Distributed Diagnosis of Permanent and Intermittent Faults in Wireless Sensor Networks

Manmath Narayan Sahoo and Pabitra Mohan Khilar

Department of Computer Science & Engineering
National Institute of Technology Rourkela, Odish - 769 008, India
{sahoom,pmkhilar}@nitrkl.ac.in

Abstract. Faults are inevitable in Wireless Sensors Networks (WSNs) because of physical defects caused due to environmental hazards, imperfection or hardware and/or software related glitches. If faults are not detected and handled properly the consequences may be inexorable in case of safety critical applications. This paper presents a distributed fault diagnosis algorithm to handle both permanent and intermittent faults in WSNs. The proposed diagnosis algorithm is based on the comparison of test results and residual energy estimations by neighboring sensor nodes. The intermittent faults are handled by iterating the comparisons for r rounds. The basic *time-out* mechanism is adopted to handle permanently faulty sensor nodes.

Keywords: wireless sensor networks, fault diagnosis, intermittent faults

1 Introduction

A WSN is a distributed, self configurable, ubiquitous and infrastructure less[1] network, without any centralized administrations. It is often composed of many tiny, low-cost, battery-powered sensor nodes. Each node is aided with sensing, data processing, and communicating capabilities. The application of WSNs have tremendously grown up over last few decades. Environmental monitoring, transportation, crisis management, and military surveillance applications are name to few. A sensor node may have faults and measurement errors due to physical defect, imperfection or hardware and/or software related glitches. The harsh operational environment further aggravates the problem. In order to provide the quality of service (QoS), it is highly required to detect faulty sensors and let all fault-free sensors to receive these faulty events. This makes the network still operational in presence of faults, of course with degraded performance. The *distributed fault diagnosis* is intended to draw a consensus among the fault-free sensors about the status of all faulty sensors in the system. It acts as a basis for designing dependable systems by isolating the faulty sensors from the network. This paper considers the problem of distributed fault diagnosis in WSNs.

Fault diagnosis has been a focused area of research since last few decades and was first explored by Preparata et al. in [1] for a wired network with point to

[1] without any fixed infrastructures such as access points or base stations

point communication links. Since then, many variants of this model have been proposed. Comparison based model; the most favorable fault diagnosis mechanism has been the key discussion in [2, 3], where the decisions about the fault status of nodes are based on the comparison outcomes of the results of the same task executed by different nodes. The distributed fault diagnosis protocols for Mobile ad hoc Networks (MANETs) are extensively investigated in [4–6]. However, due to the harsh operational environments, sensor nodes fail more frequently than the nodes in other platforms. This makes the task of fault diagnosis more challenging.

Jaikaeo *et al.* have proposed a centralized fault diagnosis algorithm in [7] addressing the response implosion problem in sensor network diagnosis, thus reducing the traffic at central manager. Lee *et al.* in [8] have discussed another centralized fault management scheme that uses a central manager provided with a global view of the network to reliably execute predefined corrective and preventive management maintenance. Nevertheless, the scheme suffers with certain limitations. It is non-scalable and cannot be advantageous for larger networks; central manager is the bottleneck due to high traffic. MANNA: a management architecture for fault detection in event driven WSNs is presented in [9]. This scheme puts an external manager having the global knowledge of the network to detect the faulty events. However, it suffers from the disadvantages of a centralized approach. According to Ding *et al.* in [10], *Neighbor coordination* is another interesting approach to detect faulty nodes in sensor networks. Based on this approach, a sensor is assumed to be faulty if it deviates significantly from the median of readings of neighboring sensors. In the fault detection scheme presented by Chessa *et al.* in [11], a fault-free initiator starts the diagnosis process by accumulating information from its neighbors and the process continues until all the faulty nodes are identified. However, authors have considered no fault types other than crash fault. In [12] Chen *et al.*, have discussed a comparison based distributed diagnosis protocol for WSNs. This scheme is developed on the basis of the comparison results of own sensed data and neighbor's data. However, the scheme suffers from high communication complexity and hence not energy efficient. Authors in [13], have presented a probabilistic approach to diagnose faulty sensors in intermittent fault environment. Nevertheless, the scheme seems to be complex in terms of diagnosis time, message exchanges and more importantly energy consumption. For faulty sensor identification considering transient faults, a comparison based method that uses time redundancy have been discussed in [14] by Lee and Choi. Some more fault management schemes are briefed in the survey [15].

In this paper we present an efficient Fault Diagnosis Algorithm (FDA) for static topology WSNs, in presence of permanent and intermittent faults. The rest of the paper is organized as follows. Section 2, describes the network and fault model for WSNs. The proposed FDA is presented in Section 3. In Section 4, we discuss the simulation results for the algorithm, concluding in Section 5.

2 Network and Fault Model

We consider a WSN, consisting of n sensor nodes. The sensor nodes are assumed to be homogeneous and stationary. A permanently faulty node does not change its state until it is repaired and/or replaced. In contrast, an intermittently faulty node fluctuates between fault-free and being faulty, irregularly. The proposed FDA eyes on the detection of nodes with following fault types:

- permanent or intermittent faults in sensors
- permanent fault in communication unit

The sensor nodes with permanently faulty communication units are to be excluded from the network. However, the nodes with malfunctioning sensors still remain associated with the network since they have the ability to relay data packets among the nodes.

The undirected graph $C = (S, L^t)$, where S is the set of sensor nodes and L^t denotes the set of logical links between sensors at any given time t, represents the *communication graph* or *topology* of sensor network at time t. Sensor nodes S_i and S_j are said to be *adjacent* or *1-hop neighbors*, if they are in the transmission range of each other. $N^t_{S_i}$ denotes the set of nodes adjacent to S_i at time t, called the neighborhood set of S_i.

A *test graph*, $T = (S', {L'}^t)$ can be constructed from the communication graph by excluding the nodes with permanently faulty communication units and the links associated with those nodes. So $S' \subseteq S$, ${L'}^t \subseteq L^t$, and T is a sub-graph of C. Each link, $l^t_{(S_i,S_j)} \in {L'}^t$ is labelled by a binary value $c^t_{(S_i,S_j)}$. Without loss of generality we consider the test graph and the communication graph to be the same. We consider that the maximum number of faulty neighbors for any node $S_i \in S$ is $(\lceil |N^t_{S_i}|/2\rceil - 1)$. The links of the communication system are assumed to be error free.

3 Proposed Fault Diagnosis Algorithm

The proposed diagnosis algorithm is based on the comparison of sensor measurements by neighboring sensor nodes. Let $x^t_{S_i}$ denotes the sensor measurement of node S_i at a given time t. By considering the spatial correlation in sensor networks, the measurement difference of two fault-free neighboring sensors is presumed to be very small. However, if at least one of them is faulty then the difference is significant. Hence, if $l^t_{(S_i,S_j)} \in L^t$ then

$$| \; x^t_{S_i} - x^t_{S_j} | \quad \begin{cases} \leq \delta_1, & \text{both } S_i \text{ and } S_j \text{ are fault-free} \\ > \delta_1, & \text{either or both of } S_i \text{ and } S_j \text{ is/are faulty.} \end{cases} \tag{1}$$

To aid the diagnosis process, the residual energy estimations by neighboring sensor nodes are also compared. Let $E^t_{(S_i,S_j)}$ be the estimation of node S_j about the residual energy of node S_i and $E^t_{S_i}$ be the own observed residual energy of

S_i, at time t. Hence, if $S_i \in N^t_{S_j}$ then

$$| \; E^t_{S_i} - E^t_{(S_i,S_j)}| \begin{cases} \le \delta_2, & \text{both } S_i \text{ and } S_j \text{ are fault-free} \\ > \delta_2, & \text{either or both of } S_i \text{ and } S_j \text{ is/are faulty.} \end{cases} \tag{2}$$

In Equations (1) and (2), δ_1 and δ_2 are two predefined thresholds. These thresholds may vary depending on the application. Now for each $l^t_{(S_i,S_j)} \in L^t$, $c^t_{(S_i,S_j)}$ can be defined as follows

$$c^t_{(S_i,S_j)} = \begin{cases} 0, & | \; x^t_{S_i} - x^t_{S_j}| \le \delta_1 \text{ and } | \; E^t_{S_i} - E^t_{(S_i,S_j)}| \le \delta_2 \\ 1, & \text{Otherwise.} \end{cases} \tag{3}$$

In Equation (3), $c^t_{(S_i,S_j)} = 0$, signifies both S_i and S_j are fault-free. But if at least one of S_i and S_j is faulty, then $c^t_{(S_i,S_j)} = 1$. Each sensor node, $S_i \in S$ maintains a boolean status register $StatR_{S_i}[]$ of size n, keeping the fault status of all the nodes in the network. Initially all the neighbor nodes are assumed to be fault free (0) and the status of all non neibhoring nodes are unknown (-1).

In each round, up to total of r rounds, each sensor node $S_j \in S$ sends its own observed sensor reading and expected residual energy of $S_i \in N^t_{S_j}$ to S_i i.e. it sends a message $M = (x^t_{S_j}, E^t_{(S_i,S_j)})$ to S_i. Upon receiving the message M from its neighbor S_j, node S_i performs the threshold test defined in Equation (3) and increments $StatR_{S_i}[j]$ by 1, if at least one of the test conditions fails. At the end of r rounds each sensor finds a partial diagnosis about the neighbors. Of course at this point the sensor node S_i does not have the fault status of non neighboring nodes. In order to reach a general consensus, all nodes in the network exchange their status registers. There may be a situation, when an intermittently faulty sensor node S_j sends to S_i, sensor measurement and expected residual energy of S_i, both correctly, in all r rounds; in which case S_i misdiagnoses S_j as fault-free. To overcome this situation we follow a majority voting as defined in Equation (4). We consider the maximum number of neighbors to which S_j may send such correct values in all r rounds is $\lceil n^+_{S_j}/2 \rceil - 1$, where $n^+_{S_j}$ represents the number of fault-free neighbors of S_j.

$$StatR_{S_i}[j] = \begin{cases} 0, \quad if \left(\displaystyle\sum_{\substack{(S_k \in N^t_{S_j}) \\ (StatR_{S_i}[k] \le 0) \\ (StatR_{S_k}[j]=0)}} 1 \right) \ge \left\lceil \frac{1}{2} \left(\displaystyle\sum_{\substack{(S_k \in N^t_{S_j}) \\ (StatR_{S_i}[k] \le 0)}} 1 \right) \right\rceil \\ 1, \quad if \left(\displaystyle\sum_{\substack{(S_k \in N^t_{S_j}) \\ (StatR_{S_i}[k] \le 0) \\ (StatR_{S_k}[j]=0)}} 1 \right) < \left\lceil \frac{1}{2} \left(\displaystyle\sum_{\substack{(S_k \in N^t_{S_j}) \\ (StatR_{S_i}[k] \le 0)}} 1 \right) \right\rceil \; and \; StatR_{S_i}[j] = 0. \end{cases} \tag{4}$$

In Equation (4), 0 and 1 indicates S_j to be fault-free and intermittently faulty respectively. There may be the case, when an intermittently faulty sensor node

Algorithm 1: Proposed Fault Diagnosis Algorithm

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Data: C = (S, L^t): The communication graph.
      // The test graph and communication graph are considered to be same.
      r: Maximum number of rounds.
Result: StatR_{S_i}[] for each node S_i ∈ S
Initialization: NR=0; FFCount=0; NFNbrCnt=0; FFNbrStatSum=0; IFNbrCnt=0;
for each S_i ∈ S and S_j ∈ S do
    if S_i == S_j or l_{(S_i,S_j)} ∈ L^t then
        StatR_{S_i}[j] = 0;
    else
        StatR_{S_i}[j] = −1;
    end
end
repeat

    for each S_j ∈ S and S_i ∈ N^t_{S_j} do
        S_j sends a message M = (x^t_{S_j}, E(S_i, S_j)^t) ;
    end
    if a node S_i receives a message M from S_j ∈ N^t_{S_i} then
        if |x^t_{S_i} − x^t_{S_j}| > δ_1 or |E^t_{(S_i,S_j)} − E^t_{S_i}| > δ_2 then
            StatRS_i[j]+ = 1;
        end
    end
until (++NR ≠ r) ;
for each S_i ∈ S do
    S_i broadcasts its status register StatR_{S_i}[] to other nodes in the network;
end
for each S_i ∈ S; S_j ∈ S and S_i ≠ S_j do
    for each S_k ∈ N^t_{S_j} do
        if StaR_{S_i}[k] == 0 and StatR_{S_k}[j] == 0 then
            FFCount++;
        end
        if StatR_{S_i}[k] ≤ 0 then
            NFNbrCnt++;
        end
    end
    if FFCount ≥ ⌈NFNbrCnt++/2⌉ then
        StatR_{S_i}[j] = 0;
    else if StatR_{S_i}[j] = 0 then
        StatR_{S_i}[j] = 1;
    end
end
for each S_i ∈ S; S_j ∈ S and S_i ≠ S_j do
    for each S_k ∈ N^t_{S_j} and StaR_{S_i}[k] == 0 do
        FFNbrStatSum+=StatR_{S_k}[j];
        IFNbrCnt++;
    end
    if FFNbrStatSum= (r × IFNbrCnt) then
        StatR_{S_i}[j] = 2;          // StatR_{S_i}[j] = 2 indicates S_j is permanently faulty.
    else if FFNbrStatSum>0 then
        StatR_{S_i}[j] = 1;          // StatR_{S_i}[j] = 1 indicates S_j is intermittently faulty.
    end
end
```

S_j sends sensor measurement and expected residual energy of S_i, either or both incorrectly, to the node S_i in all r rounds; in which case S_i misdiagnoses S_j as permanently faulty. To handle this situation and to determine the actual fault type, we follow Equation (5).

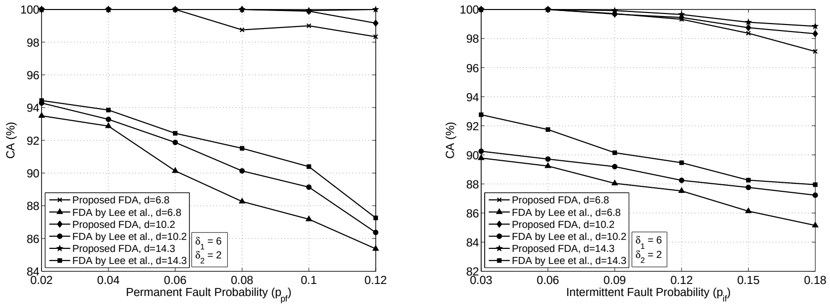
$$StatR_{S_i}[j] = \begin{cases} 1, & if \;\; 0 < \left(\sum\limits_{\substack{(S_k \in N^t_{S_j}) \\ (StatR_{S_i}[k]=0)}} StatR_{S_k}[j] \right) < r \left(\sum\limits_{\substack{(S_k \in N^t_{S_j}), \\ (StatR_{S_i}[k]=0)}} 1 \right) \\ 2, & if \;\; \left(\sum\limits_{\substack{(S_k \in N^t_{S_j}) \\ (StatR_{S_i}[k]=0)}} StatR_{S_k}[j] \right) = r \left(\sum\limits_{\substack{(S_k \in N^t_{S_j}), \\ (StatR_{S_i}[k]=0)}} 1 \right) \end{cases} \tag{5}$$

The values 1 or 2 of $StatR_{S_i}[j]$ in Equation(5) signifies S_j to be intermittently faulty or permanently faulty respectively. The proposed FDA is more precisely described in Algorithm 1.

4 Simulation Analysis

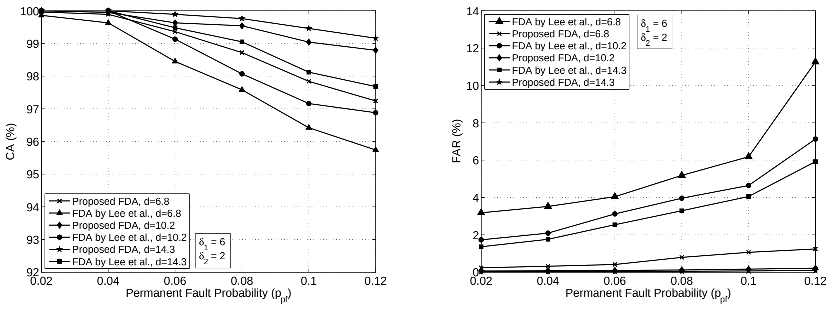
To support the feasibility of the proposed FDA, simulations are performed using the OMNET++ simulator. The results are compared with that of the detection algorithm discussed by *Lee* and *Choi* in [14]. Based on the faulty behaviour, the proposed FDA classifies the sensor nodes into three different classes: permanent fault class, intermittent fault class, and fault-free class. Two performance measures are used for evaluation, (i) Classification Accuracy (CA): The ratio of the number of nodes classified in to a particular class to the total number of nodes of that class, and (ii) False Alarm Rate (FAR): The ratio of the sum of the number of faulty nodes classified as fault-free and the number of fault-free nodes classified as faulty to the total number of nodes in the network.

A simulation scenario is created for a sensor network with 1000 nodes randomly deployed over $1000 \times 1000 \; m^2$ area.Each sensor node is equipped with AA battery with default initial energy 18720 Joule. With proper adjustment of the transmission range (common for all nodes), the desired value of average node degree (d) can be obtained. In the simulation, the sensor nodes are randomly chosen to have permanently faulty sensors with probabilities 0.02, 0.04, 0.06, 0.08, 0.10 and 0.12 respectively. We also consider that p_{if} is 150% of p_{pf}, in each case. Here, p_{if} denotes the probability of a node being intermittently faulty, and p_{pf} represents the same for a node being permanently faulty. The values of δ_1 and δ_2 are considered to be 4 and 2 respectively. In order to evaluate *Lee* and *Choi's* algorithm, we consider the same simulation scenario with $\theta_1 = \lceil d/2 \rceil$ and $\theta_2 = 2$ as the values of thresholds used in their algorithm. The FDA is run for $r(= 10)$ rounds to handle intermittent faults. The obtained simulation results for CA and FAR for different values of d are compared as depicted in Fig. (1), and (2).



(a) (b)

Fig. 1. Comparison of CA for (a) permanently faulty, and (b) intermittently faulty nodes



(a) (b)

Fig. 2. Comparison of (a) CA for fault-free nodes, and (b) False Alarm Rate.

It can clearly be observed that the CA decreases with lower node degrees; since, in case of sparse networks the fault-free sensor nodes may not always form a connected graph for fault diagnosis purpose. In such scenarios, all neighbors of a particular node may be faulty at the same time, leading to misdiagnosis of the node. Such scenarios arise with more counts for low d and high fault probability, in which case the performance even degrades.

Fig. 1(a) depicts the comparison of classification accuracy for permanently faulty nodes with d values 6.8, 10.2, and 14.3. In some rounds, if a permanently faulty node produces a sensor measurement that does not differ from the sensor measurements of its fault-free neighbors by a minimum threshold δ_1, then it is not classified as permanently faulty. The additional threshold test on residual energy in the proposed FDA handles such cases and improves the performance.

An intermittently faulty node that generates incorrect sensor measurements in less than or equal to θ_2 rounds are not classified as intermittently faulty in the fault detection algorithm by Lee et al. For low value of δ_1, fault-free nodes may be miss-diagnosed as faulty. Such miss-classification scenarios are suppressed in the proposed FDA by the additional threshold test. The comparison of false alarm rates are clearly shown in Fig. 2(b). As obvious, we found that with increase in fault probability, FAR increases.

The simulation results show that if thresholds are not chosen carefully for the applications. The average node degree, d must be adjusted to relatively high to have better performance.

5 Conclusions

In this paper we propose a distributed fault diagnosis algorithm for WSNs, in order to handle sensor nodes having permanently fault sensor or intermittently faulty processing unit. The algorithm is based on two threshold tests: (i) on sensor measurements of neighboring nodes, and (ii) on expected and actual residual energy of the sensor nodes. Two special cases of intermittent faults are considered: One, where an intermittently faulty node sends both sensor measurement and expected residual energy of neighboring nodes correctly to some of its neighbors in all r rounds; Another, where at least one of these values are incorrect in all r rounds. The simulation experimental results vows that the algorithm detects and classifies the faulty nodes with high accuracy and low false alarm rate, even in case of high fault probability, by properly choosing the threshold values. In future, endeavour will be made to handle faults in dynamic topology environment.

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