Prolonging Network Lifetime and Data Accumulation in Heterogeneous Sensor Networks

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Abstract: *Research on Wireless Sensor Networks has often assumed homogeneous nodes. In reality, homogeneous nodes have different capabilities like different levels of initial energy and drain rate. This leads to the research on heterogeneous networks where two or more types of nodes are considered within the network and the more powerful sensor nodes act as cluster heads. In this paper, we have analyzed a heterogeneous network with three types of nodes having different initial energy levels. A single hop clustering topology has been assumed and analyzed the network performance in terms of lifetime. Simulation results show that the network lifetime is much better in proposed protocol than the existing protocols.*

Keywords: *Wireless sensor networks, heterogeneous, lifetime, clustering.*

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1. Introduction

With rapid advancement in electronics industry, small inexpensive battery-powered wireless sensors have already started to make an impact on the communication with the physical world. The Wireless Sensor Networks (WSNs) consist of large number of low cost devices to gather information from the diverse kinds of physical phenomenon. The sensors can monitor various entities such as: temperature, pressure, humidity, salinity, metallic objects, and mobility; this monitoring capability can be effectively used in commercial, military, and environmental applications [5, 10, 12]. For these sensor network applications, most research has discussed problems by the deployment of large number of low-cost homogeneous devices. However, it is often feasible to consider the deployment of heterogeneous devices with different capabilities.

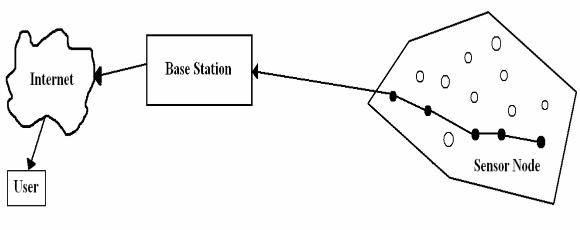


Figure 1. Architecture of a sensor network.

A sensor network is composed of tens to thousands of sensor nodes which are distributed in a wide area. Figure 1 shows the communication architecture of a sensor network in which sensor nodes are shown as small circles. Each sensor node is made up of four basic components as shown in Figure 2: a sensing unit, a processing unit, a transceiver unit and a power unit. They may also have application dependent additional optional components such as a location finding system, a power generator and a mobilizer. Sensing units are usually composed of two subunits: sensors and Analog to Digital Converters (ADCs). The analog signals produced by the sensors based on the observed phenomenon are converted to digital signals by the ADC, and then fed into the processing unit. The processing unit which is generally associated with a small storage unit manages the procedures that make the sensor node collaborate with the other nodes to carry out the assigned sensing tasks. A transceiver unit connects the node to the network. One of the most important components of a sensor node is the power unit. Power unit may be supported by a power scavenging unit such as solar cells.

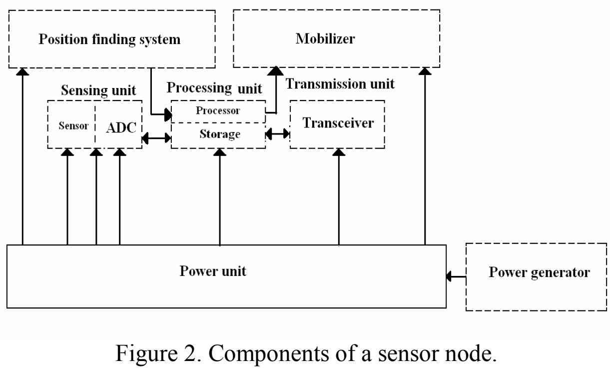


Figure 2. Components of a sensor node.

There are also other subunits, which are application dependent. Each node has the ability to sense elements of its environment, perform simple computations, and communicate among its peers or directly to an external Base Station (BS). A base station may be a fixed node or a mobile node capable of connecting the sensor network to an existing communications infrastructure or to the Internet where a user can have access to the reported data.

Hierarchical routing is one of the most popular routing schemes in sensor networks [5, 10, 11, 12, 13, 16, 19]. It is a two or more tier routing scheme known for its scalability and communication efficiency. Nodes in the upper tier are called cluster-heads and act as a routing backbone, while nodes in the lower tier perform the sensing tasks. In all the cases the lifetime of a sensor and the lifetime of the network, which directly determines the duration of the sensing task, is limited by the amount of energy each sensor has. Therefore when we examine these networks, efficient use of energy is a primary concern. While it is tempting to simply apply existing research in wireless networks to sensor networks, sensor networks have enough particular characteristics and challenges to justify their specific study [3]. Sensor networks have been quite extensively studied in the past few years; see for example [2, 4, 5, 6, 7, 8, 9, 19].

All the recent research work focuses on sensor networks that consist of identical sensors with equal capacity in terms of sensing, computation, communication, and power. Consequently we consider this type of sensor networks homogeneous. The possibility of working with more than one type of sensors within a same network is mentioned in [15], but without in depth study of this possibility. We have observed that the manufacturing of a sensor is generally application-specific. Different special purpose sensors can be used to form a single sensor network to perform more comprehensive tasks, e.g., some sensors collect image data, some sensors collect audio signal, some sensors have more processing capability, some sensors have more power, and so on. This results in a heterogeneous sensor network that can have a variety of compositions of sensors. Many organizational and communication issues arise with such a structure. The core operation of WSN is to collect and process data at the network nodes, and transmit the necessary data to the BS for further analysis and processing. In this paper, we have examined one of the simplest heterogeneous scenarios in which sensors are equipped with different battery power in an event-driven sensor network. In particular, we have considered a field randomly deployed with sensors that gather data and transmit it back to a base station, which is assumed to be located far away from the sensing field. Such a scenario is motivated by applications in which data is desired from a hostile environment, such as a volcano or a swamp, where sensors are likely to be deployed in an unmanned manner. Under such situations sensing data will be collected, aggregated, analyzed and transmitted to a more accessible location. The main issue of our interest is to maximize the lifetime of a sensor network for a given amount of energy, or equivalently, and to retrieve the same data using the least amount of energy. The rest of the paper is organized as follows. In Section 2, the related work is discussed. Section 3 shows a paradigm of heterogeneous wireless sensor networks and also describes the network model. Section 4 describes the basic system model and proposed work. Section 5 presents simulation results. Section 6 concludes the paper with future directions.

2. Related Work

In recent years, there has been a growing interest in WSNs. One of the major issues in wireless sensor network is developing an energy-efficient routing protocol. Since the sensor nodes have limited available power, energy conservation is a critical issue in wireless sensor network for nodes and network life. The issue of heterogeneity (in terms of energy) of nodes is addressed in [20]. In [16], the proposed protocol is based on random selection of cluster-heads weighted according to the remaining node energy. This approach addresses the problem of varying energy levels and consumption rates but still assumes that the sink can be reached directly by all the nodes.

In [14], they provide the optimal heterogeneous sensor deployment that minimizes the deployment cost in different communication modes. In their model, the cost of the cluster head device is determined by the amount of initial battery energy, which depends on the number of cluster members and communication mode. They do not consider the sensing coverage and aging process over time. Low-Energy Adaptive Clustering Hierarchy (LEACH) is one of the most popular distributed cluster-based routing protocols in wireless sensor networks [18]. LEACH randomly selects a few nodes as cluster heads and rotates this role to balance the energy dissipation of the sensor nodes in the network. The cluster head nodes fuse and aggregate data arriving from nodes that belong to the respective cluster. And cluster heads send an aggregated data to the sink in order to reduce the amount of data and transmission of the duplicated data. Data collection is centralized to sink and performed periodically. The operation of LEACH is generally separated into two phases, the set-up phase and the steady-state phase. In the set-up phase, cluster heads are selected and clusters are organized. In the steady-state phase, the actual data transmissions to the sink take place. After the steady-state phase, the next round begins.

$$T(s) = \begin{cases} \dfrac{p_{opt}}{1 - p_{opt}.(r \bmod \dfrac{1}{p_{opt}})} & \text{if} \quad s \in G \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

During the set-up phase, when clusters are being created, each node decides whether or not to become a cluster head for the current round. This decision is based on a predetermined fraction of nodes and the threshold T(s). The threshold is given by equation 1 where p_{opt} is the predetermined percentage of cluster heads (e.g., $p_{opt} = 0.05$), r is the current round, and G is the set of nodes that have not been cluster heads in the last $1/p_{opt}$ rounds. Using this threshold, each node will be a cluster head at some round within $1/p_{opt}$ rounds. After $1/p_{opt}$ rounds, all nodes are once again eligible to become cluster heads. In LEACH, the optimal number of cluster heads are estimated to be about 5% of the total number of nodes. Each node that has elected itself cluster head for the current round broadcasts an advertisement message to the rest of the nodes in the network. All the non cluster head nodes, after receiving this advertisement message, decide on the cluster to which they will belong for this round. This decision is based on the received signal strength of the advertisement messages. After cluster head receives all the messages from the nodes that would like to be included in the cluster and based on the number of nodes in the cluster, the cluster head creates a TDMA schedule and assigns each node a time slot when it can transmit. In [1], authors have developed a Distance-Based Segmentation (DBS), a cluster-based protocol that divides the entire network into equal area segments and applies different clustering policies to each segment that significantly decreases the energy imbalance in the wireless network and hence prolong the lifetime of the network system. To evaluate the DBS protocol, a simulator was designed by using the MATLAB software.

3. Network Model

The main goal of hierarchical cluster-based routing protocol is to efficiently maintain the energy consumption of sensor nodes by involving them in single-hop communication within a cluster and performing data aggregation and fusion in order to decrease the number of transmitted messages to sink and transmission distance of sensor nodes. To simplify the network model, we adopt few reasonable assumptions which are as follows: 1) n sensors are uniformly dispersed within a square field (200m x 200m); 2) All sensors and BS are stationary after deployment; 3) The communication is based on the single-hop; 4) Communication is symmetric and a sensor can compute the approximate distance based on the received signal strength if the transmission power is given; 5) All sensors are location-unaware; 6) All sensors are of equal significance. We use a simplified model shown in [6] for the radio hardware energy dissipation as follows. To transmit an L –bit data to a distance d, the radio expends:

$$E_{TX} = L.(S + \mu.d^4) \tag{2}$$

$$E_{TX} = L.(S + \tau.d^2) \tag{3}$$

where S is the energy dissipated per bit to run the transmitter or the receiver circuit. The first item presents the energy consumption of radio dissipation, while the second presents the energy consumption for amplifying radio. Depending on the transmission distance both the free space τ and the multi-path fading μ channel models are used. When receiving this data, the radio expends: $E_{RX}=L.S$. Additionally, the operation of data aggregation consumes the energy as E_{DA}. In the following sections, we have presented a paradigm of heterogeneous WSN and discuss the impact of heterogeneous resources.

3.1. Heterogeneous Model for WSN

Nowadays, WSNs attracted lots of researchers because of its potential wide applications and special challenges. For past few years, wireless sensor networks mainly focused on technologies based on the homogeneous wireless sensor network in which all nodes have same system resource but recently heterogeneous wireless sensor network is becoming more and more popular and the results of researches show that heterogeneous nodes can prolong network lifetime and improve network reliability without significantly increasing the cost.

3.2. Types of Heterogeneous Resources

The heterogeneous resources are basically divided into three categories: computational heterogeneity, link heterogeneity, and energy heterogeneity [17]. *Computational heterogeneity* means that the heterogeneous node has a more powerful microprocessor or microcontroller and more storage memory than the normal node. The sensor nodes with more powerful computational resources can provide complex data processing and long-term storage. *Link heterogeneity* means that the heterogeneous node has high-bandwidth and long-haul network transceiver (Ethernet or 802.11 networks) than the normal node. Link heterogeneity can provide more reliable data transmission. Therefore, the reliability of the data transmission will increase by link heterogeneity. Energy heterogeneity means that the heterogeneous node is line powered, or its battery is replaceable. Among above three categories of resource heterogeneity, the energy heterogeneity is most important because both computational heterogeneity and link heterogeneity will consume more battery energy resource. If there is no energy heterogeneity, computational heterogeneity and link heterogeneity will bring negative impact to the sensor network.

3.3. Impact of Heterogeneous Resources on WSNs

The impact of placing few heterogeneous nodes in the sensor network can bring the following benefits. Prolonging network lifetime: In the heterogeneous WSN, the average energy consumption for forwarding a packet from the normal nodes to the sink will be much less than the energy consumed in homogeneous sensor networks. Improving reliability of data transmission: It is well known that sensor network links tend to have low reliability. And each hop significantly lowers the end-to-end delivery rate. With heterogeneous nodes; there will be fewer hops between normal sensor nodes and the sink. So the heterogeneous sensor network can get much higher end-to-end delivery rate than the homogeneous sensor network. *Decreasing latency of data transportation:* Computational heterogeneity can decrease the processing latency in immediate nodes. And link heterogeneity can decrease the waiting time in the transmitting queue. Fewer hops between sensor nodes and sink node also mean fewer forwarding latency.

4. System Model Architecture

Consider the cluster based WSN with 200 sensor nodes dispersed in a field as shown in Figure 3. BS, an observer is located inside the field remotely. The observed field is composed of several clusters. Each cluster has one CH which acts as a local control centre to coordinate the data transmissions. All of these components are based on the following assumptions and the radio model.

- The WSNs consist of the heterogeneous sensor nodes.
- The BS is located inside the WSNs.
- Some sensor nodes have different initial energy.
- All sensor nodes and BS are stationary after deployment

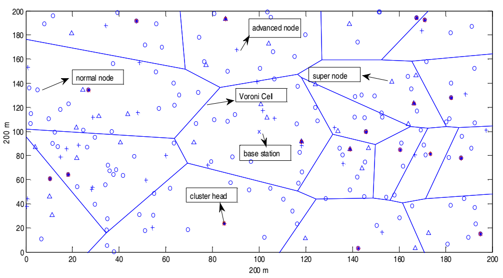


Figure 3. Network model.

4.1. Optimal Clustering

According to the radio energy model described in [5] the optimum number of clusters k_{opt} for a cluster-based network that uses LEACH communication protocol and contains n sensor nodes distributed uniformly in a region (*M*x*M*) has been calculated which is given in equation 4:

$$k_{opt} = \sqrt{\frac{n}{2\pi}}\sqrt{\frac{\tau}{\mu}}\frac{M}{d^2} \quad (4)$$

where d is the distance from the cluster head node to the BS. Substituting minimum and maximum values of d, the upper bound and lower bound of the desired number of clusters can be obtained.

4.2. Proposed Mechanism

We have considered a heterogeneous network with three types of nodes (normal, advanced and super nodes) that are deployed in a harsh environment. Advanced and super nodes are more powerful and are having higher battery power than the normal nodes. We have assumed the cluster head election is based on the battery power and residual energy of the node. We have analyzed network lifetime by using the characteristic parameters of heterogeneity, namely the few advanced and super nodes of α and β times more energy than the normal nodes in order to prolong the lifetime of the sensor network. Intuitively, super and advanced nodes have to become cluster heads more often than the normal nodes, which is equivalent to a fairness constant on energy consumption. The new heterogeneous setting has changed the total initial energy of the network and does not affect on the spatial density of the network. We assumed the following variables for the:

E_2=*Energy of super node.*
E_1=*Energy of advanced node.*
E_0=*Energy of normal node.*
E_{t2}=*Total initial energy of advanced nodes.*
E_{t1}=*Total initial energy of super nodes.*
E_{t0}=*Total initial energy of normal nodes.*

$$E_2 = E_0.(1+\beta) \quad (5)$$

$$E_1 = E_0.(1+\alpha) \quad (6)$$

$$E_{t1} = m.n.p.E_2 \quad (7)$$

$$E_{t2} = m.n.E_1.(1-p) \quad (8)$$

$$E_{t0} = n.(1-m).E_0 \quad (9)$$

The total initial energy of the new heterogeneous sensor network setting is given by equation 10.

$$Q = \alpha - p.(\alpha - \beta)$$

$$E_t = n.E_0.(1+m.Q) \quad (10)$$

Our approach is to assign a weight to the optimal probability p_{opt}. This weight must be equal to the initial energy of each node divided by the initial energy of the normal node. Let us define that P_1, P_2 and P_3 are the weighted election probabilities for the normal advanced and super nodes. In order to maintain the minimum energy consumption in each round within an epoch, the average number of cluster heads per round per epoch must be constant and equal to $p_{opt}.n$. In this type of scenario the average number of cluster heads per round per epoch is equal to $n.(1+m.Q)$. The weighed probabilities for normal, advanced and super nodes are respectively:

$$P_1 = \frac{p_{opt}}{1 + m.Q} \quad (11)$$

$$P_2 = \frac{p_{opt}}{1 + m.Q}.(1 + \alpha) \quad (12)$$

$$P_3 = \frac{p_{opt}}{1 + m.Q}.(1 + \beta) \quad (13)$$

In equation 1, we have replaced p_{opt} by the weighted probabilities to obtain the threshold that is used to elect the cluster head in each round. We define *T(s1)*, *T(s2)* and *T(s3)* are the thresholds for normal, advanced and super nodes. Thus, the threshold for normal nodes can be evaluated by equation 14.

$$T(s1) = \begin{cases} \frac{P_1}{1 - P_1.(r \bmod \frac{1}{P_1})} & \text{if } s1 \in G' \\ 0 & \text{otherwise} \end{cases} \quad (14)$$

where r is the current round, G' is the set of normal nodes that have not become cluster heads within the last $1/P_1$ rounds of the epoch, and *T(s1)* is the threshold applied to a population of $n.(1-m)$ normal nodes. This guarantees that each normal node will become a cluster head exactly once every $(1+m.Q)/P_1$ rounds per epoch, and that the average number of cluster heads that are normal nodes per round per epoch is equal to $n.(1-m).P_1$. Similarly, thresholds *T(s2)* and *T(s3)* are evaluated for advanced and super nodes.

5. Simulation Results and Discussion

The simulation has been done in MATLAB. Let us assume a heterogeneous sensor network with 200 number of sensor nodes are distributed randomly in the 200 x 200 m^2 area, as shown in Figure 3, we denote a normal node with 'o', an advanced node with '+', a super node with '^'. The base station with 'x' is located at point (100, 100). The values used in the first order radio model are described in Table 1. The horizontal and vertical coordinates of each sensor are randomly selected between 0 and maximum value of the dimension. The size of the message that nodes send to their cluster heads as well as the size of the (aggregate) message that a cluster head sends to the base station is set to 50 bytes. Lifetime is the criterion for evaluating the performance of routing protocols in sensor networks. In this work, we measure the lifetime in terms of the round when the first node and half of the nodes die. We have simulated LEACH in the presence of homogeneous parameters.

Table 1. Parameters values used in the simulations.

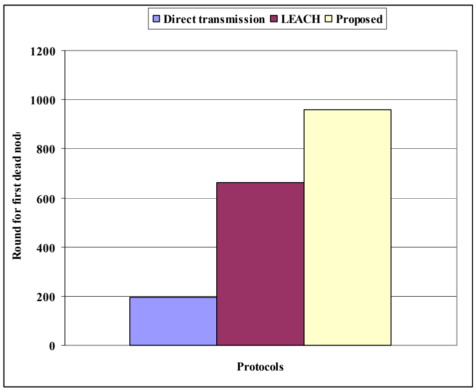
Parameters	Value
Network Span	(0,0) to (200,200)
n	200
d_0	70 m
BS Position	(100,100)
Packet Size	500bytes
E_{DA}	5nJ/bit/report
τ	10pJ/bit/m^2
μ	0.0013pJ/bit/m^4
S	50nJ/bit
E_0	0.5J
p	0.5
m	0.3
α	2
β	1

Direct transmission and all proposed protocol are simulated in the presence of different heterogeneity parameters in the network. The results of proposed, direct transmission and LEACH simulations are shown in Figures 4 and 5. A detailed view of the behaviour of LEACH, direct transmission and proposed protocols is illustrated in Figures 4 and 5 for different distributions of heterogeneity. Figure 4(a) shows that the first node die earlier in case of LEACH and direct transmission. Figure 4(b) indicates that in direct transmission all nodes remain alive for 193 rounds before the first node dies, all nodes remain alive for 661 rounds in LEACH to base station, and in Proposed scheme the number of nodes remain alive for 959 rounds, which is more than LEACH and Direct transmission. This extended the lifetime and stability of network system. Figure 4(c) indicates the other metric parameter (i.e., Half Node Dead (HND)) that also illustrates the network lifetime which is more in Proposed protocol by the factor of 25% than the other protocols. On the other hand, Figure 5(a) shows the number of messages received by the BS. Since in the Proposed protocol more number of alive nodes exists, therefore the packets received by the Proposed protocol is more over more number of rounds. Residual energy is indicated in Figure 5(b). It presents that more residual energy is left in case of Proposed protocol than LEACH since LEACH and Direct transmission dissipates their energies faster as compared to developed protocol.

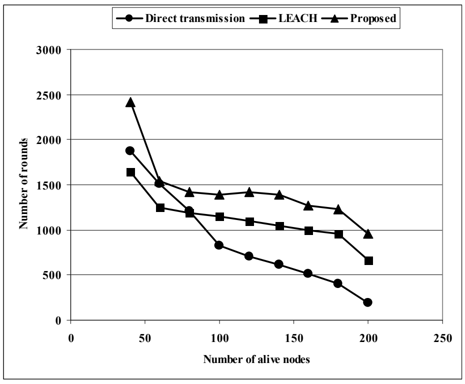
We have also compared the performances of Proposed protocol with Distance Based Segmentation (DBS) in terms of network lifetime that can be evaluated by comparing two metrics (such as FND and HND). Table 2 shows that the Proposed protocol prolongs the network lifetime as compared to DBS if we compared both the protocols with the LEACH. Thus, LEACH, DBS and Direct transmission have shorter network lifetime than the proposed protocol.

Table 2. Comparison of network lifetime by using metrics FND and HND between DBS and proposed protocol with LEACH.

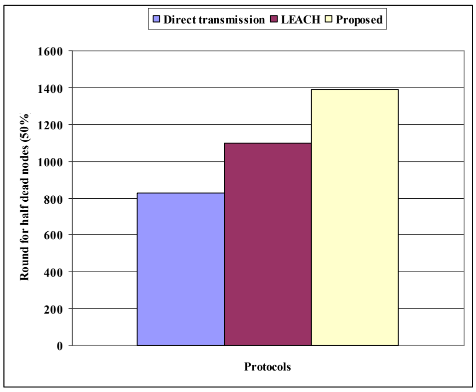
Protocols	Lifetime Improvements in Percentage	
	First Node Dead (FND)	Half Node Dead (HND)
DBS	24(%)	23(%)
Proposed	31(%)	25(%)



a. Round for first dead node.

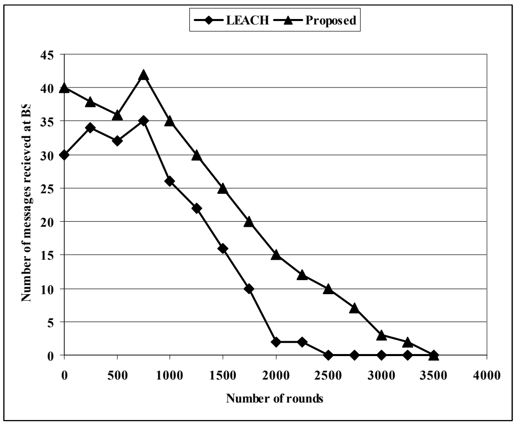


b. Network lifetime.

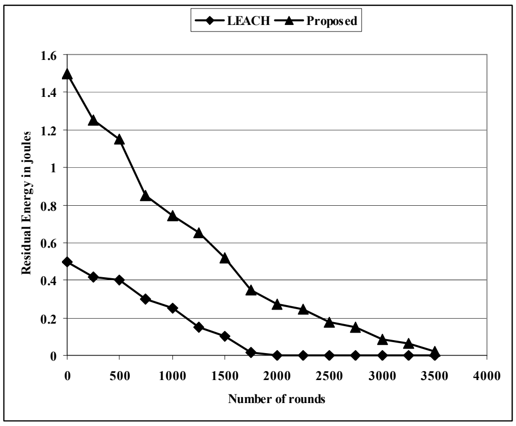


c. Round for 50th dead node in the network.

Figure 4. Proposed, direct transmission and LEACH simulations.



a. Messages received by BS over rounds.



b. Residual energy of the system over rounds.

Figure 5. Proposed, direct transmission and LEACH simulations.

6. Conclusions

In this paper, we have presented clustered heterogeneous wireless sensor networks where more powerful sensor nodes act as cluster heads for more number of rounds. The energy drain rate of battery source is less in advance and super nodes as compared to normal nodes in the system. Based upon the simulation results, the proposed protocol has confirmed that it provides a longer network lifetime as compared to DBS, LEACH and direct transmission. One of our future works will include multihop clustering and fault tolerant mechanism in heterogeneous sensor networks.

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