A Review on Fault Diagnosis in Wireless Sensor Networks

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Abstract: With the wide utilization of wireless sensor networks (WSN), higher reliability and stability are being pursued gradually. In most cases, the communication capability for sensor network is influenced by the complex environmental conditions, the open characteristics of channels, the energy limitations of nodes, as well as network protocol design issues, ultimately leading to the high possibility of network failure. As a result, a timely and accurate fault diagnosis is of much significance for a network to ensure the stable operation and execution efficiency. This article firstly demonstrates the diagnostic process on the following three aspects, including the collection for network fault information, fault detection, and diagnosis process. In addition, the features of commonly used technologies are also analyzed and compared in order to identify their application scope respectively. Finally, this paper makes the summary for the possible development trends and future research directions of fault diagnosis.

1. Introduction

Nowadays, modern society enters the new networks and big data era due to the rapid and wide utilization of intelligent terminals, Internet of Things and cloud computing technologies. As the basis of these technologies, wireless communication is taken into consideration as the mainstream and fundamental supporter for information exchange and communication process.

Wireless sensor network (WSN) is a wireless network composed of a large number of sensor nodes in a self-organizing and multi-hop manner. These nodes can be deployed in a relatively complex environment to sense the external environment in a collaborative pattern. Therefore, WSN can process and transmit information regarding the perceived objects in the network’s coverage area after collecting them by means of human intervention. Currently, it has been widely applied to various industries \cite{1}, such as military \cite{2}, intelligent transportation \cite{2, 3}, environmental monitoring, health monitoring and so on.

WSN is an infrastructure-free network, and its nodes generally exhibit battery-powered characteristic. However, these nodes are usually placed in remote areas with unattended circumstance, causing that the battery could not be replenished or replaced in time, leading to the high limitation of the node energy \cite{4}. In most cases, the energy in wireless nodes is primarily consumed by the communication modules. Therefore, if the protocol design of the sensor network is unsuitable or abnormal during operation, the energy of some nodes will be exhausted rapidly, which will eventually result in premature death of these nodes. Additionally, other factors such as insufficient power of the sensor nodes, the misalignment of the sensor nodes, as well as the unstable state of the wireless links could also negatively influence the system working efficacy \cite{5}, further leading to the abnormalities and...
failures of sensor networks, which could ultimately affect the scheduled function and execution efficiency [6]. Therefore, more reliable, robust, and scalable networks could be achieved by both detection and diagnosis of a network in time and the accurate identification of any failure causes.

In order to efficiently detect and diagnose WSN failures, a series of technologies and algorithms have been investigated by many researchers both at home and abroad. This paper summarizes these techniques and algorithms and discusses the trend of WSN development, which may provide certain guidance for the depth research of fault diagnosis in wireless sensor network.

The main contributions of this paper can be summarized as follows:
(1) We firstly discuss the commonly used techniques and algorithms based on the fault diagnosis process including network status information collection, fault detection, and fault diagnosis.
(2) Then we summarize both advantages and disadvantages after analyzing each related technology and algorithm.

2. Fault Diagnosis Basis of Wireless Sensor Network

2.1. Reasons for Failure
Network failure refers to the network service out of order or the service quality reduction, which is mainly ascribed to communication protocol design and operation, the influence of the harsh environments, and the way of node interactions, including network unsuitable protocol design or abnormal during operation, data transmission conflicts, and even the atmospheric disturbance and their like.

2.2. Fault Classification
Network failures could be classified depending on the following two aspects, including network connectivity and network performance.

Network connectivity failures are easier to be detected. In a wireless network, the ratio of the synchronization packet to the end connection packet is approximately 1:1. Thus, if a big difference of proportion taken place, the obstructions will soon emerge during the data transmission and reception process, which could indicate that connectivity failures are existed in the network.

Network performance failures represent the low network execution efficiency. For instance, several factors such as data transmission speed slower than normal, network congestion, and packet loss will take negative impacts on the scheduled function of the network, and even causing routing loops, as well as a large amount of network bandwidth consumption problems, which eventually result in the network performance reduction or even paralysis.

As is shown in Figure 1, this section first analyzes the reasons for the failures in wireless sensor networks, and then classifies the network faults according to network connectivity and performance, and finally describes the specific failure phenomenon according to the classification.
3. Fault Management
Based on the phenomenon of the network failure, the causes can be caught via the following steps: (1) acquisition of the network state information using monitoring devices; (2) analysis of the collected...
information utilizing the fault detection techniques to reduce the fault range and find out the broken-down node; (3) discovering the fault causes by diagnosis related technology. Hence, these three steps of network information collection, fault detection and fault diagnosis could be totally summed up as fault management.

In general, information collection, fault detection and diagnosis usually constitute a cyclical process. For instance, packet loss, could also be considered as a fault phenomenon to further enter a new round of fault detection and diagnosis. As a result, related errors caused by several factors could be efficiently detected to finally achieve a stable and reliable network. The overall framework of sensor network fault diagnosis is illustrated in Figure 2.

3.1. Network Information Collection
The collection of network information plays a fundamental role in fault management. In this process, single node status, communication performance among nodes, and link status could be easily acquired. The network information is often obtained via the monitoring platforms, which enclose a set of specific nodes with the monitoring characteristics. This kind of node is further combined with each node to acquire its performance and status information, as is demonstrated in Figure 3.

![Figure 3. Monitoring platform](image)

In general, techniques for collecting network status data is divided into two parts: passive data acquisition and active data acquisition.

Passive data acquisition mainly contains two working ways including Simple Network Management Protocol (SNMP) [7], and Passive Monitoring System in Wireless Sensor Networks (PMSW) [8].

SNMP consists of three aspects: the managed device, the SNMP agent, as well as the network management system (NMS). NMS could easily attain message through the SNMP protocol. Additionally, the SNMP agent is a network management software module on the managed device. It could easily attain the relevant information of the local device and convert it into a compatible format with SNMP, eventually delivering the information to NMS. The SNMP-managed network is shown in Figure 4.
In order to overcome the shortcomings of little or incomplete message recorded from passive monitoring system, PMSW puts forward amalgamate and related machine to infer the lost packets, implicit information, and network events. On one hand, PMSW applies a time adjustment strategy to enhance the integrity of the data tracking. On the other hand, it also utilizes a finite state machine to deduce the lost packets. In a word, no special modification is needed in passive data collection process, and the normal operation of the network will not be impacted.

However, this passive collection manner could only passively monitor but not forwardly interact with the tested network. In most cases, active data acquisition methods are put to use in most of the test systems both here and abroad, such as Minerva [9] and SensLAB [10], and so on.

3.2. Fault Detection
Fault detection aims to analyze the network state information, and decrease the fault range, as well as identify and locate faulty nodes in the network. It could be divided into the centralized manner and the distributed manner.

For the centralized manner, each sensor node communicates with the sink node, and the sink node will further propagate the testing results after judging and analyzing the data. On account of the simple structure of the centralized method to exchange info by means of query and response and the complete network state information received from the aggregation node, the fault detection accuracy is high.

In the past decades, many centralized protocols have been proposed to sense error. Among them, Lau et al. [11] proposed a centralized Bayesian detector for fault detection through end-to-end transmission time. the Markov chain model was used to classify the state of the nodes by probability calculation. According to the state of the nodes, the aggregation node can predict the areas where errors occur frequently. This method can improve the miss detection rate of the fault detection. Considering the
network congestion caused by the congestion of the aggregation nodes, Singhal et al.[12] developed an artificial neural network-based congestion detection algorithm to accurately detect the block status and congestion level.

The aggregation node has large and strong computational power, and more complex algorithms can be calculated by machine learning to diagnose the network. However, centralized methods also have a number of shortcomings, including the following:

1. Some nodes will be unable to communicate with the aggregation node and the accuracy of the fault detection will be influenced once the network information received from the aggregation node is incomplete.

2. The aggregation node is in charge of measuring the status of all the other nodes, and once it fails, detection will not be in progress.

3. The "one-to-many" communication method will increase the energy consumption of nodes especially the neighbor nodes of the center node, making the life of the neighboring nodes shorter, prone to failure and death.

4. The state of the remote node in a large-scale network may change when the amount of data transmission is large and the sink node makes a judgment.

Aiming at the shortcomings shown above, a distributed detection method has been proposed. Since each node implements a fault detection algorithm and generates a fault local view propagated across the network, each faultless node detects the state of all the nodes in the network by rule and line [13].

The distributed method can be divided into the following: node self-detection method, neighbor node cooperation method, and hybrid method.

1. Self-detection method

The node self-test method uses the node’s own state information to detect failure. In a WSN, the nodes have a certain time correlation that it has relatively stable data for a period of time if no faults exist. Therefore, once the node status data is found to be inconsistent with the time correlation, node failure can be determined.

The node uses time-related characteristics to detect whether it is faulty [14] by comparing the local data and the historical data. In [15], Hidden Markov models have been introduced to characterize the trend in the failure of each node, and thus, node failure can be predicted.

The node self-detection method can reduce the burden of communication but may get inaccurate result.

2. Neighbor node cooperation method

The neighbor node cooperation’s method detects fault in the network by the information interaction of the neighbor nodes. In SN, nodes have a certain spatial correlation that two nodes within a certain spatial range have similar data. Consequently, the protocol can find the faulty node by finding out the data of irrelevant spatial correlation.

A historical data and neighbor node self-test (NDHN) algorithm, was proposed to use the deviation of historical data and neighbor data to test breakdown. The algorithm is hierarchical and can be extended to large networks. Considering the communication channel fault of a sensor network, a local fault view was constructed in based upon the spatial correlation of the node data. After that, propagating the partial view to the cluster head generates a global fault view before detecting the faulty node. In view of that the data loss problem will affect fault detection.

The method of neighbor collaboration can enhance the detection accuracy with the decrease of burden on the aggregation node and the increase of the communication burden. Moreover,

3. Hybrid method

The hybrid method is a distributed protocol that combines the node self-detection and the cooperation of neighbor nodes techniques. First, some parts of the fault are detected by using the time correlation of the node’s own data. Then for some nodes that were not located the position of fault, spatial correlation is used to determine if the node is faulty.

The hybrid method can reduce the burden of communication between the neighbor nodes and avoid the problem of inaccurate detection results of a single node. Thus, the hybrid method is an ideal distributed fault detection algorithm.
The distributed approach helps minimize the number of exchange messages and end-to-end latency maximally, to improve detection speed. So, the distributed approach can be applied to large networks, but it still has some drawbacks.

**Table 1.** A summary of the various methods of fault detection.

| Method                        | Advantage                                                                 | Disadvantage                                                                 |
|-------------------------------|--------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Node self-test method         | Reduces the communication burden                                         | Single node detection inaccuracy                                              |
| Neighbor node cooperation method | Improves the detection accuracy                                          | Increases the communication burden                                            |
| Hybrid method                 | Reduces the communication burden and the inaccurate detection of the individual nodes | Increases processing complexity                                               |
| Bayesian network              | The lack of a certain data input can still build accurate models, easy to train | The computational reasoning is more complicated. The results of changes based on feature combinations cannot be processed. |
| Support Vector Machines       | Excellent performance on nonlinearly separable problems                  | The training parameters are prone to over-fitting. It is hard to train.       |
| Fuzzy theory                  | No need to build accurate mathematical models                             | The learning ability is weak, and the detection system is highly complex when the network is complicated. |

3.3. Fault Diagnosis

The fault diagnosis technology refines the fault type and diagnoses the cause of the fault in the network on the basic of fault detection.

The fault diagnosis method can be divided into four subcategories of diagnosis methods based on the following: an expert system, a neural network, fuzzy mathematics, and data mining.

1. Diagnostic method based on expert system

The diagnostic method is based on the expert system, using the knowledge of human experts to understand and judge the network to ultimately diagnose the cause of the fault. The expert system establishes a fault self-learning ability through both an expert experience fault database and real-time collected network data and then intelligently diagnoses the network faults [23].

The expert system has strong reasoning ability, but there are still difficulties in acquiring knowledge and weak generalization ability in obtaining rules of judgment. Therefore, fault diagnosis is often performed together with a genetic algorithm [24], a neural network algorithm [25].

2. Neural network-based diagnosis method

The neural network algorithm can classify faulty nodes in the network to realize network fault diagnosis. A fault diagnosis method based on fuzzy neural network (FNN) for wireless communication module has also been proposed. Besides, a feedforward neural network (FFNN) technology to improve the effectiveness of the diagnosis. On the other hand, the combination of quantum genetic algorithm and hybrid hierarchical genetic algorithm promotes the training efficiency of the neural network in literature [26].

The neural network algorithm, with good self-learning ability, utilizes fault examples and diagnostic experience to train and perfect the neural network model. Moreover, it does not require the expertise of the expert system and solves the issue of the expert system about having difficulty acquiring knowledge. However, there are still shortcomings such as long training time and weak generalization ability.

3. Diagnosis method based on fuzzy mathematics
In network fault diagnosis, the relationship between the faults and phenomena is often ambiguous and difficult to express with accurate mathematical models. Fuzzy mathematics-based diagnostic methods can deal with uncertain information in network fault diagnosis.

The fuzzy C-means clustering algorithm is used to classify the sample library, confirm the cluster center, and check the acquired data which type of breakdown in network, thereby bring about the network fault diagnosis [27]. For the sake of better reflecting the ambiguity between fault phenomena and their causes and enhancing the rationality of the fuzzy rules and their ability to represent and reason, Zhao proposed a weighted multi-dimensional multi-fuzzy inference algorithm that satisfies the reduction.

There is no uniform way to confirm the membership degree of the elements in the fuzzy set and the mapping law between the two sets, which can accordingly usually be determined only by experience.

4. Diagnostic methods based on data mining

Data mining refers to the process of searching for hidden knowledge in a large amount of data through algorithms. Data mining algorithms consists of association rules, decision trees, and the like. The association rule, a commonly used data mining diagnosis algorithm, finding a correlation between the fault phenomenon and the fault in the data and then determine the most likely reason of the fault.

Data mining can also be applied to the fault diagnosis of cellular networks, such as using the association rules to diagnose large amounts of data, or combining statistical learning methods with decision trees. Since there is a vague relationship between network failures and the root cause of network failures, the related fuzzy theory and fuzzy inference control technology [28] are united in diagnosing the network fault. Data mining can discover hidden information in the data and effectively find out the cause of the failure. However, it has the disadvantage of requiring complicated calculations that the processing efficiency is not high with the increasing amount of data. A summary of the various methods of fault diagnosis is shown in Table 2.

**Table 2.** A summary of the various methods of fault diagnosis.

| Method           | Advantage                                | Disadvantage                                           |
|------------------|------------------------------------------|--------------------------------------------------------|
| Expert system    | Strong reasoning ability                  | Difficulties in accessing knowledge and weak generalization |
| Neural Networks  | High learning capability                  | Long training time and weak generalization             |
| Fuzzy mathematics| No need to build accurate mathematical models | Need to rely on empirical knowledge                      |
| Data mining      | Discover data hiding information          | Large amount of calculation, low processing efficiency  |

Note: ¹ Generalization ability is the ability of a trained neural network model to predict data that does not exist in a training set.

4. Conclusion and Discussion

This paper first introduces the basic characteristics of wireless sensor network fault diagnosis, analyzes the sources of such faults, and classifies the faults. Then from the point of view of fault management, the technology of information collection, fault detection, and fault diagnosis are elaborated in detail.

The passive method only passively monitored in the network state information collection method does not affect the network performance. While proactive methods allow the information to interact but have an impact on productivity. Besides, the centralized method in fault detection has a high detection accuracy with shortcomings of the large detection delay, which is only suitable for small networks. The expansibility of distributed method in contrast is good to be suitable for large networks in a fast diagnosis speed. A variety of artificial intelligence algorithms in fault diagnosis technology are usually combined to have complementary advantages and improve the diagnostic accuracy, such as expert systems, neural networks, genetic algorithms, fuzzy mathematics, data mining methods and so on.
The fault diagnosis of wireless sensor networks in the future will be developed in the direction of large-scale, distributed and artificial intelligence technology. More and more types of faults will occur since the size of the network increases. Additionally, a large amount of information integration, the integration of multi-level diagnosis, and remote collaborative diagnosis will be the main subjects of research in the future.

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