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The effect of interdependence on the percolation of interdependent networks

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HIGHLIGHTS

- Two stochastic models are built to generate two different interdependent networks.
- The effects of dependence relation and strength are considered.
- The robustness of two interdependent networks are compared.
- Another network elimination mechanism is proposed and different results are given.

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ABSTRACT

Two stochastic models are proposed to generate a system composed of two interdependent scale-free (SF) or Erdős–Rényi (ER) networks where interdependent nodes are connected with an exponential or power-law relation, as well as different dependence strength, respectively. Each subnetwork grows through the addition of new nodes with constant accelerating random attachment in the first model but with preferential attachment in the second model. The two subnetworks interact with multi-support and undirectional dependence links. The effects of dependence relations and strength between subnetworks are analyzed in the percolation behavior of fully interdependent networks against random failure, both theoretically and numerically, and as a result, for both relations: interdependent SF networks show a second-order percolation phase transition and the increased dependence strength decreases the robustness of the system, whereas, interdependent ER networks show the opposite results. In addition, the power-law relation between networks yields greater robustness than the exponential one at the given dependence strength.

1. Introduction

Nowadays, with the enhanced development of modern technology, the interaction between networks becomes increasingly intensive and complicated [1–3]. Examples of interdependent networks are ubiquitous and include the subway network and the airport network in the transportation system, the bank network and the company network in the economy system, the communication network and the power grid network in the infrastructure system, and so forth. In these

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interdependent networks, the failures of nodes in one subnetwork generally will lead to the failure of dependent nodes in the other subnetworks [4–9]. This may happen recursively and might lead to a cascade of failures. Understanding how robustness is affected by the interdependence between subnetworks becomes one challenge when designing resilient systems. Very recently, several studies presented a theoretical framework for studying the process of cascading failures in interdependent networks and showed that interdependencies significantly increase the vulnerability of the entire networks to random attack [10–13]. In addition, the first-order phase transition presented in interdependent networks is totally Q2 different from the second-order phase transition which occurred in an isolated network.

Most existing studies have focused almost exclusively on random interdependent networks in which the interdependent nodes are randomly connected, which is at odds with real complex systems. Taking the Italian power grid and communication networks as an example [4,10,14], it is very common that a central communication station depends on a central power station and vice versa. Similarly, well-connected seaports are found more likely to depend on well-connected airports in Ref. [15] where positive correlation exists between the interaction of subnetworks. Based on this feature, interdependence with correlation, not random, has attracted much attention to the robustness of interdependent networks currently. Parshani [15] and Cho [16] have shown a similar result that the positively correlated interdependence enhances the robustness of networks, respectively. Buldyrev et al. [17] have analytically investigated the situation with one simple correlation that all pairs of interdependent nodes have the same degree. In addition, Refs. [6,18] have discussed the interdependence relation represented by the Poisson distribution and power-law distribution in stochastic models, respectively. Furthermore, the effect of the dependence strength between subnetworks also plays the key role in the percolation of interdependent networks. Ref. [10] has found that when the dependence strength is reduced, the percolation transition becomes second-order transition at a critical coupling strength, which enhances the robustness of the system. How and to what extent the relation of interdependence between subnetworks might influence the entire system's structure and function are still not well known.

In the present work, discussing the effect of different dependence relations and dependence strength on the robustness of the interacting system under random attack is our focus and motivation. Two types of relations are generated by two stochastic growing network models whereby the origin of relations is explained. One is that interdependent nodes randomly depend on each other with an exponential degree distribution; the other is that they preferentially depend on each other with a power-law degree distribution. In addition, two interdependent scale-free (SF) and Erdős–Rényi (ER) networks are also created in these two models, respectively. The influences of dependence relations and coupling strength of multi-support, undirectional dependence links on the robustness of networks are theoretically analyzed and simulated. As a result, it is found that, (1) two different interdependence links could be generated by the addition of dependence links; (2) for interdependent SF networks and ER networks, different types of phase transition and opposite effects of dependence strength are presented; (3) for the effect of interdependence, the power-law distribution of dependence degree yields higher robustness than the exponential one with given dependence strength. Furthermore, we consider another dependency mechanism in models that several giant components, not only one giant component, could exist after the cascading failure, which results in unexpected findings and is helpful in designing robust interdependent networks with more realistic consideration.

2. The first model

In both the two models, there are two types of links among the nodes: connectivity links (intra-links in each subnetwork) that enable the nodes to function cooperatively as a network, and dependence links (cross-links between subnetworks) that bind the failure of one subnetwork node to the failure of other subnetwork nodes. These two kinds of links correspond to two kinds of degree of each node in networks, connectivity degree (k_{con}) and dependence degree (k_{dep}), respectively. The first model of two interdependent scale free (SF) networks is built by the following considerations.

Initially, both subnetworks A and B contain m_0 nodes and n_0 connectivity links, without dependence links between subnetworks. At each time step t, two new nodes are introduced simultaneously, one belonging to subnetwork A and the other belonging to subnetwork B. The new node joining to subnetwork A with m_A links added, preferentially attaches $1-q_A$ fraction of its links as connectivity links to pre-existing nodes in subnetwork A. The rate of acquiring a link replies on the degrees of pre-existing nodes in subnetwork A. And then this new node randomly or preferentially attaches q_A fraction of links as dependence links to pre-existing nodes in subnetwork B. In other words, the connectivity degree and the dependence degree of the new node joining to subnetwork A are equal to $m_A(1-q_A)$ and m_Aq_A at time step t through different addition methods, respectively. The similar process is executed when a new node joins to subnetwork B, where the new node has m_B links added from which $1-q_B$ fraction of them randomly connect to pre-existing nodes in subnetwork B and q_B fraction of them randomly or preferentially connect to pre-existing nodes in subnetwork A, and its connectivity degree and dependence degree are equal to $m_B(1-q_B)$, m_Bq_B, respectively. q_A and q_B are defined as the strength of dependence between two subnetworks. Larger $q_A(q_B)$ means more dependence links between subnetworks or the more intensively two subnetworks depend on each other. The process ends when the size of both subnetworks increases up to N. In fact, through this model, the subnetworks A and B generated are equivalent to the classical random graph studied by Barabási–Albert with a power-law degree distribution ($p(k_{\mathrm{con}})$), and thereby named two interdependent SF networks. Two dependence relations between interdependent nodes are represented by the degree distribution of dependence links $p(k_{\mathrm{dep}})$. One is the