An Energy Efficient and Optimal Randomized Clustering for Wireless Sensor Networks

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Abstract— **Wireless sensor networks (WSN) is widely used for gathering data in the distributed fashion. In WSN, each node has limited energy resource, and thus the lifetime of the network is one of the most critical issues. In this paper we propose an energy efficient and optimal randomized clustering protocol for self-organizing WSNs. The proposed scheme decides optimal number of clusters by employing a new approach for setting threshold value, including the probability of optimum number of cluster-heads and residual energy of the nodes. We also introduce a new approach maximize the network lifetime by tree construction in each cluster. Computer simulation shows that the proposed scheme effectively reduces and balances the energy consumption among the nodes, and thus significantly extends the network lifetime compared to the existing schemes.**

Keywords— *Wireless sensor networks; Cluster-head selection; Energy efficiency; Network lifetime; Tree construction.*

I. INTRODUCTION

Advanced integrated circuit technologies have led to the development of small sensor nodes equipped with sensing, data processing and communication capability. Distributed in the target area, they form a network which can sense the environmental data and react to the surrounding condition. This makes the WSN suitable for a wide range of civil and military applications - target field imaging, intrusion detection, weather monitoring, security and tactical surveillance and disaster management, etc [1,2]. WSN is composed of a large number of sensor nodes and a base station (BS). The BS processes and stores the information it receives from the sensor nodes [3-5]. The sensor nodes are usually deployed randomly in the region of interest. A sensor node, despite its limited energy, processing capability and memory, collaborates with other sensor nodes, queries the physical environment, compiles the received data and transmits them to the BS. With their capabilities for monitoring and control, the network can provide a fine global picture of the target area through the integration of the data collected from many sensors each providing a coarse local view [6].

Since sensor nodes have limited power supply which cannot be recharged or replaced, their operation needs to be energy efficient. The limited energy in each node affects the lifetime of the entire network, and thus energy efficiency has been a critical design issue for the protocols and algorithms developed for WSN [7-8]. Cluster-based routing protocol is effective for prolonging the life time of WSN [9]. In cluster-based routing, the nodes in the network take different roles according to a variety of conditions and metric. Each cluster has a leader referred to as cluster-head and other ordinary member nodes. The cluster-heads can form another hierarchy among them. The clustering approach allows a WSN of high scalability, less consumed energy and thus longer lifetime for the whole network. This is mainly due to the fact that most of the sensing, data processing and communication activities can be performed within the clusters. However, energy consumption at a cluster head is significantly larger than that at other ordinary sensor nodes because cluster-head is responsible for delivering aggregated data in its cluster to the BS. This problem can be relieved by rotating the role of cluster-head among all nodes.

In this paper we propose an energy efficient and optimal randomized clustering protocol employing tree topology for self-organizing WSN. The proposed scheme utilizes a new probability function to decide the number of cluster-heads (CHs) in each round. The function involves energy level, round information, frequency selected as CH of each node. The main focus of the proposed protocol is the minimization of energy consumption of the nodes for maximizing the network lifetime. For this, the proposed protocol adopts the tree topology inside each cluster. After leveling of the member nodes is completed with the CH as the root, a tree in a cluster is constructed by broadcasting the topology via a hybrid medium access control approach. The proposed scheme significantly reduces energy consumption and increase the lifetime of the sensor network compared to the existing schemes. Also, through the uniformly distributed CHs, the proposed scheme balances the energy consumption among the sensor nodes. The simulation results demonstrate that the proposed scheme effectively extends the network lifetime compared with the existing schemes.

The remainder of the paper is organized as follows. Section II presents the related work, and Section III introduces the proposed scheme. The performance of the proposed scheme is evaluated by computer simulation in Section IV. Finally, Section V concludes the paper and outlines future research direction.

II. RELATED WORK

Low-Energy Adaptive clustering Hierarchy (LEACH) [10] is one of the representative clustering schemes. In LEACH sensors are organized into clusters and one node in each cluster

acting as CH takes the responsibility to collect data, aggregate them, and finally transmit them to the distant BS. They showed that the network is optimal in the sense of energy dissipation when around 5 percent of the total nodes act as CHs. The operation of LEACH is divided into rounds, where a round begins with set-up phase followed by steady-state phase. During the setup phase each node decides whether it becomes the CH or not. After that, the CH broadcasts an advertisement message to the rest of the nodes. Depending on the received signal strengths, each node decides the CH to which it wants to belong for that round. Each CH then creates a TDMA schedule for all the member nodes in its cluster and sends it to them. During the steady state phase, the member nodes start sensing and transmitting data to the CHs according to the TDMA schedule, and the fused information by the CH is sent to the BS. At the end of a given round, a new set of nodes become CHs for the subsequent round and the process repeats.

In LEACH-C [17], the clusters are decided by the BS. In the set-up phase, the BS receives the messages containing the information on the location and amount of remaining energy of each sensor node. The BS then calculates the average energy of the nodes, and the ones having larger energy than the average are picked as candidate CHs. From the candidates, the nodes of smaller distance to the neighboring nodes are selected as CHs using the simulated annealing algorithm. After that, the BS broadcasts a message containing the IDs of the CHs for that round to the nodes in the network. When a node receives the message, it elects itself as CH if its identifier (ID) is included in the list of CHs. If not, the node determines its cluster and identifies the TDMA slot in which data are transmitted to the CH. The operation of LEACH-C in steady-state phase is identical to that of LEACH.

Proxy-Enable Adaptive Clustering Hierarchy for wireless sensor network (PEACH) [11] improved LEACH by selecting a proxy node which can assume the role of the current CH of weak power during one round of communication. It is based on the consensus of healthy nodes for the detection and manipulation of failure of any CH. It allows considerable improvement in the network lifetime by reducing the overhead of re-clustering.

The authors of [12] propose a protocol called Energy-Driven Adaptive Clustering Hierarchy (EDACH), which can increase the lifetime and reliability of sensor network in the presence of faults at the CHs. This is achieved by selecting a proxy node which can assume the role of the current CH during one round of communication. EDACH is based on consensus of healthy CHs to detect and handle faults in any faulty CH. EDACH employs the simulation-based fault injection method for performance evaluation, which assumes that errors occur according to a predetermined distribution. It provides improvement in the stability of the system and reduces the overhead of re-clustering and system reconfiguration.

[13] proposed a novel algorithm called EECH (Energy Efficient Clustering Hierarchy). Here the node of more energy has higher probability to be selected as CH than other nodes. Besides, the CHs are set to use multi-hop forwarding and routing when they communicate with the BS. The EECHS

scheme [14] adjusts the threshold value of the stochastic CH selection algorithm of LEACH. It considers residual energy of the nodes, distance between the nodes and the BS, and the number of consecutive rounds in which a node has not been a CH in CH selection. We next present the proposed scheme.

III. THE PROPOSED SCHEME

We first discuss the system model and energy model used in the proposed routing scheme.

A. System and Energy Model

We consider a WSN of a number of sensor nodes distributed randomly in the target area. The sensing nodes periodically form the clusters and have enough transmission power to reach the BS. The following assumptions on the sensor nodes and underlying network employed:

- All nodes are homogeneous and have the same capabilities. Each node is assigned a unique identifier.
- All sensor nodes are started with the same initial energy.
- When two communicating sensor nodes are not within each other's radio range, data are forwarded through other nodes.
- The BS has no energy constraint and is located far away from the target area.
- A routing and MAC infrastructure are in place, and the communication environment is contention and error-free.
- Data fusion or aggregation is used to reduce the number of messages in the network.

We use the radio model adopted in [10-14], which is the first order radio model. To derive the energy consumption per any type of node, both the free space (d^2 power loss) and the multipath fading (d^4 power loss) channel model are used which are based on the distance between the transmitter and receiver. Power control is used to invert the loss by suitably configuring the power amplifier. For the communication between a non-cluster-head and its CH, the free space (*fs*) model is used. Between the CHs and the BS, the multipath (*mp*) model is used. The radios have power control and can expend minimal energy to reach the intended recipients. The radio can be turned off to avoid receiving unintended transmissions. The energy consumption model is described as follows. When a node transmits l bit over distance d, the energy it consumes is:

$$E_{Tx}(l,d) = E_{Tx\text{-}elec}(l) + E_{Tx\text{-}amp}(l,d)$$

$$= \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2 & , d < d_0 \\ lE_{elec} + l\varepsilon_{mp}d^4 & , d \geq d_0 \end{cases} \quad (1)$$

and a node receives l-bit data, energy it consumes is:

$$E_{Rx}(l) = E_{Rx\text{-}elec}(l) = lE_{elec} \quad (2)$$

Here E_{elec} is the unit energy consumed by the electronics to process one bit data, ε_{fs} and ε_{mp} are the amplifier factor for

free-space and multi-path models, respectively, and d_0 is the reference distance to determine which model to use. In these models, a radio dissipates $E_{elec} = 50nJ/bit$ to run the transmitter or receiver circuitry, $\varepsilon_{fs} = 10pJ/bit/m^2$ and $\varepsilon_{mp} = 0.0013pJ/bit/m^4$ for the transmitter amplifier. For simplicity of calculation, we assume that the transmission range of each node is same on one condition that the transmission range should cover all the neighbors in the network. Also, we assume that all data packets contain the same number of bits and the energy for data aggregation is set as $E_{DA} = 5nJ/bit/signal$.

B. The Proposed Approach

In this subsection we introduce the proposed scheme which employs tree topology in each cluster to evenly distribute the energy load among the sensors in the network. The proposed scheme consists of two phases, clustering phase and data transmission phase. In the following sub-sections we discuss each of them in detail.

1) Optimal Number of Clusters:
The cluster-based protocols adopting a simple hierarchical path selection approach do not need any information on the location of the nodes or upper layer control. Since each node is selected as CH with the same probability, the load can be balanced. However, the following issues need to be resolved.

Firstly, the optimum number of clusters, k_{opt}, needs to be decided. If the number of clusters is smaller than k_{opt}, some nodes may exhaust its energy for transmitting data to the CH locating far. With excessive number of clusters, on the other hand, the nodes will quickly deplete their energy for direct communication to the BS. LEACH sets k_{opt} as 5% of the nodes without any formal model.

Secondly, each node has equal probability to be a CH. If a node of low energy is selected as a CH, however, it will quickly deplete its energy due to the heavy load of CH. This shortens the network lifetime. Therefore, we need to introduce a new threshold value, which is decided based on the probability of optimal number of CHs and the residual energy of the nodes, to properly select the CHs.

During one round of operation, the energy consumption of a CH, E_{CH}, is due to three factors: data reception, data aggregation, and transmission of the aggregated data to the BS. Since the distance between the CH and BS is usually long, the multi-path (d^4 power loss) model is used, and E_{CH} becomes:

$$E_{CH} = lE_{elec}N_1 + lE_{DA}(N_1 + 1) + lE_{elec} + l_{mp}d_{toBS}^4 \qquad (3)$$

where l is the number of bits in each data packet. N_1 is the number of member nodes in a cluster having Poisson distribution, E_{DA} is the energy cost of data aggregation, d_{toBS} is the distance from the CH to the BS. With full data aggregation, each CH needs to process n/k_{opt} signals of length-l. The average number of member nodes in each cluster is [15]:

$$E[N_1 \mid N = n] \approx E[N_1] = \lambda_0 / \lambda_1 \qquad (4)$$

Here λ_0 and λ_1 denote the density of CHs and member nodes, respectively. $\lambda_1 = p\lambda$, $p = k/n$, and $\lambda (=\lambda_0 + \lambda_1)$ is the density of Poisson distribution process. $n(=\lambda \times A)$ is the number of nodes, while A is the size of the target area of square shape

where the sensor nodes are deployed, k is the number of clusters, p is the probability for a node to be CH.

Without loss of generality, assume that the BS locates at the center of the target area. Hence the average distance from each CH to the BS for a square area of unit side length is:

$$E[D_1 \mid N = n] = \iint D_1 \cdot P_A d_x d_y$$
$$= \int_{-a}^{a} \int_{-a}^{a} \sqrt{x^2 + y^2} \frac{1}{4a^2} d_x d_y = 0.765 \qquad (5)$$

Here D_1 is the variable of Poisson distribution denoting the distance from the CH whose coordinate is (x,y) to the BS. P_A is the probability density of CH in the area A.

According to Equation (4) and (5), Equation (3) can be expressed by:

$$E_{CH} = \frac{n-k}{k} lE_{elec} + \frac{n}{k} lE_{DA} + lE_{elec} + 0.342a^4 l\varepsilon_{mp} \qquad (6)$$

Because each member node needs to transmit only l-bit data to its CH and the distance between them, d_{toCH}, is relatively short, the free space model is used. Thus the energy used in each member node is:

$$E_{non-CH} = lE_{elec} + l\varepsilon_{fs}d_{toCH}^2 \qquad (7)$$

d_{toCH} is [15]:

$$E[L_1 \mid N = n] \approx E[L_1] = \lambda_0 / 2\lambda_1^{3/2} \qquad (8)$$

Here L_1 is the variable of Poisson distribution signifying the sum of the distance from the member node to the CH. Then, the average distance from the member node to its CH, $E[H_1]$, is:

$$E[H_1 \mid N = n] = \frac{E[L_1 \mid N = n]}{E[H_1 \mid N = n]} = 0.5\left(\frac{k\lambda}{n}\right)^{-\frac{1}{2}} \qquad (9)$$

Therefore,

$$E_{non-CH} = lE_{elec} + \frac{n}{4k\lambda} l\varepsilon_{fs} \qquad (10)$$

The energy dissipated in a cluster during a single round, $E_{cluster}$, and the total energy consumption, E_{total}, are:

$$E_{cluster} = lE_{CH} + N_1 E_{non-CH} \qquad (11)$$
$$E_{total} = kE_{cluster} \qquad (12)$$

According to Equation (6), (10), (11), Equation (12) can be expressed by:

$$E_{total} = l \cdot \left[(2n-k)\right]E_{elec} + nE_{DA} + 0.342d^4 k\varepsilon_{mp} + \frac{n(n-k)}{4k\lambda}\varepsilon_{fs} \qquad (13)$$

Setting the derivative of E_{total} with respect to k to zero,

$$\frac{d}{dk}E_{total} = -E_{elec} + 0.342a^4\varepsilon_{mp} - \frac{n^2}{4k^2\lambda}\varepsilon_{fs} = 0 \qquad (14)$$

Because $n = \lambda(4a^2)$, $\lambda = \dfrac{n}{4a^2}$. The optimum number of cluster, k_{opt}, and optimal probability for any node to be CH, p_{opt}, are then

$$k_{opt} = \sqrt{\frac{na^2\varepsilon_{fs}}{0.342a^4\varepsilon_{mp} - E_{elec}}} \qquad (15)$$

$$p_{opt} = \frac{k_{opt}}{n} = \sqrt{\frac{a^2\varepsilon_{fs}}{n\left(0.342a^4\varepsilon_{mp} - E_{elec}\right)}} \qquad (16)$$

2) Selection of Cluster-head: LEACH adopts the random mechanism of CH selection, in which CH is randomly selected and all the sensor nodes within a cluster take turns to be the CH. This leads to balanced energy consumption of all nodes, and hence a longer lifetime of the network. However, this approach can locate the CHs unevenly. It causes the energy consumption of the nodes unbalanced and reduces the lifetime of the network. In order to solve this problem, the proposed scheme introduces three parameters to stochastically select the CH. The first parameter is the energy ratio between the current energy vs initial energy. The second one is the round number. The third one is the count that the node has been selected as the CH. The probability function of Node-n in the proposed scheme is expressed as follows with the three factors:

$$T(n) = \left(\frac{p_{opt}}{1 - p_{opt} \times (r \bmod \frac{1}{p_{opt}})}\left(\frac{E_{residual}}{E_{init}}\right)\right)\left(\frac{p_{opt}\sqrt{r}}{C_{ch} \bmod \frac{1}{p_{opt}}} + 1\right) \qquad (17)$$

where p_{opt} is the probability to be CH, C_{ch} is the number of times the node has been selected as the CH until the current round, $E_{residual}$ is the residual energy, E_{init} is the initial energy, and r is the round number, respectively.

After the CHs are selected using the proposed probability function, each node electing itself as a CH for the current round broadcasts an advertisement message (*ADV_Msg*) to other nodes. When a node receives an *ADV_Msg* messages from the CHs, it sends the join-request message (*Join_REQ*) to the CH which it chooses as its CH based on the received signal power. After the CH receives the message (*Join_REQ*), the CHs identify their member nodes based on the received *Join_REQ* message. Once the clusters are created, tree configuration in each cluster begins.

3) Tree Configuration in Cluser: After the clusters are formed, a tree is built with the member nodes where the CH is the root. In the tree structure one sensor node can have one parent and many children nodes. All member nodes in a cluster are arranged in m levels starting from a CH. The CH is the root of tree, and it is at level 0.

In this phase each node selects a parent node. For this, the member nodes compute their tree level according to the distance from the CH. The distance between tree levels in a cluster, called communication radius (*CR*), is decided a priori based on node density in the target area considering the connection among the nodes. In [16], the critical transmission range for multi-hop connectivity was presented. The authors assume that the nodes are uniformly distributed in the field and each cell of size C x C contains at least one node. In this case, the network is guaranteed to be connected if the transmission range is $R_t = (1+\sqrt{5})C$. A cell in this context is defined as an area in the 2-dimensional space in which every node can communicate with every other node residing in every neighboring cell. In a clustered network, a cell can be defined as an area where every node can reach every other node residing in the same cell. According to [16], we obtain that *CR* is equal or longer than $(1+\sqrt{5})(\sqrt{L\times L/N})$, where L is the length of one side of a square field.

Each member node computes its tree level, *L*, as follows.

$$L = \left\lceil \frac{D_{CH}}{CR} \right\rceil + 1 \qquad (18)$$

where D_{CH} is the distance to its CH based on the power of a signal received from the CH. Thus, D_{CH} can be obtained using the *RSSI* model. We also calculate the maximum tree level, L_{max}, as follows.

$$L_{max} = \frac{The\ longest\ length\ of\ a\ field}{CR} + 1 \qquad (19)$$

After leveling of the member nodes is completed, tree inside a cluster is constructed by assigning a level to each member node. For the tree construction, this phase requires a number of iterations (steps), which we refer to as time interval T_i (i=1, 2, …, L_{max}). Here each step takes T_R, which should be long enough for the nodes of same tree level to communicate with the neighbor nodes. The path setup based on the level starts from the nodes of the smallest tree level, and terminates with the nodes of the level of L_{max}.

During iteration i, the nodes of level_i broadcast a message using CSMA, which is composed of the node's ID, level number, and ID of the parent node. Fig. 1 shows the broadcast process for tree construction in a cluster. Here each node decides a node as its parent node that transmits signal of the strongest power. When a node receives the reply from a node one level outer layer, it lists it as a child node. Then they turn off their radio until the data collection begins. The nodes of level_1 elect the CH as their parent node. The tree construction process continues until the tree covers all the nodes in the cluster.
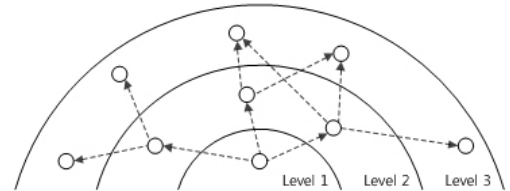

Fig. 1. Broadcast for tree construction in a cluster.

4) Data Collection and Transmission: Once the level-based tree construction in each cluster is complete, the data collection and transmission phase begins. In this phase each

node sends the collected data to the parent node during the pre-allocated time slot appointed by the CH. We choose to implement a time division multiple access (TDMA)-based MAC layer for the slot assignment.
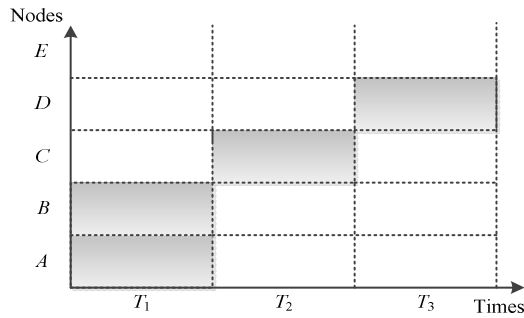

Fig. 2. The TDMA schedule in a cluster.

Each CH generates a TDMA schedule for the transmission and circulates it with the tree topology. In the allotted time-slot the nodes transmit gathered data to the lower level nodes. The lower level nodes fuse the received data with sensed data, and then send the result to the next lower level nodes. When the data from the nodes of all the levels in the cluster have been received, the CH applies data fusion to the received data. After this, it sends the fused data to the BS. Fig. 2 shows an example of data transmission schedule employed by the proposed scheme. In Fig. 2, node_A and B are located in the same level and node_C is lower level than them. The level of node_D is lower than that of node_C. Thus, in T_1, only node_A and B transmit data to the parent nodes of the next level. The transmission process continues until the data transmission of all the nodes is completed.

IV. PERFORMANCE EVALUATION

In this section we evaluate the performance of the proposed scheme using a simulator developed in C++, and compare the performance with the existing protocols. The simulation evaluates the number of CHs per round, the round number of FND (*first node die*) and HNA (*half of the nodes alive*), and the network lifetime with the protocols compared. Table I provides the parameters used in the simulation.

TABLE I
THE PARAMETERS USED IN THE SIMULATION

Parameter	Value
Network size	100m × 100m
Location of BS	Center of target area
Number of nodes	100
Data packet size	500 byte
Packet size for path set-up	20 byte
Network topology	Random
Initial energy of each sensor	1.0J
E_{elec}	50 nJ/bit
ε_{fs}	10 pJ/bit/ m^2
ε_{mp}	0.0013 pJ/bit/ m^4
E_{DA}	5 nJ/bit/signal

To investigate the effectiveness of cluster formation of the proposed approach, we first examine the performance of CH selection. Fig. 3 shows the distribution of the number of clusters in LEACH, EECHS, and the proposed scheme, which is achieved from 100 rounds of the simulation. In Fig. 3, it is apparent that the number of clusters with the proposed scheme is more stable than that with LEACH and EECHS. LEACH uses a fully random approach to select the CHs with a pre-determined probability. As a result, the number of CHs with LEACH and EECHS varies significantly as shown in Fig. 3. The selection of CH with the proposed scheme is made considering several operation parameters of each node. Therefore, the proposed scheme allows more effective and consistent formation of clusters than LEACH and EECHS.
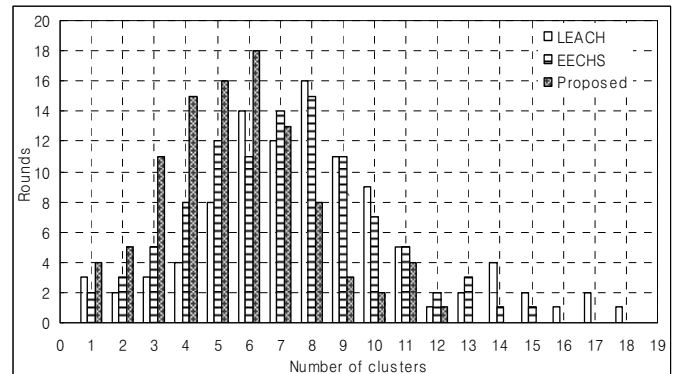

Fig. 3. The distribution of the numbers of clusters in each round.

We compare the proposed scheme with LEACH, EDACH, and EECHS in terms of network lifetime using FND and HNA. Fig. 4 shows that the proposed scheme improves FND approximately 70%, 51%, and 17% than LEACH, EDACH and EECHS, respectively. The improvements of HNA are approximately 58%, 40%, and 16%, respectively. Based on these results, the proposed scheme can be said to be better than the existing schemes in balancing the energy consumption of the sensor nodes.
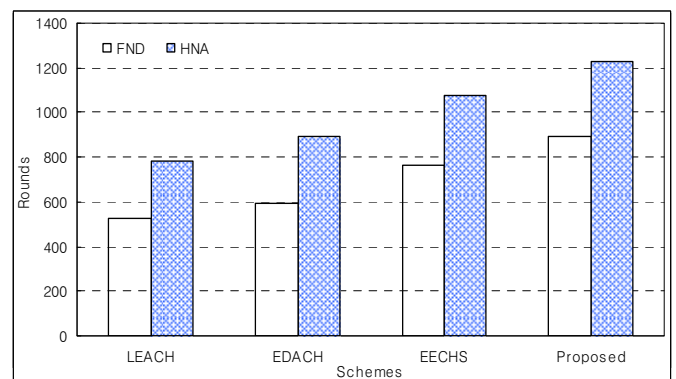

Fig. 4. The comparison of the schemes in terms of FND and HNA.

We also evaluate the energy efficiency of the schemes by examining the network lifetime. Fig. 5 shows the number of sensor nodes still alive over the simulation time. The proposed scheme clearly outperforms the others with respect to the network lifetime. Note that the existing schemes select the CHs based on a random approach. The proposed scheme allows considerable improvement in the network lifetime by

conspicuous selection of the CHs and tree formation inside the clusters.
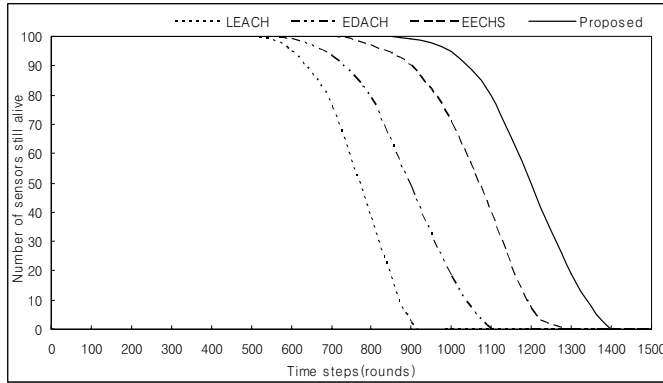

Fig. 5. The comparison of network lifetimes.

V. CONCLUSION

In this paper we have proposed an energy efficient clustering protocol for self-organizing wireless sensor network. The proposed scheme introduces a new threshold value used in selecting the cluster heads in the network. We have also introduced a new tree construction approach inside each cluster to minimize the energy consumption of the sensor nodes. As a result, the proposed scheme can significantly reduce energy consumption and increase the lifetime of the network compared to the existing schemes.

In the future we will continue to study the maximization of network lifetime for heterogeneous sensor network. In addition, mobility in sensor network is an ever-growing requirement in recent applications. Extension of the proposed scheme to cope with the mobility and the related challenges is yet another important issue remaining as future work.

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