Pak. J. Engg. & Appl. Sci. Vol. 6, Jan., 2010 (p. 9-16)

Analyzing the Factors Affecting Network Lifetime for Cluster-based Wireless Sensor Networks

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Abstract

Cluster-based wireless sensor networks enable the efficient utilization of the limited energy resources of the deployed sensor nodes and hence prolong the node as well as network lifetime. Low Energy Adaptive Clustering Hierarchy (LEACH) is one of the most promising clustering protocol proposed for wireless sensor networks. This paper provides the energy utilization and lifetime analysis for cluster-based wireless sensor networks based upon LEACH protocol. Simulation results identify some important factors that induce unbalanced energy utilization between the sensor nodes and hence affect the network lifetime in these types of networks. These results highlight the need for a standardized, adaptive and distributed clustering technique that can increase the network lifetime by further balancing the energy utilization among sensor nodes.

Key Words: *Wireless Sensor Networks; Adaptive & Distributed Clustering; Network Lifetime, Scalability; Energy Utilization Analysis*

1. Introduction

Wireless Sensor Network (WSN) consists of a large number of nodes which work collaboratively to achieve some common objective [1]. Major advantages of WSNs over the conventional networks deployed for the same purpose are greater coverage, accuracy and reliability at a possibly lower cost. Some early works on these networks [1], [2], [3] have discussed these benefits in detail. Networking hundreds or even thousands of unattended sensor nodes is receiving a lot of interest in the research community. These networks form a new class of ad-hoc networks having their specific characteristics and challenges. Dense deployment, less mobility and serious energy utilization constraints are some of the exclusive characteristic of these networks. Random distribution of the nodes in the sensing field makes battery recharge or exchange an impossible fact. Small size and dense deployment of these nodes also creates some serious energy utilization constraints. Generally speaking, sensor nodes operate as long as their battery is not depleted. This employs that performance metrics of these networks are different from those of conventional networks. For WSNs, main emphasis in on controlled and balanced power utilization and low cost rather than data throughput or channel efficiency [1].

Considering the broader range of envisioned applications for WSNs like environmental monitoring [4], precision agriculture [5], critical infrastructure protection [6], home and industrial automation [7], monitoring, classification and tracking of moving objects [8], health-care [9], etc. and also the specific performance requirements for these networks, many protocols have already been developed. Clustering is one of the popular techniques that have been used to achieve the specific performance requirements of WSNs. Specially, in large scale networks; clustering techniques can enable scalability, resource allocation, data aggregation, and energy conservation. It is a process of dividing a network into groups of sensor nodes called clusters. Each cluster is managed by a chosen cluster-head (CH). CHs are either selected by the local base station using a centralized algorithm or they contend for this using a distributed algorithm and then ordinary nodes join these CHs based upon cluster joining algorithm. After the completion of the clustering phase, CHs collect data from their member nodes. This collected data can be aggregated if required and then this aggregated data is sent to the BS. Role of CHs can be rotated to balance the energy utilization by sharing the work load among sensor nodes. Although formation and maintenance of clusters introduces additional cost due to the control messages required for the formation and maintenance of clusters but still cluster-based networks have taken much attention of the researchers due to their better performance. Being a popular clustering protocol, Low Energy Adaptive Clustering Hierarchy (LEACH) [10], [11], has attracted intensive attention of the researchers and has become a well studied and popularly referred baseline [12], [13], [14]. A lot of research work has been carried out to further improve the performance of LEACH protocol.

For many envisioned applications for WSNs, sensor nodes can be tasked with periodic reporting of the measured values. The reporting period for the measured values is an application dependent parameter. This paper provides an analysis of those factors that affect the network lifetime by inducing unbalanced energy utilization among sensor nodes in cluster-based WSNs based upon LEACH protocol [10], [11], for periodic monitoring applications. The paper has been arranged as follows. Section-II of this paper provides the background about cluster-based WSNs based upon

LEACH protocol. Using the specifications of the LEACH protocol, the theoretical analysis about node and network lifetime and energy utilization has been carried out in section-III. In section-IV we have discussed the methodology for the development of the simulation environment using OPNET. Also in this section, based upon the simulation results, we have tried to identify the factors that affect the network lifetime by inducing unbalanced energy utilization among sensor nodes. Based upon the simulation results from section-IV, conclusions have been drawn and some recommendations for the future work have been proposed in section-V.

2. Background

LEACH [10], [11] is a distributed clustering protocol which utilizes randomized rotation of local CHs to evenly distribute energy utilization between the nodes of WSNs. The whole operation of the LEACH protocol is divided into rounds. Each round consists of a set-up phase and a steady-state phase. During the set-up phase all nodes are organized into clusters with each cluster having its own CH through short messages communications. During this phase, all nodes broadcast their short messages by using Carrier Sense Multiple Access (CSMA) MAC protocol [15]. For all of its member nodes, every CH sets up TDMA schedules, which are later used to exchange data between the member nodes and the CH. With the exception of their time slots, the member nodes can spend their time in sleep state to conserve energy. The steady state phase is divided into many frames. Number of frames during the steady state phase can be varied as per requirements. During each frame of the steady-state phase data are transferred from member nodes to CHs according to the TDMA schedule. This collected data is aggregated by the CHs to reduce redundancy. The aggregated data is then passed on to the base station (BS) at the end of the frame. Fig.1 shows the timeline diagram of one stretched round [16]. As per specifications of the LEACH protocol, clusters are formed in a distributed manner. Individual nodes make independent decisions without any centralized control. Each node elects itself to be a CH at the beginning of round r with probability $P_i(t)$ such that the expected number of CHs for that round is k. Thus, if there are N nodes in the network.

$$E[\#CH] = \sum_{i=1}^{N} P_i(t) * 1 = k \tag{1}$$

To ensure that all nodes are CHs the same number of time, LEACH protocol requires each node to be a CH once in N/k rounds. If $C_i(t)$ is the indicator function which determine whether or not a node has been a CH in the most recent (r mod N/k) rounds (i.e. $C_i(t) = 0$ if node has been a CH and one otherwise), then as per specifications of the LEACH protocol, each node should choose to become a CH at round r with probability.

$$P_i(t) = \begin{cases} \dfrac{k}{N - k * (r \bmod N/k)} & : \quad C_i(t) = 1 \\ 0 & : \quad C_i(t) = 0 \end{cases} \tag{2}$$

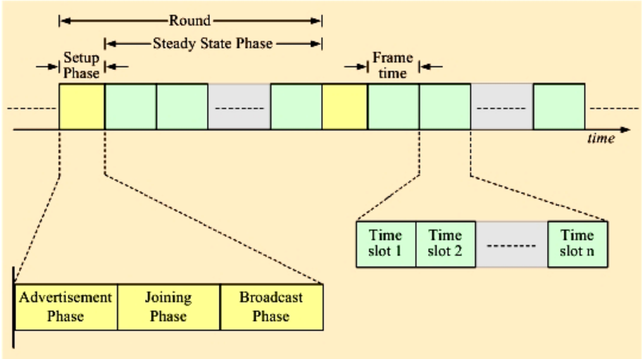


Fig.1 Time-line diagram of LEACH Protocol

Fig. 2 shows the radio energy dissipation model as described in [10], [11]. For the theoretical and simulation work described in this paper, both the free space model (d2 power loss) and the multi-path fading (d4 power loss) channel models were used, depending on the distance between the transmitter and receiver [17]. Thus, to transmit an l-bit message over a distance d, the radio expends

$$E_{Tx}(l,d) = E_{Tx-elect}(l) + E_{Tx-amp}(l,d) = \begin{cases} lE_{elect} + l\varepsilon_{fs} d^2 & d < d_0 \\ lE_{elect} + l\varepsilon_{mp} d^4 & d \ge d_0 \end{cases} \tag{3}$$

where Eelec is the RF radio circuitry energy, εfs is the amplification energy required to overcome the free space loss, and εmp is the amplification energy required to overcome multi-path loss. To receive the same message, the radio expends

$$E_{Rx}(l) = E_{Rx-elect}(l) = lE_{elec} \tag{4}$$

Table I summarizes different communication energy parameters as proposed in [10], [11]. These parameters were used for the theoretical and simulation work described in this paper.

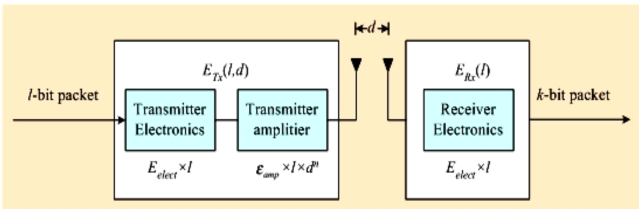


Fig. 2 Radio energy dissipation model

Table 1: Radio Model Communication Parameters

Parameter name	Notation	Value
RF radio circuitry energy	E_{elect}	50 nJ/bit
Amplifier energy for free space loss	ε_{fs}	10 pJ/bit/m^2
Amplifier energy for multi-path loss	E_{mp}	0.0013pJ/bit/m^4
Threshold distance	d_0	87m
Data aggregation energy	E_{DA}	5nJ/bit/signal

3. Theoretical Analysis

The lifetime of a WSN can be defined as the time elapsed until the first node dies, the last node dies, or a fraction of nodes die [11], [18], [19]. Our objective is to identify the factors that induce unbalanced energy utilization between the nodes of WSNs and hence reduce the network lifetime. In this section, we will determine some important parameters that influence the overall network lifetime based upon the theoretical analysis of the LEACH protocol.

A. Number of Clusters in Each Round

LEACH expects k clusters in each round. The optimized value of k (kopt) by using the following equation:

$$k_{opt} = \frac{\sqrt{N}}{\sqrt{2\pi}} \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \frac{M}{d_{toBS}^2} \tag{5}$$

where dtoBS is the distance of the individual nodes from the BS.

B. Number of Member nodes in each cluster

As already described in the specifications of the LEACH protocol, individual nodes of the WSN are expected to be distributed uniformly all around the sensor field. In addition LEACH also expects that elected CHs for each round are also distributed uniformly all around the sensor field. Based upon these facts, number of member nodes for each cluster (NMNs/cluster) is given by:

$$N_{MNs/cluster} = \frac{N}{k} - 1 \tag{6}$$

C. CH-node Energy Dissipation per Frame

As per specifications of the LEACH protocol, each CH node will dissipate energy while receiving signals from its member node and then aggregating the received signals. In addition it will also consume energy while transmitting the aggregated signal to the BS. Thus the energy dissipated by the CH node during for single frame (ECH/frame) is given by

$$\begin{aligned} E_{CH/frame} = lE_{elect} \ N_{MNs/cluster} \\ + lE_{DA} \ N_{MNs/cluster} + 1 \\ + l \ E_{elect} + \varepsilon_{mp} d_{toBS}^4 \end{aligned} \tag{7}$$

D. CH-node Energy Dissipation per Frame

Each non-CH or member node will only transmit its data to its CH once during a frame. Assuming that the distance between the member nodes and their corresponding CH-node is small, the energy dissipated by each non-CH node (Enon−CH/frame) during a frame is given by:

$$E_{non-CH/frame} = lE_{elect} + \varepsilon_{fs} d_{toCH}^2 \tag{8}$$

The expected value of distance of member nodes from their CHs (dtoCH) can be calculated using equation (9) as it has been described in [10], [11].

$$E \ d_{toCH} = \sqrt{\frac{1}{2\pi} \frac{M^2}{k}} \tag{9}$$

E. Energy Dissipation per Cluster per Round

If (Nframes/round) is the number of frames per round for any cluster, then using equations (6), (7) and (8), to calculate the energy dissipation for each cluster during a complete round (Ecluster/round), we can use the following equation

$$\begin{aligned} E_{cluster/round} = N_{frames/round} \times \ E_{CH/frame} + \\ N_{MN/cluster} \times E_{non-CH/frame} \end{aligned} \tag{10}$$

F. Network Energy Dissipation per Round

From equation (5), it has already been mentioned that LEACH expects k clusters for each round. Using equation (10), total energy for a complete round (Eround) can be calculated as:

$$E_{round} = k \times \ E_{cluster/round} \tag{11}$$

Table 2: Sensor Network Parameters

Parameter name	Notation	Value
Sensing area	M	$100\times100m^2$
Number of sensor nodes	N	100
Minimum distance to base station	$d_{toBS}(min)$	$75m$
Maximum distance to base station	$d_{toBS}(max)$	$185m$
Initial energy level of individual nodes	E_{init}	$2.0J$
Data packet size	l	5nJ/bit/signal

For theoretical as well as simulation analysis of LEACH protocol for periodic monitoring applications, we used a 100 node network with the same network specifications as were used in [11]. Some important network specifications are listed in Table II. As per requirement of the periodic monitoring applications, the reporting period (frame time) should be a fixed value. In our analysis frame time was set to 4 sec. In order to have a detailed analysis, we set three different values of number of frames per round so that each node can act as CH at least once, twice and four times respectively.

Using equations (5) to (11), and considering the specifications of proposed scenario for periodic monitoring applications, and also the network specifications listed in table II, the number of frames per round, optimum value of number of CHs for every round, non-CH, and CH energy utilization per round and hence the energy utilization during each round can be calculated. Analytical results for these parameters are listed in table III. These results were later compared with the simulation results.

4. Simulation Work

Based upon the specifications of the LEACH protocol from section II and the theoretical results as given in section III, there is a need to verify the validity of these results regarding balanced energy utilization among sensor nodes and network life time. For this purpose, we developed an OPNET based simulation environment.

Table 3: Sensor Network Parameters

	Number of CH role assignments		
Parameter	**once**	**twice**	**Four times**
k_{opt}	5	5	5
$N_{frames/round}$	24	12	6
$E_{non\text{-}CH}$	0.0432J	0.0216J	0.0108J
E_{CH}	1.116J	0.558J	0.279J
E_{round}	9.684J	4.842J	2.421J

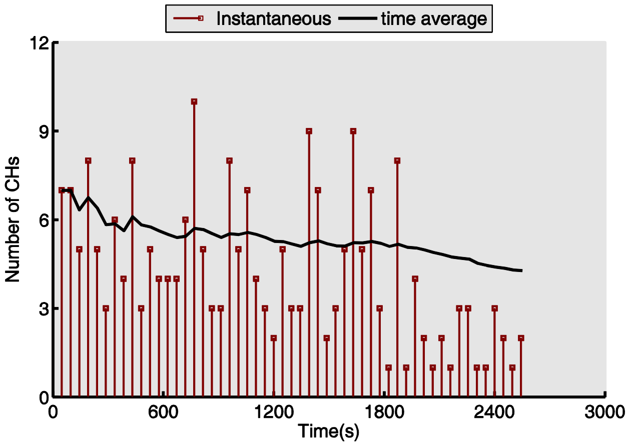
Fig. 3(a), (b) & (c) show the graph for the instantaneous as well as time average values of number of CHs for every round while each sensor node acting as CH once, twice and four times respectively. As we can observe from these graphs, even though time average values are approximately equal to the optimized values for number of CHs during each round listed in Table III, but the instantaneous values vary tremendously. Fig. 4(a), (b) & (c) show the instantaneous as well as time average values for non-CHs nodes average energy utilization during each round, while each sensor node acting as CH once, twice and four times respectively. Similarly 5(a), (b) & (c) show these results for CH nodes and 6(a), (b) & (c) for round energy utilization. It can be observed that instantaneous values vary considerably from the time average values and also time average values are much higher than those of the analytical values listed in Table III. Unbalanced energy utilization in different rounds among senor nodes, either acting as CHs or as member nodes led to the non uniform energy levels among these nodes after different rounds and hence affected the overall network performance.

Total number of data signals received at the BS versus the simulation time has been shown in Fig. 7(a), while each sensor node acting as CH once, twice and four times respectively. In Fig. 7(b) we have plotted the total number of data signals that were received at the BS per unit amount of energy, while each sensor node acting as CH once, twice and four times respectively. In Fig. 7(c) we have shown the number of remaining alive nodes versus the simulation time, while each sensor node acting as CH once, twice and four times respectively. In Fig. 7(d) we have plotted the number of remaining alive nodes versus the amount of data signals that were received at the BS, while each sensor node acting as CH once, twice and four times respectively.

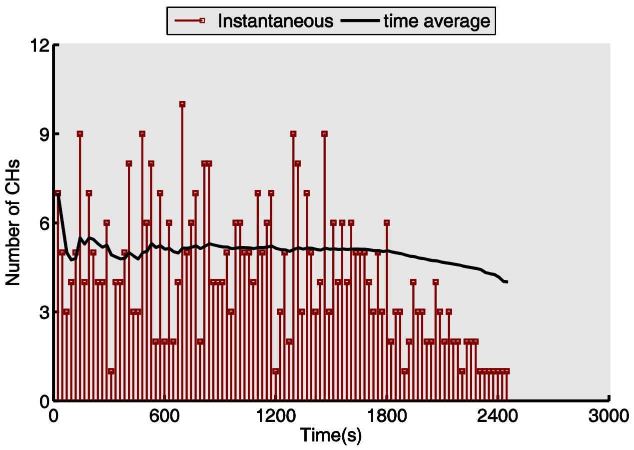
Simulation results indicate that due to the probabilistic nature of the LEACH protocol for CH election, the number of CHs in each round vary tremendously from that of optimized number of CHs. On the other hand since LEACH protocol do not have any control over the distribution of CHs in the network and the cluster joining algorithm proposed by this protocol recommends the member nodes to join the nearest CH for efficient energy utilization of these nodes, so the clusters so formed are of unequal sizes hence contributing to unbalanced energy utilization between the sensor nodes of these networks. All these factors contribute not only to the increased energy utilization among member nodes, CHs and for each round but also induce unbalanced energy utilization between the nodes of WSNs. Although we can neutralize the affect of unbalanced energy utilization among sensor nodes by having more frequent clustering process (compare the results of Fig. 7(a), (b), (c),& (d) for different values of role as CH during network lifetime), but this contributes to overhead caused by control messages that will be required for more frequent clustering process. All these factors highlight the need for a generalized, standardized & adaptive clustering technique that can increase the network lifetime by further balancing the energy utilization between the sensor nodes of these types of networks.

5. Conclusion and Recommendations

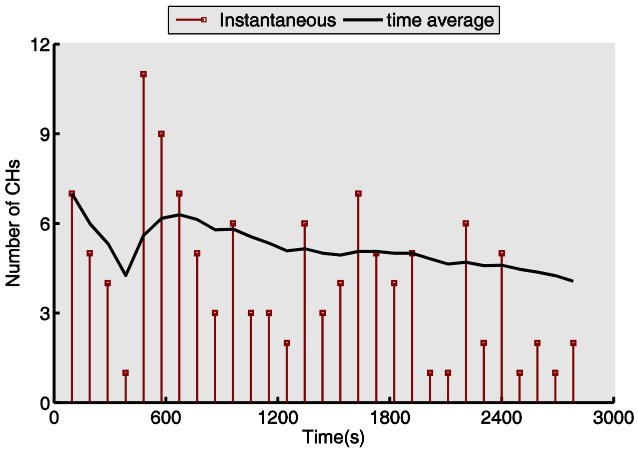
In this paper we have carried out network lifetime and energy utilization analysis for cluster-based wireless sensor networks based upon LEACH protocol. First we carried out the theoretical analysis then we compared these theoretical results with the simulation results using the OPNET based simulation environment for the said protocol. Simulation results indicate that because of the probabilistic nature of the LEACH protocol for CH election, total number of CHs for every round varies tremendously from that of optimized number of CHs. On the other hand since LEACH protocol do not have any control over the distribution of CHs in the network and the cluster joining algorithm proposed by this protocol recommends the member nodes to join the nearest CH for efficient energy utilization of these nodes, so the clusters so formed are of unequal sizes hence contributing to unbalanced energy utilization among the nodes of WSNs. All these factors contribute not only to the increased energy utilization among member nodes, CHs and for each round but also induce unbalanced energy utilization between the nodes for these types of networks. Although we can neutralize the affect of unbalanced energy utilization between the nodes of WSNs by having more frequent clustering process for different values of role as CH during network lifetime, but this contributes to overhead caused by control messages that will be required for more frequent clustering process. All these factors highlight the need for a generalized, standardized & adaptive clustering technique that can increase the lifetime of these networks by further balancing the energy utilization between the sensor nodes.



(a)

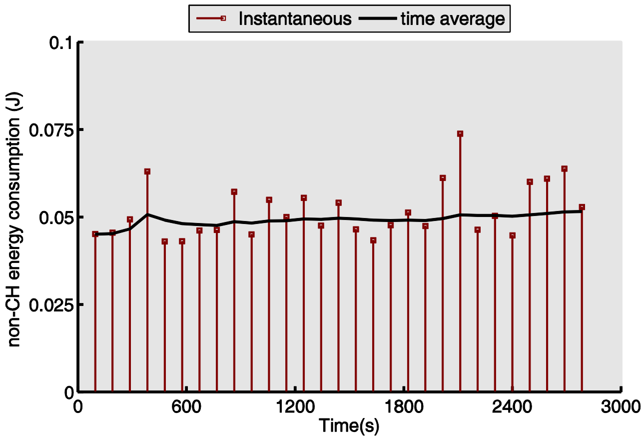


(b)

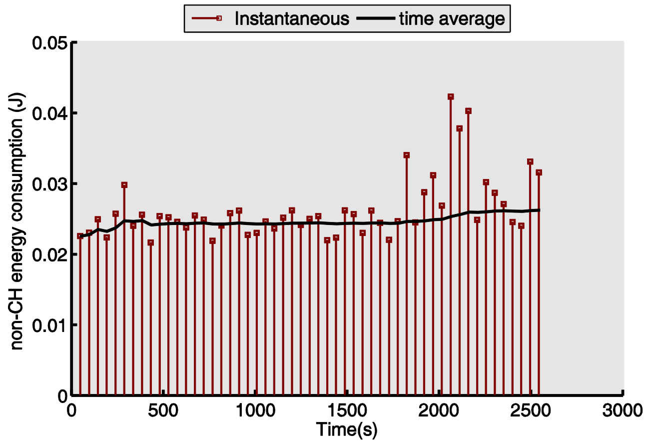


(c)

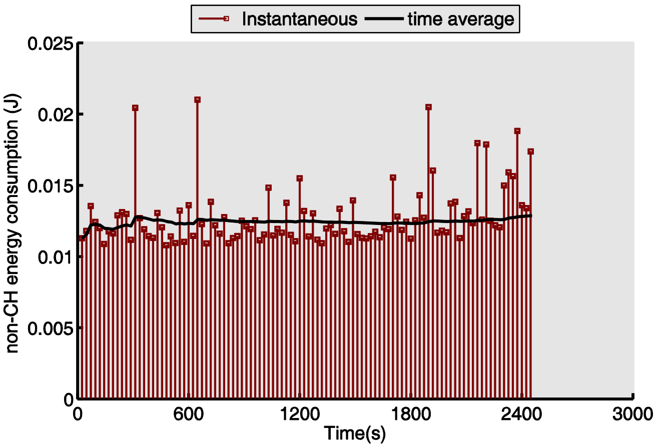
Fig.3 Number of CHs during each round while each node acting as CH at least (a) once, (b) twice, (c) four times, throughout the simulation lifetime



(a)

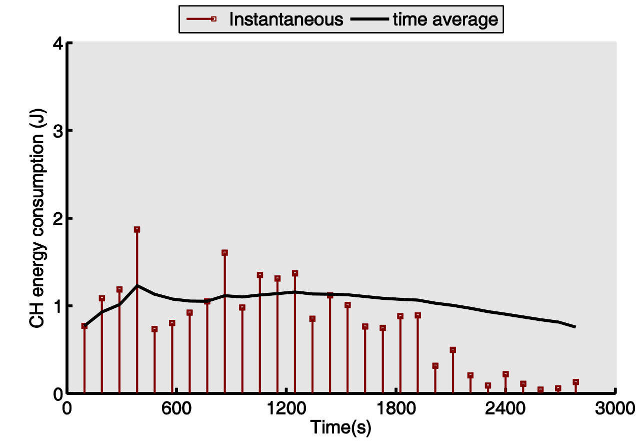


(b)

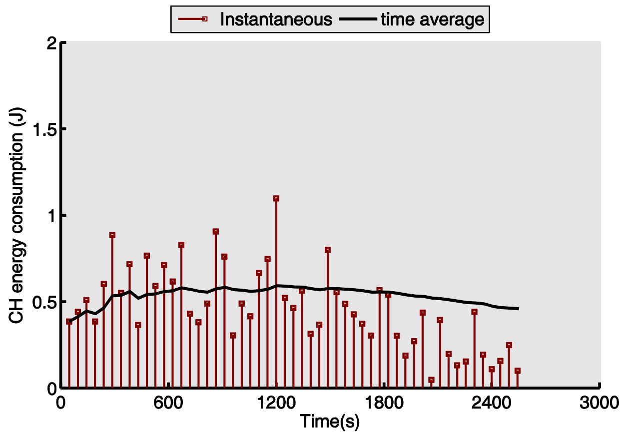


(c)

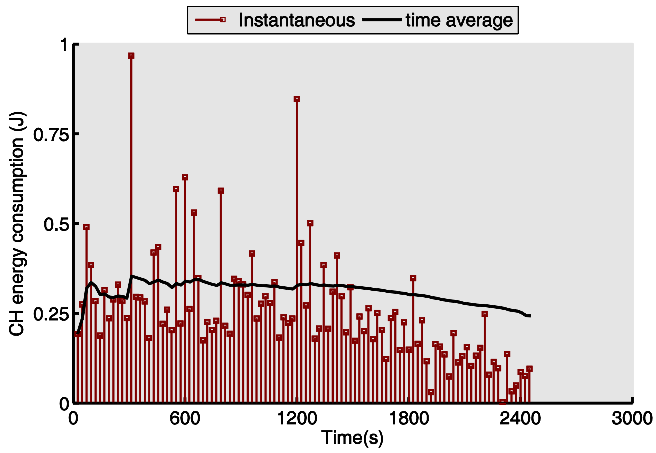
Fig.4 Non-CH node average energy consumption during each round while each node acting as CH at least (a) once, (b) twice, (c) four times, throughout the simulation lifetime



(a)

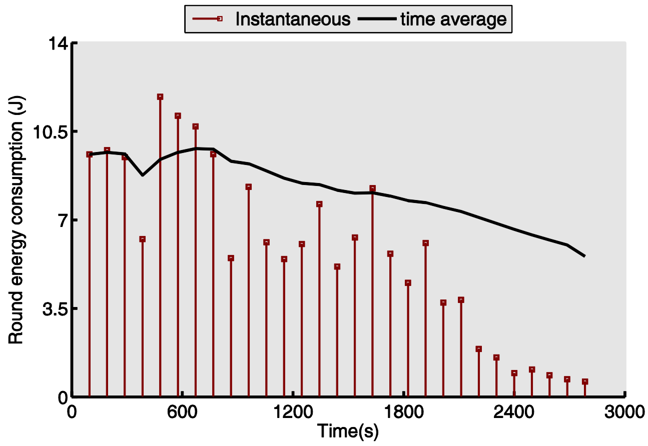


(b)

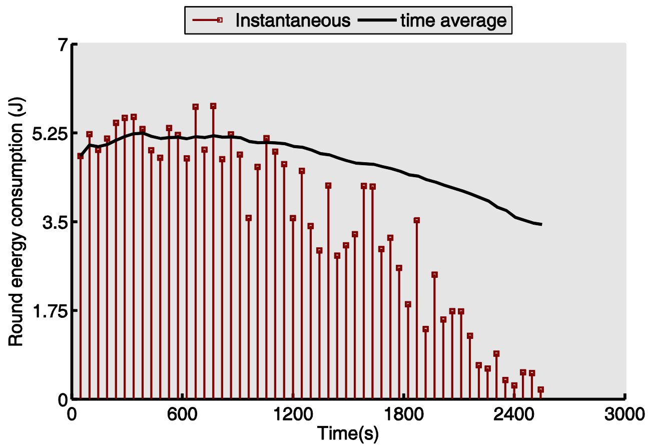


(c)

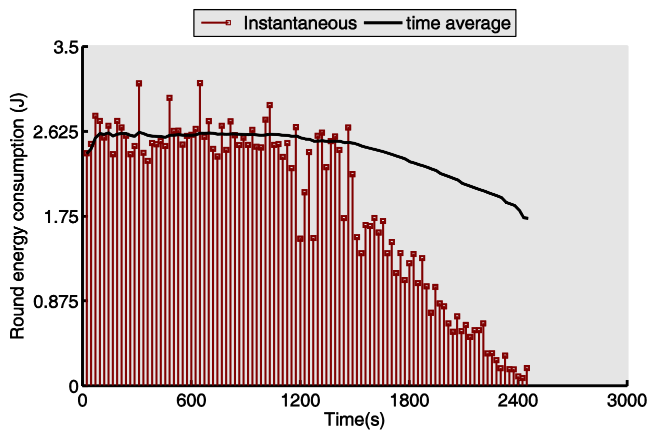
Fig.5 CH node average energy consumption during each round while each node acting as CH at least (a) once, (b) twice, (c) four times, throughout the simulation lifetime



(a)

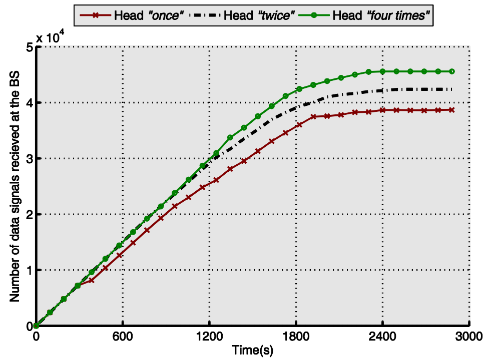


(b)

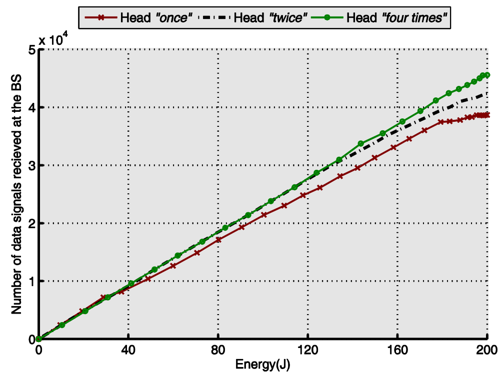


(c)

Fig.6 Energy consumption during each round while each node acting as CH at least (a) once, (b) twice, (c) four times, throughout the simulation lifetime



(a)



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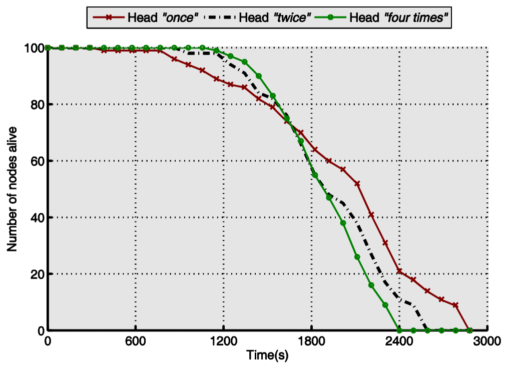
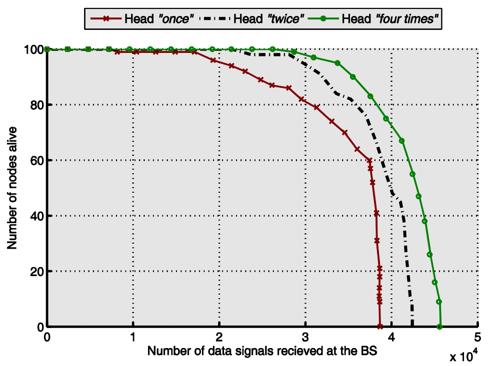


(c)



(d)

Fig.7 Simulation results for (a) Number of data signals received at the BS over time, (b) Number of data signals received at the BS per given amount of energy, (c) Number of nodes alive over time, (d) Number of nodes alive per amount of data sent to the BS, for different values of role as CH during network lifetime

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Biography

Abdul Sattar Malik received the B.S. and M.S. degrees in electrical engineering from University of Engineering & Technology, Lahore, Pakistan, in 2000 and 2005 respectively. He received his Ph.D. degree from Beijing Institute of Technology, Beijing, P. R. of China in December 2009. He is assistant professor at the Department of Electrical Engineering, UCET, BZU Multan, Pakistan. His research interests include low-power ad-hoc wireless networks protocol architecture, and distributed clustering protocols for wireless sensor networks.

Prof. Dr. Suhail Aftab Qureshi born in 1958. All his schooling was completed in renowned institutions of Lahore, Pakistan. Then he did his B.Sc. UET Lahore, Pakistan, another renowned institution of Pakistan. He received his M.Sc. and Ph.D. degrees from University of Manchester, UMIST, UK, in 1990 & 1993 respectively. He is affiliated with UET since 1981 and currently he is working as Professor at the Department of Electrical Engineering. He has more than 100 Research publications. In addition, more than 110 M.Sc. research projects got completed under his supervision. Currently, he is also supervising six Ph.D. research projects. He is also the winner of *Best University Teacher's Award* awarded by the Higher Education Commission (HEC) of Pakistan in 2005.