A Fault-Tolerant and Energy-Aware Mechanism for Cluster-based Routing Algorithm of WSNs

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***Abstract*—Wireless Sensor Networks (WSNs) are prone to faults due to battery depletion of nodes. A node failure can disturb routing as it plays a key role in transferring sensed data to the end users. This paper presents a Fault-Tolerant and Energy-Aware Mechanism (FTEAM), which prolongs the lifetime of WSNs. This mechanism can be applied to cluster-based WSN protocols. The main idea behind the FTEAM is to identify overlapped nodes and configure the most powerful ones to the sleep mode to save their energy for the purpose of replacing a failed Cluster Head (CH) with them. FTEAM not only provides fault tolerant sensor nodes, but also tackles the problem of emerging dead area in the network. Our experimental results and simulations show that FTEAM outperforms conventional protocols in terms of network lifetime and energy consumption. In addition, an analytical evaluation using the Markov model is performed to determine the reliability of the FTEAM.**

Keywords—Wireless Sensor Networks; Fault-Tolerant Routing; Energy-Aware; Cluster Head failure.

I. Introduction

Recent advances in the Wireless Sensor Network (WSN) have enabled a large number of low-cost and low-power sensor nodes to participate in sensing and monitoring the environment. In WSN applications such as medical information systems and industrial monitoring, failure of nodes may cause either the loss of human life or environmental disasters [8][14][17].

Among fault sources, energy dissipation of node is the main reliability challenge in WSNs because battery depletion discontinues the process of delivering sensed data to the end user [11]. This disconnection can result in a non-uniform network topology due to time progresses and continuous nature of battery depletion in WSNs. The problem of battery depletion is more serious in routing algorithms as it is preferred to use lower energy consumption in routing sensed data to CH. Among the routing algorithms in WSNs, the cluster-based routing algorithms are the most energy-efficient algorithms [11][7]. Fault due to battery depletion can seriously treat the functionality of theses routing algorithms. In cluster-based routing algorithms, the network nodes are divided into sub-sections called a cluster. Every cluster has a node as a Cluster Head (CH) which is generally the most powerful node in those clusters [3]. CH aggregates data [20] and sends it to the Base Station (BS) while other nodes are only responsible for sensing data and sending these data toward the CH. Any disconnection due to battery dissipation can menace the process of routing the sensed data to CH. Checking the energy of all nodes periodically to recognize the faulty nodes can provide fault tolerance against permanent faults due to battery depletion.

One way to make WSNs fault tolerant due to battery depletion is to use supervisor nodes in the same cluster to make CHs fault tolerance [9][6].The supervisor checks the energy of all nodes periodically to recognize the faulty nodes. This supervision can be done locally by a neighboring CH [3], or by other sensor nodes in the same cluster [7]. The main serious drawback of these fault-tolerant mechanisms is huge energy consumption of nodes to make a CH fault tolerant and also high volume of messages transmission through the network. This causes reduction in the network's lifetime and energy consumption increase through network.

The sensors in a cluster have more similar sensed data rather than the sensors in other clusters, and a CH can use this similarity for aggregation [12][5][1]. Therefore, the volume of sending data and the processing performance of the end user in the network will be decreased by using the cluster-based WSNs [11][7]. This paper presents a Fault-tolerant and Energy-aware Mechanism, called FTEAM. In this mechanism, CHs identify overlapped nodes close to each other.

These overlapped nodes sense almost similar data, and CHs configure the most powerful ones into sleep mode [19] with the intention of using them when the CHs fail, and ensure the CH failure recovery procedure to achieve a high level of reliability by means of optimizing lifetime and energy. To the best of our knowledge, there is no work which utilizes the energy saving by considering sleep mode for overlapped nodes in the clusters to replace with faulty CH. To estimate the overall reliability of the FTEAM, an analytical reliability evaluation using Markov model is presented. Evaluations show that FTEAM not only helps to improve the network lifetime, but also reduces the overhead of the transmission message through the network and prevents the dead area appearing around CHs.

The rest of the paper is organized as follows. To assemble as much of the necessary context as possible, Section II provides a brief overview of the related work. Details of the proposed mechanism (FTEAM) come to the core in section III which is a key in understanding FTEAM in a better way. In Section IV, the results of a simulation are analyzed. An analytical evaluation is presented in Section V. And finally, Section VI concludes the paper.

II. Related Work

This section briefly focuses on some of the solutions from existing fault tolerance mechanisms in WSN literature for balancing and efficient cluster formation [2][4]. To tackle faults in WSNs, different mechanisms for fault detection and fault recovery have been proposed in the literature [15][18]. In fault detection mechanisms, the main idea is to detect faulty functionality of WSNs and predict the lifetime of the node. Basically, there are two types of detection techniques: self-diagnosis and cooperative diagnosis. In self-diagnosis detection mechanisms, faults can be determined by a sensor node itself and adopt self-diagnosis detection.

For example, faults caused by depletion of battery can be detected by a sensor node itself and the remaining battery of the sensor node can be predicted by measuring the battery voltage. Detection of failure links is another example of self-diagnosis mechanisms. In these mechanisms, a sensor node may detect faulty links by not receiving any message from the neighboring nods within a predetermined interval.

Some other kinds of fault detection mechanisms use cooperative diagnosis among a set of sensor nodes. A large portion of fault detection mechanisms in WSNs is in this category. Detection mechanism proposed in [8] is based on the assumption that sensor nodes in the same region should have similar sensed value unless a node is at the boundary of the event region. This mechanism takes measurements of all neighbors of a node and uses the results to compute the probability of the node being faulty. Using cooperative diagnosis has been applied in some of the clustering algorithms, too. Some algorithms consider fault-tolerant mechanism by using neighbor CHs to watch out for each other [3][7]. The main drawbacks of these algorithms are energy loss of the Neighbor Cluster Head (NCH) to detect a failure of its neighbors and overhead of transmission acknowledge message to detect failure in the network. In addition, the failure in CHs of neighboring is not supported by these algorithms. It means that if a group of NCHs become faulty, no one is responsible for selecting new CH, and all clusters will fail; therefore, dead areas appear in the network. It is noticeable that in [7], neighbor clusters become larger by failure of one CH and this affects the lifetime of that cluster.

After the network detects a fault, fault recovery mechanisms enable the network to recover from the faults. The most commonly used technique for fault recovery is replication or redundancy of components that are prone to be a failure. For example, WSNs are usually used to periodically monitor a region and forward sensed data to a BS. When some nodes fail to provide data, the BS still gets sufficient data if redundant sensor nodes are deployed in the region. The Fault-Tolerant Target Tracking (FTTT) protocol [3] presents an energy-aware and fault-tolerant clustering algorithm which uses redundant nodes to improve the network lifetime. The CH calculates the overlapped nodes and sends a "sleep" message to them. When a CH failure occurs, NCH will respond to that cluster. NCH will send an "active" message to sleep nodes of that cluster and selects one of them as a new cluster head. The network presented in [8] considers a spare node for each of the CH, when the CH becomes faulty, and this node is replaced with failed CH. The mechanism presented in [6] consists of an organizer in each cluster that monitors the CH failure in the cluster and assists other nodes not to lose their energies. The drawback of these mechanisms is that the spare node, or the organizer is the single point of failure, and its failure causes the whole cluster failure, exactly the same as CH failure. Therefore, dead areas appear in the network. Multiple paths routing is another example. In the case of providing a single route, a requested call cannot be set up or maintained if some nodes/links along the route fail. Keeping a set of candidate routes provides high reliability of the routes for routing. It requires K-connectivity of the network if it is able to tolerate the failure of K-1 nodes.

The other fault tolerant prominent clustering mechanism in fault tolerance WSN literature that uses fault detection and recovery simultaneously is Low-Energy Adaptive Clustering Hierarchy (LEACH) [5]. LEACH is one of the most popular self-organizing and clustering algorithms [13][16]. In each round of LEACH algorithm, some nodes are selected as new CHs, randomly. These nodes have the same initial energy. New cluster formation in each round prevents a single sensor node from battery draining, but randomized rotation is not an energy-efficient operation because extra energy is needed for exchanging message to select new CH and new cluster formation. In addition, all nodes have to choose their CH according to their signal strength while the CH may be located far from them in some situations, which increases the network energy consumption.

By Using FTEAM, we always have some nodes in each cluster to sense data by considering failed CHs replacing with the optimal number of sleep nodes, which prevents the dead area from appearing in our network. The most outstanding drawback of FTEAM is the loss of sensing accuracy by using sleep during network operation. However, many parameters are not so strict for sensing continuously in short distance WSNs. The real-world examination to support this claim is evaluated in this paper.

III. Fault-Tolerant and Energy-Awar Mechanism

The main aim of fault tolerance mechanisms is to boost the reliability of cluster base protocols of WSNs. Reserving energy in a specific node, by entering overlapped nodes in sleep mode in the cluster, is an efficient way to sustain the network by an energetic CH. In FTEAM, CHs identify overlapped nodes by closeness relationship. These overlapped nodes sense almost similar data, and CHs configure the most powerful ones into sleep mode with the intention of using them when the CHs fail. This ensures the CH failure recovery procedure to achieve the high level of reliability by means of optimizing lifetime and energy. It is notable to mention that in FTEAM, nodes are aware of their remaining energy budget. In FTEAM mechanism, network nodes are categorized into three groups: Cluster Heads (CHs), Normal Nodes (NNs), and Sleep Nodes (SNs). SNs keep their radios turned off to save energy to avoid idle listening and overhearing, this process is considered as Sleep mode. The network area is divided into equal parts with respect to the number of CHs. The energy, considered for CHs, is γ times [3] more than NNs. Employing more powerful CHs is a reasonable decision to achieve fault tolerance.

Since CH is the single point of failure in the network, it would be worth giving more energy to CH in order to improve the network reliability. CHs are deployed in the center of the gravity of those parts and NNs are randomly distributed in the network. CHs calculate the overlapped NNs and send "sleep"

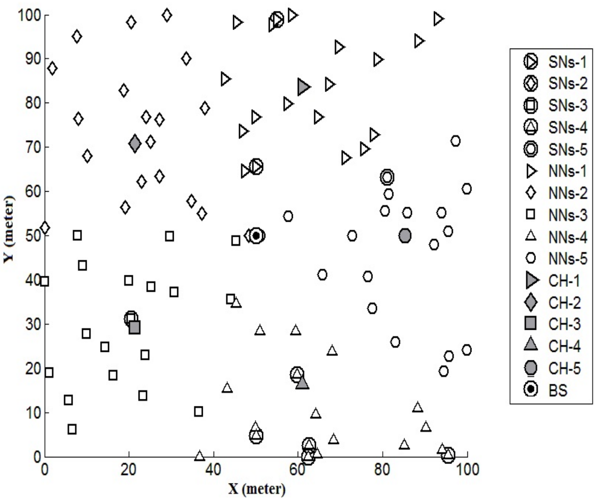

Fig.1. Cluster formation and sleep nodes

message to them. Figure 1 shows the proposed network with the number of five CHs. FTEAM consists of 4 states: Cluster Formation State (CFS), Error Free State (EFS), CH Failure State (CHFS) and Error Recovery State (ERS).

In CFS state, CH broadcasts a "membership" message to all NNs. NNs calculate their locations by using a straight forward mathematical algorithm, internal RSS (Radio Signal Strength module). RSS uses the strength of signal three other nodes to calculate the location of target node. GPS is a power consuming module and it is not utilizable in ordinary WSNs. Each NN selects the appropriate CH and sends its "join" message. This join message includes the ID, place and remaining energy to selected CH. CH determines its overlapped member NNs which sense the similar data. FTEAM uses this similarity to save more energy by configuring one of these NNs to the sleep mode without missing the significant data. CH calculates the distance among all of the NNs in its cluster. If the distance between them is less than φ, they are overlapped and sensing same data, therefore, CH sends "sleep" message to the most powerful ones with the purpose of replacing a failed CH with them. Since CHs duties are more than NNs, and they need more energy for gathering and aggregating data from other nodes and sending aggregated data to the BS, CHs should have more energy than NNs. When they are put into the sleep mode, their energy would be saved during the network operation. It is noticeable that there may be a situation which no sleep node exists.

Then CH uses Time Division Multiple Access (TDMA) schedule and allocates a time slot to each of the members to send their sensed data in allocated time slot, and in the other time slots, the nodes would be in idle mode, which means their radio component is turned off and the energy can be saved. Putting NNs to idle will not prevent critical information to be sensed and forwarded to the BS since its sensing unit will be on and only the radio will be turned off.

Given the importance of φ, to estimate amount of φ, we performed an experiment with MicaZ [21] WSN nodes to specify the most proper value of φ in a real world application. The nodes were equipped with MTS400 sensor board which contains air pressure, temperature, humidity and acceleration sensors. In our experiment, we put the MicaZ nodes outdoor and change their position each hour. The distance between the nodes was one meter in the first hour and was increased to two, three, five, seven and nine meters in subsequent hours. Sensed parameters differ less than 5% till 4th hour of sensing, and this difference can be disregarded in many applications like agriculture, forest fire monitoring system and smart buildings. The maximum distance between nodes which did not violate 5% of difference is five meters (4th hour); therefore, we chose five meters for φ in our simulations.

In EFS state, all of the alive nodes continue to sense the environment and send their data to their CHs. CHs aggregate data and send aggregated data to the BS. During this state, some NNs may become Dead Node (DN) because of the loss of their energy. This state will continue, until the energy of CHs reduces to the threshold. The amount of threshold depends on the required energy to send an "active" message to sleep nodes and to determine the new CHs. Just then, the cluster will switch to CHFS and ERS. In these states, CH which is aware of its remained energy sends an "active" message to all of its members.

All of the NNs become alive and send their remained energy to the CH. CH sorts energies of NNs and 5% [5] of the most powerful ones would be selected as new CHs, as CH is a single point of failure and needs more energy than other NNs. Note that the energy of the nodes should be more than a threshold to be aptitude for the candidate as CH. These new CHs broadcast the "membership" message to NNs in the same cluster and all states would be repeated. There is a particular situation that 5% of the nodes are equal to one in which the old CH would broadcast the ID of the new CH to all of the cluster members; in this way we do not need to have a CFS. Therefore, the dynamic clustering would be stopped and more energy would be saved. Finally, when the last CH wants to die, receives the remained energy of all the alive nodes and if the energy of none of them was more than that CH candidate threshold, the algorithm would be stopped and the network would fail.

IV. Simulation Results

To evaluate the proposed mechanism, MATLAB environment has been used. We distribute 100 nodes randomly in a $100 \times 100\ \mathrm{m}^2$ region with the BS which is located at $(x = 50, y = 50)$ and $ø = 5\mathrm{m}$. We compared FTEAM with LEACH and FTTT algorithms as they were among the prominent works in clustering protocols and reviewed in more details in the related work section. We suppose that the initial energy of the sensor nodes is 2J for NNs and 6J for CHs. The radio model is according to Table I. For each chart that is presented for the comparison, the results are obtained by averaging of 100 simulated results for each algorithm.

To illustrate the efficiency of the FTEAM mechanism, the alive nodes per round and the remained energy of all nodes are compared. Two different network models are proposed in our evaluations: in the first model, we randomly distribute 100 nodes with the same energy to compare LEACH with different CH configurations shown as FTTT-i and/or FTEAM-i where i is the number of CHs. In the first model, LEACH is compared with FTTT-5S and FTEAM-5S, which indicates simulation with 5 CHs which have the same initial energy as NNs.

TABLE I. Radio Characteristics [5]

Operation	Energy Dissipated
Transmitter Electronics	50 nJ/bit
Receiver Electronics	50 nJ/bit
Transmit Amplifier	100 pJ/bit/m^2

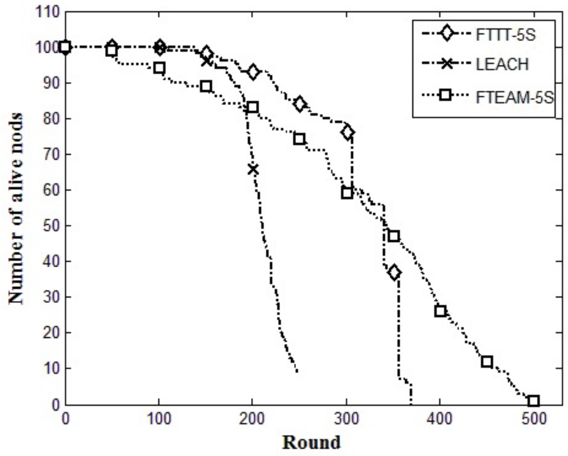

Fig.2. Number of alive nodes per round in the first model

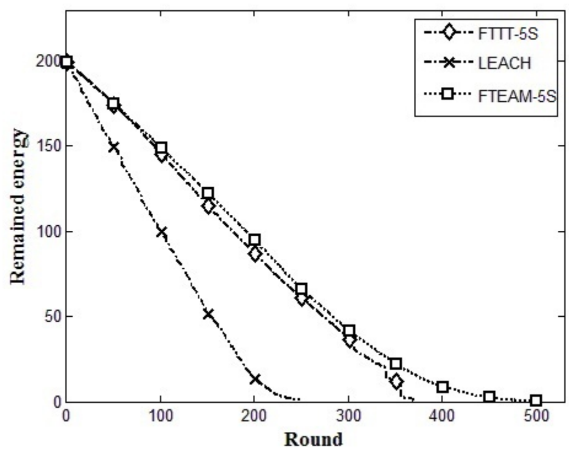

Fig.3. Remained energy of 100 nodes per round in the first model

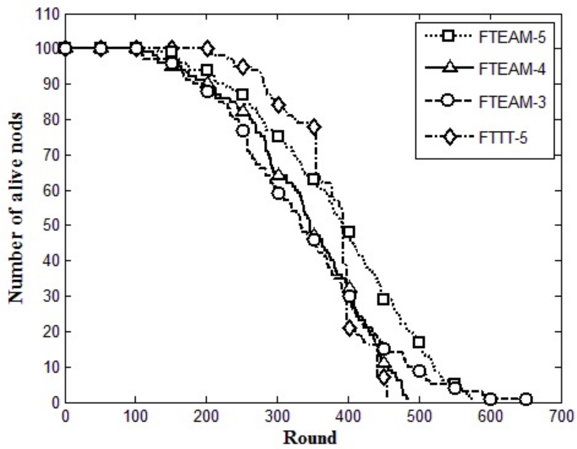

Fig.4. Number of alive nodes per round in the second model

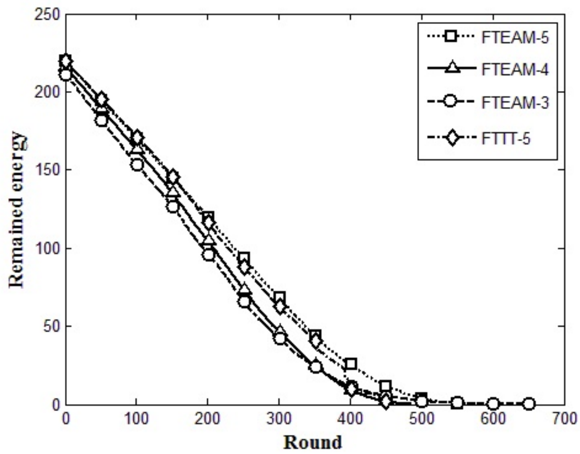

Fig.5. Remained energy of 100 nodes per round in the second model

In the second model, CHs are three times more powerful than NNs, and FTEAM-3, FTEAM-4, FTEAM-5 and FTTT-5 are compared which indicate the simulation with 3, 4 and 5 models such as radio model, network size, and number of nodes, are considered the same in simulations. As in LEACH, the steady state phase of FTEAM will also be continued until remained energy of CH becomes less than the threshold. Comparisons of results show that FTEAM outperforms LEACH and FTTT in terms of network lifetime and energy consumption.

A. First Model

Since, in the LEACH, the initial energy of all nodes are equal, the main goal behind the first model is to compare the FTEAM, FTTT and LEACH fairly; in this regard, in the first model, FTEAM-S5 and FTTT-5S are used with the same energy for CHs and NNs. In other words, all of them have 2J energy. Figure 2 presents the simulation result of the alive nodes per round in the first model. According to Figure 2, in the same condition, FTEAM-5S have increased lifetime about 103.61% in comparison to LEACH and about 37.03% in comparison with FTTT-5S.

In the first 139 rounds, the number of alive nodes in LEACH is better, however, after 140 rounds the number of alive nodes in LEACH and FTTT-5S is declined dramatically and in this way, some dead areas are appeared in the network. In FTEAM-5S, by using sleep mechanism and selecting the most powerful node as a CH, the number of alive nodes fell steadily, and we always have alive nodes all around the network. FTEAM-5S still executes after 205 round whereas the LEACH is completely terminated. Figure 3 illustrates the remained energy of all alive nodes in every round. In FTEAM-5S, the remained energy goes down stably. It is obvious that this lower energy consumption of FTEAM-5S increases the network lifetime. FTEAM-5S decreases the energy consumption of network two times (50%) in comparison to LEACH. The trend of decreasing of remained energy in FTEAM-5S and FTTT-5S is the same. The results show the improvement of 1.48% in remained energy of FTEAM-5S as compared with FTTT-5S.

B. Second Model

In the second model, CHs are considered three times more powerful than NNs. Figure 4 depicts the number of the alive nodes per round for FTTT, FTEAM-3, FTEAM-4 and FTEAM-5. FTEAM-5 experiences the most numbers of the alive nodes in each round because when the number of CH increase, NNs in the network do not have to transmit their data very far to reach the CH, causing more energy to be saved. However, in Figure 4, it can be seen that around the round 360, the number of the alive nodes of FTEAM-4 is less than FTEAM-3. The main reason of this exception is because of the implementation process of FTEAM algorithm.

Since in each round only 5% of the alive nodes are selected as CH in a cluster, for FTEAM-4 and FTEAM-5 only one node

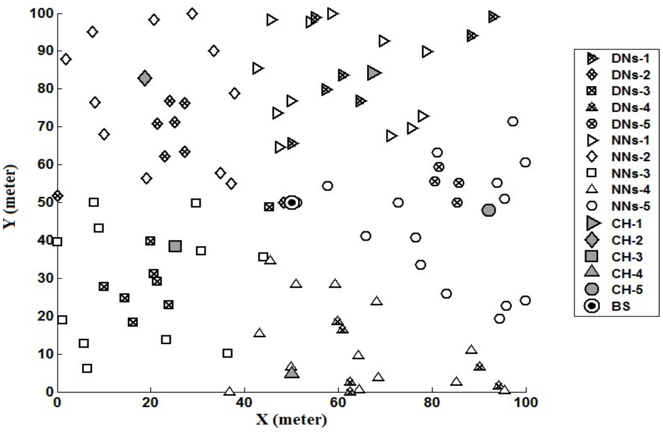

Fig.6. Cluster formation and sleep nodes

exists to be selected as the new CH. However, for FTEAM-3 there are two nodes for the first change of CH, and more CHs of FTEAM-3 save more alive nodes in the network as compared to FTEAM-4. As mentioned in the previous model, until 350th round, the number of alive nodes in FTTT-5 is better, but after that the numbers of alive nodes in FTTT-5 is declined dramatically; in this way, some dead areas appear in the network.

Figure 5 depicts the remained energy of all the alive nodes in every round for FTTT-5, FTEAM-3, FTEAM-4 and FTEAM-5. By increasing the number of CHs, the energy consumed with FTEAM will decrease. As shown, the trend of decreasing of the remained energy in FTTT-5, FTEAM-3, FTEAM-4 and FTEAM-5 is the same. Finally, the results show that the improvement of 164.25% in lifetime of FTEAM-3 is met as compared with LEACH and about 44.6% in comparison with FTTT.

Figure 6 presents the distribution of the dead nodes in FTEAM-5. By the use of FTEAM, we always have some nodes in all around the network to sense data whereas LEACH and FTTT completely have a dead area. This shows the better policies of FTEAM for selecting CHs and forming clusters.
Table II shows the number of Sleep Nodes (SNs) in the network for different value of α, considering φ= 3m, 5m and 7m. According to Table II, the optimal value of our network and system parameters is φ = 5m. Considering this optimal value which is 5% of the network area leads to providing enough sleep nodes for every cluster that can be replaced with the failed CH.
For smaller values of φ, the probability of the more powerful nodes near the failed CH to become the new CH increases which causes a dead area to be appeared around the first failed CH; on the other hand, for larger values of φ, the similarity of sensed data by nodes which is the main reason of putting nodes to the sleep mode may not be satisfied.

TABLE II. DIFFERENT VALUE OF φ

Value of ∅	Number of SNs
$\emptyset = 3m$	9
$\emptyset = 5m$	20
$\emptyset = 7m$	35

V. ANALYTICAL RELIABILITY EVALUATION

We perform Markov model to determine the reliability of FTEAM to facilitate WSN application-specific. Markov chain is used to model a sensor node, a cluster and the whole network [10]. The fault tolerance parameter in our Markov model is sensor failure probability. Sensor failure probability $P_{Non\text{-}FT\text{-}Node\text{-}Failure}$ can be achieved by using an exponential distribution with the failure rate during period t, according to equation (1):

$$P_{Non-FT-Node-Failure} = 1 - e^{-\lambda t} \tag{1}$$

A. Sensor Node Model

We propose a fault-tolerant sensor node model consists of one node which can be in the state of normal, CH, sleep or fail as it is shown in Figure 7. The states in the Markov model represent the probability of the node which is in that state. The differential equations describing Markov model for a sensor node are considered to be solved, and we have the reliability of the sensor node that is given by equation (2):

$$P_{Node}(t) = 1 - P_{fail}^{Node}(t) \tag{2}$$

B. Cluster Model

As mentioned before, in hierarchical protocols, network is divided to sub-sections which are named clusters, and we assume all of the nodes in a cluster are neighbors. The average number of nodes in a cluster is n. We assume that a cluster fails if the number of alive (non-faulty) sensor nodes in that cluster reduces to n_{min}. The failure probability of a cluster is according to equation (3):

$$P_{fail}^{Cluster}(t) = \sum_{n_{min}=threshold\ (Cluster)}^{n} \binom{n}{n_{min}} \left(P_{fail}^{Node}\right)^{n_{min}} \left(1 - P_{fail}^{Node}\right)^{n-n_{min}} \tag{3}$$

The cluster reliability is given as equation (4):

$$R_{Cluster}(t) = 1 - P_{fail}^{Cluster}(t) \tag{4}$$

C. WSN Model

A typical WSN consists of k = ns/n clusters where ns denotes the total number of sensor nodes in the WSN and n denotes the average number of nodes in a cluster. We assume that the WSN fails to perform its assigned task when the

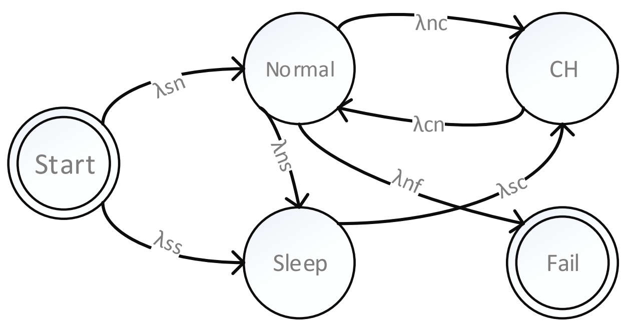

Fig.7. Sensor node Markov model

number of alive clusters reduces to k_{min}. The differential equations describing the WSN Markov model are according to equation (5):

$$P_{fail}^{Network}(t) = \sum_{k_{min}=threshold\ (Network)}^{k} \binom{k}{k_{min}} \left(P_{fail}^{Cluster}\right)^{k_{min}} (1 - PfailClusterk-kmin \qquad (5)$$

The WSN reliability is given as equation (6):

$$R_{Network}(t) = 1 - P_{fail}^{Network} \qquad (6)$$

We performed the reliability calculation for a sensor node, cluster and complete WSN in FTEAM-5. Based on these reliability calculation, Table III shows FTEAM reliability with different values of sensor failure probability P, evaluated at t = 100 days when k = 5 and $k_{min} = 2$. For the clusters with the average of n = 20 and $n_{min} = 5$, we observe similar trends as sensor node reliability, cluster reliability and WSN reliability. These results show that the percentage improvement in reliability attained by FTEAM increases when $P_{Non-FT-Node-Failure}$ decreases.

TABLE III. RELIABILITY FOR FTEAM-5 WSN

P	R_{Node}	$R_{Cluster}$	$R_{Network}$
0.05	0.9996409	0.9999756	0.9999999
0.1	0.9993000	0.9999075	0.9999999
0.2	0.9984446	0.9995477	0.9999999
0.3	0.9975500	0.9988883	0.9999999
0.4	0.9964300	0.9976670	0.9999999
0.5	0.9951560	0.9957616	0.9999999
0.6	0.9935950	0.9927100	0.9999996
0.7	0.9915930	0.9877014	0.9999980
0.8	0.9888000	0.9788034	0.9999899
0.9	0.9839000	0.9584023	0.9993207
0.99	0.9678000	0.8597000	0.9959070

VI. CONCLUSION

In this paper, we have proposed a Fault-Tolerant and Energy-Aware Mechanism for cluster-based routing algorithms, called FTEAM. This mechanism saves the energy of the powerful sensor nodes for the intention of recovering CHs failures. CH is the single point of failure in the network, and they would become faulty due to energy depletion. As sensors are energy-aware, when their remained energy of a CH falls below the predetermined threshold, it selects 5% of the most energetic nodes as new CHs. Simulation results show that FTEAM pays more attention to the energy consumption and load balancing as compared to the LEACH and FTTT. Using FTEAM, we always have some nodes in each cluster to sense data by considering failed CHs replacing with the optimal number of sleep nodes, which prevents the dead area from appearing in our network. Results of the Markov model show that the proposed FTEAM is an efficient solution to improve the reliability of WSNs.

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