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Improving interdependent networks robustness by adding connectivity links

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HIGHLIGHTS

- Considering interdependent relationships, two novel connectivity link addition strategies are proposed.
- Performance comparisons among six link addition strategies are conducted in three types of interdependent networks.
- The robustness of interdependent networks can be improved by adding connectivity links.
- Double-network link allocation strategy yields better performance to single-network link allocation strategy.
- Simulation results indicate that our proposed methods are superior to the current link addition strategies.

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ABSTRACT

Compared with a single and isolated network, interdependent networks have two types of links: connectivity link and dependency link. This paper aims to improve the robustness of interdependent networks by adding connectivity links. Firstly, interdependent networks failure model and four frequently used link addition strategies are briefly reviewed. Furthermore, by defining inter degree–degree difference, two novel link addition strategies are proposed. Finally, we verify the effectiveness of our proposed link addition strategies by comparing with the current link addition strategies in three different network models. The simulation results show that, given the number of added links, link allocation strategies have great effects on the robustness of interdependent networks, i.e., the double-network link allocation strategy is superior to single-network link allocation strategy. Link addition strategies proposed in this paper excel the current strategies, especially for BA interdependent networks. Moreover, our work can provide guidance on how to allocate limited resources to an existing interdependent networks system and optimize its topology to avoid the potential cascade failures.

1. Introduction

In the past fifteen years, single-layer complex network theory has been studied extensively [1–5]. By modelling a complex system into a network, many useful outcomes have already been applied in the areas of vulnerability analysis [6–16], optimal bandwidth allocation [17], network evolution evaluation [18], isolated communities detection and predictive control strategies [19,20]. However, in modern society, critical infrastructures are not self-sufficient but highly interdependent [21].

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Local failures within one system may be deteriorated by spreading to its dependent networks and cause recursive damages, such as the 2003 North America blackout [22], the 2003 Roman blackout [23] and the 2004 Italia blackout [24]. Hence, it is of theoretical significance and practical value to improve the robustness of interdependent networks system.

Several enhancement methods have been conducted to protect interdependent networks. (1) The first approach is to protect the critical nodes. Ruj et al. [25] point out that interdependent networks disintegrate faster under high degree node attacks compared to random attacks. Liu et al. [26] show that attack strategy considering the connectivity of nodes in both networks will be more effective than only considering the degree of one single network. Further, Nguyen et al. [27] prove that critical node identification problem in interdependent networks is a NP-hard problem and propose a greedy framework to identify the critical nodes in a timely manner. Sen et al. [28] propose a new model to identify the K most vulnerable nodes of interdependent networks. (2) The second approach is to deploy autonomous nodes. Shao et al. [29] conclude that interdependent network's robustness can be improved by deploying autonomous nodes which do not need any support from other network. Schneider et al. [30] propose the strategy based on degree centrality and betweenness centrality to decrease the necessary number of autonomous nodes that guarantee the robustness of the system. (3) The third approach is to adjust dependency link allocation. Parshani et al. [31] find that as the networks become more inter-similar, the system becomes significantly more robust to random failure. Yagan et al. [32] show that the regular allocation strategy that allots exactly the same number of bi-directional interlink to all the nodes in the system yields better performance compared to random allocation and unidirectional interlinks. Reis et al. [33] demonstrate that if interconnections are provided by network hubs, and the connection between networks are moderately convergent, the system of networks is stable and robust to failures. (4) The fourth approach is to refigure the topology of single network by rewiring. Zhou et al. [34] indicate that decreasing assortativity within single network by rewiring could improve the robustness of entire system.

It is worth mentioning that for an existing interdependent networks system, e.g., power grid and its communication network, the current enhancement strategies may have some limitations. Protecting critical nodes is a passive approach since it only aims to decrease the possibility of damages rather than improve the robustness of network. Deploying autonomous nodes, which can effectively increase the robustness of interdependent networks, is expensive and needs to make major technical modifications. Furthermore, adjusting interdependent relationships or refiguring its topology by rewiring in a wide range is difficult to realize due to economic or other various constraints.

In order to improve the robustness of interdependent networks system, adding some connectivity links will be a proper strategy since it is both technically feasible and without impairing the current services. However, previous link addition strategies, e.g., random addition strategy [35–37], low degree addition strategy [36,37], low betweenness addition strategy [36] and algebraic connectivity based addition strategy [38,39], are all designed to optimize single-layer network. In interdependent networks, the vulnerability of isolated network is both affected by its own topology and coupled network. Thus, the effectiveness of the single-layer network link addition strategies should be validated and link addition strategies designed for interdependent networks should be investigated to address the problem.

The rest of this paper is organized as follows: in Section 2, interdependent networks failure model and four frequently used link addition strategies are briefly reviewed. In Section 3, by defining inter degree–degree difference and average inter degree–degree difference, two link addition strategies, i.e., low inter degree–degree difference addition strategy and random inter degree–degree difference addition strategy, are proposed. In Section 4, the impacts of different addition strategies on the robustness of interdependent networks are compared under both single-network link allocation scenario and double-network link allocation scenario. Some conclusions and summaries are shown in Section 5.

2. The model

In Section 2, we review the interdependent networks failure model and make slight modification to better illustrate the vulnerability of interdependent networks under random failures from the perspective of industrial demands. Then, four frequently used single network link addition strategies, namely random addition (RA) link addition strategy, low degree (LD) link addition strategy, low betweenness (LB) link addition strategy and algebraic connectivity based (ACB) link addition strategy, are introduced.

2.1. Interdependent networks failure model

To model interdependent networks, the "one-to-one correspondence" model proposed by Buldyrev et al. [24] is adopted in this paper. For simplicity, we assume networks A and B have the same number of nodes N, namely $N_A = N_B$, and share the same topology. Each node in network A is randomly interdependent with only one node in network B and vice versa. If node i in network A stops functioning as a result of failure or attack, its coupled node j in network B stops functioning too. Thus, the interdependent relationship between coupled nodes can be described as a bidirectional link $A_i \leftrightarrow B_j$. Furthermore, notice that only the nodes belonging to the largest connected component are valid. Since the interdependent networks model we use in this paper is one-to-one correspondence, the number of nodes remaining in network A at the final stage is equal to that remaining in network B, namely $N'_A = N'_B$.

To model the robustness of interdependent networks under random failures, we define p, instead of $(1 - p)$ adopted by Ref. [24], as the fraction of nodes is randomly removed from network A at the first stage since it is more obvious to observe