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Fuzzy rule-based faulty node classification and management scheme for large scale wireless sensor networks

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A R T I C L E   I N F O

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A B S T R A C T

In a wireless sensor network (WSNs), probability of node failure rises with increase in number of sensor nodes within the network. The, quality of service (QoS) of WSNs is highly affected by the faulty sensor nodes. If faulty sensor nodes can be detected and reused for network operation, QoS of WSNs can be improved and will be sustainable throughout the monitoring period. The faulty nodes in the deployed WSN are crucial to detect due to its improvisational nature and invisibility of internal running status. Furthermore, most of the traditional fault detection methods in WSNs do not consider the uncertainties that are inherited in the WSN environment during the fault diagnosis period. Resulting traditional fault detection methods suffer from low detection accuracy and poor performance. To address these issues, we propose a fuzzy rule-based faulty node classification and management scheme for WSNs that can detect and reuse faulty sensor nodes according to their fault status. In order to overcome uncertainties that are inherited in the WSN environment, a fuzzy logic based method is utilized. Fuzzy interface engine categorizes different nodes according to the chosen membership function and the defuzzifier generates a non-fuzzy control to retrieve the various types of nodes. In addition, we employed a routing scheme that reuses the retrieved faulty nodes during the data routing process. We performed extensive experiments on the proposed scheme using various network scenarios. The experimental results are compared with the existing algorithms to demonstrate the effectiveness of the proposed algorithm in terms of various important performance metrics.

1. Introduction

Wireless sensor network (WSN) is a collection of thousands of low-cost, low power electronically programmable devices, which are deployed in a monitoring area in stochastic manner. Due to rapid growth in Micro-Electro-Mechanical System (MEMS) and Very Large-Scale Integrated (VLSI) circuit it is possible to fabricate the portable smart sensor nodes at low cost with better accuracy that makes WSN an attractive solution for a plethora of applications such as military tracking, fire monitoring, clinical monitoring and many more (Collotta, Bello, & Pau, 2015; Heinzelman, Chandrakasan, & Balakrishnan, 2002; Kosar, Bojaxhiu, Onur, & Ersoy, 2011). Hence, in such applications, a large number of sensor nodes are deployed in the target field to improve the Quality of Service (QoS) of the network (Attea, & Khalil, 2012; Geeta, Nalini, & Biradar, 2013; Jain & Reddy, 2015). In such WSNs, several deployed sensor nodes suffer from hardware and software faults due to the environmental hazards like heavy rainfall, flood, heavy wind, fire, and so on (Chen, Kher, & Somani, 2006; Lee & Choi, 2008). The probability of sensor node failure increases with increase in number of deployed sensor nodes within the network. Faulty nodes are unable to transmit data to the Base Station (BS) or may transmit erroneous data. Hence, faulty sensor nodes can potentially degrade the functionality of WSNs, it is desirable to detect and locate these faulty nodes within the network. Existing fault detection approaches suffer from high energy overhead and poor performance that create an urgency to propose a fault detection and management scheme for WSNs.

In WSNs, node faults are broadly classified into two groups, viz. software fault and hardware fault. In software fault, the system software of a node executes erroneously (Chessa, & Santi, 2001; Jing, & Weo, 2011). However, in hardware fault, different hardware components of a node are damaged and hence transmitted data packet cannot be reached to the destination node or BS. Hardware faulty nodes can be classified into five categories, viz. transmitter circuit fault, receiver circuit fault, microcontroller fault, sensor circuit fault, and power/battery fault (Banerjee, Chanak, Rahaman, & Samanta, 2014). Existing fault detection approaches are unable to control the proliferation of faulty node with increase in network lifetime (Ding, Chen, Xing, & Cheng, 2005). They only detect faulty sensor nodes on the basis of hypothetical test results and exclude

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them from the network during normal operation of the network. As a result, the percentage of dead nodes is rapidly increased within the network that can potentially degrade network lifetime and performance of the network throughout the monitoring period. In this scenario, a realistic fault detection and faulty nodes reusability scheme can control dead nodes proliferation in the WSNs and maintain high performance of the network throughout the monitoring period.

In this paper, we propose fuzzy rule based faulty nodes classification and management scheme for WSNs. A fuzzy-logic method shows better performance to deal with the uncertain information during the process of diagnosis. Therefore, in order to overcome the uncertainties inherent in the WSN environment, a fuzzy logic based faulty nodes classification scheme is proposed in this work. In addition, proposed fault detection system can benefit from nonlinear fuzzy modeling in the form of linguistic rules, because of a more transparent nature of the model, its fast and robust implementation, its ability of generalization and its capabilities to deal with imprecise or noisy data. The major contributions of this paper can be summarized as follows.

1. We propose a fuzzy rule based Faulty Node Classification and Management (FNCM) scheme for WSNs that detects and classifies faulty sensor nodes into different categories according to their present hardware status. Hence, faulty sensor nodes can be properly reused during the data routing process.
2. We propose an efficient data routing algorithm that improves usability of the recovery faulty nodes and provides better QoS throughout the network lifetime.
3. We derive an expression to estimate the energy gain due to reuse of the faulty node which are retrieved by the proposed scheme.
4. We carry out extensive simulations. The effectiveness of our proposed fault detection and data routing algorithm are verified by comparing with other fault detection and data routing algorithms.

The rest of this paper is organized as follows. Section 2 of this paper describes literature review. In Section 3, the problem statement is presented. Section 4 lays down the design rationale. Then our proposed FNCM algorithm is introduced and discussed in Section 5. The energy gain and fault detection characteristics of the proposed algorithm are described in Section 6. Section 7, provides performance evaluation of the proposed scheme through analysis and comparative study of simulation results. Finally, Section 8 concludes the paper.

2. Related works

Several fault diagnosis approaches have been proposed in recent years to address the fault detection problem in WSNs. Most of classical existing approaches for sensor network fault diagnosis follow similar patterns: they gather sense information from the deployed sensor nodes and then diagnose node fault by mean, median, majority voting, or hypothetical test results. Some researchers propose to scan the node sensing information and other parameters of the node in the running time, so that the sink/BS can analyze the status of the deployed sensor nodes. Khan, Daachi, and Djouani (2012) proposed a sensor circuit fault identification strategy using Fuzzy Inference System (FIS) where sensor circuit faulty nodes are detected through neighbors' data analysis. In this approach, BS collects all sensor nodes data and analyzes this data by the FIS to detect sensor circuit faulty nodes within the network. However, this approach suffers from the poor detection accuracy due to lack of detail node information. As a result, a large number of non-faulty nodes detected as faulty nodes during the diagnosis process. Lau, Ma, and Chow (2014) proposed a centralized Probabilistic Fault Detection scheme for WSN (PFDWSN). In this approach, hardware fault of a sensor node is detected through the end-to-end transmission delay analysis. This approach uses Naïve Bayes classifier for network status determination during the testing phase. However, this centralized hardware fault detection algorithm suffers from the hotspots problem. Therefore, after some rounds network is divided into different subnetworks. Unlike fully connected network, some sensor nodes cannot forward data to the central node via wireless link and hence this centralized hardware detection algorithm does not work properly due to lack of status information of deployed sensor nodes. A cluster based fault detection and recovery technique is proposed and evaluated by Venkataraman, Emmanuel, and Thambipillai (2007). This approach leads to a large number of messages exchanges over the network for data and status exchange which rapidly decreases the energy of the deployed sensor nodes. On the other hand, it also puts a large overhead for the large scale WSNs during the cluster formation phase. A cellular approach of fault detection and recovery is proposed by Asim, Mokhtar, and Merabit (2009). This approach suffers from poor performance due to high energy overhead. However, cellular approach is not an efficient algorithm in terms of detection accuracy. Venkataraman, Emmanuel, and Thambipillai (2008) proposed a failure detection technique to avoid energy exhaustion. The main mechanism of this technique is that a node notifies its neighboring nodes before it is completely shut down due to energy exhaustion. In this approach, each sensor node knows the fault status of other sensor nodes which are present in the network which is a time and energy consuming process. Jing et al. (2011) proposed a Self-Monitoring algorithm for WSN (SM-WSN). It is a distributed fault detection algorithm where each sensor node compared its own sensed data with neighbors' data in order to detect its own fault status. The disadvantage of this approach is that it requires huge time to diagnose fault status of a node since in this approach every sensor node collects data from their neighbors for multiple number of times.

Lee and Choi (2008) proposed a distributed algorithm for Fault Detection in Wireless Sensor Network (FDWSN). This approach first detects faulty sensor nodes within WSN and then isolates them from the network. Here, malfunctioning nodes are used as communication nodes but these nodes are logically separated from the network. Sensor nodes with malfunctioning are detected through neighbor nodes comparison method. Each sensor node compares its own sensing data with its neighbor nodes sensing data. If sensing data difference is less than the threshold value, it detects as a non-fault node, otherwise it detects as a faulty node. In this approach, fault detection threshold value depends on the application. It only detects sensor circuit fault of a node but other faults due to receiver failure and transmitter failure do not detected by this approach. In addition, in this approach each sensor node collects data from their neighbors from c times which increases fault detection delay within the network. Cellular Automata (CA) based faulty nodes reused scheme is given by Banerjee et al. (2014) where faulty nodes are managed by some particular CA rules set. In this approach, each sensor node sends its sense information to the central node which is usually sink/BS. The central node diagnoses fault status of each node by analyzing this sensing information and then broadcasts the fault status to all nodes within the network. The main drawback of this technique is that if the central node becomes faulty, it is difficult to diagnose status of all sensor nodes in the network. On the other hand, CA rules make fault diagnosis system more complex which leads to less performance. Yuan, Zhao, and Yu (2015) proposed a distributed Bayesian algorithm for data fault detection in WSN. This approach calculates probability of fault by introducing some border nodes within the network. It puts a large message overhead for large scale WSNs. On the other hand, fault detection accuracy of this approach is very poor due to transmission faults. A fuzzy based fault detection scheme is given by Chanak, Banerjee, Samanta, and Rahaman (2012). In this approach, initially each sensor node transmits its fault status to the BS and then BS manages faulty sensor nodes through the fuzzy rule. The disadvantage of this approach is that it is a centralized fault technique where each sensor node transmits their fault status to the central node. Therefore, sensors close to the central node need to relay many status/data packets