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A quantitative fault tolerance evaluation model for topology in wireless sensor networks based on the semi-Markov process ☆

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ABSTRACT

Fault tolerance evaluation has gained increasing importance. In this paper, the semi-Markov process is introduced to describe the fault tolerance of topology in wireless sensor networks. Considering that the changes of topology states leaded by node failure and the changes of topology states leaded by responding to node failure, the topology fault-tolerant state transfer model is established firstly. Then a new fault tolerance evaluation index of topology is proposed based on the property of topology providing network services under different states. The numerical result shows that the topological fault tolerance calculated by the evaluation index and its actual value are consistent, which verifies that the proposed evaluation index can reflect the topological fault tolerance accurately. Moreover, the key factor influencing the topological fault tolerance is also obtained from calculating the sensitivity of parameters in the evaluation index.

1. Introduction

Wireless sensor networksconsist of a large number of sensor nodes, which are usually deployed in remote and hostile surroundings where people cannot access. These unattended sensor nodes are prone to be failure due to bad environment and battery energy consumption. The failure nodes may lead to cavity and disconnection of the original topology. Then the service properties like network coverage and connectivity are greatly decreased. So a fault-tolerant topology is needed to continuously provide critical network services in the condition of nodes failure [1]. In order to evaluate fault tolerance of this topology, it is significant to establish the fault tolerance evaluation index of topology.

We can predict the performance of the future topology by evaluating its fault tolerance [2]. Recently, many researches on fault tolerance evaluation for topology have been done. Ma et al. described the fault tolerance and intrusion tolerance for topology based on the multi-version multi-path graph [3]. In the literature, the fault tolerance of topology was evaluated by the connectivity of multiply connected graph. The connectivity is defined as the minimum number of removed nodes resulting in the disconnection of the network. So the connectivity as evaluation index of fault tolerance is too rigid. Wang et al. proposed the evaluation index of fault tolerance and intrusion tolerance by using the statistic method [4]. The evaluation index is the number of survival nodes after removing the failed nodes. The number of survival nodes can better reflect the fault tolerance of topology than the connectivity. But it depends heavily on the statistic precision that the evaluation index is uncertainty.

Markov chain is a parameterized model based on a suitable definition of time distributions describing error actions and system's reactions over time. The core idea of this mathematical model is that the whole topology is divided into different states, thus the property of whole topology is transformed into the property of different states and the transition property between individual states. The Markov chain makes the topology property more prominent in each state, and it is also easier to extract the critical attributes influencing topology property. Considering the advantage, this mathematical model has been analytically solved to calculate the desirable quantitative security metrics, such as mean time to security failure and steady-state security [5–8].

Jha and Wing measured the survivability of topology based on Markov chain, NDFA theory and Bayesian networks [5]. They proposed a quantitative fault tolerance evaluation index for topology in a traditional complex network, without considering the requirements of sensor nodes with finite energy supply in

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wireless sensor networks, so that the calculation of the proposed evaluation index consumes too much energy. According to the limited energy resource of sensor nodes, Shen et al. simplified the intermediate states of the Markov chain [6]. They measured the fault tolerance of topology in terms of reliability, average lifetime, and availability in the steady state. Considering that the time spent at various states of the topology can be nonexponential functions, the Markov chain is recognized to be a semi-Markov chain [7]. Some scholars converted the fault tolerant evaluation of topology into the semi-Markov process.

Using the semi-Markov process, Kim et al. proposed the general framework of fault tolerance model for wireless sensor networks. In the fault tolerance model, the phenomenon of software aging because of resource degradation is discussed. Some security attributes are also obtained [8]. Madan et al. presented the approach for quantitative assessment of security attributes, and analyzed the effects of security breaches on the security attributes such as availability, reliability and confidentiality [9]. Combining the resource degradation and security breaches, Gupta and Dharmaraja proposed an analytical framework of fault tolerance model which obtains the availability, reliability and confidentiality attributes in the presence of resource degradation as well as in the case of security breaches [10]. At the same time, Distefano et al. proposed semi-Markov model-based solutions to provide the measures required for the availability attribute. The main contribution of this literature is to consider several dynamic aspects altogether, in order to study in depth the impact of mixing dynamic behaviors in availability [11]. Now, according to the semi-Markov process, the fault tolerance evaluation indexes of topology are quantified in terms of availability in the steady state, stability, integrity and so on [12,13].

In the literature mentioned above, the quantitative fault tolerance evaluation indexes of topology are proposed based on various attributes. The evaluation indexes above cannot reflect the service ability of different topological states under node failure. While the whole topology's service ability depends on the service ability of different topological states, so the evaluation indexes above cannot reflect the whole topology's service ability accurately. Then the fault tolerance of topology which provides network service under node failure is not evaluated correctly.

The main contributions of this paper are as follows: firstly, the topology fault-tolerant state transfer model is put forwarded based on the semi-Markov process considering the failure behavior and response behavior of topology. Secondly, a novel quantitative fault tolerance evaluation index with the accumulated service properties of different topological states is proposed. Thirdly, to validate the proposed evaluation index, a representative fault-tolerant topology EAEM is studied as an empirical example. The proposed evaluation index is validated through empirical experiments. Finally, the key factor influencing the fault tolerance of topology is obtained using the proposed evaluation index.

The rest of the paper is organized as follows. In Section 2, the topology fault-tolerant state transfer model is established. In Section 3, the value of accumulated service properties is quantified as the fault tolerance evaluation index of topology. In Section 4, based on the empirical experiments, the effectivity of the quantitative evaluation index is validated, and then the sensitivity analysis of parameters in the evaluation index is discussed. We conclude the paper in Section 5.

2. Topology fault-tolerant state transfer model

In this subsection, the node failure behavior and topology response behavior are all considered to evaluate topological fault tolerance. The topology fault-tolerant state transfer model is shown in Fig. 1. Fig. 1 shows how the topology fault-tolerant state transfers. The topology fault-tolerant state transfer model has general characteristics, so any topological fault tolerance analysis can be made.

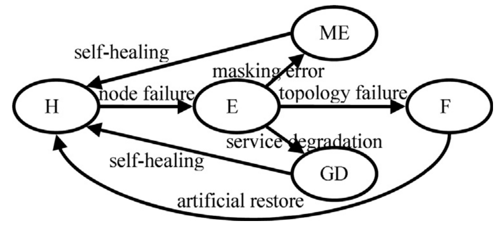

Fig. 1. The topology fault-tolerant state transfer model.

At the initial moment, the topology enters into state H (Health), there is no node failure. When some nodes fail caused by environmental factors and energy exhaustion, the topology enters into state E (Error). During state E, the harm caused by node failure can be reduced by making use of the fault tolerance of the topology. Because the fault tolerance of topology is different, the topology response behavior to node failure is different. When the topology can completely tolerate the node failure, the topology enters into the state ME (Masking Errors). If the topology cannot completely tolerate the node failure, the topology guarantees the network services to meet the basic application requirements in a graceful degradation way. At this moment the topology enters into state GD (Graceful Degradation). Otherwise, the topology enters into state F (Failed). It can clearly be seen that the topology fault-tolerant state transfer model contains two styles of state and describes the node failure behavior and the response behavior to node failure. The two states H and E describe the change of node failure behavior. The three states ME, GD and F are the states which describe the behavior of topology responding to the node failure.

For the topology fault-tolerant state transfer model, the future state depends on the current state, and the state transition occurs at the discrete time. In this work, we model the topology fault-tolerant state transfers as a semi-Markov process.

Definition 1. Let $S(t)$ be the topology fault-tolerant state space, $S(t)=S_i(i=\mathrm{H, E, ME, GD, F})$ is the semi-Markov model following the condition under

(1) Let Z_n denotes the state of the n-th transition. $\{Z_n, n \geq 0\}$ is the embedded Markov chain, P is the transition probability matrix of the embedded Markov chain.
(2) When current state is S_i and next state is S_j, the sojourn time in S_i obeys the distribution F_{ij}. The sojourn time of a state is the duration time during which topology stays in the state.

Now it is possible to analyze the topology fault-tolerant state transfer model based on transition probability matrix P and sojourn time F_{ij}.

2.1. Transition probability matrix P

Since the transitions between states have the Markov property (see Fig. 2), the embedded Markov chain is used to evaluate the transition probability of topology fault-tolerant state transfer model.

The transition probability matrix P denotes the probabilities of the transition between states, whose value can be obtained by using the priori knowledge or the intrusion experiment. The definition of each transition probability in the above model is as follows:

$p_\mathrm{H} = 1 - p_\mathrm{E}(\mathrm{H} \rightarrow \mathrm{H})$ is the probability that no node failure occurs;