Diagnosis of Wireless Sensor Networks in Presence of Permanent and Intermittent Faults

Manmath Narayan Sahoo · **Pabitra Mohan Khilar**

Abstract In this paper we consider the problem of distributed fault diagnosis in Wireless Sensor Networks (WSNs). The proposed Fault Diagnosis Algorithm (FDA) aims to handle both permanent and intermittent faults. The sensor nodes with permanent communication faults can be diagnosed by using the conventional *time-out* mechanism. In contrast, it is difficult to detect intermittent faults due to their inherent unpredictable behavior. The FDA is based on the comparison of sensor measurements and residual energy values of neighboring sensor nodes, exploiting their spatial correlations. To handle intermittent faults, the comparisons are made for r rounds. Two special cases of intermittent faults are considered: one, when an intermittently faulty node sends similar sensor measurement and similar residual energy value to some of its neighbors in all r rounds; another, when it sends these values, either or both of which deviates significantly from that of some neighbors in all r rounds. Through extensive simulation and analysis, the proposed scheme is proved to be correct, complete, and efficient to handle intermittent faults and hence, well suited for WSNs.

1 Introduction

The adoption of Wireless Sensor Networks (WSNs) in various industrial, healthcare, environmental monitoring, transportation, crisis management, and military surveillance applications have tremendously grown up over the last few decades. Ease of implementation, ability to operate in harsh environments, easy troubleshooting and repair, and high levels of perfor-

M. N. Sahoo (✉) · P. M. Khilar
Department of Computer Science and Engineering,
National Institute of Technology Rourkela, Rourkela 769008, Odisha, India
e-mail: sahoom@nitrkl.ac.in

P. M. Khilar
e-mail: pmkhilar@nitrkl.ac.in

mance are the main reasons behind the popularity of such networks. A WSN is a distributed, self configurable, ubiquitous, and infrastructure-less network, often composed of many tiny, low-cost, battery-powered sensor nodes. Each node has sensing, data processing, and communicating capabilities. The adversarial and harsh operational environments in which WSNs are deployed makes the sensor nodes error prone and hence, unreliable. A sensor node may have faults and measurement errors due to physical defects, imperfections or hardware and/or software related glitches. The application of WSNs in various critical scenarios makes it more demanding to detect faulty sensors and let all fault-free sensors to receive these faulty events; thus making the network still operational in presence of faults. The *distributed fault diagnosis* is intended to draw a consensus among the fault-free sensors about the status of all other sensors in the system. It acts as a basis for designing dependable systems by isolating the faulty sensors from the network. The fault-free sensors can proceed with their computations, however, with degraded performance. In this paper, we consider 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. [1] for wired networks with point to point communication links. Since then, many variants of this model have been proposed as discussed in the literature [2–6]. Comparison based model; the most favorable fault diagnosis mechanism has been the key discussion in [7,8], 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 investigated in [9–11]. 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 in WSNs.

Replication of sensors for a node is treated to be the most ancient approach for fault tolerance in WSNs [12]. However, it increases the cost of a node and eventually the cost of the network along with the increased power consumption and network complexity. Jaikaeo et al. [13] have proposed a centralized fault diagnosis algorithm, addressing the response implosion problem in sensor network diagnosis. The main objective of their approach is to reduce the traffic at central manager. Lee et al. [14] have discussed another centralized 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 from 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 by Ruiz et al. [15]. This scheme puts a manager external to the network 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. [16], *neighbor coordination* is another interesting approach to detect faulty nodes in sensor networks. In their approach, a sensor is considered faulty if it deviates significantly from the median of readings of neighboring sensors. In the fault detection scheme presented by Chessa et al. [17], 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 faults. A self-monitoring fault detection model has been proposed by Chihfan et al. [18]. But, the network requires some initial self-configuration, and this model is constrained with static sensors only. Chen et al. [19] 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. Khilar et al. [20] 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 (recurring transient faults are called intermittent faults), a comparison based method that uses time redundancy have been discussed by Lee and Choi [21]. In their algorithm, sensor readings of neighboring sensors are compared for r consecutive rounds. If the readings of two neighboring sensors, say S_i and S_j, match for minimum θ_2 rounds then the final comparison outcome, say c_{ij}, is 0 (pass); otherwise c_{ij} is 1 (fail). To determine the actual status of any node S_i, a majority voting is followed among $c_{ij}; \forall S_j \in N_{S_i}^t$. Node S_i is considered fault-free if $|c_i| \geq \theta_1$, where $|c_i|$ is the number of 0's in c_{ij}. Their approach can be used to classify the faulty nodes into permanently or intermittently faulty, based on the number of rounds a node had generated similar sensor readings as its neighbors. However, considering a fixed θ_1 is not promising and may affect the accuracy. For instance, if $\theta_1 = 3$ and a fault-free node has two neighbors then the node is not detected as fault-free, even in case both the neighbors are fault-free. In contrast, an adaptive threshold for each node would be more appropriate and can improve the accuracy. Some more fault management schemes are briefed in the survey [22].

In this paper, we present an efficient Fault Diagnosis Algorithm (FDA) for static topology WSNs in presence of permanently and intermittently soft faults, along with hard 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 Sect. 3, and the analytical proofs of correctness and completeness of the algorithm are shown in Sect. 4. Simulation results are discussed in Sect. 5 to support the effectiveness of the algorithm. In Sect. 6, we give a concluding remark of the work.

2 Network Model

We consider a WSN, consisting of a finite collection (say n numbers) of sensor nodes randomly deployed across a geographical area to monitor the environment. The sensor nodes are assumed to be homogeneous and stationary, and the transmission range for all sensor nodes are the same. By homogeneous, we mean sensors have the same processing power and initial energy. Each sensor has a unique identity and they communicate via a multi-hop packet radio network. At the time of deployment the nodes are assumed to be healthy i.e. fault-free. Each sensor node has the knowledge of the identity of its 1-hop neighbors along with their neighborhood information. This is a feasible requirement in sensor networks [23–25].

2.1 Fault Model

After deployment, a sensor node at any point of time can be in one of the possible binary states: faulty (0) or fault-free (1). A permanently faulty node does not change its state until it is repaired and/or replaced. Either it communicates with faulty behavior at all times, or it can't communicate at all. Apart from permanent fault, there exist two variants of faults based on the duration for which they persist; *transient* and *intermittent* faults. A transient fault occurs and perishes suddenly without any apparent intervention, whereas the intermittent fault recurs itself irregularly. Due to the unpredictable behaviors of transient and intermittent faults, they are hard to diagnose and handle as compared to permanent faults. The proposed FDA eyes on the detection of nodes with following fault types:

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

Sensor nodes with permanently faulty communication unit can be detected with conventional *time-out* mechanism, and 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. Therefore, our main focus is to detect the permanent faults in sensors and intermittent faults in sensors or communication units.

Let the probability of a node being faulty is p_f and that of a faulty node having fault-free communication unit is p_f^+. Hence, the number of faulty nodes having faulty communication units is $n.p_f.(1 - p_f^+)$. This leaves $n' = n - n.p_f.(1 - p_f^+)$ nodes that actually take part in fault diagnosis. Out of them, however, $n.p_f.p_f^+$ nodes are faulty, even though they act as relay nodes. Now the probability of a node being faulty after excluding the nodes that cannot communicate at all can be put as follows,

$$\hat{p}_f = \frac{n.p_f.p_f^+}{n - n.p_f.(1 - p_f^+)} = \frac{p_f.p_f^+}{1 - p_f.(1 - p_f^+)}. \tag{1}$$

2.2 Communication Framework

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. Henceforth, we use the superscript t to quantify the attributes at a given time t; however, they may be removed from the notations when there is no explicit requirement of notion of time. Let $(S_{(i,x)}^t, S_{(i,y)}^t)$ represent the Cartesian coordinates of the node S_i. Two sensor nodes; S_i and S_j are said to be *adjacent or 1-hop neighbors*, iff the Euclidean distance between those two sensors,

$$d_{(S_i,S_j)}^t = \sqrt{(S_{(i,x)}^t - S_{(j,x)}^t)^2 + (S_{(i,y)}^t - S_{(j,y)}^t)^2} \tag{2}$$

does not exceed the communication range, r_c i.e.

$$l_{(S_i,S_j)}^t \in L^t \iff d_{(S_i,S_j)}^t \leq r_c. \tag{3}$$

Since the links in the communication graph are undirected, we have

$$l_{(S_i,S_j)}^t \in L^t \iff l_{(S_j,S_i)}^t \in L^t. \tag{4}$$

The set of nodes adjacent to S_i at time t, called the neighborhood set of S_i is denoted as $N_{S_i}^t$, and can be defined as follows,

$$N_{S_i}^t = \{S_j | S_j \in S \text{ and } l_{(S_i,S_j)}^t \in L^t\}. \tag{5}$$

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, $l_{(S_i,S_j)}^t \in L'^t$ is labelled by a binary value $c_{(S_i,S_j)}^t$. The number of faulty neighbors for any node $S_i \in S'$ is upper bounded by $(\lceil |N_{S_i}^t|/2 \rceil - 1)$. This is an implicit requirement for a conventional majority voting protocol [19,26,27] which is followed in the proposed algorithm.

3 Proposed Fault Diagnosis Algorithm

In this section, we describe the proposed fault diagnosis algorithm for WSNs. The algorithm executes in three phases. In the first phase (*comparison phase*), each fault-free node compares its sensor reading and residual energy level with that of the neighboring sensor nodes to classify them as fault-free, intermittently faulty, or permanently faulty.

In order to have global view of the network at each fault-free node, the local diagnostic views are to be disseminated. Flooding based approach is a trivial information exchange approach in WSNs. However, the biggest deficiency of this approach that makes it unsuitable for WSNs is *message implosion* problem [28,29]. To overcome this, several efficient flooding mechanisms and improvements have been proposed [30–43]. Threshold based flooding improvements (counter-based, distance-based, and location-based) are discussed in [30,31], where nodes decide whether to rebroadcast the flooding packet or not, depending on certain thresholds. In self-pruning, dominant pruning [32] and neighbor-coverage scheme [31], a node relays received packet only if it has neighbors not covered by previous forwarding nodes. Multipoint Relay (MPR) scheme [33–37] improves flooding efficiency by choosing a minimal set of neighbors, that covers all 2-hop neighbors of a node, for flooding. In [38], authors have discussed a Topology Broadcast based on Reverse-Path Forwarding (TBRPF) scheme where each node generates spanning tree (also called source tree) providing paths to all reachable nodes. Only the nonleaf nodes in the source tree, where the root is the source node, rebroadcasts the flood packet. However, maintenance of multiple source trees is complex. In cluster based flooding schemes [30], only the cluster heads and gateway nodes act as forwarding nodes. Ogier et al. [39] have discussed a Connected Dominating Set (CDS) based flooding in which MANET Designated Routers (MDRs) are responsible for flooding link state advertisements (LSAs). Adjacencies are formed only between MDRs or Backup MDRs and a subset of their neighbors to reduce flooding overhead. Some MDRs serve as Backup MDRs which provide flooding when neighboring MDRs fail. The set of MDRs forms a connected dominating set, and the set of MDRs and Backup MDRs forms a biconnected dominating set. Baccelli et al. [40] have discussed an overlay subgraph based on a Relative Neighbor Graph (RNG) scheme called Synchronized Link Overlay-Triangular (SLOT), with the objective to have low overlay link density, and low overlay link change rates. Authors have claimed SLOT to be efficient with respect to control traffic; thus useful in dense networks. Cordero et al. [41] have discussed the impact of jitter on flooding that reduces the number of packet collisions and the number of transmissions, but with increased delay. Although these approaches are improvements to blind flooding technique, but would incur more communication cost to achieve the objective of the proposed algorithm, i.e., to disseminate the local diagnostic views for generating global view at each fault-free node in the network. Another efficient dissemination scheme called RPL (Routing Protocol for Low-Power and Lossy Networks) is the key discussion in [42]. RPL organizes the topology as a set of one or more Destination Oriented Directed Acyclic Graphs (DODAGs) that are used for message dissemination.

The generation, and dissemination of global diagnosis view among fault-free nodes in the network requires a connected topology among them. This is possible with minimum $(n-1)$ number of edges, where n is the number of fault-free nodes. Therefore, we adapt a spanning tree (ST) based dissemination mechanism [17], similar to DODAGs in RPL, to have less communication complexity for dissemination. A distributed ST, rooted at a robust node (*initiator*), that overlays all fault-free nodes in the network is constructed during *building phase*. Here, the term *distributed* means no sensor has the complete ST information, rather each node in the tree keeps the information about its parent and the list of children.

In the last phase (*dissemination phase*), the ST is used to exchange the local and global diagnostics among the nodes. We discuss these phases in sequel.

3.1 Comparison Phase

Considering spatial correlation in sensor networks, the measurement difference of any 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 $x^t_{S_i}$ is the sensor measurement of node S_i at a given time t and $l^t_{(S_i, S_j)} \in L'^t$ then

$$|x^t_{S_i} - x^t_{S_j}| \begin{cases} \leq \delta_1, & \text{if both } S_i \text{ and } S_j \text{ are fault-free} \\ > \delta_1, & \text{otherwise.} \end{cases} \tag{6}$$

To aid the diagnosis process the residual energy levels of neighboring sensor nodes are also compared. In a homogeneous sensor network, the nodes in close proximity have similar level of residual energy since they do same duty [44,45]. Hence, if $E^t_{S_i}$ represents the residual energy of node S_i and $S_j \in N^t_{S_i}$ then

$$|E^t_{S_i} - E^t_{S_j}| \begin{cases} \leq \delta_2, & \text{if both } S_i \text{ and } S_j \text{ are fault-free} \\ > \delta_2, & \text{otherwise.} \end{cases} \tag{7}$$

In Eqs. (6) and (7), δ_1 and δ_2 are two predefined thresholds. These thresholds may vary depending on the application.

The residual energy comparison not only strengthens the diagnosis process, but also helps in detecting the malicious nodes that are compromised by Denial of Service (DoS) attacks, as faulty. This is due to the fact that such malicious nodes show abnormal energy consumption rate [46,47].

Now, the comparison outcome, $c^t_{(S_i, S_j)}$, of any two neighboring nodes S_i and S_j can be defined as follows

$$c^t_{(S_i, S_j)} = \begin{cases} 0, & \text{if } |x^t_{S_i} - x^t_{S_j}| \leq \delta_1 \text{ and } |E^t_{S_i} - E^t_{S_j}| \leq \delta_2 \\ 1, & \text{otherwise.} \end{cases} \tag{8}$$

In Eq. (8), $c^t_{(S_i, S_j)} = 0$ 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 array $Stat R_{S_i}[]$ of size n, to store the fault status of all the nodes in the network. Initially all 1-hop neighbors are assumed to be fault-free (0) and the status of all non-neighboring nodes are unknown (-1) as given in Eq. 9.

$$Stat R_{S_i}[j] = \begin{cases} -1, & \text{if } S_j \notin N^t_{S_i} \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

In each round, upto total of r rounds, each sensor node $S_j \in S'$ sends message of type DATA, containing its observed sensor reading and residual energy level, to $S_i \in N^t_{S_j}$ i.e. $m_{S_j} = (\text{DATA}, x^t_{S_j}, E^t_{S_j})$. Upon receiving such m_{S_j} from its neighbor S_j, node S_i performs the threshold test defined in Eq. (8) and increments $Stat R_{S_i}[j]$ by 1, if at least one of the test condition fails. At the end of r rounds, each sensor finds a local diagnosis view about the 1-hop neighbors. However, these local views may not be correct. Consider the following cases:

Algorithm 1: Comparison Phase

Data: $T = (S', L'^t)$: The test graph.
　　　　r: number of rounds.
Result: $Stat R_{S_i}[]$ for each fault-free node $S_i \in S'$
Initialization: NYF=0; NYF0=0; StatSum=0;

1　**for** *each $S_i \in S'$ and $S_j \in S'$* **do**
2　　　**if** $S_i == S_j$ *or* $l_{(S_i, S_j)} \in L'^t$ **then**
3　　　　　$Stat R_{S_i}[j] = 0$;
4　　　**else**
5　　　　　$Stat R_{S_i}[j] = -1$;
6　　　**end**
7　**end**
8　**for** *r rounds* **do**
9　　　**for** *each $S_j \in S'$ and $S_i \in N^t_{S_j}$* **do**
10　　　　　S_j sends a message $m_{S_j} = (\text{DATA}, x^t_{S_j}, E^t_{S_j})$;
11　　　**end**
12　　　**if** *a node S_i receives a message M from $S_j \in N^t_{S_i}$* **then**
13　　　　　**if** $|x^t_{S_i} - x^t_{S_j}| > \delta_1$ *or* $|E^t_{S_i} - E^t_{S_j}| > \delta_2$ **then**
14　　　　　　　Increment $Stat R_{S_i}[j]$;
15　　　　　**end**
16　　　**end**
17　**end**
18　Each node sends status array to its 1-hop and 2-hop neighbors;
19　**for** *each $S_i \in S'$; $S_j \in N^t_{S_i}$* **do**
20　　　**for** *each $S_k \in N^t_{S_j}$* **do**
21　　　　　**if** $Stat R_{S_i}[k] \leq 0$ **then**
22　　　　　　　Increment NYF;
23　　　　　　　**if** $Stat R_{S_k}[j] == 0$ **then**
24　　　　　　　　　Increment $NYF0$;
25　　　　　　　**end**
26　　　　　**end**
27　　　**end**
28　　　**if** $NYF0 \geq \lceil NYF/2 \rceil$ **then**
29　　　　　$Stat R_{S_i}[j] = 0$;
30
31　　　**else if** $Stat R_{S_i}[j] = 0$ **then**
32　　　　　$Stat R_{S_i}[j] = 1$;
33　　　**end**
34　　　**if** $Stat R_{S_i}[j] > 0$ **then**
35　　　　　**for** *each $S_k \in N^t_{S_j}$* **do**
36　　　　　　　$Stat Sum = Stat Sum + Stat R_{S_k}[j]$;
37　　　　　**end**
38　　　　　**if** $Stat Sum == (r \times |N^t_{S_j}|)$ **then**
39　　　　　　　$Stat R_{S_i}[j] = 2$;　　　　// $Stat R_{S_i}[j] = 2$ indicates S_j is permanently faulty.
40
41　　　　　**else**
42　　　　　　　$Stat R_{S_i}[j] = 1$;　　　　// $Stat R_{S_i}[j] = 1$ indicates S_j is intermittently faulty.
43　　　　　**end**
44　　　**end**
45　**end**

Case-I:

Node S_i may misdiagnose an intermittently faulty neighbor S_j as fault-free. This case arises if S_j sends similar sensor measurement and similar residual energy value to S_i in all rounds.

To overcome this situation, S_i follows majority voting among the decisions of all $S_k \in N^t_{S_j}$ about the fault status of S_j. However, the views of all nodes $S_k \in (N^t_{S_j} \cap N^t_{S_j})$ that are already

detected as faulty by S_i can be discarded to reduce the computation overhead. We consider the maximum number of neighbors to which S_j may send such similar values in all rounds is $\lceil n^+_{S_j}/2 \rceil - 1$, where $n^+_{S_j}$ represents the number of fault-free neighbors of S_j. Of course, this necessitates that each node sends the local view to its 2-hop neighbors. We follow conventional flooding for this, at a cost of $O(n \times d)$, where d is the average node degree (refer Theorem 3).

So S_i finds the set of neighbors of S_j that are not yet detected faulty by S_i. Let this set be denoted as $NYF^t_{(S_i,S_j)}$ and defined as in Eq. (10).

$$NYF^t_{(S_i,S_j)} = \{S_k | S_k \in N^t_{S_j} \text{ and } StatR_{S_i}[k] \leq 0\}. \tag{10}$$

Let $NYF0^t_{(S_i,S_j)} \subseteq NYF^t_{(S_i,S_j)}$ represents the set of neighbors of S_j in $NYF^t_{(S_i,S_j)}$ that have detected S_j to be fault-free i.e.

$$NYF0^t_{(S_i,S_j)} = \{S_k | S_k \in NYF^t_{(S_i,S_j)} \text{ and } StatR_{S_k}[j] = 0\}. \tag{11}$$

Now, S_i can follow majority voting and update its status array as follows:

$$StatR_{S_i}[j] = \begin{cases} 0, & \text{if } |NYF0^t_{(S_i,S_j)}| \geq \left\lceil \frac{1}{2}|NYF^t_{(S_i,S_j)}| \right\rceil \text{ and } StatR_{S_i}[j] \neq 0 \\ 1, & \text{if } |NYF0^t_{(S_i,S_j)}| < \left\lceil \frac{1}{2}|NYF^t_{(S_i,S_j)}| \right\rceil \text{ and } StatR_{S_i}[j] = 0. \end{cases} \tag{12}$$

In Eq. (12), the value 0 or 1 of $StatR_{S_i}[j]$ indicates S_j to be fault-free or intermittently faulty, respectively. Nevertheless, we can consider any positive value less than r to signify intermittent fault. Additionally, majority voting can cope with packet losses to certain extent. For instance, loss of packets in some rounds from a fault-free neighbor which affects the decision of S_i can be overridden.

Case-II:

Node S_i may misdiagnose an intermittently faulty neighbor S_j as permanently faulty. This case arises if S_j sends sensor measurement and residual energy value, either or both of which deviates significantly from that of S_i in all rounds.

To handle this situation and to determine the actual fault type, S_i follows Eq. (13) if $StatR_{S_i}[j] > 0$. The equation is based on the rationale that a permanently faulty node is always detected as faulty by all neighbors in all rounds.

$$StatR_{S_i}[j] = \begin{cases} 1, & \text{if } \left(\sum_{(S_k \in N^t_{S_j})} StatR_{S_k}[j] \right) \neq r \times |N^t_{S_j}| \\ 2, & \text{otherwise.} \end{cases} \tag{13}$$

The values 1 or 2 of $StatR_{S_i}[j]$ in Eq. (13) signifies S_j to be intermittently faulty or permanently faulty, respectively. The steps followed in this phase are more precisely described in Algorithm 1.

3.2 Building Phase

During this phase, messages of type SPANTREE are exchanged to construct a ST covering all fault-free nodes. This is initiated by a robust node called *initiator*. In general, a node S_j transmits $m_{S_j} = (\text{SPANTREE}, Parent_{S_j})$. If S_j is the initiator then $Parent_{S_j} = \phi$. Node S_i,

upon receiving the first SPANTREE message from $S_j \in N_{S_i}^t$, verifies from its local view if S_j is fault-free. After confirmation, S_i adds S_j in its children set if S_j has already chosen S_i as its parent i.e. $S_i = Parent_{S_j}$; otherwise, S_i chooses fault-free S_j as its parent in the ST, and intimates the same to its neighbors by sending its own SPANTREE message. These steps are precisely given in Algorithm 2.

Algorithm 2: Build Spanning Tree

Data: $T(S', L'^t)$: Test graph of WSN.
Result: Spanning Tree covering all fault-free nodes.
1   msg=SPANTREE message received from $S_j \in N_{S_i}^t$ i.e. $m_{S_j} = $ (SPANTREE, $Parent_{S_j}$)

2   **if** $StatR_{S_i}[j] == 0$ **then**
3   **if** $Parent_{S_i} == \phi$ and $S_i \neq initiator$ **then**
4       $Parent_{S_i} = S_j$;
5       $\_rb$(SPANTREE, $Parent_{S_i}$)
6
7   **else if** $S_i == Parent_{S_j}$ **then**
8       $Children_{S_i} = Children_{S_i} \cup \{S_j\}$;
9   **end**
10 **end**

3.3 Dissemination Phase

The objective of the *dissemination* phase is to generate global diagnostic view at each fault-free node by exchanging their local diagnostics. Once the ST is constructed, all leaf nodes start disseminating their local diagnostics to their parent.

A mobile node S_i handles two types of messages during *dissemination* phase.

(i) LOCALDIAGNOSTIC—After receiving such message from its child S_j *i.e. msg* = (LOCALDIAGNOSTIC, $StatR_{S_j}[]$), node S_i updates its local view to include the local view of S_j. Each mobile S_i maintains a set $ChildrenSentLD_{S_i}$, to keep track the list of children those have already sent their local diagnostics. S_i disseminates its local diagnostic only when all its children have sent their local views to it. However, if S_i is the initiator then it has deduced the global view, and starts disseminating it down the ST.
(ii) GLOBALDIAGNOSTIC—If S_i receives a GLOBALDIAGNOSTIC message from its parent S_j then it updates its status array to incorporate the global view, and subsequently broadcasts it to its children if it is not a leaf node.

Algorithm 3 shows the steps followed in this phase.

4 Analytical Study of Proposed FDA

In this section we follow mathematical analysis to prove the correctness and completeness of the proposed algorithm.

4.1 Proposed FDA Correctness

If every fault-free sensor $S_i \in S'$ deduces the correct state of all other sensors in the network, then the proposed FDA is said to be correct. This can be defined with respect to *correct local diagnosis* and *correct dissemination* of local and global diagnosis information. We define the following lemmas to support the correctness of the proposed FDA.

Algorithm 3: Dissemination Phase

    Data: $T(S', L'^t)$: Test graph of WSN.
           ST: Spanning Tree.
    Result: Each fault-free node S_i has the global diagnostic view.
1 **if** *($Children_{S_i} == \phi$)* **then**
2 | $-rb(m_{S_i} = (\text{LOCALDIAGNOSTIC}, StatR_{S_i}[]))$;
3 **end**
4 msg = Message received from mobile $S_j \in N^t_{S_i}$;
5 **switch** *($msg.Type()$)* **do**
6 | **case** LOCALDIAGNOSTIC: *// i.e. msg = (LOCALDIAGNOSTIC, $StatR_{S_j}[]$)*
7 | | **if** *($S_j \in Children_{S_i}$)* **then**
8 | | | Update $StatR_{S_i}[]$;
9 | | | $ChildrenSentLD_{S_i} = ChildrenSentLD_{S_i} \cup \{S_j\}$;
10 | | **end**
11 | | **if** *($ChildrenSentLD_{S_i} == Children_{S_i}$)* **then**
12 | | | **if** *($S_i \neq initiator$)* **then**
13 | | | | $-rb(m_{S_i} = (\text{LOCALDIAGNOSTIC}, StatR_{S_i}[]))$;
14 | | | **else**
15 | | | | $-rb(m_{S_i} = (\text{GLOBALDIAGNOSTIC}, StatR_{S_i}[]))$;
16 | | | **end**
17 | | **end**
18 | **end**
19 | **case** GLOBALDIAGNOSTIC:
20 | | **if** *($S_j == Parent_{S_i}$)* **then**
21 | | | Update $StatR_{S_i}[]$;
22 | | | $-rb(m_{S_i} = (\text{GLOBALDIAGNOSTIC}, StatR_{S_i}[]))$;
23 | | **end**
24 | **end**
25 **end**

Lemma 1 *Let $T = (S', L'^t)$ be the test graph for a sensor network, where S' and L'^t, respectively represents the set of sensor nodes without permanently faulty communication unit and the set of logical links between them at time t. If $S_j \in S'$ is an intermittently faulty node, then at the end of comparison phase, it is neither misdiagnosed as fault-free nor as permanently faulty by any other sensor node $S_i \in (N^t_{S_j} \cap FF^t)$; where $FF^t \subseteq S'$ is the set of fault-free nodes at time t.*

Proof In case, an intermittently faulty sensor node $S_j \in S'$ sends to $S_i \in (N^t_{S_j} \cap FF^t)$, similar sensor measurement and similar residual energy value in all rounds; S_i misdiagnoses S_j as fault-free. However, this misdiagnosis is resolved once S_i follows the majority voting defined in Eq. (12), after receiving the local views of all neighbors of S_j. The validation of Eq. (12) can be given as follows.

    If S_i finds any node $S_k \in N^t_{S_j}$ to be faulty then it discards the decision of S_k from voting. Hence, the maximum number of neighbors of S_j that may take part in voting is $|N^t_{S_j}|$. This case arises when none of the neighbors of S_j have been detected faulty by S_i. The minimum number of neighbors of S_j that may take part in voting is $\lfloor |N^t_{S_j}|/2 \rfloor + 1$. This case arises when S_j has maximum number of faulty neighbors i.e. $\lceil |N^t_{S_j}|/2 \rceil - 1$, and all of them are in the neighborhood of S_i and are correctly detected faulty by S_i. Hence,

$$\lfloor |N^t_{S_j}|/2 \rfloor + 1 \leq |NYF^t_{(S_i, S_j)}| \leq |N^t_{S_j}|. \tag{14}$$

The maximum number of fault-free neighbors that may detect S_j as fault-free is $\lceil$ (*minimum number of fault-free neighbors of* S_j)/2$\rceil - 1$ i.e.

$$|NYF0^t_{(S_i,S_j)}| \leq \left\lceil \frac{|\lfloor N^t_{S_j}|/2 \rfloor + 1}{2} \right\rceil - 1. \tag{15}$$

Now, consider a worst case scenario where $|NYF^t_{(S_i,S_j)}|$ is the minimum i.e. $\lfloor |N^t_{S_j}|/2 \rfloor + 1$ and $|NYF0^t_{(S_i,S_j)}|$ is the maximum i.e. $\left\lceil \frac{|\lfloor N^t_{S_j}|/2 \rfloor + 1}{2} \right\rceil - 1$. The condition $|NYF0^t_{(S_i,S_j)}| < \left\lceil \frac{1}{2}|NYF^t_{(S_i,S_j)}| \right\rceil$ holds. Hence, if S_i has misdiagnosed S_j as fault-free i.e. $StatR_{S_i}[j] = 0$, then it would update $StatR_{S_i}[j]$ to 1 (line 31, Algorithm 1); thus classifying S_j correctly as intermittently faulty.

It is also necessary to prove that S_i, after correctly diagnosing the intermittently faulty neighbor S_j, does not override its decision by subsequently following Eq. (13). This can be verified with the following reasoning.

The inequality

$$\left(\sum_{(S_k \in N^t_{S_j})} StatR_{S_k}[j] \right) \neq r \times |N^t_{S_j}|$$

holds, since there are non-zero number of fault-free neighbors of S_j that have correctly diagnosed S_j i.e. for some fault-free node $S_k \in N^t_{S_j}$, $0 < StatR_{S_k}[j] < r$. Therefore, $StatR_{S_i}[j]$ will remain unchanged. Hence, each node $S_i \in (N^t_{S_j} \cap FF^t)$ correctly diagnoses the state of an intermittently faulty neighbor S_j at the end of the comparison phase. □

Lemma 2 *Let S', the set of sensor nodes without permanently faulty communication unit and L'^t, the set of logical links between them at time t, collectively define an undirected graph $T = (S', L'^t)$, that represents the test graph of a sensor network. Let $FF^t \subseteq S'$ be the set of fault-free nodes in the network at time t. At the end of the comparison phase, the status of a fault-free node S_j is correctly detected by each node $S_i \in (N^t_{S_j} \cap FF^t)$.*

Proof It is clear from Eqs. (6) and (7) that a fault-free node $S_j \in S'$ can be misclassified as faulty by a node $S_i \in \{N^t_{S_j} \cap FF^t\}$, if S_j sends to S_i: its sensor measurement and residual energy value, either or both of which deviates significantly from that of S_i in at least one round. Nevertheless, by definition, a fault-free node always sends similar sensor measurement and never gives significantly different remaining energy value compared to its neighbors. So S_j can never fail any of the threshold tests performed by S_i in Eqs. (6) and (7), in any round. Hence, it is properly classified as fault-free by all $S_i \in (N^t_{S_j} \cap FF^t)$. Moreover, this decision is not affected by the majority voting. The reasoning is as follows.

For each node $S_i \in (N^t_{S_j} \cap FF^t)$, the inequality in Eq. (14) holds and the explanation is the same as given in Lemma 1. The minimum number of neighbors, out of those participated in voting, that have correctly identified S_j as fault-free can be given as in Eq. (16).

$$|NYF0^t_{(S_i,S_j)}| \geq \left(\left\lfloor |N^t_{S_j}|/2 \right\rfloor + 1 \right). \tag{16}$$

From Eqs. (14) and (16), it can easily be verified that,

$$|NYF0^t_{(S_i,S_j)}| \not< \left\lceil \frac{1}{2}|NYF^t_{(S_i,S_j)}| \right\rceil. \tag{17}$$

So the majority voting in Eq. (12) would not affect the decision of S_i about its fault-free neighbor S_j. Furthermore, Eq. (13) is followed by S_i if $StatR_{S_i}[j] > 0$. So it cannot alter the value of $StatR_{S_i}[j]$ in this case. Therefore, a fault-free node S_j is always diagnosed as fault-free by each node $S_i \in (N^t_{S_j} \cap FF^t)$ at the end of the comparison phase. □

Lemma 3 *Let the test graph of a sensor network be represented as $T = (S', L'^t)$; where S' is the set of sensor nodes having fault-free communication unit and L'^t is the set of logical links among them at time t. Let $FF^t \subseteq S'$ represents the set of fault-free nodes at time t. If a node S_j is having permanently faulty sensor, then it is neither diagnosed as fault-free nor as intermittently faulty by any node $S_i \in (N^t_{S_j} \cap FF^t)$.*

Proof By convention, a node S_j with permanently malfunctioning sensor gives wrong sensor readings to all its neighbors, in all rounds. A node $S_i \in \{N^t_{S_j} \cap FF^t\}$ increments $StatR_{S_i}[j]$ by one, upon receiving wrong sensor readings from S_j, in each round. So at the end of r rounds, $StatR_{S_i}[j]$ carries the value r. It can easily be seen, as follows, that the majority voting does not alter this decision. The inequality in Eq. (14) holds due the same reasoning as described in Lemma 1, and $|NYF0^t_{(S_i,S_j)}| = 0$. Hence, it is clear that

$$|NYF0^t_{(S_i,S_j)}| < \left\lceil \frac{1}{2}|NYF^t_{(S_i,S_j)}| \right\rceil, \tag{18}$$

since all fault-free neighbors of S_j have properly identified it and two faulty nodes never give the same incorrect readings. However, Eq. (12) does not alter $StatR_{S_i}[j]$ since $StatR_{S_i}[j] \neq 0$, i.e., because S_j is permanently faulty.

It is also important to validate Eq. (13) for this scenario. For permanently faulty node S_j,

$$\left(\sum_{(S_k \in N^t_{S_j})} StatR_{S_k}[j] \right) = r \times |N^t_{S_j}|$$

holds, due to the fact that each $S_k \in N^t_{S_j}$, irrespective of whether it is faulty or not, has $StatR_{S_k}[j] = r$ at the end of diagnosis. So, $StatR_{S_i}[j]$ is set to a value 2, signifying it as permanently faulty. Hence, it can be concluded that S_j; a node with permanently faulty sensor is always diagnosed correctly by any node $S_i \in (N^t_{S_j} \cap FF^t)$. □

Lemma 4 (Correct Local Diagnosis View). *In an undirected graph, $T = (S', L'^t)$ that represents the test graph of a sensor network, where S' is the set of sensor nodes without permanently faulty communication unit and L'^t is the set of logical links among them at time t, let $FF^t \subseteq S'$ represents the set of fault-free in the network at time t. If a node S_j is fault-free, it is never misdiagnosed as faulty, and if it is faulty with certain fault type (permanent or intermittent), then it is neither misclassified as fault-free nor as a wrong fault type by any other node $S_i \in (N^t_{S_j} \cap FF^t)$.*

Proof The proof of Theorem 1 directly follows from Lemma 1, 2, and 3. Referring Lemma 2, if a node S_j is fault-free, then it is always diagnosed as fault-free by any fault-free node in $N^t_{S_j}$. Lemma 1 asserts that, if S_j is an intermittently faulty node then it is never classified as fault-free, nor as permanently faulty by any other node $S_i \in (N^t_{S_j} \cap FF^t)$. Again, the permanently faulty nodes are always detected as permanently faulty by all fault-free neighbors, that is vouched by Lemma 3. □

Lemma 5 *Let the test graph of a sensor network be represented as $T = (S', L'^t)$; where S' is the set of sensor nodes having fault-free communication unit and L'^t is the set of logical links among them at time t. At the end of the building phase, the ST contains all and only fault-free nodes in the network.*

Proof It is clear from Lemma 4 that each fault-free node obtains correct local view. In the building phase, SPANTREE messages from the faulty nodes can be discarded by the fault-free sensors after confirming the same from their local views. This eliminates any faulty node from becoming a member of the ST.

Furthermore, the subgraph generated from T excluding all faulty nodes is connected. So, each fault-free node receives SPANTREE messages and broadcasts its own, after choosing its parent. Thus, all fault-free nodes become part of the ST. Hence, the ST contains all and only fault-free nodes. □

Lemma 6 *Let the undirected graph, $T = (S', L'^t)$ represents the test graph of a sensor network, where S' is the set of sensor nodes without permanently faulty communication unit and L'^t is the set of logical links among them at time t. At the end of the dissemination phase, each node in the ST has the global view of the network.*

Proof Given that nodes are able to verify if they are leaves of the ST, all leaves start dissemination of their local views to their parents. A non-leaf node collects the local views of all its children and combines them with its own to generate an aggregated view, which is then transmitted to it parent up in the ST. Once the root node collects the aggregated views of all it children, it then generates the global diagnostic view. The root disseminates the global view to its children, which is then relayed to the nodes in the subsequent levels in the tree. In this way, correct dissemination of the global view is achieved. □

Theorem 1 (Proposed FDA Correctness) *In an undirected graph, $T = (S', L'^t)$ represents the test graph of a sensor network, where S' is the set of sensor nodes without permanently faulty communication unit and L'^t is the set of logical links among them at time t, let $FF^t \subseteq S'$ represents the set of fault-free in the network at time t. At the end of the diagnosis, each node $S_i \in FF^t$ has the consistent global diagnostic view of the network.*

Proof The proof of this theorem follows Lemma 4, 5, and 6. Lemma 4 asserts that the local diagnosis view of any node $S_i \in FF^t$ is correct. According to Lemma 6, these local views are properly disseminated to the root of the ST. Subsequently the global view generated at the root is disseminated to all nodes in the ST. Moreover, the ST overlays all and only fault-free nodes, which is proved in Lemma 5. Therefore, each node $S_i \in FF^t$ has the consistent global diagnostic view of the network, at the end of the diagnosis session. □

4.2 Proposed FDA Completeness

The proposed diagnosis algorithm is said to be complete if no node in the network is left undiagnosed, and the proof can be given as in Theorem 2.

Theorem 2 (Proof of Completeness) *Let the test graph of a sensor network is represented as an undirected graph $T = (S', L'^t)$, where S' is the set of sensor nodes with good communication unit and L'^t is the set of logical links among them at time t. If a node $S_i \in S'$, then at the end of the fault diagnosis session, $S_i \in (FF^t \cup F_P^t \cup F_I^t)$ i.e. $S' = (FF^t \cup F_P^t \cup F_I^t)$, where $FF^t \subseteq S'$, $F_P^t \subset S'$, and $F_I^t \subset S'$ respectively represent the set of fault-free, permanently faulty, and intermittently faulty nodes in the network at time t.*

Proof From Lemma 1 and 3 it is clear that, if a node S_i is faulty, then at the end of the fault diagnosis session, $S_i \in F_P^t$ *(if S_i is permanently faulty)* or $S_i \in F_I^t$ *(if S_i is intermittently faulty)*. Lemma 2 conveys that, if S_i is fault-free then $S_i \in FF^t$, at the end of the fault diagnosis session. Hence, it can be concluded that, if $S_i \in S$ then $S_i \in (FF^t \cup F_P^t \cup F_I^t)$; thus $S' = (FF^t \cup F_P^t \cup F_I^t)$ at the end of the fault diagnosis session.   □

Theorem 3 *The communication complexity of the proposed FDA is $O(n(r + d))$, where n is the number of nodes in the network, r is the number of rounds, and d is the average node degree.*

Proof In the worst case scenario, all the nodes in the network are fault-free. The message complexity of each phase of the algorithm can be found as follows.

(i) *Comparison phase*—Each node sends its sensor measurement and residual energy value for r rounds. So the total number of DATA messages is $n \times r$. Each node broadcasts it local view to its 1-hop and 2-hop neighbors. Total number of such broadcasts is $n \times (d + 1)$, where d is the average node degree. This stems from the fact that each node broadcasts its local view, and subsequently all 1-hop neighbors broadcast the received local view to make it available at 2-hop neighbors of the sender.

(ii) *Building phase*—Each node sends SPANTREE message once. Hence, total number of messages exchanged during the construction of the ST is n.

(iii) *Dissemination phase*—Each node, except the *initiator*, sends the LOCALDIAGNOSTIC message. So, total number of LOCALDIAGNOSTIC message exchanged is $n - 1$. Each node, except the leaves, sends transmits GLOBALDIAGNOSTIC message once. The maximum number of such message exchange is $n - 1$, and this case arises when the depth of the ST is $n - 1$.

Thus, the total number of messages exchanged during diagnosis is $n(r + d + 4) - 2$, and the communication complexity is $O(n(r + d))$.   □

5 Simulation Analysis

The performance evaluation of the proposed FDA is presented in this section. A set of simulations are performed using the Castalia-3.2 simulator on OMNET++ platform, to study the feasibility of the proposed algorithm. The results are compared with that of the detection algorithm discussed by Lee and Choi [21].

Based on the faulty behavior, the proposed FDA classifies the sensor nodes into three different classes: permanent fault class, intermittent fault class, and fault-free class. The following two performance measures are used as the evaluation metrics.

- Classification Accuracy (CA): The ratio of the number of nodes classified into a particular class to the total number of nodes of that class. Hence, CA is defined with respect to each of the three classes mentioned above.
- 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.

FAR is defined with an observation that the severity of a fault-free node being misdiagnosed as faulty or a faulty node as fault-free is more, as compared to a permanently faulty node being misdiagnosed as intermittently faulty or vice-versa.

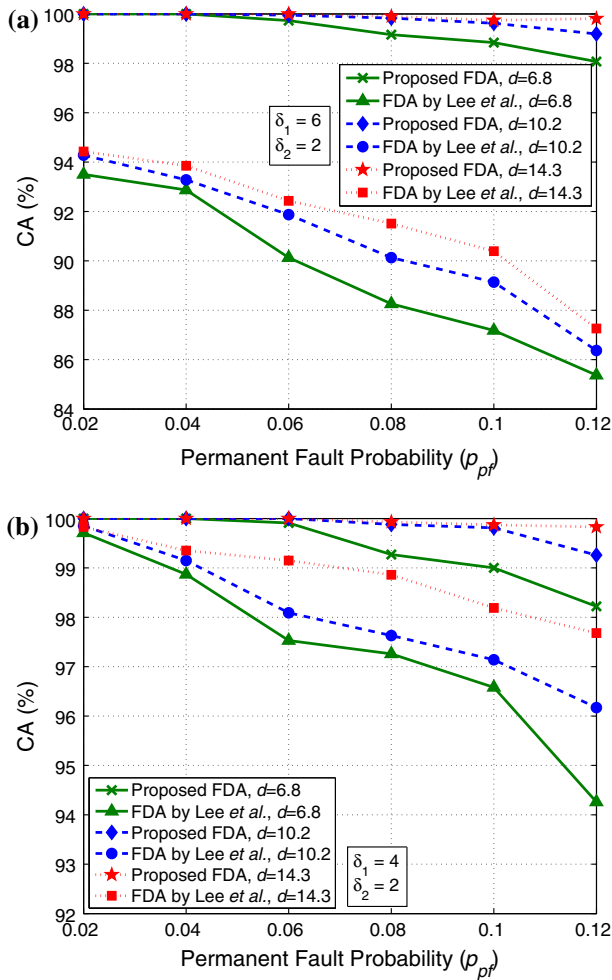The performance of the proposed algorithm depends on many factors *viz.*

Fig. 1 Comparison of permanent fault CA with **a** $\delta_1 = 6$, $\delta_2 = 2$ and **b** $\delta_1 = 4$, $\delta_2 = 2$

- d—the average node degree.
- p_{pf}—the probability that a sensor node has a permanently faulty sensor.
- p_{if}—the probability that a sensor node has an intermittently faulty sensor.
- p_{fc}—the probability that a sensor node has a faulty communication unit.
- δ_1, δ_2—thresholds used.

The following two simulation scenarios are considered for discussion.

5.1 Simulation Scenario 1

The first simulation scenario is created for a sensor network with 1,000 nodes randomly deployed over $1,000 \times 1,000 \, \mathrm{m}^2$ area. With proper adjustment of the transmission range (common for all nodes), the desired value of d can be obtained. In the simulation, the sensor nodes are randomly chosen to have permanently faulty sensors with probabilities 0.02, 0.04,
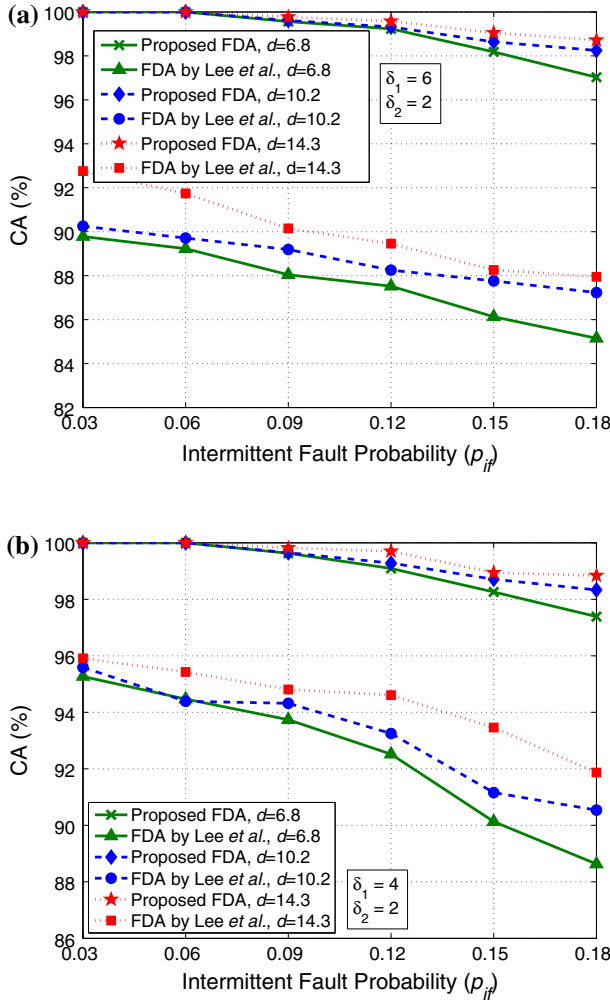
Fig. 2 Comparison of intermittent fault CA with **a** $\delta_1 = 6, \delta_2 = 2$ and **b** $\delta_1 = 4, \delta_2 = 2$

0.06, 0.08, 0.10 and 0.12, respectively. It is also considered that p_{if} is 150 % of p_{pf}, in each case.

The values of the thresholds δ_1, and δ_2 are considered 6 and 4, respectively. In order to evaluate Lee and Choi's algorithm, the same simulation scenario is considered with $\theta_1 = \lceil d/2 \rceil$, and $(r - \theta_2) \simeq \hat{\theta}_2 = 2$ 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 are compared as depicted in Figs. 1a, 2a, 3a, and 4a.

5.2 Simulation Scenario 2

The second simulation scenario is created with same fault percentage as in scenario 1. However, the thresholds δ_1, and δ_2 are considered to have values 4 and 2, respectively. The values
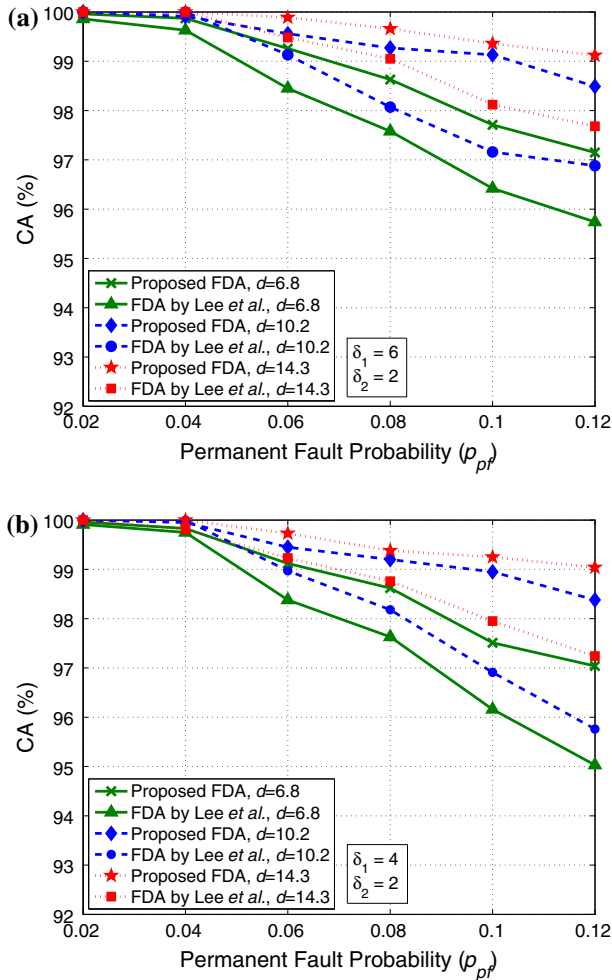
Fig. 3 Comparison of fault-free CA with **a** $\delta_1 = 6$, $\delta_2 = 2$ and **b** $\delta_1 = 4$, $\delta_2 = 2$

of the parameter in Lee and Choi's algorithm are the same as in first simulation scenario. Figures 1b, 2b, 3b, and 4b shows the obtained results for CA, and FAR in this scenario.

5.3 Discussion

It can clearly be observed that the CA decreases with lower node degrees. This is because the fault-free sensor nodes may not always form a connected graph for fault diagnosis purpose, in case of sparse networks. 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.

Figure 1 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. Moreover,
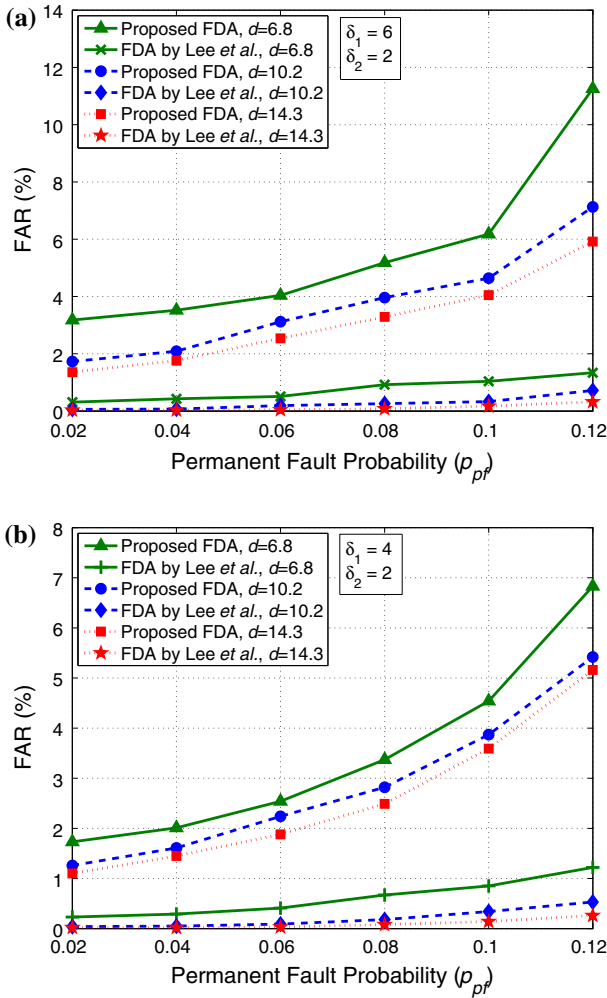
Fig. 4 Comparison of false alarm rates with **a** $\delta_1 = 6$, $\delta_2 = 2$ and **b** $\delta_1 = 4$, $\delta_2 = 2$

high value of δ_1 boosts the occurrence of such scenarios. 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 and Choi.

Fault-free nodes are diagnosed with better accuracy for high value of δ_1. If the value of δ_1 is chosen to be small, and in some rounds a fault-free node generates sensor measurements that differs from the sensor measurements of its neighboring nodes by the minimum threshold δ_1, then it will not be diagnosed as fault-free by its neighbors. Such miss-classification scenarios are suppressed in the proposed FDA by the additional energy based threshold test.

The comparison of false alarm rates are clearly shown in Fig. 4. As obvious, it is found that with increase in fault probability, FAR increases. Moreover, the FAR is high for high

value of $\delta_1(=4)$ as compared to low value of $\delta_1 = (2)$; with respect to the same value of $\delta_2(=2)$ in both cases.

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

6 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 proposed FDA not only diagnoses the faulty sensor nodes, also classifies those based on their fault types. The algorithm is based 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 handled: One, where an intermittently faulty node sends similar sensor measurement and similar residual energy value to some of its neighbors in all rounds; Another, where at least one of these values are dissimilar in all rounds. Through mathematical analysis the proposed FDA has been proved to be correct and complete. The simulation experimental results show 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.

References

1. Preparata, F. P., Metze, G., & Chien, R. T. (1967). On the connection assignment problem of diagnosable systems. *IEEE Transactions on Electronic Computers*, *EC–16*(6), 848–854.
2. Barsi, F., Grandoni, F., & Maestrini, P. (1976). A theory of diagnosability of digital systems. *IEEE Transactions on Computers*, *25*(C–6), 585–593.
3. Kuhl, J. G., & Reddy, S. M. (1980). Distributed fault-tolerance for large multiprocessor systems. In *Proceedings of the 7th annual symposium on computer architecture, ISCA'80* (pp. 23–30). ACM.
4. Hakimi, S. L., & Amin, A. T. (1974). Characterization of connection assignment of diagnosable systems. *IEEE Transactions on Computers*, *C–23*(1), 86–88.
5. Xu, J., & Lilien, L. (1987). A survey of methods for system-level fault diagnosis. In *Proceedings of the 1987 fall joint computer conference on exploring technology: today and tomorrow* (pp. 534–540). Silver Spring: IEEE Computer Society Press.
6. Somani, A. K. (1997). *System level diagnosis: A review*. Technical Report,Lowa State University.
7. Malek, M. (1980). A comparison connection assignment for diagnosis of multiprocessor systems. In *Proceedings of the 7th annual symposium on computer architecture, ISCA'80* (pp. 31–36). ACM.
8. Chwa, K., & Hakimi, S. L. (1981). Schemes for fault-tolerant computing: A comparison of modularly redundant and t-diagnosable systems. *Information and Control*, *49*(3), 212–238.
9. Chessa, S., & Santi, P. (2001). Comparison-based system-level fault diagnosis in ad hoc networks. In *Proceedings of the 20th IEEE symposium on reliable distributed systems* (pp. 257–266).
10. Elhadef, M., Boukerche, A., & Elkadiki, H. (2006). Diagnosing mobile ad-hoc networks: Two distributed comparison-based self-diagnosis protocols. In *Proceedings of the 4th ACM international workshop on mobility management and wireless access, MobiWac'06* (pp. 18–27). ACM.
11. Elhadef, M., Boukerche, A., & Elkadiki, H. (2008). A distributed fault identification protocol for wireless and mobile ad hoc networks. *Journal of Parallel and Distributed Computing*, *68*(3), 321–335.
12. Guerraoui, R., & Schiper, A. (1996). Fault-tolerance by replication in distributed systems. In *Proceedings of the 1996 Ada-Europe international conference on reliable software technologies* (pp. 38–57). Berlin: Springer.
13. Jaikaeo, C., Srisathapornphat, C., & Shen, C. (2001). Diagnosis of sensor networks. *IEEE International Conference on Communications*, *5*, 1627–1632.

14. Lee, W. L., Datta, A., & Cardell-oliver, R. (2006). *Winms: Wireless sensor network-management system, an adaptive policy-based management for wireless sensor networks*. Technical Report, The University of Western Australia.

15. Ruiz, L. B., Siqueira, I. G., Oliveira, L. B., Wong, H. C., Nogueira, J. M. S., & Loureiro, A. A. F. (2004). Fault management in event-driven wireless sensor networks. In *Proceedings of the 7th ACM international symposium on modeling, analysis and simulation of wireless and mobile systems, MSWiM'04* (pp. 149–156). ACM.

16. Ding, M., Chen, D., Xing, K., & Cheng, X. (2005). Localized fault-tolerant event boundary detection in sensor networks. In *Proceedings of the 24th annual joint conference of the IEEE computer and communications societies (INFOCOM'05)* (Vol. 2, pp. 902–913).

17. Chessa, S., & Santi, P. (2002). Crash faults identification in wireless sensor networks. *Computer Communications*, *25*, 1273–1282.

18. Hsin, C., & Liu, M. (2006). Self-monitoring of wireless sensor networks. *Computer Communications*, *29*(4), 462–476.

19. Chen, J., Kher, S., & Somani, A. (2006). Distributed fault detection of wireless sensor networks. In *Proceedings of the 2006 workshop on dependability issues in wireless ad hoc networks and sensor networks, DIWANS'06* (pp. 65–72). ACM.

20. Khilar, P. M., & Mahapatra, S. (2007). Intermittent fault diagnosis in wireless sensor networks. In *10th international conference on information technology (ICIT'07)* (pp. 145–147).

21. Lee, M., & Choi, Y. (2008). Fault detection of wireless sensor networks. *Computer Communications*, *31*(14), 3469–3475.

22. Yu, M., Mokhtar, H., & Merabti, M. (2007). Fault management in wireless sensor networks. *IEEE Wireless Communications*, *14*(6), 13–19.

23. Diop, M., Pham, C., & Thiare, O. (2013). 2-Hop neighborhood information for cover set selection in mission-critical surveillance with wireless image sensor networks. In *IFIP wireless days (WD)* (pp. 1–7).

24. Krontiris, I., Benenson, Z., Giannetsos, T., Freiling, F., & Dimitriou, T. (2009). Cooperative intrusion detection in wireless sensor networks. In *Wireless sensor networks, volume 5432 of lecture notes in computer science* (pp. 263–278). Berlin: Springer.

25. Mallery, C. J., Medidi, S., & Medidi, M. (2008). Relative localization with 2-hop neighborhood. In *International symposium on a world of wireless, mobile, and multimedia, networks* (pp. 1–4).

26. Parhami, B. (1991). Voting networks. *IEEE Transactions on Reliability*, *40*(3), 380–394.

27. Parhami, B. (1994). Voting algorithms. *IEEE Transactions on Reliability*, *43*(4), 617–629.

28. Heinzelman, W. R., Chandrakasan, A., & Balakrishnan, H. (2000). Energy-efficient communication protocol for wireless microsensor networks. In *Proceedings of the 33rd annual Hawaii international conference on system sciences* (pp. 1–10).

29. Heinzelman, W. R., Kulik, J., & Balakrishnan, H. (1999). Adaptive protocols for information dissemination in wireless sensor networks. In *Proceedings of the 5th annual ACM/IEEE international conference on mobile computing and networking, MobiCom'99* (pp. 174–185).

30. Ni, S.-Y., Tseng, Y.-C., Chen, Y.-S., & Sheu, J.-P. (1999). The broadcast storm problem in a mobile ad hoc network. In *Proceedings of the 5th annual ACM/IEEE international conference on mobile computing and networking, MobiCom'99* (pp, 151–162). ACM.

31. Tseng, Y.-C., Ni, S.-Y., & Shih, E.-Y. (2003). Adaptive approaches to relieving broadcast storms in a wireless multihop mobile ad hoc network. *IEEE Transactions on Computers*, *52*(5), 545–557.

32. Lim, H., & Kim, C. (2001). Flooding in wireless ad hoc networks. *Computer Communications*, *24*(34), 353–363.

33. Qayyum, A., Viennot, L., & Laouiti, A. (2000). Multipoint relaying: An efficient technique for flooding in mobile wireless networks, INRIA Report.

34. Qayyum, A., Viennot, L., & Laouiti, A. (2002). Multipoint relaying for flooding broadcast messages in mobile wireless networks. In *Proceedings of the 35th annual Hawaii international conference on system sciences, HICSS'02* (pp. 3866–3875).

35. Baccelli, E., Cordero, J. A., & Jacquet, P. (2009). Multi-point relaying techniques with OSPF on ad hoc networks. In *Fourth international conference on systems and networks, communications, ICSNC'09* (pp. 53–62).

36. Baccelli, E., Jacquet, P., & Clausen, T. (2009). OSPF multipoint relay (MPR) extension for ad hoc networks, RFC 5449.

37. Baccelli, E., Cordero, J. A., & Jacquet, P. (2010). Ospf over multi-hop ad hoc wireless communications. *International Journal of Computer Networks and Communications*, *2*(5), 37–56.

38. Ogier, R., Templin, F., & Lewis, M. (2004). Topology dissemination based on reverse-path forwarding (TBRPF), RFC 3684.

39. Ogier, R., & Spagnolo, P. (2009). Mobile ad hoc network (MANET) extension of OSPF using connected dominating set (CDS) flooding, RFC 5614.
40. Baccelli, E., Cordero, J. A., & Jacquet, P. (2010). Optimization of critical data synchronization via link overlay RNG in mobile ad hoc networks. In *7th IEEE international conference on mobile adhoc and sensor systems* (pp. 402–411).
41. Cordero, J. A., Jacquet, P., & Baccelli, E. (2012). Impact of jitter-based techniques on flooding over wireless ad hoc networks: Model and analysis. In *IEEE INFOCOM* (pp. 2059–2067).
42. Winter, T., Thubert, P., Brandt, A., Hui, J., Kelsey, R., Levis, P., et al. (2012). RPL: IPv6 routing protocol for low-power and lossy networks, RFC 6550.
43. Yi, Y., & Gerla, M. (2003). Efficient flooding in ad hoc networks: A comparative performance study. In *Proceedings of the IEEE international conference on communications (ICC)* (pp. 1059–1063).
44. Zhao, Y. J., Govindan, R., & Estrin, D. (2002). Residual energy scan for monitoring sensor networks. *IEEE Conference on Wireless Communications and Networking*, *1*, 356–362.
45. Ding, M., Chen, D., Xing, K., & Cheng, X. (2005). Localized fault-tolerant event boundary detection in sensor networks. In *Proceedings of the 24th annual joint conference of the IEEE computer and communications societies* (Vol. 2, pp. 902–913).
46. Chen, R., Hsieh, C., & Huang, Y. (2010). An isolation intrusion detection system for hierarchical wireless sensor networks. *Journal of Networks*, *5*(3), 335–342.
47. Shen, W., Han, G., Shu, L., Rodrigues, J. J. P. C., & Chilamkurti, N. (2012). A new energy prediction approach for intrusion detection in cluster-based wireless sensor networks. In *Lecture notes of the institute for computer sciences, social informatics and telecommunications engineering* (pp. 1–12). Berlin: Springer.

Manmath Narayan Sahoo received his M.Tech. degree in Computer Science in 2009 from National Institute of Technology Rourkela. He is an Assistant Professor in the Department of Computer Science and Engineering, National Institute of Technology Rourkela, India. He is a reviewer in Journal of Computing (Springer), the Guest Editor of Special issue on "Advances in Information Systems and Network Systems Security" (Innovations in Systems and Software Engineering, Springer). His research interests include Mobile Ad hoc Networks, Fault Tolerance, and Sensor Networks.

Pabitra Mohan Khilar received his Ph.D. in Computer Science in 2009 from Indian Institute of Technology, Kharagpur. He is an Assistant Professor in the Department of Computer Science and Engineering, National Institute of Technology Rourkela, India. His research interests include Distributed and Parallel Computing, Fault Tolerant Systems, Wireless Networks and VLSI design.