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Exploiting global information in complex network repair processes

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Abstract Robustness of complex networks has been studied for decades, with a particular focus on network attack. Research on network repair, on the other hand, has been conducted only very lately, given the even higher complexity and absence of an effective evaluation metric. A recently proposed network repair strategy is self-healing, which aims to repair networks for larger components at a low cost only with local information. In this paper, we discuss the effectiveness and efficiency of self-healing, which limits network repair to be a multi-objective optimization problem and makes it difficult to measure its optimality. This leads us to a new network repair evaluation metric. Since the time complexity of the computation is very high, we devise a greedy ranking strategy. Evaluations on both real-world and random networks show the effectiveness of our new metric and repair strategy. Our study contributes to optimal network repair algorithms and provides a gold standard for future studies on network repair.

1. Introduction

Many systems can be modeled as complex networks, where nodes represent elements of a system and links represent the relationship between elements. Examples include, but are not limited to, social,[1,2] economic,[3,4] traffic,[5–7] biological,[8,9] and technological networks.[10,11] Complex networks are often vulnerable under disruptions, e.g., those caused by natural disasters or human intentional attacks.[12,13] Therefore, research on network robustness and resilience has gained significant attention.[14,15] Most researchers focus on network robustness, aiming to simulate network percolation processes; with the result that networks are often rather vulnerable.[16–19] One example of high-impact network failures is the power grid break-up in Northeast of the U.S and parts of Canada on August 14th, 2003, which resulted from only a few power station failures. Another example is the air transportation delay occurred in Beijing on July 21st, 2012 caused by a rainstorm, which led to a widespread cascading failure of air traffic. Small events can lead to wide-ranging (cascading) failures.

Network repair, the inverse problem of network attack, is less studied, albeit the quick recovery of network functionality is a tremendous challenge. During a network disruption, either

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nodes or links can be attacked. Similarly, for network recovery, new links can be added between unaffected nodes, or damaged nodes can be repaired.[20,21] After a careful review of relevant research, we find that most researchers have chosen to attack nodes in a network and then repair the network by adding links, mostly because adding links between existing nodes should be much easier than building a new node. Under realistic conditions, attacked nodes are often disabled forever, or even though they can recover from damage, the process is very time-consuming, during which the whole network would be influenced significantly. Therefore, the problem we study here is that under a disruption, nodes in the networks would be attacked, and in the recovery process, links are generated between surviving nodes.

In this paper, we discuss a very recently proposed network repair strategy, self-healing.[22] This strategy repairs networks only using local information with the goal to obtain a larger size of the giant component (GC-size) and at the same time to limit the cost of the repair. The cost here is defined to be the sum of the shortest path lengths of the added links in the original network, and this definition is used in the evaluation section in our paper. However, this twofold goal of self-healing makes it a multi-objective optimization problem. Thus far, the optimality of self-healing has not been analyzed, i.e., the question is, how much does the exploitation of local information affect the repair quality? Motivated by this point, we propose a shortest-path related network repair evaluation metric. The new evaluation metric is based on the shortest path lengths (SPLs) of all node pairs in the network. In the new evaluation metric, the shortest path length between two nodes from different components is defined, since in the traditional complex network theory, the shortest path length exists only between two connected nodes, no matter they are connected directly or indirectly. Besides, because of its constraint that only local information is needed, self-healing may not guarantee the repair quality. To assess the limitation of self-healing, global information is exploited in a new greedy ranking repair strategy. Experiments on real-world and random networks show that the new metric can evaluate the optimality of self-healing very well, and that the greedy ranking repair strategy restores networks' functionality in terms of the new metric.

The major contributions of this paper are summarized as follows:

(1) We discuss the optimality of a recent network repair strategy, self-healing. Motivated by the limitation of self-healing, we create a new shortest-path related evaluation metric of network repair, which can measure the connectivity between all node pairs.
(2) Based on the new evaluation metric, we propose a greedy ranking repair strategy, and provide an efficient implementation.
(3) We evaluate the optimality of self-healing and the effectiveness of our strategy on six real-world networks and three kinds of random networks. Our results show that self-healing's optimality can be substantially improved in terms of the new metric.

This paper is structured as follows. In Section 2, we introduce the recently proposed network repair strategy, self-healing. The limitation of this repair strategy is also discussed in this section. In Section 3, evaluation metrics of network repair are presented. A new evaluation metric and a greedy ranking strategy are proposed, and we make an improvement on the general strategy. In Section 4, both the optimality of self-healing and the effectiveness of our strategy are evaluated on six different real-world networks and three kinds of random networks. The conclusions and future work of this paper are presented in Section 5.

2. Self-healing

In this section, both the details and limitation of self-healing will be discussed. An introduction of self-healing is presented in Section 2.1. The limitation is classified into three aspects: non-deterministic network repair (Section 2.2); constraints of local information and the shortest path length (Section 2.3); redundancy of ineffective links (Section 2.4).

2.1. Introduction of self-healing

Self-healing is a very recently proposed strategy to repair complex networks. This strategy detects the level of the damage only relying on local information accessible to each node (its degree), and makes new connections with low cost. Therefore, in self-healing, each surviving node decides by itself whether it needs to generate a new link with another node. The process of self-healing can be divided into three parts:

(1) An original network, the number of nodes to be attacked, and two thresholds p and $r_{\max}$ should be given. For each surviving node, the original degree k_{orig} and the degree after attack k_{dam} of each node should be recorded. p is the threshold for the fraction of remaining neighbors, and each node observes whether the fraction of its neighbors is less than this threshold. $r_{\max}$ means the limitation of the new links' distance.
(2) For each surviving node, the value $q = k_{\text{dam}}/k_{\text{orig}}$ should be recorded, and if $q < p$, the node is supposed to select a surviving node randomly to generate a new link.
(3) For each new link, only if its distance (the shortest path length in the original network) is no longer than $r_{\max}$, the link would be finally generated.

In Fig. 1, the process of self-healing on an example network is shown. Fig. 1(a) shows an attack of two nodes on the example network; Fig. 1(b) shows the network after the attack; the orange link in Fig. 1(c) is the added link with self-healing under the best condition at a probability of 10%, while there would be no link to be added at a probability of 90% (the parameters of self-healing here are $p = 0.5$ and $r_{\max} = 2$); Fig. 1(d) presents one of the possible results with self-healing, while $p = 0.8$ and $r_{\max} = 3$. The settings of the parameters in Fig. 1(c) are the same as those used in the evaluations in a self-healing paper,[22] and are also used in the following evaluations of this section.