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Non-Homogeneous Cluster Head Selection for Energy-Aware Hierarchical Routing Protocols in Wireless Sensor Networks

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Abstract — **In Wireless Sensor Networks (WSNs), sensor nodes are equipped with a limited energy battery. Energy consumption is a very challenging field in WSN. In this paper, we modify the Low Energy Aware Clustering Hierarchy (LEACH) and the Extended LEACH (XLEACH) protocols to increase the lifetime of the network. The main difference of our protocol is based on non-homogenous probability of Cluster Head (CH) selection. We consider a virtual reference node in the protocol. Each node chooses its probability of CH selection properly so that its energy consumption would be close to the energy consumption of the reference node. Our simulation illustrate that the lifetime of the network increases considerably without increasing the complexity of the protocols. According to the simulations, this method makes energy consumption more efficient than the LEACH or XLEACH, and consequently prolongs the network lifetime. Moreover, the modification does not affect the delay in the protocols.**

Keywords - ***Wireless Sensor Network (WSN), Routing, Energy efficiency, Network Lifetime, Cluster Head Selection.***

1. INTRODUCTION

Wireless Sensor Network (WSN) consists of hundreds or thousands of nodes. Usually these nodes need to be cheap and small, so we cannot equip them with big batteries. Energy resources of these nodes are limited and they cannot transmit their data too far. Although low energy hardware is a very effective solution for energy saving, but energy aware algorithms in other layers are important to prolong lifetime of the network [1].

These nodes are usually scattered randomly in a field. The nodes sense a phenomenon in the field and they send the sensed data to a Base Station (BS). The BS is the destination node and is located somewhere inside or near the field.

The cost of communication with the BS is related to the node's distance from the BS. This relation is not linear and the far nodes consume much more energy than the close nodes. When nodes send their data directly to the BS, the far nodes will die so soon and we lose the coverage of the sensor. Cooperation can solve this problem. The nodes can help each other to relay their data to the BS. In other word, transmission range will be smaller and thus energy consumption reduces.

We can use three type of solutions to reduce energy consumption in the network. The first is assistant approach, such as aggregation, data compression, and deployment assistant [2]. The second is node distribution strategies. As we said before, distance of nodes from the BS is different and this makes energy consumption unbalanced between nodes. With balancing nodes's density, we could have uniform energy consumption between nodes [3, 4]. The third is adjustable transmission range. Decreasing the maximum transmission range of the nodes for communication, is a very effective solution for energy saving [5].

Low-Energy Adaptive Clustering Hierarchy (LEACH) is a routing protocol designed to collect and deliver data to the BS. The nodes divide into clusters. A selected Cluster Head (CH) manages each cluster. The cluster head is responsible to gathering data from the members of the cluster and transmit the aggregated data directly to the BS. In Extended LEACH (XLEACH) protocol, the lifetime of the network increases by considering the level of residual energy in CH selection.

In this paper, we modify the CH selection (second strategy) to increase the network lifetime of some hierarchical protocols such as the LEACH and XLEACH. In LEACH protocol, the CHs are selected randomly and uniform [6]. We investigate a procedure that chooses the far nodes less than the near nodes as CH. We generate a virtual reference node in the protocol. The other nodes attempt to adjust their appearance as CH so that the energy of selected CH would be the same as virtual reference node. Simulation results indicate that the lifetime of the network prolongs considerably.

2. Related Works

Energy optimization is one of the major problems in WSNs. Many solutions would propose saving energy consumption. Each method has some benefits and some defects. Transmission range control [5] and Medium Access Control (MAC) [7, 8] are very effective solutions to manage energy consumption. Almost every routing protocol in WSN tries to minimize the radio transmission range and avoids collision in the medium, by a proper MAC protocol, in order to reduce the energy consumption.

We can divide routing protocols to two categories. First flat routing protocols such as Direct Diffusion (DD) [9] and Sensor Protocol for Information via Negotiation (SPIN) [10]. The second category is clustering routing protocols such as the LEACH and Power Efficient Gathering in Sensor Information System (PEGASIS) [11]. In addition, there are hybrid protocols such as Threshold-sensitive Energy Efficient Network (TEEN) and Adaptive Periodic TEEN (APTEEN) that combine these categories in order to compensate their defects [6, 12, 13].

Hierarchical protocols are suitable methods that have many benefits. Scalability is one of the most benefits in hierarchical protocols. In such protocols, the network has several levels and the nodes in each level have different tasks. Simulations show that increasing levels till 5 give us good result in performance [14].

We concentrate our work on the LEACH protocol that is a very well known hierarchical protocol in WSN. The major advantage of the LEACH protocol is simplicity of implementation in a distributed manner. Different modification of the LEACH protocol are presented. In [15] enhance the performance of the LEACH protocol via variable rounds' time. In [16] the residual energy of a node is considered in cluster head selection in the LEACH protocol for prolonging of the network lifetime. In [17] the performance of the LEACH protocol improve by sub-cluster head selection. In [18] the LEACH protocol is modified for heterogenous networks. In this paper we introduce a different approach for improving the performance of the LEACH protocol. The method bases on nonuniform cluster head selection in the area. In the next section, we introduce the protocol.

3. Proposed Scheme

In this section at first we review the LEACH protocol. Then we derive an expression for energy consumption of each node. Finally, we use this expression to modify suitable value for probability of CH selection in the LEACH protocol.

3.1. The LEACH Protocol

LEACH is a hierarchical protocol that splits time to rounds. Each round has two phases, setup phase and steady state phase. In the setup phase, the nodes divide into clusters. In the steady state phase, data will be sent to the BS. The setup phase repeats rarely according to the dynamic of the networks. Fig. 1 shows the time diagram of the LEACH protocol.

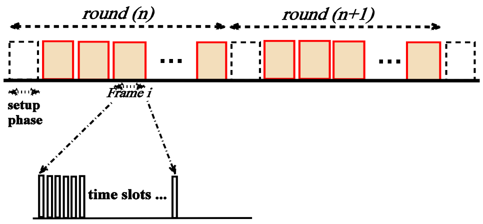

Figure 1. Time diagram of the LEACH protocol.

Each round starts with the setup phase. In this phase, the nodes divide into clusters. At first, each node has to decide to be a CH or not. The $n'th$ node produces a uniform random variable in the interval $[0,1)$ and compares it with the threshold, $T(n)$. If the random variable is smaller than $T(n)$, this node is a CH in this round. Threshold is as the following:

$$T(n) = \begin{cases} \dfrac{p}{1 - p(r \bmod (\frac{1}{p}))} & n \in G \\ 0 & n \notin G \end{cases} \qquad (1)$$

Where p is the probability of CH selection, r is the round's number and mod returns remainder of the modular division. The variable G represents the set of nodes that have not been selected as CH in the past $\frac{1}{p}$ rounds.

The CH chooses a Code Division Multiple Access (CDMA) key and broadcast it for all nodes in the network using Carrier Sense Multiple Access-Collision Avoidance (CSMA-CA). All CHs use the same power to transmit their CDMA key. Non-CH nodes receive these keys. Each node supposes the channel is homogenous and communicate with a CH that has strongest signal. Non-CH nodes, by measuring the strength of the received signal, estimate their distances from CHs and use enough power in transmission to communicate to the nearest CH. After receiving all requests by CHs, each CH prepares a Time Division Multiple Access (TDMA) schedule for its own cluster's nodes and broadcasts it to them.

After setup phase, network enters the steady state phase. In this phase, each node goes to sleep and according to TDMA schedule, wakes up, and sends its data to the CH. Time in steady state phase divide into frames. Each frame has enough time slots for TDMA schedule in each cluster. At the end of a frame, CHs aggregate their collected data from cluster's nodes, and send to the BS directly. We suppose the length of aggregated packet is the same as data packets that have sent from non-CH nodes.

CH's task work is a very energy-consuming job. Therefore, after several frames, new round begins and some of the other non-CH nodes will be CH in the new round. This prevents a node to be a CH for long time [6].

3.2. The XLEACH Protocol

XLEACH is an energy aware version of the LEACH protocol [19]. The only difference between them is in their thresholds. Threshold in the XLEACH at round r is:

$$T(n) = \frac{p}{1-p(r \bmod (\frac{1}{p}))}\left[\frac{E_{n,current}}{E_{n,max}} + (r_{n,s}\ div(\frac{1}{p}))(1-\frac{E_{n,current}}{E_{n,max}})\right] \quad (2)$$

Where $E_{n,current}$ is current energy, and $E_{n,max}$ is initial energy of the sensor node. The variable $r_{n,s}$ is the number of consecutive rounds in which a node has not been a CH and is set to zero when a node becomes a CH. The operator div returns constituent of division.

3.3. Modification of the protocols

In this section, we modify the LEACH and XLEACH protocols in such a way that prolongs the lifetime of the network. First, we want to look at energy consumption in the LEACH protocol. In the LEACH protocol, a node either transmits data or receives it. When a node is a non-CH, it just transmits data to its own CH. However, a CH node must stay active during the frame and receive data from nodes. Then a CH transmits aggregated data directly to the BS. Therefore, energy consumption is different between nodes. We want to express an estimation of energy consumption in a node.

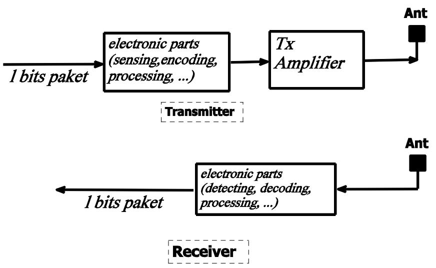

Figure 2. Energy consumption parts in transmitting and receiving l bits of data stream.

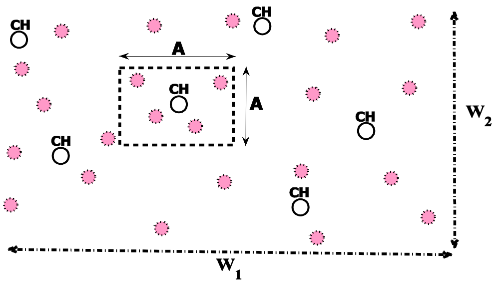

Figure 3. An $W_1 \times W_2$ area with an example of a cluster area with $A \times A$ dimension.

At first, we need to select a suitable energy consumption model in nodes. Fig. 2 illustrates energy consumption parts when a node transmits or receives l bit of data stream. In transmitter, we can model energy consumption per bit in transmission for d meter distance as [3, 5, 12, 14, and 20]:

$$E_{Tx}(d) = \begin{cases} E_{elect} + \xi_{fs}\, d^2 & if \quad d < d_0 \\ E_{elect} + \xi_{mp}\, d^4 & if \quad d \geq d_0 \end{cases} \quad (3)$$

Where E_{elect} is the consumed energy in electronic parts, ξ_{fs} is energy dissipation coefficient for transmitter amplifier in free space model, ξ_{mp} is for multi path model and d_0 is reference distance. For continuity of the energy model, the reference distance, d_0, must satisfy:

$$d_0 = \sqrt{\frac{\xi_{fs}}{\xi_{mp}}} \quad (4)$$

In receiver, energy consumption per bit is as:

$$E_{Rx} = E_{elect} \quad (5)$$

When a node is non-CH, it just needs to transmit its data to the CH. We denote the distance between the node and its CH by d_{to-CH}. This distance depends on the p value in the threshold formula. When p is small, the number of CHs is low in the area and consequently d_{to-CH} has high value. In the other word for non-CH nodes, by increasing the p value, energy consumption decreases. For expressing energy consumption in a closed formula, we need to find the d_{to-CH}. We consider a field with N nodes in an area with $W_1 \times W_2$ sides. We suppose all clusters are square shaped and CHs are in the center of the clusters as in the Fig. 3. We denote the dimension of a cluster with A. Suppose that the nodes are scattered uniformly in the field with probability density function $f_{x,y}(x,y)$. Thus,

$$f_{x,y}(x,y)=\begin{cases}\dfrac{1}{W_1W_2} & \forall(x,y)\in W_1\times W_2\\ 0 & otherwise\end{cases} \quad (6)$$

If there are k cluster in the area, we have:

$$A=\sqrt{\frac{W_1W_2}{k}} \quad (7)$$

Note that p is the probability of CH appearance in the area. Thus, where there are N nodes in the area, we have approximately Np cluster heads in the area. We assume the number of clusters is so high that we have free space propagation for inter cluster communication. Therefore the expectation of energy consumption for a non-CH is:

$$\begin{aligned}\overline{E}_{non-CH} &= E\{E_{elect}+\xi_{fs}\, d^2\}\\ &= E_{elect}+\xi_{fs}\, E\{d^2_{to-CH}\}\end{aligned} \quad (8)$$

The expectation of $E\{d^2_{to-CH}\}$ is as:

$$\begin{aligned}E\{d^2_{to-CH}\} &= \int_{-\frac{A}{2}}^{\frac{A}{2}}\int_{-\frac{A}{2}}^{\frac{A}{2}}(x^2+y^2)f_{x,y}(x,y)dxdy\\ &= \frac{W_1W_2}{6k^2}\end{aligned} \quad (9)$$

Thus from 8 and 9 we have,

$$\overline{E}_{non-CH} = E_{elect}+\xi_{fs}\frac{W_1W_2}{6k^2} \quad (10)$$

Whenever the dimension A of a cluster is not small, the free space propagation is not valid. For simplicity, with tolerant, we use $(E\{d^2_{to-CH}\})^2$ instead of $E\{d^4_{to-CH}\}$.

When a node is CH, it receives data from other nodes in the cluster and at the end of the frame, aggregates these data, and sends it to the BS. We denote the node distance from BS as d_{to-BS}. Energy consumption for a CH is as follow:

$$\overline{E}_{CH} = \frac{N}{k}E_{elect}+E_{Tx}(d_{to-BS}) \quad (11)$$

Where $\frac{N}{k}$ is the average number of nodes in a cluster and E_{elect} is consumed energy in receiving one bit. In equation 11, $E_{Tx}(d_{to-BS})$ indicates the consumed energy of the CH for transmitting one bit to the BS.

We define the lifetime of the network as the First Node Die (FND). FND Lifetime is the time that first node consumes all its energy and it cannot communicate anymore. For increasing the lifetime of the network, we have to distribute energy consumption uniformly over the nodes. One reason of lifetime reduction is related to the fact that we used the same probability of CH selection, p, for all nodes. However, as could be seen from the equation 11, a node with longer distance to the BS, consumes more energy than a node that is near the BS. Thus, when we use the same probability for all nodes, some nodes die sooner than the others do. Consequently, the lifetime decreases. If we set different probability of CH selection for each user, we could distribute energy consumption uniformly over the nodes and consequently the lifetime increases.

Suppose that for the $i'th$ node, we use the probability of CH selection p_i in threshold formula. In the other word, the node i is a CH with probability p_i. The expectation of energy consumption in the node i is:

$$\begin{aligned}\overline{E}_i &= (1-p_i)\overline{E}_{non-CH}+p_i\overline{E}_{CH} =\\ & p_i\left(E_{Tx}(d_{to-BS})+(\frac{N}{k}-1)E_{elect}-\xi_{fs}\frac{W_1W_2}{6k^2}\right)\\ & +E_{elect}+\xi_{fs}\frac{W_1W_2}{6k^2}\end{aligned} \quad (12)$$

For increasing FND lifetime, we balance the energy consumption between nodes. We define mean square error of nodes' energy consumption as:

$$e=\frac{1}{N}\sum_{i=1}^{N}(\overline{E}_i-E_m)^2 \quad (13)$$

In which E_m is a predetermined level of energy consumption. In order to balance energy consumption, we minimize the mean square error e in equation 13. Thus, we must have:

$$\frac{\partial e}{\partial E_m}=0 \quad (14)$$

$$\frac{\partial e}{\partial p_j} = 0 \quad , \quad j = 1,2,...,N \qquad (15)$$

From equations 14 and 15 we have,

$$E_m = \frac{1}{N}\sum_{i=1}^{N}\overline{E}_i \qquad (16)$$

$$\overline{E}_j = E_m \quad , \quad j = 1,2,...,N \qquad (17)$$

This leads uniform energy consumption and consequently increases the FND of the network. We suppose, E_m is the energy consumption of a virtual reference node with probability of cluster head p. Thus from equation 12,

$$E_m = p\left(E_{Tx}(d_{to-BS}^{ref}) + (\frac{N}{k} - 1)E_{elect} - \xi_{fs}\frac{W_1W_2}{6k^2}\right) + E_{elect} + \xi_{fs}\frac{W_1W_2}{6k^2}$$

Where d_{to-BS}^{ref} is the distance of reference node from the BS. From equations 10, 11, 12 and 17, we have:

$$p_i = \frac{E_m - E_{elec} - \xi_{fs}\frac{W_1W_2}{6k^2}}{(\frac{N}{k} - 1)E_{elec} + E_{Tx}(d_{to-BS}) - \xi_{fs}\frac{W_1W_2}{6k^2}} \qquad (18)$$

The probability p_i is restricted to the interval $[0,1]$. Thus for any node, we must have:

$$\overline{E}_{non-CH} \le E_m \le \overline{E}_{CH} \qquad (19)$$

The equation 19 might not approved for some nodes. The level E_m has critical effect in the improvement of FND lifetime. We have to choose E_m the moderate of energy consumption of the nodes. In this case, some nodes that have more energy consumption than E_m, reduce their candidacy to being CH. Similarly some nodes that have lesser energy consumption than E_m, increase their candidacy as CH. This improves uniformity of energy consumption and consequently increases the FND.

We create a virtual reference node with energy consumption E_m, the probability of cluster head p, and distance d_{to-BS}^{ref} to the BS. Although we could choose different reference node, but our investigation denote the following choose is proper.

Algorithm 1 (Reference node generation):

1. BS broadcasts a packet to start network task. Every node in the network estimates its distance from the BS and sends it directly to the BS, using CSMA-CA method. BS collects these distances and create d_{to-BS}^{ref} as the following :

$$d_{to-BS}^{ref} = (Mean(d_{to-BS}^{4}))^{\frac{1}{4}}$$

2. BS broadcasts d_{to-BS}^{ref}, p and N to all nodes in the network.
3. Every node in the network estimates E_m as the following :

$$E_m = (1-p)(E_{elec} + \xi_{fs}\frac{W_1W_2}{6(Np)^2}) + p(\frac{N}{Np}E_{elec} + E_{Tx}(d_{to-BS}^{ref}))$$

Now we modify the LEACH and XLEACH protocols as the following:

Algorithm 2 (Modified Protocols):

1. Generate a virtual reference node (algorithm 1).
2. Each node estimates its probability p_i as the following:

$$p_i = \frac{E_m - E_{elec} - \xi_{fs}\frac{W_1W_2}{6(Np)^2}}{(\frac{1}{p} - 1)E_{elec} + E_{Tx}(d_{to-BS}) - \xi_{fs}\frac{W_1W_2}{6(Np)^2}}$$

3. Each node estimates its threshold using p_i instead of p in the equations. The rest of the protocols are the same as LEACH or XLEACH.

For static networks, we can execute the first and the second step in the algorithm 2 only once. The node can store the values of E_m and p_i, and utilize these values in the third step of the algorithm 2. In this approach, we only need to execute the third step of algorithm 2 for future times. Therefore, the complexity of the algorithm does not increase.

For dynamic networks, the problem is different. We should run the step 1 and step 2 of the algorithm 2, repeatedly according to time constant of dynamic changes. The complexity here would increase depends on the rate of changes.

In the next section, we evaluate the improvement of the protocols through simulation of a typical environment.

TABLE 1. SIMULATION PARAMETERS

Parameter	Value
N (number of nodes)	100
Field area	$200 \times 200\, m^2$
Initial energy in nodes	2 joule
E_{elec}	50 nano joule
ξ_{fs}	10 pico joule
ξ_{mp}	0.0013 pico joule
d_0	87 m
Control packet length	25 byte
Data packet length	500 byte
Data header length	25 byte
Round length	30 frame
Frame length	20 sec
BS position	[200,200]

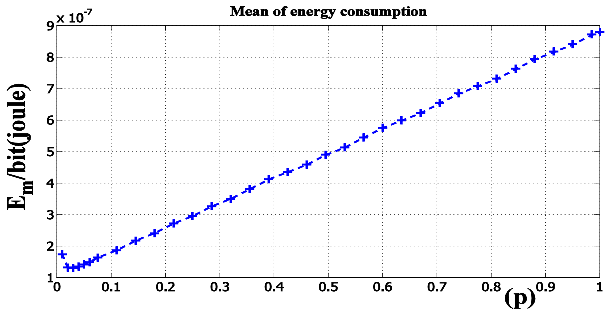

Figure 4. Energy consumption in virtual node (E_m) versus the probability of cluster head selection.

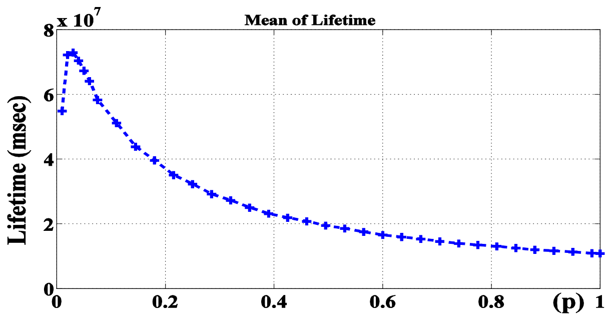

Figure 5. The lifetime of reference node versus the probability of cluster head selection.

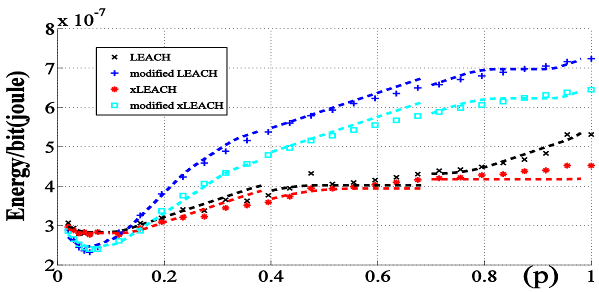

Figure 6. The average of energy consumption per bit versus the probability of cluster head selection.

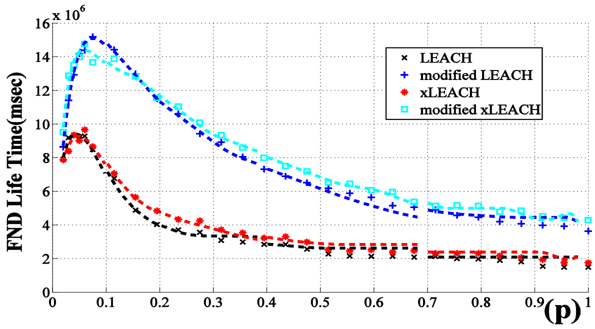

Figure 7. The average FND lifetime versus the probability of cluster head selection.

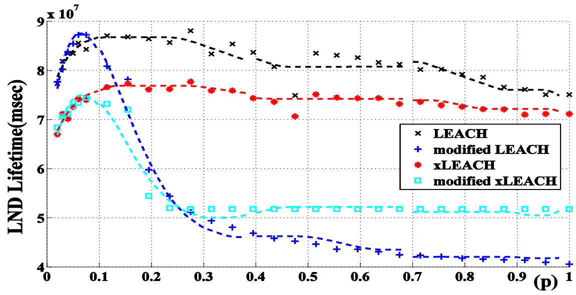

Figure 8. The average LND lifetime versus the probability of cluster head selection.

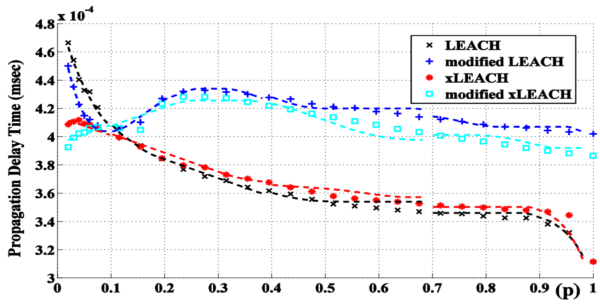

Figure 9. The average Propagation delay versus the probability of cluster head selection.

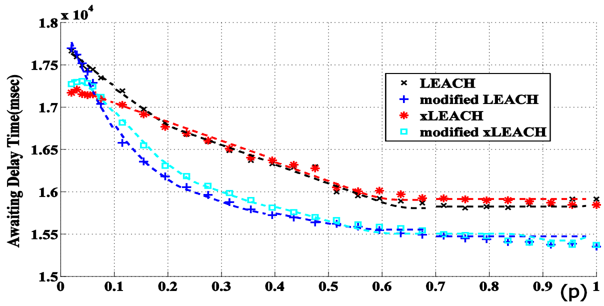

Figure 10. The average awaiting delay versus the probability of cluster head selection.

4. Simulation Results

We used the MATLAB to simulate our network. Our simulation parameters are shown in Table (1) [6, 21]. The nodes have distributed uniformly on the area in each trial. The results are the average of 50 trials. In the simulation, we suppose that time interval between events in a node, is a Poison random variable with $\lambda = 10sec$.

We first compute the average lifetime of the reference node. The reference node with initial energy $E_{initial}$ and energy consumption per bit E_m could send

$\frac{E_{initial}}{E_m}$ bit through its lifetime. In each time frame t, the reference node sends $8 \times D_{Len}$ bits, where D_{Len} denotes the data length of transmitted data in each frame's time t. Thus, the average lifetime of the reference node is as:

$$Lifetime = \frac{E_{initial}}{E_m} \times \frac{1}{8 \times D_{Len}} \times t \qquad (20)$$

The effect of energy consumption in control bits in each round is negligible and for simplicity, we ignore it in the above equation.

Fig. 4 illustrates the energy consumption per bit of the virtual reference node versus the probability of CH selection p. Fig. 5 shows the lifetime of the reference node for the parameter of Table 1.

Fig. 6 illustrates the average energy consumption of four protocols versus the probability of CH selection (p). The points in the figures are samples from simulating the protocols. For better viewing, we used interpolation to draw lines in every figure. As we see in the Fig. 6, the average of energy consumption in the modified LEACH is so close to energy consumption of the reference node in Fig. 4.

Fig. 7 and 8 show the First Node Die (FND) and Last Node Die (LND) lifetimes of the protocols respectively. LND is the time that for all nodes in the network residual energy is less than 10% of nodes' initial energy [22]. For $p \simeq 0.08$ without any decreasing of the LND lifetime, we have above 50% increasing in the FND lifetime in the modified protocols. Comparing these two lifetimes with Fig. 5, we can see that the lifetime of the reference node is almost between the FND and LND lifetimes. Also for $p \simeq 0.08$, energy consumption for transmitting a bit is minimal. This means the number of transmitted packets for $p \simeq 0.08$ is maximal. As a result, we can choose $p \simeq 0.08$ for the modified protocols to have maximum FND lifetime without reducing the LND lifetime.

When a node wants to send a data packet, it must wait until its TDMA slot. Then the node sends the packet to its CH. The CH waits until the end of the frame. At the end of the frame, CH sends the aggregated packet to the BS. We call this delay as awaiting delay and denote this delay with T_{aw}. In addition, there is the propagation delay T_{pg} that related to the speed of radio waves and the distance between CH and BS. According to the processor ability and available bandwidth (transmission bit rate), there are the processing and transmission delay (T_{pr} and T_{tr}) respectively. Total delay of packet will be as:

$$T_{total} = l_1 T_{pr} + l_2 T_{tr} + T_{pg} + T_{aw} \qquad (21)$$

Where l_1 is the length of packets that a CH needs to process, and l_2 is the length of aggregated packet that must be transmitted to the BS. Values of T_{pr} and T_{tr} depends on electronic technology and we do not discuss it here. The last two terms are related to the routing protocol.

The T_{pg} and T_{aw} are plotted in Fig. 9 and 10 for the four protocols respectively. As we see, T_{aw} is dominant and almost alike between all four mentioned protocols. This is a good result and illustrates that our modifications do not affect the delay significantly. Thus, here the improvement of the FND lifetime achieves without affecting the delay in the protocols.

5. Conclusions

In this paper, we considered the energy consumption in the LEACH and XLEACH protocols. The close nodes to the BS, need less energy than the far nodes in order to communicate with the BS. Therefore, they should have different value for probability of CH selection. We expressed energy consumption in a node as a closed formula. Then we used this expression to choose different value of probability of CH selection in each node to make energy consumption more efficient than the LEACH and XLEACH protocols. Simulations illustrated the FND lifetime has become much more than the LEACH and XLEACH protocols and the delay in delivering packets do not change significantly.

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