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The effect of capacity redundancy disparity on the robustness of interconnected networks

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HIGHLIGHTS

- We consider the model where two networks with different capacity redundancy are interconnected.
- We show that it is possible that more capacity redundancy may cause worse robustness.
- We compare different cases and find that this counterintuitive feature only appears in interconnected networks with redundancy disparity.

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ABSTRACT

Cascading failures in interconnected networks have received more and more attention. In previous works, the basic assumption is that networks share the same capacity redundancy. However, this setting cannot capture the real case very well. Hence, in this paper, we analyze the effect of capacity redundancy disparity on the robustness of interconnected networks. In isolated networks, it is well known that the complex network's robustness can be improved by increasing its capacity redundancy. In interconnected networks where two networks share the same capacity redundancy, the similar result holds. Yet this result is not necessarily true in interconnected networks where two networks are different in capacity redundancy. We find that when the capacity redundancy of one network is fixed, the robustness of the whole system may not follow another network's capacity redundancy. More specifically, when the fixed network's capacity redundancy is very small or very large, the robustness of the whole system increases as another network's capacity redundancy increases. But there exists a certain range within which the increase of one network's capacity redundancy results in the robustness decline of the whole system. This counterintuitive feature appears under different coupling patterns such as assortative, disassortative, or random coupling. This result advances our understanding of the robustness of interconnected networks.

1. Introduction

In the past decades, the research on complex networks has helped us make a deeper understanding of the interplay between network structure and dynamics [1], including cascading failures [2–4], epidemic spreading [5–7], evolutionary games [8–11], and traffic dynamics [12–14]. Among them, cascading failures in real-world infrastructure networks, such

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as the Internet, power grids and transportation systems, have received much attention. Taking the Internet as an example, when a router fails owing to perturbations or targeted attacks, the loads on this router will be redistributed, which can lead to overload on other routers. These overloaded routers then fail and are removed from the network, causing a new redistribution of loads. As this process keeps going, cascading failures take place, which can cause large catastrophes of the whole network. Over the past decade, cascading failures in isolated networks have received wide attention [3,4,12,15–28]. It was found that scale-free networks are robust to random failures but fragile to intentional attacks on hubs, while random graphs are robust to both random failures and intentional attacks [3]. So far, researchers have been focusing on cascading failure models [3,15–17], cascade defense strategies [18–23], attack strategies [12,24–27], and so on.

The above-mentioned works, however, are mainly focused on the isolated networks. Actually, various real-world networks always interact with each other, forming more complicated systems, *i.e.*, networks of networks [29–31]. Recently, to further capture real-world systems, some coupled network models have been established. One typical model is the interdependent networks proposed by Buldyrev et al. [32], where two networks are dependent on each other. The dependency between nodes in two networks are referred as interdependent links. It should be noted that these links only denote the logical interdependency between two networks, rather than physical links [30]. It was found that interdependent networks are quite fragile even to random failures [32]. Based on this model, some deeper issues on the robustness of interdependent networks have been studied, including coupling probability [33–36], coupling pattern [37–40], attack pattern [41], inter-link types [42,43], and networks structures [44,45]. The interdependent networks model helps us understand the interaction in real-world networks more readily.

As another kind of interaction, the interconnected networks model has also been established, where two networks do not depend on but interact with each other [14,46–48]. In such networks, the interconnected links represent the physical connections between networks, which is different from the interdependent links in interdependent networks. These physical interconnected links provide paths for the traffic from one network to another. The US power systems, for instance, are formed by three main power grids which interact with each other [49]. In interconnected networks, cascades can propagate from one network to another through interconnected links. Brummitt et al. [46] and Tan et al. [47] have explored cascades in interconnected networks based on different cascading models. In their research, the optimal coupling probability could be found to improve the robustness of interconnected networks against cascading failures. Since interconnected links provide path for the traffic from one network to another, how to allocate these links has great impact on the robustness of the whole system. Tan et al. [47] found that the interconnected networks with assortative coupling are more robust than the networks with disassortative or random coupling.

In real world, interconnectivity between different networks is ubiquitous, such as the interaction in transportation systems, the interconnection among power grids, and the cooperation in communication networks. In these infrastructure networks, each node can only handle limited loads. The maximal load a node can handle is defined as the capacity of this node. Obviously, there should be some redundancy between a node's capacity and the actual load it handles. For simplicity, most studies on interconnected networks assume that networks share the same capacity redundancy. This assumption simplifies the traffic model and helps us focus on how the interconnected network structure affects the traffic performance including the robustness. However, we should understand that this is not the case in most real-world applications, because different networks are always designed with different processing capabilities, which we call as capacity redundancy disparity. It makes the interconnected networks more complicated, and may lead to some important features which distinguish the interconnected networks from each individual network. In this paper, we try to explore the effect of network capacity redundancy disparity on cascading failures, and display the robustness of interconnected networks under such a more realistic condition. We will show that our common sense from isolated complex networks may become invalid in this interconnected networks case.

2. Models

2.1. Network model

Considering that the scale-free feature is common in many real-world networks, we study the interconnected networks composed of two Barabási–Albert (BA) scale-free networks [50] labeled as A and B. For simplicity and clarity of the results, we assume that they share the same size ($N_A = N_B$) and same average degree ($\langle k\rangle = \langle k_A\rangle = \langle k_B\rangle$). Here these two networks are fully coupled by interconnected links, and each node has one and only one interconnected link.

As mentioned in previous studies, coupling patterns, *i.e.*, the ways to add interconnected links have great impact on the interconnected networks' robustness. Here we consider three kinds of coupling patterns which are described as follows [47]:

- Random coupling. We randomly choose a node in each network. If neither of these two nodes has the interconnected link, then connect them. Otherwise, do not connect them. Repeat this process until all interconnected links are added.
- Assortative coupling. We sort nodes in networks A and B respectively, both in the descending order of loads, labeled as $a_1(b_1), a_2(b_2), \ldots, a_{N_A}(b_{N_B})$. If two or more nodes share the same load, they are sorted at random. Then connect a_1 with b_1, a_2 with b_2, and so on. Repeat this process until all interconnected links are added.
- Disassortative coupling. We sort nodes in both networks as mentioned above, and connect a_1 with b_{N_B}, a_2 with b_{N_B-1}, and so on. Repeat this process until all interconnected links are added.