Abstract

Wireless sensor networks (WSNs) are commonly used for continuously monitoring applications. This paper investigates a base station assisted energy efficient routing for hierarchical clusters. The base station determines the number of clusters and the initial set of head-set members. Moreover, instead of a single cluster head, a set of associates called a head-set manages the network clusters. The head-set approach not only optimizes energy consumption by reducing the number of elections but evenly distributes the long-range transmissions among the network nodes. Due to the controlled addition of redundant associates, the network is available for longer number of transmissions. The simulation results show that the proposed protocol outperforms the traditional clustering techniques.

1. Introduction

With rapid advancement in electronics industry, small inexpensive battery-powered wireless sensors have already started to make an impact on the communication with the physical world. The wireless sensor networks (WSNs) can be deployed in a wide geographical space to monitor physical phenomenon with acceptable accuracy and reliability. The sensors can monitor various entities such as: temperature, pressure, humidity, salinity, metallic objects, and mobility; this monitoring capability can be effectively used in commercial, military, and environmental applications. Since WSNs consist of numerous battery-powered devices, the energy efficient network protocols must be designed. Due to large network size, limited power supply, and inaccessible remote deployment environment, the WSN-based protocols are different from the traditional wireless protocols [3, 4]. For instance, instead of address-based point-to-point communication, the routing decisions are data centric in WSNs, where the goal is to efficient query dissemination and data aggregation.

Heinzelman et al. [5] describes the LEACH protocol, which is a hierarchical self-organized cluster-based approach for monitoring applications. The sensor area is randomly divided into several clusters. Based on time division multiple access (TDMA), the sensor nodes transmit data to the cluster heads, which aggregate and transmit the data to the base station. A new set of cluster heads are chosen after specific time intervals. A node can be re-elected only when all the remaining candidates have been elected. The approach however, assumes that all the clusters are uniform which is not true in reality. This results in some clusters with very large sizes and thus causes rapid energy depletion of the cluster heads. We propose additional members to share the burden of the cluster head.

Lindsey et al. propose PEGASIS [8], an extension of LEACH, where nodes transmit to their nearest neighbor and messages are transmitted to the base station on rotation basis. The PEGASIS protocol is shown to be more robust than LEACH when several nodes are not working.

There are several cluster-based research studies. For example, the work in [9] shows that a 2-tier architecture is more energy efficient when hierarchical clusters are deployed at specific locations. Bandyopadhyay and Coyle [1] describe a multi-level hierarchical clustering algorithm, where the parameters for minimum energy consumption are obtained using stochastic geometry.

Cluster-based approaches are suitable for habitat and environment monitoring, which requires a continuous stream of sensor data. Directed diffusion and its variations are used for event-based monitoring. Intanagonwiwat et al. [7] describes a directed diffusion protocol where query (task) is disseminated into the
network using hop-by-hop communication. While the query is traversed, the gradients (interests) are established for the result return path. Finally, the result is routed using the path based on gradients and interests. Braginsky et al. [2], a variation of directed diffusion, use rumor routing to flood events and route queries; this approach is suitable for a large number of queries and a fewer events.

The structure of the remaining paper is as follows: Sec. 2 describes our hierarchical cluster-based routing protocol. In Sec. 3, we briefly describe the simulation and experimental setup. Section 4 evaluates the proposed protocol. Finally, Sec. 5 concludes the paper.

2. Base Station Assisted Hierarchical Cluster-Based Routing

Our base station assisted hierarchical cluster-based routing scheme is suitable for habitat and environmental monitoring applications. Our routing scheme is based on the fact that the energy consumed to send a message to a distant node is far greater than the energy needed for a short range transmission. We extend the LEACH protocol by using a set of associates called a head-set, instead of a single cluster head. Moreover, in the result packets, the base station is informed about the energy status of the nodes. The base station determines the energy efficient clusters using the energy status of the nodes and the query type. The members of a head-set are responsible for transmitting messages to the distant base station. At one time, only one member of the head-set is active and the remaining head-set members are in sleep mode. The task of transmission to the base station is uniformly distributed among all the head-set members.

First, we describe a few terms that are used in defining our protocol. A head-set consists of nodes that act as cluster heads on rotation basis. The cluster head receives data from the cluster members and transmits the aggregated sensor data to the distant base station. A round consists of two stages: an election phase and a data transfer phase. In an election phase, the sensor nodes self-organize to create clusters for the cluster heads that were chosen by the base station. The data transfer phase consists of pre-determined number of transmissions to the base station, where the head-set members transmit aggregated data to the base station. An iteration is completed when all the nodes in the network get their chance to become a head-set member.

2.1. Radio Communication Model

For energy consumption, we use a radio model as described in [5]. A long distance such as between a cluster head and the base station is given by \( d_1 \). The length of the message is \( l \) bits. The energy consumed to transmit \( l \) bits for \( d_1 \) distance is given by:

\[
E_T = lE_e + l\epsilon_s d_1^4
\]

Similarly, the energy consumed to transmit a message of length \( l \) bits for a shorter distance \( d_s \), such as within clusters, is given by:

\[
E_T = lE_e + l\epsilon_s d_s^2
\]

Moreover, the energy consumed to receive the \( l \) bits is given by:

\[
E_R = lE_e + lE_{BF}
\]

Equation 3 includes the cost of beam forming approach that reduces energy consumption. The values for the estimation of energy consumption are as follows: 1) energy consumed for short range transmission: \( \epsilon_e = 10 \) pJ/bit/m², 2) energy consumed for long range transmission: \( \epsilon_s = 0.0013 \) pJ/bit/m², 3) energy consumed in the electronics circuit to transmit or receive the signal: \( E_e = 50 \) nJ/bit, 4) energy consumed for beam forming: \( E_{BF} = 5 \) nJ/bit, and 5) number of bits: \( l = 4000 \).

2.2. Election Phase

Consider a sensor network of \( n \) nodes and the number of clusters as \( k \). In our proposed protocol, the values of \( n \) and \( k \) determined by the base station. In other words, the base station knows the number of active nodes and determines the suitable number of clusters using the energy status and the type of query. In the beginning, we assume that all the nodes are at the same energy level.

First, the base station chooses a set of cluster heads and broadcasts this information in the network. At this stage, all nodes in the network have their radios in the receiving state. Second, these chosen cluster heads transmit a short range advertisement broadcast message. Third, sensor nodes receive the advertisements and choose their cluster heads based on the signal strengths of the advertisement messages. Fourth, each sensor node sends an acknowledgment message to its cluster head. Fifth, the cluster heads receive the acknowledgement messages from their cluster members. Sixth, each cluster head chooses a set of associates for its cluster; the decision is based on the signal strengths of the received acknowledgements.
For uniformly distributed clusters, each cluster contains \( \frac{n}{k} \) nodes/cluster. Using (2) and (3), the energy consumed by a cluster head is estimated as follows:

\[
E_{CH\text{-election}} = \{lE_e + lE_{BF} + lE_e d^2\} + \left\{ \left( \frac{n}{k} - 1 \right) lE_e \right\} \tag{4}
\]

The first part of (4) represents the energy consumed to transmit the advertisement message; this energy consumption is based on a shorter distance energy dissipation model. The second part of (4) represents the energy consumed to receive \( \left( \frac{n}{k} - 1 \right) \) messages from the sensor nodes of the same cluster. Equation 4 can be simplified as follows:

\[
E_{CH\text{-election}} = lE_e \left( \frac{n}{k} \right) + lE_{BF} + lE_e d^2 \tag{5}
\]

Using (2) and (3), the energy consumed by non-cluster head sensor nodes is estimated as follows:

\[
E_{non\text{-}CH\text{-election}} = \{k lE_e\} + \{lE_e + lE_{BF} + lE_e d^2\} \tag{6}
\]

The first part of (6) shows the energy consumed to receive messages from \( k \) cluster heads; it is assumed that a sensor node receives messages from all the cluster heads. The second part of (6) shows the energy consumed to transmit the decision to the corresponding cluster head. Equation 6 can be simplified as follows:

\[
E_{non\text{-}CH\text{-election}} = lE_e (1 + k) + lE_{BF} + lE_e d^2 \tag{7}
\]

During election, the energy spent in a cluster is estimated as follows:

\[
E_{e\text{-election}} = E_{CH} + \left( \frac{n}{k} - 1 \right) E_{non\text{-}CH} \tag{8}
\]

### 2.3. Schedule Creation

Once all clusters are created with head-sets, the current cluster head creates a TDMA schedule for the head-set members, and the cluster members. The TDMA schedule allows the head-set members to keep their radios off when they are not acting as cluster heads. Moreover, a schedule is created for the data acquisition and transfer time intervals for the sensor nodes that are not head-set members. In the allotted time slots, the member nodes transmit a short range broadcasts, which are received by their cluster heads; the cluster heads forward the aggregated data to the base station.

### 2.4. Data Transfer Phase

During data transfer phase, the nodes transmit messages to their cluster head and cluster heads transmit an aggregated messages to a distant base station. The energy consumed by a cluster head is as follows:

\[
E_{CH\text{/frame}} = \{lE_e + lE_e d^1\} + \left\{ \left( \frac{n}{k} - m \right) lE_e + E_{BF} \right\} \tag{9}
\]

The first part of (9) shows the energy consumed to transmit a message to the distant base station. The second part of (9) shows the energy consumed to receive messages from the remaining \( \left( \frac{n}{k} - m \right) \) nodes that are not part of the head-set. Equation 9 can be simplified as follows:

\[
E_{CH\text{/frame}} = lE_e d^1 + \left( \frac{n}{k} - m + 1 \right) lE_e + \left( \frac{n}{k} - m \right) E_{BF} \tag{10}
\]

The energy, \( E_{non\text{-}CH\text{/frame}} \), consumed by a non-cluster head node to transmit the sensor data to the cluster head is given below:

\[
E_{non\text{-}CH\text{/frame}} = lE_e + lE_e d^2 \tag{11}
\]

### 2.5. Number of clusters for minimum energy consumption

In a cluster, the energy consumed to transmit an aggregated reading to the base station is as follows:

\[
E_c = E_{CH\text{/frame}} + \left( \frac{n}{k} - m \right) E_{non\text{-}CH\text{/frame}} \tag{12}
\]

The first part of (12) is due to the energy consumption as an active member of the head-set. The second part of (12) is due to \( \left( \frac{n}{k} - m \right) \) non-cluster head nodes. The total energy consumed by \( \kappa \) clusters is as follows:

\[
E_{total\text{/frame}} = k E_c \tag{13}
\]

The number of clusters \( \kappa \) for minimum consumed energy can be determined as follows:

\[
\frac{dE_{total}}{dk} = 0 \tag{14}
\]

Using (13) and (14) the value of \( \kappa \) for minimum energy consumption is given by (15), the details are given in [6].

\[
k = \sqrt{\frac{n}{2\pi}} \sqrt{\frac{E_e}{E_e d^4 - (2m-1)E_e - m E_{BF}}} M \tag{15}
\]

### 3. Simulation

The proposed protocol is simulated in Java. The simulated protocol features are as follows: 1) election phase, 2) data transfer phase, 3) round, 4) iteration, 5)
energy consumption according to the given radio communication model, 6) different network layouts, and 7) clusters with head-set members.

The simulation is based on the following assumptions: 1) all the nodes have same start energy, 2) symmetric channel, 3) no packet drops, 4) no malfunctioning or damage nodes, and 5) queries are continuous and persistent.

In the simulation, three types of nodes layouts are used: 1) random, 2) grid, and 3) cluster grid, as shown in Figure 1.

![Random Layout (Seed)](image)
![Random Layout](image)
![Grid Layout](image)
![Cluster Grid](image)

**Figure 1. Types of nodes layouts.**

Part a) of Fig. 1 shows a random layout with the given seed; this layout is used for debugging, verification, and validation purposes. Part b) of Fig. 1 shows the random layout, which is used for performance evaluation; this layout is used to obtain confidence in the results. Part c) of Fig. 1 shows the grid layout that creates the nodes at fixed distances; this layout can be used to incorporate location awareness in our HCR protocol. Finally, part d) of Fig. 1 shows the cluster grid that is a combination of grid and random, where nodes are randomly created but there are fixed number of clusters. The cluster grid can be used to validate the cluster formation of the protocols.

Moreover, the network size can be scaled in the simulation. Due to scaling, the layout remains same but the spacing between the nodes is adjusted according to the given network size. The sink is located in east direction of the network.

4. Results

In this section, the simulation results are used to analyze the proposed protocol. For most of the experiments, unless stated otherwise, the number of nodes is 200, the network size is 200m, the distance to base station is 200m, the number of clusters is 5.

![Figure 2. The number of clusters that give minimum energy consumption.](image)

Figure 2 shows the graphs that give the number of clusters for different head-set sizes such that the energy consumption is minimum. The graph obtained by plotting (15) is identical to the values obtained from the simulation. These graphs validate the accuracy of the mathematical analysis as well as the simulation. As the mathematical analysis is based on uniform clusters only, we have compared the simulation for grid layout only. For random layouts the clusters will not be uniform and the mathematical analysis would be very complicated. Moreover, for a large number of transmissions, a few nodes will deplete their energy and the condition of a fixed number of nodes and uniform clusters will not hold. Hence, the simulation experiment was continued until all the nodes were alive.

Figure 3 shows the graphs for the percentage of alive nodes with respect to the number of transmissions. The graphs show that the LEACH protocol dissipates more energy than our proposed hierarchical cluster-based routing (HCR) protocol. However, the head-set size variation can change the performance of the protocol. The head-set size of 6 gives the best overall performance.

Since the head-set members are only used for management, the head-set members do not report the sensor
readings. For the head-set size of 10, the head-set size is approximately half the cluster size, which is approximately 20. In other words, half the nodes report the sensor readings for each transmission; the remaining half are used for management purpose only. In our future work, the head-set members will perform the work of cluster management as well as the sensor data collection.

Figure 3. Percentage of alive nodes with respect to transmissions.

Figure 4 show the effects of different layouts on the percentage alive nodes with respect to the number of transmissions. As shown in part a) of Fig. 4, most of the random layouts give similar performance, which shows the confidence in the results. Part b) of Fig. 4 show that our protocol (HCR) with random layout is more energy efficient than LEACH. However, our protocol performs better for random layouts as compared to grid and cluster grid. Hence, increasing the head-set size will not necessarily increase the performance. We have to consider other aspects such as the network layout.

Figure 4. Effect of different network layouts

Figure 5 show the graphs of percentage of alive nodes with respect to the number of transmissions for different number of transmissions per data transfer phase. As the number of transmissions per data transfer phase increases, the network becomes more energy efficient. For a few transmission, LEACH and our HCR protocol are quite similar. However, for a larger number of transmissions, our protocol perform better in the beginning but at the end LEACH performs relatively better. When more than 60% nodes are alive, HCR is better because there are sufficient number of nodes to become head-set members. When the number of alive nodes is less than 60%, the cost of maintaining the head-set size is relatively higher. For our future work, we propose to use adaptive head-set size. In other words, the head-set size will depend on the cluster size. It would be more energy efficient to adjust the head-set with respect to the number of transmissions and with respect to the percentage of alive nodes.

Figure 5. Effect of number of transmissions per data transfer phase.

Figure 5 show the graphs of percentage of alive nodes with respect to the number of transmissions for different network sizes and for different distances from the base station. As expected, for a larger distances, the energy of nodes will deplete more rapidly. Moreover, as consistent with the previous results, LEACH performs better when a fewer nodes are left and our proposed protocol retains nodes for a longer period of time.
5. Conclusion

The simulation of the proposed hierarchical protocol shows that our protocol retains more number of nodes for a longer period of time. However, when less than 40% of nodes are alive, our proposed protocol depletes the nodes energy more rapidly. The proposed protocol outperforms the LEACH protocol for most of the time. Moreover, as the head-set cannot be adjusted linearly, the protocol must be carefully engineered for energy-efficient clusters. An unusually large or a small head-set size can give undesirable results. In our future work, we will incorporate adaptive head-set size and the energy-efficient clusters would be retained for a longer period of time.

References


