Physica A 513 (2019) 555–564

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Research on the connection radius of dependency links in interdependent spatial networks against cascading failures

Zhengcheng Dong [a], Meng Tian [b], Jiaqi Liang [a,*], Yanjun Fang [a], Yuxin Lu [a]

[a] School of Power and Mechanical Engineering, Wuhan University, China
[b] Electronic Information School, Wuhan University, China

HIGHLIGHTS

- The connection radius of dependency links is studied based on network connectivity.
- A hybrid coupling is proposed to ensure invulnerability and short dependency links.
- A simplified localized attacking strategy is studied based on percolation theory.

ARTICLE INFO

Article history:
Received 2 May 2018
Received in revised form 3 August 2018
Available online xxxx

Keywords:
Connection radius
Dependency links
Percolation theory
Cascading failures
Hybrid coupling pattern

ABSTRACT

Most of previous research on complex networks always concentrates on topology, ignoring the coordinates of components. However, the spatial information of components may be a key factor influencing the invulnerability of actual networks. For interdependent infrastructures, considering space constraints, dependency links may be established locally, where only nodes within certain connection radius $r_{connect}$ can be connected as dependent node pairs. Therefore, based on the topology-based cascading failure model, the invulnerability of interdependent scale-free networks is studied by introducing five coupling patterns in this paper, including global and local random couplings *GR* and *LR*, global and local degree–degree inter-similarity couplings *GD* and *LD* and nearest neighbor coupling *NN*. Under topological attacks, the inter-similarity couplings *GD* and *LD* have better performance, and as $r_{connect}$ increases, the effect of *LD* will gradually approach to *GD*. In order to ensure a good invulnerability and low construction cost, a novel hybrid coupling pattern of *NN* and *LD* is proposed. With numerical simulations, we find that selecting nodes with large degree to establish *LD* coupling has significant effect, and there is an optimal selection fraction. Under localized attacks, the local couplings perform better, and *LD* is better for small $r_{connect}$ while *NN* is better for large $r_{connect}$. In addition, we also study a simplified localized attacking strategy analytically based on percolation theory, which is proved to be consistent with the numerical results. For *LD* coupling, the effect will be influenced by $r_{connect}$, and there are minimum and maximum invulnerability values for topological and localized attacks, respectively. These findings can help to understand the characteristics of spatially embedded interdependent infrastructures.

1. Introduction

Since the network was found to have small-world and scale-free natures [1,2], complex network theory has made its progress and been applied to various research fields [3–12], such as electricity, traffic, finance, biology, social and so

* Corresponding author.
E-mail address: jqliang@whu.edu.cn (J. Liang).

https://doi.org/10.1016/j.physa.2018.09.007
0378-4371/

on. With the continuous development and integration of technology, the interaction between not only individuals but also systems becomes more intensive, forming coupled networks [13–15]. If the systems depend on each other, there will be dependent or interdependent networks [13], which are common in interrelated infrastructures. The interaction and integration make systems more efficient and intelligent while also creating conditions for the propagation of failures (cascading failures) [13,16]. Typically, the modern smart grid is a coupled system composed of power system and information system, namely cyber physical power system (CPPS) [17,18]. The existence of information system (such as SCADA and WAMS systems) facilitates the uploading and decision-making of power system information so as to make the whole system more efficient. However, the failure or fault of information equipment may also cause the collapse of power system, for example, the Ukrainian blackout in 2015 [19]. Therefore, for interdependent systems, studying on each single system cannot help to understand the actual coupled systems.

Most research used to focused on the topology of network, ignoring the spatial coordinates and location information of components, such as nodes and edges. However, for some spatial networks, the spatial information may be an important factor influencing their characteristics [20,21]. For an actual infrastructure system, the length of edge may be equal to its construction cost, and thus long-range edges will increase the complexity and construction cost of system, such as highways, transmission lines, communication lines and pipelines. Therefore, in spatial network, nodes may be more likely to establish connections with local nodes rather than global ones. Similarly, in interdependent spatial networks, the selection of dependent nodes may also follow the local connection rule, that is, nodes only can establish dependency links within certain specific range (connection area). Due to the fact that interdependent networks are very common and present some different features with single network [22–24], it is of great significance to study the local dependency links. Li et al. [20] studied the relationship between the length of dependency link r and vulnerability in interdependent lattice networks. It was found that a critical value r_c existed to make the system the most vulnerable while greater or lesser r_c will show different phase transitions. Since then, researchers also studied other parameters of interdependent spatially embedded networks [21,25,26], for example, the relationship between r_c and the proportion of autonomous nodes q. Although these findings provide some novel ideas for the research on interdependent spatial networks, there are still few studies about the length of dependency links. In addition, the existing literatures mostly adopted lattice network, which belongs to a kind of regular network with extremely regular topology, and the distance r does not refer to Euclidean distance but the unit number between each pair of dependent nodes.

On the other hand, for spatial network, besides the location information of components, the attacking strategy will also change. In traditional attacking strategy, initially failed nodes (or edges) are selected globally based on the network topology without considering their spatial information (topological attack). However, the external attacks faced by some actual infrastructures are always localized attacks [27,28], that is, an attacking area will be produced in space, and only the components falling into it will fail, such as wars and natural disasters as earthquakes and tsunamis [28].

Some research indicates that compared with random coupling, assortative (inter-similarity) coupling [24,29] can improve the invulnerability of interdependent networks. However, considering the connection radius of dependency links in spatial networks, does local inter-similarity coupling have the same effect? Based on a two-dimensional (2D) square space, we study the connection radius of dependency links in scale-free networks with a topology-based cascading failure model in this paper. Different from some existing work on dependency links, this paper adopts scale-free network instead of regular network, and all the parameters are defined by Euclidean distance. First, we define a local connection rule and introduce five global and local coupling patterns. Second, we present the localized attacking strategy and the method to judge failed components. In the end, we investigate the impacts of coupling preference and connection radius on cascading failures in interdependent scale-free networks. In addition, some numerical simulations under localized attacks are analyzed based on percolation theory, and the impact of network size on results is studied. We find that the connection radius of dependency links will influence the network invulnerability, but the effects differ under different attacking strategies. Under topological attacks, the inter-similarity couplings have better performance while under localized attacks, the networks with shorter dependency links perform better. Besides, we also propose a hybrid coupling pattern, which can balance the link length and network invulnerability. âĂĺ The rest of this papeâĂĺr is organized as follows: in Section 2, the local connection rule is proposed, and five global and local coupling patterns are introduced; in Section 3, the localized attacking strategy is explained, and the impact of network size on the invulnerability of interdependent networks is studied; in Section 4, based on the topology-based cascading failure model, the impact of the connection radius of dependency links on cascading failures is investigated, and the hybrid coupling pattern is proposed; the relevant conclusion is summarized in Section 5.

2. Local coupling of interdependent spatial networks

We assume that an interdependent networks system consists of two scale-free networks located in a 2D space randomly, denoted as A and B, respectively, and each node has random coordinates. All the interdependent networks are constructed with one-to-one correspondence, that is, each node has one and only one dependent node. The coupling pattern of interdependent networks refers to the selection and connection method of dependent nodes. In order to compare with local coupling, two traditional global couplings are introduced, namely global random coupling (*GR*) and global degree–degree inter-similarity coupling (*GD*), where *GR* is to select nodes in the two networks randomly as dependent node pairs while *GD* is to connect nodes according to their degree rankings sequentially. To establish the degree–degree inter-similarity coupling, we respectively sort the nodes of the two networks by degree and obtain their degree sequences. For *GD* coupling, each pair of connected dependent nodes has the same degree ranking.