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BOOK OF ABSTRACT

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Significant improvement of network robustness by enhancing loops through rewiring

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1 Introduction

Many real networks have power-law degree distributions and are extremely vulnerable for malicious attacks [1]. However, it is discovered that onion-like networks with positive degree-degree correlations [2] have optimal robustness against the attacks [3][4]. To improve the robustness by enhancing the correlations, some methods based on edges swaps [5] or rewirings [3] have been proposed. In addition, an efficient algorithm proposed by Z.-X. Wu and P. Holme generates nearly optimal robustness [6].

In this paper, for improving the robustness of connectivity, we focus on enhancing loops measured by feedback vertex set (FVS) which is a subset of vertices that removal makes the graph cycle-free, because network dismantling and decycling problems can be considered as asymptotically equivalent [7]. Furthermore, it has been pointed out that the robustness is stronger as a larger fraction of FVS in incrementally growing onion-like networks [8]. Thus, enhancing loops on a network is crucial for improving network robustness. The purpose of this study is to clarify a deeper relation between robustness and loops than correlations. In previous works, robustness is usually discussed in a relation to degree-degree correlations. We propose new methods to enhance loops and numerically show a significant improvement of robustness by enhancing loops.

Followings are the background. Although the minimum FVS problem is intractable called as NP-hard, there exists an efficient approximation algorithm by applying belief propagation (BP) based on a cavity method in statistical physics [9]. It calculates marginal probability q_i^0 for the state 0 of node i, which denotes the candidate probability of belonging to FVS. In another related topic, increasing the number of spanning tree by rewiring is corresponded to enhancing loops. The number of spanning tree represent varieties of loops in a network, since each edge that does not belong to a spanning tree is one-to-one corresponding to a loop, whose set consists of a linearly independent basis called fundamental cycles [10]. In other words, any cycle on a network can be represented by a linear combination of the fundamental cycles.

2 New type of rewiring to enhance loops

We introduce new rewiring methods based on edge rewiring with or without degree-preserving in order to enhance loops. Increasing the size of FVS means enhancing loops. When low q^0 nodes are connected, it is expected that the size of FVS increases, because they are not concerned with any loops and make new loops by the connections.

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To keep the degree in increasing the size of FVS, we remove edges between low and high q^0 nodes, and add two edges: an edge between low q^0 nodes and an edge between high q^0 nodes. The degree-preserving method is summarised as follows.
Step 1.) Select two nodes i and j which are disconnected and have the highest $q_i^0 + q_j^0$.
Step 2.) Select a node l which is the lowest q_l^0 node in the neighbor nodes of node j. Similarly, select a node k which is the lowest q_k^0 in the neighbor nodes of node i and unconnected to node l.
Step 3.) Add edges (i, j) and (k,l), and remove edges (j,l) and (i,k).
Instead of degree-preserving, in another non-preserving method [1] , the differences are
Step 1.) Remove an edge (i, j) which have the highest $q_i^0 + q_j^0$.
Step 2.) Add an edge (k,l) which have the lowest $q_k^0 + q_l^0$.
For comparison, we also consider other methods in which q^0 is replaced with degree.

3 Deeper relation of robustness and loops than correlations

We numerically investigate the improvement of robustness for our proposed method in comparing with other conventional methods [6] [10]. We apply them to 10 real networks. Figure 1 shows typical results for the robustness against hub attacks [3] by measuring the size of the giant component, the number of nodes in the FVS [9] and assortativity for the correlations [2] versus increasing the number of rewiring. In particular, degree-non-preserving methods improve robustness more than degree-preserving methods. The result suggests that degree-preserving has a restriction on improving robustness. In comparison with the rewiring on OpenFlights at #Rewire=8000, our degree-non-preserving method is twice as robust as the best in degree-preserving methods. In Fig 1, the ordering of lines in robustness is almost the same as in FVS. However, they are greatly different from the ordering in assortativity. Therefore, the robustness is related to the size of FVS rather than assortativity focused conventionally.

Summary. We propose rewiring methods to enhance loops and obtain the result with significant improvement of robustness by enhancing loops. Moreover, our result suggests that loops are more essential for the robustness than the degree correlations.

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[1] They are the best selections for the robustness in operations several combinations for the highest or the lowest nodes and the ordering of add and remove.

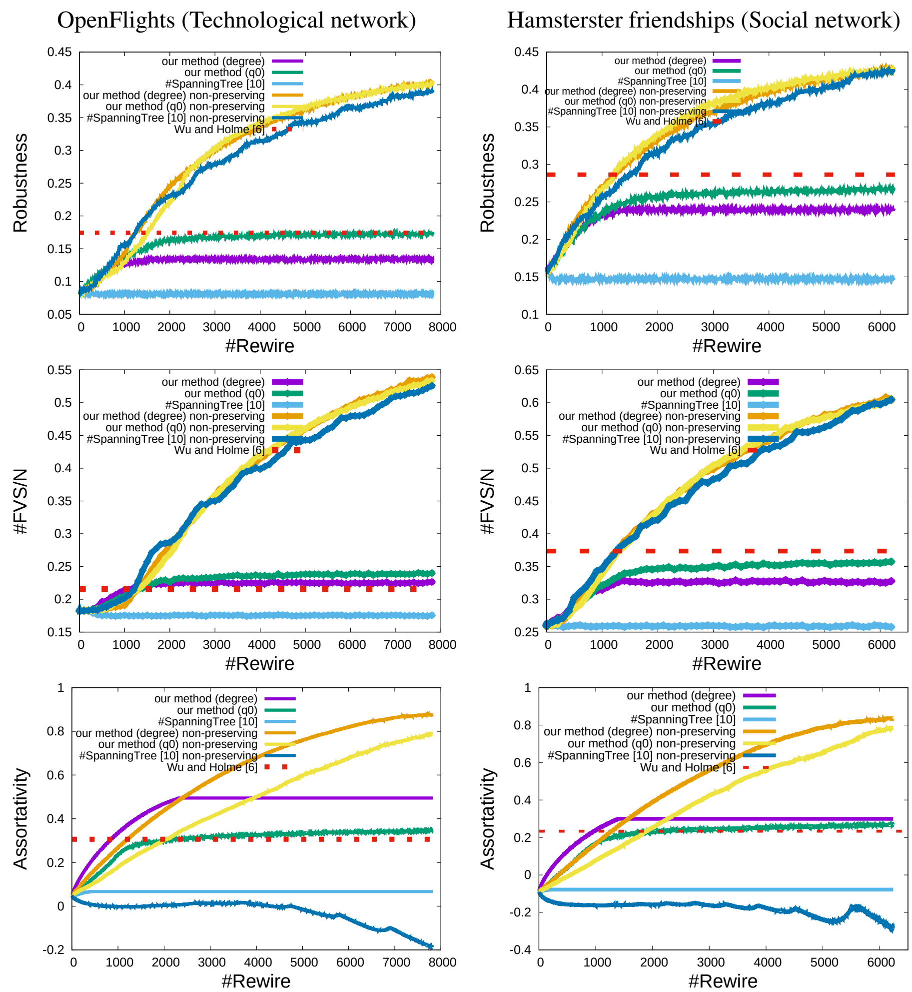

Fig. 1. Comparing the results for our proposed and the conventional rewiring methods in real networks. The red dotted line indicates the conventional best case for the robustness in each network. The large difference between green and yellow lines for the robustness is caused by whether or not degree-preserving. In the ordering, the green line is higher than the violet line in both the robustness and the size of FVS but lower in the assortativity. The data can be obtained from OpenFlights: http://konect.uni-koblenz.de/networks/opsahl-openflights, Hamsterster friendships: http://konect.uni-koblenz.de/networks/petster-friendships-hamster.