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Robustness of complex networks with an improved breakdown probability against cascading failures

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HIGHLIGHTS

- A new cascading failure model with an improved breakdown probability is proposed.
- Corresponding to the new model, a protection strategy is proposed.
- We quantify how much the protection resources should be allocated to each node.
- Compared with WR model, our model can make the network more robust with the same cost.
- The advantage of the current model is more obvious in scale-free networks.

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ABSTRACT

The robustness of complex network is a core issue in complex network research. We agree that not all overload nodes will be removed from the network in real networks because some effective measures can be taken to protect them. But only a few researches consider this issue. Based on previous researches, we propose a cascading model with an improved breakdown probability. Different from previous breakdown probability model, the current model brings in some parameters to explore the optimal distribution strategy of the protection resources. Furthermore, we quantify the allocation of the protection resources. We explore the relationship between the parameters of our cascading model and the robustness of three networks (two typical networks and one real network), based on which we find out the optimal value of the parameter. It in turn helps us to quantify the allocation of protection resources and form an optimal protection strategy. Our work may be helpful for improving the robustness of complex networks.

1. Introduction

Infrastructure networks, such as power grids [1,2], transportation networks [3,4] and computer networks [5] etc., play an important role in human society. Cascading failures can happen in many infrastructure networks [6]. The robustness of these networks directly affects the quality of people's lives. These networks provide great convenience for our life. However, a disastrous incident in these infrastructure networks may lead to a cascading breakdown of the whole network and serious economic consequences [7]. So cascading failure on a network has been a great concern and widely investigated.

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As is known to all, there exists the load on nodes in many complex networks [8]. Hence the failure of nodes can cause the redistribution of the load of failure nodes. And it will make the load of some nodes exceed their capacities, which can lead to further overload failures and load-redistribution and finally result in the collapse of the entire network. In order to improve the robustness of complex networks many researchers do a lot of effort in many aspects and make great progress. Several important properties shared by most networks have been discovered, such as the small-world (SW) and scale-free (SF) properties [9–11]. The construction of cascading failure model is necessary, and many models have been proposed and studied [12]. The global load-based cascading model [13–20] has been widely used to improve the robustness of networks. Many scholars define the initial load of a node as the betweenness of the node [1,18]. Considering that transmission paths can be adjusted by arbitrarily given link weights, Yang et al. [19] define the initial load of a node as the total number of weighted shortest paths passing through the node. However, calculating the betweenness of a node needs the global information which is not readily available in large-scale network. So some researchers define the initial load of a node as a function of its degree [17,20]. And the capacity of a node is usually assumed to be proportional to its initial load [1,7,17,20–22]. Li et al. [23] did not agree with the linear correlation between extra capacity and initial load and proposed a novel allocation mechanism of limited resources of capacity against cascading failures. Moreover, Kim et al. [24] find that the node with smaller capacity tends to have larger unoccupied portions of the capacity in real networks. Furthermore, load-redistribution strategy [20,25] has been discussed in literature. However, in many researches cited above, the node is immediately removed as long as the load of the node exceeds its capacity. In fact, not all overload nodes will be removed from the network owing to certain monitoring and effective measures [26]. Anghel et al. [27] claim that the power lines do not fail immediately after being overloaded. That allows for control schemes such as the one in Ref. [13], which are predicted to greatly reduce the avalanche size. Wang et al. [26] propose a new cascading model with a breakdown probability, where a new parameter γ is used to represent the removal probability of an overload node. And the parameter γ is the same for all nodes. Moreover, they did not give a protection strategy corresponding to the cascading model with a breakdown probability. In fact, to prevent the overload nodes being removed from the network, some effective measures should be taken. But the effective measures are severely limited by cost in real networks. There is no need to protect all the nodes in the same strength. A fundamental concern is how to efficiently allocate limited resources to prevent the overload nodes being removed from the network and make the network more robust.

To this end, we raise a new model for cascading failure with an improved breakdown probability and then propose a protection strategy corresponding to the new model to allocate the protection resources. In this paper we try to use this model to explore the effect of some parameters on the robustness of network and figure out a reasonable strategy to allocate the protection resources. Moreover, we quantify how much the protection resources should be allocated to each node. Taking into account the very common and conspicuous features, the small-world (SW) and scale-free (SF) properties [18], we investigate the effect of our model on the robustness of two typical networks (WS network [9] and BA network [10]). And the simulation results show the relationship between the robustness level of complex networks and some parameters in our cascading model. Furthermore, we find out the optimal value of the parameter and quantify the allocation of the protection resources. Our findings may be useful in allocating the protection resources over the whole network to decrease the influence of the cascading failure. Finally, we examine the effectiveness of the current model on improving the robustness of the airport network against cascading failures.

The rest of this paper is organized as follows: in Section 2, we describe the cascading model in detail. Simulations and discussions based on our model are presented in Section 3. And in Section 4, some summaries and conclusions are given.

2. Cascading model and protection strategy

For concreteness, we consider the cascading model proposed in Ref. [26], which is defined as follows. The initial load of node j is $L_j(0) = (k_j \sum_{m\in\Gamma_j} k_m)^\theta$, where $L_j(0)$ is the initial load of node j, k_j and Γ_j is the degree of node j and the set of neighbors of node j. θ is a tunable parameter and governs the strength of the node load. The definition of initial load is reasonable because the product of the degree of node and the sum of the degree of its neighbors is in positive correlation with betweenness centrality [28,29]. As is known to all, the larger the node capacity is, the stronger the network robustness is. However, the capacity of a node is severely limited by cost in real networks. Thus, Motter–Lai [30] assume that the capacity of node is proportional to its initial load, $C_j = (1+\delta)L_j(0)$, where C_j is the capacity of node j, $\delta(\geq 0)$ is a tolerance parameter. Generally speaking, in real networks, such as Internet, when a router fails, the untreated information will be redistributed to its neighbor nodes and the information flow tends to choose routers with high processing capacity so as to keep the smooth of the whole network. So the load of removed node i will be redistributed to its nearest neighbor j, depending on $\Pi_j = \frac{C_j - L_j(t)}{\sum_{n\in\Gamma_i}(C_n - L_n(t))}$. And the extra load allocated to node j is $\Delta L_{ji} = L_i(t)\frac{C_j - L_j(t)}{\sum_{n\in\Gamma_i}(C_n - L_n(t))}$, where $L_j(t)$ is the load of the node j after some time t.

The model of breakdown probability in Ref. [26] (WR model) can be described as:

$$P(L_j(t)) = \begin{cases} 0, & C_j > L_j(t) \\ \dfrac{L_j(t) - C_j}{\gamma C_j - C_j}, & C_j \leq L_j(t) < \gamma C_j \\ 1, & \gamma C_j \leq L_j(t), \end{cases} \tag{1}$$