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A Study on Cluster Head Selection and a Cluster Formation Plan to Prolong the Lifetime of a Wireless Sensor Network

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Abstract

The energy of a sensor in a Wireless Sensor Network (WSN) puts a limit on the lifetime of the network. To prolong the lifetime, a clustering plan is used. Clustering technology gets its energy efficiency through reducing the number of communication occurrences between the sensors and the base station (BS). In the distributed clustering protocol, LEACH-like (Low Energy Adaptive Clustering Hierarchy - like), the number of sensor's cluster head (CH) roles is different depending on the sensor's residual energy, which prolongs the time at which half of nodes die (HNA) and network lifetime. The position of the CH in each cluster tends to be at the center of the side close to BS, which forces cluster members to consume more energy to send data to the CH. In this paper, a protocol, pseudo-LEACH, is proposed, in which a cluster with a CH placed at the center of the cluster is formed. The scheme used allows the network to consume less energy. As a result, the timing of the HNA is extended and the stable network period increases at about 10% as shown by the simulation using MATLAB.

Key Words : WSN, Clustering, LEACH, Heterogeneous, Residual Energy, LEACH-like

1. Introduction

With the recent emergence of IoT (Internet of Things), WSN is gaining attention interests as a base technology of IoT. WSN consists of a large number of low-power multi-function sensors (hereafter, “node”) with sensing, computation and wireless communications capabilities that can be connected to the Internet via a BS[1]. With its use in IoT, WSN with densely deployed sensors can be applicable to various fields, including environment monitoring, battlefield surveillance, smart homes, health analysis, and agriculture[2].

Many routing protocols are proposed for WSN, aiming to find ways for the efficient usage of energy and the reliable transmission of sensed data to the BS. For the time period during which sensors send data reliably, the WSN is known as stable. As long

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as the network is stable, as many sensors as possible are live. Clustering is a key technique to consume less energy by reducing the number of communication attempts between nodes and BS, which prolong the network lifetime. Sensor nodes in a cluster, which are called cluster members, send data to a special sensor node which is called CH, not to the BS directly, and the CH then sends the data to a BS, where the WSN can be connected to the Internet. Fig. 1 Shows a WSN with BS and Clusters that is composed of a CH and members.

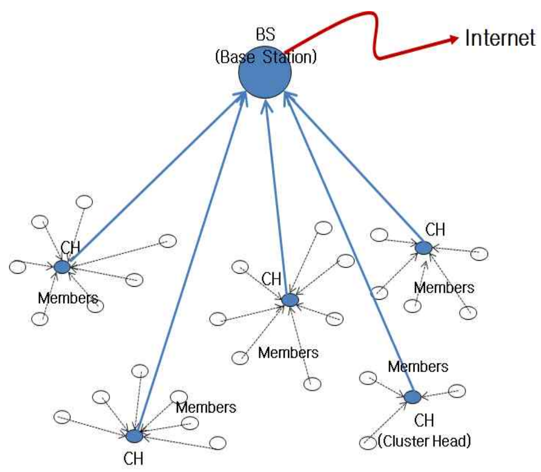

Fig. 1. A WSN with a BS and Clusters

A CH consumes more energy than cluster members in sending data because the distance between the CH and BS is usually much longer than the distance between a CH and its members. In the distributed clustering protocol, LEACH (Low Energy Adaptive Clustering Hierarchy)[3], every sensor in a network plays a CH role once during a certain time period called an epoch. A sensor's residual energy is assumed to be distributed evenly over the network. An epoch is composed of rounds. In each round, some of the sensor nodes play the CH role, and the other nodes are cluster members. After all the sensor nodes in the network have played a CH role once, then an epoch is completed, and a new epoch begins.

Even though every sensor node plays the CH role once during an epoch, the energy consumed is different because the distance from every CH to the BS is different. So, the residual energy of the sensor is different, which results in a heterogeneous network with respect to energy, just like SEP (Stable Election Protocol)[4] protocol. So, in order to distribute energy evenly over the network, there should be a difference in the number of sensor's CH roles. A sensor with more energy plays the CH role more often, as proposed by the HEED (Hybrid Energy-Efficient Distributed clustering)[5] Protocol.

A protocol known as LEACH-like[6] has been proposed, which uses LEACH's algorithm to rotate a sensor's CH role over the network and uses the residual energy, the idea of HEED. Using the LEACH-like protocol, the remaining energy distributes evenly in the network, and the time at which the first node dies (FND) is extended compared to the LEACH, which makes the network stable for a longer time. But in LEACH-like protocol, a CH is inclined tends to be at a corner of a cluster, which makes the distance between CH and its members longer, and makes communication between CH and members consume more energy. In this paper, a pseudo-LEACH protocol, where the cluster head selection and cluster formation process is used to locate the CH of a cluster at the center, is proposed. The simulation with the pseudo-LEACH protocol shows that the lifetime of a stable network increases at about 10 % in regards to HNA.

2. Wireless Sensor Networks and Evaluation Factor

Consider a wireless sensor network consisting of N sensors uniformly distributed in the network.

Some assumptions are made about the sensors and network.

- A BS is located far from the square sensor network.
- The sensors and the BS are all stationary.
- All nodes are homogeneous and have the same capabilities.
- Links are symmetric
- Nodes have no location information.
- Nodes can use power control to vary the amount of transmission power. which depends on the distance to the receiver.
- Nodes can compute the approximate distance to another node based on the received signal strength, if the transmitting power is given.

2.1 Radio Energy Dissipation Model in WSN

Fig. 2 shows a simplified communication model for radio hardware energy dissipation.

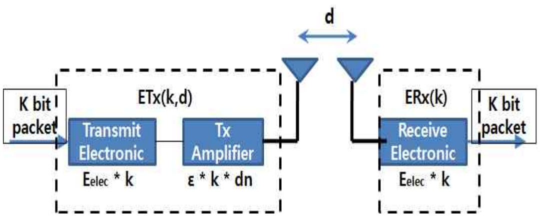

Fig. 2. Radio Energy Dissipation Model of a Sensor Node

Both the free space (d_2 power loss) and multi-path fading (d_4 power loss) channel models are used, depending on the distance, d, between the transmitter and receiver. Energy dissipation for Transmission (E_{Tx}) and Receiving (E_{Rx}) is calculated in equation (1) and (2) respectively, as follows:

$$E_{Tk}(k,d) = \begin{cases} kE_{dec} + k\epsilon_{fa} a^2, d < d_0 \\ kE_{dec} + k\epsilon_{ma} a^2, d \geq d_0 \end{cases} \quad (1)$$

$$E_{Rk}(k) = kE_{dec}(= E_{Fx-dec}(k) = E_{tk-dec}(k)) \quad (2)$$

Where k is the length of the message in bits. The threshold d_0 can be determined by equating the equations (1) and (2), resulting in equation (3) for d_0.

$$d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{ma}}} \quad (3)$$

If the communication distance between CH and BS is longer than d_0, a multi-path fading channel model is used and more energy is consumed. A sensor node also consumes E_{DA} (nJ/bit/signal) for data aggregation. Assuming that the sensed information is highly correlated, the CH can always aggregate the date gathered from its members into a single fixed length packet.

2.2 A Round and an Epoch in LEACH

In LEACH, there is a round, which is composed of two phases, the Set-Up phase and the Steady State phase, as shown in Fig 3. In the Set-Up phase, some nodes are elected as CHs and the other nodes join a CH, as a cluster member, forming a cluster. There are as many clusters as CHs. After cluster formation, each CH broadcasts TDMA schedules to its members and each member sends the sensed data to the CH. In the Steady State phase, each CH sends data that have been gathered from members and compressed to BS. After the Steady State phase of a round, new CHs are elected and clusters are re-formed with new CHs. A new Round begins.

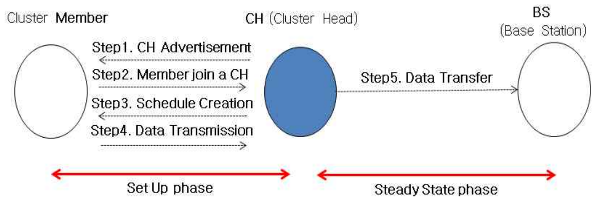

Fig. 3. A Round of LEACH Protocol

In each CH election process, each node can become a CH with a probability p_{opt}. On average, N * p_{opt} nodes become CHs per round. The decision to be a CH is made by each node n ∈ G by independently choosing a random number in [0,1]. If the random number is less than the threshold T(n) shown in equation (4), then the node becomes a CH in the round.

The threshold is set as:

$$T(n)=\begin{cases}\dfrac{p}{1-p^{*}(r \bmod 1/p)} & \text{if } n\in G \\ 0 & otherwise\end{cases} \qquad (4)$$

where r is the current round number, p is p_{opt}, and G is a set of nodes that has not been a CH. The Equation (4) shows that the election probability of nodes ∈ G to be elected as CHs increases in each successive round and becomes equal to 1 in the $1/p_{opt}$ rounds. The time period in which all the nodes in a network play a CH role once is called an epoch. Nodes that are elected to be CHs in the current round can no longer become CHs in the same epoch.

The nodes in a network play a CH role once, and consume much more energy compared with the time they play a cluster member role. As a result, the energy consumption of a node is well distributed and is balanced among the nodes of the network. If the nodes are homogeneous, which means that all the nodes in the network have the same initial energy, the LEACH protocol guarantees that each of them will become a CH exactly once every $1/p_{opt}$ rounds, an epoch.

2.3 Evaluation factor of a network and clusters

The prolonged lifetime of WSN is a main goal and a protocol evaluation factor. The two metric FND and HNA are used to denote a network lifetime[7].

FND: The first time a node dies. This is important when it is necessary that all nodes remain alive as long as possible, since the network quality decreases considerably as soon as one node dies.

HNA (Half of the Nodes Alive): the time when half of the nodes have died. This is important when sensors are placed in proximity to each other. Thus, adjacent sensors could record related or identical data. Hence, the loss of a single or few nodes does not diminish the quality of service of the network.

According to the CH selection and cluster formation, which is related to the internal structure of the cluster or how it relates to other, clustering protocols display different results. The following are considered as metrics[8].

Inter-cluster topology: Random selection of CHs from the deployed sensor nodes usually gives a variable number of clusters. The number of CH in each round should be almost the same and the clusters should be distributed evenly over the network.

Intra-cluster topology: The number of cluster members be distributed evenly over each cluster. The CH can be placed at the center to minimize member's energy consumption for communication with the CH.

3. The LEACH-like and pseudo-LEACH protocols

In LEACH protocol, there is an optimal percentage, p_{opt} of nodes with which nodes are elected as CHs in each round, assuming uniform distribution of nodes in space. After the initial round, the remaining energy of each node is different. In a LEACH-like protocol, the characteristics of the heterogeneousness of a node are considered in the election process of CHs. But this forms an un-balanced cluster. Usually, the CH tends to be located at the center of a side close to the BS. This results in more energy consumption by cluster members for communication with the CH because of the increased distance between them. The pseudo-LEACH protocol considers this problem.

3.1 Cluster Head Selection and Cluster Formation in LEACH-like protocol

During cluster formation, just like in LEACH protocol, each sensor node elected as the CH according to equation (4) makes a claim for the CH (called 1_{st} CH) and nodes not elected as a CH join a CH, as a member, forming a cluster (called 1_{st} cluster). In the LEACH-like protocol, when the members join a CH, they send their residual energy (E_{res}) and distance to BS (D_{2BS}) to CH. With this information, each 1_{st} CH tries to find a 2_{nd} CH that has the highest value of CH_{able} among its members including itself. The CH_{able} is shown in Equation (5).

$$CH_{able} = \frac{E_{res}}{\beta \times D_{2BS}} \tag{5}$$

where β is a scaling factor. The node with the highest value of CH_{able} is the node that has greater residual energy than the other cluster members, and is closer to the BS than the other cluster members. Because the distance is short, the 2_{nd} CH consumes less energy during its CH role. Because it has more energy, even after the CH role the residual energy distributes evenly over the network. The 1_{st} CH re-advertises the 2_{nd} CH to its cluster member nodes. All the member nodes of the cluster join the 2_{nd} CH forming the 2_{nd} cluster, and know that the CH has changed from a 1_{st} CH to 2_{nd} CH. The entire 2_{nd} cluster has the same 1_{st} cluster members, only the CH changes. Even after an epoch has passed, there may be a node that did not play a CH role once. This process is shown in Fig 4.

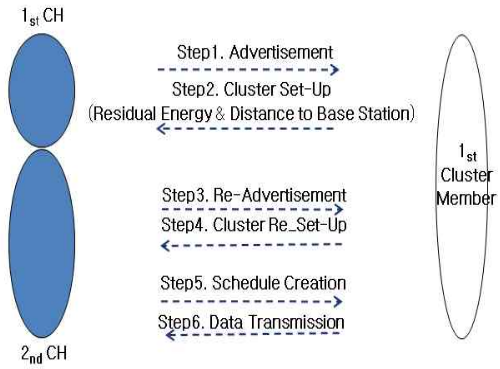

Fig. 4. A Cluster Set-Up phase of LEACH-like Protocol

3.2 Problems with the LEACH-like Protocol

It was found that, in a LEACH-like protocol, CHs are placed at the center of the upper side of a cluster, which is close to the BS. This makes communication distance longer between the cluster members and CH, resulting in increased communication energy consumption. The reason for this is due to the CH selection and the cluster formation. In a LEACH-like protocol, after the initial 1_{st} cluster formation, the 2_{nd} CH is chosen by equation (5), which chooses a member node with more residual energy and which is closer to the BS. A node closer to the BS tends to have more residual energy than the node farther from the BS because of the distance needed for communication, which results in choosing a node closer to the BS in a cluster. During 2_{nd} cluster formation, the members of the 2_{nd} cluster are not changed from the members of 1_{st} cluster, and only CH the changes. This leads to the cluster formation shown in Fig. 5.

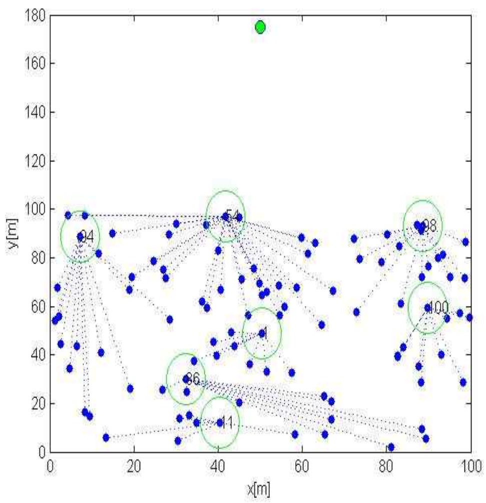

Fig. 5. Location of a CH in a Cluster in a LEACH-like Protocol

3.3 Enhanced Cluster Head Selection and Cluster Formation in a pseudo-LEACH protocol

In a pseudo-LEACH protocol, the CH selection and cluster formation is enhanced to allow the cluster members to consume less energy in communicating with the CH. The 1_{st} CH selection and cluster formation (step 1 and 2 in Fig. 4.) is same as in the LEACH and the LEACH-like protocols. In pseudo-LEACH protocol, just as in LEACH-like protocol, when members join a cluster, members send their information, residual energy, and distance to the BS. In the selection of the 2_{nd} CHs (step 3 in Fig. 4), the 1_{st} CH uses equation (6) instead of equation (5). The cluster head selection parameters CH_{able} shown below in equation (6), considers residual energy and distance to BS, as in LEACH-like protocol. Equation (6) considers the energy and distance not in absolute mode, but in comparative mode with the 1_{st} CH, which makes it easy to compare the values. Equation (6) uses the additive function of energy and distance, which allows the attribution of measure to be controlled by controlling the α scaling factor.

$$CH_{able} = \frac{E_{res}(C_{member})}{E_{res}(C_{hems})} + a \times \left(\frac{D_{2BS}(C_{hems})}{D_{2BS}(C_{member})} \right) \tag{6}$$

Here, α is the scaling factor. If α increases, the node closer to BS is chosen, and otherwise, the node with more energy is chosen for the 2_{nd} CH.

After the 2_{nd} CH selection, the 2_{nd} CH advertizes itself as the 2_{nd} CH over the network, and the nodes that are not the CH joins the 2_{nd} CH (step 4 in Fig. 4.) that is the closest to itself just as in LEACH protocol. This is unlike the LEACH-like protocol, however, where only the members of the 1_{st} cluster join the 2_{nd} CH. In the pseudo-LEACH protocol, as shown in Fig. 6, all the nodes that are not a 2_{nd} CH can join any 2_{nd} CH even if the 2_{nd} CH was not in the same 1_{st} cluster.

As a result, a cluster is formed with the CH that is located at the center of a cluster. Using the pseudo-LEACH protocol results less energy consumed for communication between CH and members. Just as in the LEACH-like protocol, even after an epoch has passed there can be a node that did not play a CH role once.

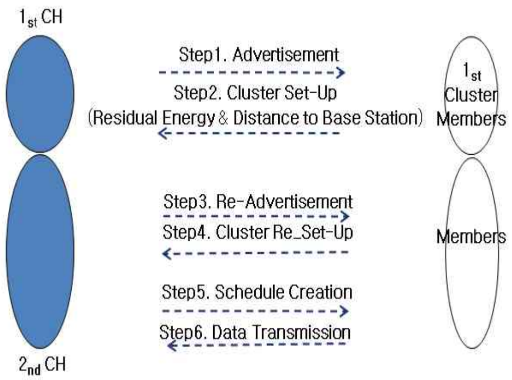

Fig. 6. A Cluster Set-Up phase of the pseudo-LEACH Protocol

4. Simulation

The performance of the pseudo-LEACH protocol implemented was simulated with MATLAB. A clustered wireless sensor network with dimensions 100m * 100m from (x=0, y=0) to (x=100, y=100) was used. The population of the sensors was equal to N=100 and the nodes were randomly distributed over the network. The BS was located at x=50m, y=175m. The size of the message that the nodes sent to the CHs and the size of the (aggregate) message that the CH sends to the BS was set to 6400 bits. The probability of becoming a CH, p_{opt}, was set to 0.1.

4.1 Simulation Parameters

Nodes dissipate energy to send, receive and aggregate data. To calculate the energy consumed by the CH and members during a round, the following values shown in Table 1 were used.

Table 1. Parameters for energy Dissipation

Parameter	Value
E_{elec}	50nJ/bit
E_{DA}	5nJ/bit
ε_{fs}	10pJ/bit/m^2
ε_{mp}	0.0013pJ/bit/m^4
d_0	87.7m
p_{opt}	0.1
E_{max}(initialenergy)	0.5J
k(length of message)	6400bit

4.2 Simulation Results

The simulation results show that the HNA extends by about 10%, compared with a LEACH-like protocol having the same condition, and the shape of the cluster shows that a CH is located at the center of the cluster. For the scaling factor α, 12 was used.

4.2.1 The Time Period between FND and HNA

In Fig. 7, the simulation result (R875-R901) using LEACH-like protocol shows that the number of dead nodes increases rapidly during the period between FND and HNA. But the simulation result (R641-R980) using pseudo-LEACH protocol shows a step by step increase of dead nodes. The FND of pseudo-LEACH protocol happens earlier than that of LEACH-like protocol, but the HNA of the pseudo-LEACH extends at about 10 % more than that of the LEACH-like protocol. This result means that the pseudo-LEACH protocol controls the sensor's energy more conservatively than the LEACH-like protocol, and prolongs the lifetime of the network.

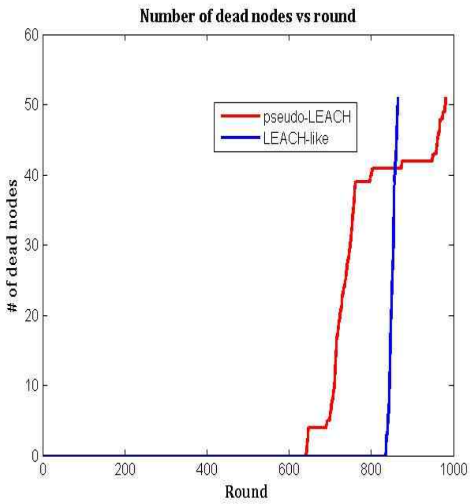

Fig. 7. HNA of LEARCH-like and pseudo-LEACH Protocol

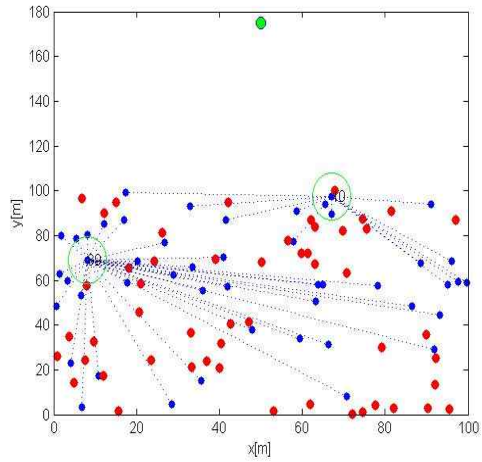

Fig. 8. Cluster Formation (HNA-901R, LEACH-like)

4.2.2 Cluster Formation at HNA

The shape of the cluster and the position of the CH in the cluster are shown in Figs. 8 and 9, corresponding to LEACH-like and pseudo-LEACH protocol, respectively. In Fig. 8, the CH is located at the center of the side close to the BS, but the CH in Fig. 9 is located at the center of a cluster. As the distance between CH and member nodes becomes longer, the more energy member nodes consume. So, for the case of the LEACH-like protocol, nodes consume more energy to transmit data to the CH. The simulation results shown in Figs. 8 and 9, show that the dead nodes, which are not connected with the CH, are distributed over the network, which is different from the LEACH protocol.

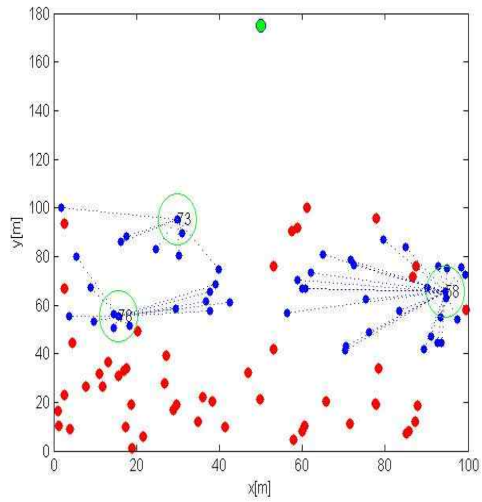

Fig. 9. Cluster Formation (HNA-980R, pseudo-LEARCH)

5. Conclusion

In a WSN, a clustering plan prolongs the lifetime of a network. Clustering reduces the number of communication attempts between sensor nodes and the BS, resulting in efficient energy usage. In the LEACH-like protocol, the number of times a sensor plays the CH role is different between sensors with different energy. A node with more energy plays the CH role more often, which distributes energy consumption evenly over the network and prolongs the lifetime. The position of the CH in each cluster tends to be at a corner of a cluster, which makes the energy consumption of the node larger than when the CH is located at the center of a cluster. In this paper, a pseudo-LEACH protocol is proposed to enhance the CH selection and cluster formation plan to put the CH at the center of a cluster. The simulation using MATLAB shows the timing of HNA occurrence extends to about 10 %, which means that the stable network period increases at the same rate. Experiments are needed to verify the simulation results and research regarding the selection of CHs in a round, such as the number and distribution over a network, to extend the lifetime of WSN.

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