Increasing Energy-Efficiency in Hierarchical Communication Protocols

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Abstract

Energy-efficiency and scalability are the most important considerations in designing a communication protocol for wireless sensor networks. This project presents an energy-efficient hierarchical communication protocol that aims at balancing the energy load among sensors in a wireless sensor network. We have proposed two approaches that use distance parameter to distribute the energy load uniformly throughout the sensor network. Our first approach divides the entire network into segments with equal area and applies different cluster head election policies to each segment. The second approach uses cluster heads’ approximate distance from the base station to select a more efficient relay point, and thus, avoids wasteful transmissions. Moreover, none of the approaches requires centralized support from a controller node which contradicts network scalability. In order to evaluate our two approaches, a simulator was implemented using MATLAB. Extensive simulations show that using our approaches, the lifetime of the network improves comparing with current hierarchical protocols by 25% in the first approach and by 10% for the second approach.

1. Introduction

Recent advances in wireless communications and digital electronics have enabled sensor networks to contain large number of low-cost and low-power sensor nodes that can collaborate as a group [19,20,21]. This capability enables applications to achieve high quality and fault tolerant sensing networks with larger coverage area over conventional sensing networks [7,13]. Since sensing applications generate a large quantity of data, these data must be fused or aggregated to lower the energy consumption. There are many tight constraints in the design of sensor networks such as small size, light weight, low energy consumption and low cost. Among these energy efficiency should be considered as one of the most important issues since it is impossible to replace batteries on thousands of sensors considering the fact that these sensor networks are deployed in remote or inhospitable environments such as military command control [17,14], intelligence and tracking systems [13,18] and medical monitoring [15,16]. A wireless sensor network generally consists of a base station that can communicate with a number of wireless sensors via a radio channel. Data is collected at the sensor node and transmitted to the base station directly or through other nodes. These tiny sensor nodes are battery-driven, and hence operate on an extremely frugal energy budget. Sensor nodes must have a lifetime on the order of weeks or months, since battery replacement is not an option for networks with thousands of physically embedded nodes. Typically, a sensor node consists of one or more sensing elements (accelerometer, temperature, humidity, etc.), data processing unit, communicating components and a power unit (battery). Conventional low power design techniques and hardware architectures only provide point
solutions which are insufficient for these highly energy constrained systems. Energy efficiency, in the case of sensor networks, is far more complex, since it involves not only reducing the energy consumption of a single sensor node, but also maximizing the lifetime of an entire network. Network lifetime can be improved to a great extent by incorporating energy-awareness at the node and network level.

Communication protocols highly affect the energy-efficiency of sensor networks. Thus, designing an energy-efficient protocol is a must for energy load balancing and prolonging the network lifetime. Among the proposed communication protocols, hierarchical (or cluster-based) ones have significant savings in total energy consumption of the wireless sensor network. In such protocols, assigning special tasks to cluster heads can greatly contribute to overall system scalability, lifetime and bandwidth efficiency [7]. Cluster-based communication protocols can be self-contained and do not necessarily require a centralized algorithm to form clusters. One important issue in such communication protocols is to balance the energy load among sensor nodes and avoid networks to fall into dead-areas after a number of iterations. However, current hierarchical protocols (LEACH [1,2], TEEN [3], FTPASC [4], PEGASIS [5], HEED [6]) do not consider energy load balancing and the effect of distance parameter on sensors energy dissipation. In this project, we have developed two approaches (see sections 4.1. through 4.4.) using MATLAB and investigated the effect of distance parameter on two different network configurations. In both approaches we significantly decrease the energy imbalance along with increasing the network lifetime. Furthermore, the proposed approaches do not require any centralized support from the base station or any other powerful node as opposed to works in [3,4,5,6].

2. Related work / Background

When sensor nodes periodically have data to transmit to the base station, hierarchical communication protocols have significant savings in comparison with other communication protocols. Low-energy Adaptive Clustering Hierarchy (LEACH) presented in [1,2] is a self-organizing, adaptive clustering protocol that uses randomization to distribute the energy load evenly among the sensors in the network. In LEACH, the nodes organize themselves into local clusters, with one node acting as the local base station or cluster head (cluster head). It is worth mentioning that if the cluster heads were chosen a-priori and fixed throughout the system lifetime, the unlucky nodes that become cluster head would die quickly. LEACH takes a randomized approach in choosing cluster heads and distributes the energy load among nodes as time goes by. As cluster heads consume much more energy than non-cluster head nodes, LEACH rotates cluster head job among all sensors in order to not drain the battery of a single sensor.

LEACH use data-aggregation at the cluster heads to filter and compress the redundant data sent to the base station. Sensors elect themselves to be local cluster heads at any given time with a certain probability. These cluster heads broadcast their status to the other nodes in the network. Each sensor node determines to which cluster it wants to belong according to the received signal strength from the cluster heads. Once all the nodes are organized into clusters, each cluster head creates a schedule for the nodes in its cluster. Non-cluster head nodes communicate in TDMA with the cluster head when sending their data and this allows the non-cluster head nodes to turn off their radio components at all times except during transmission time. Hence, it further minimizes the energy dissipation of each sensor node.

LEACH divides the operation of the network into many rounds. Each round consists of a set-up phase and some number of time frames that construct the steady-state phase. During the set-up phase some sensor nodes elect themselves as cluster heads and broadcast their cluster head position to the rest of the nodes in the network, and then other nodes organize
themselves into local clusters by choosing the most appropriate cluster head (normally the closest cluster head). During the steady-state phase the cluster heads receive sensor data from the members (according to TDMA schedule that was created and sent to them), and transfer the compressed data to the base station (Figure 1).

![Figure 1. Timing in LEACH protocol.](image)

At the beginning of each round, the decision of each node to become cluster head is taken based on the suggested percentage of cluster head nodes $p$, which is equal to $K_{opt}/N$, current round $r$, and an indicator function that shows whether or not the node has been cluster head in the recent $(r \mod (1/p))$ rounds denoted by $C_i(t)$. Each sensor $i$ may become cluster head at the beginning of round $r$ (which starts at time $t$) with probability:

$$P_i = \begin{cases} \frac{p}{1 - p \times (r \mod \frac{1}{p})} & \text{if } C_i = 1 \\ 0 & \text{if } C_i = 0 \end{cases}$$  \hspace{1cm} (1)$$

Here, $C_i$ indicates if node $i$ has been a cluster head in the recent $(r \mod (1/p))$ rounds (if yes, it is not eligible for cluster head position in the next round).

Regarding the MAC protocols, LEACH employs non-persistent carrier-sense multiple access (CSMA) during the set-up phase and direct-sequence spread spectrum (DSSS) in the steady-state phase. See Table 1 for more detailed explanation on MAC protocols used in LEACH.

In some wireless sensor networks multi-hop routing is used [8]. This approach makes a node that wants to transmit data to the base station find one or multiple relay nodes. The main advantage of this approach is that the transmission energy may be reduced to a great extent [11,12]. The drawback is that the closer nodes to the base station are heavily different in terms of power consumption and the network experiences early loss of coverage and potentially will be segmented into dead-areas around the base station [9,10].
Table 1. MAC Protocols used in LEACH.

<table>
<thead>
<tr>
<th>Phase</th>
<th>MAC Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set-up</td>
<td>Nonpersistent CSMA</td>
</tr>
<tr>
<td></td>
<td>Nonpersistent CSMA</td>
</tr>
<tr>
<td></td>
<td>Nonpersistent CSMA</td>
</tr>
<tr>
<td>Steady-State</td>
<td>Different spreading code for each cluster</td>
</tr>
<tr>
<td></td>
<td>TDMA for cluster members (CDMA)</td>
</tr>
<tr>
<td></td>
<td>DSSS but all cluster heads use the same</td>
</tr>
<tr>
<td></td>
<td>spreading code and CSMA (CDMA)</td>
</tr>
</tbody>
</table>

3. Preliminaries

3.1. Energy model

The radio model we used in this project to measure the energy dissipation is the same as [2,18] in which $E_{elec}$ is the energy being dissipated to run the transmitter or receiver electronics to transmit or receive one bit of the data packet. $e_{amp}$ is the energy dissipation of the transmission amplifier to deliver one bit of data destined node who is $d$ meters away (Figure 2).

Energy consumption for the receiver and transmitter is calculated as follows:

$$E_{Tx}(l, d) = lE_{elec} + l e_{amp} d^n$$
$$E_{Rx}(l, d) = lE_{elec},$$ (2)

Above $l$ is the length of the transmitted/received message in bits, $d$ is the distance between transmitter and the receiver node and $n$ is the path loss exponent which is two for the free
space model and is four in multipath model. We can observe that the transmitter dissipates energy to run the radio and power amplifier, while the receiver only expends energy to run the radio electronics. In this project we assume free space model \((n = 2, \varepsilon_{amp} = \varepsilon_{fs})\) for transmissions between nodes in one cluster and multi-path model \((n = 4, \varepsilon_{amp} = \varepsilon_{mp})\) for transmissions from cluster heads to the base station.

3.2. Optimum number of clusters

Based on the energy model described before, in [2] the optimum number of clusters \(k_{opt}\) for a two-tired network is as follows:

\[
k_{opt} = \frac{\sqrt{N}}{\sqrt{2\pi}} \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}} \frac{M}{d_{toBS}^2}},
\]

where \(N\) is the number of sensor nodes that are distributed uniformly in an \(M \times M\) grid. \(d_{toBS}\) is the distance from the cluster head node to the base station. Substituting minimum and maximum values of \(d_{tobase\,station}\), the upper and lower bound of the preferred number of clusters can be achieved. In this interval, \(k_{opt}\) is proportional to average energy dissipation per round and number of data packets received at the base station per time and we should choose the best value for \(k_{opt}\).

4. Our proposed approaches

In our first and second approach we improve cluster head election and cluster head selection methods of LEACH protocol respectively.

4.1. The first approach (improving cluster head election method)

As we discussed before, one important issue in hierarchical communication protocols is to balance the energy load among sensor nodes and avoid network to experience dead-areas after a certain number of round. The current hierarchical protocols do not consider the distance of the sensor nodes from the base station, and its effect on energy dissipation. From the radio model shown in section 3.1., the power consumption in the free space model is proportional to the square of the distance. Thus, reducing the power dissipated by taking the distance parameter into consideration can extend network lifetime. LEACH assumes that performing as a cluster head consumes the same amount of energy for each node. Therefore, with the energy model demonstrated in section 3.1., it is evident that the cluster heads farther away from the base station are heavily penalized with respect to closer cluster heads. The energy consumed at the farther cluster heads can be so large that a near cluster head can communicate about five times with the base station using the same energy. Accordingly, after a certain number of rounds battery drainage of farther cluster heads leads to appearance of dead-areas in the network. Hence, data will no longer be collected from the dead-area, and that decreases the performance and initial purpose of the network.

Figure 3 is the exact figure taken from [1] which is a result of MATLAB simulation of LEACH ran over a network of 100 sensor nodes. The base station in this figure is at \((0, -75)\), and each node start with equal amount of energy (2 J). The probability of each node to become a cluster head in each round is \(p=0.05\). After 1200 rounds, the above simulation generates dead-areas at farther places. The dots represent the dead nodes, and we can observe
that a section of the network is completely disabled and data can no longer be studied from that section of the network.

![Figure 3. Appearance of dead-area.](image)

Here we define wasteful transmissions when a non-cluster head node has to send its data to a cluster head farther relative to the base station. In the figure below nodes A, B, and C have to choose the cluster heads which have greater distance from the base station than the nodes themselves. Nodes E and D are a good example of a case where their cluster head is in their path to the base station.

![Figure 4. Wasteful transmissions in LEACH protocol.](image)

These kinds of transmissions waste the energy resources of the network, and we consider them as wasteful transmissions. In case of A, B, and C, a portion of the energy could be saved by choosing a cluster head that has a shorter distance to the base station than the nodes themselves.
Our first approach proposes an adaptive clustering protocol based on the distance from the base station. The main idea of this protocol is that the nodes with more distance from the base station should be cluster head less often than the nodes with closer distance to base station (to avoid a great difference in energy level between the farther and the closer nodes). Our protocol divides the sensor field into \( m \) segments with equal area by drawing concentric circles around the base station and differentiates the number of cluster heads for each segment. The best number of segments is obtained by simulation results. Nodes can approximate their distance from the base station based on signal strength of the packet received from the base station. The distance estimation process does not have to be accurate. Thus, each node knows to which segment it belongs and it uses the appropriate probability for becoming cluster head. The probabilities can be programmed into the nodes as a priori. More number of segments makes the partitioned areas smaller; however, we have learned that increasing the number of segments makes the network complex in a sense that heavy-duty computational resources are required to precisely estimate the distance to the base station. In closer segments the probability of becoming cluster head is more than distant segments and thus the number of cluster heads in these segments is more. The same cluster formation sequence as LEACH is exploited in this approach, but the cluster head election method is different from LEACH and as we show later, offering more energy-efficient communications in the network. Assuming \( N \) is the number of nodes and \( m \) is the number of segments, we assume that the number of nodes per segments is equal to \( (N/m) \). The nodes in each segment have their own expected number of cluster heads \( k_{\text{segment}} \), and \( p_{\text{segment}} \) is the probability of each node becoming a cluster head in each round which equals \( k_{\text{segment}}/(N/m) \). Therefore, the network in each segment acts as a regular network in LEACH, with the difference that the closer segments to the base station will have more cluster heads than farther segments.

Assuming that the closest segment has the lowest index, node \( i \) in the segment \( j \) may become a cluster head at round \( r \) (which starts at time \( t \)) with probability:

\[
P_{i,j} = \begin{cases} 
    p_{\text{segment} \ j} & \text{if } C_{i,j} = 1 \\
    1 - p_{\text{segment} \ j} \times \left(r \mod \frac{1}{p_{\text{segment} \ j}}\right) & \text{if } C_{i,j} = 0 \\
    0 & \text{otherwise}
\end{cases}
\]

In this equation, \( C_p(t) \) is the indicator that is one if the node has not performed as cluster head in the most recent \((r \mod (1/p_{\text{segment}}))\) rounds, and zero otherwise. If the number of segments is odd, \( p_{\text{segment}} \) will be:

\[
p_{\text{segment} \ j} = \begin{cases} 
    p_{\text{LEACH}} & \text{if } j = \frac{m + 1}{2} \\
    p_{\text{LEACH}} + (\frac{m + 1}{2} - j) \times \delta p & \text{otherwise}
\end{cases}
\]

Where \( p_{\text{LEACH}} \) is equal to \( k_{\text{opt}}/N \), and \( k_{\text{opt}} \) be the optimum number of clusters in LEACH algorithm which must be computed according to (3). And \( \delta p \) is the difference of the two nearby segments probabilities. In simulations, we start with small value for \( \delta p \), increasing it until reaching the optimal value. Further increasing \( \delta p \) leads to declining the energy-efficiency, since no cluster head will be elected in distant segments and by increasing the size
of far clusters, non-cluster head nodes often have to transmit data very far to reach the cluster head nodes hence, draining their energy.

4.2. Simulation results (first approach)

In both approaches we ran our simulations on two different network configurations (Figure 5a and Figure 5b). In the first configuration we placed the base station away and outside from the sensor nodes at (100,175), and drew concentric segments around the base station. We simulated this configuration with 200 of sensor nodes each start with equal amount of energy (0.5 J). $p_{LEACH}$ is set to 0.04 and $\delta p$ is set to 0.02 for 2-segment case and 0.005 for 10-segment case.

In the second configuration we placed the base station inside and at the center of the network at (0,0), and drew concentric circles around the base station. In this configuration the network grid is bigger than the first configuration (400 m by 400 m as opposed to 100 m by 100m in the first configuration). We simulated this configuration with 200 of sensor nodes each start with equal amount of energy (0.5 J). $p_{LEACH}$ is set to 0.04 and $\delta p$ is set to 0.02 for 2-segment case and 0.01 for 5-segment case.

In the first configuration after running the simulation and averaging it over 100 simulations we observed 15% gain for the time that first node dies in contrast to the similar simulations for LEACH (Figure 6).
Also, the total energy dissipated in the case with 10-segments gave us a boost at about 8% percent relative to LEACH after 1200 rounds.

As we discussed before a wasteful transmission is considered when a node has to send its data to a cluster head farther away from base station relative to its distance to the base station. In the case with 10 segments, after 200 rounds we have 70 wasteful transmissions as opposed to LEACH that has 81 wasteful transmissions during this period. In addition, in the 10-segment network the amount of packets sent per each unit of energy is 1920 packets whereas for LEACH we have 1806 packets sent per unit of energy which approves a better energy throughput in our approach.
In the second configuration after running the simulation and averaging it over 100 simulations, we observed up to 25% gain for the time that first node dies relative to the corresponding experimentation for LEACH (Figure 8).

![Figure 8. Number of alive nodes after 800 rounds of simulation (Second configuration).](image)

It should be noted that, as result of a bigger terrain size in this configuration, the first node dies much earlier as compared with the previous configuration. Also, the total energy dissipated in the case with 10-segments gave us a boost at about 16% percent relative to LEACH after 1200 rounds and averaging over 100 simulations.

![Figure 9. Total dissipated energy after 800 rounds of simulation (Second configuration).](image)
In the case with 10 segments, after 200 rounds we have 63 wasteful transmissions as opposed to LEACH that gives 82 wasteful transmissions. Furthermore, in the 10-segment network the amount of packets sent per each unit of energy is 1071, and for the same network in LEACH we got 880 packets sent per unit of energy. As it can be seen again we have more energy throughput than that of LEACH.

Figure 10 shows the second network configuration after 400 rounds of running LEACH protocol (Figure 10.a) and 400 rounds of running our first approach with 2 segments. As illustrated, nodes die in a more manner in our approach than LEACH. Increasing the number of segments from 2 can yield a more random distribution of node deaths.

Figure 10. Sensors that remain alive (circles) and those that are dead (dots) in the second network configuration a. After running LEACH for 400 rounds b. After running our first approach with 2 segments for 400 rounds.

4.3. The second approach (improving cluster head selection method)

Similar to the first approach, our second approach also utilizes distance parameter to increase energy efficiency and balance the energy load among the sensor nodes in a wireless sensor network. In this approach too, each sensor node estimates its distance to base station using signal strength (note that, it has to be done only once at start up since the network is static.) In this approach, the same scheme as one used in LEACH is applied for cluster head election. Another word, each node becomes cluster head with a certain probability as discuss previously (equation 1). Subsequently, elected cluster heads broadcast advertisements to other non-cluster head nodes. In the LEACH protocol, each sensor node chooses the closest cluster head to join. LEACH protocol does not consider the distance from cluster heads to the base station. Therefore, we might experience occurrence of wasteful transmission. In our proposal, we modified the cluster head selection mechanism so that a sensor node chooses a cluster head that leads to a near optimal path to base station utilizing path characteristic estimation (PCE) techniques. Consequently, each cluster head needs to include its approximate distance to base station in its advertisement message. Sensor nodes receive advertisement messages and calculate the travel distance to base station through different cluster heads then join the cluster head that leads to shortest path to base station:
Preliminary simulation on above proposal shows that sensor nodes aggressively choose cluster heads close to the base station. As a result, nodes near base station carry out a greater workload and tend to die earlier; causing appearance of dead area near base station and energy imbalance in the sensor network. To avoid dead-areas and segmentation in the network, we introduced a threshold radius around each node. Thus, sensor nodes would not consider the cluster heads which are located outside a predefined threshold radius. This gives us a handful of advantages: i) We avoid the aggressive nature of our algorithm by restricting its cluster head selection and avoid dead-areas near base station. ii) Typically, sensor nodes in a certain areas carry similar data; therefore, by restricting nodes in a same region to choose a same cluster head we improve aggregation process in cluster heads. iii) Sensor nodes do not need to consume much energy to transmit their data to the cluster heads.

4.4. Simulation results (second approach)

We ran our simulation on the same on configurations as previous approach (Figure 5a and Figure 5b). In the first configuration after running the simulation and averaging it over 100 simulations, at best we observed 8% gain for the time that first node dies relative to the corresponding experimentation using LEACH algorithm (Figure 10).

![Figure 10. Number of alive nodes after 1500 rounds of simulation (first configuration).](image-url)

In the network with a threshold radius of 20 meter, after 200 rounds we have 61 wasteful transmissions as opposed to LEACH that has 81 wasteful transmissions during this period; causing a better energy dissipation in network (Figure 10).
In the second configuration after running the simulation and averaging it over 100 simulations, at best we observed 10% gain for the time that first node dies relative to the corresponding experimentation in LEACH algorithm (Figure 11).

![Figure 11. Number of alive nodes after 1500 rounds of simulation (second configuration).](image)

In the network with a threshold radius of 40 meter, after 200 rounds we have 54 wasteful transmissions as opposed to LEACH that has 81 wasteful transmissions during this period; causing a better energy dissipation in network (Figure 11).

5. Discussion and future work

In this work we have eliminated some of the problems of previously proposed LEACH communication protocol for wireless sensor networks; the huge difference between energy levels of near nodes and far nodes has been compensated by changing the cluster head election and cluster head selection methods in the first and second approach respectively. In both approaches sensor nodes need to find their distance from the base station, this distance, however, does not need to be accurate and only a rough approximation of it is enough for each node to find to which segment it belongs in the first approach and to detect wasteful transmissions in the second approach.

In the first approach, further increasing the $\delta p$ leads to declining the energy-efficiency, since no cluster head will be elected in distant segments and by increasing the size of far clusters, non-cluster head nodes, in many rounds, have to transfer their data to a far away place to reach the cluster head node which results in using up their energy. Consequently there is a direct relation between $\delta p$ and the size of distant clusters. Regarding the number of segments, more number of segments makes the dead-areas smaller; nevertheless, we have learned that increasing the number of segments makes the network complex in a sense that heavy-duty computational resources are required to precisely estimate the distance to the base station which is at odds with network scalability.

Wireless sensor networks are used in enormous new applications [22,23,24,25,26]. In the second approach, we find the suitable value for the threshold distance based on simulation
results. Increasing the threshold distance further leads to selecting the cluster heads that reside near the base station, again, introducing dead-areas but this time near the base station. Decreasing the threshold distance results in similar problems that we had in LEACH.

In the proposed protocol, it is assumed that the sensor nodes are high data rate sensors such as strain, accelerometer, and vibration, so that the nodes always have data to send [27,28] to the base station. The protocol can be made more applicable by changing into an event-driven protocol so that nodes send data when they detect an important event. Further, with some modifications, we can handle network dynamics such as nodes mobility [31] in the proposed approaches.

In order to minimize overhead, the steady-state phase (duration of each time-frame) is assumed to be long compared to the set-up phase [29,30]. We can further improve the outcomes of our protocol by accurately computing the optimum number of time frames per round (see figure 1) by noting that long steady-state phase results in minimizing overhead due to the set-up phase communications and short steady-state phase leads to more energy load balancing. In future work for running the proposed protocols on larger networks we should consider multi-hop schemes in order to route the data to the base station. This job have to be done wisely since multi-hop routing will introduce energy load balancing problems again. Considering some QoS metrics in order to determine the accuracy of the data in our approaches is another thing that we have to take into account since in our approaches, the size of clusters are different as compare with LEACH. In addition, we are thinking of making our approaches more intelligent in terms of energy balancing by considering the square of the distance in clustering policies in the first approach and specifying the optimal threshold distance in the second approach. Finally it is worth to point out that the proposed approaches do not require any centralised support from a certain node, otherwise we had easier ways to obtain energy efficiency. Therefore our proposed protocols are scalable in terms of number of sensor nodes in the wireless sensor network.

The proposed protocols still have rooms to improve. For example, by applying different initial energy levels according to the distance of the nodes from the base station, we can entirely suppress the difference between energy levels of near nodes and distant nodes, hence maximizing the network lifetime along with totally preventing dead-areas. This way, we can expect that sensor nodes would die in a more random fashion than figure 10b.

6. Conclusions

In two proposed communication protocols, we have solved some of the problems of previously proposed LEACH protocol; the huge difference between energy levels of near nodes and far nodes from the base station has been reduced by dividing the network grid into multiple segments and applying different probabilities to them in the first approach (improving cluster head election method) and making the transmissions toward the base station in the second approach (improving cluster head selection method). Furthermore, in these two new schemes, nodes burn energy in a more balanced way across the network ensuring a more tolerable degradation of service with time. Scalability together with energy balancing make our proposed approaches very useful for large wireless sensor networks especially those used for continuous monitoring of an environment. Results from our experiments confirm that regarding the network lifetime, energy consumption, wasteful transmissions and energy throughput the proposed approaches can outperform conventional cluster-based protocols remarkably.
7. References


