Journal of Network and Computer Applications 36 (2013) 1174–1185

Contents lists available at SciVerse ScienceDirect

Journal of Network and Computer Applications

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

Fault tolerance in wireless sensor network using hand-off and dynamic power adjustment approach

D.D. Geeta [a,*], N. Nalini [b], Rajashekhar C. Biradar [a]

[a] Department of Electronics and Communication Engineering, Reva Institute of Technology and Management, Bangalore 560 064, India
[b] Department of Computer Science and Engineering, Nitte Meenakshi Institute of Technology and Management, Bangalore, India

ARTICLE INFO

Article history:
Received 5 August 2012
Received in revised form
21 December 2012
Accepted 6 February 2013
Available online 19 February 2013

Keywords:
Wireless sensor networks
Fault tolerance
Active node

ABSTRACT

Wireless Sensor Network (WSN) is deployed to monitor physical conditions in various places such as geographical regions, agriculture lands, office buildings, industrial plants and battlefields. WSNs are prone to different types of failures due to various environmental hazards like interference and internal failures (such as battery failure, processor failure, transceiver failure, etc). In such a situation, the sensed data cannot be transmitted correctly to the data center and the very purpose of deploying WSNs is not effective. Since it is difficult to monitor the network continuously through a manual operator, the nodes in WSN need to be capable of overcoming the failures and transmit the sensed data in proper order to the data center. Sensor network should be designed such that it should be able to identify the faulty nodes, try to rectify the fault and be able to transmit the sensed data to data center under faulty condition of a network and thereby make the network fault-free and thus enhance the fault tolerant capability.

In this paper, we propose a novel idea of an Active node based Fault Tolerance using Battery power and Interference model (AFTBI) in WSN to identify the faulty nodes using battery power model and interference model. Fault tolerance against low battery power is designed through hand-off mechanism where in the faulty node selects the neighboring node having highest power and transfers all the services that are to be performed by the faulty node to the selected neighboring node. Fault tolerance against interference is provided by dynamic power level adjustment mechanism by allocating the time slot to all the neighboring nodes. If a particular node wishes to transmit the sensed data, it enters active status and transmits the packet with maximum power; otherwise it enters into sleep status having minimum power that is sufficient to receive hello messages and to maintain the connectivity. The performance evaluation is tested through simulation for packet delivery ratio, control overhead, memory overhead and fault recovery delay. We compared our results with Fault Detection in Wireless Sensor Networks (FDWSNs) for various performance measures and found that AFTBI outperforms compared to the results of FDWSN.

1. Introduction

Wireless Sensor Networks (WSNs) are emerging as computing and communication platforms for monitoring various environments such as remote geographical regions, office buildings and industrial plants (Lee and Choi, 2008). The applications of WSNs are in various areas ranging from environment monitoring to battlefield scenarios. Sensor networks are composed of a large number of tiny sensor nodes equipped with limited computing and communication capabilities.

Each sensor node in WSN typically comprises of four units as shown in Fig. 1. They are as follows. (a) *Sensor unit* consists of a sensor to sense the environmental conditions such as temperature, pressure, humidity, etc. The sensed parameters are converted into digital form using ADC (Analog Digital Converter). (b) *Processor unit* includes a processor such as microcontroller and memory. (c) *Transceiver unit* includes wireless radio transmitter and receiver sections and (d) *Power unit* uses batteries that provide necessary power to remaining units. Each sensor node is operated by a battery, and usually, it is not feasible to replace or recharge this battery after deployment. The useful operational period or the lifetime of a sensor network is considered over as soon as the battery power of the critical nodes in the network is completely depleted (Bari et al., 2012).

Sensor nodes are used for monitoring environmental conditions such as temperature, pressure, humidity, fog, rainfall, smoke, etc.

* Corresponding author. Tel.: +91 80656878563.
E-mail addresses: geetha_dd2005@yahoo.com (D.D. Geeta), nalinaniranjan@gmail.com (N. Nalini), raj.biradar@revainstitution.org (R.C. Biradar).

1084-8045/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jnca.2013.02.005

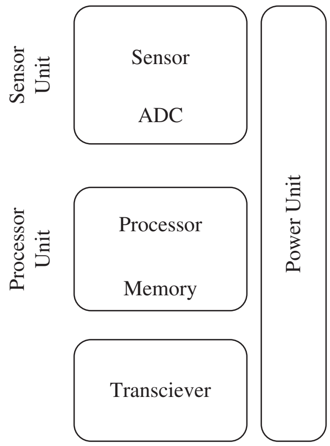

Fig. 1. Components of a typical sensor node.

These environmental conditions are monitored by exchanging the information among sensor nodes that are in the coverage area with the help of communication protocols. Communication protocols designed to exchange such information among the nodes of a sensor network should be designed to adapt to the dynamic conditions of either fixed topology or changing topology of a network depending upon the application for which the network is designed.

In the application scenario described above, there is a prime requirement to make the operation of a network without any type of disturbances. The disturbances in WSN are triggered by various reasons such as network failure, connectivity failure, node failure, link failure, unavailability of network due to misbehaving nodes that lead to inefficient functioning of the network. It is necessary to identify such faults in a network and fix them appropriately.

1.1. Causes of faults in WSN

It is obvious that sensor networks are vulnerable to failures mainly because of two reasons such as node failures and/or communication failures. Since low-cost sensor nodes are often deployed in an uncontrolled or even harsh environment, they are prone to have faults. A deployed sensor network may suffer from many faults due to several reasons such as environmental impacts, hardware defects, and software bugs (Chen et al., 2012). These faults can cause high loss rates, long transmission delays or even network disconnection, and hence severely affects the normal operations of the network. Consequently, failures of nodes become an inevitable phenomenon which can reduce dramatically the overall network lifetime and make the communication infrastructure unusable (Challal et al., 2011).

There is a need to design an effective architecture and techniques to monitor the health of the network and quickly detect such faults. It is thus desirable to detect, locate the faulty sensor nodes, and exclude them from the network during normal operation unless they can be used as communication nodes (Chitnis et al., 2009). One of the effective methods to identify and locate the faults in a network is to monitor the status of every node in the network, whether the node is in active or inactive status. Primary components to assess whether a node is in active or inactive state are its battery power level and interference effects from its neighbor nodes.

In this paper, we propose an Active node based Fault Tolerance using Battery power and Interference model (AFTBI) in WSN where the node active condition is arrived at by considering battery power and interference. Based on these models, we propose fault tolerance solutions to retain the proper functioning of the network and hence enhance the network lifetime.

1.2. Related works

Some of the related works are as follows. The work given in Lee and Choi (2008) proposes FDWSN—a distributed algorithm for detecting and isolating faulty sensor nodes in wireless sensor networks. Nodes with malfunctioning sensors are allowed to act as a communication node for routing, but they are logically isolated from the network as far as fault detection is concerned. It employs local comparisons of sensed data between neighbors and dissemination of the test results to enhance the accuracy of diagnosis. Transient faults in communication and sensor reading are tolerated by using time redundancy. Faulty nodes are isolated by correctly identifying fault-free nodes. Both the network connectivity and accuracy of diagnosis are taken into account since fault-free nodes isolated might be of little or no use even if they are determined to be fault-free, unless they can participate in the network via intermediate communication nodes with faulty sensors.

A tree-based aggregation techniques to detect faults in sensor network is proposed in Chitnis et al. (2009). A fault model identifies failure traits and the tree aggregation is analyzed with fault model. Redundant trees are removed by rebuilding or locally fixing the tree. The cost-benefit analysis is made using the hash functions. A fault-tolerant mechanism using out-of-band monitoring for WSN (Chen et al., 2012) uses some of the nodes as monitor nodes placed so that all sensor nodes are monitored. For smaller networks, Integer Linear Programming (ILP) problem is formulated for large networks, approximation and heuristic algorithms are used. The work given in Bari et al. (2012) proposes two-tier sensor network architecture, where some relay nodes are used as cluster heads with higher power. The relay nodes are resilient to node failures. Placement strategy for the relay nodes is based on ILP problem that assigns the sensor nodes to the clusters. Load-balanced routing scheme provides fault tolerance for both the sensor nodes and the relay nodes and enhances network lifetime by limiting the maximum energy consumption of the relay nodes.

The work in Challal et al. (2011) proposes intrusion–fault tolerant routing scheme that offers better reliability through a secure multipath routing construction. The protocol is based on a distributed and in-network verification scheme without the intervention of base station. Multipath selection is employed to enhance the tolerance of the network and conserve the energy. In the consensus problem algorithm proposed in Hsieh et al. (2010) divides all sensors into different autonomous local networks, where all the nodes perform corresponding actions without the help of sink nodes which solves the single-point of failure problem and reduces the hopping process time. The proposed consensus based algorithm also improved the decision result even when the sensor fault and transmission media fault exist simultaneously.

The work given in Feng et al. (2011) proposes a fault tolerant data aggregation protocol that updates aggregation and reschedules the aggregation process after a node is out of service. Data is aggregated according to the basic aggregation scheduling strategy. The amendment strategy starts after a middle sensor node is out of service. Some properties of the original aggregation tree will be lost due to the change of aggregation path after the amendment. The amendment strategy consists of aggregation tree amendment strategy and aggregation rescheduling strategy. The work given in Zhaoa et al. (2011) proposed a fault diagnosis mechanism for WSNs. The diagnosis model consists of probabilistic analysis of the local and global performances of approach. In this model, every node and its neighbor nodes form a cluster. The diagnosis mechanism is updated and operates in four sessions: (1) start a diagnosis session, (2) testing session,

(3) comparison session and (4) dissemination session. The work in Kashyap et al. (2011) proposed relay placement for fault tolerance wherein a small number of additional relay nodes are added to a network of static nodes with limited communication range so that the induced communication graph is 2-connected. The work in Sa de Souza (2007) proposes a framework to improve fault tolerance in heterogeneous WSNs that satisfies six major requirements such as extensibility, transparency, support to heterogeneous WSNs, identify crash, omission, value and arbitrary failures, isolate failures, provide automatic recovery techniques. Group fault detection is used to identify, outlier readings and crash failures.

The work in Anurag and Somprakash (2008) proposes a probability based routing algorithm that merges the structure of a hierarchical tree with the flexibility of AODV (Ad hoc On Demand Distance Vector Routing). When new devices join a network, they are given an address to satisfy the hierarchical property. When hierarchical property is disturbed, a route table entry, similar to AODV, is created for this non-conforming node. This route table entry is also created when a node/link fails thus preventing other nodes from having to change their addresses or depth. The mechanism of making route table entries has inherent support for fault tolerance.

The work in Gupta and Younis (2003) proposes a run-time recovery mechanism based on consensus of healthy gateways to detect and handle faults in one faulty gateway. A two-phased detection and recovery mechanism is proposed to limit the performance impacts caused by a gateway failure. The work in Aslanyan and Rolim (2010) proposes a polynomial time approximation algorithm which finds a connected network with the minimal interference of the given network. The work in Xu et al. (2007) proposes channel surfing to reduce interference, where the sensor nodes adapt their channel assignments to restore network connectivity in the presence of interference. Two different approaches are discussed in channel surfing: (1) co-ordinated channel switching, where the entire sensor network adjusts its channel and (2) spectral multiplexing, where nodes in a jammed region switch channels while nodes on the boundary of a jammed region act as radio relays between different spectral zones.

The work in Fussen (2004) proposes Nearest Component Connector (NCC) algorithm, which produces at most $O(\log n)$ interference in any network in polynomial time compared to any topology Control algorithm which constructs a resulting network with least interference. The concept of topology control confines interference by having the network nodes reduce their transmission power levels and drop long-range connections in a coordinated way. At the same time, transmission power is reduced in a controlled manner in order to preserve connectivity of the network.

In Hassan and Abuhaiba (2011), an Interference-Aware Connected Dominating Set-based topology construction algorithm (IACDS) algorithm is proposed, which has distributed, interference-aware and energy-efficient topology to find a sub-optimal Connected Dominating Set (CDS). IACDS algorithm utilizes a weighted (distance-energy-interference)-based metric that permits the network operator to trade-off the lengths of the branches (distance) for the robustness and durability of the topology. The work given in Yoon et al. (2010) proposes an Adaptive Channel Hopping (ACH) mechanism to avoid interference from other sources and narrow-band jamming. During interference, ACH allows sensors to switch to a new operating channel. ACH reduces the channel scanning and selection latency by ordering available channels using link quality indicator measurements and weights.

The work given in Hassan and Chickadel (2011) proposes graph theoretical model to reduce interference. A graph coloring methods are used to model the interference reduction problem. To reduce the collisions and signal interference, the problem is modeled as a coloring problem on the interference graph. Nodes of different colors in the graph will be assigned separate channel of radio frequency. Effective channel selection method that lowers the wireless interference is obtained by efficient coloring algorithms.

A fault tolerance execution model by using of mobile agents to obtain consistent and correct performance with a required function for a specified period of time is proposed in Qu et al. (2009). Failures are classified into two intrinsic different effects on mobile agents. For each kind of failure, a specific handling method is adopted. The introduction of exceptional handling method allows performance improvements during mobile agents execution. The behaviors of mobile agents are analyzed through several key parameters, including the migration time from node to node, the life expectancy of mobile agents, and the population distribution of mobile agents, to evaluate the performance.

The work given in Guo et al. (2012) proposes Hybrid On-demand Distance Vector Multi-path (HODVM) routing protocol for Spatial Wireless Ad Hoc (SWAH) networks that divides SWAH into backbone and non-backbone networks to perform static and dynamic routing. To provide load balancing, HODVM adaptively establishes and maintains multiple node-disjoint routes by multi-path routing. HODVM provides better performance in terms of scalability, survivability and load balancing.

Optimal cluster size minimization to reduce energy consumption in WSN is proposed in Amini et al. (2012) where all sensor nodes communicate data through their elected cluster heads to the base station. The paper compares three cluster based protocols such as LEACH, LEACH-Coverage, and DBS that do not require centralized support from a certain node. Energy consumption in each case is analyzed.

Some of the related works have been compared in Table 1 with proposed AFTBI in terms of fault/interference model, overheads, delay, and efficiency.

Above mentioned works performed the fault analysis in WSN by considering only either battery power or interference and none of them considered the integrated approach of battery power and interference. Our proposed AFTBI uses integrated model of battery power and interference to find active nodes in WSN thereby eliminating all possible types of faults in WSN and enhance the network lifetime.

Table 1
Comparison of few fault analysis protocols.

Protocol	Fault/interference model	Overheads	Delay	Efficiency
[1]	Transient sensor fault detection and finding communication faults	Moderately high	High	Moderate
[2]	Tree based aggregation	High	Moderate	Low
[6]	Many small autonomous networks	High	High	Moderate
[9]	Additional relay nodes	Very high	High	Moderately low
[14]	Channel switching to reduce interference	High	Low	Low
[18]	Color based graph segregation	Low	Low	Moderate
AFTBI (Proposed work)	Integrated power and interference model	Moderately high	Less	High

1.3. Our contributions

Our contributions in this paper are as follows. (a) Modeling node active status to identify node faults using the parameters such as battery power of a node and interference. (b) Designing fault tolerant mechanisms based on node battery power and interference. (c) Initiation of hand-off mechanism to a neighboring node whenever a node battery power reduces. (d) Dynamic power level adjustment of neighboring nodes if not involved in communication. (e) Performance evaluation of AFTBI for Packet Delivery Ratio (PDR), control overhead and fault recovery delay are analyzed. (f) Comparison of simulation results of AFTBI with FDWSN.

The rest of the paper is organized as follows. Section 2 discusses the active node model to identify faulty nodes along with an algorithm for assessing active node status. In Section 3, we described the fault tolerant mechanism using redundancy provisioning, Section 4 discusses the simulation environment, its procedure, parameters and results are discussed in Section 5. Section 6 concludes the paper.

2. Active node model for wireless sensor networks

Fault tolerance in wireless sensor networks may be arrived through monitoring and analyzing node conditions which primarily requires finding the status of a node as whether the node is active or inactive. The number of active nodes in a network defines the fault tolerance level of the network wherein the active state of every node contributes to the network survivability. The proposed active node model is based upon identifying the number of nodes that are in active state in a given period of time. The *active state of a node* is defined as state vector (n_a) and is represented as

$$n_a = [b_p, I] \tag{1}$$

where b_p is the battery power of a sensor node and I is the interference component due neighboring nodes. Active state of a node is defined by the node condition in which it is able to be sensed in its coverage area and it is able to transmit the signal to its neighbors effectively. We can correlate these conditions with reference to some conditions imposed by coefficients of state vector such as α and γ given as

$$n_a = [\alpha b_p, \gamma I] \tag{2}$$

Eq. (2) is defined with the condition that $\alpha + \gamma = 1$, where $0 < \alpha < 1$ and $0 < \gamma < 1$. We consider that the node is in active state if the individual components of n_a are above the pre-decided thresholds. The models for the components of n_a are given by battery power model and interference model.

2.1. Battery power model

The battery power model is derived based on the sensor node's battery condition. This model assumes that the node is active if the battery power level is sufficient for smooth functioning of the node. The node is effectively functioning if it is able to transmit the signal effectively within its coverage area. As the battery power of a node varies due various reasons, it is necessary to assess the battery power in a time window in which the battery power is assumed to be fairly constant. The time window may dynamically vary depending upon the environmental effects. For convenience of representation, we assume that the time windows are fixed as shown in Fig. 2.

Let b_f be the full battery power at the beginning of the first time window $t=0$ and later, it is represented by b_i, where

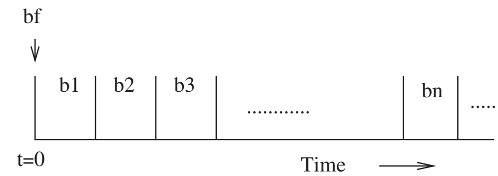

Fig. 2. Time window for battery power model.

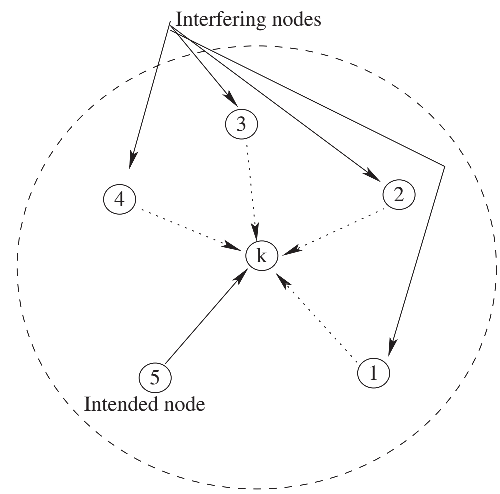

Fig. 3. Interference model.

$i = 1,2,3,\ldots n$ as shown in Fig. 2. For any window k, the battery power of a node b_k is given by

$$b_k = \begin{cases} b_f - b_{drain_k} & \text{for active } k\text{th window} \\ b_f & \text{for inactive windows} \end{cases} \tag{3}$$

and update $b_f = b_k$. The node is active if $b_k \geq b_{th}$, b_{th} is the threshold level of a battery power beyond which the node cannot transmit the signals. In Eq. (3), b_{drain_k} represents the battery drain in kth duration. The threshold level b_{th} is dynamically adjusted by the administrator as per the requirement.

2.2. Interference model

The node active status is also affected by assessing whether the effective communication is possible with its neighboring nodes. Effective communication is possible when a node receives better signals from its neighbors. This fact helps us in defining signal to interference ratio S/I. For this purpose, we need to consider the received signal from one of its neighbors and the signal from the rest of the neighbors operating in the same frequency range as an interference. Assume that all the neighbors transmit the same average power and the received signal at the node of interest is S. We use the model given in Rappaort (2004) to find the S/I ratio as

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{N-1} I_i} \tag{4}$$

where S is the signal power received at a node k from its intended neighbor node, I is the sum of interfering signal power from the rest of the neighboring nodes. $N-1$ is the number of neighboring nodes. The intended neighboring node is the one which has relevant data to be transmitted to the node k. Eq. (4) represents the interference caused due to all the neighboring nodes (nodes 1 to 4) except the intended node (node 5) at node k as shown in Fig. 3.

Assuming that an interference signal from node i is inversely proportional to distance, we consider a path loss component p that contributes to the signal degradation and thus an Eq. (4) can be written as

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{N-1} d_i^{-p}} \tag{5}$$

where d_i is the distance between node k and its ith neighbor node which is given by an Euclidean distance $d_i = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$, with (x_1, y_1) and (x_2, y_2) as the coordinate values of two nodes. The interference caused at a node due to several neighbors is the function of the distances d_i, where $i = 1,2,3,..$ are the neighbors.

3. Fault tolerance against battery power drain and interference

The fault tolerance in sensor network against battery power drain and interference due to neighboring nodes is arrived whenever there is a link failure between any two communicating nodes. The battery power model and interference model presented in Sections 2.1 and 2.2 helps us to devise a scheme that re-establishes the communication of a failed link. In this section, we discuss the hand-over mechanism for link failure against battery power drain and dynamic power level adjustments of neighboring nodes to overcome interference effects.

3.1. Hand-off mechanism for battery power drain

The link failure of a communicating node (here after, this node is called as faulty node) occurs due to the reduction of its battery power level beyond b_{th} in active time window as shown in Fig. 2. Fault tolerance for such a link failure is addressed by monitoring battery power level of a faulty node and providing an alternate path for a failed link so as to maintain the connectivity of a failed link. To obtain better fault tolerance, hand-off mechanism is suitable for WSN where in the faulty nodes are avoided without losing the information that is delivered to such nodes. In order to enhance the PDR and fault tolerance capability of WSN, we use hand-off mechanism that leads to reduce power required to recover the data from failed nodes. Our effort in the proposed work is to enhance the number of active nodes in network so as to provide better fault tolerance capability.

Whenever a faulty node identifies that its battery power level reduces towards b_{th}, i.e., if $b[k] \le b_{th}$ (where $b[k]$ represents kth time window), it initiates connection hand off to its neighbor node. The connectivity hand off comprises of transmitting the hand off parameters with neighboring node having highest battery power. The faulty node collects the battery power status of all its neighboring nodes. The collection of battery power has two following phases: (1) In the first phase, it sends a battery power request packet to all its neighbors. (2) In the second phase, all the neighbor nodes send reply packet that includes their respective current battery power level. Request/reply packets are simple type of ''hello'' message transfers.

The faulty node transmits the connectivity hand off parameters to the node having highest battery power. The parameters that are transmitted by the faulty node are as follows: *source node address*, *sink node address*, *previous hop address*, *next hop address* and *time-stamp*. The neighbor node having highest battery power uses these parameters and sets up a route to the next hop neighbor and re-establishes the connection. The connection hand off procedure is given in Algorithm 1.

Nomenclature: $b[k]$ is the battery power of a faulty node in kth time window, b_f the full battery power of a node, b_{th} the battery power threshold constant, n the number of neighbor nodes, RQ the Request packet, RP the Reply packet, b_{ph} the highest battery power.

Algorithm 1. Connection Hand-off.

```
b[k] ← b_f;
b_th = a constant;
for k = 1 to n in steps of 1 do
  if b[k] < b_th then
    Send RQ packets to all n−1 neighbors except next hop neighbor;
    Receive RP packets from all n−1 neighbors;
    for i = 1 to n−1 do
      if b_p[i] > b_p[i+1] then
        b_ph = b_p[i];
        Send connection hand-off parameters to node i;
        Node i establishes a connection from previous hop node to next hop node;
      end if
    end for
  end if
end for
```

Node i uses all the connection parameters to establish a connection from previous hop node to next hop node.

3.2. Dynamic power level mechanism for interference

The interference model discussed in Section 2.2 assumes that all the neighboring nodes including the intended node transmit the signal with same power. The meaning of interference with respect to two neighboring nodes B and A is defined as the node B interfere with another node A if B's interference range unintentionally covers the node A. When a particular node is interfered by many nodes then the quality of the signal it receives from intended node is naturally degraded and the packets transmitted by this node cannot be received properly. Since the transmitted power of a node is directly proportional to the coverage area, the transmission radius r is assigned to each node to make it connected and at the same time to minimize the maximum number of overlapping transmission ranges on each node of a network as shown in Fig. 4.

To reduce interference signal, we use dynamic power level mechanism where the power of a node is adjusted automatically depending on whether the node is in active state or in sleep state.

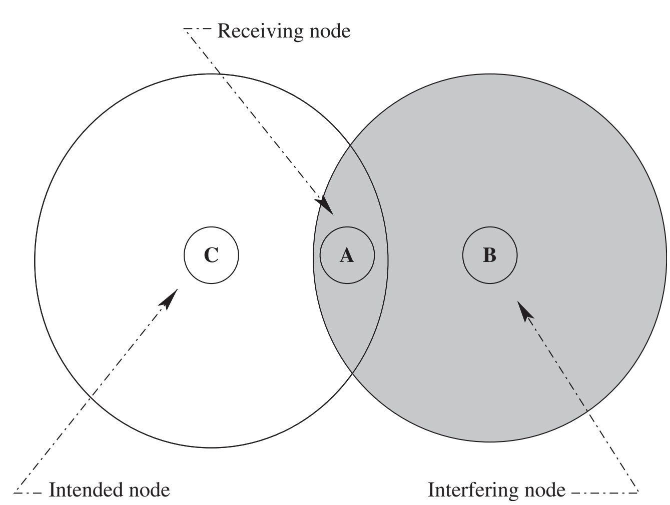

Fig. 4. Equal transmission power: signal overlapping.

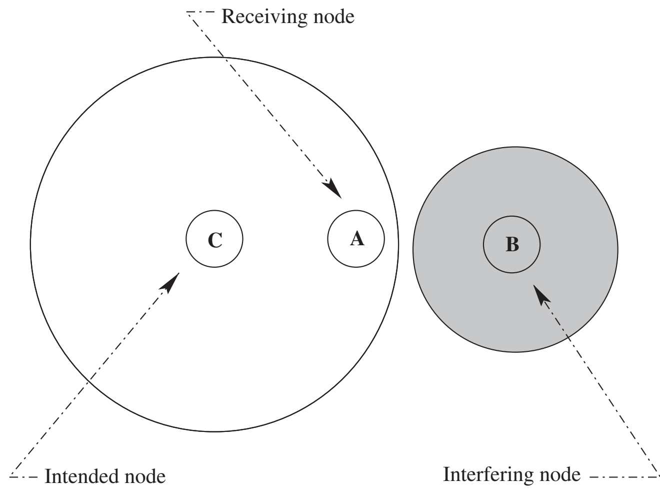

Fig. 5. Unequal transmission power: no signal overlapping.

The node is said to be in active state if it wishes to transmit a packet and it is in sleep state if it is waiting to receive the packet. It is assumed that while transmitting a packet in active state, it does so with maximum power and while the node receives the packet, it receives in sleep state with minimum power. The minimum power level is sufficient to maintain the link connectivity. For example, the interference signal from a node B is reduced compared to the signal from the intended node C on A as shown in Fig. 5 and the node B operates in minimum power level.

The dynamic node power adjustment of neighboring nodes reduce the overlapping interference effects at a node irrespective of their distances d_i. The effect of simultaneous transmissions can be avoided if the nodes are allowed to transmit only within a time slot. The time slot allocation is initiated by the receiving node that operates in the following steps. (1) At the beginning of time slot, the receiving node allocates fixed time slots to each neighbor during which the nodes are allowed to transmit. (2) First slot is allocated to the intended node and the subsequent slots are allocated to each neighboring nodes in clockwise direction. (3) If a node within its allocated time slot happens to send the packet, it can send the packet or if it does not have any packet to send, it should be kept in sleep status. (4) The time slots allocated on round robin basis, i.e., every node gets a turn to transmit the packet for one complete cycle of neighbors. (5) The current time slot used by an active node is made known to all the remaining nodes. (6) The node transmitting in a current time slot should operate in active status with maximum transmission power and the remaining nodes are in sleep status thereby reducing the interference effect.

With dynamic power adjustment, the interfering node is in sleep state and the interference signal I_{id} from such a node is always less than the interfering signal I without dynamic power adjustment. Hence the signal to interference ratio S/I with dynamic power adjustment is given by

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{N-1} I_{id}} \tag{6}$$

This mechanism reduces the interference due to neighbor nodes since $\sum_{i=1}^{N-1} I_{id} < \sum_{i=1}^{N-1} I_i$, where $\sum_{i=1}^{N-1} I_i$ is the denominator of Eq. (4). The dynamic power adjustment is shown in the flowchart in Fig. 6.

The scenario for reduction in interference may be illustrated for the network topology shown in Fig. 7, where the node 1 has 4 neighboring nodes (nodes 2, 3, 4 and 5) and the node 6 is an intended node. We wish to reduce the interference of all 4 neighboring nodes and receive only the signal from the intended node 6. Node 1 allocates time slots to each neighboring nodes and every node is permitted to transmit the packets in allocated time slot switching to maximum power level, else the nodes are switched to minimum power level mode. In case, if a node does not have any packet to transmit in the currently allocated time slot, it remains in a minimum power level mode. Effectively, the node 6 is able to transmit to node 1 with less interference.

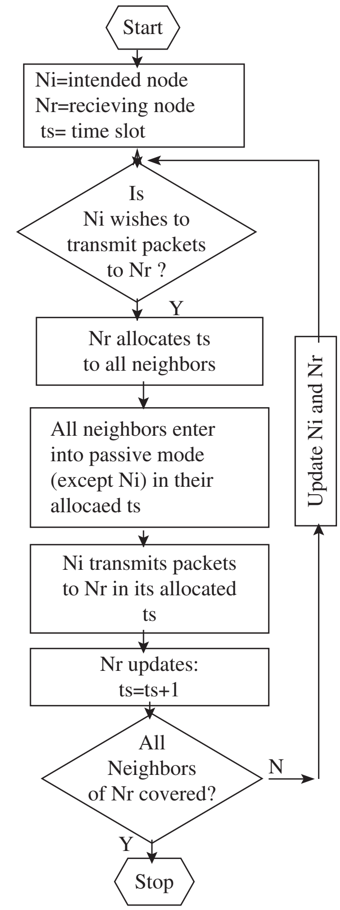

Fig. 6. Interference suppression.

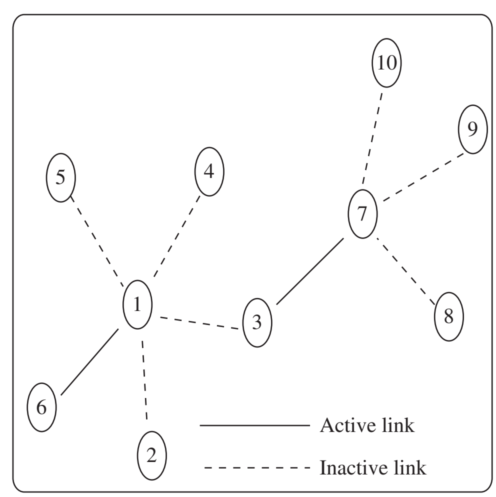

Fig. 7. Example: dynamic power level adjustment.

The problem that may arise if any of the neighboring nodes (say, node 3) other than intended node has a packet to transmit to its another node (say, node 7). Now, node 7 allocates time slots to all its neighbors (nodes 3, 8, 9, 10). Node 3 has two different time slot allocations, i. e., one time slot allocation by node 1 and another time slot allocation by node 7 (overlapping pattern of transmission). If these two time slots allocated at node 3 are synchronized, then we can achieve minimal in interference; otherwise, the interference is above the minimum achievable level (since node 3 has overlapping pattern of transmission). The interference above the minimum level is dependent upon how many neighboring nodes have overlapping pattern of transmission. The worst case would occur when all the neighboring nodes are transmitting simultaneously to their different neighbor nodes other than intended nodes.

3.3. *Power and interference models integrated*

The fault tolerance mechanism in WSN to enhance the lifetime of the network is effectively realized under following cases. (1) Optimal triggering of hand-off mechanism to a neighbor node having highest power whenever the power level reduces beyond a threshold and (2) Switching the node to sleep status of the non-intended node to reduce the interference. Optimal triggering the hand off mechanism is controlled by the parameter α and switching to sleep status is controlled by the parameter γ. Both the parameters α and γ are monitored and controlled by the system administrator. The integrated model to enhance the total number of active nodes in WSN against node failures due to node's battery power drain or node failures due to neighboring node interference. For example, when there are large number of node failures due to battery power drain, α is kept at the higher value and when the nodes experience higher interference, γ is kept at higher value. The objective is to keep the maximum number of nodes in active status under node battery power drain and interference. The integrated fault tolerance mechanism in WSN operates as per the flowchart given in Fig. 8.

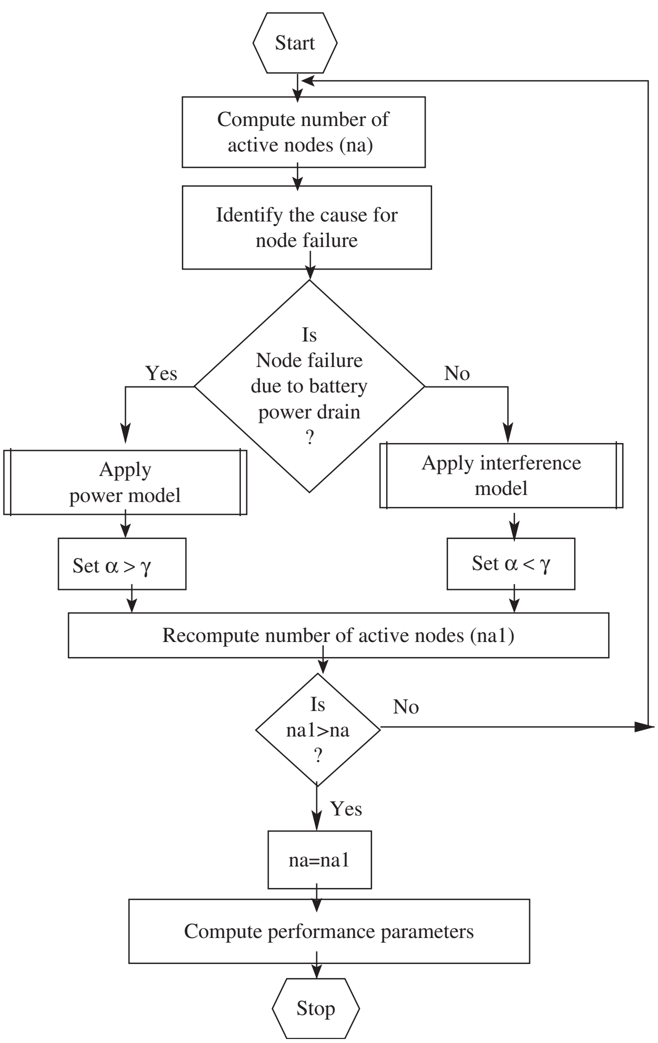

Fig. 8. Flow diagram of integrated power and interference model.

Table 2
Fault recovery database.

Faulty node address	Neighbor nodes	Transmitted power (mW)	Time stamp
192.123.53.4	192.123.53.5	0.44	2012-07-07 06:02:3
	192.123.53.6	1.23	2012-07-07 06:02:7
	192.123.53.12	0.81	2012-07-07 06:02:52
	192.123.53.8	0.32	2012-07-07 06:02:9
	192.123.53.20	0.41	2012-07-07 06:02:4

3.3.1. *Fault recovery database*

The Fault Recovery Database (FRD) is the average amount of additional memory required to store fault recovery related information on the nodes affected during the active node based fault recovery mechanism. The nodes involved in fault recovery operation are the neighbor nodes of a faulty node. The components of FRD are power level of each node involved in fault recovery operation and the time stamp at which the neighbor node transmits the signal. A typical FRD entries for a scenario is shown in Table 2.

For example, a faulty node 192.123.53.4 stores the information in FRD such as its neighbor node addresses, power transmitted by the neighbor nodes and the time stamp of transmitted signal from each of the neighbors. Time stamp is necessary to identify the valid neighbor node since the time stamp confirms a node's validity as neighbor if a signal received within a time stamp bound. For a given time stamp bound, one can easily identify a neighbor as valid if its time stamp is well within a bound. For example, for a given time stamp bound of 50 s, all the neighbor nodes are valid neighbor nodes except the node 192.123.53.12 since its time stamp exceeds the required bound. Excluding such neighbor nodes reduces various overheads and thus decreases the fault recovery time in WSN.

4. Simulation model

The fault tolerant scheme is simulated in various network scenarios to assess the performance and effectiveness of the approach. Event driven simulation is used in which the execution of various functions takes place at discrete events in a chronological sequence. Simulation environment for the proposed work consists of five models: (1) Network model, (2) Battery power model, (3) Interference model, (4) Propagation model and (5) Traffic model. The models are discussed below.

- *Network model*: A sensor network is generated in an area of $l \times b$ square meters. It consists of N number of mobile nodes that are assumed to be connected to a base station at the boundary of a network.

- *Battery power model*: Every node has its full battery power b_f at the beginning of a time window and there is a battery drain of b_{drain} at the end of every time window. The node is in active status in a particular time window until the battery power reduces beyond a threshold b_{th}.
- *Interference model*: Signal power S and interference power I received at a node are used to find the signal to interference ratio. With dynamic power adjustment, the non-interfering node will be in sleep state and the signal received from such a node is I_{id}.
- *Propagation model*: Free space propagation model is used with propagation constant β. Transmission range of a node is r for a one-hop distance.
- *Mobility model*: We use random way-point (RWP) mobility model based upon three parameters; speed of movement, direction and time of mobility. In RWP, each node picks a random destination within a geographical area, and travels with an average velocity v and node pause time Z. Eight directions are considered for node movement: east, west, north, south, north–east, north–west, south–east and south–west.
- *Traffic model*: Constant bit rate model is used to transmit fixed size packets, Tr_{pkts}. Coverage area around each node has a bandwidth, $BW_{single\text{-}hop}$, shared among its neighbors.

4.1. Simulation procedure

The proposed scheme is simulated using the following simulation inputs. $l=1000$ m, $b=1000$ m, $N=[50–200]$, $b_f=4$ mW, $b_{drain}=[0.01$ mW per packet], $b_{th}=0.1$ mW, $\beta=3.0$, $r=350$ m, $v=[0$ to 24 m/s], $Z=0.1$ ms, $Tr_{pkts}=$ multiples of 1000, $BW_{single\text{-}hop}=20$ Mbps.

Simulation procedure involves following steps.

1. Generate sensor network environment: The nodes are randomly deployed in a fixed area and the topology changes for every instant defined by simulation inputs. Within certain interval, the performance evaluation is carried out.
2. Set a time window and monitor the battery power within a window. Compare the battery power with threshold value.
3. In case if the battery power is reducing below its threshold value, use hand-off algorithm to transfer the connection hand-off to a neighbor node having highest battery power.
4. Apply the interference model using dynamic power adjustment scheme.
5. Compute performance parameters of the system: Performance parameters are assessed and plotted with different variables.

The following performance parameters are assessed.

- *Packet Delivery Ratio* (*PDR*): It is defined as the number of packets received at destination to the number of packets sent from a source.
- *Control overhead*: It is defined as number of control packets needed to identify the faulty nodes and implement the fault tolerance models to nullify the effect of faulty nodes in a network and hence improve the performance.
- *Memory overhead*: It is the average number of bytes required to be stored in FRD of all the nodes that are involved in fault recovery mechanism.
- *Fault recovery delay*: It is the average time taken to recover from the effect of a faulty node. It is defined by

$$\textit{Fault recovery delay} = \sum_{j=1}^{j=k} (d_h + d_i)_j \tag{7}$$

where d_h is the average delay incurred due to hand-off to a neighboring node in case of node power depletion and d_i is the delay incurred due to dynamic interference suppression and k is the number of neighboring nodes.

5. Results

The simulation is carried out on Pentium IV machine using 'C' language. The analysis of performance parameters are given in this section.

5.1. Analysis of Packet Delivery Ratio (PDR)

The assessment of PDR with number of nodes for active node based fault tolerance (with node transmission power set to 2 mW) is shown in Fig. 9 for three cases: (1) before node failures, (2) after node failures (due to either battery power drain or due to

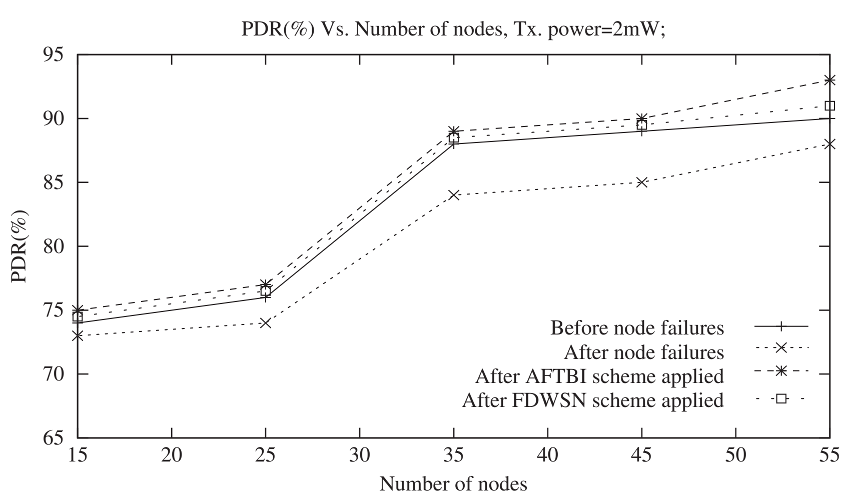

Fig. 9. PDR vs. number of nodes, transmission power=2 mW.

interference from neighbor nodes or both) and (3) after applying the proposed AFTBI scheme. In case (1), it is assumed that there are no node failures or all the active nodes are working in a good condition without having the influence of battery power drain and neighbor node's interference. We have reasonable PDR achieved for this case. Some of the node failures occur due to the drain in node battery power and neighbor node interference and hence the PDR drops in case (2) compared to the case (1). Case (3) shows an improvement in PDR since the number of active nodes is increased and dropped packets are recovered with hand-off mechanism in proposed power model and reduction of interference. Thus, the third case PDR in AFTBI is greater than or almost equivalent to the first case. For all three cases, we observe that there is an improvement in PDR with increase in the number of nodes. This is due to the increase in better connectivity with increase in the number of nodes since the node density improves with number of nodes in a given area. We observe the PDR for AFTBI is better than FDWSN because the later uses transient phase for fault detection where in the faulty nodes are involved in communication and it does not consider node failures due to interference. In AFTBI, once the set of active nodes are identified the routes becomes stable and hence PDR is improved.

Figure 10 shows the improvement in PDR when the node transmitted power is increased to 4 mW. This improvement is achieved because the number of active nodes is increased which in turn increases the difference between the battery power threshold b_{th} and maximum power of a node in AFTBI. The increase in the number of active nodes improves the PDR. For a similar threshold in FDWSN, PDR is less compared to AFTBI because FDWSN involves several iterations of comparing neighbor node parameters that consume lot of battery power of nodes and decreases the number of active nodes and hence there is a decrease in PDR.

5.2. Analysis of control overhead

Figure 11 shows control overhead with increase in the number of nodes. For a given transmitted power of 2 mW, the control overhead (number of control packets) increases with increase in the number of nodes for both cases. We observe that the control overhead is more in both AFTBI and FDWSN compared to without having fault tolerance implemented. This is because the fault tolerance scheme requires the additional number of control packets to implement the hand-off and dynamic power adjustment mechanisms in AFTBI. However, this increase in control overhead yields better fault tolerance and hence enhances PDR. Control overhead in FDWSN is more compared to AFTBI since FDWSN uses several iterations to gather neighbor node information in transient fault identification to detect faulty nodes whereas in AFTBI such iterations are completely eliminated.

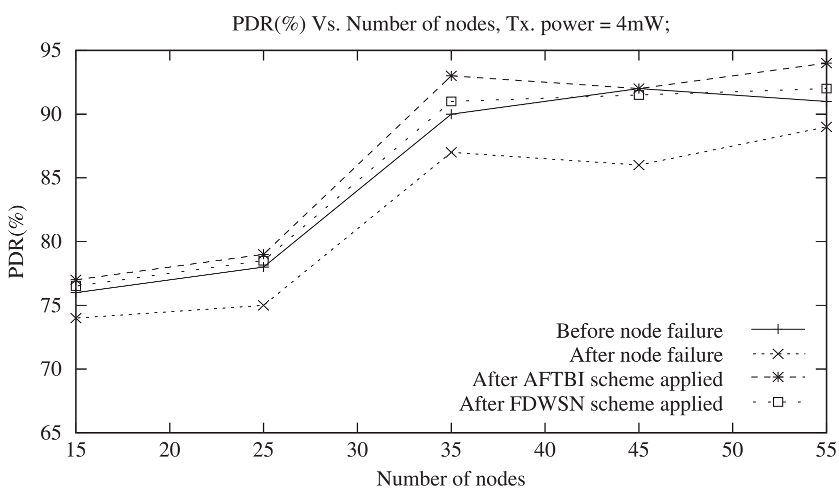

Fig. 10. PDR vs. number of nodes, transmission power = 4 mW.

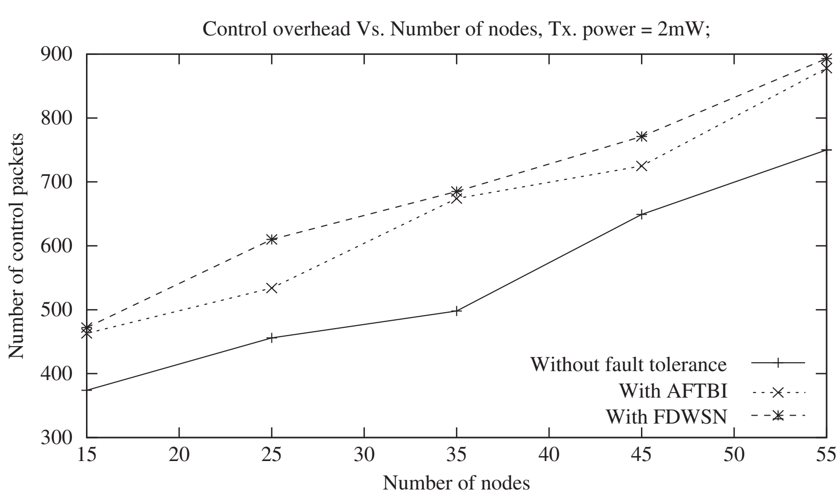

Fig. 11. Control overhead vs. number of nodes, transmission power = 2 mW.

Figure 12 shows the behavior of control overhead with transmitted power of 4 mW for AFTBI and FDWSN. With increase in node transmission power, we find that there is a decrease in number of control packets required to recover the faults. This is due to the fact that there are less number of faulty nodes with increase in node transmission power compared to the earlier transmission power of 2 mW and thus reduces the control overhead. However, the reduced control overhead is achieved at the cost of increased node transmission power.

5.3. Analysis of memory overhead

Additional memory required to be stored in FRD (in bytes) of sensor network node is plotted as a function of simulation time as shown in Fig. 13 for transmitted power of 2 mW and 4 mW with number of nodes equal to 60 for both AFTBI and FDWSN. Memory overhead shows the average number of bytes required to identify and recover the network from faulty nodes.

The fluctuation in memory overhead is due to the nature of topology distribution of sensor nodes and the number of neighbor nodes of a faulty node. In AFTBI, average memory overhead for higher transmitted power (4 mW) is less because for higher node transmitted power, the probability of number of active nodes is greater than that of the active nodes for lower transmitted power (2 mW). For lower transmitted power, there are many chances that the node's battery power drains quickly and thus resulting into faulty condition. Memory overhead in AFTBI is better than FDWSN since FDWSN requires more memory to store various parameters in its database such as node status, fault status, neighbor list, thresholds, transient fault matrix, node degree and re-computation of these parameters in transient phase. Thus, for both cases, AFTBI needs lesser memory storage.

As the number of nodes increases, we observe that the memory overhead is more since the number of faulty nodes increases in 120 node topology for both AFTBI and FDWSN (see Fig. 14). In this case also, we find that the memory overhead is more for transmitted power of 2 mW compared to that of 4 mW.

5.4. Analysis of fault recovery delay

Fault recovery delay for AFTBI and FDWSN are shown in Fig. 15 for 100 node and 200 node topology. In AFTBI, this delay includes the time taken to perform hand-off scheme in case of node power reduces and the time taken to suppress the neighboring node interference. The delay increases with increase in number of faulty nodes. As the number of faulty nodes in a network increase, the delay to recover from such nodes increases and this increase is not steep because there may be faulty nodes located at a distance more than 3 hops away that lead to simultaneous recovery and thus reducing fault recovery delay. The existence of increase in delay with number of faulty nodes may be due to the neighboring nodes

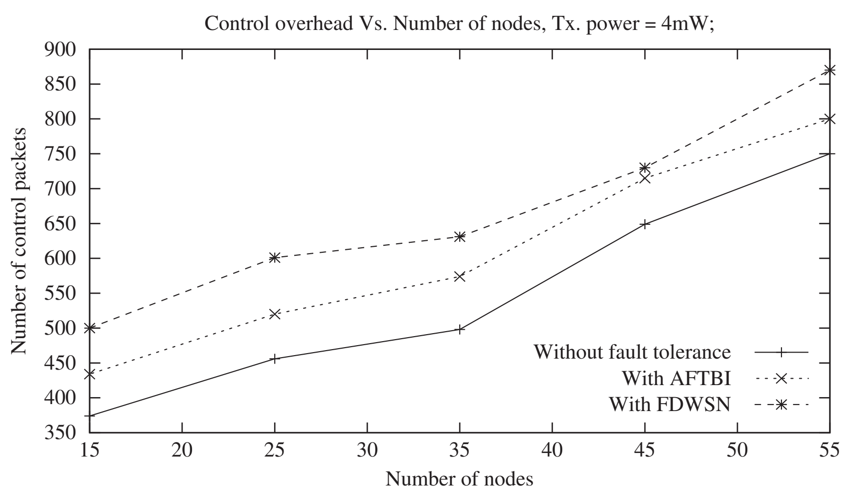

Fig. 12. Control overhead vs. number of nodes, transmission power = 4 mW.

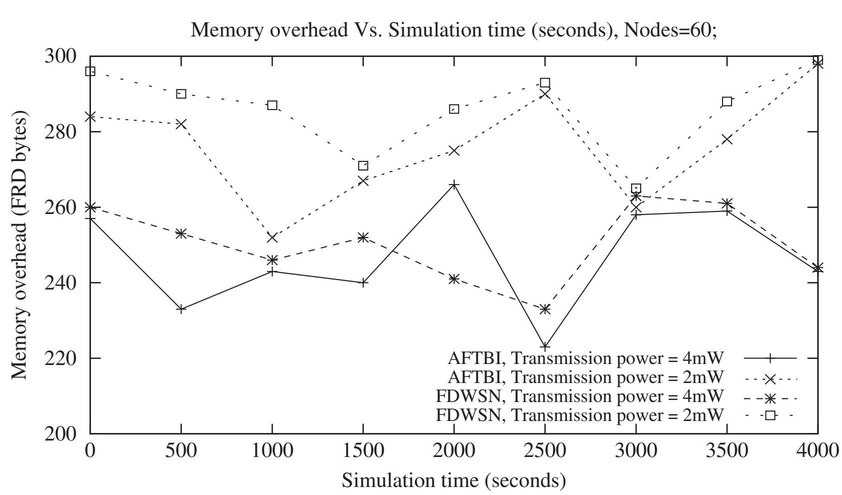

Fig. 13. Memory overhead vs. simulation time, nodes = 60.

become faulty and the recovery mechanism invoked in sequential manner. Corresponding delay to recover from faulty nodes in FDWSN is substantially higher than AFTBI because FDWSN needs more time to generate and compare transient fault matrices which requires time redundant collection of sensed data.

The higher delay is observed as the number of nodes increase from 100 to 200 and this delay is almost constant. It is due to the fact that when the number of nodes in a network increases, the neighbor nodes of a faulty node increases and the recovery from such nodes takes longer time.

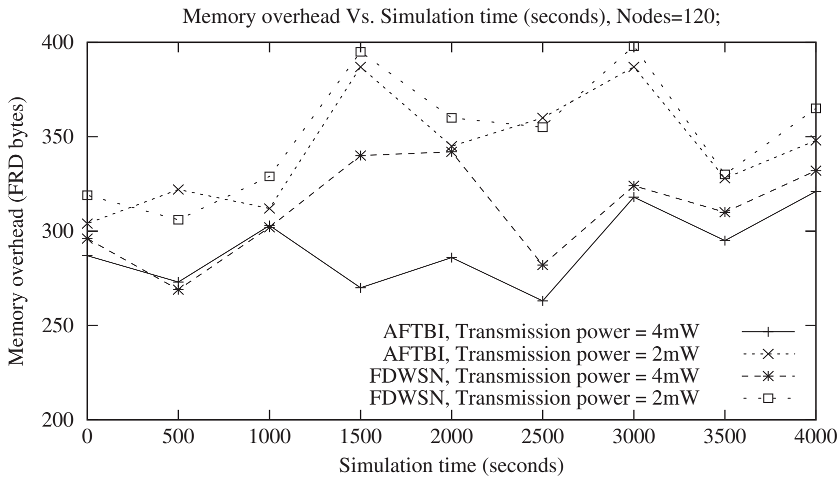

Fig. 14. Memory overhead vs. simulation time, nodes = 120.

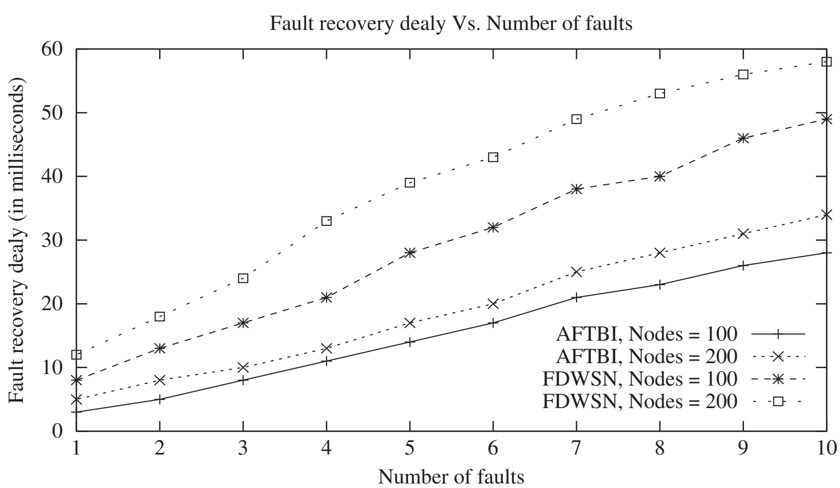

Fig. 15. Fault recovery delay vs. number of faults.

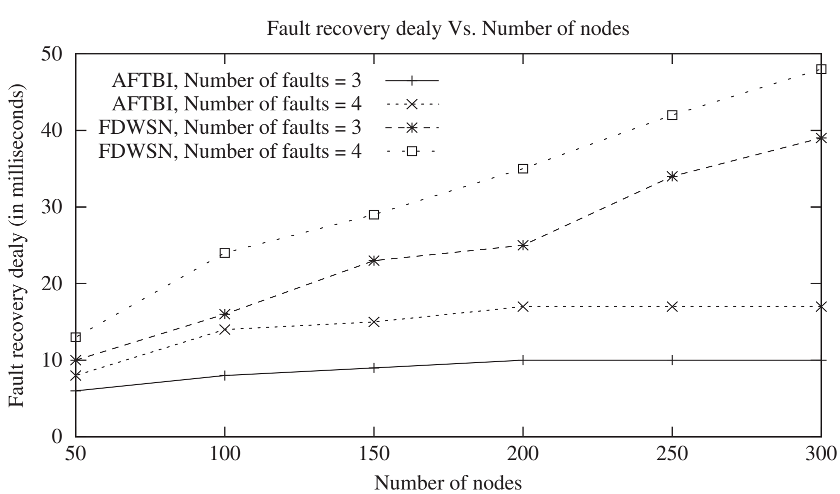

Fig. 16. Fault recovery delay vs. number of nodes.

However, there is a saturation in fault recovery delay in AFTBI as the network scales to large number of nodes as shown in Fig. 16 where in the fault recovery delay increases marginally with increase in number of nodes up to 200 and later, the delay remains constant thereafter. As node density increases, the fault recovery time becomes constant since there might be more number of neighbor nodes for a faulty node and the recovery delay from such a node remains constant due to simultaneous recovery. This shows that the fault recovery scheme has the ability to sustain scalability. The transient fault handling in FDWSN involves higher delay compared to AFTBI and there is a linear increase in fault recovery delay since the faulty nodes are also involved in fault recovery process with increase in number of faulty nodes.

6. Conclusions

In this paper, we proposed a novel idea of an Active node based Fault Tolerance using Battery power and Interference model (AFTBI) in WSN to identify the faulty nodes using battery power model and interference model. We used hand-off mechanism whenever a battery power of a node reduces below a threshold. In the hand-off mechanism, the faulty node selects one of its neighboring nodes having highest battery power and transfers all the services that are to be performed by the faulty node to the selected neighboring node. The dynamic power level adjustment mechanism is adopted for fault tolerance against interference. In the allocated time slot, neighbor nodes dynamically adjust their power level so as to reduce the effect of interference on the faulty node. Performance evaluation is assessed through simulation for PDR, control overhead, memory overhead and fault recovery delay. We compared our results with Fault Detection in Wireless Sensor Networks (FDWSNs) for various performance measures and observed that AFTBI outperforms compared to the results of FDWSN.

Acknowledgements

The authors wish to thank the editors and reviewers for their valuable suggestions to improve the quality of the paper. This project is funded by Visvesvaraya Technological University (VTU), Karnataka, INDIA, under VTU Research Scheme (Grant No. VTU/Aca./2011-12/A-9/753, Dated: 5 May 2012).

References

Anurag D, Somprakash Bandyopadhyay. Achieving fault tolerance and network depth in hierarchical wireless sensor networks. In: Proceedings of the world congress on engineering and computer science (WCECS 2008), San Francisco; 2008.

Amini Navid, Vahdatpour Alireza, Xu Wenyao, Gerla Mario, Sarrafzadeh Majid. Cluster size optimization in sensor networks with decentralized cluster-based protocols. Computer Communications 2012;35:207–20.

Aslanyan Hakob, Rolim Jose. Interference minimization in wireless networks. In: Proceedings of international conference on embedded and ubiquitous computing, Hong Kong; 2010. p. 444–9.

Bari Ataul, et al. Design of fault tolerant wireless sensor networks satisfying survivability and lifetime requirements. Computer Communications 2012;35: 320–33.

Challal Y, et al. Secure and efficient disjoint multipath construction for fault tolerant routing in wireless sensor networks. Journal of Network and Computer Applications 2011;34:1380–97.

Chen Xian, et al. Fault-tolerant monitor placement for out-of-band wireless sensor network monitoring. Ad Hoc Networks 2012;10:62–74.

Chitnis Laukik, Dobra Alin, Ranka Sanjay. Analyzing the techniques that improve fault tolerance of aggregation trees in sensor networks. Journal of Parallel and Distributed Computing 2009;69:950–60.

Feng Yunxia, et al. Fault tolerant data aggregation scheduling with local information in wireless sensor networks. Journal of Science and Technology 2011;16:451–63.

Fussen Martin. Sensor networks: interference reduction and possible applications. A Thesis, Institute for Pervasive Computing, Zurich; 2004.

Guo Lei, Zhang Lincong, Peng Yuhuai, Wu Jingjing, Zhang Xiaoying, Hou Weigang, Zhao Jun. Multi-path routing in spatial wireless Ad Hoc networks. Computers and Electrical Engineering 2012;38:473–91.

Gupta Gaurav, Younis Mohamed. Fault-tolerant clustering of wireless sensor networks. In: Proceedings of wireless communications and networking (WCNC 2008), New Orleans; 2003.

Hassan Maaly, Abuhaiba Ibrahim. Interference reduction through topology control in mobile ad hoc and sensor networks. In: Proceedings of international conference sciences of electronic, technologies of information and telecommunications (SETIT), Tunisia; 2011.

Hassan1 Maaly A, Chickadel Andrew. A review of interference reduction in wireless networks using graph coloring methods. International Journal on Applications of Graph Theory in Wireless ad hoc Networks and Sensor Networks (GRAPH-HOC) 2011;3(1).

Hsieh Hui-Ching, et al. A fault-tolerant scheme for an autonomous local wireless sensor network. Computer Standards and Interfaces 2010;32:215–21.

Kashyap Abhishek, et al. Relay placement for fault tolerance in wireless networks in higher dimensions. Computational Geometry 2011;44:206–15.

Lee Myeong-Hyeon, Choi Yoon-Hwa. Fault detection of wireless sensor networks. Computer Communications 2008;31:3469–75.

Qu Wenyu, Kitsuregawa Masaru, Shen Hong, Shan Zhiguang. A novel fault-tolerant execution model by using of mobile agents. Journal of Networks and Computer Applications 2009;32(3):423–32.

Rappaort TS. Wireless communication: principles and practice. 2nd ed. PHI Publishers; 2004.

Sa de Souza Luciana Moreira. FT-CoWiseNets: a fault tolerance framework for wireless sensor networks. In: Proceedings of international conference on sensor technologies and applications (SensorComm 2007), Valencia, Spain; 2007.

Xu Wenyuan, Trappe Wade, Zhang Yanyong. Channel surfing: defending wireless sensor networks from interference. In: Proceedings of information processing in sensor networks (IPSN), Cambridge; 2007.

Yoon Suk-Un, et al., Adaptive channel hopping for interference robust wireless sensor networks. In: Proceedings of IEEE international conference on communications (ICC 2010), Capetown; 2010.

Zhaoa Xibin, et al. A novel fault diagnosis mechanism for wireless sensor networks. Mathematical and Computer Modelling 2011;54:330–43.