A Cluster-Based Energy-Efficient Routing Protocol without Location Information for Sensor Networks

Giljae Lee*, Jonguk Kong*, Minsun Lee*, and Okhwan Byeon*

Abstract: With the recent advances in Micro Electro Mechanical System (MEMS) technology, low cost and low power consumption wireless micro sensor nodes have become available. However, energy-efficient routing is one of the most important key technologies in wireless sensor networks as sensor nodes are highly energy-constrained. Therefore, many researchers have proposed routing protocols for sensor networks, especially cluster-based routing protocols, which have many advantages such as reduced control messages, bandwidth re-usability, and improved power control. Some protocols use information on the locations of sensor nodes to construct clusters efficiently. However, it is rare that all sensor nodes know their positions. In this article, we propose another cluster-based routing protocol for sensor networks. This protocol does not use information concerning the locations of sensor nodes, but uses the remaining energy of sensor networks and the desirable number of cluster heads according to the circumstances of the sensor networks. From performance simulation, we found that the proposed protocol shows better performance than the low-energy adaptive clustering hierarchy (LEACH).

Keywords: Wireless sensor networks, ubiquitous sensor networks, cluster-based routing protocol, energy-efficient routing.

1. Introduction

With the recent advances in Micro Electro Mechanical System (MEMS) technology, low cost and low power consumption wireless micro sensor nodes have been available. Wireless sensor networks (WSN) usually consist of a base station and many sensor nodes. The sensor nodes are randomly distributed over the sensor network's field. The sensor nodes monitor environmental factors such as temperature, air pressure, and motion, and send those sensing data to the base station. The base station acts as a gateway to deliver information from the sensor nodes to outside users who need it. In WSN, it is too difficult to initialize the sensor nodes and manage the sensor networks due to the large number of sensor nodes, which may number tens of thousands. Therefore, self-configuring sensor nodes are desirable in WSN. Moreover, in order to save energy, sensor nodes carry out data aggregation and compression before sending data to the base station, and execute energy efficient routing [1].

Sensor nodes can send their data to the base station by direct communication protocol or a multi-hop communication method such as the Minimum Transmission Energy (MTE) routing protocol. In direct communication protocol, sensor nodes, which are far from the base station, dissipate faster than others do because they send their data to the base station directly; sensor nodes do not only transmit their own sensing data, but also serve as routers for other sensor nodes if they use the MTE routing protocol. Therefore, the energy of the sensor nodes that are near to the base station is rapidly consumed in the MTE routing protocol [4].

Various data centric protocols have been proposed to solve problems in conventional routing protocols, including Sensor Protocols for Information via Negotiation (SPIN) [5] and directed diffusion (DD) [6]. As far as data transmission and data collection are concerned, the data centric algorithm is more efficient than conventional transmission methods (direct transmission protocol and MTE routing protocol). However, they should have many control messages and long latency to set routing paths. A more suitable method involves cluster-based protocol. Cluster-based routing protocols have some advantages such as reducing control messages, bandwidth re-usability, enhanced resource allocation, and improved power control. However, cluster-heads are fixed in the existing cluster-based protocols. Therefore, the overall network lifetime is decreased in the sensor network environment because cluster-heads involve an energy intensive process and their energy consumption is greater than non-cluster-head nodes. Many of the cluster-based routing protocols adapted for sensor networks have been proposed to take advantage of the conventional cluster-based routing protocols [2].

A low-energy adaptive clustering hierarchy (LEACH) was proposed to solve the problems caused by conventional cluster-based protocols. LEACH is based on a hierarchical clustering structure model and energy efficient

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cluster-based routing protocols for sensor networks. In order to prolong the overall lifetime of the sensor networks, LEACH changes cluster heads periodically. LEACH has two main steps: the set-up phase and the steady-state phase. In the set-up phase, there are two parts, the cluster-head electing part and the cluster constructing part. After the cluster-heads have been decided on, sensor nodes (which are chosen as cluster-heads) broadcast an advertisement message that includes their node ID as the cluster-head ID to inform non-cluster sensor nodes that the chosen sensor nodes are new cluster-heads in the sensor networks. They use the carrier-sense multiple access (CSMA) medium access control (MAC) protocol to transmit this information. The non-cluster sensor nodes that receive it choose the most suitable cluster-head according to the signal strength of the advertisement message, and send a join request message to register on the chosen cluster-head. After receiving the join message, the cluster-heads make a time division multiple-access (TDMA) schedule for data exchange with non-cluster sensor nodes. Then, the cluster-head informs the sensor nodes of its own cluster and the sensor nodes then start sending their data to the base station via their cluster-head during the steady-state phase.

In LEACH, each sensor node uses the value of probability in order to decide whether to be a cluster-head or not. As far as optimal energy consumption is concerned, it is not advisable to select cluster-heads arbitrarily and construct clusters. However, as repeating round, the total energy dissipation and performance in the sensor network can be improved upon. In spite of its advantages, it has some shortcomings in that the remaining energy is not considered in the construction of clusters and the desired number of cluster-heads of the sensor networks is fixed. Therefore, it is not suitable for either expansion or reduction of the size of the sensor networks. Moreover, the distribution of the cluster-heads and their number are not guaranteed because cluster-heads are only determined by the value of probability [4].

Various cluster-based protocols are proposed to overcome LEACH, such as LEACH-centralized (LEACH-C) and Base-Station Controlled Dynamic Clustering Protocol (BCDCP). In these protocols, the base station selects the cluster-heads and composes the clusters by itself in the sensor networks. LEACH-C is an extended protocol of LEACH. Apart from the set-up phase, it is the same as LEACH. During the cluster composition step, all of the sensor nodes of the sensor networks broadcast their own information, which includes their ID, remaining energy level, and positional information. Then, the base station can calculate the average energy of the sensor networks. Using the broadcast information of the sensor networks, sensor nodes that have a higher than average energy amount become a candidate of the cluster-heads. In addition, the base station executes an *annealing algorithm* in order to compose clusters of the most optimal number and minimal transmission energy in the cluster with a set of cluster-head candidate nodes. After composing the clusters, the base station transmits information about cluster-heads, members of each cluster, and the TDMA schedule for them to each sensor node in the sensor networks. Thereafter, non-cluster-head sensor nodes decide their own TDMA slot and enter a sleep-state until their own data transmission time [3].

In BCDCP, the base station changes cluster-heads randomly, composes cluster-to-cluster routing paths, and achieves other energy intensive works such as data aggregation, compression, and fusion. The key ideas in BCDCP are the formation of balanced clusters where each cluster-head serves an approximately equal number of member nodes to avoid cluster-head overload, the uniform placement of cluster-heads throughout the whole sensor field, and the utilization of cluster-head to cluster-head (CH-to-CH) routing to transfer the data to the base station. As LEACH-C, in the set-up phase, the energy information sent by all sensor nodes is used to compose clusters. The base station uses a *balanced clustering technique* to distribute the load of cluster-heads, and an *iterative cluster-splitting algorithm* to obtain the ideal number of clusters. After that, it makes multiple CH-to-CH routing paths. Finally, it creates a schedule for each cluster and broadcasts it to the sensor networks. In the data communication phase, cluster heads transfer data from the sensor nodes to the base station according to the CH-to-CH routing paths after processing them [7].

In this article, we propose a cluster-based energy-aware routing protocol without location information of the sensor nodes, which is also base station centralized, to prolong the lifetime of the sensor networks. The composition of the rest of this article is as follows. First, in chapter 2, we explain the proposed protocol to solve the controversial point raised by conventional cluster-based routing protocols. After a detailed description of the proposed protocol, we analyze simulated performance results in chapter 3. Finally, we offer some conclusions and a discussion of future works.

2. Proposed Protocol

In this section, we explain our proposed protocol in detail. LEACH-C and BCDCP prolong the lifetime of sensor networks efficiently using the base station, which has relatively fewer restrictions where energy is concerned. However, we focus on the fact that it is rare for all sensor nodes to have their own positional information. Furthermore, because the number of sensor nodes is large, there are many overheads that all sensor nodes pass their own information simultaneously to the base station at every set-up phase.

The proposed protocol uses the random cluster-head decision paradigm of LEACH. For cluster-head decisions, it instead uses the total remaining energy of the sensor networks and each sensor node. Moreover, in the proposed protocol, the base station (rather than the sensor nodes) broadcasts information to the sensor networks for cluster construction in the cluster construction phase. Sensor nodes then transmit it together with the sensing data, so we can avoid overheads originated by sending the set-up information of the sensor nodes to the base station directly in the cluster construction phase. In addition, the proposed protocol can select the suitable number of cluster heads through the base station according to changes in the sensor networks, and this information is used to construct clusters in the cluster construction phase.

2.1 Network Model

In this article, we assume a sensor network model, similar to those used in LEACH, with the following properties.

- Sensor nodes are energy constrained.
- The base station uses an external power supply, and has enough memory and computing capability for energy intensive tasks.
- Each sensor node always has data to transmit to the base station at a fixed rate.
- Each sensor node can communicate with other sensor nodes directly by varying their transmitting power in the sensor networks.
- The position of each sensor node is fixed.

The proposed protocol can change the desirable number of cluster heads according to changes in the sensor networks. It determines cluster-heads based on the remaining energy level of each sensor node and the sensor networks, and the changed number of cluster-heads. In the proposed protocol, sensor nodes do not send energy information to the base station in the cluster construction phase, but rather in the data communication phase.

2.2 Cluster Construction Phase

In the cluster construction phase, the base station broadcasts an advertisement message - which includes the total energy of the sensor networks and the suitable number of cluster-heads - to the sensor networks (BS_ADV). In the first cluster construction phase, it sends total energy as zero and the suitable number of cluster-heads as a default value because the base station cannot recognize the total energy and the number of sensor nodes in the sensor networks.

Sensor nodes determine the cluster-head nodes using information received from the base station. When total energy is zero, the sensor nodes carry out the cluster-head selection algorithm (1) of LEACH to decide the cluster head nodes. Otherwise, they use the energy-based cluster-head selection algorithm (2), which is also proposed in LEACH. The other operations in the cluster construction phase are identical to those of LEACH. The cluster-heads broadcast an advertisement message that indicates that they are new cluster-heads (CH_ADV). Non-cluster-head nodes determine their own cluster-head according to the strength of the signal and then send a joining message to register it (JOIN). As the cluster composition ends, the cluster-heads create a schedule for their own sensor nodes and broadcast it to them (CH_SCHE).

N represents the node number of sensor networks, and k represents the desirable number of cluster-heads. $P_i(t)$ represents the probability that a sensor node i is able to be a cluster-head. It is identical to the formation of LEACH. $E_i(t)$ is the remaining energy level of a sensor node i.

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

$$P_i(t) = \min\{ \frac{E_i(t)}{E_{total}(t)} k, 1\} \tag{2}$$

$$E_{total}(t) = \sum_{i=1}^{N} E_i(t) \tag{3}$$

2.3 Data Communication Phase

In the data communication phase, each sensor node transmits sensing data to its own cluster-head according to the TDMA slot (SN_DATA). Cluster-heads gather data from the sensor nodes and carry out aggregation, fusion, and compression. After that, the cluster-heads transmit (this) to the base station, including the energy level of the sensor nodes (CH_DATA). The base station passes raw data out through the Internet or cellular networks, and it stores the energy level information of each sensor node for use in the next cluster construction phase. Now, the base station can calculate the total energy level of the sensor networks and calculate the number of sensor nodes in the sensor networks by using the data sent by the cluster-heads. The base station can use various kinds of algorithms to calculate the suitable number of cluster-heads by considering the size of the sensor networks and the number of sensor nodes. In this article, we use 5 percent of the total number of sensor nodes as the optimum cluster-head number, which was arrived at by experiment in the LEACH.

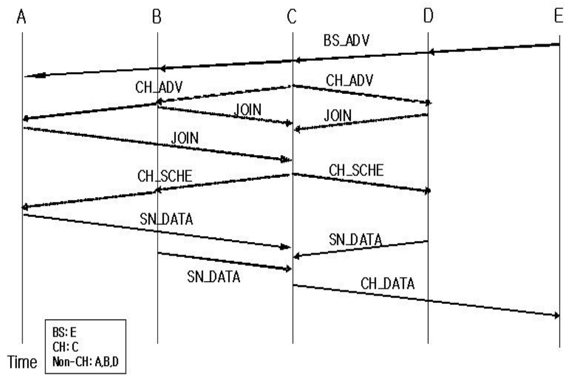

Fig. 1. The message flow of the construction phase and the data communication phase in the proposed protocol

Fig. 1 shows the flow of the cluster construction phase and the data communication phase as we explained above.

2.4 Energy Model

The energy model of the proposed protocol is based on the energy model of LEACH and is briefly summarized [3]. Energy consumption consists of two main parts; receiving and transmitting a message. In transmission, it needs additional energy to amplify a signal according to the distance of the destination. In this article, we suppose that power attenuation depends on the distance between a transmission node and a reception node. The propagation loss is inversely proportional to d^2 while it is inversely proportional to d^4 for long distances. Energy is consumed by the radio to transmit a *k*-bit message over distance *d* as follows:

$$E_{T_x}(k,d) = E_{T_{x-elec}}(k) + E_{T_{x-amp}}(k,d)$$
$$= \begin{cases} E_{elec} * k + \varepsilon_{friss-amp} * k * d^2 & if d < d_{crossover}, \\ E_{elec} * k + \varepsilon_{two-way-amp} * k * d^4 & if d \geq d_{crossover} \end{cases} \quad (4)$$

Exhausted energy at reception is given by:

$$E_{R_x}(k,d) = E_{R_{x-elec}}(k) = E_{elec} * k \quad (5)$$

where E_{elec}, $\varepsilon_{friss-amp}$ and $\varepsilon_{two-way-amp}$ are identical to those of LEACH.

3. Performance Evaluation

In this chapter, the performance evaluation of the proposed protocol is shown. A simulation with ns-2 LEACH extension [8] and implementation [9] is carried out. The simulation environment and parameters are the same as those for LEACH, as shown in Table 1.

We considered two initial energy levels for the sensor nodes: one has the same initial energy level, 2J; the other has a different energy level between 1J and 2J. We also considered two cases regarding the number of cluster-heads in the proposed protocol: one with a fixed number of cluster-heads, the other with a variable number. Here, it is assumed that the base station is located inside the sensor networks. To characterize the performance of the proposed protocol, the average system lifetime, and the total number of messages successfully delivered to the base station, and the number of nodes that are alive were all measured. The results from the simulation were compared with those from LEACH.

Fig. 2 shows the number of sensor nodes alive as a function of time for the equal initial energy level case. The figure shows that the proposed protocol with the fixed desirable number of cluster-heads produces as long a lifetime as LEACH. Meanwhile, the proposed protocol with the variable suitable number of cluster-heads produces a longer lifetime for the sensor networks than LEACH because it uses both the remaining energy information and the number of sensor nodes to select the cluster-heads and to construct the clusters. In LEACH, the number of working sensor nodes decreases rapidly after 300-simulation time. This is because the cluster-heads are selected randomly without considering the energy level of the sensor nodes. On the other hand, the number of sensor nodes alive in the proposed protocol with the variable suitable number of cluster heads diminishes slowly because the proposed protocol constructs clusters by considering the energy level of the sensor networks.

Table 1. Parameters for simulation

Parameter	Value
Network grid	(0, 0) x (100, 100)
Base station	(50,175)
$D_{crossover}$	87m
ϵ_{elec}	50 nJ/bit
$\epsilon_{friss-amp}$	10 pJ/bit/m^2
$\epsilon_{two-way-amp}$	0.0013 pj/bit/m^4
$\epsilon_{aggregation}$	5 nJ/bit
Data packet size	500 bytes
Packet header size	25 bytes
Number of nodes (N)	100

Fig. 3 shows the total number of data received at the base station as a function of time. The proposed protocol with the variable desirable number of cluster-heads sends more data to the base station than LEACH, since the lifetime of the sensor networks of the proposed protocol is longer than LEACH. Fig. 4 represents the number of nodes alive per amount of data sent to the base station. From the figures, it is evident that the performance of the proposed

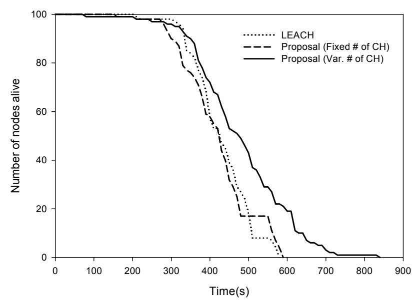

Fig. 2. Number of nodes alive during simulation time with equal initial energy level

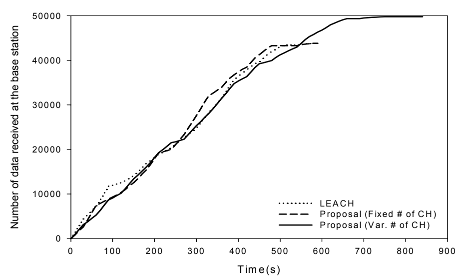

Fig. 3. Total amount of data received at the base station during simulation time with equal initial energy level

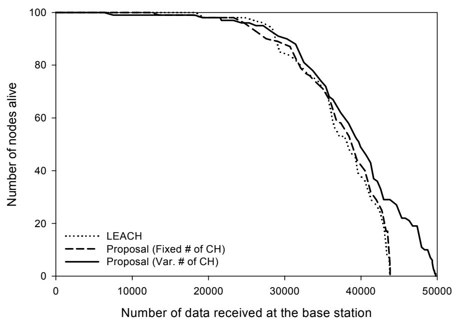

Fig. 4. Number of nodes alive per amount of data sent to the base station with equal initial energy level

protocol is better than LEACH when the number of cluster-heads is variable. Thus, it can be seen that the number of cluster-heads plays an important role in the overall performance of the energy-constrained sensor networks.

In the next experiment, the proposed protocol is simulated with a different initial energy level between 1J and 2J. In Fig. 5 it can be seen that the proposed protocol with the fixed desirable number of cluster-heads exceeds the system lifetime of LEACH by 14 percent. Meanwhile, the proposed protocol with the variable suitable number of cluster heads produce a longer lifetime for sensor networks than LEACH by 67 percent. Fig. 6 shows the total number of received data at the base station. The proposed protocol with the fixed and variable number of cluster-heads sends more data to the base station than LEACH - by 16 percent and 25 percent respectively. Fig. 7 shows the number of nodes alive per amount of data sent to the base station. It is

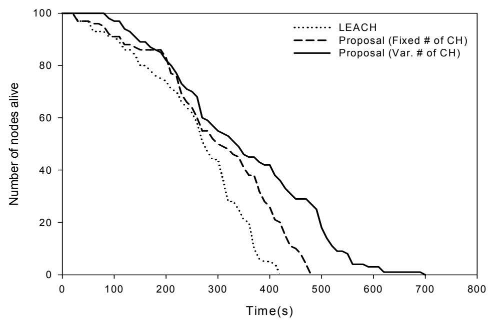

Fig. 5. Number of nodes alive during simulation time with different initial energy level

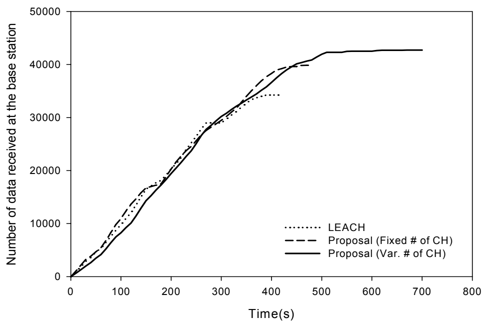

Fig. 6. Total amount of data received at the base station during simulation time with different initial energy level

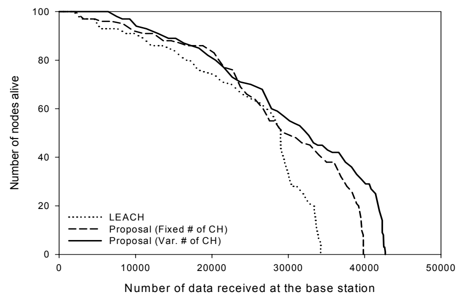

Fig. 7. Number of nodes alive per amount of data sent to the base station with different initial energy level

evident that the performance of the proposed protocol is better than LEACH when the number of cluster-heads is variable. Through this experiment, it can be shown that the proposed protocol with a different energy level outperforms LEACH.

From these experiments, it is clear that the variability of the number of cluster- heads plays an important role in the overall performance of energy-constrained sensor networks.

4. Conclusions and Future Works

In this article, we proposed a cluster-based energy-aware routing protocol without location information of the sensor nodes for sensor networks. In the proposed protocol, the focus was placed on the fact that all sensor nodes do not necessarily know their own position. Moreover, to send information on their position every cluster construction phase may cause unnecessary overheads. However, it is desirable to send their information with their sensing data in order to construct optimal clusters. Therefore, the proposed protocol constructs clusters without inefficient sensor-node-broadcasts to notify the base station of the information of each sensor node. In addition, the proposed protocol changes the desirable number of cluster-heads when composing optimum clusters. Simulation was carried out with two initial energy levels: equal and different initial energy level between 1J and 2J. Throughout the simulation, it was shown that the proposed protocol improves the lifetime of the sensor networks and data rate compared with LEACH at the two initial energy levels.

However, the proposed protocol still does not guarantee the uniform distribution of cluster-heads and the number of cluster-heads selected. Further study will be conducted to solve the above-mentioned problems.

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