Microelectronics Reliability 87 (2018) 33–51

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

A new hierarchical belief-rule-based method for reliability evaluation of wireless sensor network

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ARTICLE INFO

Keywords:
Wireless sensor network (WSN)
Reliability evaluation
Belief rule base (BRB) model
Semi-quantitative information

ABSTRACT

With the wide applications of wireless sensor network (WSN), its reliability evaluation has been attracted more attention. The reliability of a WSN is affected mainly by internal and external factors, which include internal faults and external attacks. In this paper, a reliability evaluation method based on a hierarchical belief rule base (BRB) method is proposed for the reliability evaluation of the WSN. First, the factors affecting the reliability of a WSN are analysed, and the reliability evaluation process that considers the WSN fault evaluation and WSN security evaluation is described. Second, the reliability evaluation model is constructed based on the hierarchical BRB model. The qualitative knowledge is used by the BRB model to build initial belief rules, and the quantitative data are used to optimize the initial parameters of the BRB model, which can utilize various types of uncertainty information effectively. Therefore, the proposed method can be applied to the WSN reliability evaluation, which is a complex and uncertain problem. Finally, a simulation case study and an actual case study of wellhead blowout monitoring are conducted to verify the effectiveness of the proposed method. The reliability results of actual WSN are obtained by the standard testing method, where the loss and accuracy rates of the collected data are treated as the observation factors for obtaining the actual reliability values. The estimated results of hierarchical BRB model are very close to the actual reliability values, which shows that the proposed method can be used for evaluating the reliability of the actual WSN accurately.

1. Introduction

As an important technology of the Internet of things, the wireless sensor network (WSN) has been widely applied [1] in many fields. The WSN is composed of numerous sensor nodes. The environmental data are detected by the sensor nodes with different functions such as temperature, humidity, pressure and light intensity. The WSN is a data-centric network. The core issue of WSN is how to measure the reliability and to ensure the accuracy of the collected data from the detection area. However, there are numerous of factors that can affect the reliability in the WSN, and these factors can be described as follows:

1) The computing power and storage capacity of the sensor nodes are limited. Too much data processing can lead to the overflow of node data.
2) The energy supply of the sensor nodes is limited, and the energy supply is not renewable. Excessive energy consumption will lead to the abnormal work of node hardware, which will affect the accuracy of data collection and data transmission.
3) The system structure of the sensor node is simple. When complex problems are processed by the system, software failures occur easily.
4) The WSN wireless communication bandwidth is narrow. The problem of large packet loss occurs when too many pieces of data are transmitted.
5) The WSN is more vulnerable to attack because of the special communication methods and protocols of the sensor nodes.
6) Sensor nodes are usually placed in a harsh environment, so the nodes always break down.
7) The WSN is vulnerable to external network attacks because the data is transmitted by the public network between users and the WSN.

Thus, the reliability of the WSN is dynamically variable under the

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https://doi.org/10.1016/j.microrel.2018.05.019
Received 29 October 2017; Received in revised form 6 May 2018; Accepted 30 May 2018
0026-2714/

joint effect of many factors. To master the current running state of the WSN and ensure the accuracy and effectiveness of data acquisition by the WSN, the real-time reliability evaluation of the WSN has become a core issue because its reliability is affected by many factors and its operating stability cannot be guaranteed [2]. Therefore, it is necessary to establish an effective evaluation method for determining the WSN reliability.

At present, there is no clear standard to assess the reliability of the WSN. Many scholars have studied this problem from different perspectives. In the perspective of sensor nodes, reliability studies are performed mainly on the problem of node fault, energy consumption, and data security [3–8]. Distefano proposed using sensor node reliability to describe the reliability of the WSN and studied the WSN reliability evaluation problem from the dynamic system reliability perspective [3]. In the case of individual components and common cause failure of the sensor, Chowdhury et al. proposed a reliability calculation method based on Monte Carlo simulations [5]. To avoid data corruption in sensor nodes due to lack of receiving nodes and network attacks, Bahi et al. designed a data survival method in unattended WSNs based on an epidemiological approach [8]. From the perspective of the WSN wireless communication network, the reliability of the WSN is studied mainly from a routing, reliable transmission and network connectivity perspective [9–13]. After comparing the reliability and performance of different WSN routing algorithms, Zonouz et al. proposed a dynamic routing algorithm to achieve end-to-end reliable transmission [9]. Based on the transmission scheme, Cai et al. studied the reliability of a data flow in event-driven WSN [10]. To meet the needs of users to evaluate the reliability of WSN transmission, Zhu et al. proposed mission-oriented and transmission-paths-based models for transmission reliability evaluation of the WSN [13]. In view of the design problem of the WSN reliability evaluation framework, different scholars have approached the design scheme from different angles [14–16] such as the extraction of reliability factors from the WSN topology, the protocol stack structure and reliability mechanisms. Li et al. proposed a reliability evaluation model of the WSN based on a fuzzy neural network [15]. An increase in reliability usually leads to an increase in power consumption. For this reason, a model for evaluating the reliability of the WSN is proposed by Damaso et al., which considers the battery level as a key factor [16]. In addition, the reliability of the WSN in a special environment is also studied. For example, Silva et al. studied the reliability of the WSN in industrial applications [17], and Wang et al. studied the reliability of body sensor networks [18].

Through the above analyses, there are some defects in the research on the reliability evaluation of the WSN. On the one hand, most studies are more concerned with the reliability of the WSN from a certain perspective. However, there are many kinds of reliability-influencing factors in a WSN. These factors have interrelated characteristics. Therefore, it is necessary to establish a comprehensive and scalable reliability evaluation framework. On the other hand, most of the studies pay more attention to the reliability evaluation of the WSN design. However, a WSN is complex, polymorphic and dynamic, so a real-time reliability evaluation method of the WSN needs to be designed.

The recent research into WSN reliability evaluation methods can be classified as three types: qualitative knowledge evaluation methods, data-driven evaluation methods and mixed evaluation methods. In the qualitative knowledge evaluation methods, the working process of the WSN is analysed, and the indicators that can affect the reliability of the WSN are chosen. The reliability evaluation values are calculated by the designed algorithm such as the fuzzy logic and expert systems. In the data-driven evaluation methods, large amounts of historical data are used, and the reliability evaluation is realized by the classification of data features such as with a neural network, extreme learning machine (ELM), random forest (RF) or cluster analysis method. The research into WSN reliability evaluation based on data-driven factors is a hot issue. In the mixed evaluation methods, qualitative knowledge and quantitative data are combined. This method integrates the advantages of the qualitative and quantitative analysis methods. Like the fuzzy neural network, this method represents a new field of research for the WSN reliability evaluation.

Although the above methods have some advantages in the reliability evaluation of the WSN, there are some shortcomings in these methods. For the qualitative knowledge evaluation methods, the WSN is a complex system with numerous reliability factors. Experts cannot define the model accurately. For data-driven methods, the accuracy of the reliability evaluation depends on the integrity of the sample. However, there are great differences in the number of normal and abnormal samples in the actual project, and even the data in some special cases cannot be obtained and simulated. The incompleteness of the data samples will affect the accuracy of the reliability assessment. For the mixed evaluation methods, the current evaluation method is difficult to learn and is highly dependent on the sample, and the extension ability of the model is poor. At the same time, neither of the methods can use the semi-quantitative information that contains both qualitative knowledge and quantitative data. Furthermore, the existing methods cannot utilize the various types of uncertainty information effectively and completely. In the WSN, numerous pieces of uncertainty information about the reliability can be collected, where the expert experience and historical data are included. Such semi-quantitative information is particularly important in the evaluation process.

To overcome these shortcomings and obtain more accurate evaluation results, the belief rule base (BRB) evaluation method is proposed. The essence of the BRB model is an expert system. Furthermore, the BRB evaluation method can effectively use the various types of information and establish a nonlinear model between the input and output [19, 20]. The BRB method has been widely used in engineering because of its ability to address various uncertainties [21–29]. These advantages of the BRB method are very suitable to solve the problem of the WSN reliability evaluation. Therefore, to make effective use of expert experience and massive data in the WSN, a reliability evaluation method based on a hierarchical BRB method is proposed in this paper. By analysing the influencing factors of data reliability in the WSN, the initial BRB model is constructed by expert experience. The rules of the BRB model are trained through the massive data from the WSN. Thus, the comprehensive reliability evaluation of the WSN is realized. In view of the research on the WSN reliability evaluation, two innovative points are proposed in this paper, which can be described as follows:

1) In view of the reliability evaluation of the WSN, a WSN reliability evaluation framework based on a hierarchical BRB model is constructed through the analysis of the factors affecting the reliability. The framework can achieve a real-time reliability assessment based on the change in the reliability factors, and the framework is adaptable and easy to expand.
2) For the first time, the BRB model is introduced into the study of the WSN reliability evaluation. By using the ability of the BRB model to handle various uncertain information, the reliability evaluation of the WSN under the incomplete sample environment is realized, and the problem that the expert knowledge cannot effectively define the evaluation model in the complex WSN environment is solved.

This paper is organized as follows. In Section 2, the problem of the WSN reliability evaluation is analysed, and the reliability evaluation process is described. In Section 3, the reliability evaluation model based on the hierarchical BRB model is constructed. In Section 4, a simulation and a practical case study are designed to verify the effectiveness of the reliability evaluation model. In Section 5, the future work for the WSN reliability evaluation is described.

2. Problem formulation

The typical architecture of a WSN is shown in Fig. 1, including sensor nodes, a transmission channel, sink nodes, a transmission