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Analysis of robustness for cascading failures against networks generated by inversion preferential attachments

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Cascading failures may undergo in real networks considering flows such as packets in telecommunications and logistics on the road. Failures of one or very few nodes propagate and cause the network to malfunction entirely. Models and measures for cascading failures are discussed for SF(SF) structures that exist in the real world. In particular, further selective removal of nodes and links, reconnecting links, and routing strategy are investigated as measures against cascading failures. However, the measures are impractical, because the normal nodes and links are wasted and it needs that the network structure can be changed immediately. Furthermore, recent studies interest in cascading failures of interdependence networks. We believe that the essential solution to reduce the damage of cascading failures is to find a more robust network structure, rather than the measures.

By the way, recently been known that networks become loopless at critical points where they are fragmented. Here, the minimum set of necessary nodes to be removed to make the network loopless is called the feedback vertex set (FVS). Therefore, the size of FVS must be increased to enhance robustness against attacks. Onion-like networks that focus on positive degree-degree correlation, are proposed as more robust networks with a larger number of loops, compared to conventional SF and ER networks Analysis of the generating function and numerical simulations have shown that when the degree distribution is fixed and the degree-degree correlation is varied, a network with an onion-like structure with optimal tolerance emerges when the positive degree-degree correlation becomes somewhat large. However, higher degree-degree correlations do not necessarily lead to higher robustness, but robustness is maximized at moderate positive degree-degree correlations. There have been a small number of studies against cascading failures, and onion-like networks have been found to be more tolerant than SF networks. However, since networks with extremely high positive degree-degree correlations are not optimally robust, there is room for an approach to enhancing robustness that is more intrinsic than degree-degree correlation. Therefore, recent research has focused on enhancing loops to improve robustness. The results suggest that robustness and FVS size increase substantially as the variance of the degree distribution decreases. Thus, we focus on the variance of the degree distribution to improve robustness against attacks. Recently, the IPA model has been proposed as a model for generating networks by varying the degree distribution. In IPA model, the network is generated by inverse preferential attachments, the opposite of preferential attachments in SF networks. The degree distribution changes continuously with the parameter β that controls the degree of inverse preferential attachments. Consequently, the variance of the order distribution decreases as the value of β increases. Recent studies have shown that networks with small variances of the network degree distribution have optimal robustness against attack.

Back to cascading failures. The load of the initial failure node that triggered the cascading failures must be borne by the other nodes. Because the failed node can not pass through the flow, therefore the flow passes through a detour that passes through another node. In other words, the damage against cascading failures can be reduced by distributing the load among multiple detours if many detours exist. Since a detour is a loop, an aforementioned network with a smaller variance of the degree distribution is expected to be highly tolerant against cascading failures due to the presence of many loops.

In this study, simulations of cascading failures are performed for BA model generated by preferential attachments (PA) with a SF structure, and inversion preferential attachments (IPA) model with a smaller variance of the degree distribution. The general method of generating a network with attachments is as follows. A new node is added to the network and connected to m existing nodes at each time step. Self-loops and multiple loops are prohibited. Here, the probabilities to choose existing nodes are different in each of the two models. First, the probability to choose existing nodes of BA model is proportional to the degree k. On the other hand, IPA model employs probability to choose existing nodes proportional to k^{β}. The degree distribution can be varied continuously by adjusting the value of the parameter β in IPA model. However, the network efficiency decreases as chain structure emerges on the network as this β is increased. Therefore, configuration model is applied after generating the network to randomize the network structure in order to perform an analysis focusing on the degree distribution of the network. In addition, this study uses the most basic Motter-Lai model for cascading failures. The load Li is defined by betweenness centrality on the assumption that flows are supposed to exceed every pair of nodes and transmitted along the shortest path connecting them. This is attributed to the flows such as packets and vehicles in communication and transportation networks generally transmitting along the shortest path. The capacity C_i is defined as a value proportional to the initial load $L_i(0)$. Where α is a tolerance parameter. As larger α, the less likely it is that cascading failures will occur. However, it should be as small as possible from the standpoint of capital investment and other costs. In cascading failures, if the load Li exceeds the capacity, $L_i > C_i$, node i is removed from the network. After node removal, the load is redistributed to the remaining nodes throughout the network. Here, nodes with $L_j > C_j$, are further removed from the network. Load redistribution and removal of overload nodes are repeated until all nodes are removed or $L < C$. The method to choose initial failures that trigger cascading failures uses random, max-degree, and max-load node removal and localized attack. Localized Attack assumes damage from tsunamis and earthquakes in infrastructure networks. The damage against cascading failure is defined by the relative size G of the largest connected component before and after the cascading failure.

The results of the simulation show that the network generated by IPA model is more tolerant against cascading failures than SF networks at the degree distribution is homogeneous according to the parameter β. Optimal tolerance against cascading failures was obtained at $\beta = 50$ is also suggested. Furthermore, networks with homogeneous degree distributions were found to meet the small-world property. In other words, achieving both tolerance and efficiency against cascading failures is possible.