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Complex networks repair strategies: Dynamic models

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HIGHLIGHTS

- A dynamic repair model which was affected by energy transfer was established.
- A Shell Repair Strategy was proposed to find out the coupling structures.
- The number of nodes that face the risk of secondary failure during repair process is very small.
- Switching nodes have a significant impact on network repair and defense.

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ABSTRACT

Network repair strategies are tactical methods that restore the efficiency of damaged networks; however, unreasonable repair strategies not only waste resources, they are also ineffective for network recovery. Most extant research on network repair focuses on static networks, but results and findings on static networks cannot be applied to evolutionary dynamic networks because, in dynamic models, complex network repair has completely different characteristics. For instance, repaired nodes face more severe challenges, and require strategic repair methods in order to have a significant effect. In this study, we propose the Shell Repair Strategy (SRS) to minimize the risk of secondary node failures due to the cascading effect. Our proposed method includes the identification of a set of vital nodes that have a significant impact on network repair and defense. Our identification of these vital nodes reduces the number of switching nodes that face the risk of secondary failures during the dynamic repair process. This is positively correlated with the size of the average degree $\langle k \rangle$ and enhances network invulnerability.

1. Introduction

Complex networks [1] arise in natural systems and are an essential part of modern society. Since their discovery, complex networks have received extensive attention from many fields of study [1,2]. Complex networks applications have been utilized in many fields, such as aeronautics and astronautics, transportation, communication, management, sociology, and other important areas [3–9]. Many scholars have studied the structural features [10] and dynamic characteristics [11] of real networks through the theory of complex networks, and their findings have allowed them to construct optimal network structures [12] and develop appropriate energy transfer rules [13] to improve the robustness, invulnerability, and security of networks. To date, most studies have focused on the following 3 aspects: (1) vital nodes identification in complex networks, for which Lü et al. [14] summarized important advancements and described state-of-the-art technology; (2) network invulnerability [15] and robustness [16], for which Holme [15] studied the attack vulnerability of complex networks. Moreover, Gao et al. [16,17] established a framework for interdependent networks and studied the robustness of

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a network of networks (which is more complex than a single network). (3) network controllability, for which Liu et al. [18] developed an approach that offers a framework to address the controllability of an arbitrary network, representing a key step toward the eventual control of complex systems.

Few scholars, however, have systematically studied network repair strategies [19,20]. Moreover, most research on network repair focuses on static networks. Studying network repair is crucial because it can help us improve the security of networks by determining the most suitable repair strategy for each individual network without increasing the redundant paths of networks. This creates a strategic method for restoring the efficiency of damaged networks. For instance, Chi et al. [3,19] studied the stability of complex networks while they were under attack and while they were being repaired; however, they isolated the functional coupling between nodes, and only analyzed them from the network structure level. Robert et al. [20] studied optimal networks on regular lattices, and determined that they had an expected cost of reconnection proportional to the lattice length. Sun et al. [21] studied target recovery in complex networks, because, in real-world situations, recovering the most significant nodes first is crucial. Additionally, Antonio et al. [22] studied spontaneous recovery in dynamic networks.

However, complex networks repair exhibits completely different characteristics in dynamic models. Similar to cascading failures caused by attacks, multiple node failures (typically) occur around the node being repaired. As such, the repaired node is exposed to severe redistribution load shocks and is more prone to secondary failures. Importantly, the risk of secondary node failures can be reduced by suitable repair strategies, which indicates that the nodes most at risk of secondary failure during the repair process cannot be identified by network structure information alone. Compared to static models, dynamic repair is more complex and polytropic; however, nodes repaired using a suitable strategy are not only restored to their previous roles, they also reduce the impact of adjacent node failures and restore network function more effectively. Therefore, in this study, we propose the Shell Repair Strategy (SRS) to minimize the risk of secondary node failures due to the cascading effect. We also establish that a specific set of vital nodes (discovered by our Shell Repair Strategy) have a significant impact on network repair and defense as a whole.

The remainder of this paper is organized as follows: In Section 2, we introduce the failure model and repair model. In Section 3, we discuss the construction of the Shell Repair Strategy of coupling structures and switching nodes filtering. In Section 4, we discuss the simulation results of our repair strategy and verify the impact of the switching nodes on network invulnerability. Finally, we provide our summaries and conclusions in Section 5.

2. Modeling

Complex networks are a type of theoretical method for studying complex systems from a global properties perspective. Theoretically, we can abstract the units of complex systems as nodes, and links stand for the interactions between nodes where energy is passed. We can then analyze the characteristics of the networks to study complex systems. Assume $G = (V, E)$ is an undirected and unweighted graph, $V = \{v_1, v_2, \dots, v_n\}$ is a set of nodes, and $E = \{e_1, e_2, \dots, e_m\}$ is a set of edges.

2.1. Failure model

Cascade failures are a chain reaction in which an initial failure triggers a global failure as one failure offsets another failure in a domino-like effect. Motter and Lai [23] presented the classic load–capacity model (ML) ($C_i = (1+\alpha)L_i$) in 2002, but their model is difficult to apply to large-scale networks due to the large amount of calculations it requires. Many scholars have attempted to improve the ML model. These newer models depict the transfer law in real complex systems in more detail. For instance, Wang et al. [24] defined a new model in which the initial load L_i of the node i is correlated with its link degree k_i as $L_i = k_i^{\theta}$, θ is the load parameter. Additionally, Rui et al. [25] established a nonlinear load–capacity model $C_i = \alpha + \beta L_i = L_i + \Delta C_i$, α and β are tolerance coefficients, and ΔC_i is the redundant capacity. Significantly, previous studies have shown that the preferential allocation strategy more closely mirrors real-world situations. For instance, when a node fails, the load is reassigned to its neighboring nodes according to the following rules, and may cause more nodes to fail.

$$\Delta L_{ij} = L_i \times \frac{L_j}{\sum\limits_{k \in \Gamma_i} L_k}, \tag{1}$$

where ΔL_{ij} is the redistribution of the load from the failed node i to a functioning node j, and Γ_i is the set of functioning nodes adjacent to the failed node i.

2.2. Repair model

Network repair can be divided into (1) node function recovery and (2) network function recovery. Node function recovery means that the node has been repaired, whereas network function recovery means that the node has been repaired and connected to the network. Our goal is to accomplish the latter. At present, most of the research on network repair has been confined to static models, which are biased toward node function recovery. Moreover, static models completely isolate the