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Robustness of interdependent networks with different link patterns against cascading failures

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HIGHLIGHTS

- A two-stage cascading model in the interdependent networks is proposed.
- We compare three kinds of link patterns between interdependent networks.
- We find that the link patterns have important effects on dramatically improving the robustness of the interdependent networks.

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ABSTRACT

Taking into account the load, the load redistribution, and the node capacity, we study the robustness of two interdependent networks *A* and *B* against cascading failures, where each node in network *A* depends on one node in network *B*, and vice versa. We adopt three kinds of link patterns between two interdependent networks, i.e., the assortative link (AL), the disassortative link (DL), the random link (RL), where the RA refers to connect randomly two nodes in networks *A* and *B*, the AL refers to that high-degree (low-degree) nodes in *A* network link high-degree (low-degree) nodes in *B* network, while the DL refers to the fact that high-degree nodes in *A* network link low-degree nodes in *B* network. We investigate the robustness of the interdependent networks constructed by two artificial networks and the power grid, taking into account two stages of the cascading propagation. We numerically find that both the different link patterns and the parameters in the cascading model have important effects on dramatically improving the robustness of the interdependent networks against cascading failures. In addition, we obtain the better link pattern and the matching network structure to effectively avoid the cascading propagation.

1. Introduction

In recent years network safety [1–8] has been one of the most central topics and has been extensively studied. In particular, an important subject related to network safety is the so-called cascading failure dynamics [9–11], addressing how the failure of a node or a small part of nodes in a network induces other nodes' failure over the network. Owing to the correlation between nodes, the load redistribution, and the limited capacity of the node, cascading failures on networks are common phenomena and can occur in many infrastructure networks [12–15], such as electrical power grids, the Internet, traffic networks, and global economic system networks.

According to various dynamic mechanisms of cascading failures on different real-life systems, to effectively mitigate or control the cascading propagation, focused on artificial or infrastructure networks, a number of important aspects of cascading failures have been discussed in literature, including avalanche size distributions [16,17], the cascade control and defense strategy [18–23], the comparison of different attacking strategies [24–28], the cascading modeling [29–32]

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in real or artificial networks, and so on. In all cited studies above, taking into account the theoretical simplicity and the complexity of the actual system, almost all research on cascading failures has been only concentrated on the case of a single or isolated network, ignoring that many real-world networks interact with and depend on each other to provide proper functionality. The interdependence between networks has catastrophic effects on their robustness, i.e., node failure in one network may trigger the failure of dependent nodes in other networks which may produce an iterative cascade of failures in several interdependent networks, leading to a global cascade of failures. A dramatic real-world example of cascading failures in interdependent networks is the electrical blackout that affected much of Italy on 28 September 2003: owing to the coupling between the power grid and its communication support system, the shutdown of power stations directly caused the failure of nodes in the Supervisory Control and Data Acquisition (SCADA) communication network, which in turn led to the further breakdown of power stations [33,34]. Recently, based on the motivation that modern infrastructures due to their technological need are becoming more and more mutually coupled and depend on each other, cascading failures on interdependent networks have started to be studied actively [35–45]. A seminal work in this respect is that Buldyrev et al. [33] develop a framework for understanding the robustness of interdependent networks against cascading failures and present exact analytical solutions for the critical fraction of nodes and find that a broader degree distribution increases the vulnerability of interdependent networks to random failure, which is opposite to how a single network behaves. Vespignani [34] also obtains that the failure in interdependent networks highlights the vulnerability of tightly coupled infrastructures and shows the need to consider mutually dependent network properties in designing resilient systems. After that, some aspects of cascading failures in interdependent networks have been discussed and many valuable results have been found. In particular, great efforts have been dedicated to the research on how the coupled pattern between two networks affects the robustness of interdependent networks, which has been one of the most central topics in inter-networks safety. Buldyrev et al. [35] investigate the cascading phenomena in the interdependent networks with identical degrees of mutually dependent nodes. Parshani et al. [36] show both by simulation models and by analyzing the port–airport system that as the networks become more inter-similar the system becomes significantly more robust to random failure. Cho et al. [37] study the impact of correlated inter-layer couplings on the network robustness of coupled networks using percolation concept and find that the positive correlated inter-layer coupling enhances network robustness. In addition, Zhou et al. [38] also find that the internal node correlations in each of two interdependent networks significantly changes the critical density of failures that triggers the total disruption of the two-network system. They obtain that the assortativity (i.e., the likelihood of nodes with similar degree to be connected) within a single network decreases the robustness of the entire system. However, in all cited studies above, most works on an iterative cascade of failures in the interdependent networks have only concentrated on the static properties of the interdependent networks, while not considering the load on the node, the dynamic changes of the load, and the capacity of the node to handle the extra load in the actual interdependent infrastructure networks. Specially, how and to what extent the pattern of couplings between interdependent networks may influence the interlaced structure and function of coupled networks, and how to protect these networks and reduce their vulnerability are rarely studied. Therefore, in the interdependent networks, identifying, understanding, and analyzing the vulnerability induced by the interdependences and the effect of the coupled patterns on the robustness are the major challenges for designing resilient infrastructures, which we address here.

To this end, considering the load, the load redistribution on a failed node, and the node capacity, we study the cascading propagation in the interdependent networks. To better investigate the effect of the link pattern on the network robustness, we consider for simplicity, two networks A and B with the same number of nodes to model interdependent networks. We adopt three kinds of coupled patterns to link networks A and B, i.e., the assortative link (AL), the disassortative link (DL), and the random link (RA), where the RA refers to connecting randomly two nodes in networks A and B, the AL refers to that high-degree (low-degree) nodes in A network link high-degree (low-degree) nodes in B network, while the DL refers to that high-degree nodes in A network link low-degree nodes in B network. The cascading propagation in the interdependent networks includes two aspects: the cascading spreading only in network A (or network B) induced by the load redistribution, and the dependent failure that refers to the fact that if a node A_i in network A stops functioning, the node B_j in network B connected to node A_i also stops functioning owing to interdependence of nodes A_i and B_j in their normal and efficient function. By the above two-stages cascading propagation, we compare the robustness of the interdependent networks A and B with three coupled patterns, where networks A and B are selected in a power grid and two artificial networks, i.e., the Barabási–Albert (BA) scale-free network [46] and the Erdös–Rényi random network [47]. We numerically find that both the network structure coupled with each other and the different link patterns have important effects on dramatically improving the robustness of the interdependent networks against cascading failures. In addition, for a given network, we can obtain the better coupled network and the coupled pattern to effectively avoid the cascading propagation. Our findings will be helpful for interdependent networks to effectively improve their robustness against cascading failures.

The rest of this paper is organized as follows: in Section 2 we explain the link pattern and propose a two-stages cascading model. In Section 3 we numerically investigate the effect of the link pattern on the robustness of the interdependent networks against cascading failures. Finally, some summaries and conclusions are shown in Section 4.

2. The link pattern and the two-stages cascading model

The aim of this paper is to investigate how the robustness of the interdependent networks is affected by the inter-networks coupled patterns. To model interdependent networks, we consider for simplicity two networks A and B with the