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The critical load of scale-free fault-tolerant topology in wireless sensor networks for cascading failures

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HIGHLIGHTS

- We model the load redistribution based on the variable load and the fixed capacity in WSNs.
- We investigate the relationship between the variable load and the cascading failure scale of scale-free topology in WSNs.
- Increasing load will increase the scale of cascading failures triggered by removing a single random failed node.
- The critical load triggering massive cascading failures increases along with the rising of capacity.

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ABSTRACT

Considering the cascading failures of scale-free fault-tolerant topology in wireless sensor networks (WSNs), based on the power function of load and the fixed capacity, a new load redistribution model is proposed under a single random node failure. Adopting the probability generating function method, the relationship between the load and the largest connected component after cascading failures on scale-free fault-tolerant topology is studied. Then the critical load triggering large-scale cascading failure is obtained. This discovery reveals the cascading failure principium of scale-free fault-tolerant topology in WSNs. It may have practical implications for controlling cascading failure disasters of scale-free fault-tolerant topology in the single random node failure.

1. Introduction

The research on network robustness against node failures has been the concern of many scholars. A single node failure runs the redistribution of loads. Because of the limitation of node capacity, the fact that node load will surpass its capacity probably results in further failure when the loads are redistributed. This dynamic process is called cascading failure. Once the network emerges cascading failure, the entire network can be largely affected, even resulting in global collapse [1]. Because the cascading failure is essentially a relevant failure, and there is no deep insight into the related failure principium, it is very difficult to solve the cascading failure of the network [2].

Recently, many searches on the robustness of wireless sensor networks (WSNs) subject to random node failures based on the scale-free topology. But the robustness on scale-free topology existed in the assumption that a node failure does not lead to other node failures [3]. Evidence has demonstrated that cascading failure is a common phenomenon in many networks, including scale-free topology. Therefore, cascading failure of scale-free topology in WSNs has been widely investigated.

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A number of important aspects of cascading failure in scale-free topology have been discussed in the literature and many valuable results have been found. Motter et al. proposed the cascading failure model based on the failure of nodes [4]. Liu et al. discussed the cascading failure model with energy exhaust of nodes [5]. Crucitti et al. studied the cascading failure model according to node failure and edge failure [6]. In the study of the cascading failure model, Goh et al. focused on the cascading failure process of scale-free topology, and found the scale and the duration of cascading failure in scale-free topology have power-law characteristics [7]. In addition, Bao et al. investigated the performance of the small-world and scale-free topology subject to cascading failure. Simulation results suggested that node failures can result in larger cascading failures than edge failures in scale-free topology [8].

Considering the cascading failure caused from node failures, Dobson et al. deduced the cascading failure scale of scale-free topology, and then presented an analysis on the critical capacity generating the cascading failure with power-law scale by adopting the branching process method [9]. Li et al. used the probability generating function method to study the cascading failure of logistics network with uniform capacity and explored the critical capacity subject to cascading failure [10]. Liu et al. designed the node capacity based on its importance and improved the ability to defend against cascading failure in scale-free topology by optimizing capacity [11]. Wang et al. and Dou et al. studied the cascading failure of scale-free topology for linear and nonlinear node capacity and pointed out the critical capacity to relieve cascading failure of scale-free topology [12,13].

The studies cited above not only focused on the cascading failure model of scale-free topology, but also were more concerned with the critical condition of cascading failure in scale-free topology. However, most existing works are inferior owing to their consideration of the relationship between node capacity and cascading failure scale under the condition of a given node load (i.e., its consideration loses the case that the node capacity is fixed and the node load is variable in the running of the WSNs). Therefore, the conventional strategy of dynamically allocated capacity to resist cascading failure of scale-free topology in WSNs is unreasonable.

In this paper, considering the characteristics of node load and node capacity in scale-free topology for WSNs, we propose a new load redistribution model of scale-free topology in WSNs under a single random node failure. Then we discuss the effect of load changes on cascading failure phenomenon of scale-free topology in WSNs. By adopting the probability generating function method, the critical load triggering the large-scale cascading failure of scale-free topology in WSNs can be obtained. Our findings reveal the cascading failure principium of scale-free topology with fixed capacity and variable load in WSNs; it may be useful in furthering studies in defense against cascading failure of scale-free topology in WSNs.

This paper is organized as follows. In Section 2, we propose the load redistribution model for cascading failure. The critical load triggering large-scale cascading failure is discussed based on load redistribution model in Section 3. In Section 4, the theoretical results are verified by the numerical analysis. Finally, some conclusions are given in Section 5.

2. Cascading failure load redistribution model

Our studies only focus on the cascading failure of scale-free topology in WSNs. A single random node failure will change the balance of the load and lead to redistribution of the load over other nodes. If the fixed capacity of these nodes is sufficient to handle the extra load, load will be redistributed in turn, and then trigger the cascading failure and a large drop in the performance of topology. Therefore, according to the variable load and the fixed capacity of scale-free topology in WSNs, a load redistribution model is proposed under the condition of a single random node failure. Next, the initial load/capacity assignment of a node and the redistribution rule of the load will be introduced.

For scale-free topology in WSNs, suppose that at each time step one packet is exchanged between every ordered pair of nodes. The load at a node is the total number of packets through the node. We consider the definition of node load introduced in Ref. [14]; the node load is related to its degree. We assume the initial load of a node v_i to be

$$L_i = k_i^{\alpha}, \tag{1}$$

where L_i and k_i represent, respectively, the load of the node v_i and its degree, α is a tunable parameter, and could govern the strength of the node load.

The capacity of node is the maximum load that the node can handle. For scale-free topology in WSNs, the node capacity is limited by hardware. Thus, it is natural to assume that the capacity c_i of node v_i is fixed during the running process of network, that is,

$$c_i = c_0, \tag{2}$$

where the constant c_0 is the capacity of node. This is a realistic assumption in the analysis of cascading failure for scale-free topology in WSNs, as the node load is variable and capacity is fixed.

Based on the characteristics L_i and c_i, we will discuss the load redistribution process of cascading failure triggered by removing a single random failed node. For scale-free topology in WSNs, when the node v_i fails, the load at the node v_i needs to be rerouted. Accordingly, the load of its neighbor node v_j can be increased

$$L_j(\text{new}) = L_j + L_i/k_i, \tag{3}$$

where $L_j(\text{new})$ is the new load of node v_j. Therefore, the load of the single failed node v_i will be redistributed to all neighbors equally (i.e., the neighbor v_j). If the load of some neighbors can increase beyond the capacity, that is, $L_j(\text{new}) > c_0$, the