Performance of an Energy Efficient Clustering Algorithm for Cluster-Based Wireless Sensor Networks

Yung-Fa Huang and Chih-Wei Chang
Graduate Institute of Networking and Communication Engineering
Chaoyang University of Technology, Taichung 413, Taiwan
yfahuang@mail.cyut.edu.tw

Abstract

In this paper, a fixed clustering algorithm (FCA) is proposed to improve energy efficiency for wireless sensor networks (WSNs). In order to reduce the energy dissipation in sending information from each sensor to the sink, the proposed FCA uniformly clustering the sensing area where the cluster head is deployed in the centric of the cluster area. Simulation results show that the proposed algorithm definitely reduces the energy consumption of sensors and extends the lifetime of the networks nearly more than 80% compared to the random clustering (RC) scheme.

Keywords: Wireless sensor network, clustering algorithm, energy efficiency, network lifetime

1. Introduction

Recently, the rapidly developed technologies of microelectro-mechanical systems and telecommunication battery make the small sensors comprise the capabilities of wireless communication and data processing [1]. These small sensors could be used as the surveillance and the control capability under a certain environment. Specially, the location of wireless sensor network (WSN) could be a region where people could not easily reach and there is a difficulty to recharge the device energy. Therefore, the energy efficiency of the sensor networks is an important research topic and the lifetime of networks could be considered as the performance of the WSN [2].

The energy in WSN is mainly consuming on the direct data transmission [2]. Firstly, each sensor collects data and delivers the data to the base station directly, called as “sink”. Applying this mode, the sensor will have quick energy exhaustion if it is apart from the base station. Thus, this kind transmission scheme is not suitable in a large area [2]. Then, secondly, to enable communication between sensors not within each other’s communication range, the common multi-hop routing protocol is applied in the ad hoc wireless sensor communication networks [3]-[5]. In this scheme, several multi-hop paths exist to perform the network connectivity. Each path in the configuration will have one link head to collects data from sensors.

Every sensor node in the WSN sends both the sensing data of itself and the receiving data from previous nodes to its closer node. Then, the destination node delivers the data collection in the path to the base station [4]. The nodes closer to the base station need more energy [4] to send data because the scheme uses hierarchy transmission. However, due the highly complexity in routing protocols and the most likely heavy load on the relaying nodes, this scheme is not suitable for the highly densely WSNs.

The third scheme is the clustering-based one that those closer sensors belong to their own clusters. One of sensors, called “cluster head,” in each cluster is responsible for delivering data back to the base station. In this scheme, the cluster head performs data compressing and sending back to the base station. Thus, the lifetime of cluster head [5-7] may be shorter than that of other sensors. However, if the cluster head has more energy, the cluster can prolong the life time. Therefore, in this paper we discuss how to divide the cluster region uniformly and how to select the cluster head under the clustering structure. The lifetime prolong problem can be mainly divided to two issues: energy dissipation minimization and balancing. For wireless sensor networks with a large number of energy-constrained sensors, it is very important to design an algorithm to organize sensors in clusters to minimize the energy used to communicate information from all nodes to the base station. In this paper, we propose a fast, centralized algorithm for organizing the sensors in a wireless sensor network into clusters with an objective of minimizing the energy dissipated in communicating the information to the cluster head and prolong the lifetime of the WSNs.

In the following section, the network models and structure for the WSN is described. The fixed clustering algorithm (FCA) is proposed in Section 3. In order to analyze the efficiency on this proposed algorithm, the simulation works are shown in Section 4. Finally, some conclusions are given in Section 5.
2. Network Models and Structure

In practical, the geometry of the WSN is non-regular. However, the square is a basic area to be consisted of non-regular area. Thus, for simplification, in this paper we adopt a square area with the length $D$. The sensor area is with a uniformly distributed cluster heads and is shown in Figure 1. In Figure 1, the symbol “+” is represented as a location of cluster head whereas the symbol “o” is represented as a location of the sensing node. When the cluster area is of random distributed, the energy efficiency of sensor nodes on data transmitting is terrible [3]. Therefore, the FCA is proposed to divide the sensor area into clusters and deploy cluster heads uniformly over the network area. Based on the configuration of square area, the sensors are supposed to be spread out uniformly to the whole area. The data from each cluster will be collected by the cluster head and these data will be sent back to the base station located at the point $(0, -B)$.

In wireless communication, the channel models are modeled by

$$P_t = c \frac{P_r}{d^\alpha},$$

where $P_t$ and $P_r$ are the received power at receiver and the transmitted power at transmitter respectively, $c$ is the propagation coefficient, and $\alpha$ is the path loss exponent, $2 \leq \alpha < 6$. For s free space area, the path loss exponent is set by $\alpha = 2$. The location of the nodes is assumed to be known to base station by GPS.

In Mac layer, the sensing nodes are assumed to know the belonging cluster head by centralized based station broadcasting. Based on the configuration of square area, Figure 1 shows the investigated environment in this paper. In Figure 1, the total $Q$ sensors are supposed to be spread out uniformly to the whole area where is divided into $q$ clusters. The data from each cluster will be collected by the cluster head and these data will be sent back to the base station located at the point $(0, -B)$.

To evaluate the lifetime of the network, one round is defined as a cycle in which the base station receives data from the sensor node. In one round, it contains the time from the data collected at sensor to the corresponding cluster head and the time from the cluster head to the base station.

Thus, the total energy of networks in one round can be expressed by

$$E_T = \sum_{i=1}^{q} \left( \eta_i \cdot E_{ch,i} \cdot \frac{Q}{q} \right) + \sum_{j=1}^{N} E_{n,j},$$

where $\eta_i$ is a data compressing factor for the $i$th cluster with $0 < \eta_i < 1$, $E_{ch,i}$ and $E_{n,j}$ are the transmission energy of one packet for the $i$th cluster head and the $j$th normal sensor, respectively.

Moreover, the dissipation energy of nodes depends on the path loss.

3. Fixed Clustering Algorithm

In order to minimize the energy dissipation of the sensor nodes, an FCA is proposed to normalize the clustering region. The defined parameters for the FCA are depicted in Table 1. There is a cluster head located at the area centric of each clustering area.

In order to divide the area into uniform clusters in size, we calculate the location of the cluster head according to the number of clusters $q$ as shown in Figure 2. In Figure 2, $x(i)$ and $y(i)$ are the axis of corresponding position of the cluster head. Then, the fixed cluster sensor network can be deployed by FCA. The proposed FCA is described as follows.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q$</td>
<td>Number of clusters</td>
</tr>
<tr>
<td>$D$</td>
<td>Length of sensing area</td>
</tr>
<tr>
<td>$p$</td>
<td>$\sqrt{q}$</td>
</tr>
<tr>
<td>$n$</td>
<td>$\left\lceil \frac{q}{p} \right\rceil$</td>
</tr>
<tr>
<td>$k$</td>
<td>$\text{mod} \left( \frac{q}{n} \right)$</td>
</tr>
<tr>
<td>$s$</td>
<td>$\left\lfloor \frac{q}{n} \right\rfloor$</td>
</tr>
<tr>
<td>$l$</td>
<td>$\frac{D_s(n-1)}{q}$</td>
</tr>
</tbody>
</table>

Class A:

When the number of clusters equals to $p \times p$, that is, the clusters in row and those in column are the same. For example, Figure 3(a) shows the sensor region and the position of the fixed cluster network when the number of clusters is equal to 9. In Figure 3(a),
the maximum sending distance is $25\sqrt{2}/|p|$ from the sensor node where $\lfloor \cdot \rfloor$ is the floor function and $p = \sqrt{q}$ is the square decision factor.

$$p = \sqrt{q}, \ a = \lceil p \rceil, \ k = \text{mod}(\frac{q}{p}), \ s = \left\lfloor \frac{q}{p} \right\rfloor$$

Class B:
Depending on the parameter $k$, if $k = 0$, the clustering is performed by Class B. Otherwise, Class C will be applied in the clustering. In Class B, the number of clusters are with $1 \times 2, 2 \times 3, 3 \times 4, 4 \times 5, \ldots, M \times (M+1)$, $M \in \mathbb{N}$. The axis of cluster heads are obtained as shown in Figure 3 by applying class B. One example of Class B is depicted in Figure 3(b) which shows the position of the fixed cluster network when the number of clusters is equal to 12.

Class C:
When the number of clusters is not satisfied Class A or B, then the clustering algorithm is classified in to class C. One example of Class C is depicted in Figure 3(c) which shows the position of the fixed cluster network when the number of clusters is equal to 11. In addition, in Class C, we first compare the values between $s$ and $(n - 1)$. Then, there are two sub-classes C1 and C2 for the conditions $s < n - 1$ and $s \geq n - 1$, respectively, as shown in Figure 2. In the clustering algorithms, to normalize the size of clusters area is the most important. Thus, in a rectangle cluster area, the length and the width should be made almost the same.

In FCA, we assume that the sensor nodes are uniformly distributed in the area of the cluster. Therefore, the power dissipation of a cluster head to relay the information of the cluster in one round can be obtained by

$$E_{ch,i} = \eta_i \cdot e_i \cdot W_i \cdot \frac{D}{q},$$

where $e_i$ is the energy dissipation sending one packet per square meters, the energy dissipation due to the path loss of a distance between the $i$th cluster head and the base station is expressed by

$$W_i = d_i^\alpha c = d_i^\alpha = x^2(i) + y(i) + B^2,$$

where $\alpha = 2$ and $c = 1$. Moreover, the energy dissipation for a sensor node to transmit one packet in a clustering area can be obtained by

$$E_{n,j} = e_j \cdot Z_j,$$

where $Z_j = d_j^2$ is the random variable of the rectangular square of the distance between the $j$th normal sensor node and the cluster head of the cluster. Thus, the expected power dissipation for a
sensor node to transmit one packet in a rectangular clustering area can be obtained by

\[
E[Z] = E \left[ \left( x - \frac{L_1}{2} \right)^2 + \left( y - \frac{L_2}{2} \right)^2 \right] = \frac{1}{12} \left( L_1^2 + L_2^2 \right),
\]

where \( L_1 \) and \( L_2 \) are the width and length of the rectangular area of the cluster in which the cluster head is located at \((L_1/2, L_2/2)\).

In the RC, the cluster head is selected randomly. Therefore, the energy dissipation of each cluster in transmitting one packet is expressed by

\[
E[Z] = E[\left( x^2 + (y + B)^2 \right)] = \frac{5D^2}{12} + B \cdot D + B^2,
\]

where \( D \) is the length of the square and \( B \) is the distance between the original and the base station.

Therefore, by the number of clusters we can choose the suitable algorithm to equally cluster the cluster area. In Figure 2, \( x(i) \) and \( y(i) \) are the axis of corresponding position of the cluster head for the \( i \)th cluster. Then, the fixed clustering sensor network can be performed by FCA.

4. Simulation Results

In order to verify and compare the energy efficiency of the proposed FCA, a simulation work is presented. In the simulation, we assumed that the energy dissipation sending one packet by each sensor is \( e = 5 \times 10^{-7} \) Joule \((\text{J})/\text{m}^2\). In our simulation, the total number of sensors nodes is one hundred, \( Q=100 \). Then, the normal sensor nodes are 100-\( q \). The length of sensing square area is set \( D=50 \) meters. The base station is deployed at \((0, -B)=(0, -10)\). To be generalization, the worst case in data fusion with data compressing factors for all clusters \( \eta=1 \) is performed in the simulations.

Firstly, we compare the energy efficiency between the performance of the proposed FCA and the random clustering (RC) [3], in which the cluster heads are randomly selected to perform clustering. The performance of RC had been analyzed in [3]. Figure 4 shows the energy consumption of one round vs. the number of clusters. It depicts that the consuming energy of the sensor nodes is getting less when number of clusters increases. The reason is that when cluster region gets smaller, the distance from sensor node to cluster head gets shorter. Contrarily, when the number of cluster increases, the energy consumed in cluster heads increases. Therefore, from Figure 4, it is obviously observed that the proposed FCA outperforms the RC with the number of cluster \( 1 < q < 20 \).

We assumed that the life time is time duration of WSN working until the energy of any one node runs out. With the assumption of perfect energy distribution on the nodes and the total energy of all nodes \( E_T = 100J \), Figure 5 thus depicts the comparison of lifetime of WSN for FCA and RC. It is obvious that the lifetime with FCA is almost twice of that with RC while \( 1 < q < 7 \). When the number of cluster increases, the lifetime with FCA is always longer than that of RC due to the energy efficiency of sensor nodes.

![Figure 3](image)

Figure 3. The axis of cluster heads with number of clusters (a)9 (b)12 (c)11 for FCA.
In Figure 5, the network lifetime is evaluated based on perfect energy distribution for all sensor nodes and cluster heads. In reality, the distributed energy for every sensor node is almost the same. Moreover, when number of cluster is small \((q<10)\), cluster head should be distributed more energy in order to send more data. Similarly, energy for all cluster heads is the same. Therefore, we distributed different energy to both sensor nodes and cluster heads to investigate the lifetime performance of a heterogeneous WSN.

Figure 5. Lifetime comparison of FCA and RC with optimal energy distributed sensors.

To investigate the lifetime of proposed FCA with heterogeneous sensors, we distribute different total energy \(E_n\) and \(E_{ch}\) to sensor nodes and the cluster heads, respectively. Figure 6 shows the comparison of network lifetime vs. number of clusters for FCA and RC. From Figure 6, with the proposed FCA when the distributed energy for cluster head is higher of \(E_{ch}=5 E_n= 500J\), the network lifetime is limited to 4500 rounds by the lifetime of sensor node with the number of cluster \(q = 10\). Besides, when the distributed energy of cluster heads decreases to \(E_{ch}=2.5 E_n= 250J\), the network lifetime is limited to 3000 rounds when the number of clusters is equal to 8. However, with the RC, when the number of clusters is equal to 12 the network lifetime is limited to 2000 rounds which is shorter than that of FCA.

When the distributed energy of cluster head decreases to the same as that of sensor nodes \((E_{ch}= E_n= 100J)\), the network lifetime of FCA and RC is limited to 2000 and 1100 rounds respectively. Moreover, the optimal number of clusters \(q_{opt}\) are 5 and 8 for FCA and RC respectively. Thus, it is easily seen the tradeoff of the distributed energy of cluster heads and sensor nodes with the number of clustering in WSNs.

Besides, the rising curve in Figure 6 depicts the energy dissipation of sensor nodes is decreased with the increasing number of clusters. But contrarily the curve going down illustrates that the consuming energy of cluster head increases with the increasing number of clusters. To compare the energy efficiency of WSNs, we further define the energy efficiency \((EE)\) as the ratio of total consumed energy to the network lifetime by

\[
EE= \frac{\text{Lifetime}}{(E_{ch} + E_n)}.
\]

Moreover, the energy ratio \((ER)\) of energy of cluster heads to distributed energy of cluster heads and distributed energy of sensor nodes is defined by

\[
ER= \frac{E_{ch}}{E_n}
\]

for the WSNs. Therefore, we can maximize the lifetime of WSN by deploying adequate number of clusters according to the \(ER\) and \(EE\) as shown in Table 2. From Table 2, it is obviously that the proposed FCA outperforms the RC scheme. Moreover, the FCA and RC perform the highest energy efficiency at \(q=5\) and \(q=8\) respectively.
Table 2. The comparison of energy efficiency and optimal number of clusters for FCA and RC with heterogeneous sensors

<table>
<thead>
<tr>
<th></th>
<th>ER</th>
<th>0.5</th>
<th>1</th>
<th>2.5</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCA EE</td>
<td></td>
<td>8.34</td>
<td>9.935</td>
<td>8.66</td>
<td>7.58</td>
</tr>
<tr>
<td>q_{opt}</td>
<td>4</td>
<td>5</td>
<td>8</td>
<td>10</td>
<td></td>
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<tr>
<td>RC EE</td>
<td>5.21</td>
<td>5.92</td>
<td>5.61</td>
<td>4.87</td>
<td></td>
</tr>
<tr>
<td>q_{opt}</td>
<td>5</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

5. Conclusion

In this work, an energy efficient clustering algorithm is proposed to prolong the lifetime of cluster-based WSN. The proposed FCA gives uniform area of cluster area for the WSN and save the energy dissipation of normal sensor nodes in the cluster. Simulation results show that the FCA outperforms the RC with more 80% energy efficiency and prolong the life time for both homogeneous and heterogeneous WSNs. Moreover, the FCA and RC perform the highest energy efficiency at number of clusters q=5 and q=8 respectively.

6. References