Chapter 4

Cluster Head Election for Energy and Delay Constraint Applications of Wireless Sensor Network

Designing of multi-hop Wireless Sensor Network (WSN) depends upon requirements of the underlying sensing application. The main objective of WSNs is to monitor the physical phenomenon of interest in a given Region of Interest using sensors and provide collected data to sink. WSN is made of a large number of energy, communication and computational constraint nodes, to overcome the energy constrain replacing or recharging the batteries of the WSN nodes is an impossible task, once they are deployed in hostile environments. Therefore, to keep the network alive as long as possible, communication between the WSN nodes must be done with load balancing. Time critical applications like forest fire detection, battle field monitoring demands reception of data by the sink with the bounded delay to avoid disasters. Hence, there is a need to design a protocol which enhances the network lifetime and provides the information to sink with a bounded delay. The chapter will address this problem and solution. In the chapter, a routing algorithm is proposed by introducing Energy Delay Index for Trade-off (EDIT) to optimize both objectives – energy and delay. EDIT is used to select Cluster Heads (CHs) and “next hop” by considering energy and/or delay requirements of a given application. The proposed approach is derived using two different aspects of distances between a node and the sink named Euclidean distance and Hop-count, and further proven using realistic parameters of radio to get
data closest to the test bed implementation. The results aspires to give sufficient insights to others before doing test bed implementation.

4.1 Introduction

Recent development in sensor technology and wireless communication makes the sensor nodes inexpensive. Researchers across the globe are giving attention to these very attractive cost-effective applications like environmental monitoring, battle field monitoring, structural monitoring to name a few. A WSN network is made of a large number of sensor nodes, which are densely deployed in an area required to be monitored called Region of Interest (ROI). Sensor nodes collect data and forward it to sink or Base Station (BS) directly, or through multi-hop communication. But these sensor nodes have limited amount of memory, processing capacity, communication range, and above all limited amount of energy (power) because sensor nodes are battery powered. It is difficult to replace or recharge batteries of the sensor nodes when they operate in hostile environments. Hence, energy saving is an important issue for a WSN. Many techniques for energy savings are developed, which includes sleep scheduling, MAC protocols, routing protocols, data aggregation, topological control, etc. (Li, Bandai, and Watanabe)

This chapter focuses on the cluster formation process by considering energy-delay trade-off. Cluster formation is a part of hierarchical routing protocols. These protocols are energy efficient and provides scalability (Al-Karaki and Kamal). A survey on various routing techniques and protocols can be found in (Al-Karaki and Kamal Akyildiz et al. Akkaya and Younis). Each cluster consists of member nodes and a cluster head (CH). CH is responsible for collecting and aggregating data from the member nodes and sending it to other CH or BS.

A survey on different attributes of clustering of WSN is given in (Abbasi and Younis). As mentioned previously, energy is the most scarce resource of WSN. Hence, the objective of the CH election is to provide energy efficiency to enhance the lifetime of the WSN. Data aggregation is one of the ways which can provide energy efficiency (Li, Bandai, and Watanabe). Routing between the clusters can be direct or multi-hop. Direct transmission is very easy to use, and therefore, this technique is widely used in many applications (Shahraki, Rafsanjani, and Saeid). Efficiency of
direct transmission will be reduced, if the geographical zone is bigger than the certain threshold (Chiang, Huang, and Chang Shahraki, Rafsanjani, and Saeid). Hence, to enhance the lifetime of the scalable network, it is required to use multi-hop communication for intra-cluster routing as well as inter-cluster routing. There are some applications of WSN like forest fire detection for which information must be received by the BS within the bounded delay to avoid disaster. For such delay constraint applications, it is difficult to enhance the lifetime of a WSN (Ammari Manjeshwar and Agrawal, “TEEN: A Routing Protocol for Enhanced Efficiency in Wireless Sensor Networks.” “APTEEN: A Hybrid Protocol for Efficient Routing and Comprehensive Information Retrieval in Wireless Sensor Networks.”). Direct transmission provides minimal delay, but increases energy consumption of WSN nodes. On the other hand, multi-hop communication is energy efficient as nodes have to transmit over a shorter distance; and energy consumption is directly proportional to the distance (Ammari Younis, Youssef, and Arisha), but it increases the delay. Also, one should select direct transmission or multi-hop transmission between CH and member nodes, and between CH and other CHs or BS to balance between the energy consumption of a node and delay encountered by the data. If a multi-hop communication is used, then the selection of the “next hop” is also a challenging issue. If the same node is selected as a “next hop”, then it runs out of energy within a short period. Hence, there is a need to design a CH election process which takes care of the trade-off between energy and delay by selecting direct transmission or multi-hop transmission for intra-cluster and inter-cluster communication. If multi-hop transmission is used, then selection of “next hop” to balance between the energy and delay is also a challenging task.

4.1.1 Major contributions

Following is the summary of contributions:

- A Cluster Head Election approach EDIT is proposed to optimize two conflicting objectives named “Energy” and “Delay”.

- A trade-off between Energy and Delay is found by considering two different types of distances between CH and its member nodes: i) Euclidean distance and ii) Hop-count.
• It is shown that how the selection of “next hop” in multi-hop communication affects the Energy and/or Delay requirements of the underlying application.

• It is also shown that how controlling parameters of EDIT affect on Energy and Delay.

• The proposed approach is proven by extensive simulations using realistic radio parameters to get simulation results closest to the test bed.

4.2 Related Work

In (Bandai and Watanabe), authors have analyzed trade-off between delay and energy for data aggregation. They have shown that WSN suffers with energy consumption with non-aggregation methods and WSN suffers with delay when the full aggregation method is used. In (Zhang et al.), a lower bound of energy-delay trade-off and energy efficiency was proposed by the authors using a realistic unreliable link model in AWGN, Rayleigh fast fading and Rayleigh block fading channels. In (Akkaya, Younis, and Youssef), the authors have proposed a packet scheduling mechanism at each node and it is based on Weighted Fair Queuing to get bounded delay for constrained traffic with maximal possible energy saving with data aggregation. In (Durresi, Paruchuri, and Barolli), the authors have proposed Delay-Energy Aware routing Protocol (DEAP) for heterogeneous sensor and actor networks. Energy saving is achieved by using the resources of actor nodes whenever possible. It not only uses adaptive energy management scheme to control wakeup cycle of the sensor nodes based on the delay experienced by the packets, but also uses geographical information for load balancing to achieve energy conservation.

In (Pothuri, Sarangan, and Thomas), the authors have used topological control techniques to find energy efficient paths for delay constrained applications. In (Moscibroda, Von Rickenbach, and Wattenhofer), the authors have analyzed energy delay trade-off during the deployment of the sensor network. They have proposed a formal model that can be used to compare performance of the different protocols and algorithms. In (Cohen and Kapchits), the authors have divide energy efficient routing into two sub problems: i) How to construct efficient routing trees? and ii) How to assign wakeup frequency assignment with multiple routing trees? The authors
have provided a solution to the first problem by optimal algorithm and they have proven second problem as NP-hard and provide a polynomial time approximation algorithm. In (Ammari), the authors have proposed data forwarding protocols for Trade-off Energy with Delay (TED) by slicing communication range of sensors into concentric circles. In (Bai et al.), the authors have proposed Delay-bounded Energy constrained Adaptive Routing (DEAR) problem by considering adaptive multi-path routing, energy and delay constrained jointly. In (Shahraki, Rafsanjani, and Saeid), the authors have proposed energy delay trade-off for intra-cluster routing in WSN.

In this chapter, Energy Delay Index for Trade-off (EDIT) for WSN is proposed by considering two different types of distances: i) Euclidean Distance and ii) Hop-count. This chapter is the first attempt to find the energy delay trade-off using two different kinds of distances for delay constrained applications. The proposed protocol along with the results are presented and discussed in the following sections.

4.3 Cluster Head election with Energy Delay Trade-off

The proposed algorithm works in rounds and each of these rounds are divided into two phases: i) Cluster Setup Phase and ii) Steady State Phase. A neighbor discovery phase executed once before the commencement of the first round and it is explained below.

4.3.1 Neighbor discovery phase

The algorithm begins with neighbor discovery phase, which is initiated by the sink by sending a Hello packet. A Hello packet consists of Sender Id, Hop-count and Euclidean distance to reach the sink and the location of the sender. Hop-count and Euclidean distance both are used to measure distance from the sink. Receiving nodes of a Hello packet, add the sender as its neighbor and record information like Sender Id, Hop-count and location, and then send Hello Reply to the sender. Each receiving node also forwards the Hello packet by setting its id as Sender Id, location parameter, and both distances, Hop-count and Euclidean distance, to reach the sink.

Whenever any node is having its energy less than the threshold (depending on the application), it will broadcast itself as a dead node by sending Dead message. The
receiving nodes update their neighbor table on reception of *Dead* messages. Neighbor discovery phase should be done only once at the time of network deployment.

### 4.3.2 Cluster Setup Phase

\[
\text{WaitTime}_{\text{Energy}} = \frac{1}{\text{Remaining Energy}} \tag{4.1}
\]

At the end of Neighbor discovery phase, each node waits for \(\text{WaitTime}_{\text{Energy}}\), before it broadcasts its energy level. A node compares its energy level with the energy level of the nodes from which it has received *Energy Messages*. If a node has less energy, then the node will cancel its timer and decides to be a cluster member.

The probable cluster heads are the set of nodes, which have sent *Energy Messages* and after that, either they do not receive any *Energy Messages* or their energy is higher than the energy received in *Energy Messages*. It may possible that more than one node may have the same energy level and they are in communication range of each other. To break a tie in such cases, Energy Delay Index for Trade-off (*EDIT*) is used. *EDIT* is calculated from Equation 4.2 only for the probable cluster heads. Values of \(\alpha\) and \(\beta\) lie in the range of \([0,1]\) and \(\alpha + \beta \neq 0\) in Equation 4.2.

\[
\text{EDIT} = \left( \frac{\text{TotalNeighbors}}{\text{TotalNodes}} \right)^{\alpha} + \left( \frac{1}{\text{Avg\_Dist\_from\_Sink}} \right)^{\beta} \tag{4.2}
\]

Each probable cluster head will wait for \(\frac{1}{\text{EDIT}}\) time before doing announcement that it is a final cluster head. All probable cluster heads, which receives *Final Cluster Head* announcement becomes the member nodes for the current round provided that a *Final Cluster Head* announcement is yet to be done by them. These member nodes cancel their *EDIT* timers and go to *sleep* state until the commencement of Steady State Phase. It helps to save energy of nodes. This double filtering scheme ensures that the node with the highest energy among the neighboring nodes will be elected as cluster head. It also ensures that these highest energy nodes must also have more number of neighboring nodes (good amount of aggregation helps to save energy) and minimal distance from the sink (helps to reduce communication delay) for a given value of \(\alpha\) and \(\beta\). After CH announcements, non-CH nodes will select one of the CHs as their Cluster Head. Selection of CH is based on minimum communication energy expenditure between non-CH node and selected CH node. After selection
of CH node, non-CH nodes will send \textit{Cluster Join} message, including their current energy level. Each final CH node prepares TDMA schedule for its own member nodes from which it has received \textit{Cluster Join} messages. It also selects one of the member nodes as a gateway node, if two CH nodes are not in a communication range of each other. Selection of a gateway node depends on the energy/delay requirements of the underlying application. If network longevity is a prime concern for underlying application, then the highest energy member node will be selected as a gateway node, and if the delay is a prime concern for a given application, then a node having minimum distance from the sink would be selected as a gateway node. A TDMA schedule itself carries information regarding the active time period for the identified gateway node. This piggybacking scheme helps to save energy of a CHs by reducing the number of bits required to be communicated. This scheme also helps to save energy of gateway nodes as the duration to activate gateway nodes is informed by CHs in advance. Steady State Phase begins after TDMA schedule is informed to all the nodes.

4.3.3 Steady State Phase

All nodes remain in the \textit{sleep} state except CHs nodes. Data transmission from non-CH nodes to CH node is done as per TDMA schedule announced by the CH. This scheme avoids collision of the data messages, and each member node remains in \textit{transmit} state for a short duration. This helps to save energy of member nodes.

4.4 Simulation Parameters and Result Discussion

4.4.1 Simulator and Parameters used for experiments

\textit{EDIT} protocol is tested using Castalia Simulator (Boulis, “Castalia: revealing pitfalls in designing distributed algorithms in WSN” “Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User’s manual”). Energy-Delay Trade-off is analyzed by considering two different types of distances of neighboring nodes from the sink: i) Euclidean distance ii) Hop-count. WSN nodes were uniformly deployed in the area of 250mx250m with varying node density between 50 to 250. Each simulation was carried out for 1500 seconds and repeated five times. The results were plotted by taking the mean value of the parameter of interest. Simulation parameters
are shown in Table 4.1.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node Deployment Area</td>
<td>250m X 250m</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>1) 50</td>
</tr>
<tr>
<td></td>
<td>2) 100</td>
</tr>
<tr>
<td></td>
<td>3) 150</td>
</tr>
<tr>
<td></td>
<td>4) 200</td>
</tr>
<tr>
<td></td>
<td>5) 250</td>
</tr>
<tr>
<td>Initial Energy/Node (in Joules)</td>
<td>1) 10</td>
</tr>
<tr>
<td></td>
<td>2) 18720</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>1500 seconds</td>
</tr>
<tr>
<td>Transceiver</td>
<td>CC2420</td>
</tr>
<tr>
<td>Maximum Transmission Power</td>
<td>0 dBm</td>
</tr>
<tr>
<td>Baseline Node Power</td>
<td>6mW</td>
</tr>
<tr>
<td>Packet Size</td>
<td>30 Bytes</td>
</tr>
<tr>
<td>Sink Node Id</td>
<td>Node 0</td>
</tr>
<tr>
<td>Simulation Runs</td>
<td>Repeated 5 times for each configuration and mean value is recorded for the parameter of interest</td>
</tr>
</tbody>
</table>

Table 4.1: Parameters used for the simulation of the EDIT protocol

### 4.4.2 Result Discussion

End to end latency is shown in Figure 4.1. Figures are kept side by side to compare latency values recorded with Euclidean distance and Hop-count for a given node density. Each node was given the initial energy of 18720 Joules which is equivalent to AA batteries (Boulis, “Castalia: A simulator for wireless sensor networks and body area networks: Version 3.2: User’s manual”). It can be easily seen from the Figure 4.1 that end to end delay felt by the packets are small when Euclidean distance is used in Equation 4.2 compared to Hop-count. An average energy consumption per node is also measured for the same simulation set up and it is shown in Figure 4.2.
Energy consumption per node is more when Euclidean distance is used in Equation 4.2 compared to Hop-count.

Simulations are repeated by giving 10 Joules of initial energy to each node. Results for end to end delay is shown in Figure 4.3. This result also confirms the result that obtained with 18720 Joules of the initial energy.

Network lifetime is measured in terms of First Node Dies (FND), Half of the Nodes Alive (HNA) and Last Node Dies (LND) and it is shown in Figures 4.4-4.6 respectively. Number of rounds after which first node dies, 50% of the nodes alive and the last node dies is more when Hop-count is used as a distance in Equation 4.2 compared to Euclidean distance.

Nodes have to transmit for a longer distance when Euclidean distance is used in EDIT protocol. Since, there would be a less number of forwarders encountered by the packet to reach to the sink. Hence, smaller delay felt by the packets. As mentioned earlier that energy expenditure of a node is directly proportionate to the distance. Hence, there would be huge energy expenditure when Euclidean distance is used in the EDIT protocol. The same reason is also applicable to Hop-count for getting higher delay and lower energy consumption.

4.4.3 Effect of $\alpha$ and $\beta$

$\alpha$ and $\beta$ are controlling parameters of EDIT protocol, and it is application dependent. $\alpha$ is used to control the importance of energy conservation and $\beta$ is used to control the importance of end to end latency. To see the effect of $\alpha$ and $\beta$ on EDIT protocol, values of $\alpha$ and $\beta$ are set to 1 and 0 respectively, and end to end delay and energy consumption values are measured. The experiment is repeated by setting values of $\alpha$ and $\beta$ to 0 and 1 respectively.

When $\alpha = 0$ and $\beta = 1$, variation in the values of EDIT in Equation 4.2 is due to $\beta$. Hence, it indicates that end to end delay is more important for a given application. On the other hand, when $\alpha = 1$ and $\beta = 0$, variation in the values of EDIT in Equation 4.2 is due to $\alpha$, which indicates that energy conservation is more important for the underlying application compared to end-to-end delay. The same is proven with the simulation and it is shown in Figure 4.7.
Figure 4.1: End to End delay for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 18720 Joules.
Figure 4.1: (Continued) End to End delay for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 18720 Joules.

Figure 4.2: Per Node Energy Consumption for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 18720 Joules.
Figure 4.3: End to End delay for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 10 Joules.
CHAPTER 4. EDIT PROTOCOL

70

End to End Latency with Euclidean Dist. for a network of 200 nodes with initial energy 10 Joules/Node

End to End Latency with Hop Count for a network of 200 nodes with initial energy 10 Joules/Node

End to End Latency with Euclidean Dist. for a network of 250 nodes with initial energy 10 Joules/Node

End to End Latency with Hop Count for a network of 250 nodes with initial energy 10 Joules/Node

First Node Dies (FND) with Euclidean Distance

First Node Dies (FND) with Hop-count Distance

Figure 4.3: (Continued) End to End delay for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 10 Joules.

Figure 4.4: First Node Dies (FND) for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 10 Joules.
CHAPTER 4. EDIT PROTOCOL

(a) Half of the Nodes Alive (HNA) with Euclidean Distance
(b) Half of the Nodes Alive (HNA) with Hop-count Distance

Figure 4.5: Half of the Nodes Alive (HNA) for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 10 Joules.

(a) Last Node Dies (LND) with Euclidean Distance
(b) Last Node Dies (LND) with Hop-count Distance

Figure 4.6: Last Node Dies (LND) for a network of varying node density between 50 to 250 nodes and each node was given initial energy of 10 Joules.
4.5 Summary

The protocol, *EDIT*, is proposed, examined and derived to analyze energy-delay trade-off by doing extensive simulations. The effect of two types of distances to be used to elect cluster heads using *EDIT* protocol is successfully demonstrated and their effect on delay and energy. In the course of research, the effect of controlling parameters for *EDIT* protocol were manifested. The simulation results presented will be useful to other researchers to analyze of two contradicting parameters, namely energy and delay before implementing it on a real test bed.

In the next chapter, a protocol for energy efficient routing is proposed through cross-layer optimization, wherein, Ant Colony Optimization (ACO) is used to elect the cluster heads. Later, an approach is proposed to minimize cluster formation overhead by relaxing maximum energy criteria to elect cluster heads. In addition to that, a scheme is proposed that enforces a node to become the cluster head, if it has not received any cluster head announcement within the specified duration.