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A proposal of distributed algorithm to reconstruct
a robust network by self-healing

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Many infrastructures in real world have been known to be represented by Scale-free(SF) networks. However, in a SF network, malicious attacks to a few hubs break down the connectivity easily. Furthermore, these networks are also threatened by frequently occurred natural large disasters. To overcome these problems, we propose a self-healing method based on enhancing loops for improving robustness. Enhancing loops is adopted because of the following recent works. Network dismantling and decycling problems are asymptotically equivalent. In addition, for finding the minimal set of nodes for spreading information to the whole network, the optimal influencers are defined as the set whose removals cause the fragmentation into many local clusters. These facts indicate that removing all loops make the network into tree structure which lead to be easily fragmented by removing articulation nodes. Therefore, it is important for making robust networks to maintain as many loops as possible. In fact, enhancing loops is strongly related to make onion-like structure with the optimal robustness of connectivity. For example, enhancing loops by intermediate attachments with selecting low degree nodes is effective to make the onion-like structure. Unlike SF network, onion-like network with positive degree-degree correlation is robust against malicious attacks as well as random failures.

In recent years, several healing methods have been proposed. In a distributed local healing, the most damaged node has new connection with randomly selected node in the neighbors of attacked nodes. In this healing, the number of healing links are controllable according to the damage. However, the selection of healing nodes is heuristic in order of the most damaged ones. Another is the healing method on interdependent two lattices. When adding healing links, the candidate of new connections is expanded beyond nearest neighbors to maintain whole connectivity except failed components.

Such expanding of connection range is important for our method, in which healing links are added to the network after removal of high degree nodes. The neighbors of attacked nodes lose a part of their links, while the unbroken links of removed nodes can be reused. Therefore, some links emanated from removed nodes are reused as healing links between the extended neighbors. We consider that the number of reusable links depends on situations of damage.

To expand the connection range of healing link, each node transfers information to other nodes in three hops. If a node can communicate within

two hops, new connections are created only between nearest neighbors. However, by communicating other nodes in three hops, candidates of healing links could be extended over the nearest neighbors in distributed manner.

We emphasize enhancing loops in the following self-healing method. First, a ring as the simplest loop is created within extended neighbors to maintain the larger connectivity. In case of incomplete rings without enough healing links, the order of linking is decreasing order of its connected component size to obtain larger connectivity after healing. Next, if healing links are residual after making rings, loops on the rings are enhanced between low degree nodes.

We numerically evaluate our proposed method in comparison with the conventional self-healing method in implementing sequential algorithms. For several infrastructure networks, such as flight routes, power grid, and Internet, we consider the three measures: the connectivity, the robustness of connectivity and efficiency of paths. In addition, we discuss the number of additional ports as the resource of healing.

Through numerical simulations, we obtain the following results.

- The reconstructed networks by our proposed method maintains the higher connectivity than ones by the conventional method.

- In case of sufficiently using healing links, it obtains both higher robustness and efficiency than the conventional method.

- However, a larger number of additional ports is required than that in the conventional method.

The sequential algorithm is not always practicable because of time delay for transferring and cost of communication paths between center and other nodes, etc. Therefore, we describe a distributed algorithm for applying our self-healing on real systems. On the asynchronous system, our distributed algorithm consists of five phases. The outline of algorithm is as follows.

1. After the initiation at a node (healing node) that detect the malfunction nodes, each healing node sends messages of notification to other healing nodes in three hops directly. Through interacting with other healing nodes in three hops by sending the messages, each healing node knows the healing node's IDs over the three hops and makes the temporary routing table to communicate further healing nodes.

2. To make a ring, the order of connecting ring is determined by the size of the connected components. Therefore, each healing node uses a delivery tree to know the size of its component. After knowing the

size, in order to reduce the number of required messages such as in floodings, a leader node is decided. A role of leader is determining the order of ring and requesting to other healing nodes for new connections to make a ring.

3. Each healing node sends the size of component to a leader. A leader decides the order of connecting ring by received information of component sizes. For making a ring, a leader sends requesting message to others healing nodes. The healing nodes received the message make new connections.