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An efficient reliability evaluation method for industrial wireless sensor networks

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Abstract: Aimed at the difficulties in accurately, comprehensively and systematically evaluating the reliability of industrial wireless sensor networks (WSNs), a time-evolving state transition-Monte Carlo (TEST-MC) evaluation method and a novel network function value representation method are proposed to evaluate the reliability of the IWSNs. First, the adjacency matrix method is used to characterize three typical topologies of WSNs including the mesh network, tree network and ribbon network. Secondly, the network function value method is used to evaluate the network connectivity, and the TEST-MC evaluation method is used to evaluate network reliability and availability. Finally, the variations in the reliability, connectivity and availability of these three topologies are presented. Simulation results show that the proposed method can quickly analyze the reliability of the networks containing typical WSN topologies, which provides an effective method for the comprehensive and accurate evaluation of the reliability of WSNs.

Key words: wireless sensor networks; topology structure; reliability evaluation; connectivity; availability

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A wireless sensor network (WSN) is considered to be the peripheral nerves of the IOT[1], which is emerging as an information perception and processing technology. WSNs have been widely implemented in security systems, detection and identification of targets, and environmental monitoring[2].

Due to limited energy resources, harsh industrial environments, and the applicability limitation of the nodes in the WSNs, the entire network operates in unreliable working conditions. To better ensure the reliable operation of the WSNs, knowledge of probability theory, graphic theory, and statistics is required. Even with these advantages, it is difficult to obtain a pure analytical solution for network reliability. Therefore, establishing a reliable assessment theory for industrial WSNs is the basis for optimizing network design which is of theoretical and practical importance. This study investigates the influences of harsh environments, limited resources, faults and external disturbances in service quality, and the network reliability of WSNs. To accomplish this, the time-evolving state transition-Monte Carlo (TEST-MC) method is used to evaluate network reliability.

1 Related Work

Recently, reliability analysis of networks has attracted considerable attention by researchers. This work mainly focuses on two aspects. One is the research on the methods to improve the reliability of wireless sensor networks and the other is the study of the methods needed to establish a reliable model of WSNs. Although many scholars have evaluated the reliability of many WSN models, a unified model has yet to be developed.

Cai et al.[3] analyzed the channel fading mechanism and reliability parameters that affect the zonal network and designed a routing algorithm for saving energy. Zonouz et al.[4] evaluated the reliability of a data transmission route in a WSN and proposed a dynamic routing algorithm to achieve the most reliable end-to-end path transmission. Aijaz et al.[5] designed an effective MAC protocol with high reliability to improve the efficiency and reliability of a network. Luo et al.[6] studied the simultaneous relationship between energy and reliability and proposed a novel reliability algorithm of data collection based on data fusion inside the network. Lin et al.[7] reported the establishment of a WSN model that utilizes a processing method based on the system components, which is used to calculate the system reliability by processing the reliabilities of each component. It is apparent that these efforts provide only partial solutions for the problem of network reliability. Since most of them focused on specific scenarios, they are restrictive in regard to the definition of network failure conditions, dependability metrics, topology, network reconfiguration and redundancy, as well as potential application to industrial scenarios.

As a result, reliability analysis of the network usually

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involves the following two aspects: accomplishment of tasks and the evaluation of the operational failure of nodes[8]. However, problems persist for adequately addressing the nature of network reliability. In this regard, addressing the issue of network reliability, we must consider the following issues: 1) The redundancy method, which is relatively more intuitive and effective, but it cannot be infinitely redundant because the environmental requirements including cost, etc. must be considered[9]. 2) Establishing a life-based reliability model requires that the life of WSNs be based on the life of the sensor nodes[10]. However, like the wired network, the life of an information transmission path must be considered. 3) In a complex system, it is necessary to separately consider the importance of each element. In a wireless sensor network, it is also necessary to optimize the sensor nodes or topology. This is an important reference point for determining how to improve the reliability of WSNs.

In this study, the basic concepts and principles of the network reliability are analyzed and a wireless sensor network reliability evaluation model is proposed based on the TEST-MC method.

2 Theoretical Analysis

2.1 TEST-MC method and network function value

2.1.1 Description of network function value

To evaluate the reliability of the network operating in a complicated environment with high reliability, in this paper we use the TEST-MC method to evaluate the reliability status of the wireless sensor network. According to the fault distribution of nodes and the recovery ability of the network, the status variation series of the network nodes is randomly generated during the time interval and the variation property of the reliability status of the network is simultaneously recorded[11].

The basic steps of the TEST-MC network reliability simulation of WSNs are shown as follows [12]:

1) Variable initialization.

$$\boldsymbol{T}_{\mathrm{r}} = \begin{cases} \{0, 0, \dots, 0\}_{1\times m} & \text{if node is completely reliable} \\ \{0, 0, \dots, 0\}_{1\times(m+n)} & \text{otherwise} \end{cases}$$

$$\boldsymbol{T}_{\mathrm{f}} = \{\}, \quad \boldsymbol{T}_{\mathrm{er}} = \{0, 0, \dots, 0\}_{1\times n_r}$$

where $\boldsymbol{T}_{\mathrm{f}}$, $\boldsymbol{T}_{\mathrm{r}}$, $\boldsymbol{T}_{\mathrm{er}}$ are the time queues denoting the moments of network element failure, restoration (for repairable networks), finish repair (for networks with limited repair) and change state, respectively; n, m are the number of sensor nodes V and links E.

2) The failure time intervals ΔT_{f} of each node are randomly generated according to the life-time distribution of the nodes in $\boldsymbol{T}_{\mathrm{r}}$. For the exponential distribution,

$$P(\Delta t) = \mathrm{e}^{-\lambda \Delta t} \tag{1}$$

where λ is the failure rate of network nodes.

3) The calculation of failure time of each node.

$$t_{\mathrm{f}_i} = \Delta t_{\mathrm{r}_i} + \Delta t_{\mathrm{f}_i} \tag{2}$$

The failure time t_{f_i} is greater than the given time period t_{e}, so it does not need to be calculated.

4) The final results are output if there is no repair or all of the nodes have been processed; otherwise, the simulation continues.

5) For each new element t_{f_i} added to $\boldsymbol{T}_{\mathrm{f}}$, a repair time Δt_{r_i} is randomly generated according to the distribution of repair time Δt_{r_i}. For Γ distribution, there is

$$P(\Delta t) = \frac{\left(\dfrac{\Delta t - \mu}{\beta}\right)^{\gamma - 1} \exp\left(-\dfrac{\Delta t - \mu}{\beta}\right)}{\beta \Gamma(\gamma)} \qquad \Delta t \geqslant \mu;\ \gamma, \beta > 0 \tag{3}$$

where μ is the location parameter; γ is the shape parameter; β is the scale parameter; and Γ is the Γ function,

$$\Gamma(\gamma) = \int_0^{\infty} t^{\gamma-1} \mathrm{e}^{-t} \mathrm{d}t \tag{4}$$

6) The completion time for each node is calculated for the wireless sensor network which limits repair ability:

$$t_{\mathrm{r}_i} = \max(\min(\boldsymbol{T}_{\mathrm{et}}), t_{\mathrm{f}_i}) + \Delta t_{\mathrm{r}_i} \tag{5}$$

7) If the repair completion time $t_{\mathrm{r}_i} < T_{\mathrm{r}}$, record the corresponding node number, or return to Step 2.

2.1.2 Calculation method for network function value

The network function value f_{v} is a quantitative indicator of network performance and it is used to represent the connectivity state of overall communications in the network. It represents a quantitative expression of the ordinary working range within certain performance requirements. The sensor node state vector is $\boldsymbol{X} = \{x_1, x_2, \dots, x_n\}$.

$$x_i = \begin{cases} 0 & \text{if sensor node } i \text{ fails} \\ 1 & \text{otherwise} \end{cases} \tag{6}$$

$\boldsymbol{Y} = (y_{ij})_{n\times n}$ is the adjacency matrix denoting the state of the links, and

$$y_{ij} = \begin{cases} 0 & \text{if no normal link connects } v_i \text{ to } v_j \\ 1 & \text{otherwise} \end{cases} \tag{7}$$

For an arbitrary undirected or directed graph G, if the node status in a given network or the state vector $\boldsymbol{X}$ and adjacency matrix $\boldsymbol{Y}$ are determined, the following algorithm can be implemented to compute the function value f_{v} of the whole network, so that the reliability of a link in the wireless sensor network is due to the likelihood that the link maintains its connectivity.

The specific algorithm to calculate the function value of a wireless sensor network is as follows[12].

1) Zero elements in state vector $\boldsymbol{X}$ are marked and the corresponding rows and columns in adjacency matrix $\boldsymbol{Y}$ are deleted. The remaining elements of matrix $\boldsymbol{Y}$ are obtained.

2) Initialization of variables: $\boldsymbol{C} = \{0, 0, \dots, 0\}_{1\times n'}$, n_{c}

$=0$, $X^{T}=\{0,0,\ldots,0\}_{1\times n'}$, $X^{c}=X^{T}$. n_c is the number of isolated connected subgraphs in G.

$$X^{c}=(x_{ij}^{c})_{n_c\times n} \tag{8}$$

3) To determine whether there is a need to block a new node set of X^c, X^c is the matrix denoting the affiliation of the sensor nodes to the isolated connected subgraph and

$$x_{ij}^{c}=\begin{cases}1 & \text{if sensor node } j \text{ belongs to the } i\text{-th subgragh}\\ 0 & \text{otherwise}\end{cases} \tag{9}$$

If $\sum_{ij} x_{ij}^{c} < n'$, $\|C\| < n'$, then $I_k=\{\min\{i \mid i_{k_j}=0\}\}$ and the process executes step 4), otherwise go to step 5). I_k is the index set for the sequentially failed nodes.

4) Searching for the sub-graph. If $I_k=\varnothing$, $n_c=n_c+1$, the process returns to step 3), otherwise returns to step 4).

5) The WSNs are the S/C type networks, the function network value f_v is calculated as

$$f_v = \sum_{i=1}^{n} x_i^{c} \tag{10}$$

where the subscript i is the i-th sensor node.

6) Finally, the absolute value and normalized value of f_v are computed.

2.2 Network reliability evaluation model based on TEST-MC method

The input information of the evaluation method for network reliability based on the TEST-MC includes the network topology, the reliability of the nodes, links and maintenance information. For a repairable network, a range of the longest observation time t_{end} is also required and the simulation steps are as follows:

1) According to the lifetime distribution types, maintenance types and parameters of the nodes, we simulate the change state of nodes in the networks and obtain the nodes' state transition time series T_g and the corresponding sequence I_g.

2) The states of all the nodes are initialized to be normal. That is, the network function values of nodes and links are set to be 1.

3) According to the evolution process of the node state, the state value of the network node is changed in turn; that is, the corresponding values of nodes or links are changed. The f_v changing with the time of each node is calculated by the network function algorithm.

4) Repeat the above steps to reduce the estimation error if necessary.

5) We can obtain the reliability parameters of wireless sensor networks by the statistics results.

2.3 Reliability evaluation indices

The reliability evaluation indices of the wireless sensor networks include connectivity, reliability and availability. The calculation methods for determining these parameters are described as follows:

1) Calculation of connectivity. Connectivity is an important parameter for evaluating the connectivity and the survivability of the network. Here, we use the network function value f_v to represent the connectivity of the network. The greater the network function value f_v, the higher the connectivity of the network. On the contrary, the lower the connectivity of the network, the worse the network reliability.

2) Calculation of reliability. During a given period of time (t_1, t_2), the reliability of WSNs R is greater than the minimum value of f_v, which is defined as

$$R_w(t_1,t_2)=P(f(t)\geqslant f_w \mid t_1<t<t_2) \tag{11}$$

where $f(t)$ represents the function values at time t and f_w is the worst function value that state w allows.

3) Calculation of availability. Network availability is the point at which faulty components in the network can be used as a reliable measure of network restoration. The network availability A is defined as the percentage of time weighted with time period from t_1 to t_2:

$$A(t_1,t_2)=\frac{1}{f_{max}(t_2-t_1)}\int_{t_1}^{t_2} f(t)\,dt \tag{12}$$

where f_{max} represents the maximum function value.

3 Simulation and Analysis

Currently, there are few reports in the literature that deal with network reliability in terms of the topological structure of the network. To determine the influence of the topological structure on network reliability, three typical industrial wireless sensor networks (mesh network, tree network and ribbon network) were examined. Fig. 1 shows that the topology of the mesh network, tree network and ribbon network consists of 10 nodes, respectively in conjunction with the corresponding adjacent matrices.

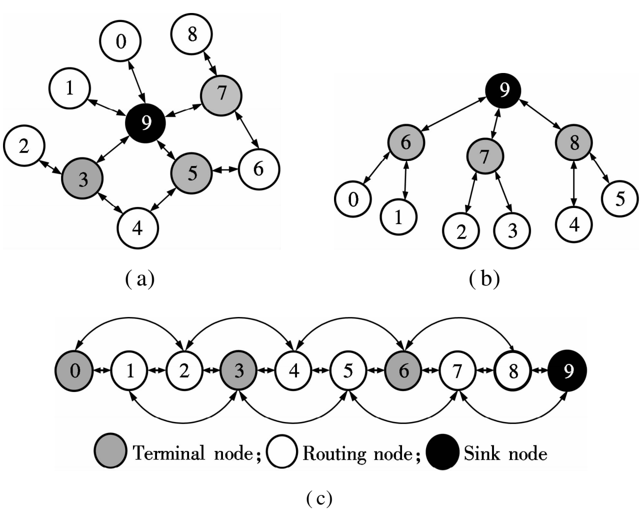

Fig. 1 Three kinds of WSN topological structures. (a) Mesh network; (b) Tree network; (c) Ribbon network

3.1 Simulation environment

We use the Matlab simulator to conduct a performance analysis of the proposed method. The main assumptions considered in these experiments are listed below[13].

Scenarios: mesh, tree and ribbon topologies.

Failure rate: Assume that device failures occur at a constant rate (i. e., exponential distribution). The gateway and the access points have higher reliability than other typical network devices. The failure rate of the sensor nodes ψ is 10^{-5} h^{-1} and the fault rate of the link λ is 10^{-7} h^{-1}.

Repair rate: Field devices can be repaired after failing if necessary. After repair, the device is considered to be new. We consider the repair processes to be independent and the mean time for repair (MTTR) t_R is 0.5 h.

3.2 Network connectivity simulation results

In this study, the connectivity reliability of the WSNs is developed based on the perspective of network topology. Figs. 2, 3 and 4 show the distribution network connectivity of mesh, tree and ribbon networks, each of which contain 10 nodes with the condition $t_R = 0.5$ h.

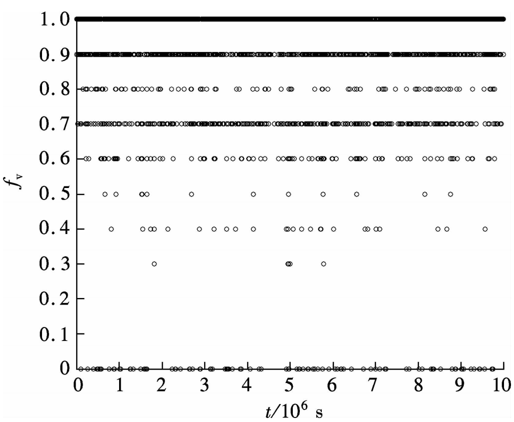

Fig. 2 Mesh network connectivity

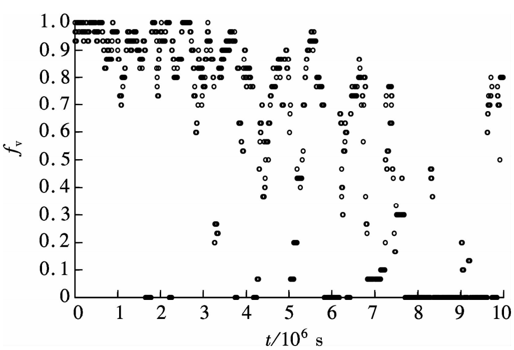

Fig. 3 Tree network connectivity

Figs. 2, 3 and 4 show that the connectivity of the networks maintaining between 0.9 and 1.0 at the initial time of simulation, regardless of the topology distribution. So that at that moment, the network is connected to all sensor nodes. It can be seen that the ribbon network suffers a

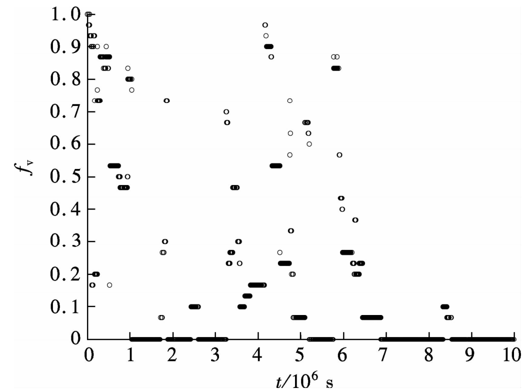

Fig. 4 Ribbon network connectivity

drastic decline in connectivity and the network connectivity decreases gradually.

3.3 Network reliability simulation results

The initial function value of f_v is set to be 1. If $f_v <$ 0.8, the network will fail to operate, which is defined as an unreliable condition. In addition, the time interval from the initial value of 1 to 0.8 is recorded, and this procedure is repeated 100 times. The obtained data is normalized and ordered from large to small. Eventually, the reliability and the distribution of the mesh, tree and ribbon networks are obtained, as shown in Fig. 5.

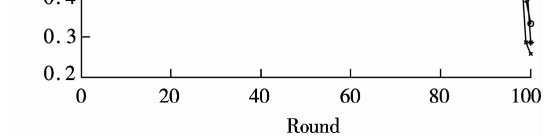

Fig. 5 Network reliability simulation results

After executing system calculations, the average reliability of the mesh, tree and ribbon networks are 0.825, 0.797, and 0.772, respectively. Fig. 5 shows that the reliability of the mesh network is better than that of the tree network, which is, in turn, better than that of the ribbon network.

3.4 Network availability simulation results

In Fig. 6, we give the availability of 10 nodes of the mesh, tree and ribbon networks with the change of days, months and years. As shown in Fig. 6, the availability in the shorter time intervals has a broader distribution range. Among the three topologies, the mesh network availability is the highest, the value of which is between 0.75 and 0.95; the availability of the tree network is between 0.65

and 0.8, and the availability of the ribbon network is shown to be the greatest, with an availability value between 0.55 and 0.8.

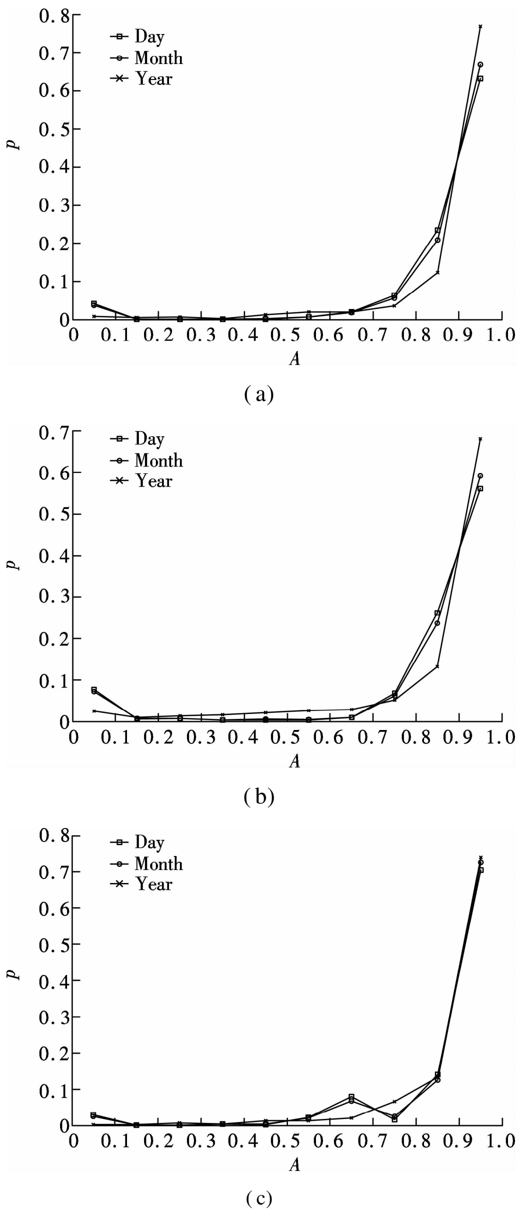

Fig. 6 Network availability distribution under $t_R = 0.5$ h. (a) Mesh network; (b) Tree network; (c) Ribbon network

To better characterize the availability of the topologies, we simulate the average availability distributions of three topological structures with four different t_R of 0.2, 0.5, 0.8 and 1 h under the failure rate of ψ of 10^{-5} h^{-1} and the failure rate of λ of 10^{-7} h^{-1}, as shown in Fig. 7.

As can be seen in Fig. 7, the average network availability decreases as t_R increases, regardless of the network topology. However, the availability in the mesh network decreases the least, then the tree network, and the ribbon network exhibits the greatest decrease. Under the same failure rate, the average availability of the ribbon network decreases more obviously than those of the tree and mesh networks.

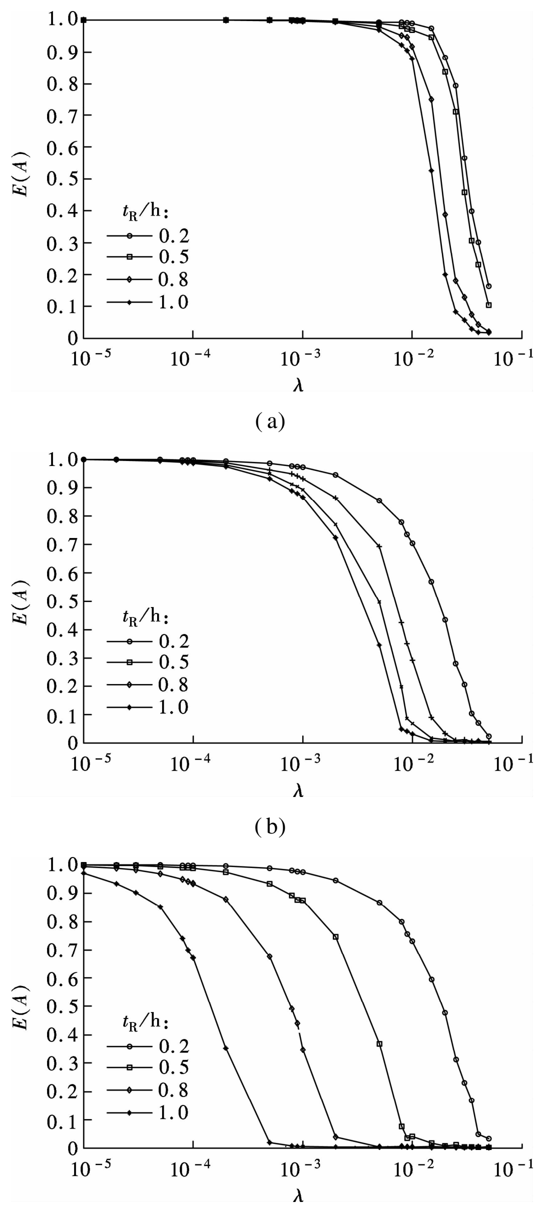

Fig. 7 Average availability of three topologies. (a) Mesh network; (b) Tree network; (c) Ribbon network

3.5 Network average availability simulation

To better evaluate the reliability of the typical topology of WSNs, simulation experiments were conducted to validate the network's average availability, and the time consumed for the evaluation of network reliability with $\psi = 10^{-5}$ h^{-1}, a link failure rate $\lambda = 10^{-5}$ h^{-1} and $\lambda = 2 \times 10^{-5}$ h^{-1}. Tab. 1 shows a comparison of the average value of the network average availability and the time consumption from evaluation for the mesh, tree and ribbon networks.

It can be seen from Tab. 1 that all three networks exhibit high availability when the network failure rate is low, achieving up to 0.85, indicating that the network reliability is better and the network simulation requires more time. The average network availability of the three

Tab. 1 Network Average availability and time-consuming of networks

Topology	$\lambda = 10^{-5}$ h^{-1}		$\lambda = 2 \times 10^{-5}$ h^{-1}	
	$E(A)$	Time/s	$E(A)$	Time/s
Mesh	0.92	6.11	0.63	5.62
Tree	0.9	9.53	0.35	6.52
Ribbon	0.86	10.58	0.16	6.76

topological structures decreases as the network fault rate increases, and the availability of the mesh network decreases less than that of the others.

4 Conclusion

The TEST-MC evaluation method and the network function value representation method are used to evaluate the reliability of WSNs including mesh networks, tree networks and ribbon networks. The proposed model can provide a useful analysis of three typical WSN topology structure and provides an effective method for a comprehensive and reliable assessment of WSNs. However, the reported assessment focuses on static wireless sensor networks, and future work will include an assessment of the reliability of mobile wireless sensor networks.

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一种有效的工业无线传感器网络可靠性评估方法

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摘要:针对工业无线传感器网络可靠性难以准确、全面、系统的评估问题,提出了随时间演进的状态转移蒙特卡罗评估方法和网络功能值表示方法,用于评估无线传感器网络可靠性. 首先运用邻接矩阵的方法表征 WSNs 的网状网络、树形网络和带状网络 3 种典型拓扑结构;然后运用网络功能值表示方法评估网络连通度;运用随时间演进的状态转移蒙特卡罗评估方法评估网络可靠度和可用度,最后给出了 3 种拓扑结构网络的可靠性、连通度和可用度的变化趋势. 仿真结果表明,所提方法可快速对 WSNs 典型拓扑结构的网络可靠性进行准确的分析,为全面、准确地评估无线传感器网络可靠性提供了有效的手段.

关键词:无线传感器网络;拓扑结构;可靠性评估;连通度;可用度

中图分类号:TP393