the UCLA "Internet Topology Collection" [23]. Its data sources include routing tables and updates provided by RouteViews, RIPE-RIS, and Abilene [24]. It also uses data from route servers and looking glasses. Data are collected over two months, which is believed to be the optimal period [1].
2) IRR data: The FTP server of APNIC (Asia Pacific Network Information Center) [25] provides the IRR data of Korea, which is updated daily.
3) IXP data: Korea has four IXPs. KISA (Korea Internet & Security Agency) provides the Internet connectivity map between ASes and IXPs, which is updated every month. The Internet connectivity map [26] is constructed based on the data input every month by Korean ASes. One IXP connects its members through a common layer-2 switch and the other three IXP's through layer-3 routers. If we click the ISP name on the map, we can see the corresponding AS number and the link connectivities with other ASes. Since these data are provided by government agency and updated every month, we can guarantee the accuracy and up-to-dateness of data.

2.2. Korea AS graph

In our previous study [19] we built the AS graph using three data sources and the results are summarized in Table 1. The final AS graph constructed from the three data sources has 685 nodes and 1,428 links. Let G_B, G_R, and G_X represent the graphs built from BGP, IRR, and IXP data, respectively. Table1 shows the comparison of G_B, G_R, and G_X

In "only G", the number of nodes (ASes) and links in the AS graph constructed only from a data source are given. For example, 70 nodes and 101 links can be newly found only in G_x, which can be constructed from IXP data. In $G_B \cap G_R$, we list the number of nodes and links, which appear in both G_B and G_R.

Table 1. Comparison of G_B, G_R, and G_X

	Number of nodes	Number of links
Only GB	420	773
Only GR	56	49
Only Gx	70	101
GB∩GR	207	345
GB∩GX	89	146
GR∩GX	8	5
GB∩GR∩GX	12	9
Sum	685	1428

Ⅲ. Characteristics of Korea Internet AS-level Topology

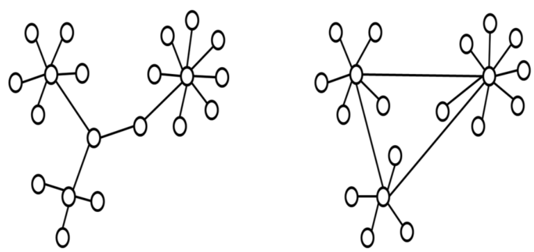
To identify the characteristics of the Korea Internet AS-level topology we need to answer the following questions.

- Does degree distribution follow a power-law that is observed in most of the global Internet AS-level topologies??

- Is AS connectivity good enough to guarantee robustness under network attack?

- Information networks (e.g., World Wide Web and Internet) have been classified as disassortative networks (in which high-degree tend to connect with low-degree nodes). We would like to know whether the Korea AS graph is disassortative.

- Even though AS-level Internet is disassortative, this property does not imply that high-degree nodes are tightly interconnected to each other (see Figure 1.a). If high-degree nodes are tightly interconnected (see Figure 1.b), we can expect network robustness and high routing efficiency.



(a) (b)

Fig. 1. Two Disassortative Networks [12]

- We are interested in the average distance between a random pair of nodes and the standard deviation, which can tell us the routing efficiency and the network robustness.

We introduce the following topology metrics and use them to try to characterize the Korea Internet AS-level topology: 1) node degree metrics (average, maximum, and distribution), and 2) node connectivity metrics (clustering coefficient, assortative coefficient, rich club connectivity, and distance distribution).

3.1. Node Degree Metrics

These are the basic metrics that characterize local connectivity in a network:

- Average degree: average number of links incident to a node

- Maximum degree: maximum number of links incident to a node

- Degree distribution: degree distribution of a node.

The above metrics are compared with those of the global AS graph, which is built from BGP data of the UCLA "Internet Topology Collection." The results are summarized in Table 2.

Table 2. Node Degree Metrics

	Korea AS graph	Global AS graph
Number of nodes	685	40,023
Number of links	1,428	141,842
Average node degree	4.17	7.09
Maximum node degree	384	3,675

About 93.7% of Korea ASes has a node degree less than the average, which is highly skewed. In the global AS graph, 85% of nodes have a node degree less than the average.

Using BGP data collected from RouteViews [20], Faloutsos et al. [10] showed that Internet AS-level topology exhibits a power-law degree distribution. This means that a few nodes have a very large number of links; however, the vast majority of nodes have only a few links.

We investigated whether the Korea and global Internet AS-level topologies follow power-law degree distributions. It was found that neither topology followed the power-law; their correlation coefficients were 0.718 and 0.885, respectively. The main reason is that frequencies of high- degree nodes do not change, as shown in Figure 2. Like Faloutsos in his analysis, we eliminated some nodes with a high degree: 12 high-degree nodes (1.8%) with frequency 1 in Korea data, and 246 high-degree nodes (0.6%) in the global data. After eliminating these high-degree nodes, it was found that the Korea and global Internet AS-level topologies follow a power-law degree distribution. The power-law exponent of the Korea AS topology is 2.49 and the correlation coefficient is 0.931; for the global AS topology, these values are 1.92 and 0.979, respectively. Figure 2 shows that there are many nodes with frequency 1. Assuming that the AS number assignment policy, which allows a customer to have an AS number only if it has multiple providers, is strictly enforced, this is due to missing links, which include hidden (backup) and invisible peer links.

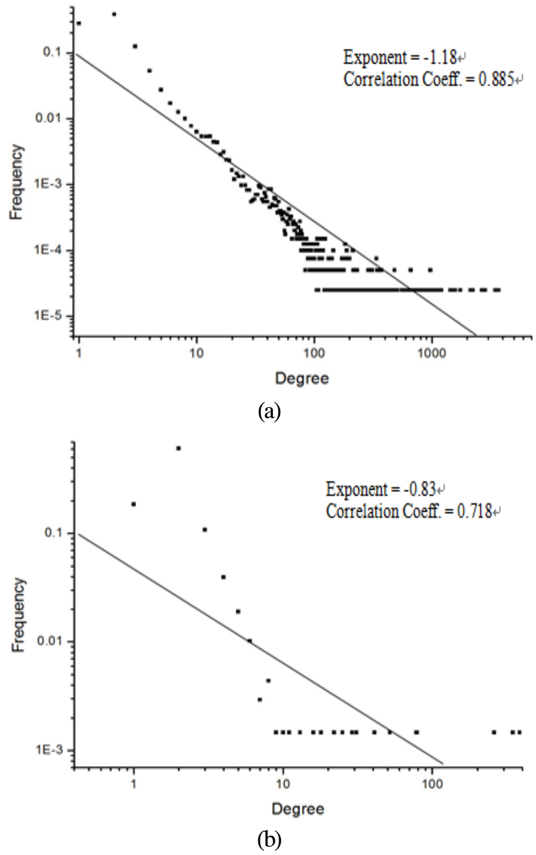


Fig. 2. Node Degree Distribution (all nodes are included)

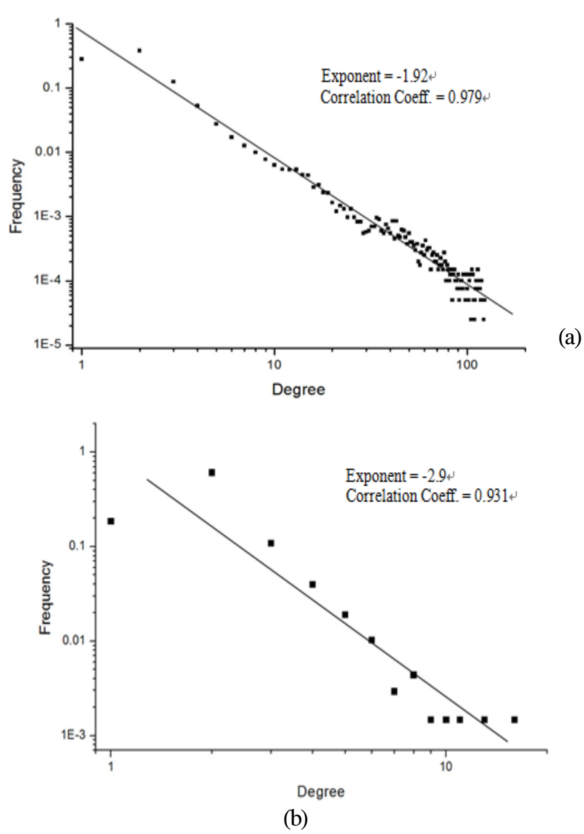


Fig. 3. Node Degree Distribution (eliminating high degree nodes)

3.2. Node Connectivity Metrics

There are more sophisticated metrics of node connectivity, which show a measure of how close a node is to its neighbor. These are:

- Clustering coefficient: let l(k) be the average number of links between the neighbors of k degree nodes. Local clustering, C(k), is the ratio of l(k) to the maximum possible number of such links, $_kC_2$. Now, mean local clustering, Cmean, is defined as Cmean = $\Sigma_k C(k)\cdot P(k)$ where P(k) is a degree distribution. The global clustering coefficient, Ccoeff, is based on triplets of nodes, where a triplet consists of three nodes that are connected by either two (open triplet) or three (closed triplet) undirected ties. This is the percentage of closed triplets among all connected node triplets in the entire graph. The exact definition is given in [27].

- Assortative coefficient (r): This is a measure that shows a preference for high-degree nodes to attach to other high-degree nodes. The mathematical definition is given in [28,29]. Depending on the value of r, we have a disassortative (r < 0) or an assortative network (r>0).

- Rich club connectivity: One of the structural properties of the AS-level Internet is that it contains a small number of high-degree nodes. The set containing them is called the "rich club." Let k be the first k nodes ordered by their non-increasing degrees in an AS graph. Rich club connectivity is defined as the ratio of the number of links in the subgraph induced by the k largest-degree nodes to the maximum possible number of such links, $_kC_2$.

- Distance distribution: This is defined as the probability that a random pair of nodes are at a distance of x hops from each other. The average distance is the mean value of this distribution. The performance of routing algorithms and the robustness of the network to viruses depend strongly on this measure.

Table 3 compares the node connectivity metrics of the Korea Internet AS-level topology with those of the global one.

Table 3. Node Connectivity Metrics

	Korea AS graph	Global
Clustering coeff. - Cmean - Ccoeff	 0.66 0.0025	 0.44 0.05
Assortative coeff	-0.51	-0.209
Rich club conn. - Exponent (corr. coeff.) - RCC of top 1% nodes	1.10 0.809	1.55 0.219
Shortest path Distance - average - standard deviation	 2.49 0.58	 3.71 0.66

As shown in Table 3, the value of Cmean of the Korea AS graph is 0.66, which is higher than that of the global one, 0.44, whereas the value of Ccoeff of the Korea AS graph is less than that of the global one. In the Korea AS graph, most stub ASes are directly connected to large ASes with a backup link (node degree 2), and large ASes are connected to each other (mesh configuration), as shown in Figure 4. Therefore, most stub ASes form triangles with two different large ASes. The value of Cmean (= ($\Sigma_k C(k) \cdot P(k)$) depends on the local clustering of nodes with high node degree frequencies. It is found that out of 415 stub ASes with node degree 2, 352 form triangles with two large ASes, and the value of C(2) becomes 0.848 (352/415). Node degree 2 has the highest degree frequency p(2) = 0.605 (= 415/685). Therefore, we have a high value of Cmean and local robustness in the graph.

Ccoeff is the percentage of triangles (closed triplets) among all connected node triplets in the entire graph. The node connected to N different neighboring nodes can produce N·(N-1)/2 triplets, and large ASes with a high node degree produce a large number of triplets. As shown in Figure 3, Korean stub ASes are directly connected to large ASes (neighbors of large Ases are mainly stub Ases) and are not connected to each other (a very disassortative network). Among many triplets, we have few triangles, and the value of Ccoeff becomes almost 0.

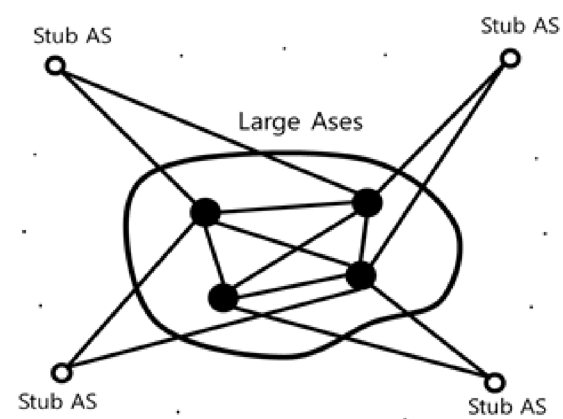


Fig. 4. Disassortative Korea AS Graph

The large difference between Cmean = 0.66 and Ccoeff = 0.0025 is believed to be intrinsic to a highly disassortative network [30]. As shown in Table 6, the assortative coefficient of the Korea AS graph is less than that of the global one, which also shows that the Korea AS is more disassortative than the global graph.

As shown in Figure 5, the rich club connectivity of Korea and global Internet AS topologies follows power-laws with exponent 1.1 and 1.55, respectively. The top clique size of the Korea AS graph is 4, which means the 4 largest degree nodes are connected with each other (full mesh). The rich club connectivity of the top 1% of Korea AS nodes is 0.809 and that of the top 1% of global AS nodes is 0.219. As shown in Figure 5, the Korea AS graph shows more rich club connectivity than the global one. We have seen that the Korea AS graph shows both strong connectivity among rich club nodes and highly disassortative properties, which is believed to contribute to the routing efficiency of the network.

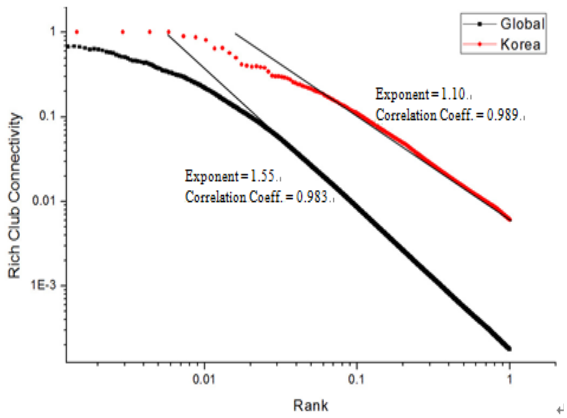


Fig. 5. Rich Club Connectivity

Fig. 6 shows the distance distribution and average distance is 2.49, which is less than that of the global AS graph, which is 3.71. In the Korea AS graph, the probability that the distance between nodes is less than three hops is 93%.

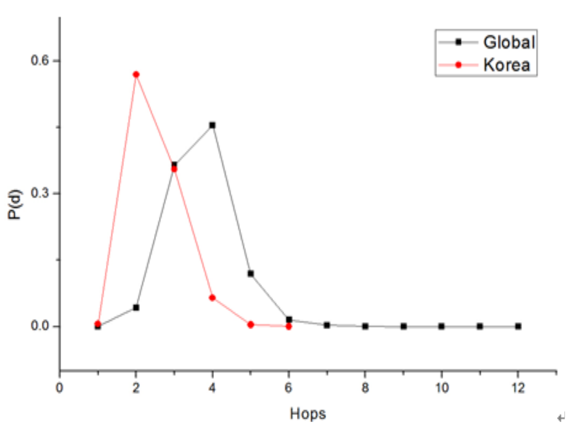


Fig. 6. Distance Distribution

Ⅳ. Internet Topology Generator

When we have new Internet protocol, BGP routing policy or algorithm, the best way to verify their performance is to test them on the real Internet. However, it is almost impossible. Instead, we construct Internet topology model, which has similar topological characteristics as the real Internet, and test the newly-developed Internet protocol, BGP routing policy or algorithm on the constructed model. For this purpose, several Internet topology generators have been suggested [31,32], which include the Waxman model [33], the BA (Barabasi-Albert) model [34], the GLP (General Linear Preference) model [35], the Inet (Internet Topology Generator) model [36], etc. Now we want to answer the question, "Which model is best suited to Korea AS graph?". That is, we investigate whether the Korea AS-level topology can be modeled by some of the Internet topology generators. To investigate this, topological metrics of the Korea Internet AS-level topology are compared with those of the graphs constructed by Internet topology generators.

The Inet model requires that the number of nodes should be at least 3,037. Since the number of nodes in the Korea AS-level topology is only 685, we exclude Inet. The Waxman, BA, and GLP models are used for comparison.

4.1. Node Degree Metrics and Power-laws

Table 4 compares the node degree metrics of the Korea AS graph with those of graphs built by Internet topology generators.

Table 4. Comparison of Node Degree Metrics

	Korea AS graph	Waxman	BA	GLP
Number of links	1,428	1,370	1,367	1,276
Average node degree	4.17	4.00	3.99	3.72
Maximum node degree (number of nodes)	384 (1)	19 (1)	55 (1)	92 (1)
Minimum node degree (number of nodes)	1 (193)	2 (222)	2 (345)	1 (517)

In terms of the number of links and average node degree, there is a 5-10% difference among the graphs. However, there are big differences in the maximum node degree and the number of nodes with minimum node degree.

Table 5 and Figure 7 show that all the graphs follow power-laws. For the Korea AS and GLP graphs, we eliminated some high-degree nodes as in Section 3.1. Even though the graphs built by generators follow power-laws, they cannot represent the highly skewed characteristic of the Korea AS graph. The percentage of nodes whose degrees are less than the average node degree is 93.7% for the Korea AS graph, which is much higher than those of graphs built by generators.

Table 5. Node Degree Distribution

	Korea AS Graph	Waxman	BA	GLP
Power-law exponent	2.49	2.64	1.91	1.38
Correlation coefficient	0.931	0.973	0.944	0.924
Percentage of nodes whose degrees are less than average node degree	93.7	55.3	69.4	81.5

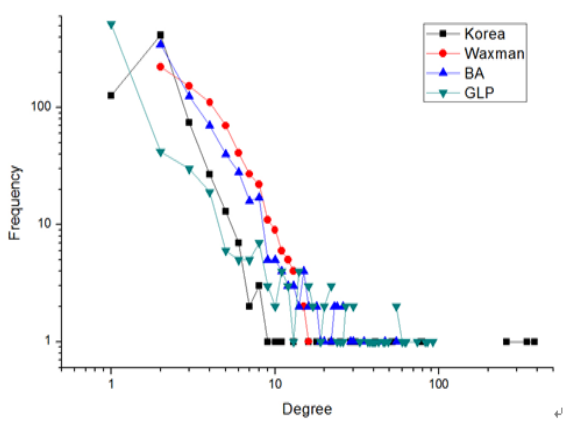


Fig. 7. Node-Degree Distribution

4.2. Node Connectivity Metrics

Node connectivity metrics are summarized in Table 6. In Section 4.2, we have shown that the Korea AS graph is highly disassortative and its rich club nodes are strongly interconnected. The Waxman and BA models do not reveal any of these properties. The GLP model reveals both disassortative and high rich club connectivity properties. However, the value of C_{mean} of the GLP graph is much lower than that of the Korea AS graph. In the Korea AS graph, there is a large difference between C_{mean} and C_{coeff}, which is intrinsic to a highly disassortative network. This property cannot be seen in the GLP model. Average path distances of the graphs built by generators are longer than those of the Korea AS graph.

Table 6. Node Connectivity Metrics

	Korea AS graph	Waxman	BA	GLP
Clustering coeff. - C_{mean} - C_{coeff}	 0.66 0.0025	 0.0074 0.0027	 0.008 0.0022	 0.046 0.02
Assortative coeff.	-0.51	0.12	-0.094	-0.29
Rich club conn. - Exponen (corr. coeff.) - RCC of top 1% nodes	 1.1 1.2(0.989) 0.81	 0.847 (0.997) 0.19	 0.886 (0.991) 0.38	 1.367 (0.974) 1.00
Shortest path distance -Average -Standarddeviation	 2.49 0.58	 4.68 0.88	 4.00 0.66	 3.28 0.59

Ⅴ. Conclusion

Based on the Korea AS graph constructed in our previous study [19] we attempt to identify the topological properties which characterize the Korea Internet AS-level topology. The Korea Internet AS-level topology is a small regional subgraph of the massive global one. We also want to see how well the Korea Internet preserves the topological characteristics of the global one or how different they are. For this purpose we introduce the several topology metrics and use them to characterize the Korea Internet AS-level topology. In this study we also attempt to answer the question, "Which Internet topology generator is best suited to Korea AS graph?". For this purpose, topology metrics of generated models are compared with those of Korea AS graph.

After eliminating a few high-degree nodes with frequency 1, we can observe a power-law in the node degree distribution of the Korea Internet AS-level topology. We showed that the Korea AS graph is highly disassortative and also includes strong connectivity between rich club nodes, which can provide network robustness and routing efficiency. In the Korea AS graph, the probability that the distance between nodes is less than three hops is 93%.

AS graphs were constructed by three Internet topology generators: Waxman, BA, and GLP. We have seen that these generators cannot fully represent the characteristics of the Korea AS graph, which says new Internet topology generator is required to model the Korea Internet AS graph.

Acknowledgement

We would like to thank Prof. Michalis and Prof. Srikanth of UCR for their helpful comments and suggestions.

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