An Enhanced Fault-tolerant Version of LEACH for Wireless Sensor Networks

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Abstract

In wireless sensor networks (WSN), routing protocols have been designed to balance energy and prolong network lifetime such as LEACH. However, the occurrence of failures could degrade them of their performance. In this paper, we propose an improved version of LEACH so it becomes a fault-tolerant protocol. Moreover, we suggest a multihop routing scheme from cluster-heads to the base station to conserve energy and in the same time create a backup path between cluster-heads that provides a better resilience to various failures in WSN. We conducted several simulations to illustrate the performance of our contribution in realistic environments. Simulation results have shown that our contribution greatly enhances the original version of LEACH in terms of energy consumption and network lifetime.

Keywords: *Fault-tolerance, LEACH, Multihop scheme, WSN.*

1. Introduction

Wireless sensor network is a collection of a large number of sensor nodes that sense physical phenomena, treat sensed data locally and send information to the base station through wireless communication. These sensors can be randomly deployed in hostile environments and even inaccessible to the human being in order to monitor and control a particular phenomenon [1]. However, some events such as energy resource depletion since their batteries cannot be recharged or replaced due to hostile environments, sensor damages, communication link errors, etc. can occur in WSN and may preclude the network of functioning correctly [2][3], whereas, WSN should have a long lifetime to accomplish their requirements tasks successfully. Therefore, the failure of some nodes may disturb network operation and may make other unreachable nodes hence the data can be lost and could not attain the destination. Consequently, the communication links between the nodes will be disturbed and in this case, it proves necessary to establish a fault-tolerant scheme that ensures fidelity routing even when failures occur in the network.

Since energy is the major constraint in WSN [4], several energy-efficient routing protocols have been proposed to solve the energy constraint problem such as LEACH [5] in order to prolong network lifetime by changing cluster distribution in a laps of time (round) to balance the energy consumption between the nodes in the network. These protocols assume that the sensors are deployed in an ideal environment i.e. the sensors are not subject to failure. In this optic, several protocols have been proposed to tackle the consequences of failures in LEACH protocol, among them our contribution, which consists of two propositions:

- Create a CH-to-CH paths to minimize energy consumption of the network,
- Create a backup path between cluster-heads to ensure fault-tolerance in the network when some clusterheads fail.

The remainder of this paper is organized as follows: in section 2, we present briefly LEACH protocol and discuss some works that improve LEACH related to our requirements. Section 3 is an improved version of LEACH, and in section 4, we illustrate performance of LEACH and the proposed contribution when failures occur. Finally, we conclude our paper and present some perspectives in section 5.

2. Related work

Several hierarchical routing protocols have been proposed in the literature such as LEACH, which is the first and well-known energy-efficient routing protocol. Moreover, several approaches have addressed to improve LEACH in order to reduce its limitations. In this section, we briefly present LEACH and some of its variants protocols.

LEACH (Low-Energy Adaptive Clustering Hierarchy) [5] is a distributed clustering protocol that utilizes randomized rotation of local cluster-heads to evenly distribute energy consumption among sensors in the network. The main objectives of LEACH are:

- Extension of the network lifetime
- Reduction of energy consumption by each sensor node
- Use of data aggregation to reduce the number of communication messages.

The basic idea of LEACH protocol is that nodes elect themselves as cluster-heads according to some probability generated by the base station. Nodes that are not cluster-head join the cluster of the closest cluster-head, as shown in figure 1. After the formation of clusters, nodes send their packets to their corresponding cluster-heads. The latter aggregate received packets and send the aggregated data to the sink directly. The election of cluster-head process is performed once every round, and nodes that have been selected as cluster-heads will not become cluster-heads again in the following rounds to do not quickly deplete their batteries. Moreover, LEACH ensures that every sensor node in the network has a probability to be chosen as a cluster-head, thus energy consumption is evenly distributed among the nodes. Therefore, this process increases network lifetime compared with conventional routing protocols.

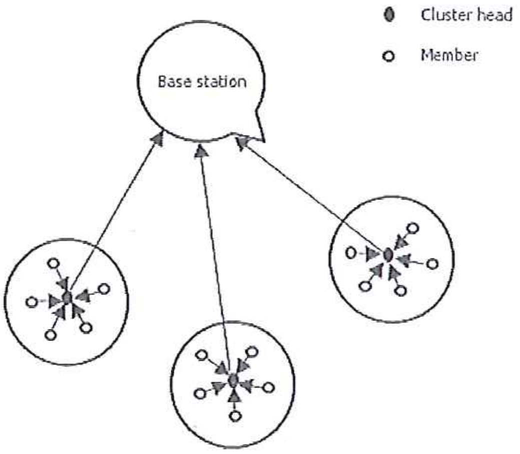

Figure 1. LEACH protocol model

In LEACH, nodes have the capability to adjust their transmission power such that they can use low transmission power for intra-cluster communications, and use high transmission power to send packets directly to the sink. If all nodes send packets to the sink directly, nodes will die out very soon, especially those that are far from the base station. If nodes use the Minimum Transmission Energy (MTE) routing protocol [4] to forward packets to their closest neighbors, closer nodes to the sink will handle more traffic than farther nodes away from the sink, and therefore will deplete their energy quickly. LEACH outperforms these limitations by selecting some nodes, which are the cluster-heads, to send packets to the sink directly, and member nodes send data to their corresponding cluster-heads. However, if the cluster-heads are fixed, they would consume more energy than other nodes and die quickly because they are involved in all communications. Therefore, LEACH randomly selects different nodes as cluster-heads in each round to avoid this problem.

LEACH is performed into rounds, wherein each round contains a set-up phase and a steady phase. In the step-up phase, each node decides whether or not to become a clusterhead by choosing a random number between 0 and 1. If the generated number is less than a threshold, then the node becomes a clusterhead. Each node *i* calculates the threshold as follows:

$$T(i)=\begin{cases} \frac{p}{1-p*\left(r \bmod \frac{1}{p}\right)} & \text{if } i \in G \\ 0 & \text{otherwise} \end{cases}$$

Where: *p* is the percentage of nodes that are clusterheads, *r* is the current round, *G* is the set of nodes that have not been selected as clusterheads in the last (1/p) rounds. Using this threshold function, all nodes take turns to be clusterheads in a random order. After (1/p) rounds, all nodes start over to participate in the clusterhead selection process again.

During the set-up phase, nodes that are elected clusterheads, broadcast an advertisement message in their neighborhoods and each non-cluster-head node could receive multiple advertisement messages. Assuming the radio channel is symmetric; choosing the cluster-head with the strongest signal strength minimizes the required energy to transmit packets. Therefore, each node joins the cluster of the clusterhead based on the highest radio signal strength received.

After cluster formation, in each cluster, TDMA schedules are assigned to member nodes and the steady phase is triggered. In this phase, each member node transmits data to the corresponding clusterhead in its scheduled time slot. Clusterheads receive all packets from their cluster members, compress the data into one packet, and send the resulting packet to the sink directly. However, nodes in different clusters may be scheduled to transmit in the same time slot, which will cause packet collisions and affect transmission in neighboring clusters. To reduce interference, each cluster chooses one CDMA code that is different from other clusters to communicate within the cluster. The CDMA codes are broadcast when the clusterheads broadcast their advertisement messages.

In this improved version of LEACH [3], the authors propose two versions of LEACH to make it a fault-tolerant protocol. In the first version called FT1-LEACH, each cluster contains two cluster-heads: primary clusterhead (CH_p) and secondary clusterhead (CH_s), and the members of each cluster transmit data to both CH_p and CH_s. In this version only the CHp is responsible to transmit data to base station and within a threshold time interval, if this task is not performed CHs considers that CH_p is down and sends collected data to base station. In the second version called FT2-LEACH, the authors propose to use the checkpoint technique, which is able to tolerate the failure of the whole network. In this approach, it is proposed that the base station is responsible to store availability information about clusterheads and their members and if during a period, the base station does not receive a message from a clusterhead, it considers it as failed node, and the election of the new CH is done among their members.

In the version of LEACH presented in [6], the authors propose an election of two clusterheads in each cluster, and the failure of clusterhead (CH) is detected if no response is sent from CH to the base station. It is assumed that only one token will be used by the two clusterheads (CH_1 and CH_2) hence when CH_1 is active then the token will be used by CH_1 and if CH_1 becomes defective, then CH_2 takes this role. However, when the two clusterheads fail, the node with the highest energy in the cluster is chosen as a novel CH.

In [7], the authors propose a new algorithm of fault-tolerance for LEACH protocol to determine the failure of clusterheads within a few seconds after the beginning of each round. So to detect the failure of CH, this later sends a small Hello message to all nodes that are ready to receive this message, and if no transmission is received, the nodes can advertise that clusterhead has failed. After detecting the clusterhead failure, the failure recovery model chooses a position value to designate the new CH based on the position of nodes.

In this new version of LEACH [8] called V-LEACH, each cluster contains a cluster-head (CH) which is responsible only for sending data received from its cluster members to the base station and a vice-CH node that will become the CH of cluster when CH fails. Cluster members gather data from environment and send it to the corresponding CH.

In the original version of LEACH, the CH is responsible for gathering data received from its members and sends it to the base station that might be located far away from it, thereby CH will die earlier because the operations of receiving, sending and overhearing are costly in terms of energy. To avoid the failure of the clusters, the proposed protocol (V-LEACH) involves a second CH (vice-CH) in the cluster and this later takes the role of clusterhead when the primary CH fails.

In [9] the authors propose an enhanced version of LEACH to achieve an effective fault tolerance. They have proposed a new phase besides those defined in the original version of LEACH called fault-detection phase in which when the faulty cluster-head is detected, the faulty recovery phase process is triggered. Moreover when a dead cluster-head is identified, all the cluster members are informed about the faulty CH, and for the CH recovery operation, the base station chooses a new CH based on residual energy of the members to replace the faulty CH.

In [10] the authors propose two recovery mechanisms when the CH is faulty: replace the faulty cluster-head by the next highest energy node in the cluster and, maintain two cluster-heads in each cluster by using token to avoid redundancy effect. It is assumed that all members of the cluster send sensed data to both CH1 and CH2 and only CH1 is responsible for gathering information and send them to base station and CH2 is receiving data only. If at a moment CH1gets faulty CH2 will be the new CH. However, if CH1 and CH2 will stop working simultaneously, the entire process began from advertising phase.

3. Proposed work

At first, the original version of LEACH provided good results in terms of energy saving despite it uses direct communications with the base station regardless of the location of the clusterheads. However, the use of multi-hop communications could improve energy saving than direct communications. Moreover, in LEACH, it is assumed that the deployment of the nodes is ideal i.e. the nodes do not undergo any failures until the depletion of their batteries. Hence, we propose two contributions. The first aims to extend network lifetime by using multi-hop communications, and the second aims to make LEACH a fault-tolerant protocol in a non-ideal environment.

3.1. Contribution 1

3.1.1. In setup phase

At the beginning of the setup phase, the base station broadcasts a Hello message to all nodes in the network and each node that receives this message, it could know its position relative to the base station i.e. if it is near or far from the base station, based on the received signal strength (RSSI). After that the round of clusterhead selection is triggered.

During the formation of clusters, we distinguish two kinds of clusterheads: clusterheads that are close to the base station and clusterheads that are far from the base station. The first have "ChSup" status while others have "ChInf" status. Each clusterhead, whose status is "ChSup" broadcasts a Hello message and each "ChInf" clusterhead that receives this message, calculates the new RSSI received to choose its relay node among "ChSup" clusterheads. Moreover, we involve credibilty parameter to select relay nodes. Hence, the selection of "ChSup" clusterheads as relay nodes by "ChInf" clusterheads is based on two parameters:

- RSSI2 received from each message sent by cluster head (chsup).
- Credibility (Cred) where "Cred" is a random number comprise between 0 and $1 (0<Cred<1)$.

3.1.2. In steady phase

Each "ChInf" clusterhead creates a list to save all Hello messages received and to choose the relay node among all "ChSup" clusterheads based on the two parameters mentioned above.

3.2. Contribution 2

The multihop communication increases the energy efficiency but it prone to failure when a relay node ("ChSup" clusterhead) stops working and therefore the path in which this node belongs could be corrupted. To avoid these failed nodes a backup path is established to guarantee data transmission to the base station. Hence, when a clusterhead noted that its first relay node became faulty then it switches to another relay node that belongs to the backup path. This process provides fault tolerance and system availability during lifetime network.

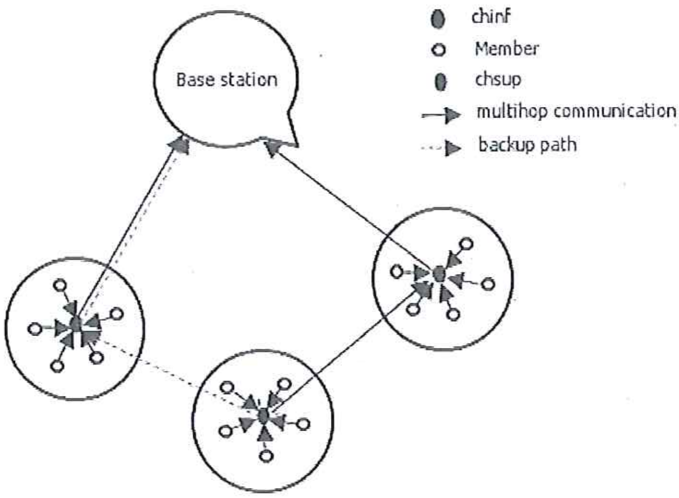

Figure 2. Modified LEACH

3.3. Strengths and weaknesses of the proposed method

Strengths:

- Minimize energy consumption
- In the presence of faults, the protocol is resistant to failures.
- The ratio of lost packets is almost negligible
- Ensure network availability.

Weaknesses:

- More of advertisement exchanges messages.
- Overhead is high

4. Simulation and evaluation

We have conducted several simulations to illustrate the performance of our contribution using TOSSIM simulator [11], and we have compared them with the original version of LEACH in terms of energy consumption and the ratio of successful received packets at the base station. For that, we used a network that contains respectively 50, 100, 150 and 200 stationary nodes, which are randomly deployed on a 100mx100m square area and the initial energy is equal to 2 joules for every node except the base station. The simulations were performed in 600 seconds. Table I summarize simulation parameters.

Table1. Simulation Parameters

Parameter	Value
Deployment area	100m x 100m
Simulation time	600 sec
Number of nodes	50, 100, 150, 200
Packet size	29 octets
Initial node energy	2 J

In this context, the energy consumption is calculated according to the model of Shnaydar et. al [12]. In this model, the energy consumption of the transmission and reception of one bit using MICA2 sensor [13] is respectively 4.602 µj, 2.34 µj. We also considered a model of failures i.e. there is a probability that a clusterhead might stop working.

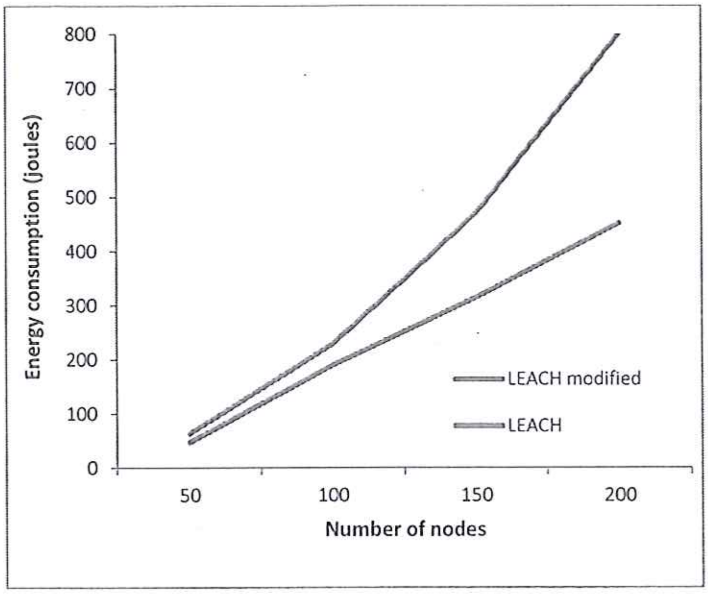

Figure 3. Variation of energy consumption with number of nodes

Figure 3 shows that the energy consumption in our proposed contribution is less than in the original version of LEACH because in our contribution, we have assumed that if the base station is far enough from the clusterhead that wants to send information, this latter could involve another clusterhead as relay node which is close to the base station. However, in the original version of LEACH, heads directly send the data to the base station regardless of the distance that separates them. Moreover, it is proved that the use of a multihop routing scheme consumes less than direct communication.

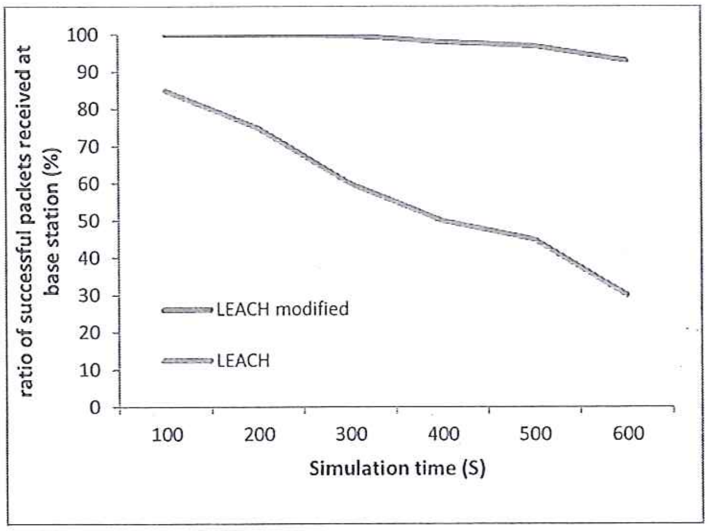

Figure 4. Ratio of successful packets received over time

Figure 4 shows that the ratio of successful packets received at the base station over simulation time in LEACH modified is higher than in the original version of LEACH. In LEACH when a clusterhead fails it affects its own cluster and data of its members could not reach the base station but in our contribution if a clusterhead stops working it would not be used as a relay node and the clusterhead that used it as relay node uses the backup path.

5. Conclusion

In this paper, we have proposed an enhanced version of LEACH to improve the performance of the original version of LEACH by using a multihop routing scheme and to deal with fault-tolerance in WSN. The evaluation of LEACH by using a multihop routing scheme greatly increases the amount of data received at the base station during network lifetime. Moreover, we proposed another improved version of LEACH to make it a fault-tolerant protocol. In this context, the simulation results showed that our contribution has successfully attained an effective behavior in terms of energy consumption and ratio of packets successfully received at base station.

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