Connectivity and Energy-aware Clustering Approach for Wireless Sensor Networks

Chun-Jung Hsu
Department of Information and Communication Engineering, Chaoyang University of Technology
s10130602@cyut.edu.tw

Hung-Chi Chu*
Department of Information and Communication Engineering, Chaoyang University of Technology
hcchu@cyut.edu.tw

Jiun-Jian Liaw
Department of Information and Communication Engineering, Chaoyang University of Technology
jjliaw@cyut.edu.tw

Abstract—The wireless sensor network consists of large sensor nodes which are employed in a sensing environment. The sensor node with properties including small size, low cost and low power consumption is activated by batteries with limited electricity. Accordingly, it has become a critical issue to extend a network’s lifetime by effectively manipulating limited energy. For fewer isolated nodes, the change of a node’s connectivity should be considered apart from energy, that is, the node with high connectivity and energy is selected as the cluster head for moderating disadvantage of isolated nodes. In a large-scale sensor network, the clustering technique is one method for energy efficiency by reducing a single node’s loading during data transmission. In this study, we refer to a node’s connectivity and energy and provide a cluster-based method for reduction of energy consumed by sensor nodes with clusters’ field size dynamically adjusted in a changed network environment. As indicated in experimental results, our method improves a conventional wireless sensor network, for example, energy saving of nodes and extension of a network’s running time.

Keywords—Wireless Sensor Network; Connectivity Control

I. INTRODUCTION

With wireless communications and microelectronic processes advancing recently, the wireless sensor networks have been widely used in household automation, environment and habitat monitoring, military system, industrial automation [1-3] and health care. The Wireless Sensor Network (WSN) which consists of hundreds or thousands of sensor nodes randomly deployed in the environment to be detected is intended to sense ambient changes in temperature, humidity, carbon dioxide, heat beat, body temperature, or oxygen saturation, all of which are collected and transmitted to Base Station (BS) or Sink via node-based wireless communications and controlled by an administrator for real-time monitoring and management.

For mass deployment, the sensor node featuring low cost, small size and low power consumption is restricted in hardware design which dominates computing power, battery life and memory space of the sensor node. Moreover, an environment to be monitored by an administrator in a wireless sensor network may be hardly accessible and complicate recharges of numerous sensor nodes deployed in the environment because of hardware and resource constraints.

Against this background, it has become an important issue to get longer lifetime of a network on the basis of limited power resources.

In addition to the energy issue, the fewer isolated nodes are requisite because of their effects on the overall network and more power consumed in transmission. Accordingly, the node with more other nodes connected and more energy reserved should be taken as the cluster head for minimized isolated nodes in view of changes in connectivity among several nodes.

The energy consumption in a wireless sensor network usually occurs in three main parts: sensing information, data transmission and data processing wherein most energy is expended in data transmission. The energy consumed in data transmission is highly correlated with both signal strength and distances, that is, more energy will be expended among nodes which are separated by long distances during data transmission between nodes and the destination. The modes of data transmission which are divided into direct transmission, multi-hop transmission and clustering transmission are shown as follows:

A. Direct transmission

Data collected by sensor nodes is directly and quickly transmitted to remote BS but more energy for wide-range sensing is consumed by some far-off nodes which may die early and cause imbalance of energy loading because of different energy consumption rates.

B. Multi-hop transmission

The multi-hop transmission organizes sensor nodes as one or several chain structures, each of which has one chain head so that data collected by nodes is transmitted to the chain head’s neighbor nodes and further to remote BS via the chain. The multi-hop transmission which is economic because of less energy expended in long-distance data transmission may delay transmission when data is transmitted among numerous nodes in the network or by some nodes far away from BS.

C. Clustering transmission

The clustering transmission is characteristic of the cluster head (CH), i.e., the specific sensor node among
various sensor nodes, and its allied clustering members consisting of other sensor nodes based on predetermined conditions for development of a complete cluster. The cluster head is responsible for aggregating data collected by its clustering members and transmitting it to BS. It is probable that clustering transmission manifests better energy efficiency than the other two transmission modes when the cluster head, which takes charge of not only sensing but also data processing and transmission in the same cluster, consuming more energy and being possibly dead earlier than ordinary sensor nodes, properly rotates among different sensor nodes to overcome imbalance of loading.

To avoid early death of some single nodes, each of which may have heavy loading in a large-sized running sensor network with no several districts divided in the sensing range, we prefer the comparatively better transmission modes, multi-hop transmission and clustering transmission, and develop a cluster-based method with connectivity and energy incorporated for low energy consumption. Under the clustering architecture, a new cluster-based partitioning method is intended to divide a sensing area into a number of parts in which energy and connectivity of sensor nodes are continuously monitored for dynamic adjustment of clusters’ field size, data effectively and economically transmitted to BS, and improved efficiency of the network which is operated in the cluster-based partitioning mechanism balancing energy loading.

II. RELATED WORKS

The simplest method for data transmitted to BS from sensor nodes sensing environmental information is direct transmission featuring high speed but early death of sensor nodes which are far away from BS and consume more energy for remote data transmission. The chain-based transmission corrects the problem of more energy consumption induced by remote data transmission but delays data transmission through multiple sensor nodes. Accordingly, the clustering transmission reducing transmission distances among sensor nodes and moderating excessive delay of data transmission is selected in our research. The cluster-based routing methods are described as follows.

LEACH (Low Energy Adaptive Clustering Hierarchy) [4] is one of the most important clustering mechanism. Based on the probability, the cluster head of LEACH is randomly determined in each round and other nodes are assigned to the adjacent cluster head and possibly taken as the cluster head in the next round. This mechanism is able to quickly organize a cluster without requirements of excessive information.

LEACH contains two phases, set-up phase and steady-state phase. In the set-up phase, the random number, 0 or 1, created by a single node is compared with the threshold, \( T(n) \), and the single node is possibly selected as the cluster head when the random number is less than the threshold, \( T(n) \). The calculation of a threshold for the cluster head is shown in Equation (1):

\[
T(n) = \begin{cases} 
1 - p \times \left[ r \mod \frac{1}{p} \right], & \text{if } n \in G \\
0, & \text{otherwise}
\end{cases}
\]  

Where \( p \) is the probability of a single node to become the cluster head first, \( G \) is the set of nodes which were selected as the cluster head before the \( 1/p \) round, and \( r \) is the number of rounds. As shown in Equation (1), the threshold, \( T(n) \), of a single sensor node, which is not selected as the cluster head in this round and waiting the opportunity in the next round, will increase for the higher probability to become the cluster head.

This mechanism is advantageous to the cluster head rotating among most sensor nodes in a certain number of rounds without imbalance of energy loading induced by some sensor nodes repeatedly selected as the cluster head. With the cluster head determined, the ordinary sensor nodes will join the adjacent cluster head which replies the request for joining and informs the node of the transmission schedule based on Time Division Multiple Access (TDMA) for completion of the set-up phase. In the steady-state phase, each sensor node should be responsible for its own task for data sensing and data transmission to the cluster head based on TDMA; the cluster head should aggregate collected data and transmit it to BS for completion of the steady-state phase.

LEACH-C (LEACH-Centralized) [5 modified from LEACH is characteristic of establishment of clusters from BS directly that supposedly possesses information of all sensor nodes such as residual energy and position, which are used to assign a single node to be the cluster head and analyze deployment of the cluster head for a uniform cluster without the problem of the cluster head randomly determined, respectively.

An energy efficient cluster head selection for wireless sensor network [6] modified from LEACH, the calculation of a threshold for the cluster head is shown in Equation (2):

\[
T(n) = \begin{cases} 
\frac{p}{1 - p \times \left[ r \mod \frac{1}{p} \right]} \times \frac{E_{\text{residual}}}{E_{\text{total}}} \times K_{\text{opt}}, & \text{if } n \in G \\
0, & \text{otherwise}
\end{cases}
\]  

Where \( E_{\text{residual}} \) is the residual energy of a single node, \( E_{\text{initial}} \) is the initial energy of a single node, and \( K_{\text{opt}} \) is the number of optimal clusters (i.e. \( K_{\text{opt}}=4 \)).

\[
K_{\text{opt}} = \sqrt{\frac{N}{2\pi}} \times \sqrt{\frac{\mu_{fs} E_{\text{opt}}}{d_{\text{dss}}} \times \frac{M}{d_{\text{dss}}}}
\]  

Where \( N \) is the number of total nodes, \( M \) is the size of the network, and \( d_{\text{dss}} \) is the distance between a node and BS.

In this paper, we depend on a sensor node’s residual energy to determine the cluster head for balance of loading among nodes and improved lifetime of a network.

ESSCSTA (Energy Efficient Sleep Scheduled Clustering & Spanning Tree based data aggregation in wireless sensor network) [7] modified from LEACH includes additional functions, for example, the sleep mechanism in the steady-state phase and determination of the cluster head based on correlations of collected data and existing electricity in the set-
up phase. With the cluster head determined, the sleep mechanism is available to half the sensor nodes and other sensor nodes transmit data to the cluster head; then, the sleep mechanism is available to the nodes which completed data transmission previously for energy saving of half the idle nodes. With data transmitted to sink node by cluster heads which complete data collection and aggregation directly, ESSCSTA different from LEACH depends on the tree structure from cluster heads to cluster heads for the multi-hop transmission to Sink and contributes to less energy consumption in direct long-distance data transmission.

SEP (A Stable Election Protocol for clustered heterogeneous wireless sensor networks) [8] modified from LEACH and applied to the heterogeneous wireless sensor network with different sensor nodes corrects the problem of imbalance of energy loading in the heterogeneous wireless sensor network based on LEACH. The sensor nodes are divided into two groups, high-level sensor nodes and ordinary sensor nodes, in which the cluster heads have distinct thresholds according to their initial energy and are assigned to the sensor nodes with more energy, in order to avoid imbalance of residual energy in nodes with different initial energy.

DEEC (Distributed Energy-Efficient Clustering) [9] modified from SEP and it depending on residual energy as references to determine the cluster head. A round-based mechanism which refers to residual energy for selection of the cluster head was used in DEEC. that is, the node with higher residual energy is more probably selected as the cluster head in multiple rounds than other nodes.

III. CONNECTIVITY AND ENERGY-AWARE CLUSTERING APPROACH

The steps of the Connectivity and Energy-aware Clustering Approach (CECA) are shown in the following paragraphs.

A. Operating Environment

1) All sensor nodes possess identical initial energy;
2) No power supply connected to sensor nodes can be changed or recharged;
3) The energy consumptions for distinct transmission distances are different according to the energy consumption module;
4) The sensor nodes are capable of communicating with BS directly.

B. Energy Consumption Module

As the basic element of lots of studies for the wireless sensor network, the energy consumption module [1, 4, 5] is used in calculating energy consumption of sensor nodes as shown in Figure 1.

The energy to be consumed with k-bit data transmitted to a target node for the distance of d is:

\[ E_{Tx}(k,d) = \begin{cases} k \cdot E_{elec} + k \cdot s_f \cdot d^2, & d \leq d_0 \\ k \cdot E_{elec} + k \cdot e_{mp} \cdot d^4, & d > d_0 \end{cases} \]  \hspace{1cm} (4)

Where the threshold distance \( d_0 \) is:

\[ d_0 = \frac{\epsilon_f}{\sqrt{e_{mp}}} \]  \hspace{1cm} (5)

The energy to be consumed with the k-bit data received by a sensor node is:

\[ E_{Rx}(k) = k \cdot E_{elec} \]  \hspace{1cm} (6)

Equation (4) for energy consumption during data transmission is derived from two transmission models, ideal transmission model for a transmission distance less than the threshold distance (\( d \leq d_0 \)) and multi-access interference model for a transmission distance greater than the threshold distance (\( d > d_0 \)). Moreover, \( E_{elec} \) is the energy to be consumed by electronics in the communications module and required by amplifiers in two different types of transmission modes. Equation (6) indicates the energy to be consumed by a sensor node receiving k-bit data.

C. Operating Steps

In the method to select a cluster head, the threshold (\( S_{i,DE} \)) depends on two factors such as node’s connectivity and residual energy. The node with high connectivity implies more neighbor nodes around the position at which the node is located. With all nodes set up in the beginning, the information of each node’s threshold broadcasted in the network will be exchanged by all nodes including their neighbor nodes for selection of the node with a high threshold as the cluster head. The threshold of a sensor node is calculated in Equation (7).

\[ S_{i,DE} = \left( 1 - \alpha \right) \cdot \frac{E_{residual}}{E_{initial}} + \alpha \cdot \frac{d_s}{d_{max}} \]  \hspace{1cm} (7)

Where \( d_{max} \) is the maximum connectivity in the same cluster, \( d_s \) is the connectivity of a single node and its neighbor node in the same cluster, \( E_{residual} \) is the residual energy of a single node,
$E_{\text{initial}}$ is the initial energy of a single node, and $(1-\alpha)$ and $\alpha$ are weights of energy and connectivity, respectively.

The detailed steps of the connectivity and energy aware clustering approach shown in Figure 2 are presented as follows.

**Fig. 2. Steps of the connectivity and energy aware clustering approach**

1. **Start**
2. **Step 1**: Initialize
3. **Step 2**: Are all nodes dead? (Yes/No)
   - Yes: End
   - No: Go to Step 3
4. **Step 3**: Calculate $d_i$, the connectivity of the node among neighbor nodes
5. **Step 4**: Broadcast node $d_i$
6. **Step 5**: Calculate $d_{\text{max}}$, the maximum connectivity in the same cluster and the threshold of each node according to Equation (7)
7. **Step 6**: Broadcast each node’s properties such as ID, position and threshold to be received by its neighbor nodes
8. **Step 7**: Compare a node’s threshold with those of its neighbor nodes in the same cluster and find the maximum $S_{i,\text{at}}$ for determination of the cluster head
9. **Step 8**: Assign the node with the maximum threshold as the cluster head and other nodes as members of the cluster with all nodes’ thresholds compared
10. **Step 9**: Organization Clustering: Establish the cluster
11. **Step 10**: Each node performs sensing and transmits data to the cluster head in the same cluster
12. **Step 11**: The cluster head aggregate data
13. **Step 12**: The cluster head transmit data to sink node
14. **Step 13**: Go back to Step 2 for reorganization of a cluster, if necessary.

**IV. SIMULATION AND RESULT ANALYSIS**

As shown in Figure 3, the network environment of simulations conducted in Matlab is a district with the field size of 100 m × 100 m in which 100 sensor nodes (initial energy=0.5J) are deployed and classified into four clusters marked by four symbols including X, ◇, ○ and * and BS with coordinates of (50,175) is located beyond the sensing area. The details for parameter settings are presented in Table 1.

**Fig. 3. Network environment with nodes deployed for simulations**
TABLE I  Parameter settings for simulations

<table>
<thead>
<tr>
<th>Parameter Settings for Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field size ($M \times M$)</td>
</tr>
<tr>
<td>Number of nodes, $N$</td>
</tr>
<tr>
<td>Location of BS (Base Station)</td>
</tr>
<tr>
<td>Threshold distance ($d_0$)</td>
</tr>
<tr>
<td>$C_{th}$</td>
</tr>
<tr>
<td>Initial energy of a sensor node</td>
</tr>
<tr>
<td>Energy for aggregation ($E_{aAg}$)</td>
</tr>
<tr>
<td>$E_{elec}$</td>
</tr>
<tr>
<td>$C_{mp}$</td>
</tr>
<tr>
<td>$E_{agg}$</td>
</tr>
<tr>
<td>Cluster-head probability</td>
</tr>
<tr>
<td>Data packet size</td>
</tr>
<tr>
<td>Control packet size</td>
</tr>
</tbody>
</table>

The number of nodes which are kept immobile and continue to be alive are presented in Figure 4 ($C_{th}$=10m). In this regard, the connectivity of an immobile node is not changed and has weak effect. The first nodes dead in different methods are indicated in Round No. 1209 (LEACH), Round No. 1384 (DEEC), Round No. 1312 ($\alpha=0.19$) and Round No. 1457 ($\alpha=0.1$).

As shown in Figure 6 for changes of nodes’ connectivity ($\alpha=0.5$), the maximum and minimum changes of connectivity, the maximum and minimum standard deviations, and the mean standard deviation are 10, 0, 0.99, 0.31 and 0.29, respectively. It can be thus seen that a node’s lifetime in a highly mobile environment is affected by the significantly changed connectivity.

The number of nodes which are kept mobile randomly within a range of ±5m in the x-axis or the y-axis and continue to be alive are presented in Figure 5 ($C_{th}$=5m). In this regard, the connectivity of a mobile node has its critical effect. The first nodes dead in different methods are indicated in Round No. 1378 (LEACH), Round No. 1509 (DEEC) and Round No. 1564 ($\alpha=0.5$). For $\alpha \geq 0.5$, the status of nodes alive in our method is superior to those of other methods.

The number of nodes which are kept mobile randomly within a range of ±5m in the x-axis or the y-axis and continue to be alive are presented in Figure 7 ($C_{th}$=10m). In this regard, the connectivity of a mobile node has its critical effect. The first nodes dead in different methods are indicated in Round No. 1378 (LEACH), Round No. 1509 (DEEC) and Round No. 1564 ($\alpha=0.5$). For $\alpha \geq 0.5$, the status of nodes alive in our method is superior to those of other methods.
As shown in Figure 8 for changes of nodes’ connectivity ($\alpha=0.5$), the maximum and minimum changes of connectivity, the maximum and minimum standard deviations, and the mean standard deviation are 17, 0, 1.73, 0.35 and 0.62, respectively. It can be thus seen that a node’s lifetime in a highly mobile environment is affected by the significantly changed connectivity.

It can be seen from simulation results that our method recommended herein has no special advantage in a network with immobile sensor nodes and unchanged connectivity ($\alpha=0.19$) but effectively extends lifetime of a network with randomly mobile sensor nodes and changed connectivity ($\alpha=0.5$) in contrast to other methods. Therefore, our method has the superiority to extend a network’s lifetime with energy of a node and connectivity between a node and its neighbor nodes considered.

V. Conclusions

In this study, we offer a connectivity and energy aware clustering approach to improve nodes’ energy consumption and extend a network’s lifetime in experimental simulations with sensor nodes fixed or randomly moving. It can be seen from experimental results that a network based on connectivity has longer lifetime and is effectively managed. These findings can be applied to monitoring climbers or swimmers according to the concept that the inferior connectivity of a sensor node disappearing in a highly-linked network for effective data transmission to BS will contribute to positioning of the disappearing node under control of an administrator.

For research in the future, other factors should be incorporated in the connectivity clustering mechanism for extending a network’s lifetime and balancing nodes’ energy consumption.

ACKNOWLEDGMENT

This research was supported in part by the National Science Council, Taiwan, ROC, under Grant NSC 102-2221-E-324-023.

References