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Cascading load model in interdependent networks with coupled strength

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HIGHLIGHTS

- We propose a new method to define the initial load on an edge in interdependent networks.
- We construct a cascading model with coupled strength.
- We find that coupled strength has an important effect on cascading failures.

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ABSTRACT

Considering the coupled strength between interdependent networks, we introduce a new method to define the initial load on an edge and propose a cascading load model in interdependent networks. We explore the robustness of the interdependent networks against cascading failures by two measures, i.e., the critical threshold β_c quantifying the whole robustness of the interdependent networks to avoid the emergence of cascading failure, and the new proposed smallest capacity threshold $\beta_{c,s}$ quantifying the degree of the worst damage of the interdependent networks. We numerically find that the AL (high-degree nodes in network A connect high-degree ones in network B) link between two networks can greatly enhance the robust level of the interdependent networks against cascading failures. Especially we observe that the values of β_c in the interdependent networks with both the DL (high-degree nodes in network A connect low-degree ones in network B) link and the RL (nodes in network A randomly connect ones in network B) link increase monotonically with the coupled strength, while the values of $\beta_{c,s}$ in the interdependent networks with three types of link patterns almost monotonically decreases with the coupled strength. In the interdependent networks with the AL, the value of β_c first decreases and then increases with the coupled strength. We further explain this interesting phenomenon by a simple graph. In addition, we study the influence of the coupled strength on the efficiency of two attacks to destroy the interdependent networks. We find that, when the coupled strength between two networks is weaker, attacking the edges with the lower load is more easier to trigger the cascading propagation than attacking the nodes with the higher load, however, when the coupled strength in two networks is stronger, the case is on the contrary. Finally, we give reasonable explanations from the local perspective of the total capacity of all neighboring edges of a failed edge.

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1. Introduction

Over the past several years, network safety has been a classical research topic. In particular, an important issue of network safety is the prominent resilience of real networks subject to random failures and intentional attacks [1–3]. Considering the theoretical simplicity and the complexity of the actual system, almost all researchers has been concentrated on the case of a single or an isolated network, ignoring that many real-world networks interact with and depend on each other to provide proper functionality, for example water supply networks, traffic networks, fuel and power stations are coupled together. Owing to this coupling and the interdependence, interdependent networks are extremely sensitive to random failure, i.e., a random removal of a small fraction of nodes from one network may trigger the failure of dependent nodes in other networks which may produce an iterative cascade of failures in interdependent networks, leading to a global cascade of failures. A dramatic real-world example of cascading failures in interdependent networks is the electrical blackout in Italy on 28 September 2003, owing to the coupling between the power grid that need communication network to transmit control signals and its communication support system that need power grid to provide power supply, 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 [4,5].

To better protect infrastructure networks, researchers have discussed a number of important aspects of cascading failures in literature by analyzing the cascading dynamics including the cascading modeling [6–13], the cascade control and defense strategy [14–22], the comparison of different attack strategies [23–27], the cascading analysis in real networks [28–34], and so on. However, previous research still focuses on the limited case of a single, non-interacting network. Recently, based on the motivation that modern, crucially important infrastructures significantly interact, analyzing and understanding how robustness is affected by the coupling between interdependent networks is one of the main challenges in designing resilient infrastructures. A seminal work in this respect is that Buldyrev et al. [5] develop a framework for understanding the robustness of interdependent networks against cascading failures and find that interdependent networks become more vulnerable compared to their noninteracting counterparts. Vespignani [4] 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. By protecting the edges between the interdependent networks, Wang et al. [35] only investigate its efficiency of improving the robustness of the interdependent networks against cascading failures and find that adjusting the capacities of the edges among networks can better improve the robustness of the interdependent networks against cascading failures. After that, the question of the robustness of interdependent networks has attracted a large amount of interests from many researchers. In particular, there has been the extensive effort to study and understand the cascading dynamics in the interdependent networks, including the robustness of the interdependent networks [36–41], the cascading modeling in interdependent networks [42–48], and the impact of coupling on cascading failures in the interdependent networks [49,50], and so on. However, to facilitate the analysis, many studies only focus on the interdependency losses on the basis of the percolation theory, while not considering the cascading propagation induced by the overload failure on an edge in the interdependent networks. Therefore, in order to understand load-failure-induced disasters better, it is natural and important to construct the cascading load model and investigate the load cascading dynamics in the interdependent networks.

To this end, taking the overload failure of an edge into account, we study the robustness of the interdependent networks against cascading failures. Our aim is to find some efficient approaches to improving the robustness of interdependent networks subject to random failures or targeted attacks. To achieve this goal, according to the coupled strength between two networks, we first give a reasonable method to assign the initial load on an edge and propose a cascading load model. The cascading propagation in the new model mainly includes two processes: (a) the overload failure of an edge resulting from its limited capacity; (b) the dependency failure of the interconnection between two networks, i.e., the failure of nodes in one network can lead to the failure of dependent nodes in the other network. To better investigate the robustness of the interdependent networks against cascading failures, we adopt three types of coupled patterns to construct interdependent networks (A and B), i.e., the assortative link (AL) that high-degree nodes in network A connect high-degree nodes in network B, the disassortative link (DL) that high-degree nodes in network A connect low-degree nodes in network B, and the random link (RA) that nodes in network A randomly connect nodes in network B. We quantify the robustness of the interdependent networks against cascading failures according to the average avalanche size and two measures, i.e., the critical threshold β_c to quantify the whole robustness of the interdependent networks and the new proposed smallest capacity threshold $\beta_{c,s}$ to quantify the degree of the worst damage of the interdependent networks. In the interdependent BA–BA networks and the interdependent BA-Power networks, we numerically investigate the cascading dynamics and find that the robustness of the interdependent networks with the AL is greatly improved when compared to the other two link patterns. We also compare the correlation between two measures and the coupled strength, and find it is different from the DL and the RL, that β_c in the AL first decreases and then increases with the coupled strength. We further explain this interesting phenomenon by a simple interdependent networks with a smaller number of nodes. In addition, in order to find what types of nodes are easier to trigger the cascading propagation, we compare the robustness of the interdependent networks subject to two targeted attacks, i.e., attacking the edges with the higher load (HL) and attacking the edges with the lower load (LL). We find some interesting results including: (a) when the coupled strength is weaker, the LL is more likely to trigger the cascading propagation than the HL; (b) for the LL, the robustness of the interdependent networks has a positive correlation with the coupled strength, while for the HL, the case is on the contrary; (c) for the LL, the critical threshold to avoid the global failures