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Modeling and analyzing cascading dynamics of the Internet based on local congestion information

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HIGHLIGHTS

- A congestion function to represent the nodes' congestion is introduce.
- The relationship between the shortest paths and the nodes' congestion can be controlled by a tunable parameter.
- The robustness of the network has a positive correlation with tolerance parameter, but it has a negative correlation with the packets generation rate.
- There exists a threshold of the attacking proportion of nodes that makes the network achieve the lowest robustness.

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ABSTRACT

Cascading failure has already become one of the vital issues in network science. By considering realistic network operational settings, we propose the congestion function to represent the congested extent of node and construct a local congestion-aware routing strategy with a tunable parameter. We investigate the cascading failures on the Internet triggered by deliberate attacks. Simulation results show that the tunable parameter has an optimal value that makes the network achieve a maximum level of robustness. The robustness of the network has a positive correlation with tolerance parameter, but it has a negative correlation with the packets generation rate. In addition, there exists a threshold of the attacking proportion of nodes that makes the network achieve the lowest robustness. Moreover, by introducing the concept of time delay for information transmission on the Internet, we found that an increase of the time delay will decrease the robustness of the network rapidly. The findings of the paper will be useful for enhancing the robustness of the Internet in the future.

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1. Introduction

The Internet has been developing quickly, and the scale of the Internet continues to expand, especially in China. Consequently, network security has become one of the most important issues in our daily life. The robustness of complex network in general is an important subject to study in the field of network security. This subject has received increasing attention and attracted a great deal of studies [1–10]. Cascading failure is a harmful phenomenon that often emerges in complex networks. Typical examples include the accidental collapse of the North American electric networks [1], the collapse

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of the power grid in South China [11], the congestions of communication networks [12], the jamming of traffic networks [13–15], and so on. These disasters are mostly caused by cascading failures. Therefore, research on cascading failures in complex networks is vital and has practical significance.

The robustness of a network is associated with its topological structure. There are many proposals of universal models for cascading failures in complex networks recently [16–20]. In those models, it is usually assumed that a node's load is only related to the network topology, which means that the node's load will not change if the topology of the network does not change. A typical example is that, assuming data packets always route along the shortest path, a node's load can be calculated by its betweenness centrality. In this setting, the node usually has two statuses, normal or failed, through the process of cascading failure. Once a node's load exceeds its maximum capacity, this node will be treated as a failed node and is then removed from the network. Many methods have also been proposed for improving the network robustness based on cascading failure models [21–27]. Those approaches are considered in three ways: modifying the topology of the network [21,22], optimizing the design of the maximum capacity of the network [23,24] and designing a better routing strategy [25–27]. The former two methods may require higher costs in design and are therefore more difficult to enact. Consequently, a more practical way to prevent cascading failure and improve the network robustness is to design a better routing policy.

In a real network, the number of data packets generated in unit time is likely uncertain. However, the abovementioned models make many ideal assumptions that do not consider the network's traffic congestion and its effects on routing selection. The models only consider the influence of the network topology on the network robustness. In the networks that have congestion situations, when the transmission efficiency of nodes is low on a path, the flow of data packets could avoid this path to route and choose another path with higher transmission efficiency. Thus, it is evident that the methods of defining a node's load in a traditional network cannot reflect the actual loading situation of the congested network. Recently, Wang et al. [27] proposed a cascading failure model having a global congestion effect on a network that is based on the global congestion information routing strategy. The global load of the network dynamically changes as the nodes' states. In their model, the influence of different network topologies, scales and nodes' processing capacities on cascading failure propagation are considered. However, in many practical problems, before data packets choose an optimal path, they need to know the congestion situations of all nodes in the feasible routing path. However, obtaining the global congestion information is extremely difficult and practically impossible.

Motivated by the above observations, a more practical cascading failure model with local congestion information is proposed in this paper. In the proposed model, a new congestion function is defined on each node, and a local congestion-aware routing strategy is proposed with a tunable parameter. According to various indicators measuring the network robustness, the influence of variable routing parameters, the tolerance parameter, the node removal rate and the congestion time delay are evaluated during cascading failures of the Barabási–Albert(BA) network and Erdös–Rényi(ER) network.

2. Analysis of the robustness of the Internet

The Internet can be described by an undirected and unweighted graph $G = (V, E)$, where $V = \{v_i | i = 1, 2, \ldots, N\}$ is the set of nodes, and $E = \{e_j | j = 1, 2, \ldots, M\}$ is the set of links between nodes. The $N \times N$ adjacency matrix $[a_{ij}]$ has $a_{ij} = 1$ if there is a link between node i and node j; otherwise, $a_{ij} = 0$.

2.1. Network model

Suppose that all nodes in the network have the ability to generate and forward packets simultaneously and that the number of packets changes continuously according to the network flows. The data-packet processing of each node is divided into three parts: packet generation, packet delivery and packet removal. Suppose that the network begins with no load. Then, at each time step, every node generates one data package with probability R, and the packet randomly selects another node as its destination. Once a packet arrives at its destination, it is removed from the network immediately.

Different from the previous methods to define the node's load based on its betweenness centrality, the load $L_i(t)$ of node i is defined as the total number of packets on node i at time t. It is expressed as follows

$$L_i(t) = L_i(t-1) + I_i(t) + \sum_j x_{ji}(t) - d_i(t), \quad \forall i, t > 0, \tag{1}$$

$$0 \le d_i(t) \le D_i \tag{2}$$

$$D_i = K \left\lceil \frac{k_i}{\langle k \rangle} \right\rceil \tag{3}$$

$$L(t) = \frac{\sum_i L_i(t)}{N'}, \qquad L_i(0) = 0, \quad i \in \{1, 2, 3, \ldots, N\} \tag{4}$$

where $I_i(t)$ is the number of packets generated by node i at time t; $x_{ij}(t)$ is the total number of packets sent by the neighbor node j to i at time t; $d_i(t)$ is the number of packets processed by node i at time t; the processing ability of node i is denoted

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