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LETTER

Enhancing Resiliency of Networks: Evolving Strategy vs. Multihoming

Wan Yeon LEE[†], **Soo KIM**[††], ***Nonmembers***, **Heejo LEE**[†††a)], ***and*** **Hyogon KIM**[†††], ***Members***

SUMMARY Network resiliency has become crucial as the failure of a group of networks happens more frequently, being caused by either natural disasters or malicious attacks. In order to enhance the resiliency of the Internet, we show that changing the evolving strategy is more important than increasing the number of links by *multihoming*, which connects a single network with two or more links. From the simulation with Internet topologies, it is shown that the resiliency of the Internet can be enhanced by replacing the current evolving strategy only in part.

key words: *resiliency, Internet, evolving strategy, multihoming*

1. Introduction

The Internet can be represented as a network topology composed of innumerable nodes like PCs, routers or autonomous systems (ASes), and links between them. Previous studies have shown that the Internet expands its topology over time and the distribution of the number of connections per node follows a *power-law* distribution [1], regardless of its size. In the power-law distribution, new nodes attach to the Internet according to the *preferential attachment*, i.e., the probability of each node to connect with a new node is proportional to its current connection degree. This preferential attachment is also called "the rich get richer," because a high-degree node increases its degree with high probability while a low-degree node does with low probability.

On the network model having the power-law distribution, the failure of a few high-degree nodes can seriously damage their connectivity [2], [3]. Moreover, disrupting the connectivity of a group of nodes happens more frequently due to malicious attacks or natural disasters such as earthquake, tsunami, deluge and typhoon. A recent report shows that annual events of natural disasters increase over the world [4]. One example is the fiber cuts by Taiwan earthquake on December 2006, which paralyzed the networks in the whole Asian region. As a result, the resiliency enhancement of the Internet against a batch of node failures has become an important issue.

The motivation of this study starts from the observation that the resiliency of the Internet is getting worse if most new nodes follow the current evolving strategy, known as the preferential attachment. In this letter, we first show that the current evolving strategy decreases the resiliency of the Internet and the change of the current evolving strategy increases the resiliency of the Internet very effectively. As an alternative of the current evolving strategy, we introduce two evolving strategies: *Avg* and *Min* strategies which connect new nodes to average-degree nodes and minimum-degree nodes with high probability, respectively. Next, we verify that these two alternatives are more effective, in terms of the resiliency enhancement and connection costs, than the *multihoming* scheme [6], which connects new nodes with two or more links using the preferential attachment. Finally, we show that the resiliency of the Internet can be enhanced by replacing the current evolving strategy with an alternative strategy only in part. The result of this study is useful for developing a guideline of network topology design.

Section 2 describes the model of network topologies and resiliency metrics used in our evaluation, and the working mechanisms of three evolving strategies and multihoming scheme. Section 3 shows the evaluation results and Sect. 4 finally provides the network design guidelines derived from the evaluation results.

2. Evaluation Model

2.1 Network Topology

We represent a network topology as an undirected graph $G = (V, E)$, where V is the set of nodes and E is the set of edges. To model the network topology, we use two power-law graphs: the connectivity graph of the real network [7] consisting of 3015 ASes (nodes) in 1997 and a synthetically generated graph attaching 200 nodes on the basis of the preferential attachment rule. The AS connectivity graph and the synthetic graph are referred to as AS_{Y1997} graph and *Power-law* graph, respectively. The AS_{Y1997} graph represents the Internet connection and the Power-law graph represents a newly generated local area network.

2.2 Resiliency Metric

The resiliency of a graph (network) is measured by two values: ν and $K(\alpha)$. ν is the ratio of vertex covering nodes over the total nodes. $K(\alpha)$ is the ratio of the graph connectivity after failures of $\alpha\%$ nodes to that before the failures. When N denotes the number of nodes in G, ν and $K(\alpha)$ are defined as follows:

- $\nu = \frac{N_{vc}}{N}$, where N_{vc} is the number of nodes in the minimum vertex cover of the graph G.

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[†]The author is with Hallym University, South Korea.
[††]The author is with TmaxSoft, South Korea.
[†††]The authors are with Korea University, South Korea.
a) E-mail: heejo@korea.ac.kr

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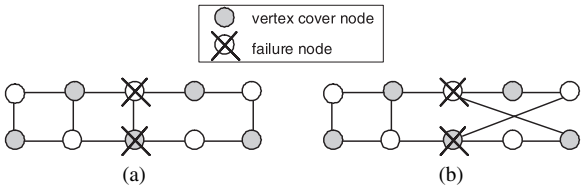

Fig. 1 Comparison of the connectivities of two graphs after node failures.

- $K(\alpha) = \frac{\sum_{i=1}^{S} n_i \cdot (n_i - 1)}{N \cdot (N-1)}$, where S is the number of subgraphs induced by removing $\alpha \cdot N$ nodes from G, and n_i is the number of nodes in the ith subgraph.

A graph with larger ν and $K(\alpha)$ is more resilient against node failures.

The metric ν has been used as a resiliency metric in the previous studies [3], [5], [9]. However, it measures only the connectivity of the initial graph but does not reflect the connectivity of the graph after node failures. In order to measure the graph connectivity after node failures, we adopt the metric $K(\alpha)$ which distinguishes the connectivity of subgraphs generated after node failures. In the example of Fig. 1, it is obvious that the two subgraphs $\{4, 4\}$ in Fig. 1(a) have better connectivity than the three subgraphs $\{4, 2, 2\}$ in Fig. 1(b), where the numbers in the brackets denote the number of nodes in a subgraph. The metric $K(\alpha)$ distinguishes the connectivity of the two groups while the metric ν can be equal. We use a metric Φ which combines ν and $K(\alpha)$ with a weight assignment. The resiliency metric Φ is then formulated as follows:

$$\Phi(w, \alpha) = w \cdot \nu + (1 - w) \cdot K(\alpha) \quad (1)$$

where w ($0 \leq w \leq 1$) is the weight factor for ν, and the weight factor for $K(\alpha)$ is $1-w$. Note that $\Phi = \nu$ if $w = 1$, and $\Phi = K(\alpha)$ if $w = 0$ by Eq. (1). In this letter, we display the results only when $w = 0.5$ and $\alpha = 0.01$ for simplicity. Note that the results of other cases show similar patterns and obey the guidelines that will be addressed in Sect. 4, although the specific value of Φ varies according to the values of w and α.

2.3 Three Evolving Strategies and Multihoming

In many real networks, nodes and edges are created dependently but their connections follow certain rules eventually [8]. We formulate the current evolving strategy of the Internet, known as the preferential attachment, into the graph expansion. We also formulate its two alternative evolving strategies, introduced in our preliminary work [5], as follows:

- **Max strategy:** A newly generated node is connected to maximum-degree nodes with higher probability. The probability P of attaching a new node to the node i is proportional to the connection degree g_i of that node, such that $P_i = g_i / \sum g_j$. It is equivalent to the current evolving strategy of the Internet.
- **Avg strategy:** A newly generated node is connected to average-degree nodes with higher probability. The probability P of attaching a new node to the node i is inversely proportional to the difference between the connection degree g_i of that node and the average degree g_{avg} of all nodes, such that $P_i = \frac{1/m_i}{\sum 1/m_j}$ where $m_i = 1 + |g_{avg} - g_i|$.
- **Min strategy:** A newly generated node is connected to minimum-degree nodes with higher probability. The probability P of attaching a new node to the node i is inversely proportional to the connection degree g_i of that node, such that $P_i = \frac{1/g_i}{\sum 1/g_j}$.

When expanding the graphs, a node is added to the graph with a constant number of edges, d_{new}. We call it **multihoming** when $d_{new} > 1$ and **singlehoming** when $d_{new} = 1$. Particularly, the multihoming when $d_{new} = 2$ is referred to as **dualhoming**.

3. Evaluation Results

We perform various simulations to measure the resiliency of the three evolving strategies and the multihoming scheme on two network graphs: the AS_{Y1997} graph when expanding 19000 new nodes and the Power-law graph when expanding 1200 new nodes. The simulator is implemented by Java SDK. The failure target nodes are selected randomly in the network graph and their number is 1% of the total nodes when the value of α in $K(\alpha)$ is 0.01.

3.1 Comparison of Three Evolving Strategies

We compare the three evolving strategies on the AS_{Y1997} graph and the Power-law graph. Newly generated nodes are added to a network with $d_{new} = 1$ (singlehoming). In Fig. 2(a), the Max strategy decreases the resiliency metric Φ from 0.25 to 0.05. On the contrast, the Avg and Min strategies increase the value of Φ from 0.25 to 0.67 and 0.65, respectively. In Fig. 2(b), the resiliency values of the Avg and Min strategies increase from 0.24 to 0.39 and 0.33 respectively, whereas the resiliency value of the Max strategy decreases from 0.25 to 0.06. It is interesting that the Avg strategy has slightly better resiliency than the Min strategy. This result comes from the fact that the Min strategy has a tendency to connect a new node to a degree-one node. On various shapes and sizes of network graphs besides of these two network graphs, our preliminary work [5] verifies that the Avg and the Min strategies have significantly better resiliency values than the Max strategy.

3.2 Comparison of the Evolving Strategy with the Multihoming

To compare the resiliency effects of the evolving strategy with the multihoming, we examine the following different combinations:

- Avg strategy with singlehoming ($d_{new} = 1$)

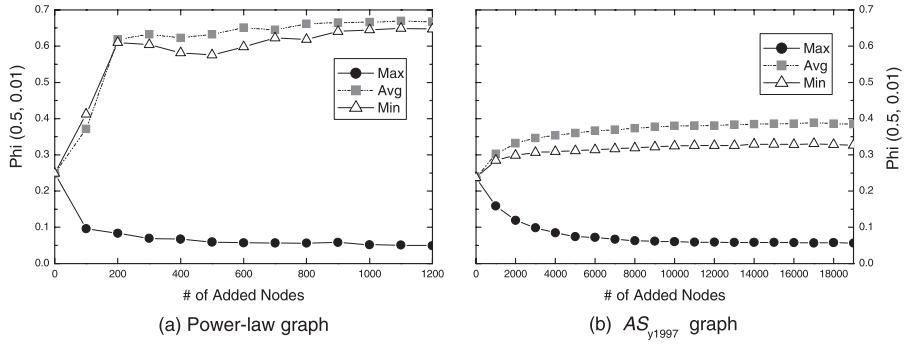

Fig. 2 Resiliency effects of three evolving strategies.

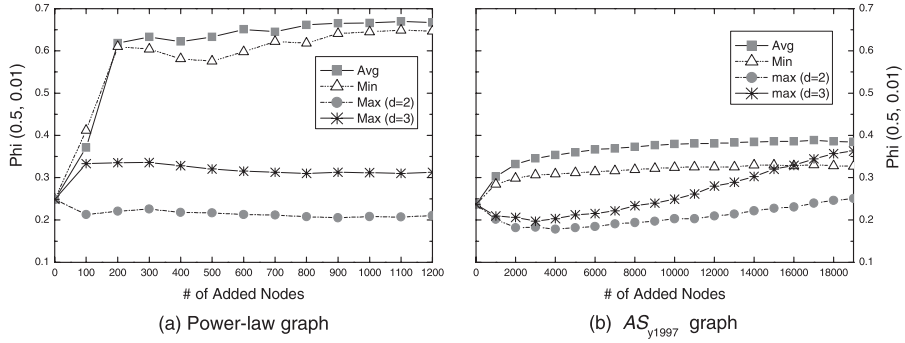

Fig. 3 Resiliency effects of the evolving strategy and the multihoming.

- Min strategy with singlehoming ($d_{new} = 1$)
- Max strategy with dualhoming ($d_{new} = 2$)
- Max strategy with multihoming ($d_{new} = 3$)

In Fig. 3(a), the Max strategy with the multihoming slightly decreases the value of Φ when $d_{new} = 2$ and slightly increases the value of Φ when $d_{new} = 3$, while the Avg and the Min strategies manifestly increase the value of Φ. In Fig. 3(b), the Avg and the Min strategies increase the resiliency value of Φ immediately, while the Max strategy with multihoming increases it slowly. In this experiment, it is verified that the Avg strategy (and the Min strategy) is more effective on the resiliency enhancement than the dualhoming. Even though the multihoming when $d_{new} = 3$ seems to be effective on the resiliency enhancement in Fig. 3(b), it is impractical from the viewpoint of the connection costs because the connections of each new node to three high-degree different nodes requires high connection costs in real networks.

3.3 Partial Replacement of the Evolving Strategy

It is not practical to change the current evolving strategy of *every new node* at once. It is caused by the fact that low-degree nodes (ASes or routers) have relatively lower bandwidth than high-degree nodes and thus users prefer the service of well-known, major Internet service providers (ISPs). Hence, we examine the resiliency effect when applying the alternative evolving strategy only to *a part of new nodes*.

Figure 4 shows the resiliency effects against the percentage of new nodes following the Avg strategy with the singlehoming ($d_{new} = 1$), the dualhoming ($d_{new} = 2$) and the multihoming ($d_{new} = 3$). Note that the initial values of resiliency in Figs. 4(a) and (b) are 0.25 and 0.24, respectively. In Fig. 4(a), the resiliency value is increased or equally maintained when partially changing the Max strategy of more than 20% new nodes with the Avg strategy, while the Max strategy of 100% new nodes decreases the resiliency value from 0.25 to 0.06 after expanding 1200 nodes. As the percentage of new nodes following the Avg strategy increases, the resiliency is also increased. In case that the Avg strategy works with the dualhoming, partial replacement of the Max strategy in 5% new nodes with the Avg strategy can maintain the resiliency equally. It implies that the combination of the Avg strategy and the dualhoming is more effective on the resiliency enhancement than the Avg strategy with the singlehoming. Figure 4(b) shows a similar pattern where the minimum percentages of new nodes following the Avg strategy are about 50% with the singlehoming and 0% with the dualhoming when maintaining the resiliency equally or better. In these figures, the differences of resiliency values between the multihoming when $d_{new} = 3$ and the dualhoming (when $d_{new} = 2$) are smaller than 0.1 in most cases. We do not display the results of the Min strategy because it shows similar but slightly worse results.

4. Conclusion

We show that the current evolving strategy of the Inter-

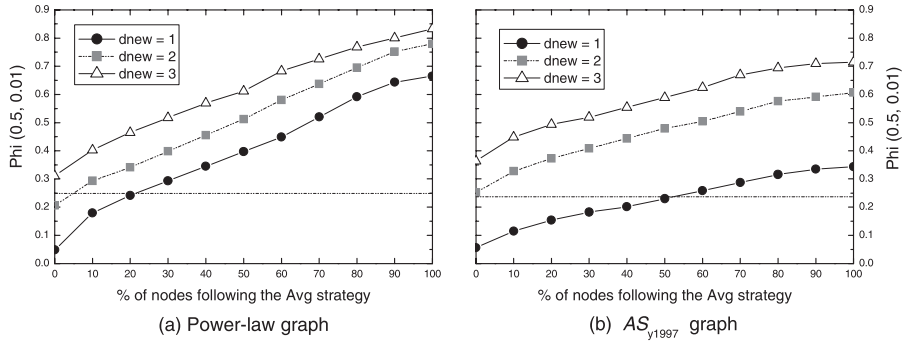

Fig. 4 Resiliency effects of partial replacement with the Avg strategy and the multihoming.

net makes the resiliency worse and worse, and changing the evolving strategy is more effective on the resiliency enhancement than increasing the number of links by multihoming. We also verify that the change of the evolving strategy in a portion of new nodes can enhance the resiliency of the Internet. Based on the observation, we derive the following guidelines for network design.

- **Inter-AS:** It is difficult to enforce the alternative evolving strategy to all nodes newly added, because new ASes prefer to attach to high-degree ASes managed by major ISPs. In order to prevent the network resiliency from becoming worse, some incentives for non-major and cooperative ISPs are required. The dualhoming also needs to be encouraged with more incentive when connecting new ASes to non-major ISPs.
- **Intra-AS:** It is relatively easy to apply the alternative evolving strategy to newly added routers, because one AS consists of a network of routers managed by one ISP. The alternative strategy is encouraged to be adopted by as many new routers as possible in order to enhance the resiliency of the network.

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