Low Energy Fixed Clustering Algorithm (LEFCA) for Wireless Sensor Networks

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***Abstract*— Wireless sensor networks (WSNs) have become an important part of our lives as they can be used in vast application areas from disaster relief to health care. As a consequence, the life span and the energy consumption of a WSN has become a challenging research area. According to the existing studies, instead of using direct transmission or multi-hop routing, clustering can significantly reduce the energy consumption of sensor nodes and can prolong the lifetime of a WSN. In this paper, we propose a low energy fixed clustering algorithm (LEFCA) for WSNs. With LEFCA, the clusters are constructed during the set-up phase. A sensor node which becomes a member of a cluster stays in the same cluster throughout the life span of the network. LEFCA not only improves the lifetime of the network, but also decreases the energy dissipation and increases the throughput significantly.**

Keywords—Wireless Sensor Networks; Clustering; Energy-Efficient Routing

I. INTRODUCTION

A WSN contains spatially distributed sensor nodes that can sense, record and distribute physical and environmental parameters. WSNs have become an active research area since they have integrated in our daily lives with a vast number of applications, such as disaster relief, target tracking, environmental control, smart cities, medicine and health care.

To distribute the sensed data, different approaches are used. With direct transmission, each sensor node directly transmits its sensed data to a remote receiver. Thus, the sensor nodes do not require any type of communication amongst themselves. With multi-hop routing, each sensor node transmits its data to the remote receiver through other sensor nodes in the network. On the other hand, with clustering, sensor nodes form clusters and a sensor in the cluster is elected as the cluster head (CH) for gathering and distributing the collected data in its own cluster. Clustering allows the use of energy to be spread as evenly as possible among the sensor nodes.

One of the major challenges for the deployment of a WSN is the lifetime of the network [1]. Limited supply of energy of the sensor nodes directly impact the network lifetime. As a consequence, energy efficient ways of operation for the WSNs is extremely important to increase the network lifetime. To achieve this objective, energy efficient protocols and algorithms are being extensively studied. Node clustering [2], in-network data processing [3], data fusion [4], network coding [5] are among the efficient measures taken to reduce the amount of data that is processed, sensed or transmitted.

Cluster based routing algorithms have better energy utilization rate when compared with non cluster routing algorithms. One major goal of cluster based routing protocols is to efficiently maintain the energy consumption of sensor nodes by involving them in multi-hop communication within a cluster and by performing data aggregation and fusion in order to decrease the number of transmitted messages to the sink and transmission distance of sensor nodes.

LEACH (low-energy adaptive clustering hierarchy) [6, 7, 8] is one of the most popular distributed cluster based routing protocols for WSNs. In LEACH, each data transmission round consists of a set-up and steady-state phase. In the set-up phase, some of the nodes in the network elect themselves as CHs according to a threshold level. After the CHs advertise themselves, the remaining nodes join to a cluster by finding the closest CH. In the steady-state phase, when the clusters are formed, the nodes transmit their data to the CHs and the CHs aggregate, compress and forward the collected data to the base station. This process is repeated every round for the entire lifetime of the WSN.

LEACH protocol can achieve a significant overall energy dissipation savings when compared to direct transmission or multi-hop routing. On the other hand, due to the nature of LEACH, cluster topology can change at every transmission round and this can induce more energy dissipation and bring extra network costs. To overcome this problem, we propose a new low energy fixed clustering algorithm (LEFCA). By this way, not only the overall energy dissipation can be reduced further but also the network lifetime can be significantly increased. LEFCA works in two phases. The first phase is set-

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up phase where the clusters are formed, and the second phase is the steady-state phase where data transmission occurs. Different from LEACH, the set-up phase is not repeated for every round by using fixed clusters, which in turn results in significant savings.

The rest of the paper is organized as follows: Section II describes the LEFCA algorithm and its phases. Section III describes the simulation environment and Section IV presents the simulation results and compares LEFCA and LEACH. The paper concludes with conclusions and the future work in Section V.

II. Low Energy Fixed Clustering Algorithm (LEFCA)

LEFCA uses the clustering approach by partitioning the nodes into fixed clusters. For each cluster a CH is responsible for collecting and delivering the sensed data to the base station. The operation of LEFCA is divided into two different phases. In the set-up phase, the clusters are formed by electing the CHs. After the determination of the member nodes for each cluster, the initial CHs set the TDMA schedule for their clusters. In the steady-state phase, the collected data is transferred to the base station through the CHs and each CH determines whether to continue as a CH or elect a new one. The operation of the steady-state phase is repeated in time frames referred to as rounds.

The following subsections explain the operation of the set-up and steady-state phases of LEFCA in detail.

1. Set-Up Phase

With the deployment of the sensors, the LEFCA algorithm initiates with the set-up phase, as illustrated in Fig. 1. Each deployed sensor node self-elects itself as a CH or a regular node. A CH node is responsible for setting up the cluster by broadcasting its identity so that neighbor nodes join its cluster. When the members of a cluster are determined, the CH sets up and announces the TDMA schedule for the member nodes which denotes the corresponding time frames of data transmission for the cluster members. This phase includes two sub phases: cluster head selection phase and cluster formation phase.

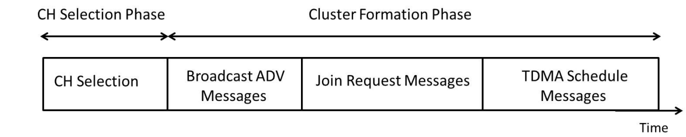

Fig. 1. The Set-Up phase for LEFCA algorithm.

a. Cluster Head Selection Phase

In LEFCA, the clusters are formed by a distributed algorithm in which each sensor node makes an autonomous decision without any centralized control.

Suppose that the desired number of clusters for the sensor network is denoted by *nc* (number of clusters) and the number of sensor nodes is *N*. Thus, each node has a $P_{CH} = nc / N$ chance to be elected as a CH.

Each node i ($1 \leq i \leq N$) in the network picks up a random probability Pi to be elected as a CH in the set-up phase.

If $Pi \leq P_{CH}$, then node i elects itself as a CH. Otherwise, that node becomes a regular cluster member. However, a node which is not chosen as a CH in the set-up phase has a chance to become a CH in the subsequent rounds. The main objective of LEFCA is to abuse the energy of a CH node, before electing a new CH node. Thus, when a CH node does not have enough energy to sustain, other cluster members can be elected as a CH during the rounds in the steady-state phase.

b. Cluster Formation Phase

Each node which has elected itself as a CH needs to notify the remaining nodes about the selection and later form the clusters for the LEFCA algorithm.

To distribute the identity of the CHs in the network, each CH node broadcasts an advertisement message (ADV) using a carrier-sense multiple access (CSMA) MAC protocol [6]. The ADV message includes the CH node's ID.

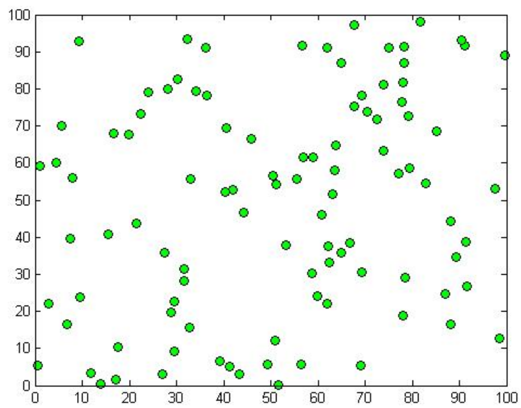

Fig. 2. The randomly deployed sensor nodes in a WSN.

When the ADV messages are distributed in the network, each regular node receiving these messages needs to determine to which cluster it belongs to. This determination is made based on the received signal strengths of the advertisement messages. A regular node chooses to join the CH with the highest received signal strength by replying back a join-request message to the associated CH using CSMA MAC protocol. The join-request message contains the regular node's ID and the ID of the CH that the node wants to join to.

With the join-request messages, the CHs learn about the identity of the members that belong to their clusters. With this information, the CHs prepare a TDMA schedule for their cluster members and broadcast this schedule to the members in their clusters. The TDMA schedule allocates specific time intervals for each of the cluster members to transmit their collected data to their CHs. TDMA schedule not only prevents the collisions among data messages but also enables the radio components of each regular node to put to sleep mode at all times except during their transmit time, thus providing energy savings.

After the reception of the TDMA schedule by the cluster member nodes, the set-up phase is completed and data transmission with the steady-state phase is ready to start. Fig. 2 shows an example of a randomly deployed sensor nodes in a WSN and Fig. 3 shows an example illustration of the clusters formed after the LEFCA set-up phase.

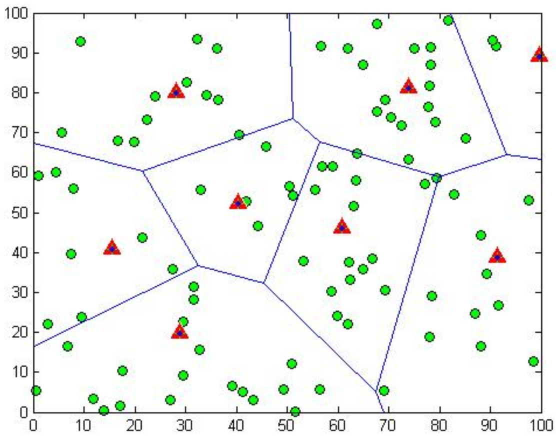

Fig. 3. The cluster formation and CHs after the set-up phase.

2. *Steady-State Phase*

The main objective of the steady-state phase is to transmit the collected data to the base station through the CHs and to determine whether a CH change needs to be made. In the steady-state phase the LEFCA algorithm works and repeats itself in rounds and Fig. 4 shows a typical round for the LEFCA algorithm. A round has two sub phases: data transmission and CH change decision.

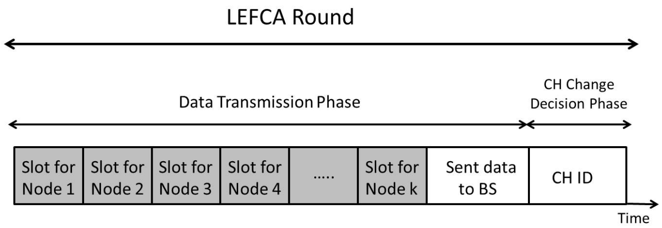

Fig. 4. The LEFCA Round. Data transfers and changing of CHs if needed occur during the steady-state phase.

a. Data Transmission Phase

This phase is divided into slots allocated for each of the cluster members, where the member nodes transmit their data to the CH. The duration for each slot is fixed, thus the time to transmit data hinges on the number of member nodes in the cluster. When the data collection from the cluster members is complete, the CH transmits the data to the base station.

Data transmission in one cluster can affect communication in neighbor clusters because of the broadcast medium of radio. To prevent inter-cluster interference, each cluster in LEFCA uses a unique code. The assignment order of these codes is predefined and they are allocated to CHs in turn referred to as transmitter-based code assignment [6].

The collected data from cluster members is transmitted from CH nodes to the base station using a constant code and CSMA. CHs sense the channel to check if it is idle. If the channel is idle, the CHs transmit the collected data to the base station. Otherwise, they wait to send the collected data to the base station.

b. Cluster Head Change Decision Phase

The LEFCA algorithm uses fixed clusters, thus a sensor node which becomes a member of a cluster during the set-up phase stays as a member of the same cluster for the entire lifetime of the sensor network. However, the CHs may change for each LEFCA round.

When the data transmission phase of a round is complete, the CH needs to decide whether it will continue to act as a CH for the next round or choose a new CH. This decision is made based on the CH's remaining energy. If the CH's remaining energy is above a predefined threshold value (*ThV*), it continues to act as the CH for the next round and notifies the cluster members by specifying its CH ID. If on the other hand, the CH's remaining energy is below the *ThV*, the current CH selects a new cluster head which will become the new CH in the next round and notifies the cluster members by specifying the new CH's ID. If a new CH needs to be elected, the current CH chooses the new one randomly among the alive members of its cluster. Fig. 5 illustrates, the CH change mechanism in LEFCA while keeping the clusters fixed.

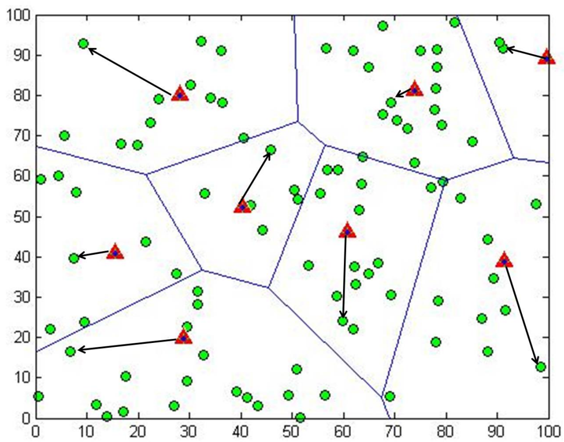

Fig. 5. CH changes in LEFCA

In a typical round, a CH node will consume significantly more energy than the regular nodes and the basic motivation behind the LEFCA algorithm is to abuse the CH node by keeping it as a CH as much as possible while trying to keep the regular nodes' energy at a maximum. This type of CH changing mechanism provides substantial energy savings, as new cluster topologies are not formed for every round. There is no need to use advertisement, join request and TDMA schedule messages for each round as the clusters are fixed.

III. Simulation Environment And Parameters

To evaluate the performance of LEFCA, the impact of the number of clusters, the system lifetime, energy dissipation and throughput is simulated and compared with the traditional LEACH algorithm.

For the experimental setup, the simulations are conducted on a *100*-node sensor network where the nodes are randomly deployed in an area of *100* by *100* meters. The base station is placed outside the sensor node deployment area at coordinates (*150, 50*).

TABLE I. Simulation Environment Parameters

Parameters	Values
Network area	100 m x 100 m
Number of nodes	100
Base station coordinates	(150,50)
Initial energy per node	2 J
Data packet size	6400 bits
Control Packet Size	200 bits
Transceiver Energy (E_{elec})	50 nJ/bit
Aggregation Energy per Bit (E_{DA})	5 nJ/bit/signal
Free Space Amplifier Energy (ε_{fs})	10 pJ/bit/m²m²
Multipath Amplifier Energy (ε_{mp})	0.0013 pJ/bit/m⁴m⁴

A simple model for the radio hardware energy consumption is used to run the simulations. The transmitting nodes dissipate energy to run the radio electronics and the power amplifier, and the receiving nodes consume energy to run the radio electronics. Depending on the threshold distance d_o, *fs* (free space with d^2 power loss) and *mp* (multipath fading with d^4 power loss) channel models which are based on the distance between transmitter and the receiver are used [6].

Thus, to transmit an *l*-bit message through a distance *d* the radio expends:

$$E_{Tx}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2, & d < d_o \\ lE_{elec} + l\varepsilon_{mp}d^4, & d \geq d_o \end{cases},$$

and to receive a message, radio expends:

$$E_{Rx}(l) = lE_{elec}.$$

The transceiver energy (E_{elec}) depends on digital coding, modulation, spreading of the signal and filtering. The free space amplifier energy (ε_{fs}) and the multipath amplifier energy (ε_{mp}) depends on the distance to the receiver and the agreeable bit-error rate. Table I summarizes the simulation environment parameters used for LEFCA and LEACH simulations.

IV. Simulation Results and Comparison of LEACH And LEFCA

1. *Impact of the Number of Clusters*

We investigate the impact of the number of clusters on the performance of LEFCA. [6] demonstrates that the optimum number of clusters should be $1<k_{opt}<6$, for a network with *100* randomly deployed sensor nodes implementing LEACH. Fig. 6 shows the lifetime of a WSN as a function of the number of clusters for different threshold values under LEFCA. It is observed that, for LEFCA the optimum number of clusters for a 100 sensor node network is $6 \leq k_{opt} \leq 8$ for various *ThV* values. Thus, for the rest of the simulations, the number of clusters is set to *8*.

The impact of the *ThV* on the network lifetime can also be observed in Fig. 6. As the *ThV* decreases, the network lifetime increases. A decrease in the *ThV* value results in a higher level of CH abuse and less number of CH changes which in turn extends the network lifetime.

Note that, the lifetime of LEACH for the same network is approximately 3200 rounds and a significant improvement for network lifetime is achieved with LEFCA.

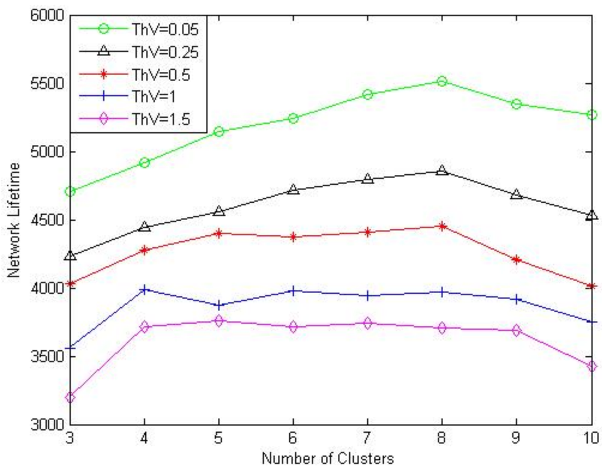

Fig. 6. Network Lifetime vs. Number of Clusters for various threshold values (*ThV*) under LEFCA

Fig. 7 shows the residual energy in the network as a function of the number of clusters for various threshold values at round *3000.* The simulations start with an initial network energy of *200 J* (2 J/node). At the end of the *3000th* round, with *8* clusters and and *ThV= 0.05 J*, LEFCA still has approximately *40 J* of residual energy. On the other hand, when the simulation is repeated on the same network with LEACH at 3000th round, the network lifetime is almost over with a residual energy of *0.3 J.* When the batteries of nodes in LEACH are almost drained, the alive nodes in LEFCA can still perform and continue with their tasks.

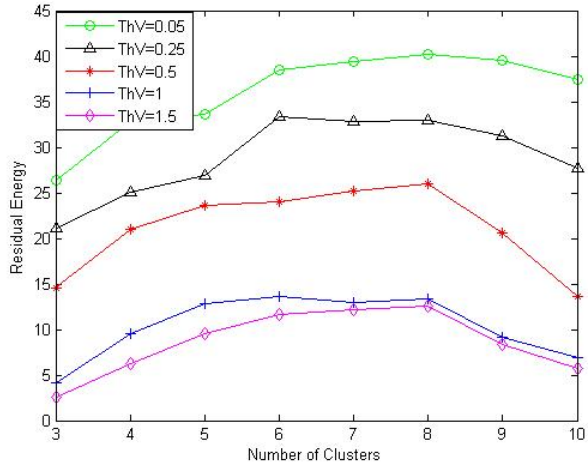

Fig. 7. Residual Energy vs. Number of Cluster for various threshold values (*ThV*) under LEFCA at round 3000.

2. *System Lifetime and The Residual Energy*

Fig. 8 shows the cumulative number of dead nodes versus round number thus the network lifetime of LEACH and LEFCA. Under LEFCA, the network lifetime increases from *3237* rounds to approximately *5600* rounds, a *57%* improvement compared to LEACH. Although, node deaths start earlier under LEFCA, since the CHs are abused, the rate of the number of dead node increases is significantly less and this yields to a longer lifetime.

One major difference between LEACH and LEFCA can also be observed from Fig. 8. Immediately following the first node death under LEACH, the remaining node deaths will occur rapidly. But with LEFCA, node deaths are distributed evenly for the network lifetime.

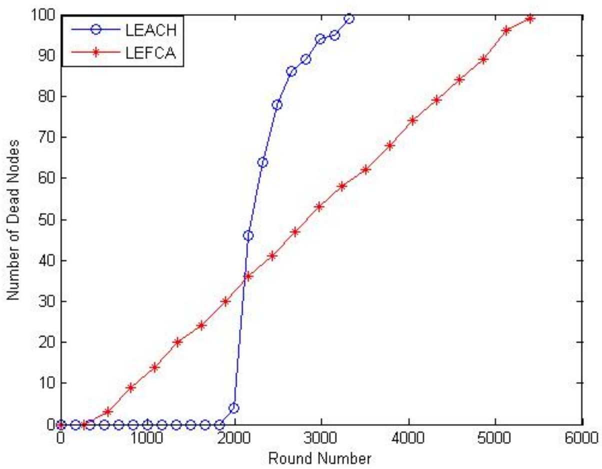

Fig. 8. Comparison of Number of Dead Nodes and Lifetime

Fig. 9 illustrates the total residual energy of the WSN for LEACH and LEFCA protocols for a selected *ThV = 0.05 J*. With fixed clustering and full utilization of the CHs, it can be observed that LEFCA provides a significant energy savings when compared to LEACH. For example, after *2000* rounds of operation, LEACH holds *15%* of its initial total energy, while LEFCA holds approximately *50%* of its initial total energy.

When the network lifetime ends under LEACH, LEFCA still maintains approximately *20%* of its total initial energy.

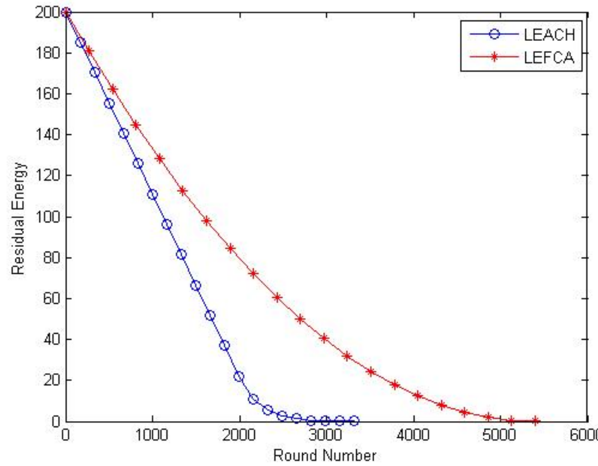

Fig. 9. Comparison of Total Residual Energy

3. *Throughput*

LEACH and other LEACH based protocols [9, 10, 11, 12, 13] in literature have an important deficiency. Under LEACH based protocols, sensor nodes elect themselves as CHs based on a probabilistic mechanism. Each sensor node generates a random number from *U(0,1)* and if the random number generated is less than a threshold level then that sensor node becomes a CH and broadcasts an announcement message to inform the other sensor nodes. However, with this mechanism it is highly probable that none or very few of the sensor nodes can elect themselves as CHs especially when the number of alive nodes is a few. Thus, for some rounds, very few or no clusters are formed. If the number of clusters is very few or zero, then data cannot be collected and transmitted in such a round and this will have a significant impact on the utilization.

Fig. 10 shows the number of clusters formed at each round under LEACH and LEFCA. With the fixed clustering mechanism, LEFCA protocol keeps the number of clusters constant until all the nodes in a cluster are dead. Later LEFCA delivers sensed data to the base station with the remaining clusters. On the other hand, with LEACH protocol the number of clusters vary continuously. After the first node death around 2000th round, clusters cannot even be formed for many rounds as node deaths occur more rapidly under LEACH.

When the throughput of both protocols is compared, the total number of packets delivered to the base station from the CHs are calculated. With this approximation, LEACH transmits *11832* packets over its lifetime, while LEFCA transmits *35327* packets over its lifetime, more than triple compared to LEACH.

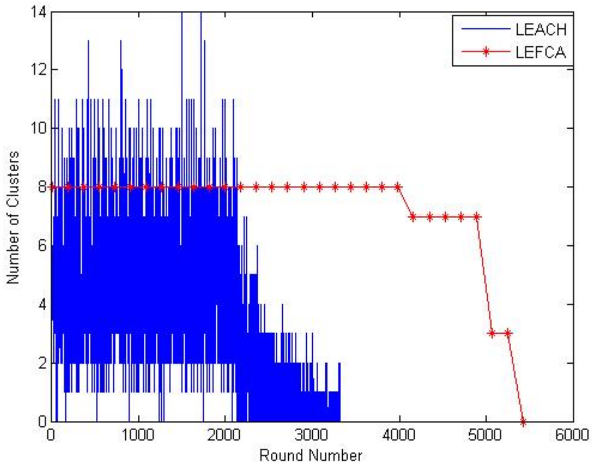

Fig. 10. Number of Clusters vs. Round Number (Throughput)

V. Conclusions And Future Work

Providing energy-efficiency [14, 15, 16], increasing lifetime and contributing to green networking solutions [17,18] for WSNs has become a key research area. By using fixed number of clusters and reducing the number of CH changes, LEFCA minimizes the cluster formation overhead. When compared with LEACH, significant improvements are obtained in terms of energy usage, lifetime and throughput. LEFCA increases the lifetime of the WSN, while decreasing the energy usage. As a result, the throughput is also increased.

In LEFCA, it has been observed that clusters that are farthest from the base station tend to consume more energy due to the distance factor. By placing relay nodes and transmitting the collected data through the relay nodes, the energy expenditure thus the lifetime of these clusters can be improved further. Another way to improve the LEFCA algorithm might be to include a smart CH selection mechanism. Instead of picking up a random cluster member to become the next CH, the nearest member or the member with the maximum remaining energy can become the next CH.

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