Energy Efficient Routing for Wireless Sensor Networks with Grid Topology

Hock Guan Goh[1], Moh Lim Sim[2], and Hong Tat Ewe[1]

[1] Faculty of Information Technology, [2] Faculty of Engineering,
Multimedia University, Jalan Multimedia,
63100 Cyberjaya, Selangor, Malaysia.
{hggoh, mlsim, htewe}@mmu.edu.my

Abstract. Agricultural monitoring using wireless sensor networks has gained much popularity recently. In this paper, we review five existing flat-tree routing algorithms and proposed a new algorithm suitable for applications such as paddy field monitoring using wireless sensor network. One of the popular data collection methods is the data aggregation approach, where sensor readings of several nodes are gathered and combined into a single packet at intermediate relay nodes. This approach decreases the number of packets flowing and minimizes the overall energy consumption of the sensor network. However, most studies in the past do not consider the network delay in this context, which is an essential performance measure in real-time interactive agricultural monitoring through Internet and cellular network. We propose an algorithm called Information Selection Branch Grow Algorithm (ISBG), which aims to optimize the network in achieving higher network lifetime and shortening the end-to-end network delay. The performance of this algorithm is assessed by computer simulation and is compared with the existing algorithms used for data aggregation routing in wireless sensor networks.

Keywords: WSN, routing algorithm, energy efficient routing, grid topology

1 Introduction

Recent technological advancement in micro-electro-mechanical systems (MEMS) has enabled small and inexpensive wireless communication nodes comprising of transducers, transceivers, and micro-controllers to be deployed on a large scale. These devices are able to communicate with each other and form a self-organized network called Wireless Sensor Network (WSN). WSN represents a new generation of real-time embedded system with wireless networking capability. Albeit it has significant energy storage constraint as compared to the traditional wireless networks meant for human or computer communications, WSN has great potential benefits when deployed in the many areas.

For paddy field monitoring, the sensor nodes are often deployed in a grid topology. The main important issues for WSN monitoring application are to maximize the network lifetime and minimize the end-to-end network delay. A node that ran out of the energy will cause data loss in the corresponding sensing area. This will also affect the routing performance of the intermediate nodes. Critical event such as sudden flooding could happen in the paddy field especially after a heavy rain. Such sensor readings are very critical and need to be sent to the user as fast as possible. Any delay in taking the right action will cause the owner of the farm a huge loss. However, most studies [1] in the past do not focus much on the network delay, which is an essential performance measure in real-time interactive agricultural monitoring through Internet and cellular network. Our work aims to optimize the network in achieving higher network lifetime and shortening the end-to-end network delay.

2 System Model

2.1 Grid Topology

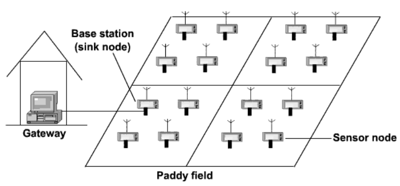

Fig. 1. Example of a grid topology deployment in a paddy field.

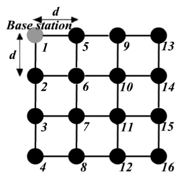

Fig. 2. Example of 2D grid topology and the base station is placed at the corner.

From the example of application deployment as shown in Fig. 1, the network topology is modeled as a 2D network with $n \times n$ fixed nodes. For illustration, a 2D grid topology with 4×4 fixed nodes as shown in Fig. 2 is considered. Distances between the two adjacent wireless nodes are the same and equal to d. Each node is denoted by an index. Communications can only occur between nodes that are linked neighbours with a separation distance of d. The base station is defined as a sensor node that is connected to a gateway (data sink) with a wired cable. Any of the nodes can be selected as a base station. Once it is deployed, it will not be moved. The base station is assumed to have an unlimited supply of power and possesses a superior computational capability.

2.2 Data Aggregation Approach

Several technical limitations of WSNs [2] have called for a need of alternative data collection approach which is more energy-efficient than the traditional approaches. One of the methods proposed for data collection in WSN is data aggregation [3], [4]. The general idea of data aggregation is to combine the data coming from multiple sources, process them into a single packet, and forward it toward the destination, namely the base station. The process will be repeated until the aggregated data reach the base station. This will eliminate redundancy, minimize the number of transmissions, and thus save the energy resource. Two approaches of data aggregation for data collection in WSNs are considered here:

Intermediate Processed Data Aggregation (IPDA): All sensor readings will be aggregated by processing and consolidating the information into a single packet at the intermediate relay nodes. Sensor data originating from each node has a fixed length of 30 bytes.

Cascaded Data Aggregation (CDA): All sensor readings will be aggregated by cascading the contents from different sources at the intermediate relay nodes without any analysis or further processing. This process will be repeated at all intermediate relay nodes before the data finally reach the base station. Sensor data originating from each node is 16 bytes long, which consists of 2 bytes of node ID and 14 bytes of actual sensor data.

2.3 Packet Format

Two kinds of packet format for data aggregation are considered here: packet format for IPDA as shown in Fig. 3 and CDA as shown in Fig. 4.

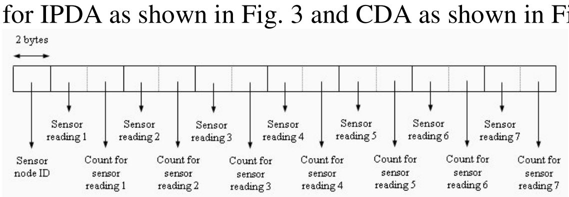

Fig. 3. Packet format for IPDA.

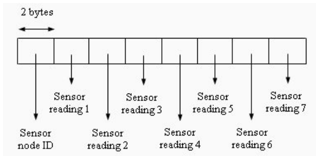

Fig. 4. Packet format for CDA.

2.4 Energy Reserve and Consumption Models

The system under study has finite reserve of energy. The energy storage of each node, namely the battery, behaves like a leaky bucket with an initial energy of E_{total} Joule. Meanwhile, various processes carried out in the operation of WSN will consume and drain out the energy reserve. In this study, we model the energy consumption due to packet transmission and packet reception, i.e., the processes that mainly consume the energy [5]. A popular radio model called the first-order radio model as discussed in [5] is used to estimate the energy cost of transmitting and receiving data. In this simple radio model, it is assumed that the energy dissipated to run the transmitter circuitry, $E_{Tx\text{-}elec}$ is the same as the receiver circuitry, $E_{Rx\text{-}elec}$ where $E_{Tx\text{-}elec} = E_{Rx\text{-}elec} = E_{elec}$. The equation used to calculate the cost of transmitting a k-bit data packet across a distance d is defined as follows:

$$E_{Tx}(k, d) = E_{Tx\text{-}elec}(k) + E_{Tx\text{-}amp}(k, d) = E_{elec} \times k + E_{amp} \times k \times d^2, \quad (1)$$

where E_{amp} is the energy dissipated by transmitter amplifier to achieve an acceptable signal-to-noise ratio. The receiving cost for a k-bit data packet is given by:

$$E_{Rx}(k) = E_{Rx\text{-}elec}(k) = E_{elec} \times k \quad (2)$$

The amount of energy consumed by a node is given by $E_{consume} = E_{Tx} + E_{Rx}$. A node is considered dead when it has run out of the energy.

2.5 Communication Delay Model – Point-to-point Delay and End-to-end Network Delay

Four kinds of delay contribute to point-to-point node delay. These are processing delay, queuing delay, transmission delay, and propagation delay. In the simulation, the transmission delay and propagation delay are assumed to be fixed for every node and queuing delay is considered to be negligible. The end-to-end packet delay, which is the time it takes for a packet to be transferred from a transmitter to a receiver, is given as:

$$T_i = T_{frame,\, i} + T_{propagation,\, i}\,, \qquad (3)$$

where $T_{frame,\, i}$ = data packet size / channel transmission rate, $T_{propagation,\, i}$ = link length / signal propagation speed, and subscript i denotes the i-th link. It should be noted that any delays due to processing, queuing, acknowledgement, or negative acknowledgement are not taken into consideration. End-to-end delay of a network is defined as the total amount of time for all the aggregated data to be sent back to the base station. In our simulation model, we consider the following equation for the time it takes for all the data to be aggregated back to the base station.

End-to-end network delay, $$T_{total} = \max_{1 \le j \le b} \left\{ \left[\sum_{i=1}^{L} (T_i) \right]_j \right\}, \qquad (4)$$

where L is the total number of links in a branch of the base station, T_i is the maximum end-to-end packet delay of the i-th link from the base station, subscript j denotes the j-th branch, and b the total number of branches of the base station.

3 Existing Routing Algorithms

3.1 Stream-based routing algorithm

In the stream-based routing algorithm [6], sequential data aggregation approach is used for data collection. Data packets are passed and aggregated sequentially from all other nodes to the base station. The disadvantage of stream-based routing is that a longer time will be needed to collect data from the entire network.

3.2 Row-To-Column routing algorithm

In the row-to-column routing algorithm [6], shortest path data aggregation approach is adopted for data collection. Each sensor node is organized into an n^2 grid and information is passed row-by-row towards the row of the base station. For the row where the base station is located, the information is passed in the column-by-column fashion to the base station node. In such a routing scheme, the information takes the shortest path from the source node to the base station in terms of number of hops.

3.3 Cluster-based routing algorithm

One of the disadvantages of row-to-column routing is that nodes that share the same row with the base station are particularly burdened. An improvement to this is the cluster-based routing scheme [6], where grouping of nodes before data aggregation is considered. Each neighbouring node is the cluster head of a group of the nodes and the information from group nodes takes the shortest path to the head. The purpose of this method is to distribute the energy dissipation in each node more equally.

3.4 Tree-based routing algorithm

Tree-based routing algorithm [7] uses a set of rules (phase 1: node searching, phase 2: parent node selection, and phase 3: link establishment) to establish the links between two nodes starting from the base station. The algorithm uses random parent selection method, where a node will randomly choose its parent node when it receives more than one message. This process of links establishment will continue until all the nodes in the network are connected.

3.5 Node-Centric Load Balancing Routing Algorithm

Construction of a balanced topology in terms of fair distribution of nodes among the branches of a network will help to increase the network performance [8]. In this case, neighbouring information plays an important role in the construction of network topology. In Node-Centric Load Balancing (NCLB) routing algorithm [8], it constructs a load-balanced tree in sensor networks of asymmetric architecture. Neighbouring information is needed to grow the routing tree by periodically broadcast the nodes existence. The algorithm consists of a basic algorithm and an adjustment algorithm. The basic algorithm constructs the routing tree by selecting the lightest most restricted branch and following by the selection from the heaviest border node with most growth space. Spiral adjustment is proposed to use for the adjustment algorithm. The adjustment algorithm will either push neighbours from the heavily loaded branches to the lighter ones or pull neighbours to the lightly loaded branches from the heavier ones.

4 Newly Proposed Routing Algorithm – ISBG Routing Algorithm

An improved algorithm may be designed by utilizing the information of the neighbouring information to construct a better balanced topology. In this paper, we propose an algorithm, which is a modification of the Tree-Based routing algorithm, called Information Selection Branch Grow (ISBG) algorithm for energy-efficient data aggregation routing in wireless sensor networks. It is clear that any node that consumes the highest energy will be the first node to run out of energy. By minimizing the energy consumption of the highest energy consumption node, the network lifetime can be prolonged. In tree topology, with balanced nodes distribution among all branches, all child nodes attached to a parent node will handle approximately the same amount of network traffic thus consume approximately the same amount of energy. The idea of minimizing end-to-end network delay is by developing branches where leaf nodes have minimum number of hops from the base station. Our proposed ISBG algorithm consists of a basic algorithm as shown in Fig. 5 and a two-stage adjustment algorithm as shown in Fig. 6 and Fig. 7. The following terminologies are defined:

- Unmarked nodes: nodes that do not have a parent node.
- Weight: the number of unmarked nodes found at the immediate neighbouring nodes.
- Degree of Freedom or "growth space" of a node: the sum of weights of the unmarked neighbouring nodes.
- Unit factor: number of children nodes and itself.
- Total aggregated unit: the sum of the unit factors along the path starting from the base station until the node.
- Balance criteria: when all branches of a base station have equal number of child nodes.

4.1 Basic Algorithm of ISBG

For the ISBG basic algorithm, it iteratively grows a balanced tree outwards from the base station root. All nodes in the topology will periodically broadcast their existence and its neighbouring nodes' information. At each step, the algorithm will first select a potential branch to grow. The step will be followed by selection of a potential node to be grown. Finally, the algorithm will update the topology information. The whole process will repeat until all the unmarked nodes have been found.

To select the potential branch to grow, this is done by considering the descending priority order in a series of Potential Branch Consideration (PBC): i) the lightest weight, ii) the smallest number of child nodes of a base station's branch, iii) minimum degree of freedom, iv) the smallest total aggregated unit, and lastly v) random selection. The next step is to select a potential node to be grown. The potential node is selected based on descending priority order in a series of Potential Node Consideration (PNC): i) the heaviest weight, ii) the maximum degree of freedom, and iii) random selection. Once the potential branch and potential node are found, a link will be established between them. Finally, the algorithm will update the topology information. The whole process will be repeated until all the unmarked nodes are found.

4.2 Adjustment Algorithm

The topology that is formed after the ISBG basic algorithm may not be able to achieve balanced distribution for a large topology, such as 10×10 grid topology. Thus, adjustment algorithms are needed to achieve better balance distribution and enhance the network lifetime after the construction of network topology using the basic algorithm. In this case, two types of adjustment algorithms can be considered: i) inter-branch adjustment and ii) intra-branch adjustment. Inter-branch adjustment is done through pushing the neighbouring branch nodes from the heavier branch to the lighter branch or pulling the neighbouring branch nodes from the heavier branch to the lighter branch. Further analysis shows that the network lifetime and the end-to-end network delay may increase after the inter-branch adjustment. Thus, intra-branch adjustment is needed to reduce the end-to-end network delay. Intra-branch adjustment is done by moving a node attached to a higher total-aggregated-unit parent node to a lower total-aggregated-unit parent node of the same branch from the base station.

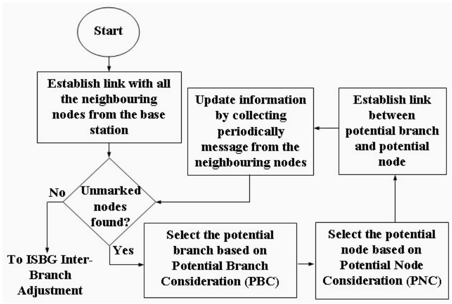

Fig. 5. Flow chart of ISBG Basic Algorithm.

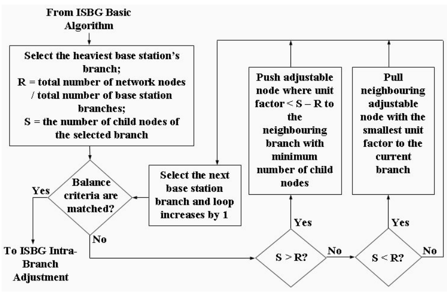

Fig. 6. Flow chart of ISBG Inter-Branch Adjustment Algorithm.

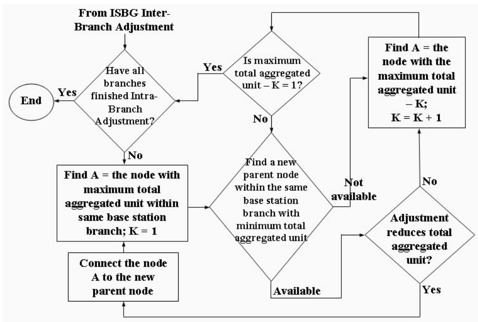

Fig. 7. Flow chart of ISBG Intra-Branch Adjustment Algorithm.

5 Simulation and Performance Analysis

For performance analysis, a discrete event based simulator has been developed using C procedural programming language. The simulation parameters (in Table 1) are used in the simulation of this study. Several comparisons have been done for the ISBG routing algorithm with the Stream-Based [6], the Row-To-Column-Based [6], the Cluster-Based [6], the Tree-Based [7], and the NCLB [8] routing algorithms through IPDA and CDA approaches. The simulation is carried out for 10×10 grid topology by selecting the base station at every location of the grid once at a time. For each location where the base station is being selected, the simulation is run for 1000 times.

Table 1. Simulation Parameters.

Simulation Parameters	IPDA	CDA
Energy dissipated by transmitter circuitry, $E_{Tx\text{-}elec}$	50 nJ/bit	50 nJ/bit
Energy dissipated by receiver circuitry, $E_{Rx\text{-}elec}$	50 nJ/bit	50 nJ/bit
Energy dissipated by transmitter amplifier, E_{amp}	100 pJ/bit/m^2	100 pJ/bit/m^2
Initial energy in each node, E_{total}	1.0 J	1.0 J
Link length, d	10 m	10 m
Channel transmission rate	10 kbps	10 kbps
Signal propagation speed	3.0×10^8 m/s	3.0×10^8 m/s
Data size in each node	30 bytes	16 bytes
Network losses	None	None

5.1 Performance Metrics

Two important performance metrics are discussed in this article: the network lifetime and the end-to-end network delay.

Network Lifetime: Energy consumption determines the lifetime of a sensor network. Communicating wirelessly consumes more power at the nodes compared with any other activities such as processing and sensing. Hence, the performance analysis does not consider energy dissipation for computation, sensing, listening for incoming packets, and other tasks. Network lifetime is defined as the time between the moment the network operates and the moment the first node runs out of its energy.

End-to-end Network Delay: End-to-end network delay is measured from the time where all the sensor readings are collected back to the base station. It is calculated starting from the time when the sensor data are sent from the leaf nodes to the intermediate nodes until all the sensor data reach the base station. Delays due to processing, queuing, acknowledgement, or negative acknowledgement are ignored.

5.2 Performance Results

Fig. 8 shows the average network lifetime for six routing algorithms. Among all the algorithms, the Stream-Based routing algorithm performs well and achieves a good network lifetime for IPDA. While for the ISBG routing algorithm, its performance is comparable to other algorithms. For IPDA, the packet sent to the neighbouring nodes each time would be the same. Therefore, the node that receives packets from or sends packets to the minimum neighbouring nodes will consume less energy. The Row-To-Column-Based, the Cluster-Based, the Tree-Based, the NCLB, and the ISBG routing algorithms have more than one child node in the intermediate nodes, so the energy consumption of the neighbouring nodes next to the base station will be higher than the Stream-Based routing algorithm. Fig. 9 shows the average end-to-end network delay for six routing algorithms using IPDA. Although the Stream-Based routing algorithm performs well in terms of network lifetime but it causes a long delay. This is because the packet needs to be forwarded sequentially and this will cause longer time to collect all the sensor readings back to the base station. The Row-To-Column-Based, the Cluster-Based, and the Tree-Based routing algorithms have shown comparable performances with the shortest end-to-end network delay as compared to others. This is because those algorithms are using the shortest path collection to the base station.

The ISBG routing algorithm performs moderately because partial of the sensor data may not be aggregated back to the base station using the shortest path. It causes longer delay as compared with the Row-To-Column-Based, the Cluster-Based, and the Tree-Based routing algorithms.

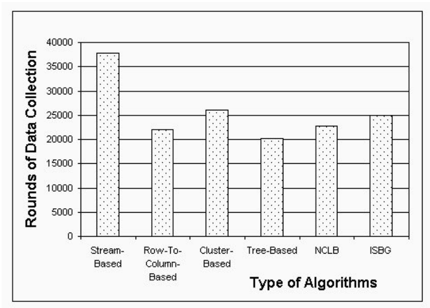

Fig. 8. Average network lifetime comparison using IPDA.

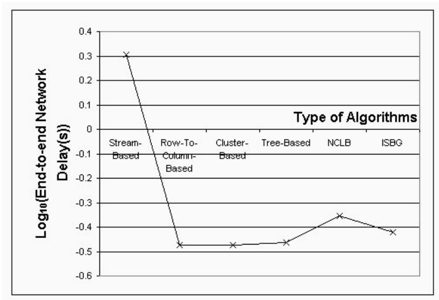

Fig. 9. Average end-to-end network delay comparison using IPDA.

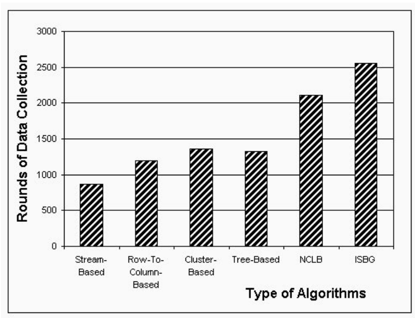

Fig. 10. Average network lifetime comparison using CDA.

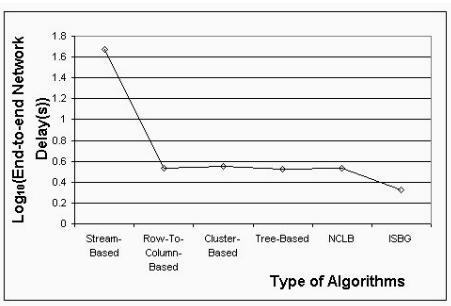

Fig. 11. Average end-to-end network delay comparison using CDA.

Fig. 10 shows the average network lifetime for six routing algorithms using CDA. For CDA, the ISBG routing algorithm performs the best among the others. The ISBG routing algorithm is able to distribute the nodes more evenly over all possible branches and thus able to achieve longer network lifetime. CDA will cause the packet length longer when the packet is closer to the base station. So, methods with sequential collection of the sensor readings, such as the Stream-Based routing algorithm will highly suffer from poor network lifetime. Fig. 11 shows the average end-to-end network delay for six routing algorithms using CDA. Sequentially in aggregation such as the Stream-Based routing algorithm performs poor for end-to-end network delay due to the packet needs to be forwarded node-by-node in a single direction. This kind of routing will cause longer time to collect all the sensor readings back to the base station. The Row-To-Column-Based, the Cluster-Based, and the Tree-Based routing algorithms have shown comparable performances with the shortest end-to-end network delay as compared to others for IPDA. This is because those algorithms are using the shortest path collection to the base station. The ISBG routing algorithm performs the best among the others. By spreading the nodes through a well-distributed topology, this will shorten the end-to-end network delay for the whole network.

6 Conclusion and Future Work

In this paper, we highlighted the major issues in WSN application for grid topology such as in the paddy field monitoring. We carried out a study on the existing flat-tree routing algorithms for end-to-end data collection. Due to the challenges in end-to-end data collection for real-time paddy field monitoring, we proposed a new algorithm called Information Selection Branch Grow (ISBG) routing algorithm, which perform reasonably well in terms of network lifetime and network delay. Although the Intermediate Processed Data Aggregation (IPDA) is able to give an overview of the conditions (maximum, minimum, or average of sensor readings) in the field, Cascaded Data Aggregation (CDA) is more appropriate to be used for precise paddy field monitoring, where all the sensor data are needed to be collected to the base station for detailed data analysis. The results show that the ISBG routing algorithm is the best selection for end-to-end data collection using CDA. This algorithm can be extended to other kinds of monitoring applications for wireless sensor networks.

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